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PREFACE

Microcircuit Engineering 80 was held at the Koninklijk Instituut voor de Tropen in Amsterdam, September 30 - October 1 and 2, 1980 and organized by the Delft University of Technology in close cooperation with the Philips Research Laboratories. Microcircuit Engineering 80 was the sixth in a series of International Conferences on Microlithography that started at Cambridge in 1975, followed by meetings at Aachen, Paris, Cambridge and Aachen.


The organizing committee of Microcircuit Engineering 80 consisted of S. Middelhoek, chairman; R.P. Kramer, secretary; S. Wittekoek, treasurer; C. Beekhuizen, O.W. Memelink, J.P. le Poole and J.P. Verwey, C. Beekhuizen deserves special thanks for his efforts in handling the local arrangements.


Microcircuit Engineering 80 was made possible by grants from the Dutch Minister for Science Policy, Perkin Elmer Corporation and N.V. Philips' Gloeilampenfabrieken.

The conference was attended by 240 workers in the field from 17 different countries. The technical program contained 6 invited and 40 regular papers. Each of the invited papers opened a topical session.

I would like to compliment the authors with their contributions to this conference and to thank the session chairmen and all of the participants for making Microcircuit Engineering 80 a successful meeting.

Roel P. Kramer

Chairman Technical Program Committee
Resolution, overlay, and field size limits for U.V., x-ray, and electron beam lithography are described. Economic trade-offs between the methods, and their suitability for particular thin film device applications, are not considered. The following are some of the conclusions that are discussed.

1) At 1μ linewidth, contrast for optical projection can be higher than that for electron beam.
2) X-ray lithography offers the highest contrast and resist aspect ratio for linewidths above about 0.1μ, but for dimensions below 0.1μ, highest aspect ratio is obtained with electron beam.
3) With electron beam exposure on a bulk sample, contrast for 50nm linewidth is the same as that for 1μ linewidth, provided the resist is thin.
4) Ultimately the range of secondary electrons limits resolution in E/B lithography, just as the range of photoelectrons limits resolution in x-ray lithography. In both cases, minimum linewidth and spacing in dense patterns is about 20nm.

INTRODUCTION

This paper discusses how small a structure can be made with methods similar to those used to fabricate microcircuits, how accurately these structures can be placed with respect to previously fabricated structures, and how large an area can be covered without the resolution and accuracy of the fabrication process becoming degraded. U.V., x-ray, and electron beam techniques are considered. Exposure speed and economic trade-offs are not discussed. In general the size limits are well beyond those employed in current semiconductor devices. Because of this, the paper does not attempt to answer the complex and difficult questions facing semiconductor technologists about what lithography to use for the next generations of microcircuits. Rather, it examines fundamental limits with the aim of clarifying the extendability of the methods.

Provided the highest resolution resists are used, resolution in thin film lithography processes is set by the resolution of the exposing tool, or by scattering of the exposing radiation in the resist or sample, and not by fundamental resist limitations such as the grain-size limitations encountered with silver halide emulsions. It should be emphasized, however, that the resist development process and resist contrast are of vital importance in determining the dimensional accuracy of the developed resist pattern. The etching, plating or lift-off processes that are used in conjunction with the resist pattern are of similar importance. Eventually, at dimensions below a few tens of nanometers, materials problems associated with thin films are encountered. In particular, polycrystalline films become non-uniform in thickness or even discontinuous.

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It is possible to produce very small structures by shadowing onto well defined surface steps. This method has been used to make semiconductor and Josephson devices, and to explore the resolution limits of x-ray lithography. Except for the last example, we will not discuss this method here.

**U.V. SHADOW PRINTING**

Resolution in a shadow image is set by diffraction between the mask and the bottom of the resist layer. Thick resists or gaps between mask and resist degrade resolution. In practice the minimum useable linewidth \( W(m) \) can be approximated by

\[
W = 15\sqrt{\frac{\lambda S}{200}}
\]

where \( \lambda(m) \) is the wavelength of the radiation used to expose the resist (it is assumed that the wavelength is the same in the resist and in the gap), and \( S(m) \) is the distance between the mask and the bottom of the resist. This is the condition where the intensity at the center of an isolated line matches the background intensity. This criterion is derived from the degradation in resolution due to Fresnel diffraction.

![Figure 1](image)

**Figure 1** Linewidth versus gap for deep U.V. and x-ray proximity printing. Theoretical points correspond to the Gruen range for the maximum energy photoelectrons. Experimental points were measured by Feder and Spiller.
Linewidth versus gap for deep U.V. radiation and soft x-rays is plotted in Fig. 1. Good agreement has been established with experiment, at least in the region of 0.5μ to 2μ. For example, 0.5μ linewidth has been produced in 1μ of PMMA resist by employing 2000Å - 2600Å radiation and maintaining intimate contact between mask and wafer. It is obviously difficult to maintain perfect contact over large areas because of contaminating dust particles, and a few square centimeters is probably a practical limit even for experimental devices. Ultimately the size of the structure that can be reproduced is limited only by the thickness of the imaging layer. For example, it should be possible to produce 200nm dimensions in 100nm of resist over very small areas (a few hundred micron).

In principle, positioning of a mask with respect to a sample can be made extremely precise (≤ 0.1μ) by using optical detection methods. Accuracy beyond the Rayleigh criterion is possible by threshold detection because, in general, the S/N ratio in the detected signal is favorable. Methods that employ diffracting components on mask and wafer have also proven effective in the laboratory, although in some instances errors arise if the mask to wafer spacing varies. Overlay accuracy over the whole sample will, of course, depend on temperature control and on the ability to control mask and wafer distortion. No fundamental limits can be identified in this instance.

OPTICAL PROJECTION PRINTING

Both reflecting optics and refracting optics have been employed in optical projection cameras developed for microcircuit lithography. To date highest resolution has been obtained with refracting lenses, although reflecting systems have proven more economic in manufacturing environments. In practice 60% modulation is necessary in the optical image for satisfactory resist exposure. This means that for an incoherently illuminated system, the minimum dimension that can be reproduced is given by λ/1.28(N.A.), where N.A. is the numerical aperture of the lens. For a 0.41 N.A. lens and λ = 405nm, minimum linewidth is 0.8μ. The contrast obtained with a 0.41 N.A. optical system is shown in Fig. 2 where it is compared to the contrast obtained with electron beam lithography. Field sizes up to 6 mm x 6 mm can be printed with a lens of this type. Depth of field is given approximately by ±λ/2(N.A.)²(± 1.2μ for the 0.41 N.A. lens) but depends on the resist process, the substrate reflectivity and the degree of coherence of the illumination. Two layer resist processes in which the image is formed in a thin, flat resist layer on top of a much thicker planarizing layer, greatly alleviate the problems of forming high resolution, high aspect ratio resist patterns.

In the limit, microscope objectives with 0.95 N.A. are available and, provided very small fields (200μ x 200μ) are adequate, linewidths < 0.4μ should be achievable under carefully controlled laboratory conditions, and in very thin resist layers. Depth of field will be reduced to about ± 0.2μ. Deep U.V. (λ = 200nm - 260nm) lenses will be difficult to build because of the lack of materials that are transparent at these wavelengths and yet have relatively high refractive indices. Elements made from low refractive index glass will have to have smaller radii of curvature and this increases higher order aberrations.

As with U.V. shadow printing, alignment to ± 0.1μ accuracy should in principle be possible through a variety of methods (e.g. Ref. 13), and fields can be joined together with similar accuracy by laser interferometry.
Figure 2  Contrast versus linewidth for electron beam and optical projection lithography. Electron backscattering coefficients for silicon substrate were obtained from reference 21.

X-RAY LITHOGRAPHY

Several promising x-ray imaging approaches are being pursued, but resolution approaching diffraction limits has yet to be obtained, even for moderate apertures.\(^4\) It is possible, however, to use soft x-rays (\(\lambda = 0.4\)nm - 5nm) for shadow printing\(^5\) and obtain resolution that is adequate in principle to replicate the smallest dimensions attainable with electron beam fabrication (i.e., about 10nm linewidths).\(^6\) Two factors set the resolution for x-ray lithography: (1) Diffraction between mask and wafer, and (2) The range of the photoelectrons formed when the x-ray photon energy is absorbed in the resist. The same diffraction criterion used above for deep U.V. shadow printing can be applied to x-rays to give the relationships shown in Fig. 1. The significant factor to be observed is that with soft x-rays, a gap in excess of 100\(\mu\)m can be used for 1\(\mu\)m linewidth. In most semiconductor applications, penumbral blurring due to finite source size is more likely to limit resolution.

The range of photoelectrons in resist has been measured experimentally by Spiller and Feder.\(^6\) The Gruen depth dose relationship\(^7\) can also be used to estimate this photoelectron range although Gruen only confirmed this relationship over the energy range of 5keV to 54kV. It has been suggested\(^2\) that the minimum linewidth will be equal to the Gruen range (\(R_G\))

\[
R_G(m) = \frac{2.57 \times 10^{-11} E(eV)^{1.75}}{\rho(gm/cm^3)} \approx 10^{-23} \lambda^{-1.75} (m)
\]
where $E(eV)$ is the maximum photoelectron energy associated with $\lambda(m)$, the wavelength of the exposing x-rays and $\rho(gm/cm^3)$ is the density of the resist (1.2gm/cm$^3$ for PMMA). The Gruen range and Feder and Spiller’s experimental points are shown in Fig. 1. As can be seen, the highest resolution predicted is about 5nm using carbon characteristic radiation (4.5nm). In support of this prediction, 4.5nm x-rays have been used to shadow-print biological samples into PMMA with a spatial resolution of about 10nm. In this case, only a relief profile was obtained in the resist layer rather than a fully developed resist image. The resist was metallized and the sample examined in a high resolution surface SEM. 17.5nm lines have also been replicated with x-ray lithography using a mask fabricated by alternate shadowing of tungsten and carbon onto the side of surface steps. (See Fig. 3.)

Figure 3 20nm lines produced in PMMA by replication with soft x-rays.$^{17}$

High aspect ratio in the resist is a significant advantage with x-ray lithography when compared to optical and electron beam methods. This advantage is very large at dimensions greater than about 0.1$\mu$, but disappears compared to E/B lithography for dimensions below about 0.1$\mu$. This is because the degradation due to diffraction with x-rays exceeds the degradation due to electron scattering with electron beam, provided high energy (100keV) electrons are used. (See Fig. 4.) Aspect ratio is still satisfactory with x-ray exposure down to linewidths of a few tens of nanometers.

As with U.V. shadow printing, mask/wafer registration for x-ray lithography should be achievable to an accuracy of 0.1$\mu$; however, overlay over a whole pattern will probably be considerably worse with conventional x-ray sources because of mask distortion and/or lack of mask or sample flatness. Overlay accuracy will be improved with the use of a small divergence source such as a synchrotron storage ring, or by limiting the exposed area to 1 cm x 1 cm or less. For many applications the latter will require step and repeat exposure and considerably slow the exposure process. Step and repeat should be feasible when a storage ring is used.$^{19}$
Figure 4  Maximum aspect ratio achievable with deep U.V. and x-ray proximity printing, and with electron beam. With proximity printing, resist thickness is determined by Fresnel diffraction. With electron beam, lateral scattering in the resist determines resolution.

ELECTRON BEAM LITHOGRAPHY

Resolution in electron beam lithography processes is limited by electron scattering effects in the resist and by backscattering from the sample substrate, and not by the resolution of the electron optical system. For dense patterns and samples thick compared to the electron penetration range, exposure dosage has to be altered according to the local pattern density in order to compensate for variations in the backscattered electron dose (proximity effect). Compensation for this effect is valuable even at dimensions of $1\mu - 2\mu$, particularly for thick (> 500nm) resist layers.

In order to measure the fundamental resolution limit for electron beam exposure of resist, the resolution of the resist PMMA has recently been measured in the absence of significant electron scattering. Thin resist layers (< 0.1μ) on thin (< 0.1μ) substrates were exposed with a 1nm diameter electron beam using a scanning transmission electron microscope (STEM). The samples were subsequently examined, after development, in the same instrument (see Fig. 5). The experimental data indicate that the exposure distribution can be approximated by a Gaussian distribution with a sigma ($\sigma$) of 12.5nm. It is assumed that this spread arises from straggling of secondary electrons into the resist. Using this knowledge, and data on resist exposure due to backscattered electrons, the contrast for electron
beam exposure can be calculated over a broad range of linewidths (see Fig. 2). The contrast \((K)\) is calculated for an ideal pattern of lines and spaces from

\[
K = \frac{Q_L - Q_S}{Q_L + Q_S}
\]

where \(Q_L\) is the dose at the center of a line, and \(Q_S\) is the dose at the center of a space. It is important to note that with a thick substrate, the contrast is the same for 0.05\(\mu\) lines as it is for 1\(\mu\) lines provided the resist is thin (< 0.1\(\mu\)). Electron scattering in thick resist layers is calculated using data obtained by Monte Carlo calculations. The calculations have been confirmed by experimental measurements.

Figure 5 Bright-field STEM image of developed resist pattern in 30nm thick PMMA. Exposure was made with a 1nm diameter, 50kV electron beam. Narrowest lines are 10nm wide, however, straggling of secondary electrons into the resist limits minimum center to center spacing to about 40nm.
Operational devices with very small dimensions have been fabricated using thin Si$_3$N$_4$ membranes and vapor deposited monolayers of silicone oil as the resist. Isolated metal lines 8nm wide have been formed and devices such as the niobium nanobridge SQUID's shown in Fig. 6 have been made and tested. The most significant advantage of thin substrates is that they allow the samples to be examined in a transmission electron microscope. These isolated structures could also have been made on bulk substrates because the backscattered electrons would have been very small. The backscattered contribution to a isolated 25nm line on a silicon substrate is .004 times the incident exposure. 40nm dimensions in a metal pattern have been obtained using a two layer resist lift-off method.

![Figure 6 Bright-field STEM image of two niobium SQUID's fabricated with vapor deposited silicone oil resist and ion etching. Narrow (black) wires are 25nm wide.](image)

The maximum field size addressable by an electron beam with a single electronic deflection system is presently limited by the noise/bandwidth of the deflection control system to 20,000 to 50,000 times the beam diameter (or the beam edge definition in shaped beam systems). Large aperture (> 3 x 10$^{-3}$ radian) focusing and deflection systems have been designed that can exceed this number of lines without the beam becoming defocused (e.g. ref. 31). Larger fields can be exposed by "stitching" together smaller patterns. Joining accuracy of ± 0.1$\mu$m has been demonstrated both by using laser interferometry to keep track of the position of the sample with respect to the electron beam, and by registering the electron beam to an array of alignment marks. As this indicates, registration on solid samples can be better than ± 0.1$\mu$m, and there is no reason why registration accuracy equal to the resolution of a good surface SEM, 5nm, cannot be reached provided suitable alignment marks can be used.

With thin film substrates, it should be possible to locate the beam with respect to the sample to an accuracy corresponding to the resolution of a transmission (< .5nm) electron microscope.

REFERENCES


1. INTRODUCTION

In scanning electron beam lithography systems, the use of combined magnetic and electrostatic deflection offers several advantages. Magnetic deflection offers high deflection sensitivity and therefore large field coverage, but the deflection speed is usually limited to a few megahertz by inductance and eddy current problems. Electrostatic deflection, on the other hand, permits much higher deflection speeds (several hundred megahertz) with lower eddy current errors, and the deflector can be made much more accurately (which reduces the asymmetry aberrations) and it can simultaneously be used as a stigmator, but the deflection sensitivity and field coverage are usually relatively small. By using a dual channel deflection system, with magnetic main-field plus electrostatic sub-field (Weber and Moore 1979), the advantages of both types of deflectors can be combined. An additional advantage of a dual channel deflection system is that the addressing requirements are less stringent, because they are divided between the two deflection channels. With a dual channel system, it should be possible to achieve a main-field size of 5 mm, a sub-field size of 0.5 mm, with 0.1 μm addressing and a stepping rate of several hundred megahertz.

Similarly, there are advantages in combining magnetic and electrostatic focusing. By using a magnetic lens, followed by an electrostatic retarding-field lens, we can reduce both the lens aberrations and the electron-electron interactions (Yau et al. 1980). Fig. 1 shows how this can be done. The beam is made to pass through the magnetic lens at a higher voltage than usual, e.g. 60 kV; this reduces the electron-electron interactions. The beam is then decelerated to, say, 25 kV at the image plane by the retarding-field electrostatic lens. This arrangement significantly reduces the lens aberrations, as has been
confirmed by computer calculations. Retarding-field electrostatic lenses are also of potential importance for low-voltage lithography systems (operating at, say, 1 kV), which offer the possibility of greatly reducing proximity effects. Furthermore, pure electrostatic focusing and deflection systems are useful for ion beam lithography, because electrostatic fields can focus heavier particles more effectively than magnetic fields.

To assist the design of such systems, we have developed a set of computer programs for calculating the fields and the optical properties of any combination of electrostatic and magnetic lenses and deflectors. Fig. 2 shows a typical system which our programs can analyze, with magnetic main-field deflectors, electrostatic sub-field deflectors, and possibly electrostatic, as well as magnetic, focusing. We will now describe the principles of our programs and some typical applications.

Fig. 1. A magnetic lens followed by an electrostatic retarding-field lens. This arrangement reduces both the aberrations and the electron-electron interactions.

Fig. 2. A combined electrostatic and magnetic focusing and deflection system.

Fig. 3. A typical electrostatic deflector, showing the general form of the electrode potentials for an x-deflection.
2. COMPUTATION OF FIELD DISTRIBUTIONS

2.1. Electrostatic deflection fields

Fig. 3 shows a typical electrostatic deflector, and the form of the electrode potentials corresponding to an x-deflection. The potential is antisymmetrical in x and symmetrical in y. Since the potential has fourfold symmetry in the (x,y) plane and obeys Laplace's equation, the potential near the z-axis has the general form

$$\phi(r,\theta,z) = -V_x \cdot \left[ f_1(z)r - \frac{1}{8} f_1''(z)r^3 + \ldots \right] \cos \theta + f_3(z)r^3 \cos 3\theta + \ldots$$

(1)

where $V_x$ = x-deflection voltage,

$f_1(z)$ = normalized deflection field at the axis,

$f_3(z)$ = third harmonic of the normalized deflection field.

A similar expression can also be written for a y-deflection. The potential for a general (x,y) deflection is then obtained simply by adding together the potentials for the two individual deflections. The functions $f_1(z)$ and $f_3(z)$ uniquely define the deflection field up to third-order terms in $r^3$; they therefore suffice for computing the optical properties of the deflector up to the third-order aberrations.

We have developed two alternative programs for computing the field functions $f_1(z)$ and $f_3(z)$ for any deflector. The first program uses the charge density method (Birtles et al. 1973), which involves calculating the charge distribution on the electrodes, from which the potential distribution can be computed using Coulomb's law. To calculate numerically the charge density distribution on the electrodes, we first sub-divide the electrode surfaces into N small sub-electrodes, and assume that the i-th sub-electrode carries a uniform surface charge density $\sigma_i$. The charge density distribution is then obtained by solving the matrix equation

$$\begin{bmatrix} P_{ij} \end{bmatrix} \begin{bmatrix} \sigma_i \end{bmatrix} = \begin{bmatrix} \phi_i \end{bmatrix} \quad (i=1,N; j=1,N)$$

(2)

where $\phi_i$ is the known potential on the i-th sub-electrode, and $P_{ij}$ represents the potential at the centroid of sub-electrode i due to unit surface charge density on sub-electrode j. The values of the coefficients $P_{ij}$ are computed using the formula

$$P_{ij} = \frac{1}{4\pi \varepsilon_0} \iint_{A_j} \frac{dA_i}{\varepsilon_{ij}}$$

(3)

where $\varepsilon_0$ is the permittivity of free space, and $\varepsilon_{ij}$ is the distance from the centroid of sub-electrode i to an element of area $dA_i$ on the surface of sub-electrode j; the integral is evaluated over the surface area $A_i$ of sub-electrode i. It can be seen from Eq. (3) that the values of the coefficients $P_{ij}$ depend only on the geometry of the sub-electrodes.
After calculating all the coefficients $P_{ij}$, we solve the matrix equation (2) for the charge densities $\sigma_{i}$. The potential at any point is then given by

$$\phi = \frac{1}{4\pi \varepsilon_0} \sum_{j=1}^{N} \sigma_j \int \int_{A_j} \frac{dA_j}{\ell_j}$$

where $\ell_j$ is the distance from $dA_j$ to the point where the potential is being calculated. This method is particularly suitable for three-dimensional structures, such as electrostatic deflectors.

In our program, we assume that the electrostatic deflector consists of cylindrical and/or conical segments, as shown in Fig. 4. Each sub-electrode is then itself a cylindrical or conical segment. For this type of sub-electrode, the integral in Eq. (3) can be reduced to a one-dimensional form, which can readily be evaluated numerically. After calculating the charge density distribution, the deflection field functions $f_1(z)$ and $f_3(z)$ can be evaluated analytically.

An additional advantage of the charge density method is that it can also be used to calculate the capacitance of the deflector. The capacitance is an important parameter, because it governs the deflection speed capability and the power supply requirements. The capacitance $C$ is calculated using the formula

$$C = 2 \sum_{i=1}^{N} \phi_i Q_i / \phi_{\text{max}}^2$$

where $Q_i$ is the charge on the $i$-th sub-electrode and $\phi_{\text{max}}$ is the maximum potential on the deflection plates. This formula is derived from energy considerations.

Our second program for electrostatic deflection fields uses the finite element method (Zienkiewicz 1971, Munro 1973). Although an electrostatic deflector is an essentially three-dimensional structure, we can exploit the fourfold symmetry of the deflector so as to obtain the field functions $f_1(z)$ and $f_3(z)$ using two two-dimensional finite element solutions. We assume that the potential varies linearly in the azimuthal gaps between the electrodes. This enables us to express the electrode potential $\phi_b$ as a Fourier series of the general form
where the $m$-th Fourier component $\phi_{mb}$ is given by

$$\phi_{mb} = \frac{1}{\pi} \int_{-\pi}^{\pi} \phi_b(\theta) \cos m\theta \, d\theta \quad (7)$$

Having assumed a linear variation of $\phi$ in the azimuthal gaps between the electrodes, the Fourier components $\phi_{mb}$ are readily calculated using Eq. (7). We now express the potential in the deflector as a sum of its harmonic components, with the general form

$$\phi(r,\theta,z) = \sum_{m=1,3,\ldots}^{\infty} \phi_m(r,z) \cos m\theta \quad (8)$$

Then, since $\phi(r,\theta,z)$ obeys Laplace's equation, the $m$-th harmonic of the potential, $\phi_m(r,z)$, satisfies the equation

$$\frac{\partial^2 \phi_m}{\partial z^2} + \frac{\partial^2 \phi_m}{\partial r^2} + \frac{1}{r} \frac{\partial \phi_m}{\partial r} - \frac{m^2}{r^2} \phi_m = 0 \quad (9)$$

To solve this equation, we replace it by the corresponding functional

$$F_m = \int \int \frac{\pi \epsilon_0 r}{2m} \left[ \left( \frac{\partial \phi_m}{\partial r} \right)^2 + \left( \frac{\partial \phi_m}{\partial r} \right)^2 + \left( \frac{m \phi_m}{r} \right)^2 \right] \, dr \, dz \quad (10)$$

We now minimize this functional numerically by the finite element method, subject to the boundary conditions imposed by Eq. (7) at the electrode surfaces, and the fact that $\phi = 0$ along the axis and at large distances from the deflector. After calculating $\phi_m(r,z)$, the field function $f_m(z)$ is given by the formula

$$f_m(z) = \lim_{r \to 0} \left[ \frac{-\phi_m(r,z)}{r^m} \right] \quad (11)$$

Using this method, we calculate the field functions $f_1(z)$ and $f_3(z)$.

### 2.2. Calculation of the magnetic deflection fields

The calculation of magnetic deflection fields has been described previously (Munro 1975), and will therefore only be summarized here. We assume that the deflection coils have a fourfold symmetry in the $(x,y)$ plane. Then, by analogy with Eq. (1), the magnetic scalar potential near the $z$-axis has the general form
\[ \phi(r, \theta, z) = I_x \left[ (d_1(z)r - \frac{1}{8}d_1''(z)r^3 + \ldots) \cos \theta + d_3(z)r^3 \cos \theta + \ldots \right] \] (12)

where \( I_x \) = current producing a field in the x-direction,
\( d_1^x(z) \) = normalized magnetic deflection field at the axis,
\( d_3(z) \) = third harmonic of the normalized deflection field.

The functions \( d_1(z) \) and \( d_3(z) \) suffice for calculating the optical properties of a magnetic deflector up to the third-order aberrations.

We have developed two programs for calculating the field functions \( d_1(z) \) and \( d_3(z) \). The first program, which is used if the coils are in free-space regions, computes the fields exactly, using the Biot-Savart formula. This formula enables us to derive analytic expressions for the field functions for any free-space deflection yoke. Expressions for the field functions for a toroidal and a saddle deflection yoke can be found in the paper by Munro (1975).

Our second program for magnetic deflection fields uses the finite element method. This program is used if ferromagnetic materials are present. To calculate the field distribution, we first express the angular distribution of the current loading in the coils as a Fourier series of harmonic components (Munro 1975). The \( m \)-th harmonic of the potential distribution, \( \phi_m(r, z) \), is then computed by minimizing an appropriate integral numerically by the finite element method. The appropriate functionals are as follows:

Toroidal yoke: 
\[ F_m = \int \int \frac{\mu_0}{2m} \left[ \left( \frac{\partial \phi_m}{\partial z} \right)^2 + \left( \frac{\partial \phi_m}{\partial r} \right)^2 + \frac{1}{r^2} \left( m \phi_m + g_m \right)^2 \right] dr \, dz \] (13a)

Saddle yoke: 
\[ F_m = \int \int \frac{\mu_0}{2m} \left[ \left( \frac{\partial \phi_m}{\partial z} \right)^2 + \left( \frac{\partial \phi_m}{\partial r} + \frac{g_m}{2m \Delta r} \right)^2 + \left( \frac{m \phi_m}{r} \right)^2 \right] dr \, dz \] (13b)

where \( g_m = \frac{4N}{\pi} \sin m \theta_o \) inside the coil,
\( g_m = 0 \) outside the coil,
\( N = \) number of turns on coil,
\( \theta_o = \) semi-angle of coil windings,
\( \Delta r = \) radial extent of the coil windings.

After calculating the \( m \)-th harmonic of the deflection potential, the field function \( d_m(z) \) is calculated using the formula
\[ d_m(z) = \lim_{r \to 0} \left[ \frac{\phi_m(r, z)}{r^m} \right] \] (14)

Using this method, we calculate the field functions \( d_1(z) \) and \( d_3(z) \).
2.3. Calculation of the lens fields
The lens fields can readily be calculated using the finite element method (Munro 1973).

3. COMPUTATION OF THE OPTICAL PROPERTIES

The computation of the optical properties is based on the principles described by Munro (1974) for purely magnetic systems and by Soma (1977) for the combined electrostatic-magnetic case.

3.1. Solution of the paraxial ray equation
The paraxial ray equation for a combined electrostatic and magnetic focusing and deflection system is

\[ w'' + \frac{\phi''}{2\phi} w' + \frac{\phi''}{4\phi} w - i \sqrt{\frac{n}{2\phi}} (Bw' + \frac{1}{2} B'w) = - \frac{VF_1}{2\phi} - \sqrt{\frac{n}{2\phi}} ID_1 \]  

where

- \( w(z) = x(z) + iy(z) \) = complex paraxial trajectory,
- \( \phi(z) \) = electrostatic lens axial potential distribution,
- \( B(z) \) = magnetic lens axial flux density distribution,
- \( F_i(z) = F_i(z) + iP_i(z) \) = complex electrostatic deflection field,
- \( D_i(z) = DX(z) + iDY(z) \) = complex magnetic deflection flux density,
- \( V = \nabla_x + i\nabla_y \) = complex electrostatic deflection voltage,
- \( I = I_x + iI_y \) = complex magnetic deflection current,
- \( n \) = charge/mass ratio of electron.

We have used complex variables in this equation, because this greatly simplifies the analysis. The paraxial ray equation can easily be solved by any of the standard numerical methods. Our program automatically adjusts the lens strengths to provide focusing at the specified image plane.

In solving the paraxial ray equation, we have separated the effects of magnetic and electrostatic deflection, by expressing a general paraxial ray \( w(z) \) starting from the axis in the form

\[ w(z) = s_o w_a(z) + V w_e(z) + I w_m(z) \]  

where

- \( s_o \) = initial slope of ray at object plane,
- \( w_a(z) \) = principal ray with zero deflection,
- \( w_e(z) \) = principal ray for unit electrostatic deflection voltage,
- \( w_m(z) \) = principal ray for unit magnetic deflection current.

![Fig. 5. Definitions of principal rays \( w_a(z), w_e(z) \) and \( w_m(z) \), and their initial conditions.](image)
We calculate the three principal rays \( w_a(z), w_e(z) \) and \( w_m(z) \); these are illustrated in Fig. 5. By using the separate rays \( w_e(z) \) and \( w_m(z) \), the first-order properties for any arbitrary ratio of electrostatic to magnetic deflection can be predicted in a single calculation. The first-order optical properties at the image plane \( z_i \) are then calculated as follows:

- **Lens magnification**: \( \left| \frac{1}{w_a'(z_i)} \right| \)
- **Lens rotation angle**: \( \text{Arg}[w_a'(z_i)] \)
- **Electrostatic deflection sensitivity**: \( |w_e(z_i)| \)
- **Electrostatic deflection direction**: \( \text{Arg}[w_e(z_i)] \)
- **Magnetic deflection sensitivity**: \( |w_m(z_i)| \)
- **Magnetic deflection direction**: \( \text{Arg}[w_m(z_i)] \)

\[ (17) \]

### 3.2. Third-order geometrical aberrations

Table 1 shows the general form of the third-order geometrical aberrations of a combined electrostatic and magnetic focusing and deflection system. The aberrations have been classified according to their dependence on the complex aperture angle \( s \), the complex electrostatic and magnetic deflections at the image plane \( \{w_e, w_m\} \), and their complex conjugates \( \{\bar{s}, \bar{w}_e, \bar{w}_m\} \). The set of 27 complex aberration coefficients in Table 1 suffices, in a single calculation, to predict the deflection aberrations for any electrostatic field size and for any magnetic field size.

To calculate the geometrical aberration coefficients, we have to evaluate 27 very complicated integrals numerically. In our program, we use a technique described by Munro and Wittels (1977), whereby all the aberration formulae have been expressed in terms of two general integration functions (one for evaluating \( K_1 - K_9 \), and the other for \( K_{11} - K_{19} \)); these functions are called with different arguments to obtain the individual aberration coefficients. This technique greatly simplifies the program for calculating the aberrations and minimizes the possibility of programming errors.

### 3.3. First-order chromatic aberrations

The first-order chromatic aberration \( \delta w_i \) has the general form

\[ \delta w_i = (\Delta \phi/\phi) \left[ L_A s(z_i) + L_E w_e(z_i) + L_M w_m(z_i) \right] \]  \[ (18) \]

where \( \Delta \phi/\phi \) = fractional change in beam voltage at image plane,
- \( L_A \) = axial chromatic aberration coefficient,
- \( L_E \) = transverse electrostatic chromatic aberration coefficient,
- \( L_M \) = transverse magnetic chromatic aberration coefficient.

These three complex chromatic aberration coefficients are evaluated with a single function, using a technique similar to that employed for the geometrical aberrations.
Table 1. Third-order geometrical aberrations of a combined electrostatic and magnetic system.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>COMA</td>
<td>$K_x^2 n_E$</td>
<td>$K_x^2 n_H$</td>
<td>$K_x^2 n_E$</td>
</tr>
<tr>
<td>FIELD CURVATURE</td>
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<td>$K_{2x}^2 n_H$</td>
<td>$K_{2x}^2 n_E$</td>
</tr>
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<td>$K_x^2 n_H$</td>
<td>$K_x^2 n_E$</td>
</tr>
<tr>
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<td>$K_{2x}^2 n_E$</td>
<td>$K_{2x}^2 n_H$</td>
<td>$K_{2x}^2 n_E$</td>
</tr>
<tr>
<td>FOURFOLD COMA</td>
<td>$K_{2x}^2 n_E$</td>
<td>$K_{2x}^2 n_H$</td>
<td>$K_{2x}^2 n_E$</td>
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<tr>
<td>FOURFOLD ASTIGMATISM</td>
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<td>$K_{2x}^2 n_H$</td>
<td>$K_{2x}^2 n_E$</td>
</tr>
<tr>
<td>FOURFOLD DISTORTION</td>
<td>$K_{2x}^2 n_E$</td>
<td>$K_{2x}^2 n_H$</td>
<td>$K_{2x}^2 n_E$</td>
</tr>
</tbody>
</table>

3.4. Plotting of spot diagrams
Because the overall effect of the aberrations is extremely complicated, it is helpful to plot the shape of the aberrated spot in the form of a "spot diagram"; this is generated by taking a large number of rays, uniformly distributed in the aperture plane, and plotting their aberrated positions in the image plane (Kingslake 1978). Fig. 6 shows a typical spot diagram, illustrating the spot shape at 9 locations in an electrostatic sub-field.

4. ACCURACY, COMPUTATION TIME AND STORAGE REQUIREMENTS OF THE PROGRAMS
The accuracy of the deflection field programs was tested by comparing the fields for typical deflectors, computed by the two alternative methods in each case (i.e. by comparing results of the charge density method or Biot-Savart formula with results of the finite element method). It was found that the computed field distributions agreed with each other to within 2%. The accuracy of the lens field programs is generally within 1% (Munro 1973). The accuracy of the optical properties program was established to be within 1%, using an analytical model for the focusing and deflection fields. All the programs can be run in a few seconds with 400K bytes of storage on an IBM 370 or with 50K words of storage on a CDC 6600.
5. ILLUSTRATIVE EXAMPLES

Figs. 7 - 10 show some initial results obtained with our programs. The results are not claimed to be optimum designs; their purpose is simply to illustrate some of the potential applications of our programs.

Fig. 7 shows a pure magnetic focusing and deflection system, similar to that reported previously (Munro 1975). Fig. 8 shows the same system, but with electrostatic sub-field deflectors added. The computed results indicate that, for a 0.5 mm sub-field, the electrostatic deflectors introduce scarcely any additional aberrations. The electrostatic deflection voltage required was computed to be ±50 volts.

Fig. 9 shows another possible modification of Fig. 7, in which an electrostatic retarding-field lens has been added. The beam passes through the magnetic lens at 60 kV, and is decelerated to 25 kV at the image plane. The computed results indicate that this retarding-field lens actually reduces the aberrations.

Fig. 10 illustrates a pure electrostatic focusing and deflection system, such as might be used for ion beam lithography. This arrangement is an electrostatic version of the "moving objective lens" concept of Ohiwa et al. (1971). Electrode E₁ is an electrostatic deflector, and electrodes E₂, E₃ and E₄ form an electrostatic einzel lens, whose central electrode E₃ is segmented so that it can simultaneously act as a deflector. For a 2 mm deflection field, the deflection voltage required was computed to be ±50 volts.

Acknowledgement: We gratefully acknowledge several helpful discussions with Dr. Gerry Owen of Hewlett-Packard Company.

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Fig. 7. Pure magnetic focusing and deflection system.

DEFLECTION FIELD SIZE = 5 mm
APERTURE ANGLE = 5 mrad
OVERALL ABERRATION BEFORE DYNAMIC CORRECTIONS = 0.40 μm
OVERALL ABERRATION AFTER DYNAMIC CORRECTIONS = 0.08 μm

Fig. 8. System with electrostatic sub-field deflection.

DEFLECTION FIELD SIZE = 5 mm
APERTURE ANGLE = 5 mrad
OVERALL ABERRATION BEFORE DYNAMIC CORRECTIONS = 0.41 μm
OVERALL ABERRATION AFTER DYNAMIC CORRECTIONS = 0.09 μm

Fig. 9. System with electrostatic retarding field.

DEFLECTION FIELD SIZE = 5 mm
APERTURE ANGLE = 5 mrad
OVERALL ABERRATION BEFORE DYNAMIC CORRECTIONS = 0.57 μm
OVERALL ABERRATION AFTER DYNAMIC CORRECTIONS = 0.05 μm

Fig. 10. Pure electrostatic focusing and deflection system, suitable for ion beam lithography.
"CHARACTER PROJECTION", A METHOD TO ENHANCE THE RECORDING VELOCITY IN ELECTRON BEAM LITHOGRAPHY

H. Koops and V. Degenhardt

The "Shaped-Beam" method allows different cross-sections of a single beam to be used in Electron Beam Lithography to record structures varying in shape (1). An enhancement of the recording velocity will be obtained if numbers of differently shaped areas are printed in one step. A transparent metal mask, structured with various "characters" forming substructures of the final pattern, is illuminated with a high current density of low power. A large area electron emitter is used. The mask is placed inside the accelerating field. To lower the radiant heat from the cathode, we employed oxide dispenser cathodes.

The mask of 2 mm in diameter is imaged by an immersion lens onto a selecting diaphragm. The diaphragm carries part of the total accelerating potential. This measure reduces the power impinging to the diaphragm. Substructure pattern areas are selected with a magnetic deflection system. The diaphragm transmits only the wanted characters, and hereby it reduces the beam current in the following second accelerating lens and in a demagnifying and positioning deflection lens system. The schematic setup of a "Character-Projection" lithography system is given in figure 1.

We studied experimentally a "Character-Projection" electron gun producing selected patterns of a current density of $10^{-2} \text{A/cm}^2$ to $6 \cdot 10^{-2} \text{A/cm}^2$ in the selector diaphragm plane (2). The axial resolution was measured in a magnified image from the 10 % to 90 % decay of the current density at mask edges using a Faraday cup. The half-maximum width of the electron energy distribution was measured with a retarding field energy analyzer with electronic readout. This distribution originates from the cathode and from the electron-electron interaction in the beam.

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Blurring of the image is caused by aperture aberrations $\delta_a$, by axial chromatic aberrations $\delta_c$, and by space charge effects $\delta_s$ according to

$$\delta^2 = \delta_a^2 + \delta_c^2(I) + \delta_s^2(I).$$

The latter two terms depend on the current $I$ in the beam. Considering the measured half-maximum width of the energy distribution of the electrons, and the measured aperture and chromatic aberrations of the immersion lens, we found that space charge effects $\delta_s$ dominate all aberrations at increasing current densities. This corresponds to theoretical prediction (3), as shown in figure 2.

Acknowledgement

The authors are grateful to the "Deutsche Forschungsgemeinschaft" for financial support.

References


2) V. Degenhardt and H. Koops, to be published in Optik

Figure 1: Schematic setup of a "Character-Projection" lithographic system (CP-system)
Figure 2: Space charge induced displacement $\delta_s(I)$ of the trajectories in a CP-electron gun at varying current density $j$ in the selector diaphragm plane.
ELECTRON BEAM LITHOGRAPHY SYSTEM FOR ULTRA-MICROSTRUCTURE FABRICATION

K.L. Lee & H. Ahmed

1. INTRODUCTION

Electron beam lithography systems are used at present to fabricate structures in electron resist on substrates or to make masks with the smallest dimension in the range 0.1 μm to a few microns. The emphasis is on speed of operation, control of complex pattern data, accuracy of overlay, registration and alignment. These systems are capable in principle of fabricating down to the smallest dimensions that may be required by the established device technology and for scaling rules that apply to conventionally reducing the size of MOS and bipolar semiconductor devices. More recently new devices have been proposed in which the smallest dimensions are much smaller than those required hitherto and lie in the range 50 Å to 1000 Å. Notable among these devices are Josephson junctions, microbridges and ballistic devices. There are many others being proposed as the possibilities of e-beam lithography become apparent and there is a growing need for ultra-microstructure fabrication.

For electron beam lithography to fabricate structures successfully in this sub-tenth micron range of dimensions it is necessary to meet new and more stringent criteria than hitherto. These criteria are discussed in this paper and the design and construction of a system capable of meeting some of the new needs is described. The conditions for fabrication are critically examined by modelling the electron beam interaction and some initial results are reported.

2. ULTRA-MICROSTRUCTURE FABRICATION SYSTEM

The parameters that have been considered in the design of an e-beam ultra-microstructure fabrication system and the range available for these parameters in a practical system are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam diameter</td>
<td>10 - 10000 Å</td>
</tr>
<tr>
<td>Beam energy</td>
<td>50 - 100 keV</td>
</tr>
<tr>
<td>Beam current</td>
<td>10^{-12} to 10^{-11} amp</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>0 - 200 μm</td>
</tr>
<tr>
<td>Resist thickness</td>
<td>0.01 - 1 μm</td>
</tr>
<tr>
<td>Resist layers</td>
<td>single and multiple layers</td>
</tr>
</tbody>
</table>

Alignment and overlay of patterns is not considered at this stage and the work is restricted to single layer device patterns.

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The system is shown in Figure (1). It uses a LaB$_6$ electron gun capable of operation up to 100keV with a brightness of approximately 5 x $10^6$ A/cm$^2$/str. The two condenser lenses C1 and C2 and the prefield of the condenser-objective are used to demagnify the cross-over to a probe of $\sim$10Å or to provide parallel illumination required in conventional transmission mode (CTEM) at the specimen plane. The post-field of the condenser-objective and the two projector lenses can be used for obtaining a magnified image of the scanning probe on the fluorescent screen. Correction of astigmatism of the probe can conveniently be done using this image.

The scintillator-photomultiplier detector system is used for scanning transmission imaging as well as for probe size measurement to be described in section 2:1. A Faraday cage is installed at the screen plane to measure the probe current. Detailed description of the column may be found in ref. 5.

The calculated performance of the column in terms of probe current and probe size is shown in Figure (2). To some extent brightness can be traded against long life and very stable operation in this system.

In resist exposure, the substrates are held in a multiposition carrier which may be accurately positioned either to calibrate the probe or to expose a resist covered substrate. The probe is deflected on the substrate by a purpose-built vector generator and amplifier designed for very high stability of coil current. The vector generator enables a range of shapes to be written. Blanking is used to provide conventional vectored-scanned lithography.

2.1. Probe size and current measurement
One problem in ultra-microstructure fabrication lies in knowing accurately and simultaneously both the size and the current in the electron probe so that the exposure conditions may be set precisely and consistently. The small probe size of around 10 - 100Å is particularly difficult to measure. An estimate had been made by imaging a calibrated grid in a CTEM-STEM machine reference (1). The rise-distance across a specimen edge may also be used in the manner described in reference (2) which involves the use of a microdensitometer on a high resolution micrograph. All these methods have the drawback of a time lag between calibration and exposure.

In our method the spot size measurement is carried out by a more direct method and provides a calibration immediately before an exposure is carried out. The method is illustrated in Figure (3). Part of the area adjacent to the specimen plane is made electron transparent and covered with latex spheres of known diameter $d$ supported on a grid. These are imaged in the STEM mode on a visual display unit (VDU) and the size of latex on the VDU is measured. Without changing objective lens current, the projector lens current is varied to obtain a minimum probe size on the screen plane. The scan generator is on again as for the STEM image and the magnified raster is scanned across an
aperture in the screen plane. The size of this aperture on the VDU and the rise distance across the aperture are measured and give a direct estimate of the probe size when the magnification of the objective and projector lenses is known. A simultaneous measurement of probe current gives an accurate setting for the exposure conditions required for fabrication.

3. THEORETICAL AND EXPERIMENTAL RESULTS

A theoretical estimate of the energy dissipation contours in the resist is used to set the correct conditions for fabrication. Information on the numbers of reflected, absorbed and transmitted electrons in resist or resist/substrate combination is also very useful. The Monte-Carlo method and program developed earlier, references (3,4) have been extended to consider the effect of substrate thickness, resist thickness and beam energy on linewidths Figure (4) in the range 50 - 100 keV. The substrate considered is silicon.

3.1. Substrate thickness effects
For the range of resist thickness considered (0.05 - 0.3μm), it is found that the substrate thickness does not have a significant effect on linewidth, particularly the neck width at the resist surface. At a given beam voltage there is only a small variation of energy dissipation distribution at either the neck or the interface in the resist layer over a range of substrate thickness between 0.1μm and 100μm. This is illustrated in Figure (5). If the development is dependent on the threshold energy dissipation then the linewidth also is relatively unaffected by the substrate thickness.

3.2. Beam voltage effects
The effect of beam voltage on energy distribution at the neck and interface is apparent from Figure (6). The peak value of energy dissipation at the neck for the beam voltages of 50, 75 and 100kV is approximately in the ratio of 4:2:1. A similar ratio is obtained for the energy dissipation at the interface. In our experiments we may use the criterion of the threshold solubility model which should apply for the thin resist layers that are used. The threshold dose D for obtaining an interface width and neck width close to that of the incident beam diameter for various beam voltages and substrate thickness are shown in Table 1.
From this table it is seen that the threshold dose remains roughly the same for different substrate thicknesses at a given beam voltage. However, the threshold dose is increased in the ratio of 1:2:3 for the beam voltage of 50, 75 and 100kV.

3.3. Dose effect on linewidth
Although there are large differences in threshold dose at different beam voltages (i.e. at 50kV $D_t \sim 4 \times 10^{-3}$C/cm²; at 100kV, $D_t \sim 2 \times 10^{-2}$C/cm²). It is of interest to compare how the neck width and interface width changes as the dose is increased from its threshold value. These variations are illustrated in Figure (7a). From these results, it is seen that the neck width is fairly insensitive to dose variation even for different beam voltages.

3.4. Resist thickness effect
The effect of resist thickness is illustrated in Figure (7b). As shown, there is a small increase in neck width with increase in resist thickness whereas the interface width changes rapidly when the resist thickness is increased from 0.1µm to 0.3µm.

CONCLUSIONS
From the results of the theoretical work, it has been shown that e-beam lithography systems can be constructed to fabricate devices with minimum dimension in the range of 1000Å - 100Å. The Monte-Carlo simulations show that it is possible to obtain fine lines of <0.1µm on thick substrate on which devices may be directly fabricated. The main
effort of the experimental work has been directed to obtain fine lines on a thick substrate. Results on substrates with single resist layer of <0.1μm thick are difficult to interpret because of the relatively poor contrast obtained in viewing with a SEM. Lines of ~0.1μm with an edge acuity of 100Å have been obtained using double layer resist technique. This is shown in Figure (8). Further experiments are being carried out to make devices on substrates with dimensions in the range of 1000Å - 100μm.

ACKNOWLEDGEMENT

The financial support from the Merz Fund by Cambridge University and Trinity College is acknowledged.

REFERENCES

FIG. (1) Schematic diagram of ultra-microstructure microfabrication column

FIG. (2) Probe diameter Vs maximum probe current at optimum angular aperture
FIG. (3) Probe size measurement principle

(i) Magnification of the objective lenses $C_0$, $P_1$ & $P_2$

$$M_{op} = \frac{L_2}{L_1}$$

(ii) Magnified probe size $d_{MP}$ on screen is determined from rise time measurement across aperture at screen.

(iii) Probe size = $\frac{d_{MP}}{M_{op}}$

FIG. (4) Profile parameter

$W_n$ - Neck width
$W_i$ - Interface width
FIG. (5) Energy dissipation Vs substrate thickness. Dia = 30Å, Beam energy = 100kV, Resist thickness = 0.1µm

FIG. (6) Energy dissipation Vs beam voltages
Substrate thickness = 100.0µm, Resist thickness = 0.1µm
FIG. (7) \( W(N) \) and \( W(RSI) \) Vs beam voltages, resist thickness
Substrate thickness = 100.0 \( \mu \)m; \( \text{Dia} = \) probe diameter = 30\( \mu \)m

(a) Beam voltage
Resist thickness = 0.1 \( \mu \)m

(b) Resist thickness
Beam voltage = 100 keV

FIG. (8) 0.10\( \mu \)m line with good edge acuity obtained using double resist technique
HIGH VOLTAGE ELECTRON LITHOGRAPHY

T.R. Neill+ and C.J. Bull+

Reduced proximity effect and enhanced resolution in resist film have been demonstrated experimentally using a 50keV electron beam. Improved definition of low micrometre and submicrometre features is attainable at a common incident dose.

INTRODUCTION

Accurate definition of fine patterns in resist, at high packing density, is limited by the well-known proximity effect whereby adjacent areas not addressed specifically by the electron beam are partially exposed. The effect is caused by backscattering, and for beam energies in the 10-25keV range used widely for lithography on silicon or glass substrates, is particularly severe at dimensions of 1μm and less; special dose-correcting strategies are then needed to compensate for exposure variation within the pattern.

The influence of such factors as the nature and thickness of the substrate, and the resist thickness, in determining the severity of scattering phenomena is well documented in the literature. As far as we are aware, the possible benefits accruing from a significantly higher energy beam for the exposure of resist on conventional silicon device substrates have not been investigated by direct experiment.

We report here the outcome of a systematic study using silicon wafers pre-coated with realistically thick (1.2μm) resist film. As described in an earlier paper (1), the resist was positive-acting crosslinked methacrylate (2), and relief images revealed by a non-critical development process, when examined in section, show the threshold exposure contour through the sample. Long line patterns composed by a 0.1μm pitch address system were exposed using a conveniently attainable 50keV source, fitted with a beam blanker under electronic control; these were compared with similar features exposed at 20keV. The beam current was fixed at 5 x 10⁻¹⁰A throughout, and the spot size was ~100nm.

SIMULATION

The relative exposure distribution for a single line source (Fig. 1) was derived from measurement of window widths, with line dose as the

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experimental parameter. Data relevant to levels close to the surface of the resist, and at the substrate, are shown. At 50keV, decay with distance from the source is initially rapid and substantial, falling by two orders of magnitude at the 'knee' beyond which the exposure is attributed solely to long range electron scattering from the substrate. The backscatter component is then fairly constant up to a distance of ~12μm. In contrast, the backscatter exposure (tail) at 20keV starts at a higher level and is less precisely identifiable, particularly at the substrate, decaying eventually at an effective range of ~4μm.

Line exposure data, taken at the substrate, permit simulation of developable features and feature composites which can then be compared with experiment. Broad indications from the computer analysis are that:

(i) for a planar electron source, the increase in exposure intensity through the bulk of the resist film is ~70% at 20keV, compared with only ~7% at 50keV.

(ii) approximately 2.5 times more electron dose is required to expose large features correctly at 50keV compared with 20keV. This scaling factor was confirmed by experiment, and is used to define the normalised dose (Q = 1) needed for exposure of a single edge, at both voltages.

(iii) expressing the substrate exposure profile in terms of two fitted gaussian distributions (3), the proportion of total exposure at 50keV due to long range backscatter is 30%, compared with ~50% at 20keV.

Fig. 2 shows the deviation from design size for a selection of isolated line windows as a function of normalised dose. Size effect at a given dose is relatively trivial at 50keV, especially in the 0.5 - 2.0μm range. It is noted that a dose Q = 1.4 is needed to define correctly a 0.5μm window at 50keV, and this has been used in a number of the practical examples described later. The same relative dose at 20keV fails to expose adequately line windows of width less than 1μm.

The exposure distribution for a single edge (4) at the substrate, (Fig. 3), is derived from convolution of the equivalent line profile, at a stepping pitch of 0.1μm. The relative steepness of the 50keV profile at the developed edge implies more latitude for dose-setting without incurring significant positional error. The abrupt onset of backscatter at a lower level compared with 20keV infers easier resolution of narrow line pads, and fine gratings; for example, the Figure predicts that, at the dose shown (Q = 1), superpositioning of two edges to form a 1μm bar in resist will yield a retained feature at 50keV after development, whereas at 20keV it will be lost. So it turns out in practice.
EXPERIMENT

Fabrication of pattern features provides further information on the quality of the lithography not immediately apparent from simulation.

A collection of line windows exposed at a common dose ($Q = 1.4$) is shown in Fig. 4. SEM micrographs for 50keV and 20keV fabrication are compared with the related exposure distributions. The threshold exposure for development is also shown as a horizontal dotted line. At 50keV, the exposure peaks in the individual features show less variation, and the latter are defined with greater precision. The 0.3μm window is resolved.

An isolated 0.5μm line window exposed at $Q = 1.4$ and viewed in section (4), (Fig. 5) is well defined at 50keV, showing vertical edges, or walls; at 20keV the exposure is inadequate. 50keV exposure of a nominal 2μm window at even higher dose ($Q = 2.2$) still shows nearly vertical walls; at 20keV the image is badly deformed by excessive backscattering.

More generally, we have compared the enlargement of various isolated line windows at the resist-substrate interface as a function of design size (4), (Fig. 6). All of the features were exposed at a common normalised dose. Without dose correction, image widening at 20keV is dramatic; in contrast the effect at 50keV is relatively trivial. Simulation agreed with the experimental results.

The defining of narrow line pads of high quality and dimensional accuracy is a relatively difficult task in electron lithography because of overlapping backscatter exposure from large irradiated areas on either side of the feature. Reference to this has been made already in the discussion of Fig. 3, and the effect becomes progressively worse with thicker resist film. In Fig. 7 is shown the cleaved section of a nominal 1μm line pad made at a reduced dose ($Q = 0.8$). At 50keV a satisfactory image is obtained, whereas at 20keV the image is severely undercut; the exposure intensity profile adjacent to the 20keV micrograph illustrates the difficulty in dose setting to give the required dimension.

Continuous gratings in resist provide more detailed information on resolution limits imposed by forward spreading of the electron beam, and build-up of background exposure associated with long range backscatter. For example, a 1μm window/1μm gap grating (Fig. 8) exposed at high dose (1.4Q) shows marginal retention of the feature at 20keV, whereas at 50keV, the background is much less, and forwardly scattered electrons play a more dominant role in defining the pattern. If the frequency of the grating is doubled (Fig. 9), the 20keV example is completely washed out in development, whereas the 50keV example is retained. Simulation suggests the possibility of defining the 20keV grating at the reduced ideal dose $Q = 1$. In practice, however, the
exposure margin below threshold in the resist bars is too small to avoid resist softening, swelling, and eventual dissolution.

Even higher resolution can be attained in thick resist using asymmetrical windows and gaps with a 50keV electron beam. Fig. 10 shows the nearly vertical walls obtained with a nominal 0.2µm window/0.4µm gap (4) at the dose setting Q = 1.4. The latter is essentially the ideal dose for the pattern, and the exposure distribution shows a ± 30% exposure margin centred on the critical level for image development. Attempts at fabrication with a 20keV beam resulted either in partial exposure, or complete pattern washout.

Further appraisal is possible, considering finally a narrow line window placed very close to a large window. The relief image of a 20µm window/1µm gap/1µm window exposed at 50keV is shown in Fig. 11, at a dose setting of 1.4Q. Excellent profiles are obtained, and the dimensions are very nearly correct. In contrast, the 20keV exposure distribution shows that at the same dose (minimum value for exposure of an isolated 1µm line window) the pattern will be lost completely in development. When the adjacent small window and gap are each reduced to 0.5µm, (Fig. 12), the result is still good with a 50keV beam, but some modification of the design size is needed to achieve the required dimensions. At 20keV the pattern cannot be resolved without significant dose and size correction.

CONCLUSION

Reduced forward spreading of electrons in resist with a high energy source permits greatly improved resolution of sub-micrometre pattern detail. The overall reduction in backscatter exposure demonstrated in this study diminishes but does not entirely eliminate the proximity effect. We note that in two recent publications (5,6) other workers have arrived independently at a similar conclusion using Monte Carlo simulation.

These benefits are gained at the expense of reduced resist sensitivity, a direct consequence of lower energy deposited per incident electron; however, compensation should be possible with a brighter electron source, and the increased current density attainable with a higher voltage beam.

At 50keV, our prognosis is that submicrometre and low micrometre features in present and future v.l.s.i. patterns could be defined adequately at a common dose, thereby simplifying the hardware and software requirements for electron beam writing. Larger features could (where necessary) be corrected by size. In the same context, higher working voltage may be of even greater significance in electron image projectors where size compensation by dose control is not easy.
ACKNOWLEDGEMENT

We wish to thank Mr. H.N.G. King for suggesting this study, Dr. H.I. Ralph who developed the computer programs, and to acknowledge the assistance given by other colleagues at our Redhill Laboratories.

REFERENCES


LIST OF FIGURE CAPTIONS

Fig. 1 A comparison of the relative exposure intensity distribution for a single line source at 20keV and at 50keV. Resist thickness 1.2μm.

Fig. 2 Size deviation in isolated line windows, at 20keV and at 50keV, as a function of normalised electron dose (simulation).

Fig. 3 Exposure profile, at 20keV and at 50keV, for a single edge, taken at the resist-substrate interface.

Fig. 4 A collection of line windows in cross-linked electron resist, exposed at the normalised dose Q = 1.4.

Fig. 5 Isolated line windows, viewed in section.

Fig. 6 Line window size deviation, at constant dose, against design
size. Simulation compared with experiment.

Fig. 7 Nominal 1µm line pad in cross-linked resist, exposed at a reduced dose.

Fig. 8 1.0µm window/1.0µm gap continuous gratings, exposed at the same normalised dose (Q = 1.4).

Fig. 9 0.5µm window/0.5µm gap continuous gratings, exposed at the same normalised dose (Q = 1.4).

Fig. 10 Asymmetric grating (0.2µm window/0.4µm gap), exposed with a 50keV beam at a dose Q = 1.4.

Fig. 11 20µm window/1.0µm gap/1.0µm window composite, exposed with a 50keV beam at a dose Q = 1.4. Exposure intensity distribution at 20keV shown for comparison.

Fig. 12 20µm window/0.5µm gap/0.5µm window composite, exposed with a 50keV beam at a dose Q = 1.4. Exposure intensity distribution at 20keV shown for comparison.
Line exposure in resist

Fig. 1

Isolated line windows at resist-substrate interface (Simulation)

Fig. 2

Fig. 3
Arbitrary line pattern in resist

Fig. 4

Line windows in cross-linked resist

Fig. 5

Simulation from single edge profile

Fig. 6
1μm line pad in cross-linked resist

![Graph](image1.png)

Fig. 7

Grating in cross-linked resist

10W/10G (μm)

![Graph](image2.png)

Fig. 8

Grating in cross-linked resist

0.5W/0.5G (μm)

![Graph](image3.png)

Fig. 9
Grating in resist

0.2W/0.4G(µm)  Thickness: 1.2µm

Fig. 10

Pattern in cross-linked resist
Nominal 20W/10G/10W (µm)

Fig. 11

Pattern in cross-linked resist
Nominal 20W/0.5G/0.5W (µm)

Fig. 12
EXPERIENCES GAINED FROM USING FIELD EMITTERS FOR SUBMICRON LITHOGRAPHY

Christer Eriksson, Björn Wiklund and Börje Åstrand+

INTRODUCTION

Today in electron beam lithography work the demands on dimensions has reached the submicron range. The linewidth, and the corresponding spotsize demand in combination with the requirements on a high beam current makes the field emitters and field emitter optics very interesting. This paper will give a presentation of experiences gained from using field emitters in submicron lithography and also present methods how to use field emitters in electron beam writing, when long exposure times are required.

THE FIELD EMITTER OPTICS

We have in our vector scan system a standard field emitter optics for scanning electron microscopy work (SEM). Our field emitter optics, shown in figure 1, is the standard electron optics modified for our electron beam writing system. The modifications are the insertion of a pair of post lens deflection coils, a beam blanking unit and a lengthening of the distance between the electrostatic lens and the specimen, working distance. The increased working distance gives a high magnification in the gun, about 8 times, which means that external magnetic stray fields or noise and hum on the lens voltages will give a deflection and/or a defocussing of the beam on the specimen. These disturbances are in the order of 0.1 μm, in our present system. In a system with an additional magnetic lens placed between the beam blanking unit and the deflection coils this figure will be reduced to about 20 nm. The beam limiting aperture in our system is 100 μm. Figure 2 shows a calculation of the spotsize with our parameters. The spotradius at the specimen for the 100 μm aperture is shown in the diagram.

Currently we are using an accelerating voltage between 20 and 30 keV. The current heating the tip is set to give a tip temperature of about 1500 K. With the 100 μm diameter beam current limiting aperture we are getting a beam current of 10-30 nA in a spot diameter of about 100 nm.

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We have during the last 3-4 years been using FE sources and during the last couple of years thermal heated field emitters (TFE). In figure 3 we have summarized our experiences from the work with field emitters. The FE tip (non heated tip) gives, as shown in the figure, a relatively low and unstable current and it has a short lifetime. When using a field emitter in the thermal heated mode the current level raises and the current becomes more stable and the lifetime also increases. Due to the increased energy spread in the TFE mode the cromatic aberration increases and it contributes to a greater spotsize. Regarding the lifetime figures one should note that in the FE case the conditioning and start up procedures for the tip are more elaborate and there is also a need for more operator involvements than required in the TFE.
Fig 2. Variation of the spot radius as a function of the aperture half angle $\alpha_0$ for the accelerating voltages 20 kV and 30 kV.
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**Fig. 3** CHARACTERISTICS OF DIFFERENT FIELD EMITTERS

*Beam current [nA]*

**Fig. 4** BEAM CURRENT VS TIME AND PRESSURE
mode of operation in order to maintain the lifetime figure given. Regarding the zirconiated tips we have only been doing initial tests and the figures should be regarded with this in mind. An example of the behaviour of the TFE source is shown in figure 4. It shows the beam current vs time and the corresponding pressure axis is also in the figure. The start up procedure is a sublimation of the gun to achieve a low pressure in the gun, a cleaning of the tip (heating to 1700-1800 K) and then a turn on of the voltages, this takes a couple of minutes. As shown in the figure the current is both long and short term stable at a pressure below $1.65 \times 10^{-8}$ Torr and above that the current is still long term stable but the short term stability is deteriorated due to an increased noise level.

COMPENSATION OF VARIATIONS IN BEAM CURRENT

As shown in figure 4 the beam current from a field emitter has a long term drift and additional noise. In our system we have implemented a feedback loop, dose control loop, in order to minimize the fluctuations in dose caused by the none constant beam current.

![Diagram](https://example.com/diagram.png)

**Fig. 5** DOSE CONTROL ELECTRONICS
The dose control loop, shown in figure 5, measures the specimen current. The current signal is converted to a voltage signal and feed into a multiplying digital to analog converter (MDAC) and from there to a voltage to frequency converter (V/F). The output from the V/F converter is a sequence of pulses with a frequency proportional to the beam current. The pulses are used as the clock signal to the area scan generator (ASG). In our vector scan system we then have a step rate in the ASG directly proportional to the beam current. E.g. with an ideal dose control loop the number of electrons given to any exposure point will be the same in all exposed areas.

In submicron electron beam lithography the backscattering of the electrons, the proximity effect, will give a varying dose in the exposed areas despite a given constant dose. With the MDAC in the dose control loop we can to each sub area (not exposure point), give a chosen dose. Which means that we can with this loop compensate for the proximity effect in our system.

Due to the noise generation within the loop and the limited bandwidth of the dose control loop there is a remaining fluctuation in the dose given to each exposure point. In figure 6 is shown the resulting error

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Fig. 6 DOSE VARIATION REDUCTION
when using our method. The current amplifier has a bandwidth $f_1$ (3 dB) and above that it will not reduce dose fluctuation arising from the noise in the beam current. At the frequency $f_2$, the exposure time per point is longer than the time constants of frequencies above $f_2$, e.g., the exposure time in each point gives a low pass filtering of the contribution to the dose with frequencies above $f_2$. Hence beam current noise between $f_1$ and $f_2$ is not reduced by the loop. In addition to the beam noise signal between $f_1$ and $f_2$, the current amplifier has a noise figure which contributes to the fluctuating dose. A calculation shows that with a beam current $i_B = 5$ nA, a dose requirement $D_0 = 1 \times 10^{-4}$ As/cm$^2$, a loop bandwidth of 1 kHz and an exposure point size of 100 nm a dose stability better than 3 percent is achieved. This stability gives the required time intervals for operator involvement in the order of 5-10 hours.

Fig. 7  RECTANGLE SUBDIVISION AND INDIVIDUAL DOSE SETTING
EXAMPLE OF EXPOSED PATTERNS

A detail of a pattern is shown in figure 7. The picture shows the partitioning of rectangles into subrectangles and it also indicates the individual dose to each subarea. In figure 8 is shown the results from exposing the pattern. The upper part of the figure shows an experiment where all subrectangles were exposed with an equal dose and the lower part shows an exposure with the varying doses according to figure 7. The critical dimensions in the figure are 1.25 μm and 0.75 μm.

Fig. 8  AN EXPOSED PATTERN IN P:W:A, WITHOUT AND WITH DOSE CORRECTION
SUMMARY

We have found the field emitters very interesting as a tool in sub-micron lithography. Especially we think that the thermal heated mode is one way to achieve the small spotsize and high current density required for a feasible throughput in an electron beam system.

REFERENCES


SUITABILITY OF VARIOUS REGISTRATION MARKS FOR PRECISE OVERLAY IN DIRECT E-BEAM LITHOGRAPHY

D. Stephani, E. Kratschmer +

1. INTRODUCTION

An important factor in fabricating multilayer semiconductor devices is the need for accuracy in overlay of subsequent circuit patterns. The overlay accuracy achievable depends on the signal derived from registration marks. The backscattered electron signal has proved to be most suitable in direct e-beam lithography /1-3/. Various types of registration marks detector configuration, and methods of signal processing have been reported /2-10/. However a comparison between the different registration signals is made difficult because of the lack of an unique quantity for their characterization. The widely used signal-to-noise ratio (SNR) is defined not uniquely by the different authors and in addition it does not reflect the suitability of a registration mark in order to determine its accurate position. We will define a unique quantity hereafter called the suitability quantity (S.Q.) which reflects the properties of the registration mark as well as the type of detector used.

2. THE SUITABILITY QUANTITY S.Q.

The determination of the relative position of a registration mark is optimally derived from the cross-correlation function (CCF) obtained from the backscattered electron signal of a registration mark - the registration signal - and a proper reference signal. If the reference signal itself is obtained from one scan over the registration mark, the profile of the CCF and the profile of the auto-correlation function (ACF) of the registration signal are identical. Properties of the optimized CCF can be discussed on the properties of the ACF of the registration signal. The definition of CCF and ACF is given in the appendix.

Only the ac-part of the registration signal contains information on the position of the registration mark. Consequently the AFC derived from the ac-part only is of interest in the further evaluations. Additionally we normalize this AFC by dividing it by its maximum. This normalized AFC is denoted by \( \Phi(r) \) where \( r \) represents the distance from the maximum.

Information on the suitability of a registration mark in order to determine its accurate position is contained in the profile of the AFC of the registration signal. For instance a sharp peak in the AFC would prove the mark is well suited. But minimum peak-width is limited in the AFC because of the scattering process backscattered electrons undergo.

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Therefore we use the maximum of the derivative of \( \varphi(r) \) with respect to \( r \) as one criterion for the suitability of a registration mark. Overall characteristics of the type of registration mark and detector system used is represented by the maximum of the AFC namely \( \bar{E} \) and the average noise power density \( N_0 \) inherent in the signal during a scan across the mark. Therefore the suitability quantity S.Q. can be defined by equation (1).

\[
S.Q. = \left| \frac{d \varphi(r)}{dr} \right|_{\text{max}} \cdot \frac{\bar{E}}{N_0}
\]

The ratio of the ac-energy \( \bar{E} \) in the registration signal to the average noise power density \( N_0 \) is the best SNR one can get from the registration signal by using a matched filter. This SNR gives an estimate of the probability for merely the detection of the registration mark. The S.Q. defined by equation (1) is the optimum SNR related to the distance and reflects the individual properties of a registration mark too.

3. MEASUREMENT SYSTEM

The suitability quantity of various registration marks was determined in the measurement system schematically shown in fig. 1. The four quadrant annular surface barrier detector is mounted at an optimized distance from the substrate /11/. At this position about 50% of all back-scattered electrons hit the detector if a cosine distribution is assumed. From this detector we can either obtain a summing signal or a difference signal. For the difference signal it must be noted that the signal depends on the angle between mark edges and scan axis. If mark edges are parallel to the scan axis, edges in x and y direction may be detected. However in this case electrons collected by two quadrants only contribute to the signal but all collected electrons contribute to noise. The difference signal is optimized in this measurement system if mark edges are parallel to sector boundaries of the detector. The variation in signal energy for the two discussed geometrical cases is at most a factor of three which was found by measurements in accordance with Monte-Carlo calculations /12/. Fig. 2 shows first registration signals of V-grooves of various width for the summing and difference mode of operation. Second the corresponding normalized AFC is plotted against distance \( r \). The electron beam has been moved in steps of 0.1 \( \mu \text{m} \) in the x direction while marked edges have been held parallel to the y direction. All following measurements have been derived in the same manner.

4. EVALUATION OF S.Q.

In order to get the quantity \( \bar{E} \) three conditions must be supplied for a stepped scan.

First: the scan length must be larger than the ac signal extension

Second: the beam stepsize must be much smaller than the inverse of the maximum spatial frequency in the registration signal

Third: the beam diameter must be equal or less than the stepsize
Let be $U_{si}$ the voltage at the input of the ADC in summing mode at beam position $i$. Now S.Q. evaluates to

$$S.Q. = \left| \frac{\Delta \gamma_D(r)}{\Delta r} \right|_{\text{max}} \frac{I_0 \Delta t}{e} \cdot \hat{U}^2 \sum_{i=0}^{M} (U_{si}-\bar{U}_i)^2 \cdot \frac{\eta^T}{F}$$

where $I_0$ is the beam current, $\Delta t$ is the dwell time, $e$ is the electron charge, $M$ is the number of steps in the scan, $\bar{U}$ is the mean input voltage at ADC averaged over $M$ steps, $F$ is the noise figure of the detector circuitry. Finally $\eta^T$ is the mean total backscatter coefficient weighted by the collection efficiency $\Gamma$ of the detector averaged over $M$ steps.

From the above discussion the S.Q.D of the difference signal straight forward evaluates to

$$S.Q. = \left| \frac{\Delta \gamma_D(r)}{\Delta r} \right|_{\text{max}} \frac{I_0 \Delta t}{e} \cdot 3 \cdot \hat{U}^2 \sum_{i=0}^{M} U_{D_i}^2 \cdot \frac{\eta^T}{F}$$

where $U_{D_i}$ denotes the voltage at the input of the ADC in the difference mode of operation while mark edges are parallel to the scan directions.

5. RESULTS

We have restricted our investigations on marks which are compatible with fabrication of semiconductor devices. The application of eq. (2) and eq. (3) include the conditions given in table 1.

The beam current $I_0$ was chosen to results in a beam diameter equal to the step size and dwelltime $\Delta t$ was selected such that resist exposure would be $10 \mu C/cm^2$. The noise figure $F$ has been calculated for the detector properties including reflection losses at the front electrode and noise contribution due to the energy distribution of backscattered electrons. These calculations are in good agreement with measurements.

If we assume an infinite scan across the mark the normalized value

$$\text{s.q.} = S.Q. \cdot \frac{e}{I_0 \Delta t} \cdot \frac{F}{\eta^T}$$

depends only on the characteristics of the mark for summing and difference signal respectively independent of the measurement system. However we will give results for the not normalized S.Q. because these values give a better idea of results in a real system.

Fig. 3 gives the S.Q. for V-grooves of various width. For narrow V-grooves, the summing signal is superior to the difference signal. If the width of the V-groove becomes larger than about 4.5 $\mu m$, from the difference signal now a higher S.Q. is obtained. However if the wafer and thereby the mark is covered with 1 $\mu m$ PMMA, the summing signal is distinctively superior to the difference signal. It is surprising that the S.Q. of a PMMA covered V-groove becomes better than the S.Q. of the uncovered V-groove if the width is larger than about 4.5 $\mu m$. This can
be understood if the additional atomic number contrast obtained from the thicker resist layer in the groove is considered. Due to resist covering the backscattered electron signal is lowered within a groove as it is lowered in the surrounding of a bar.

Fig. 4 shows the S.Q. of vertically etched grooves of 1.8 μm depth and various width. The S.Q. derived from the summing signal here is higher in all cases than that derived from the difference signal. If this type of registration mark is covered with PMMA, the disadvantage in using a difference signal for registration purposes is obvious. The S.Q. derived from this type of registration mark depends on the depth of the groove. For a depth of 1 μm and widths between 2 μm and 4 μm the S.Q. derived from the summing signal was found to be approximately constant. Such bare grooves gave a S.Q. of about 800 μm⁻¹, if covered with 1 μm PMMA the S.Q. degraded to about 400 μm⁻¹.

Fig. 5 gives the S.Q. of vertically etched bars of 1.8 μm height and of various width. Also here the summing signal leads to a better S.Q. than the difference signal in all cases. The disadvantage of the difference signal is not as high as for the opposite type of this mark especially for narrow marks.

6. CONCLUSION

We found narrow bars vertically etched to be best suited for registration purposes. But the advantage over vertically etched grooves or V-grooves respectively is not as big as might be expected. In no case we found a difference signal which is superior to a summing signal if registration marks are covered with resist. V-grooves, vertically etched grooves or bars all yield a high suitability quantity if the width is about 4 μm and the depth of vertically etched marks is about half this width.

The suitability quantity S.Q. defined here for the description of a registration mark is a signal-to-noise ratio related to the distance reflecting individual properties of a registration mark. Thus the S.Q. is superior to SNR to characterize mark suitability in registration procedures. From figures 3, 4 and 5 it is obvious that S.Q. of 1000 μm⁻¹ can easily be obtained from one scan over such registration marks. This results in a SNR related to a tenth of a micron of 100 or equal to 20 dB. This is sufficient to almost ever determine the mark position within 0.1 μm, provided optimized cross-correlation technique is applied.

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We like to thank Prof. Dr. H. Beneking for his encouragement and stimulating discussions. This work has been supported by the Federal Ministry of Research and Technology of the Federal Republic of Germany (Contract NT 0835/1).
Let be \( s(x) \) the registration signal obtained from an "infinite" scan over a registration mark and let be \( g(x) \) a reference signal. Both signals are assumed to fulfill equation (A1).

\[
\int_{-\infty}^{+\infty} s(x) \, dx < \infty, \quad \int_{-\infty}^{+\infty} g(x) \, dx < \infty
\]  

(A1)

The CCF between \( s(x) \) and \( g(x) \) is defined by equation (A2)

\[
\phi_{sg}(r) = \int_{-\infty}^{+\infty} s(x) g(x+r) \, dx
\]  

(A2)

while the ACF of \( s(x) \) is defined by equation (A3)

\[
\phi_{ss}(r) = \int_{-\infty}^{+\infty} s(x) s(x+r) \, dx
\]  

(A3)

If \( g(x) \) is one realization of the registration signal but displaced with respect to \( s(x) \) it may be written as

\[
g(x) = s(x+r_1)
\]  

(A4)

and the CCF becomes in this case

\[
\phi_{sg}(r) = \int_{-\infty}^{+\infty} s(x) s(x+r+r_1) \, dx = \phi_{ss}(r+r_1)
\]  

(A5)

which is the displaced ACF.

If the registration signal \( S(x) \) contains a dc-part \( S_0 \), the ACF of the ac-part of the registration signal is derived from equation (A6)

\[
\phi_{ss}(r) = \int_{-\infty}^{+\infty} (S(x)-S_0)(S(x+r)-S_0) \, dx
\]  

(A6)

The normalized auto-correlation function of the ac-part of the registration signal is given by equation (A7)

\[
\varphi(r) = \frac{\phi_{ss}(r)}{\phi_{ss}(0)} = \frac{\int_{-\infty}^{+\infty} (S(x)-S_0)(S(x+r)-S_0) \, dx}{\int_{-\infty}^{+\infty} (S(x)-S_0)^2 \, dx}
\]  

(A7)
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<tr>
<td>backscatter coefficient</td>
<td>$η$</td>
<td>0.174</td>
</tr>
</tbody>
</table>

Table 1: Parameters used in the evaluation of S.Q.

Fig. 1: Measurement system
Fig. 2: Registration signals of V-grooves and corresponding normalized ACF.

Fig. 3: S.Q. versus width $W$ of V-grooves.
Fig. 4: S.Q. versus width W of vertically etched grooves.

Fig. 5: S.Q. versus width W of vertically etched bars.
A HIGH SPEED, NOISE TOLERANT EDGE DETECTION ALGORITHM USING A LOW BANDWIDTH SIGNAL CHAIN FOR E-BEAM REGISTRATION

D. Cumming

A novel registration algorithm is described, which offers both accuracy and high speed and uses a low bandwidth signal chain. Experimental results are presented, and a hardware implementation proposed.

1. INTRODUCTION

Microfabrication of submicron devices by direct writing has been an ongoing activity for many years at Hughes, using a number of in-house E-beam lithography machines. In preparation for the next generation of production-orientated machines demanded by the VHSIC program, research is being done into fast resists and fast registration. In order to deploy a vector scan R&D machine with writing speeds of the order of 0.2 m/sec with a fast electron resist, low beam currents are needed with consequent signal/noise problems in the detector and registration system. An algorithm has been demonstrated which completely eliminates speed problems in the detector and signal chain, while providing the capability for accurate registration at very low beam currents. The algorithm also has the potential for extremely high speed registration with the beam currents anticipated in Hughes' fifth generation machines.

2. MACHINE DESCRIPTION

Signal acquisition is performed by the signal chain shown in Fig. 1. High energy backscattered electrons from the silicon wafer impinge on a scintillator positioned just above the wafer. A light pipe/photo-multiplier system then produces a video signal to drive a visual display. This signal is also used to drive an A/D converter attached to a PDP 11/34 computer. Because the sampling rate is low compared with the available signal bandwidth, a 5 kHz anti-aliasing filter is used before attempting any digital signal processing. To prevent overflow problems in the computer, only the nine most significant bits of the A/D converter are used. This greatly speeds up the signal processing since no overflow checking is then required.

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  Ion Physics Department
3. ALGORITHM

The basic edge detection algorithm uses a straightforward correlation technique, as shown in Fig. 2. The output signal, \( x_i \), is the cross correlation product of the input signal, \( a_i \), with the correlating function \( b_j \). Each value \( x_i \) is produced from the entire set of input samples as shown in the diagram.

The peak in the output signal corresponds with the theoretical best possible estimate of edge position (Argyle, 1971). Since each output point is produced by summing a large number of signal points, noise on the input signal tends to be averaged out. The method has been used in phase locked loops and lock in amplifiers for many years, and has outstanding noise rejection capabilities.

\[
\begin{align*}
    x_i &= \sum_{j=0}^{i-1} a_i b_j \\
    &\text{where} \\
    b_i &= 0 \quad 0 < i < \lfloor \frac{n}{2} - \delta \rfloor \\
    b_i &= 1 \quad \lfloor \frac{n}{2} - \delta \rfloor < i < j \\
    b_i &= 1 \quad \lfloor j / 2 \rfloor < i < \lfloor j / 2 \rfloor + \delta \\
    b_i &= 0 \quad (j + \delta) < i < n
\end{align*}
\]

Fig. 1 Signal Chain (System 4A).

Fig. 2 Registration Algorithm.
allow, and valuable information from the detector is ignored while the information is being processed.

The inter-sample processing is achieved as follows:

1) An array, $x_j$ is used to store values of output voltage, initially set to zero.

2) As each input sample is taken, it is either added to or subtracted from all values $x_j$, as determined by $b_i$.

3) When the last sample has been taken, the function

$$x_j = \sum_{i=1}^{n} a_i b_i$$

has been calculated for all $j$, each value $x_j$ being modified $n$ times. It remains only to find the maximum value of $x_j$ and the edge has been located.

The speed of the algorithm depends on the value of $\delta$. A large $\delta$ gives a slower, more noise tolerant and more accurate edge location. For this reason two scans are made, one coarse scan with large increments of beam movement between samples, followed by a fine scan over the edge for final, precise location.

4. PERFORMANCE

The performance of the algorithm is illustrated in Fig. 3, which is a computer simulation (written in FORTRAN). A noisy signal has been simulated by the use of a random number generator, and the correlation functions with a large $\delta$ (coarse) and a small $\delta$ (fine) are shown. As may be seen, the algorithm itself is accurate to within one lsb (0.05 μm) at a 1:2 signal to noise ratio, and it still works at a 1:5 signal to noise ratio. This corresponds with a beam current below that at which an image is visible to the human eye at TV rates. Caution must be exercised in interpreting these results because:

1) A bandwidth of 5 kHz is used by the algorithm, but 2 MHz is used to produce a TV rate image.

2) This simulation uses uniformly distributed noise rather than the Gaussian noise found in reality, although this error should be small.

3) Peak to peak noise has been quoted rather than RMS noise, and measurement of this with true Gaussian noise would be subjective.
Figure 4 is a plot of registration errors measured in the actual E-beam system, and as may be seen the algorithm itself is more accurate than the other components of the system. The measurements were made by moving the stage over carefully measured distances using a laser interferometer (Pasiecznik, Reeds and Fralick, 1979), simultaneously using the algorithm to measure the displacement of a benchmark. Registration errors include:

1) Electron resist over benchmark - Reduced by using a backscatter detector

2) Charging in column - Biggest source of error

3) Ripple line transients - About 0.1 μm in Cambridge Instruments column, even after extensive modifications

4) Long term system drift - Reduced by using a high quality filament
Fig. 4 Measured Positioning Error of Edge Detector Algorithm.

5. TIMING

Figure 5 illustrates measured times to register to a gold-on-silicon benchmark on the Hughes E-beam system 4. As discussed previously, a smaller value of $\delta$ will give faster registration with less noise tolerance. However, in the coarse scanning mode the smallest increment of electron beam movement must be less than $\delta$ in order to locate the benchmark with sufficient precision. Consequently, a small value of $\delta$ creates more sample points and hence a longer time in the coarse scanning mode. As shown in Fig. 5, it is possible to optimize $\delta$ to give the shortest possible total registration time. Naturally, the time per scan depends on the scan length, the graph being plotted for a 20 micron scan.

Fig. 5 Registration Timing Measured on a PDP 11-34.
To further speed up the registration process, a smart algorithm was developed at Hughes. This first assumes the position of a benchmark to be known, and does a very short scan. Larger scans are done only if no mark is found. Thus, registration can be done fast if the chip position is accurately known, or more slowly if the position is uncertain. The algorithm is very flexible, and has been operated successfully with uncertainties of \( \pm 50 \mu \text{m} \) in benchmark position. A set of four marks can be found in both X and Y in 1.1 seconds, at beam currents in the range of 0.1 nA - 100 nA.

6. RESULTS

Figure 6 is a photograph of a registration test pattern exposed in PMMA on silicon. A set of gold benchmarks and a vernier pattern were first laid down on the silicon, then registration was performed and a second set of verniers exposed. As may be seen, the accuracy is better than 0.1 \( \mu \text{m} \). Figure 6 also shows the smart registration algorithm in action, doing progressively larger scans until the benchmark is located.

![Image of registration test pattern with labels SMART, SMARTER, SMARTTEST, RESULTS](image-url)

Fig. 6 Registration Test.

7. FUTURE WORK

As implemented on our PDP 11/34, the speed of registration is processor limited for beam currents in excess of 0.05 nA. Below this figure, the low sample rate needed for adequate noise rejection limits the speed. On fifth generation machines with beam currents in the hundreds of nanoamps, it is clear that a hardware implementation of the registration would give a tremendous increase in speed. The basic algorithm could be the same, but the correlation function could be
performed using one of the commercially available correlators. Only the XY coordinates of the benchmark would be fed back to the computer. Another approach would be to use a microprocessor controlled registration module which automatically set the gain, offset and rotation of the deflection system on a single command from the main computer. This would eliminate data transfer problems altogether.

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Advanced electron beam delineators of three different system designs developed in the VLSI Cooperative Laboratories under a national project are reviewed. Both of a vector scan type and a raster scan type machines with a variable spot shape are shown to be capable for very fast delineation of VLSI patterns on silicon wafers. Another type is of a field-emission gun of a high brightness and shows a superior performance for very fine patterns of lower-submicrometer lines.

1. INTRODUCTION

The VLSI Cooperative Laboratories was organized in 1976 under a four-year term joint VLSI project in Japan for the research of basic VLSI technology, which terminated in last March, this year. The scope of the project, with emphasis on lithography and related fabrication technologies, is illustrated in Fig. 1. Of particular importance in these items was the development of advanced electron beam delineation systems. For this purpose, extensive exploratory works had been pursued to realize faster and more precise delineation systems capable for direct writing and mask making of high density and fine-line circuit patterns of future VLSI.

Although long, world-wide efforts for the electron beam delineation machines had been done, we had no unique and ultimate design concept for practical as well as economical machines when we started our project. Thus, so as to speed up the development, we planned to explore delineators with different designs in parallel. The achievement of the studies in the first half of the project was reported by Tarui(1). In this paper we describe a summary of latest results. Details of each technology will be individually published elsewhere.

Before fixing the design goal of the VLSI pattern delineators, we had to know the circuit pattern density of future VLSI. In Fig. 2 is shown the possible increase in the density of integration in MOS dynamic memory with the decrease in the minimum feature size. Three lines are drawn from current basic MOS technologies: the lowest line is for the single polysilicon layer technology, the middle line is for the double-polysilicon layer technology and the upper dotted line is expected...
from novel QSA-SHC (quadruply self aligned-stacked high capacitor) technology developed in our labs (2). If we assume conservatively a middle line between the two solid lines, a density of 1 Mb/cm² is realized with a minimum feature size of 1 μm. This order of density is allowed to be typical for VLSI through 1980's.

Thus, we set the primary goal of the machine designs to a reasonably fast delineation of 1 μm patterns with 5 M rectangles/cm². The capability of efficient drawing of patterns in the lower submicron region will be important for some applications as well.

2. THREE ELECTRON BEAM DELINEATORS FOR DIRECT WRITING

In the Cooperative Labs, a number of experimental electron beam machines were designed, fabricated and tested. In what follows, we report the final three models which were all completed as a total system to meet the basic requirements of VLSI patterns delineation, though they are, in general, of a prototype nature.

System VL-S2 is an extension of the first one, VL-S1 that utilized an original Variable Shaped Beam (VSB) concept (3). Although VL-S2 keeps the feature of VSB in a vector scan scheme, it is not a straightforward extension of VL-S1, but is fully upgraded in all aspects of the subsystems (4).

VL-R2 is basically a version-up of VL-R1 (5) in that both are commonly of a raster scan type and, namely, the beam is scanned in a narrow width on a continuously moving workstage. A simple extension and revision of VL-R1 was thought not to be able to meet a basic requirement of ten-times faster delineation of 1 μm patterns. Thus, the incorporation of a modified VSB was designed, keeping the feature of the raster scan. Thus, VL-S2 and VL-R2 are both of a VSB scheme, but the delineation method is entirely different. In Fig. 3 are shown the basic operations of both systems. Note that VL-S2 changes the shape of the beam and VL-R2 changes the length of rectangular shape with a pre-determined width. System VL-P1 has a feature of the use of a high-brightness field-emission gun which has been expected to obtain a sharp and intense electron beam in the range of submicrometers. Outline and preliminary results were reported in the last Microcircuit Engineering '79 (6). A latest results obtained will be briefly described.

2.1. Variable shaped beam/ vector scan system, VL-S2

The basic principle of the variable shaped beam is the double-aperture electron optical system with a beam deflection in between (3). One of the important design consideration is that there exists an optimum value of the maximum dimension of the rectangle for a given feature size of the circuit pattern, which makes the exposure time minimum provided that the edge slope is within a certain fraction of the line width (7).

The exposure time in one field in this system for a given resist sensitivity is proportional to the number of shots, M, and inversely proportional to the beam current density, J. The edge slope, ΔL, in the rectangular beam profile may be assumed to be primarily determined by
electron-electron interaction in the beam, and $\Delta L$ is proportional to the beam current. If $\Delta L$ is required to be within a fraction of the line width, $L$, this limits the maximum allowable current, $I_m$, which is shown to be proportional to the maximum side length, $L_m$; in other words, the current density, $J$, is inversely proportional to $L_m$. Thus, the shot time is increased with increase in $L_m$. On the other hand, the number of the shots, $M$, by the rectangle spot per field is decreased with increase in $I_m$. Thus, there should be an optimum value of $I_m$ for minimizing the exposure time. The dependence of $M$ on $I_m$ can be obtained from the pattern data produced for the optical pattern generator considering a typical LSI design. The result of a calculation of the optimum of the maximum side length against the line width to be drawn (design rule) is shown for the overhead time, $\tau$, (settling time to next shot) as parameter in Fig. 4. In this calculation, $\Delta L/L$ is assumed as 0.1. It is noted that when the overhead time is zero, the optimum length is about twice as long as the minimum line width. In the design of VL-S2, the size of the aperture is selected to provide $5 \times 5 \mu m^2$ image on the wafer, which corresponds to a design rule of about $1.5 \mu m$.

A schematic diagram of system VL-S2 is illustrated in Fig. 5. The beam size can be actually varied in the range 0.5 to 5 $\mu m$, with a 0.1 $\mu m$ increment and the beam position can be set at 0.05 $\mu m$ interval in a deflection field of $2.5 \times 2.5 mm^2$. The accelerating voltage is 20 kV and the current density is about $1A/cm^2$. Proximity correction can be done by programmed changes of the effective electron dose. Functions such as negative-positive reversal, scaling up and down of pattern size and mirror reversal are implemented. The step and repeat speed of the work-stage is higher than 2.5 mm/0.5 sec. System architecture and data processing and transfer have been largely improved to get a very high speed drawing. VLSI chip pattern data called from a disc storage system are converted and compacted at a very high rate and fed into a large capacity buffer memory, which has a capacity of 10.5 M Bytes (including ECC bits). A block of compacted data stored in the buffer memory is transferred to the high speed controller in which the block of data is processed and corresponding data are transferred to DAC registers. Thus, a high shot rate, higher than 1 MHz, for a variable shaped beam positioned randomly in a deflection field was achieved. The data handling system is capable for drawing $2.5\times10^9$ rectangles on a wafer of 100 mm diameter at any pattern size larger than $0.5 \mu m$ with a density of $5\times10^8$ rectangles on a $10\times10 \, mm^2$ chip.

An overall throughput of the direct writing is about 18 min per 4-inch wafer including the overhead time of the stage movement and registration when using a resist whose sensitivity is $1.2\times10^{-6} C/cm^2$. When a resist of $3\times10^{-7} C/cm^2$ may be used, the throughput is about 9 min. In Fig. 6 is shown a test result of the alignment accuracy of double exposure and field junction (stitching) by the step of the stage. The errors appeared to be less than $\pm 0.1 \mu m$. The overall accuracy including stitching and overlaying is better than $0.2 \mu m$ (3σ). A part of Fig. 6 is magnified in Fig. 7: the minimum square is $0.5\times0.5 \mu m^2$. Fig. 8 illustrates a photomicrograph of repeated test patterns on a $100 \, mm^2$ wafer, which is equivalent to the complexity of a 1 Mb memory, delineated by
VL-S2: the chip size is 9.6×9.6 mm² and it includes about 5×10⁶ rectangles with a minimum line width of 1 μm. Fig. 9 is a close-up microphotograph of one chip in Fig. 8, and a part of it is SEM-magnified in Fig. 10.

2.2. Variable-size beam/raster scan system, VL-R2

In this system the variable shaped beam concept is incorporated in such a way that the length of rectangular beam with a fixed width in the scan direction is varied as shown in Fig. 3. We call this scheme as variable size. Actually, the beam width is set at either of two modes, 0.5 and 1.0 μm and the beam length, perpendicular to the scan direction, is varied up to 4 μm, corresponding to the pattern to be drawn. That is, the line width to be drawn is selected to be 0.5 and 1.0 μm, and the minimum address is correspondingly 0.125 and 0.25 μm. The beam traverses 250 μm in width with an address frequency of 30 MHz on the moving stage. The stage moves at variable speed up to 100 mm/sec at maximum. In order to speed up the delineation, blank area can be skipped with a speed up of the stage movement. As a result, 100 mm square with a density of 5 million rectangles/cm² and 25% coverage can be delineated within 12 min in the 1.0 μm mode. The accuracy of the delineated patterns is 0.1 μm. The beam current density is 50 A/cm² by using a LaB₆ electron gun. The sensitivity of the positive resist used was 5 μC/cm². For the direct writing, a special registration technique is implemented by incorporating a high-speed position correction circuitry. The error of mark detection is 0.02 μm, when the number of addition is 32 and four scans are done on each marks placed 10 mm interval. The overlayer registration accuracy is ±0.15 μm. Under this condition, the registration time is 150 sec on a 3-inch wafer, but will be much decreased by improving the mark data processing algorithm. The details of VL-R2 are given in the following paper by Sano et al. (8).

2.3. Field-emission electron gun/vector scan system, VL-F1

System VL-F1 has been developed as a useful experimental direct writing machine providing a 0.1 μm field-emission electron beam of 40 nA with an FE noise of less than 5%. A photograph of the gun and electron optical column assembly which is the feature of the VL-F1 is reproduced in Fig. 11. In this paper new experimental results will be addressed (9). In Fig. 12 is plotted the measured probe current against the beam spot diameter with beam semi-angle of convergence, α₀, in objective lens as a parameter in the case of a field-emission current of 100 μA. V₀ and V₁ are accelerating voltage and emission voltage, respectively. Solid lines are the calculated results. Triangle data points are for a thermionic LaB₆ gun with a brightness of 1×10⁶ A/cm²str. in the case of α₀=3 mrad., which were measured in an experimental EOS similar to that of VL-F1. Dotted lines are calculated ones provided no aberration loss in lens. This result shows that the field-emission system can provide more efficient probe current than the thermal LaB₆ gun in the case of submicrometer spot diameters less than half a micron. Fig. 13 shows experimental results concerning the proximity effect in the delineation of submicron lines in comparison with a reported curve (dotted one) in
the case of LaB$_6$ (10). Exposure dosages to produce the lines of 0.25, 0.5, 0.75 and 1.0 µm wide are plotted as functions of the spacing between lines. The pattern dimension is determined at the middle point on the edge slopes in the pattern profile, measured by SEM image. The substrate material is silicon nitride of 0.1 µm thick on a silicon wafer. A PMMA resist of 0.4 µm thick was used and the developer was a one to one mixture of MIBK and IPA. $V_0$ is 20 kV. All lines in unit of 0.25 µm were delineated by multiple scanings of a same beam. The important result in this figure is that the dependence of exposure dosage on line width is smaller than that in a LaB$_6$ system, and namely, the field-emission system provides smaller proximity effects. The reason for this fact has not been yet clear, but in the field-emission EOS the beam diameter might not be well defined by the half width in order to study the proximity effect produced by primary and secondary electrons in the resist, and also the magnification lens system might produce a different profile from that in the conventional demagnifying lens systems.

3. CONCLUDING REMARKS

System VL-S2 and VL-R2 have turned out to be of powerful experimental systems which can delineate VLSI patterns in the range around 1.0 µm with the reasonably high speed. Both systems are a system combining the state-of-art technologies in computer system, electronic data processing system, electronic interface system and machinery. However, both systems still have to be improved in some points. Among these is the availability of high-sensitive and practical positive resists, although it is very common in all the electron beam systems. This is more urgent for VL-S2 because of the limit of the current density available (about 1 A/cm$^2$), comparing to 50 A/cm$^2$ in VL-R2. For VL-R2, the proximity effect correction has not been well incorporated yet, although it is not a principal difficulty. Input data format should leave that of PC-3000 to have more efficient and faster data conversion. Better data handling of complicated patterns including many slant lines should be done, which is in part related to the necessity of higher speed, higher precision D to A converters.

So far, the field-emission/vector scan system has been proved to be better in the submicrometer pattern delineation, although VL-FL does not enjoy the principal advantage of VSB. Note finally that the capability of fine-line delineation can be readily applied to systems like electron beam pattern inspection system which is inevitable for VLSI mask making.

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Figure 1. The major development items for basic VLSI technology in the VLSI Cooperative Laboratories.
Figure 2. Estimated integration density of MOS dynamic memory by different technologies.
Figure 3. Basic operational principle of the delineation schemes of systems, VL-S2 and VL-R2.
Figure 4. Optimum values of the maximum dimensions of variable shaped rectangular beams. C is the overhead time.
Figure 5. Schematic diagram of system VL-S2.
Double exposure on each side

Field junction

Double exposure alternately

0.5μ□ minimum

Field junction

Figure 6. Alignment accuracy tested by double exposure and field junction (stitching) in system, VL-S2.
Figure 7. A magnified view of one of the four corners in Fig. 6. The smallest square is $0.5 \times 0.5 \ \mu m^2$.

Figure 8. Photomicrograph of delineated VLSI chips on a wafer of 100 mm in diameter by VL-S2.

Figure 9. Photomicrograph one of the chips shown in Fig. 8. The chip size is $9.6 \times 9.6 \ \text{mm}$. Number of rectangular patterns is about 5 million.
Figure 10. A magnified photomicrograph of Fig. 9, focusing on a part of peripheral circuit and a part of memory cell.

Figure 11. Photograph of the electron gun and EOS assembly of VL-Fl.
Figure 12. Relationship between electron beam current and beam spot diameter obtained from VL-F1 and a corresponding data by a best thermionic LaB$_6$ gun.
Figure 13. Variation of exposure dosage as functions of line width and space in system VL-F1. Dotted line is for the case of a thermionic LaB₆ gun.
HIGH SPEED ELECTRON BEAM DELINEATOR: VL-R2

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A new electron beam delineator, VL-R2, which provides a new delineation method has been developed to be used for direct writing. This system is capable of writing VLSI patterns at writing speed of 8 cm²/min, and is also capable of writing 0.5 μm patterns with the complexity of 5 million rectangles/cm².

1. INTRODUCTION

Electron beam lithography has been coming up a practical technology for mask making in advanced LSI because of its inherent capability of fast and precise pattern generation.

In the first half of four years VLSI project, VL-R1 of raster scan type was developed in Cooperative Labs(1). This system has been effectively used for making master masks and reticles including 10x masks for reduction type projection aligners. However, the writing speed of VL-R1 is still slow for use of direct writing. In the second half of the project, a high speed electron beam delineator, VL-R2, has been developed. This system provides a new delineation method to have a throughput capability of ten times higher than that of VL-R1 and a drawing capability of 5 million rectangles/cm² which is equivalent to the pattern complexity of 1 Mb RAM.

In this paper we describe the delineation method, specifications and obtained results of VL-R2.

2. DELINEATION METHOD

In order to increase the writing speed, VL-R2 provides a new delineation method which utilizes variable size beam concept combined with continuously moving work-stage method. Fig. 1 illustrates a schematic of the delineation method of VL-R2. The variable size beam repetitiously scans 250 μm in width in one direction on a substrate, while the work-stage moves continuously in the other direction from end to end of the drawing area. After the stage reaches to one end of the drawing area, the stage moves the range of 250 μm in the beam scanning direction and returns to the opposite direction with continuous motion. The beam size, perpendicular to the scanning direction, is varied up to

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4 µm according to patterns to be drawn. The beam width is preset at either of two modes of operation. Two modes differ in their addresses: 0.125 µm and 0.25 µm. For the delineation of circuit patterns composed of rectangles in parallel and orthogonal to the scanning direction, the beam size is fixed for one scanning duration. On the other hand the beam size and the beam position are varied at an adequate rate for the delineation of the circuit patterns with slanted rectangles. The beam is turned on and off at an address frequency of 30 MHz.

Most effective approach to increase the writing speed in raster scan type delineator is to reduce the number of scanning. Thus blank area is skipped by deflecting the beam in the stage motion direction. The work-stage moves at an optimum speed which is predetermined by calculating the number and size of subcells as illustrated in Fig. 2. Therefore the stage-speed is changed up to 100 mm/sec at maximum at each frame drawing. Consequently, in VL-R2 system with skip-scanning and variable size beam, the number of scanning is reduced to one tenth of that in VL-R1 on the average.

3. SYSTEM DESCRIPTION

Fig. 3 shows a schematic diagram of VL-R2. System computer is a Tosbac-40D with 512 kbyte memory. Magnetic tape handler is used for input of pattern data with PG-3000 and Calma format. Converted and compacted pattern data, system control data and programs are stored in a magnetic disk with a capacity of 160 Mbyte. At the delineation, converted chip pattern data in the magnetic disk are transferred to a high-speed buffer memory with a capacity of 2 Mbyte. Then the data in the buffer memory are transferred to a writing circuit through DMA. The writing circuit decodes the compacted data to blanking data, sizing data and position data which are supplied to deflectors of an electron optical column. Scan/position circuit receives the stage position data measured by laser interferometer and generates beam scanning wave form which is supplied to the scanning deflectors. Character display terminal with key board and teletype writer are used for operation of this system.

A special registration technique is provided for direct writing. Before loading the wafer-cassette to the pre-chamber, optical pre-aligner is used to adjust the wafer setting position to the cassette. Before delineation of circuit patterns, registration marks on the wafer are scanned. The mark signal detected by back-scattered electron detector is transferred to a wave memory where the signal is converted to digital signal, which is stored in the magnetic disk as registration data. Registration data are used to correct the start position and angle of the beam scanning.

Fig. 4 shows a cross-sectional view of the electron optical column. The column consists of an electron gun with a single crystal LaB₆ cathode, 5 magnetic lenses, 2 beam sizing apertures and electro-static deflectors for beam blanking, sizing and scanning. LaB₆ chip with apex radius of 480 µm is used to illuminate uniformly the aperture with enough brightness. Two condenser lenses are used to adjust the position of the cross-over image and illumination condition. Demagnification lens and
Object lens demagnify the aperture image at 40 to the substrate. In addition to the scanning deflectors, a set of deflector is provided to shift the beam position in the stage motion direction for delineating slant lines. Typical performances of the electron optical subsystem are listed in Table 1. Current density of more than 50 A/cm² with edge resolution of 0.25 μm is attained. Beam position stability is less than 0.02 μm/2Hrs.

Constitution of the mechanical subsystem listed in Table 2 is similar to that of VL-R1 except the stage-support mechanism. Air bearing is implemented for the stage-support in the continuous motion direction (H) to drive accurately and smoothly the work-stage at the speed of up to 100 mm/sec. Temperature of the main part of the system is controlled to less than ±0.1°C by using constant temperature water flow. Turbomolecular pump and three ion pumps are used to evacuate the column and substrate chamber with clean vacuum. Typical obtained performances of mechanical subsystem are listed in Table 3.

Fig. 5 shows a software configuration of VL-R2. Operating system named R2-OS is specially developed for this system. Software of VL-R2 consists of two main programs: data conversion program and writing control program. The tasks of data conversion program are converted data generation, data edition and data check. The tasks of writing control program are stage motion control, pattern-data transfer control, registration and chip location.

Functions of scaling, resize, black and white reversal and mirror image are carried out by hardware so that these patterns are easily delineated by same pattern data.

4. RESULTS

Fig. 6 shows an overview of VL-R2 system. Main frame with electron optical column and machinery is set in a clean chamber in which temperature is controlled to less than ±1°C. Racks of control electronics and peripheral devices for computer are located at outside of the chamber. Specifications of VL-R2 are listed in Table 4. Maximum writing speed of 8 cm²/min is attained with an overlay accuracy of less than 0.2 μm. Overlay accuracy measured by double-exposure method for 5 in. mask is shown in Fig. 7. Fig. 8 shows a SEM photograph of model VLSI pattern with 0.75 μm geometry. Electron resist is EBR-9(poly-tri-fluoroethyl-α-chloroacrylate) which was developed in Cooperative Labs.

5. CONCLUSION

Electron beam delineator, VL-R2 with new delineation scheme which utilizes variable size beam concept combined with continuously moving work-stage method can delineate LSI patterns of 1 μm feature size with slant lines at writing speed of up to 8 cm²/min. The system is also capable of writing VLSI patterns whose minimum feature size is down to 0.5 μm and pattern complexity is up to 5 million rectangles/cm². Overlay accuracy of 0.2 μm is attained.
6. ACKNOWLEDGEMENT

The authors gratefully acknowledge Dr. Y. Tarui and members of VLSI Co-operative Laboratories, for their support and encouragement. They wish to thank members of Toshiba R & D Center, Akashi Seisakusho, Asia Seisakusho, Toshiba Engineering and Japan Business Automation for their technical contributions to the development of this system.

REFERENCE

Fig. 1. Schematic of delineation method of VL-R2.

VL - R1

- 125 µm (A mode)
- 250 µm (B/C mode)

VL - R2

- 250 µm

Fig. 2. Beam scanning in VL-R1 and VL-R2.
Fig. 3. Schematic diagram of VL-R2.
Fig. 4. Cross-sectional view of electron optical column.
Fig. 5. Software configuration of VL-R2.

Fig. 6. Overview of VL-R2 system.
\[ \Delta V = -0.009 \mu m, \sigma \Delta V = 0.033 \mu m \]

\[ \Delta H = 0.033 \mu m, \sigma \Delta H = 0.059 \mu m \]

Fig. 7. Overlay accuracy measured by double-exposure method.

Fig. 8. SEM photograph of model VLSI pattern.
Table 1. Performances of electron optical subsystem.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Density</td>
<td>50A/cm²</td>
</tr>
<tr>
<td>Edge Resolution</td>
<td>0.25μm</td>
</tr>
<tr>
<td>Focal Depth</td>
<td>50μm</td>
</tr>
<tr>
<td>Scan Width</td>
<td>370μm (H), 260μm (V)</td>
</tr>
<tr>
<td>Beam Position Stability</td>
<td>0.02μm/2H</td>
</tr>
</tbody>
</table>

Table 2. Constitution of mechanical subsystem.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage Support</td>
<td>Mechanical Bearing (H)</td>
</tr>
<tr>
<td></td>
<td>Air Bearing (V)</td>
</tr>
<tr>
<td>Stage Drive</td>
<td>Pulse Motor (H)</td>
</tr>
<tr>
<td></td>
<td>DC Servo Motor (V)</td>
</tr>
<tr>
<td>Temperature Control</td>
<td>Constant Temperature Water Flow</td>
</tr>
<tr>
<td>Evacuation</td>
<td>Turbo-Molecular Pump &amp; Ion Pump</td>
</tr>
<tr>
<td>Pre-Alignment</td>
<td>Optical Pre-Alignment</td>
</tr>
</tbody>
</table>
Table 3. Performances of mechanical subsystem.

<table>
<thead>
<tr>
<th></th>
<th>(H)</th>
<th>(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage Motion Speed</td>
<td>Max. 15mm/s</td>
<td>Max. 100mm/s</td>
</tr>
<tr>
<td>Pitching</td>
<td>2.2sec</td>
<td>0.8sec</td>
</tr>
<tr>
<td>Rolling</td>
<td>1.4sec</td>
<td>1.1sec</td>
</tr>
<tr>
<td>Yawing</td>
<td>2.7sec</td>
<td></td>
</tr>
<tr>
<td>Stop Position Accuracy</td>
<td>±5μm</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>25±0.1°C</td>
<td></td>
</tr>
<tr>
<td>Pre-Alignment Accuracy</td>
<td>±5 x 10^-4 rad</td>
<td></td>
</tr>
<tr>
<td>Cassette Loading Position Accuracy</td>
<td>±2.5μm</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Specifications of VL-R2.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>4in. Wafer, 5in. Mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Exposure Area</td>
<td>105 x 124mm</td>
</tr>
<tr>
<td>Min. Line Width</td>
<td>0.5μm/1.0μm</td>
</tr>
<tr>
<td>Adress</td>
<td>0.125μm/0.25μm</td>
</tr>
<tr>
<td>Scan Width</td>
<td>250μm</td>
</tr>
<tr>
<td>Address Rate</td>
<td>30MHz/40MHz</td>
</tr>
<tr>
<td>Max. Beam Size</td>
<td>4μm</td>
</tr>
<tr>
<td>Current Density</td>
<td>50A/cm²</td>
</tr>
<tr>
<td>Accelerating Voltage</td>
<td>20kV</td>
</tr>
<tr>
<td>Overlay Accuracy</td>
<td>0.2μm</td>
</tr>
<tr>
<td>Max. Writing Speed</td>
<td>8cm²/min</td>
</tr>
<tr>
<td>Input Data Format</td>
<td>Mann 3000, Calma</td>
</tr>
<tr>
<td>Function</td>
<td>Scaling, Resize, B&amp;W Reversal, Mirror</td>
</tr>
</tbody>
</table>
ELECTRON BEAM DIRECT WRITING LITHOGRAPHIC SYSTEM

J. Trotel

Electron beam direct writing is presently widely used in laboratory to study new high resolution devices, but production is only marginal, due to the lack of reasonable throughput systems.

We shall describe a system we are developing for fast direct exposure of wafers, the main specifications of the system are:

- Wafer size: up to 6"
- Throughput: 10 3" wafers/hour
- Minimum linewidth: 1 μm for maximum throughput

The system has the capability to make 0.3 μm minimum linewidth at a lower throughput.

To describe the system, we shall look at:

- The electron optics
- The writing strategy
- The control circuits
- The general architecture of the machine

1. ELECTRON OPTICS

The electron optics uses the variable shape beam concept [1],[2],[3],[4],[5].

Fig. 1 gives its principle:

The cross-over of a tungsten hairpin filament gun is magnified and imaged on an aperture A1 which has at least one right angle.

The aperture A1 is imaged at scale one on an aperture A2 similar to A1 by a nearly confocal doublet L2 and L3.
The intersection of A2 and the image of A1 forms a rectangle; the dimensions of this rectangle can be changed by a deflector D1.

This rectangle is demagnified and imaged on the sample by the final lens L4, its position over the sample can be changed by the deflector D2.

This schematic is very similar to the configuration which was used by Fontijn [1] and differs from the configuration we built first [5] and those described by other authors [2],[3],[4].

First difference is the use of critical illumination scheme instead of the Kohler illumination where the image of the cross over is on the entrance pupil of the last lens. We found that for a tungsten hairpin filament it is easier to control the homogeneity, size and stability of the cross over than the angular intensity distribution in the beam going out of the gun. This situation is even more pronounced for a high brightness LaB6 gun.

Second difference is the use of a doublet to form the image of aperture A1 on aperture A2. The coils of the two lenses are connected in series and their magnetic fields are opposed, so that focusing of the image of A1 does not induce any rotation of that image.

We use only one lens to demagnify the image of A2 on the sample, to get a 10 to 1 demagnification the focal length of L4 has to be short : 15 mm.

The low demagnification of 10 to 1 puts some constraints on the fabrication of the apertures: they have to withstand a relatively high power density of about 8 kW.cm⁻² and they have to be carefully machined because the edge roughness is only reduced by 10 on the sample.

The short focal length of L4 has some advantages:

- Low spherical and chromatic aberrations.
- Low sensitivity to spurious electric and magnetic fields due to the short path of the beam.

The main drawback of the short focal length is a high deflection aberration coefficient, so the deflection field has to be limited to 0.16 x 0.16 mm².
Electron optics characteristics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Tungsten hairpin filament</td>
</tr>
<tr>
<td>Beam energy</td>
<td>15 kV</td>
</tr>
<tr>
<td>Beam blanking</td>
<td>Magnetic</td>
</tr>
<tr>
<td>Beam shape control deflector</td>
<td>Magnetic, telecentric</td>
</tr>
<tr>
<td>Beam position deflector</td>
<td>Magnetic, telecentric</td>
</tr>
<tr>
<td>Maximum beam dimension</td>
<td>10.2 μm x 10.2 μm</td>
</tr>
<tr>
<td>Maximum beam deflection</td>
<td>162 μm x 162 μm</td>
</tr>
<tr>
<td>Maximum beam density</td>
<td>50 A.cm⁻²</td>
</tr>
</tbody>
</table>

Due to the small deflection field it would be too much time consuming to step the table and to stop it when the beam is writing, so writing is done while the table is moving.

The movement of the table is illustrated on fig. 2: the pattern of each chip is divided into 0.16 mm width stripes. The same stripe in each chip is written while the table has a meander like movement illustrated by the solid line, then the next adjacent stripe is written by moving the table according to the dotted meander line.

Deflection of the beam is of the vector scan type, but it has to take into account the movement of the table in the y direction. Fig. 3 shows the principle of the y deflection only:

On the upper right hand side is an example of a pattern to be written, comprising five rectangles R₁ to R₅; each rectangle is supposed to be smaller than the maximum dimension of the beam, so each rectangle is made by a single exposure and the time to make it is constant to a first approximation.

On the left hand side are several time diagrams:

On coordinates (y,t): the solid line Yₜ gives the movement of the sample compared to the optical axis of the electron optic column, the movement is assumed to be at constant speed although it is not mandatory.
The dotted line YR gives the movement of the beam compared to the sample, this movement has some plateaus whose length is given by the time necessary to expose the rectangles.

On coordinates (YB,t) is the representation of the deflection, that is the movement of the beam compared to the optical axis of the electron optic column.

On coordinates (B,t) is the time diagram of the intensity of the beam.

On coordinates (E,t) is an error signal which occurs when the amplitude of the deflection of the beam exceeds a given value.

It can easily been understood that curve (YB,t) is obtained by subtracting curve (YT,t) from curve (YR,t).

Curve (YT,t) is given in digital form by the output of an interferometer which monitors the movement of the table driven at constant speed by a D.C. motor.

The plateaus of curve (YR,t) are given by the output of a memory containing the description of the pattern to be drawn, with the rectangles ordered according to their y value. The read signal of that memory is derived from the (B,t) curve.

Curve (YB,t) is then obtained by making in real time the difference between the output of the interferometer and the output of the memory. The result of that difference is clipped so as not to exceed the deflection limits.

To get the maximum speed, the table must move as fast as possible without being in the situation where the deflection which would be necessary exceeds the maximum amplitude of the deflector.

The maximum speed depends on the time to make a rectangle and on the density of rectangles.

Some computer simulations have been made to get an evaluation of that maximum speed.

The simulation has been done on an actual integrated circuit and on circuits which where deduced from it by reducing the geometry by 2 and 4 and stitching these reduced circuits to get 5 mm x 5 mm and 10 mm x 10 mm chip sizes.
In all cases, the maximum dimension of the beam is 10 \( \mu m \times \) 10 \( \mu m \) and the time to make a rectangle 1 \( \mu s \).

From table I it can be seen that for the most complex stripe of the most complex level. The maximum speed of the table is 14 cm.s\(^{-1}\) for a 1.25 \( \mu m \) minimum linewidth circuit.

Once the maximum stage speed is determined, the writing time for a wafer depends on the time lost to reverse the speed in the y direction at each stripe and to step in x direction from one row to the next one. If these delays are in the range of one tenth of a second the overhead stepping time is of about 50 % of the exposure time for a 3" wafer giving a total exposure time of 5 minutes for a 3" wafer.

3. CONTROL CIRCUITS

The data corresponding to the description of one stripe of a chip are stored in a buffer memory, this buffer is made of two blocks of 250 K 16 bits words one block is filled by the computer while the other block is read as many times as the number of chips in the wafer, reading is made forward for odd number columns of chips and backward for even number columns.

Switching of the two blocks is made during the step labeled EF on fig.2.

Each rectangle is described by four 16 bits words and exposure speed can go up to \( 10^6 \) rectangles/s.

The circuits driving the deflectors which settle the size of the beam (D1) and the position of the beam (D2) have both a settling time of 0.5 \( \mu s \).

Minimum increment for size and position of the beam is equal to the measurement quantum of the interferometry i.e. 1/16 th of the helium neon laser wavelength, approximately \( 4.10^{-2} \) \( \mu m \).

Maximum dimension of the beam is \( 2^8 \) increments \( \approx \) 10.2 \( \mu m \).

Maximum deflection is \( 2^{12} \) increments \( \approx \) 162 \( \mu m \).
4. GENERAL ARCHITECTURE OF THE MACHINE

Fig. 4 gives a schematic of the machine.

The electron optics column, the interferometer and the pumping stack are hanging under a solid 1 m x 1 m metal table on which is fixed a conventional roller bearing XY stage, driven by DC motors through vice and screw mechanisms.

The samples, with sensitive side facing down are loaded through the XY stage.

A vacuum bell jar covers the whole system and holds the automatic wafer loading mechanism.

When the bell jar is lifted any part is readily accessed for maintenance.

Some attention had to be paid to the interferometer so has to get the necessary measuring speed and range, the system uses is a conventional rugged multimode helium neon laser.

The system we described reaches quite a satisfactory throughput without using extremely sophisticated techniques we then believe it has to be considered for the production of some types of devices.

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Variable spot shaping for electron-beam lithography.
14th Symposium on Electron, Ion, & Photon Beam Techn.
Palo Alto (May 1977).

Dynamic beam shaping.
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Palo Alto (May 1977).

Fig. 1
Fig. 2

Fig. 3
TABLE SPEED COMPUTER SIMULATION

<table>
<thead>
<tr>
<th>CHIP SIZE (mm x mm)</th>
<th>5 x 5</th>
<th>5 x 5</th>
<th>10 x 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF TRANSISTORS</td>
<td>5.050</td>
<td>21,000</td>
<td>323,200</td>
</tr>
<tr>
<td>MINIMUM LINEWIDTH (μm)</td>
<td>5</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>MAX. NUMBER OF RECTANGLES/STRIPE</td>
<td></td>
<td>470 00</td>
<td></td>
</tr>
<tr>
<td>MAXIMUM SPEED (cm/s)</td>
<td>57</td>
<td>29</td>
<td>14</td>
</tr>
</tbody>
</table>
ADVANCES IN PROXIMITY EFFECT CORRECTION TECHNIQUES FOR ELECTRON LITHOGRAPHY

Mihir Parikh*

IBM Research Laboratory
San Jose, California 95193

ABSTRACT: Recent developments in proximity effect correction techniques, within the self-consistent algorithm, are outlined. In particular, we present algorithms and experimental results for: (1) Judicious partitioning of patterns to optimize the quality of corrections, (2) Partitioning of patterns that extend beyond or traverse through zones, thereby optimizing computation of corrections, (3) Reduction of some overcompensation within the self-consistent algorithm by explicit consideration of edges of shapes.

I. INTRODUCTION

This paper will briefly outline three new developments that have been incorporated within the framework of SPECTRE (for Self-consistent Proximity Effect Correction Technique for Resist Exposure). These are: (1) An algorithm for judicious automatic partitioning (or subdivision) of patterns in order to optimize the corrections possible with the self-consistent algorithm, (2) An algorithm for partitioning those shapes that extend beyond or traverse through a computational "zone"; thereby optimizing the computation of correction, (3) An algorithm to explicitly consider edges of shapes within the self-consistent algorithm, thereby reducing some overcompensation to correction.

Since details of the algorithms are being published elsewhere (1,2), we will present here only an outline of the algorithms and some experimental results.

II. PARTITIONING FOR ENHANCED CORRECTIONS

The quality of correction that can be attained using the self-consistent algorithm (3a) is limited by the subdivision of a pattern into shapes. For example, if the letter V is to be

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written by an electron-beam machine, it could be described by three shapes: Two parallelograms and one triangle (Fig. 1a). Subdivision (3c) of each of these shapes (Fig. 1b) into, for example, \((2n+1)\) shapes (where \(n\) is the number of vertices), could increase the fidelity of the pattern. However, the increase in the number of shapes (and thus the data volume and computation time) necessitates an intelligent algorithm for the partitioning of a pattern only at those locations that are significantly influenced by proximity effects. Such an algorithm has been presented elsewhere (2). We present here a brief overview.

The strategy for pattern partitioning can be summarized as follows:

1. Proximity corrections are attempted on a given pattern.
2. The pattern quality is assessed at numerous "sample" points throughout the pattern.
3. If the pattern quality fails to satisfy certain "goodness" criteria (2) at certain "sample" points, such points and the associated regions are subdivided from the rest of the shape.
4. Proximity correction is re-attempted on this partitioned pattern. This procedure can be repeated until the quality criteria is satisfied everywhere or it becomes impossible to further subdivide the pattern based on physical limitations of the electron-beam machine. In our experience, a single iteration is generally adequate.

Implementation of the above algorithm to the 8 rectangles in the pattern shown in Fig. 2a leads to a partitioned pattern shown in Fig. 2b. Note that such a partitioning has been achieved only at those locations that were deemed algorithmically to be suffering from excessive proximity effect, even after the self-consistent calculation of exposure for the pattern in Fig. 2a. The exposure values calculated for the 21 shapes in the partitioned pattern are shown in Fig. 2b.

Experimental results (Fig. 3) show four regions in the pattern in the case of (a) no correction, (b) self-consistent correction, without partitioning and (c) partitioned pattern, self-consistent correction. Note that while the 1 \(\mu\)m wide resist line (region (iii)) in the uncorrected pattern is significantly underdeveloped, the resist gap (region (iv)) is already narrower than the 1 \(\mu\)m design. Further development of such a pattern leads to disintegration of the resist gap. The corrected unpartitioned pattern significantly alleviates the problem. However, definition of the pattern in terms of 8 rectangles (and thus only 8 different exposure values) leads (Fig. 3b) to widening of the 1 \(\mu\)m wide line in the vicinity of the 2 \(\mu\)m rectangles (region (iii)). In addition the resist gap suffers from curvature (region (iv)) due to the definition of the large areas on either side in terms of only two rectangles. The corrected partitioned pattern (Fig. 3c) seems to have essentially corrected all of these problems.
III. PARTITIONING FOR EFFICIENT COMPUTATION

Zoning algorithms have been devised and implemented (3b) within the self-consistent algorithm that make the computation very efficient. We will show here an enhancement (for details, see Reference 2) to previously described schemes that make the computation of corrections more efficient for shapes that extend beyond or that traverse a zone.

Consider ten rectangles in Fig. 4a that lie in and around a hypothetical zone (more correctly these are "S zones" of Reference 3b) with indices (I,J). Note that shapes A and J are of such an extent that they are assigned to some zones that are beyond the limits of Fig. 4a. Consider next the seven shapes that would be used in the self-consistent solution of the shapes in the zone (I,J). Since the shapes B, I, and J are not included in the computation, the mutual interactions between them and the long shape A are incorrectly ignored. In addition, the interaction between shapes G and J is also ignored; this can lead to serious errors in the computed exposure values for shape G.

A solution (2) to these problems can be obtained by cutting up some shapes into smaller ones so that more accurate exposure values can be computed for component pieces. The algorithm for such a shape cutting involves: (1) The definition of a "shape-cutting" frame (Fig. 4b) that circumscribes a zone, (2) The stipulation of cutting up into two pieces those shapes that belong to a zone but extend beyond such a frame, (3) The cutting of the shape, if it is found to be necessary at the zone boundary, (4) The prevention of "sliver" shape formation (for example in the case of shape G) by reassigning the entire shape to a neighboring zone. The application of these rules results in the 13 shapes shown in Fig. 4b.

Examination of Fig. 4b reveals the following. Computation of shapes belonging to the zone to the left of zone (I,J), takes into proper account the interactions between A1 and B. Similarly the computation of shapes in the zone to the right of zone (I,J) takes into proper account the interactions between A3, J, and G. Finally note that shape G was reassigned to the zone to the right of the zone (I,J) in order to prevent the formation of "sliver" shapes as well as to properly consider the interaction with shape J.

IV. EDGE COMPENSATION ALGORITHM

The self-consistent technique considers (3a) the magnitude of the proximity effect within each point in a shape democratically. This leads to an area average consideration (see, for example, Eq. (5) in Reference 3a). If certain points within a shape (e.g., along the
periphery or at a corner) are more critical than other points (e.g., within an interior of a large shape), an unequal weighting of parts of a pattern may have to be considered.

An algorithm (for details see Reference 1) that accomplishes this within the "self-consistent" framework considers values of $\varepsilon$ (see Eq. (4), Reference 3a), a measure of the magnitude of the proximity effect, at a certain point in each shape. This is arbitrarily chosen to be the midpoint along one edge of the narrower side of a rectangle. It can be shown (1), that $\varepsilon_A$ at such a point $A$ decreases with decreasing dimension of an isolated uncorrected shape. This leads to the well-known underdevelopment of smaller shapes as compared to large shapes. The self-consistent algorithm (involving area-averaging) leads to an "overcompensation". That is, while perfect compensation should yield $\varepsilon_A$ to be independent of the dimension of the shape, the self-consistent correction leads to $\varepsilon_A$ that increase with shape dimensions. This overcompensation can be exactly corrected by the multiplication of relative incident exposure $n_I$ by an analytical function $F$. Results for isolated squares and lines, Fig. 5a, shown in terms of dimensional deviation $x_d/k_d$ indicate that perfect compensation is achieved. Corresponding values of relative incident exposure $n_I$ is shown in Fig. 5b. Note that the self-consistent technique seems to significantly overcompensate only for dimensions $< 0.5 \mu m$.

V. SPECTRE

A new version of SPECTRE (for Self-consistent Proximity Effect Correction Technique for Resist Exposure), with an architecture similar to the earlier version (3c), has been created which includes the above described algorithms. Figure 6 shows the flowchart of the programs that comprise SPECTRE. As before the program is initiated via an interactive program (SPECREAD) that prepares and checks input parameters regarding electron lithographic and pattern conditions to be used for proximity correction. An arbitrary pattern is divided into various zones (3b) (via the program ZONMAP) based on whether the proximity corrections are to be performed on all shapes (if the pattern is nonrepeating) or whether only some shapes are to be corrected (if the pattern is repeating) and the results replicated to the rest of the repeating pattern. A program (WINDOW) separates the pattern data into two parts. One part with the pattern data (COMP.SHAPES-"C.S.") that are to be explicitly used for proximity computations and the other part with the pattern data (ASSOC.SHAPES) that are part of the repeating pattern, which are to be associated with the computed corrections. The "C.S." pattern data is next processed by three programs. The program ZONTAG, tags the pattern according to zones, as described previously (3b). Using the algorithm described in Section III, shapes that traverse zone boundaries
are subdivided by the program SHAPCUT. The program FRMTAG, replicates and tags shapes if they belong in the frames of zones as reported previously (3b). After a SORT, to arrange pattern data sequentially by zones, the computation of corrections is performed by the program COMPC using the self-consistent algorithm and the algorithm of Section II to automatically subdivide (and recompute corrections) of shapes via the program AUTOCUT.

REFERENCES AND NOTE


Note: Please refer to Reference 1 for a comprehensive review and citation of publications by other workers in this field.
Figure 1. Subdivision of a complex shape into (a) two parallelograms and one triangle (b) 25 shapes. In the latter case, increased pattern delineation can be obtained by exposing the edge and corner shapes with different incident electron exposures as determined using the self-consistent algorithm (from Reference 3c, by permission).
Figure 2. (a) A pattern consisting of 8 rectangles. Note regions (i)-(iv) where proximity corrections are necessary for complete dissolution of the resist as well as pattern fidelity. If this pattern is not proximity corrected, a relative exposure value of unity is given to each rectangle. If this pattern is corrected via the self-consistent algorithm, a relative exposure value as noted in parenthesis in the figure is given to each rectangle. (b) Partitioned pattern with 21 rectangles that are obtained using the algorithm described in Section II. Note the relative incident electron exposures for each of the rectangles computed using the self-consistent algorithm.
Figure 3. Scanning electron micrographs of the four regions noted in Fig. 2 under three different conditions: (a) Uncorrected pattern, (b) Corrected pattern with the 8 rectangles, each exposed with the relative exposures as noted in Fig. 2, (c) Corrected partitioned pattern with 21 rectangles, each exposed with relative exposures as noted in Fig. 2b. See text for discussions on the micrographs.
Figure 4. (a) Ten shapes that lie in and around the Zone (I,J). (b) Corresponding thirteen shapes obtained after partitioning according to the algorithm in Section III.
Figure 5. (a) Dimensional deviation ($\lambda_a/\lambda_d$) for isolated squares and lines of widths $\lambda_d$ in the case of the uncorrected patterns and of corrected patterns via (i) the self-consistent (area avg. corr.) and (ii) the edge compensation algorithm of Section IV (edge adj. corr.). (b) Corresponding relative incident electron exposures $n_1$. 
Figure 6. Flowchart to SPECTRE. See text for explanation of individual programs.
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SOME ASPECTS OF THE DESIGN OF A 4" ELECTRON IMAGE PROJECTOR

R. Ward, I.H. Lewin

1. INTRODUCTION

Electron image projection as a technique for the fabrication of high resolution integrated circuits has been known for some time(1). An electron image of a mask pattern is projected onto a resist covered silicon wafer at unity magnification using highly uniform electric and magnetic fields to focus the image. A fully automatic alignment technique with an accuracy of ±0.1 μm including magnification control has been developed(2,3). Examples of I^2-L circuits have been fabricated(4) and the technique has been used to define bubble circuits with submicron dimensions(5). In spite of these successes the technique has received relatively little attention and all the work reported so far has related to small laboratory machines capable of exposing at best 2" wafers. This paper deals with several aspects of the design of a projector capable of exposing 4" wafers and generally more suitable for development into a production tool; a brief target specification is set out in table 1. Considerable attention has been paid to controlling and reducing distortions and it is intended that wafers should be interchangeable between machines. An improved electrostatic chuck has been introduced and slice and mask handling considerably improved. The projector has been assembled and is currently undergoing trials. Some examples of the photocathode performance and the resolution capability are given in the final section.

2. GENERAL FEATURES

A simplified schematic of the projector is shown in figure 1 and the assembled machine in figure 2. The alignment system is similar to that which we have described earlier(2) and uses tantalum markers on the slice to generate X-ray signals the magnitude of which is dependent on the relative alignment between mask and slice. The X-ray signal is detected by a phosphor-light guide-photomultiplier combination which proves to be sensitive and extremely robust. A phase sensitive detector system is employed and the necessary modulation is supplied by coils wrapped around the vacuum chamber. Titanium is used for the chamber to reduce eddy currents. Deflection of the image is achieved using the large rectangular Helmholtz coils. Rotation correction is

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carried out mechanically and magnification control is achieved by varying the currents in the two halves of the focussing magnet to produce a slightly convergent or divergent field(3).

The pumping system is conventional and uses an oil diffusion pump. Pump down times of 40 secs. to the operating pressure of $5 \times 10^{-5}$ torr are regularly achieved. The UV lamp is positioned outside the coils to improve uniformity and to simplify the shutter mechanism. Figure 2 shows the loading system for wafers and the evaporator unit which is used to deposit the CsI photocathode.

3. DISTORTIONS

Controlling the image distortions in the projector presents one of the most difficult problems in the design of a practical machine. It is impossible to entirely eliminate distortion but it must at least be kept constant between one exposure and the next. If we accept that it is desirable to be able to exchange wafers between machines rather than restrict all processing of a given slice to a single machine then we must also make the distortion pattern the same for all machines. The main causes of image distortion are inhomogeneity of the focussing and deflection fields, edge effects on the mask and slice holders and process induced distortions particularly slice bowing.

3.1. The focussing field

Distortion in the projector may be reduced by using the highest possible magnetic field for focussing. For a given accelerating voltage, the gap 'd' between mask and slice is inversely proportional to the field strength. The separation d controls the magnitude of the distortions introduced by slice bowing and the range of distortions due to edge effects of the mask and slice holders. We have used a large air cored magnet with a field strength of 250 kA/m which when combined with an accelerating voltage of 20 kV giving a gap, d, of 5 mm. The design of the magnet follows our earlier work(6) and is a sixth order corrected split solenoid with a power consumption of 11 kW. The homogeneity has been measured to be better than five parts in $10^5$ over the working volume. The deflections in the X and Y directions caused by a transverse field component, $H_x$, is given by:

$$\Delta y = \frac{d}{\pi} \left( \frac{H_x}{H_z} \right)$$

$$\Delta x = d \left( \frac{H_x}{H_z} \right)$$

where $H_z$ is the axial field component of the focussing solenoid. With $d = 5$ mm we see that our homogeneity of 5 parts in $10^5$ gives distortion of only 0.1 µm and even that is only apparent if slices are interchanged between machines.
3.2. Deflection fields

The automatic alignment system has a maximum pull-in range of 100 μm. The deflection field uniformity is better than 5 parts in 10⁴. From equation 1 we see that this gives deflection distortions in the worse case of less than 0.05 μm. The deflection is also proportional to the spacing, d, which must therefore be kept constant to within ±5 μm. The mask and slice are both located in ball latches having an overall positional repeatability of better than ±2 μm. For rotational alignment the mask holder is mounted on leaf springs giving a maximum variation in the spacing of ±2 μm.

3.3. Edge effects on the mask and slice holders

The electric field is disturbed at the edge of both the mask and the slice and this can produce quite large distortions of the familiar 's' type. Usually it is necessary to locate both mask and slices on their front surfaces behind a lip of finite thickness as shown in figure 3. Also shown are some calculated distortion for a typical lip height and mask to slice separation. The magnitude of the distortion is proportional to the lip height and the distorted region extends into the slice a distance \(\propto d\). In any practical machine, several holders would be required and both slices and holders would need to be interchangeable between machines. From figure 3 this would require control over the lip height to within a few microns and accurate mechanical pre-alignment. It is possible to introduce additional electrodes to reduce the distortion but the problem remains of ensuring that the geometry is identical in different machines.

Our solution to the edge distortion problem is to mount the slice on a large flat surface and clamp it electrostatically. The distortion is now caused by the thickness of the slice but it is a property of the slice and not of the machine geometry. All that is now required to make interchangeable holders is to finish the chuck flat to within a few microns. Figure 4 shows a plot of measured and computer angular components of distortion for a 4" wafer located on its back surface on a large flat chuck. The experimental results were obtained by the usual technique of reversing the focusing field between two exposures so that all the angular components are reversed. It can be seen, as expected, that the centre 80 mm disc is distortion free.

The mask is located behind a lip as in figure 3 but its diameter is 115 mm for a 100 mm wafer. From figure 3 we see that any distortions from the mask holder only extend into the first 2 mm of the wafer.

3.4. Process induced distortions

3.4.1. Slice bowing

The slice forms the anode of the electron projector so that any change in slice bow due to slice processing is reflected in the electric field thus producing distortion. The electrostatic chuck has been recognised for some time(7) as the potential solution to this problem as well as providing a means of stabilising the temperature during
exposure. Our chuck design utilises the principle of rear surface location and is considerably simpler and more reliable than our previous models. A schematic diagram is shown in figure 5. The surface is finished flat to within ±3 μm and the insulator thickness is typically 200 μm.

We have found that it is possible to pre-charge the chuck in air so that the slice may be loaded into the machine and pumped down without the need for any retaining clamps. The slice holder thus approaches the ideal of a wafer on a semi-infinite flat surface, a geometry that is readily reproduced. Once vacuum conditions are established a voltage of about 3 kV is applied to the chuck to give a clamping force during exposure of about 0.2 atmospheres.

Experiments(4) and calculations(6) with earlier machines show that the magnitude of the distortion is about 6% of the change in slice bow in the worst case. In this machine the fields are three times higher and the spacing smaller by the same factor so that the distortion will be at worst 2% of the bow change. If we assume a maximum allowable distortion of 0.1 μm due to slice bow then the chuck must keep the wafers flat to within ±5 μm. Figure 6 shows optical interference patterns of the same 4" wafer clamped on two different chucks which satisfy this requirement. Also shown in the chuck surface and the unflattened wafer.

3.4.2. In-plane distortions

A criticism often levelled at whole slice writing techniques is their inability to deal with any random in-plane distortion that may be introduced during processing. The evidence for non-linear effects as distinct from expansion or contraction is rather sketchy and it is not yet clear whether there is likely to be a significant problem. The projector compensates for linear effects by adjustment of the machine magnification(3). In its present form there is no way to compensate for non-linear effects but it would be possible to introduce a modification so that the mask is illuminated in a raster mode. This would allow realignment over small areas giving the advantages of a step and repeat machine without the disadvantages of complex X-Y tables.

4. PHOTOCATHODE PERFORMANCE

CsI irradiated with the 1849 Å line from a low pressure mercury discharge lamp has been shown previously(8) to satisfy the requirements for the projector photocathode. We have used a large area 70 watt lamp spaced 350 mm from the mask to give good uniformity of illumination. Current densities are generally in the range 5 to 10 μA/cm² but currents as high as 100 μA/cm² have been obtained from more powerful sources.

Adequate throughput with the projector implies a large number of exposures from a single photocathode layer. Figure 7 shows the measured current density from a test mask as a function of the number of exposures. PMMA resist with a sensitivity of 160 μC/cm² was used
giving exposure times ranging from 17 secs for the early exposures to 53 secs after 50 exposures. Figure 8 shows examples of the resist image of windows and pads. The windows have widths covering the range 1.5 \( \mu \text{m} \) down to 0.2 \( \mu \text{m} \) and the pads from 1.5 \( \mu \text{m} \) down to 0.7 \( \mu \text{m} \). The image quality can be maintained over 50 exposures although some small adjustment to the dose is required as the cathode ages.

5. CONCLUSION

An electron image projector has been designed and assembled which is capable of exposing 4" wafers with a throughput of 25 wafers per hour. Lines with dimensions down to 0.2 \( \mu \text{m} \) have been resolved and 50 exposures have been obtained from a single cathode. Distortions generally have been reduced by using a high magnetic field for focussing. An electrostatic chuck has been demonstrated which exhibits the useful property of charge retention. Slices are located on a large flat surface so that the edge distortions are a property of the slice and not the geometry of the machine. The design of the projector will allow wafers to be interchanged between machines.

6. REFERENCES

TARGET SPECIFICATION

Resolution : Features down to 0.3 μm faithfully reproduced.

Exposure Uniformity: Feature size controlled to ±0.1 μm over whole wafer.

Depth of Focus : ±100 μm for 0.1 μm edge definition.

Alignment : Fully automatic with pull-in range of ±100 μm. Accuracy of 0.1 μm in X, Y, θ and magnification.

Image Distortion : Non repeatable distortion less than 0.2 μm over whole wafer inclusive of effects due to wafer bow.

Photocathode Life : At least 50 exposures from each photocathode.

Throughput : 25 4" wafers/hour.
Fig. 1 Schematic of electron image projector

Fig. 2 A prototype 4" image projector
Fig. 3  Calculated distortion due to a step
Fig. 4 Measured and computed angular component of distortion for a 4" wafer on an electrostatic chuck.

Fig. 5 Schematic of electrostatic chuck.
Fig. 6 Optical interference patterns of
(a) Unchucked wafer (b) Chuck surface (c) & (d) The same wafer electrostatically clamped on two different chucks
Fig. 7 Current density as a function of the number of exposures

Windows 0.2 - 1.5

Pads 0.7 - 1.5 μm

Fig. 8. Resist images of windows and pads
EXPERIMENTAL PHOTOCATHODE PATTERN TRANSFER SYSTEM USING A SUPERCONDUCTING MAGNET

Ichiro Mori+, Toshiaki Shinozaki+ and Shun-ichi Sano+

Submicron resist patterns are successfully replicated using a newly developed photocathode pattern transfer system. This system is equipped with a Helmholtz-type superconducting coil as the focusing magnet, which provides an intense and stable magnetic field with high homogeneity.

1. INTRODUCTION

There has been much progress in photocathode pattern transfer method, in which electrons emitted from photocathode are accelerated by a high electric field and focused by a magnetic field on to the wafer[1][2]. This pattern transfer method has been thought to be useful as a lithographic technology for VLSI fabrication, because of its inherent capability of high resolution and high throughput.

In this paper we report a newly developed experimental photocathode pattern transfer system with a superconducting magnet and experimental results about the resolution capability obtained with this system.

2. EXPERIMENTAL SYSTEM

2.1. Overall system

A schematic of this system is shown in Fig.1. The focusing magnet is made of a Helmholtz-type superconducting coil. In order to examine the effect of the accelerating voltage on the resolution capability, the accelerating voltage can be varied up to 20 kV. The mask-wafer spacings of 10 mm, 7.5 mm and 5 mm are used to investigate the effect of the spacing on the resolution capability. CsI is adopted as the photoemitting material and low pressure mercury discharge lamps are used as the illumination source. This combination of CsI and low pressure mercury discharge lamps results in a small average emitted electron energy, which is one of the important factors affecting the resolution capability[3]. Illumination is uniform to within 5% using two U-shaped mercury discharge lamps which are developed especially for this system. Specifications of this system are listed in Table 1. Fig.2 shows an overview of this system.

2.2. Superconducting magnet

Intense and stable magnetic field with high homogeneity is required to have good transferred patterns in this pattern transfer method. The

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focusing magnet of the superconducting coil easily meets these requirements. The superconducting coil can carry a large exciting current, thereby generating an intense magnetic field. The superconducting coil can be operated under the persistent current mode without ripple and drift, thereby generating a stable magnetic field. The focusing magnet of this system consists of two separated superconducting coils, which are made of Nb-Ti and are mounted in cryostats. The winding diameter is 880 mm and the spacing between two coils is 440 mm. The maximum field intensity of this magnet is 3 kG. Fig. 3 shows the distribution of the magnetic field intensity measured with NMR method. The homogeneity better than $6 \times 10^{-5}$ is obtained over the transfer area of 90 mm in diameter. Fig.4 shows the stability of the magnetic field intensity under the persistent current mode. There is a slow decrease of $1.7 \times 10^{-6}$/min. in the field intensity, which is caused by the residual electric resistance in the coils. However, this order of decrease does not cause any degradation in the resolution capability, because typical exposure time is respected to be less than 20 seconds.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The resolution capability of this pattern transfer method was evaluated by using the experimental system. The effect of the accelerating voltage on the resolution capability was examined. Fig.5 shows SEM photographs of 1 μm-thick PMMA resist patterns with minimum line width of 1 μm transferred at the accelerating voltage $V$ of (a) 20 kV and of (b) 10 kV. For thick resist layers the resolution obtained at 20 kV is higher than at 10 kV. This result can be explained by the fact that higher accelerating voltage produces deeper penetration and less lateral spreading of incident electrons[4]. Fig.4 shows a SEM photograph of 1 μm line-and-space patterns transferred in 1.3 μm-thick PMMA resist layer at 20 kV. Exposure time was 15 seconds. Development was carried out in isooamylacetate at 25°C.

The effect of the mask-wafer spacing on the resolution capability was also examined. Fig.7 shows SEM photographs of the cross section of 0.5 μm line-and-space patterns transferred at 20 kV at the mask-wafer spacing $d$ of (a) 7.5 mm and of (b) 10 mm. There is little difference between (a) and (b) in the edge resolution. However, the effect of the mask-wafer spacing will be more appreciable when the pattern size decreases down to less than 0.5 μm.

These experimental results provide us a guide to select the focusing parameters such as the accelerating voltage, the mask-wafer spacing, and the magnetic field intensity. Other factors such as the proximity effect and the pattern distortion should be taken into account to determine the focusing parameters. The most promising approach to minimize the proximity effect is to increase the accelerating voltage. The pattern distortion can be reduced by decreasing the mask-wafer spacing. For increasing the accelerating voltage and/or decreasing the mask-wafer spacing, it is necessary to increase the magnetic field. From this point of view, the focusing magnet of the superconducting coil is
favourable. In addition to the examination of the resolution capability, some other advantages of this pattern transfer method were experimentally confirmed. The depth of focus was proved to be deep about ±25 μm. This advantage is quite favourable for the pattern transfer on substrates with steps. Fig. 8 demonstrates an example of 1 μm line-and-space patterns transferred in 1 μm-thick PMMA resist layer over 0.5 μm Si steps. Exposure time of 2 seconds was attained by using CP-3 resist (poly(methyl methacrylate-co-t-butyl methacrylate)), which was developed in Cooperative Laboratories. Fig. 9 shows an example of 1 μm-thick CP-3 resist patterns, whose minimum line width is submicron.

4. CONCLUSION

Submicron patterns with steep profile in 1 μm-thick resist layers were successfully replicated by a newly developed experimental photocathode pattern transfer system using a Helmholtz-type superconducting coil as the focusing magnet. The superconducting magnet has remarkable advantages for improving the resolution capability in this pattern transfer method. Other advantages of this method such as short exposure time and deep depth of focus were also confirmed.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge Dr. Y. Tarui, Mr. K. Yada, Dr. Y. Takeishi and members of VLSI Cooperative Laboratories for their support and encouragement. They wish to thank members of Toshiba Research and Development Center for their technical contributions to this system.

REFERENCES

Table 1. Specifications of experimental photocathode pattern transfer system.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mask size (mm)</td>
<td>100 φ</td>
</tr>
<tr>
<td>Wafer size (mm)</td>
<td>75 φ, 100 φ</td>
</tr>
<tr>
<td>Spacing between mask and wafer (mm)</td>
<td>5, 7.5, 10</td>
</tr>
<tr>
<td>Accelerating voltage (kV)</td>
<td>≤ 20</td>
</tr>
<tr>
<td>Magnetic field (kG)</td>
<td>≤ 3</td>
</tr>
<tr>
<td>Photocathode</td>
<td>CsI</td>
</tr>
<tr>
<td>Illumination</td>
<td>1849 Å from low-pressure mercury discharge lamp</td>
</tr>
</tbody>
</table>

Figure 1. Schematic of experimental photocathode pattern transfer system.
Fig. 2. Overview of experimental photocathode pattern transfer system.
Figure 3. Distribution of magnetic field along x axis and y axis.

Figure 4. Stability of field in the superconducting magnet under operation of persistent current mode.
Fig. 5. Comparison of 1 \( \mu \text{m} \)-thick resist patterns transferred at the accelerating voltage of (a) 20 kV and of (b) 10 kV (d=10 mm).
Fig. 6. SEM photograph of 1 μm line-and-space patterns transferred in 1.3 μm-thick PMMA resist layer (V=20 kV; d=10 mm).
Fig. 7. Comparison of the cross section of 0.5 μm line-and-space patterns transferred at the mask-wafer spacing of (a) 7.5 mm and (b) 10 mm (V=20 kV).
Fig. 8. SEM photograph of 1 μm line-and-space patterns transferred in 1 μm-thick PMMA resist layer over 0.5 μm Si steps (V=20 kV; d=10 mm).

Fig. 9. SEM photograph of 1 μm-thick CP-3 resist patterns (V=20 kV; d=10 mm).
OPTICAL LITHOGRAPHY FOR MICROCIRCUITS

S. Wittekoek

In this paper first the characteristics of diffraction limited optical projection systems are reviewed. Then the degradation of the printed patterns are discussed that occur in the presence of topologies on the wafer and reflecting substrates. It is shown that linewidth control over steps can be improved considerably by using a lens which is corrected for both 405 and 435 nm as compared with a single wavelength lens. An advanced, second generation wafer stepper employing a two wavelength lens and an automatic alignment system based on diffraction gratings is described.

I. INTRODUCTION

At this conference a variety of papers on electron-, X-ray- and ion beam lithography will be reported which confirm and emphasize the rapid progress in these fields of lithography. From the point of view of the physical limitation, the ultimate resolution of these methods is superior to that of optical projection methods. Nevertheless there can be little doubt that till the end of the eighties optical pattern transfer will be the most widely used method for the volume production of microcircuits. There are a number of reasons for this.

Most important is that good photoresists are available which satisfy the many conflicting requirements for microcircuit processing such as resolution, sensitivity, adhesion and etch resistance. As long as the X-ray and e-beam resists do not satisfy all these requirements there will be a strong trend to stay with optical lithography.

Secondly, and equally important is the fact that the resolution of optical projection methods is being pushed continuously further. Two types of projection printing systems are now available for production, both of which are represented in other papers of this session:

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At this moment the scanning 1:1 projection aligners are the most widely used projection systems. Their resolution is being improved continuously especially by shifting to shorter wavelengths \(^1\).

Even better performance is achieved by direct step and repeat systems, where, by limiting the image field to about 1 cm\(^2\), optics with higher numerical aperture can be utilized.

It is most likely that due to these techniques optical lithography will not be the limiting factor for device shrinking in the coming 5 to 10 years. Other aspects of device processing such as etching, will have to be improved, in order to end up with 1 micron linewidths which are now possible with optical projection.

Another favourable aspect of projection printing is the speed. For example, in a step and repeat system with a numerical aperture of 0.3, 1 micron details are resolved, corresponding with \(10^8\) image points on a 1 cm\(^2\) image field. The exposure time of such a field can be about 0.1 second. This means that information can be transferred at a rate of \(10^9\) bits/sec, or a frequency of 1000 MHz. This is considerably faster than serial exposure systems like electron beam pattern generators.

This paper on optical projection methods, consists of three parts: After a summary of definitions and requirements of projection systems in Sec. 2, aspects of linewidth control are given in Sec. 3 with emphasis on the effect of the exposure spectrum. As an example of an advanced optical printer, in section 4 a step and repeat system developed at Philips Research Laboratories will be described, together with results on silicon wafers.

2. CHARACTERISTICS OF OPTICAL SYSTEMS.

2.1 Diffraction Limited Images.
In this section we review briefly two properties of ideal or aberration free optical systems, which are most useful in connection with lithographic instruments: the Modulation Transfer Function and the Edge Gradient. Some of these characteristics are useful when dealing with pattern definition in photoresist, discussed in the next paragraph.

The performance of an ideal optical system is determined by the operating wavelength \(\lambda\), the numerical aperture \(NA\) and the degree of coherence of the illumination \(\sigma\). The numerical aperture is defined as \(NA = n \sin \alpha\) where \(n\) is the refractive index in the medium (\(n = 1\) in air) and \(\alpha\) is the maximum cone angle of the rays reaching an image point. Partial coherence is measured by the degree to which the pupil of the projection optics is filled by the condensor optics: For \(\sigma = 0.5\), 50% of the pupil diameter is filled,
for \( \sigma = \infty \) the illumination is completely incoherent. Fig. 1 gives the MTF at \( \lambda = 400 \) nm and incoherent illumination for \( NA = 0.17 \), which is a typical value of a 1:1 projection system and \( NA = 0.25, 0.3 \) and 0.35 which is the range where direct step and repeat systems operate. It is generally accepted that for the definition of a certain detail in photoresist the MTF of the corresponding spatial frequency must be at least 60%. The minimum details according to this criterion decrease from \( 2 \mu m \) for \( NA = 0.17 \) to \( 0.9 \mu m \) for \( NA = 0.35 \).

Since the MTF is a function of the parameter \( NA/\lambda \), increasing the NA is for the MTF equivalent to decreasing \( \lambda \) and MTF curves at shorter wavelengths are easily derived from fig. 1. Advantages of operating at shorter wavelengths are discussed in several papers. 1,2

Fig. 2 illustrates the change in MTF curve when partial coherence in the illuminating systems is introduced. As can be seen from fig. 2 the spatial frequency at 60% MTF shifts to higher values when \( \sigma \) decreases (more coherent). For \( NA = 0.3 \), the minimum working feature decreases from \( 1 \mu m \) for incoherent illumination to \( 0.8 \mu m \) for the partial coherence factor \( \sigma = 0.5 \). However, the criterium of 60% MTF must be used cautiously when partial coherence is introduced. The MTF at higher spatial frequencies decreases, and furthermore it is known that for coherent illumination the intensities of adjacent images (e.g. narrow lines) do not add linearly, but that interference effects can occur. This makes it difficult to predict the image of a pattern of arbitrary shape, as the image quality is dependent on geometry. A partial coherence factor of \( \sigma = 0.7 \) is found to be a good compromise for optical image quality.

**Fig. 1.**
MTF for diffraction limited lenses. The curve for \( NA=0.17 \) represents a typical value for a whole wafer projector, the other three curves represents step and repeat systems.

**Fig. 2.**
MTF curves for various degrees of partial coherence. The 60% MTF line indicates the resolution limit for projection printing.
The second parameter frequently used to characterize a projection system is the edge gradient of the image of an isolated edge. Examples of this step response for some values of the NA and partial coherence are given in fig. 3. The gradient in the region where the response is linear is given by

\[ S = \frac{\Delta I}{\Delta x} = f \frac{NA}{\lambda}, \]

where \( f \) is a factor depending on the partial coherence of the illumination; for \( \sigma = 1 \), \( f = 1.63 \). Other values of \( f \) are given in table 1. Alternatively, the gradient is often indicated by the distance \( \Delta x \) between the points where the irradiance is 0.25 resp. 0.75 of the value in the transparent region. \( \Delta x \) is related to the edge gradients by

\[ \Delta x = 0.5 \frac{S}{S} = 0.5 f^{-1} \frac{\lambda}{NA}. \]

For a lens with \( NA = 0.3 \), \( \Delta x = 0.5 \) \( \mu m \) for \( \sigma = 1 \), and 0.3 \( \mu m \) for \( \sigma = 0.6 \) as indicated in fig. 3.

![Image of isolated edge](image)

**Table 1**

<table>
<thead>
<tr>
<th>( \sigma )</th>
<th>( f )</th>
<th>( S ) for ( \lambda = 4000 \AA )</th>
</tr>
</thead>
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<tr>
<td>( \infty )</td>
<td>1.56</td>
<td>1.18 ( \mu m^{-1} )</td>
</tr>
<tr>
<td>1</td>
<td>1.63</td>
<td>1.22</td>
</tr>
<tr>
<td>0.8</td>
<td>1.79</td>
<td>1.34</td>
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<tr>
<td>0.6</td>
<td>1.87</td>
<td>1.41</td>
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<td>0.4</td>
<td>1.93</td>
<td>1.45</td>
</tr>
<tr>
<td>0.2</td>
<td>1.96</td>
<td>1.47</td>
</tr>
</tbody>
</table>

**Fig. 3.**

Image of an isolated edge formed by perfect lenses.
The edge response is especially useful to determine variations in linewidth that arise in microprojectors due to variations of the printing parameters such as exposure time, light uniformity, and defocus. It is also used in more extended calculations which include resist modeling, to estimate the tolerances of processing parameters so that a desired linewidth uniformity is maintained.

2.2 Resist images.
The MTF and edge gradient describe adequately the image characteristics of ideal optical systems, but for projection systems for microcircuits degradations from the ideal image must be considered for a number of reasons:
1. Some defocussing is unavoidable due to the unflatness of masks and wafers and the imperfect setting of the projection system.
2. Residual aberrations are present which can degrade the image, especially in combination with defocussing.
3. Most important is the fact that not the aerial image we discussed above is of practical importance, but the resist profile that can be defined after development. The resist layers on structured surfaces usually vary in thickness and the reflections from the underlying substrate have a profound effect on the image quality especially by the effect of standing waves. In the next section this effect will be treated in more detail.

To summarize this part it can be said that although the MTF and edge gradient curves should be interpreted with care, they are useful characteristics since they can act as a "language" between the optical designer and the equipment user. On the one hand, the designers of optical systems should aim at systems with 60% MTF at high spatial frequencies and steep edge gradients in combination with partial coherent illumination. On the other hand, the equipment users can utilize the specified MTF values and edge gradients to judge what can be expected from the practical performance of a projector.

3. STANDING WAVES.

3.1 Simple case of two interfering waves.
As an important example, of the degradation of the diffraction limited image of a projection system we will discuss the influence of standing waves on linewidth control in more detail. The line of thought of previous authors like Widmann and Binder and Dill is followed, but with more emphasis on the effect of the spectrum of the exposure band.

First a simple example is given to illustrate the interference effect in the resist.
Consider monochromatic light of wavelength $\lambda$, which is incident on a resist film of thickness $d$ and refractive index $n$ on a perfect reflector 4,9. We assume that the exposure is done at normal incidence, which is a good approximation for most projection printers 5). The incident light wave in the film has then an amplitude:

$$E_1(z) = E_1 \sin (wt-kz+\phi)$$

where $E_1 = E_0 (1-r^2)^{1/2}$, with $E_0$ the incident light amplitude, $r = (n-1)/(n+1)$ the Fresnel reflection coefficient at the air-resist interface and $k = 2\pi n/\lambda$. If absorption effects are neglected, the reflected wave has an amplitude $E_2(z) = E_1 (\sin (wt-k(2d-z)+\phi+\pi)$. The interference of these two waves leads to an amplitude pattern given by:

$$E_{1z}(z) = 2E_1 \sin k(d-z) \cos (wt-kd+\phi)$$

and an intensity pattern:

$$I = I_1 \sin^2 k(d-z)$$

This is the characteristic intensity pattern for a standing wave, illustrated in fig. 4, which is independent of the phase of the incident light. Strong intensity maxima occur at distances $1/4 \lambda$, $3/4 \lambda$, $5/4 \lambda$ etc. from the reflecting substrate, and minima or nodes at distances $0, 1/2 \lambda$, etc. In a rigorous calculation of the intensity pattern multiple reflections and the absorption in the resist must be taken into account. This type of calculations have been performed by Dill, Widmann and Binder 5), and others. We have calculated the electric fields in a resist layer rigorously using the algorithm introduced by Braunstein 7), for the three layer configuration air, resist ($n=1.65, \chi=0.02$) aluminium ($n=0.51, \chi=5.00$) at $\lambda = 435$ nm. The results, given in fig. 5 shows a strong difference in intensity.
pattern when the thickness of the resist is an even or odd multiple of $\frac{\lambda}{4n}$.

This difference is due to multiple reflection effects and leads to a strong difference of the total absorbed energy in a layer that is an odd multiple of $\frac{\lambda}{4}$ and one that is an even multiple of $\frac{\lambda}{4}$.

We assume that the time to develop through a very thin sub-layer $\Delta z$ of the resist is inversely proportional to the local intensity:

$$\Delta t(\Delta z) = \frac{1}{c t_e l(x,y,z)}$$

where $t_e$ is the exposure time and $c$ is a constant depending on developer concentration and other processing conditions. The intensity distribution $I(x,y,z)$ can be written as:

$$I(x,y,z) = I_0(x,y)G(z,d)$$

where $I_0(x,y)$ represents the intensity distribution of the incident light in the image plane and $G(z,d)$ is the geometrical function describing the distribution in the resist, perpendicular to the image plane, for which fig. 5 is an example.

The total development time for the whole resist layer is now given by:

$$t(x,y,d) = \frac{1}{c t_e I_0(x,y)} \int_0^d \frac{\Delta z}{G(z,d)} = \frac{dB(d)}{c t_e I_0(x,y)}$$

The reason for writing the result of the integration as $dB(d)$ is that without interference effects and negligible absorption $B(d) = 1$, so that the dependence of $B(d)$ on $d$ illustrates the influence of the standing wave effects.

We consider now the important case of a step coverage illustrated in fig. 6, where a line in the $y$ direction is projected on a substrate with a height difference, leading to a difference in resist thickness. The image of the edge of a line is represented by the step response as was illustrated in fig. 3 of the previous section, and is written to a good approximation as:

$$I_0(x) = I_0(0) + sx$$

where $s$ is the edge gradient of the step response of the lens. The total development time $t_d$ becomes now a function of the position $x$. It follows from eq. (3) that:
Fig. 5.
Intensity pattern in a resist film covering an Aluminium surface, for two resist thicknesses representing the maximum and minimum light coupling into the resist.

\[ t(d, x) = \frac{I_o(0)}{I_o(x)} t(d, 0) \]  \hspace{1cm} (5)

Near a profile step, where a change in resist thickness \( d \rightarrow d' \) occurs, the position \( x \) of the projected edge will be determined by the experimental requirement that one and the same development time is employed:

\[ t(d, 0) = t(d', x') \]  \hspace{1cm} (6)

The shift in line edge is derived simply by substitution of eqs. (4) and (5) in (6):

\[ x' = \frac{I_o(0)}{s} \left( \frac{t(d')}{t(d)} - 1 \right) \]  \hspace{1cm} (7)

where \( x' \) is half the change in linewidth due to a variation in resist thickness \( d \rightarrow d' \).
With the aid of eq. (7) and Braunstein’s 7) algorithm the
development times \( t(d) \) and linewidth variations \( 2x' \) at step
coverages have been calculated for two practical cases:
exposure with monochromatic light (g line of mercury \( \lambda = 435 \))
and for simultaneous exposure with g and h line (435 and
405 nm). The results are given in figs. 7 and 8. For mono-
chromatic exposure, \( t_d \) and \( X' \) varies rapidly with thick-
ness, due to the different energies absorbed for layers
of odd or even multiples \( \lambda / 4n \). These results agree with
previous calculations 5).

For dual wavelength exposure with \( \lambda_g = 435 \) nm and
\( \lambda_h = 405 \) nm, we obtain a quite different picture (see
fig. 7). The oscillations of \( t_d \) as a function of \( d \) have
opposite signs at a resist thickness near 0.9 micron, so
that the function \( t_d \) for the simultaneous exposure is a
smooth function in that region. The corresponding linewidth
variations are given in fig. 8, for a lens with \( NA = 0.3 \),
in terms of the maximum linewidth variation that occur for
a resist thickness variation of \( \lambda_g/4n = 0.07 \) micron.
The important conclusion from fig. 8 is, that when the
resist thickness is about 0.9 micron, the linewidth vari-
ations due to standing waves are reduced by a factor of 5,
by dual wavelength exposure. Previous authors 4,8,9 have
noticed that the standing waves of different wavelengths
can have opposite phase for certain resist thicknesses, but
it was thought that these regions where too small to reduce
the negative effects of standing waves. It has been sugges-
ted 8,9 to use an extra dielectric layer (e.g. SiO2) on the

\[ \text{Fig. 7.} \]
Development times calculated for
single wavelength exposure and dual
wavelength exposure (g and h line).

\[ \text{Fig. 8.} \]
Variations of development time and
linewidth with resist thickness,
for a lens with \( NA=0.3 \). The maximum
variations are plotted that can
occur when the resist thickness is
changed from \( d \) to \( d'=d+\lambda_g/4n \).
substrate, to obtain a region of opposite phase at the bottom of the resist. The calculation above show that by arranging the regions of opposite phase near the air-resist interface an important disadvantage of the standing wave effect, i.e. linewidth variation is reduced drastically. Experimental demonstration of the improvement of linewidth control by g and h line exposure is given later in this paper when discussing results of the Philips Wafer Stepper. Eq. 7 shows that the linewidth variations are also be reduced by increasing the edge gradient s of the projection lens, which depends on the numerical aperture and coherence of illumination of the projection system, as discussed in sect. 2.1.

In Table 2 the maximum linewidth variations are given as calculated for various projection systems which differ in numerical aperture, coherence of illumination and exposure spectrum. The table shows that the influence of the spectrum of illumination is substantially stronger than variation in the numerical aperture of currently available lenses. It should be noted however that table 2 compares only the linewidth variations. For other aspects of the performance of a projection printer, such as smallest printable detail the numerical aperture is more important.

**Table 2**

Linewidth variations due to a resist thickness variation of \( \Delta d = 0.1 \) micron near \( d = 1 \) micron. Calculated with a simplified standing wave model, using eq. (7) in the text.

<table>
<thead>
<tr>
<th>Numerical Aperture</th>
<th>0.17</th>
<th>0.17</th>
<th>0.3</th>
<th>0.3</th>
<th>0.3</th>
<th>0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Coherence</td>
<td>1.0</td>
<td>0.6</td>
<td>1.0</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Illumination (lines)</td>
<td>multiple</td>
<td>multiple</td>
<td>single</td>
<td>single</td>
<td>multiple</td>
<td>single</td>
</tr>
<tr>
<td>Linewidth variation (micron)</td>
<td>0.16</td>
<td>0.14</td>
<td>0.41</td>
<td>0.35</td>
<td>0.08</td>
<td>0.30</td>
</tr>
</tbody>
</table>

4. AN ADVANCED STEP AND REPEAT WAFER IMAGING SYSTEM.

4.1 Introduction.

The favourable aspects of a two wavelength projection system have been exploited in practice in a new wafer stepper developed at Philips Research Lab. The potential advantages of step and repeat wafer imaging over whole wafer projection have been mentioned before [10] and are certainly elaborated upon in other papers in this session.
Briefly, they are:
1. By reducing the image field of a projection system to about 1 cm² the numerical aperture can be increased to about NA = 0.3 and high resolution patterns in the 1-1.5 micron range are defined.
2. A high overlay accuracy is possible by adjusting the step size in such a way that variations of the wafer dimensions are compensated.

Since 1972 Philips Research Laboratories, in cooperation with the Elica Mechanization Department and the Industry Group Science and Industry, has been developing step-and-repeat wafer imaging systems. In the first generation of machines, special attention was paid to automatic alignment. An automatic fine alignment system was developed which in combination with manual pre-alignment led to operator independent alignment accuracies of ± 0.1 micron. This system was tested at several production locations. Recently a second-generation system has been completed where special attention has been paid to two other key factors of wafer steppers for production: high throughput and high resolution on Si wafers by two wavelength exposure. This new system is described briefly below, some aspects of the machine have been described in more detail in ref. 10 and 11.

4.2. Projection Optics.
An outline of the projection optics is given in fig. 9. The projection lens corrected for 400-436 nm exposure has a 5:1 reduction and was made especially for the Philips wafer stepper by Cerco in Paris. The numerical aperture is 0.3 and the image field has a diameter of 14 mm. It consists of two parts: a collimator (C) which images the mask at infinity, and objective, which images the mask in its focal plane. The objective can be moved vertically to follow the height variations on the wafer, while mask and collimator remain stationary. The reduction ratio is realized at a value within 10⁻⁵ of the specified value by adjusting the focal length of the collimator. The lens is telecentric in both reticle and wafer plane.
Automatic focus is maintained by using the focus detection systems shown in fig. 9. Light from a diode laser (D) is focused on the wafer to realize a small and bright spot. The laser beam is reflected twice on the wafer, by making use of a retroreflector situated diametrically opposite from the diode laser. The reflected beam is focussed on a split detector, which gives an electrical error signal driving the focus servo loop. The reason that a double reflection method is used, is to eliminate possible errors due to local reflection differences on the Si substrate. With a single reflection method, local reflection differences can lead to
Fig. 10. Patterns in 1.2 micron thick resist covering 1 micron oxide steps on Silicon. Exposure with 405 nm and 436 nm. Nominal linewidth 1.1 micron.

Fig. 11. Single wavelength exposure at 405 nm of 1.1 micron wide lines covering 1 micron oxide steps. Compare with fig. 10.

Fig. 9. Projection optics and autofocus system of Philips Wafer Stepper.
an asymmetrical light spot and thus to focus errors 11). With the projection system described above, incorporated in the Philips Wafer Stepper, high resolution patterns have been printed on silicon wafers.

Fig. 10 shows a step coverage for lines of 1.1 micron wide over 1 micron oxide step. The linewidth variation is small. For comparison fig. 11 shows the same pattern but exposed with monochromatic light at 405 nm. These figures clearly show that the standing wave effect leads to appreciable linewidth variation. This result is in qualitative agreement with the calculations on linewidth variations given in section 2.3.

4.3 Alignment.
The automatic alignment system of the Philips Wafer Stepper is illustrated in fig. 12. Only a brief outline will be given here since descriptions of this alignment system have been given earlier 10). A He-Ne laser beam with $\lambda = 633$ nm illuminates an alignment marker which is imaged through the projection lens on a corresponding marker on the reticle. The wafer marker consist of a relief grating defined in the silicon, so that the reflected light consists of diffracted plane waves in directions $\theta_n$ given by the grating law $\sin \theta_n = n\lambda/p$. In the back focal plane of the objective a spatial filter is situated, transmitting only the first order beams. The advantage of this arrangement is illustrated in fig. 13: For various profiles of the markers after film depositing or other processing steps (fig. 2.a-d), the image in the reticle plane is always the same sinusoidal form (fig. 2e) being the first harmonic of the marker profile. As further discussed in ref. 10 this contributes to the accuracy of realignment after processing. By using a birefringent plate B and a polarization modulator M it is possible to modulate the image of the wafer marker at a freq- 10-100 kHz. The detector D sees alternately two images of the marker sheared over half a period. The resulting electrical alignment signal is shown in fig. 13 and is zero only when the two sheared images have a symmetrical position with respect to the grating on the mask. The modulation technique allows a determination of the alignment position with an accuracy better than $\pm 0.1$ micron. This has been verified experimentally as is illustrated in fig. 14.

4.4. Other aspects.
Other elements of this machine, which are not described here, but which all contribute to the high speed of this machine are: a fast x-y stage with hydraulic linear motors,
Fig. 12. Alignment optics of Philips Silicon Repeater.

Fig. 13. The alignment marks on the wafer can have various shapes (a-d) due to covering with films during processing. Nevertheless the image in the reticle plane has always the same shape (e) due to spatial filtering. This contributes to the alignment repeatability (fig. 16).

Fig. 14. Repeatability of the auto-align system.
a high intensity illumination system and a turntable that can insert a second reticle in 1 second so that test patterns can be projected rapidly. These factors make a throughput of 60 4" wafers per hour possible. The prototype of this new generation of steppers is now operating in Philips Research Lab. Eindhoven. During a MOS process that was run on this wafer stepper some SEM photographs have been made of the resist profiles. Fig. 15 and 16 are resist patterns on poly silicon, and show that the steep resist profiles are also defined by this machine during actual processing.

5. CONCLUSIONS

Till the end of the eighties optical projection printing will be the most widely used method for microcircuit pattern definition. Optical systems produce 1 micron resolution, operate at high speed and use an established resist technology. The highest performance is expected from direct step and repeat systems. The effect of standing waves on linewidth variations is reduced by polychromatic exposure.
Second generation wafer steppers such as developed at Philips, have the capabilities with respect to resolution, alignment and throughput to play a key role in the volume production of the future VLSI circuits.

ACKNOWLEDGEMENT

Thanks are due to J.G. Dil for many discussions and the numerical calculations of the standing wave effects.

References

During the history of the integrated circuit each increase in complexity, or reduction in size has forced a need for better process control. Current and projected design rules call for higher densities, and larger die sizes. Present production equipment has been pressed to it's limits, and as a consequence yields have been reduced and costs have increased. This in turn has forced an increase in the number of wafer starts to reach the required production levels.

To meet these needs a new generation of equipment has been developed. Both of the Electromask 700SLR and 800SLR Wafer Steppers are of the new generation.

Using interferometrically controlled stages, and high resolution reduction lenses, this system fills the requirements for high yield. The airbearing stage, which has been used successfully for many years, exhibits the necessary precision (±0.25 micron), and the projection system produces usable geometries of 1.25 microns reliably, with critical dimension control within the necessary ±5%.

To obtain maximum benefit from the system, Electromask has designed an automatic wafer-to-reticle alignment system. The technique used permits rapid, accurate evaluation of the wafer position by digital means. An alignment target on the wafer is viewed through the reduction lens system and through the reticle (See Figure 5A). The video signal from the TV camera is digitized by a high speed A/D converter, and preprocessed in the hardware. The acquired data is then transferred to the CPU which calculates the necessary position information, and issues corrections in X and Y. Figure 2 illustrates the technique in block form.

Conceptually the approach is simple, we add sampled intensity values to obtain digital profiles, one in each axis, of the video information. A 256 x 256 sample pattern is used to obtain the required position information.

Vertical position is determined by adding the intensities across the target in each line, and dividing by 256. The result is a mean intensity value for each row in the grid.

*Joseph Lauria is a Senior Staff Engineer and Thomas Kerekes is a Senior Programmer at TRE Semiconductor Equipment Corporation.
Horizontal position is derived by adding the samples in each column down the target, resulting in an average intensity for each column. Each data set is independent due to the orthogonal target.

Transfer to the computer is the final hardware function. Target position is determined by using several mathematical algorithms to be described subsequently.

Die position is corrected using the derived X and Y error. Rotational errors are adjusted at the global level.

The major advantages are speed, approximately 100 ms for most surfaces, and required accuracy, ± 0.1 micron. This permits any level of alignment from full wafer to die-by-die with a very small penalty in
time. Several possible approaches were evaluated and discarded as consuming too much time. The technique selected offers speed and accuracy. Data is simultaneously processed to extract vertical and horizontal information by handling the arithmetic in hardware. The result is a pair of 256 byte-strings profiling the mean intensity seen by the vidicon. This processing is done in real time thus reducing the need for large on-board storage, long transfer times, and therefore, the time for data reduction in the CPU.

A silicon intensified vidicon views the wafer through a reference window as shown in Figure 3. The Figure shows the auto target and the manual targets which are used in the absence of the Auto-Aligner. The quantity to be measured is the difference in the positions of the wafer target center and the reticle window center. This quantity is the misalignment for the die. The reticle window is a rectangle of dimensions 0.56 by 0.71 millimeters. The area viewed on the wafer through the reticle window is the same as that of the reticle except reduced by the minification factor of the lens. Typically, there is a 56 by 71 micron viewing area for a 10:1 reduction lens. The target on the wafer consists of two 7.6 micron wide lines, one vertical and the other horizontal, forming a cross. This target can be placed anywhere within the die including the scribe area.
Figure 2 depicts the basic hardware philosophy. The video signal is digitized by an 8-bit Analog to Digital converter operating at approximately 5 MHz. This gives rise to pixels having 256 possible gray levels. The sampled data is passed in parallel to a pair of 16-bit full adders to process horizontal and vertical information.

The acquisition cycle is initiated by the CPU. This is asynchronous with the video sync signals, therefore, the first succeeding vertical sync pulse enables the acquisition cycle and clears the scan (line) counter. Timing is now controlled by the horizontal sync pulse which advances the scan counter, and clears the sample counter at the end of each line.

Vertical position data is processed through the loop marked 'A' in Figure 2. Initially the 16-bit accumulator is cleared by the H-sync pulse. The first sampled pixel is added to zero and stored in the accumulator by the 5 MHz clock, and appears on the output pins. Successive samples are added to the previous results until the 256th sample. At this point, the register contains the sum of the intensity
along the line, and the sample counter then closes the accumulator clock line. Two hundred nanoseconds later the upper byte is transferred into the 256 x 8-bit shift register. This effectively divides the sum by 256 and therefore the register contains the average intensity of the line. This process is repeated for each line down the vidicon. The result is a profile of the light and dark areas which are perpendicular to the vertical line. A plot of typical values is shown in Figure 4. Looking at the plot, it becomes clear that the demarcation between the window edge and the wafer target is very well defined. All edges are presented as significant and easily recognized amplitude changes.

Horizontal information is obtained in a similar fashion, and processed through Loop 'B'. The major difference is in the way the data is accumulated. A 256 X 16 bit shift register functions as both storage and accumulator. Initially it is cleared by forcing the adder output to zero and clocking the shift register. During the first sampled scan line each of the 256 pixels is added to zero and shifted into the register. On the next line, the first sample, which is now sitting on the output of the shift register, is added to the first pixel of the current line; the second to the second; the nth to the nth. At the end of the field, the register contains 256 sums representing the total intensity down the screen in columns.
Now a flag is generated informing the CPU that the data is acquired. The data is moved into the CPU by taking the upper 8 bits of the 256 x 16-bit shift register and the 8 bits in the 256 x 8-bit shift register and storing it in memory. The information will then be used by the CPU to determine the misalignment for the die.

To remove any constraints on the location of the alignment target within the die, two wafer-positioning operations are required for each exposure. The first is the align position (See Figure 5A), and the second is the expose position, (See Figure 5B). The align position is such that the target on the wafer, which may be located anywhere within the die, or scribe alley, is viewed by the TV camera positioned over the reticle window. The align position must be held during the data acquisition phase. After the data is completely acquired, but before it is processed, the exposure-positioning operation of the wafer can be initiated. The exact coordinates of the wafer-positioning will be updated before the final stages of the operation.

The additional time required to die-by-die align and expose a wafer versus the standard blind move and expose method, is the sum of the additional wafer-positioning time with the data acquisition time of the aligner. Additional wafer-positioning time is used as the wafer must first move to the align position and, second, move to the expose position, instead of moving directly to the expose position. The first move can be shown to require the same average time as the blind move of the standard method. So, the additional positioning time will entirely depend on the second move. The time for the second move will vary greatly (100 to 200 milliseconds), depending on the position of the wafer target within the die. Adding this to the 24 ms average data acquisition time of the aligner, results in a total additional time of 125 to 225 milliseconds.

The data processing phase occurs during the beginning portion of the expose-positioning operation. The vertical and horizontal intensity profile arrays are passed to the system computer for interpretation by software routines. Each axis is almost entirely independent of the other and is processed independently. A typical intensity profile was shown earlier in Figure 4. To identify the reticle and wafer edges, the first software routine locates all of the intensity changes in the data set above a selected threshold. These are characterized by their approximate position in the data set and their amplitude. These intensity changes represent edges of geometries in the image.

Since each geometry will have two edges in a given dimension, desired geometries can be identified by intensity changes having a specified amplitude and separation. There are two reticle edges and two wafer edges in each axis. Since there are two axes, in order to calculate the misalignment of the wafer target with respect to the reticle window, a total of eight edges must be considered. Each edge is then processed independently to obtain a single value corresponding to the position of the edge. This value is found by fitting a function to
the data in the vicinity of the edge. This function is then solved for the position that gives the same intensity as the mean intensity around the edge. This procedure is shown graphically in Figure 6. The function is fitted to the data to both reduce noise and allow interpolation between data points. The interpolation is necessary because the intensity is sampled at 0.4 micron intervals in the horizontal axis and at 0.3 micron intervals in the vertical axis along the wafer surface. These distances are based on the use of a 10:1 reduction lens.

![Figure 5A](image1.png)

**FIGURE 5A**

![Figure 5B](image2.png)

**FIGURE 5B**
The function chosen to be fitted to the data in the vicinity of the edge was the cubic polynomial. The cubic polynomial has a characteristic shape very similar to the observed data, the coefficients are easily found, and the function can be solved quickly for a given $Y$ value. The coefficients are found by the classical least squares method as shown by the matrix equation of Figure 7. Data points

$$Y = AX^3 + BX^2 + CX + D$$

Coefficient Derivation Set

$${\begin{aligned} D & = \left[ \begin{array}{c} \sum_{i=1}^{n} Y_i \\ \sum_{i=1}^{n} X_i Y_i \\ \sum_{i=1}^{n} X_i^2 Y_i \\ \sum_{i=1}^{n} X_i^3 Y_i \end{array} \right] \\
C & = \left[ \begin{array}{c} \sum_{i=1}^{n} X_i \\ \sum_{i=1}^{n} X_i^2 \\ \sum_{i=1}^{n} X_i^3 \\ \sum_{i=1}^{n} X_i^4 \end{array} \right] \\
B & = \left[ \begin{array}{c} \sum_{i=1}^{n} X_i^2 \\ \sum_{i=1}^{n} X_i^3 \\ \sum_{i=1}^{n} X_i^4 \\ \sum_{i=1}^{n} X_i^5 \\ \sum_{i=1}^{n} X_i^6 \end{array} \right] \\
A & = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ X_1 & X_2 & X_3 & X_4 & X_5 & X_6 & X_7 & X_8 & X_9 & X_{10} \ X_1^2 & X_2^2 & X_3^2 & X_4^2 & X_5^2 & X_6^2 & X_7^2 & X_8^2 & X_9^2 & X_{10}^2 \ X_1^3 & X_2^3 & X_3^3 & X_4^3 & X_5^3 & X_6^3 & X_7^3 & X_8^3 & X_9^3 & X_{10}^3 \ X_1^4 & X_2^4 & X_3^4 & X_4^4 & X_5^4 & X_6^4 & X_7^4 & X_8^4 & X_9^4 & X_{10}^4 \ X_1^5 & X_2^5 & X_3^5 & X_4^5 & X_5^5 & X_6^5 & X_7^5 & X_8^5 & X_9^5 & X_{10}^5 \ X_1^6 & X_2^6 & X_3^6 & X_4^6 & X_5^6 & X_6^6 & X_7^6 & X_8^6 & X_9^6 & X_{10}^6 \ \end{bmatrix} \end{aligned}$$
representing edges are used to generate the terms of the equation. The equation is then solved to give the coefficients of the function. The mean intensity of the edge is found by averaging data points before and after the edge. The position where the function gives this mean intensity is found using Newton's tangent line method of polynomial solution.

Once the above value is found for each edge, the center of both the wafer target and the reticle window can easily be computed. The differences in these positions represent the misalignment measurement of the die, and can be used to adjust the expose position for the die.

This paper has presented a method of determining alignment error using highspeed digital techniques coupled with rapid computer analysis. Vernier measurements have verified alignments within 0.2 microns. A subsequent paper presented in this session (II,6) reports independent measurements of stage stepping errors, and presents representative data for full-wafer manual alignment.

The system has been proven to be accurate, fast, and reliable in the production environment intended for the Electromask 700SLR and 800SLR Wafer Steppers. The design of the aligner allows itself to be easily installed and repaired. To retrofit an automatic aligner to an existing system, only an electronic assembly and a software package must be added. The only electrical connections required are to the TV camera, and to the system CPU. Some other uses, such as logging of die stepping errors, have proven beneficial in improving general wafer fabrication line performance.
DOUBLE DIFFRACTION GRATINGS AS KEYS FOR HIGH CONTRAST ALIGNMENT ON WAFER STEPPERS

Georges DUBROEUCQ, Michel LACOMBAT, David SULLEROT +

1. INTRODUCTION

More than all the other image transfer systems, the step and repeat projection printing method requires a fast and accurate alignment system to take advantage of the die per die exposure mode.

The accuracy required is the 1/5 to the 1/10 of the features size that is to say 0.1 to 0.2 \( \mu \text{m} \) for 1 \( \mu \text{m} \) linewidths. To keep a good fabrication throughput, 60 to 100 wafers per hour, alignment time must be less than few seconds for global alignment (XY and angular) and about 0.1s for repeated realignment die per die or area per area. The periodic realignment necessity depends on the wafer distortion amplitudes and on the compatibility between different photolithographic tools if the different lithographic levels are not executed on the same tool.

An other important point is that accuracy and speed must be maintained all through the circuit fabrication process, that is to say the alignment signal must keep a good contrast whatever the thickness and the number of layers covering the wafer alignment marks, during the process.

In this paper, we describe an "on axis" alignment method using diffraction grating marks located on the reticle and the wafer, the correlation of which gives an alignment signal which satisfies the following three conditions:

- The structure of the alignment marks allows to eliminate the optical noise due to scattering and reflection on the wafer, giving a good signal contrast.
- This contrast does not depend on the layers reflectivity.
- The correlation signal can be detected by a fast photodetector.

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2. CHOICE OF AN ALIGNMENT METHOD

Two alignment modes can be proposed for wafer steppers. Either an "off-axis" global alignment or an "on-axis" alignment. The first one is fast because the global alignment of the wafer can be carried out in XY and $\theta$ simultaneously. The second one is directly referenced to the optical axis of the projection system and allows a periodic realignment. For 1 $\mu$m features on 5 inches wafers, the periodic realignment capability gives the best warranty of good overlay across the wafer.

Two main methods exist also to get the alignment signal. The first one consists in the detection of the wafer position by a scanning analysis of the image of the alignment marks [1],[2], on a vidicon target for example (fig.1-a).

The position detection is time consuming, and particularly when the mark position must be averaged by several scannings along the line, will take several ms. In this method, the accuracy depends on the contrast of the image, then on the intensity reflected by the different layers covering the substrate.

The correlation of the reticle mark with the wafer mark is an other alignment method [3],[4]. Such a method gives directly an alignment signal the intensity of which varies with the respective position $x$ of the wafer mark and the reticle mark. Alignment signal is then obtained faster (fig.1-b).

3. CORRELATION OF ALIGNMENT MARKS IN PROXIMITY

Such a method has been tested at Thomson-CSF for a submicron X-ray proximity lithography system [5]. The principle of the alignment method is represented on figure 2.

The wafer mark is a 1.5 $\mu$m line. The mask mark is a linear Fresnel zone plate (F.Z.P.). A F.Z.P. is a special planar optical lens in which the focusing action takes place by diffraction of the light beam instead of refraction as in usual optical lenses. A linear F.Z.P. acts then like a cylindrical lens (fig.2-a). A photodetector in the reflected beam path collects a correlation signal, the intensity of which is maximum when the wafer mark is aligned with respect to the F.Z.P. In practice, the specular reflection on the mask gives rise to a high background. A simple way of eliminating this unwanted light beam is to replace the wafer line mark by a small grating diffracting in the Y direction (fig.2-b).
The incident beam is now diffracted and the correlation signal can be detected in the first diffraction order with a very low background level. Detection is also easier because the return signal is spatially separated from the incident beam.

4. APPLICATION TO AN OPTICAL PROJECTION SYSTEM

Such a method allowing to suppress the unwanted light reflections, has been applied to an optical projection system, which is presented on fig. 3. The F.Z.P. has been replaced by an alignment mark similar to the wafer one the image of which is projected directly on the wafer mark through the exposure projection lens. In fact to get a high signal and to focus the alignment signal in the lens pupil, the reticle and wafer lines have been replaced by periodic gratings of L lines and spaces GR and GW (fig. 3-a). A such alignment method is, in this way, somewhat related to previously described alignment systems [6],[7].

In fig. 3-a, the wafer grating is similar to the reticle grating. When the grating GR is illuminated with a spatially coherent source, it gives a discrete diffraction pattern DR in the lens pupil. After reflection on the wafer, the correlated image returns through the lens, is imaged on the reticle grating and gives a diffraction pattern DC which is globally similar to DR. In fact, the diffracted orders intensities vary with the respective position of GR and GW, and could generate an alignment signal. But their contrast is not good enough and change with the layers reflectivities and thicknesses (fig. 4-a), and sometimes can be reversed.

In fig. 3-b, the wafer mark is a double diffraction grating. The diffraction pattern DC presents now new diffracted orders [1,i] and [-1,i] which have a very good and stable contrast and a low background because the light diffracts in [1,i] orders only when some part of the clear lines of the reticle grating GR is imaged on the wafer rectangles (fig. 4-b). This gives a correlation signal [1,0] for example with a very high contrast (> 80 %) whatever the substrate.

With such alignment marks:

- The correlation of the reticle and wafer marks gives directly an alignment signal which can be detected by fast photodetector, photodiodes or photomultipliers.

- The alignment signal is a diffraction order [1,0] for example, well focused in a conjugated plane of the pupil lens.
- The alignment signal is periodic, then the range is \( < \pm L \) where \( P = 2L \) is the pitch of the grating.

- Small defects in the grating do not change the contrast and the accuracy of the alignment signal.

5. MODULATION AND SIGNAL IMPROVEMENTS FOR DETECTION

The correlation signal of the two alignment marks cannot be used directly, and for accurate detection of alignment position, it is necessary to modulate, amplify and filter the correlation signal in a lock-in amplifier. But, as the correlation signal is a function of the position of the wafer with respect to the reticle, this means that the wafer position or the image of the reticle mark must be modulated. Moving the wafer chuck is not possible at very high frequencies. Moving the reticle image needs to introduce a scanning mirror or plate in the optical path between the reticle and the wafer. For this solution, the alignment accuracy depends on the zero position of the scanning plate.

An other modulation method represented on fig.5 avoiding these drawbacks, needs on the reticle two identical gratings \( G_{R1} \) and \( G_{R2} \) of pitch \( G.p \) where \( 1/G \) is the lens magnification, these gratings being distant of \( \Delta \), with:

\[
\Delta = G.p.(n+\varepsilon) \quad \{ n \text{ integer} \}
\]

These gratings are alternatively illuminated, by mean of an acousto-optical modulator for instance, with a commutation frequency \( f \) (\( f \sim 100 \text{ kHz} \)). A single detector receives an alternate signal function of the misalignment error \( x \). For a given position of the wafer, the detector measures a signal \( V_1 \) when \( G_{R1} \) is illuminated resulting from the correlation of \( G_{R1} \) with \( G_W \), and a signal \( V_2 \) when \( G_{R2} \) is illuminated resulting from the correlation of \( G_{R2} \) with \( G_W \) (fig.6-a). The photodetector gives then a periodic square signal of amplitude \( V_1-V_2 \) at the modulation frequency \( f \) (fig.6-b). After lock-in amplification, the alignment signal (fig.6-c) presents a good slope at the alignment position (\( \sim 5 \text{ V/\mu m} \)) allowing a good alignment resolution. Fig.7 gives an electronic diagram of the alignment signal modulation and detection.

The modulation method chosen can be used at very high frequencies and is absolute that is to say no optical part is introduced in the optical path between the reticle and the wafer.
6. RESULTS

Figures 8 and 9 show typical results of the alignment method. The displacement is obtained with a piezoceramic. The optical lens is a LIPPIA \((X 1/5, NA = 0.35 ; \phi 15 \text{ mm})\) from CERCO. The grating pitch is \(p = 10 \mu\text{m}\) and \(GW\) has about \(100 \mu\text{x} 50 \mu\text{m}\) area. The results presented here have been obtained for the last level (L5) of an usual MOS technology represented fig.8-a. In spite of the different layers covering the mark, the contrast of the correlation signal remains very good \(C = 0.86\), (fig.8-b).

Fig.9-a shows the lock-in amplifier output \((1)\) versus alignment error; the slope at the origin is \(2.8 V/\mu\text{m}\). This signal is obtained by illumination of the wafer marks at the exposure wavelength and very low light level \((E < 3 \text{ mWatts/cm}^2)\) to avoid resist exposure on the marks. The curve \((2)\) is the misalignment signal when the feedback loop is closed, showing a misalignment error less than \(\pm 0.05 \mu\text{m}\) across the piezoceramic correction dynamic range.

Fig.9-b shows two typical alignment times. For \(1\mu\text{m}\) and \(0.2\mu\text{m}\) misalignment, the time is respectively 70 and 30 ms and depends mainly on the mechanical stage.

7. ALIGNMENT IN BOTH X AND Y DIRECTIONS

In order to align in X and Y directions, one uses two similar reticle alignment marks \(RX\) and \(RY\) which are located radially, on the axis of the projection lens field, near the pattern (fig.10). Similarly the wafer marks \(WX\) and \(HY\) are located near or in the scribe lines, whatever the chip size. The location possibility in the scribe lines allows to save the maximum projection field for the electronic circuit. The radial position of the marks is the best position in order to illuminate the wafer grating symmetrically with the diffraction orders issued from the reticle grating, when the projection lens is not exactly telecentric \(^\ast\) on the image side. Otherwise, it will give a possible small error in the alignment signal.

\(^\ast\) a telecentric lens (image side) has its exit pupil located at the infinite.
8. COARSE ALIGNMENT

The previous alignment marks give only the fine alignment signal. Figure 11 shows the real alignment marks. The fine wafer alignment grating is split into two gratings W1 and W2 separated by a distance $D = m \cdot p$ and a coarse grating CW of 200 μm length is added between them, the lines of which are oriented with an angle of 60° with respect to the alignment direction (fig. 11-a). Two clear windows CR1 and CR2 are added between the reticle fine alignment marks R1 and R2 (fig. 11-b). The grating CW diffracts in well-defined angles when the windows are alternatively projected on the wafer at the modulation frequency $f$. A photodetector DC located near the fine alignment detector DF (fig. 11-c) gives alternatively a current proportional to the light diffracted by CW, and coming from the CR1 or from CR2 window. Then the lock-in amplifier gives a signal which sign is the misalignment sign with a range of ± 200 μm.

9. SIGNAL CONTRAST VARIATION ALTHOUGH THE PROCESS

To test the efficiency of the alignment method, the correlation signal contrast and the lock-in amplifier output have been measured for the different process levels of a typical MOS technology. Three typical levels are presented figure 12 on the left, a photograph of the wafer mark aspect for the given level. On the right, the corresponding layers structure on the substrate. For all the levels the correlation signal contrast remains very good. Only the signal level varies in a range of 1 to 100, depending on the diffraction efficiency of the grating marks through the upper layers and reflectivity.

All the alignment tests presented here have been realized at very low light level ($E \approx 3 \text{ mWatt/cm}^2$) at the exposure wavelength. Figure 13 shows the lock-in amplifier output (1) and the misalignment error after feed back for the three levels of fig. 12. The slope varies between 2.8 and 10 V/μm. The alignment error is always better than ± 0.05 μm.

10. CONCLUSION

In this paper, we have presented a new alignment method based on double diffraction of gratings, allowing first, a very high signal contrast, independent of the substrate reflectivity, by spatial separation of the signal and the noise due to specular reflection on the substrate and in the optics; secondary the focusing of the correlation signal in a conjugated plane of the pupil.
Such a method allows to get a very good alignment resolution (< 0.05 μm) whatever the number of layers covering the alignment marks. Acquisition of the position signal is very fast (< 1 ms) and the alignment time depends mainly on the mechanical positionning driver.

This method of alignment at the exposure wavelength without additionnal correction or modulation optics in the optical path is an "on axis" method with an absolute zero signal, this giving a precision practically equal to the alignment resolution. In addition, the marks can be located in the scribe lines whatever the chip size.

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Fig. 1 - Alignment Methods

Fig. 2 - Principle of the FED Alignment Method

Fig. 3 - Principle of the Double Diffraction Grating Alignment Method

Fig. 4 - Correlation of gratings Ga and Gb

Fig. 7 - Alignment Signal Modulation and Detection
FIG. 5 - MODULATION METHOD OF THE GRATING CORRELATION SIGNAL.

FIG. 6 - a/ LOCK-IN AMPLIFICATION OUTPUT

FIG. 9 - ALIGNMENT TEST OF THE LAST LEVEL OF A TYPICAL MOS TECHNOLOGY.
Fig. 10 - Alignment Marks Location

Fig. 11 - Coarse and Fine Alignment

Fig. 12 - Wafer Fine Alignment Marks for Three Levels of a Typical MOS Technology

Fig. 13 - Lock-in Amplifier Output for Levels L2, L3 and L5.
An advance step-and-repeat aligner for high volume production of 0.7 to 1.0-micron devices is presented. Through-the-lens alignment and full-field focusing at each step compensate for irregular wafer topography. Results showing resolution and alignment capabilities are presented.

1. INTRODUCTION

Wafer step-and-repeat exposure systems of the first generation were originally designed for mask making and were subsequently adapted for the new application of direct wafer stepping. For mask fabrication, matching to already existing structures was not necessary. Instead, images had to be generated in ideal matrix arrays, usually by means of laser-interferometer positioning, and it was assumed that the arrays would match each other. The application of this concept to direct wafer stepping implies the complete rigidity and characterization of all parameters participating in the imaging process, including the wafers. In principle, the problem inherent in the method of matching each element of a matrix array to each corresponding element in a previously generated matrix array by globally aligning the complete arrays to each other still remains.

Difficulty arises when images that are already on the wafer from preceding process steps have to be matched (Fig. 1a). The arrangement of these images might deviate from the ideal matrix array for a variety of reasons: statistical variations in the stepping system used to print the image array directly or to generate the mask for this array; systematic mechanical errors in that system; magnification error including systematic and random distortion in the total-field exposure system if the array is printed indirectly; geometry changes in the wafer itself that occurred during processing.

The difficulty to match the previously generated matrix array is enhanced by errors produced when printing the subsequent array due to following reasons: again statistical variations in the stepping system itself which cause deviations from the ideal matrix array; systematic mechanical error caused by machine-to-machine variations; temperature changes even when the same machine is used for all levels.

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The natural solution to the problem is to align each element of a matrix array individually to its corresponding element in the previously generated matrix (Figure 1b). By this principle deviations of the matrices from the ideal array have no influence on alignment accuracy which is now merely a function of the subsequent matrix generation involving one statistical operation only. In addition, through-the-lens alignment overcomes machine-induced sources of mismatch as caused by poor machine-to-machine match and temperature variations.

Ideally, a wafer step-and-repeat exposure system would not only align, but also focus and level the image field at each step. Thus the system could follow the wafer topology in three dimensions, maintaining the highest possible image quality limited by lens performance only.

As we consider the concept of local alignment as a consequent extension of the original wafer stepping concept we call step-and-repeat exposure systems using individual alignment of image fields second generation systems. As such a system aligns at each step we also use the name step-and-repeat aligner (SRA). A new developed system of this type as well as some first results obtained with this system will be described below.

2. SYSTEM DESIGN GOALS

The overall goal for system design was to create a machine which allows economical fabrication of V.L.S.I. circuits with 1 micron geometries or smaller under true production conditions. The basic requirements are:

- a superior optical system allowing for high contrast at line widths less than one micron,
- a mechanical encasement that makes the high performance optics operative in the real production world.

The second requirement can be broken down as follows:

- Alignment system. The alignment accuracy should be adequate to the high optical resolution capability, i.e. in the range of +/- 0.1 micron or better.

- Focusing system. The focusing system should explore all the potential of the high resolution optics. It should especially deal with the inherently small depth of focus and provide sharp imaging over the full field also on irregular wafer surfaces, e.g. GGG wafers.

- Automated routine operations. All wafer handling (i.e. load, unload), reticle change and alignment procedures should be automatic for reasons of speed, reliability and precision.
Convenient data entry and control. The parameters which change from device to device and level to level (i.e. field resp., die size, exposure) should be able to enter the program in a simple form. The control of routine operations, such as alignment and exposure should be facilitated by a suitable graphic display. Production data including actual throughput, wafers exposed, etc., should also be available at the display.

High throughput. The machine should be efficient for processing high-volume devices, small dice with non-square shapes and those with layers that require high exposure energy, i.e. mechanical movements should be fast, alignment should be quick and exposure should be short.

Low defect density. This is critical for large, fine-line IC's. In addition to precluding detrimental influences from outside sources, the machine should avoid internally created defects from front-side contact with the wafer substrate.

Compatibility with the fabrication environment. The machine should be a rugged manufacturing tool that fits into the fabrication area without a separately conditioned chamber isolating it from the production environment. It should include features that protect it against particle contamination, temperature variations and vibrations. On the other hand, it should not pose space problems or introduce an excessive thermal load into the fabrication area.

Cross-matching capability. To maximize its operating efficiency, the machine should be dedicated to handle critical alignments whilst less critical layers of the same wafer are aligned elsewhere. Thus, the ability to cross-match with other equipment that is capable of 2-micron line widths will be important. The machine should also cross-match with other machines of its own kind to provide optimum flexibility in a manufacturing environment.

3. SYSTEM DESCRIPTION

A schematic of the system is shown in Figure 2. The optical path has been bent twofold to obtain a compact and rugged tool in spite of the long optical distance between light source and wafer necessary for technical reasons.

3.1. Optics

The optics include a unique lens, which is produced by Carl Zeiss, West Germany. This 10:1 reduction lens offers a significant improvement in numerical aperture (N.A. = 0.35), enhancing ultimate line-width resolution to a lower limit of 0.8 micron at 50% MTF. The field diameter is 14.5 mm, offering a maximum square field size of 10.25 mm x 10.25 mm (403 mils x 403 mils). The lens and illuminator combination
allows a maximum rectangular field size of 130 mm x 64 mm (512 mils x 252 mils). The lens is g-line optimized, making it useful for most commercially available positive resists.

Lens distortion can be broken down into two parts, the systematic portion and the random portion. The systematic portion is in the order of 0.1 micron at the outer field region and arises from the lens design. As it is replicated with each lens, this part is causing no overlay errors when matching images generated with different machines of the same kind. The random portion, roughly of the same size, is due to manufacturing tolerances. This contribution to overlay-error can only be excluded by using the same machine for all fabrication levels.

3.2 Illumination
The illuminator (Figure 3) uses a proprietary 1000-Watt mercury arc lamp to produce light which is passed through a dual condenser system, beginning with a series of surface reflective elements (cold mirrors), followed by a unit consisting of a lens and a dielectric filter. The output from this unit is carried through a uniformer to the multiple condensing lens elements, which form 130 mm x 100 mm (5.12" x 4.03") rectangular field. Illumination uniformity over this field is better than +/- 2%. Light output is such that typical exposure times are between 50 and 200 ms, for 1 micron thick layers of typical positive photoresist.

3.3 Alignment principle
The superior resolution capability is coupled with a repetitive (local) alignment technology. The small depth of focus that exists at high numerical apertures demands precise focusing of individual fields. The SRA employs the local alignment principle with respect to six parameters: \(X, Y, \theta\) (alignment), \(z_1, z_2, z_3\) (focusing or z-alignment, and leveling). The system is automated to achieve the necessary accuracy and stepping frequency.

3.4 Alignment marks
The alignment system uses two different types of alignment marks; those on the reticle and those on the wafer. Their layout is illustrated in Figure 4. In addition to the reticle marks, the first layer reticle contains a 10x conjugate of the wafer marks, which will reproduce as 4 micron wide lines on the wafer. These wafer marks are arranged radially toward the center of the image field (for reasons described below) and are preferably located in the scribe lanes to save space.

The reticles used for succeeding layers contain only marks that are in the shape of rectangular windows, except fresh wafer marks are needed to replace the original ones that were lost during processing. Again,
the long sides of the rectangles are directed to the image center or optical axis. The first-layer reticles do also contain these marks which are only used for focusing/leveling of the first image.

3.5 Alignment procedure
The lens is designed for perfect diffraction-limited imaging at an exposure band of 435 +/− 3 nm, with no compromise of image quality. At an alignment wavelength of 547 nm, however, only sagittal aberrations can be minimized, so imaging is only sharp for radial lines. That is the reason why alignment marks are arranged radially. By the same arrangement, alignment precision becomes independent of eventual magnification changes.

Another constraint to imaging at 547 nm is the different focal length of the lens at this wavelength, so that the partially corrected wafer mark image in the alignment light would appear in a plane located above the reticle (see Figure 5). To compensate for the distance between the two image planes at 436 nm and 547 nm resp., the light path is folded at 547 nm. Now the partially corrected images of the wafer marks appear on the reticle and, likewise, the reticle window marks are imaged on the wafer.

When the alignment light is projected down through the four window marks and onto the wafer, the image compositions of both the wafer and reticle marks can be observed in a plane behind a semitransparent mirror, as shown in Figure 5. Intensity profiles of these images are generated by an image scanning device as explained in Figure 6. All of the information that is needed to align with respect to X, Y, θ, z1, z2 and z3 can be derived from these intensity profiles. Commands are given to the servo mechanism of the reticle stage to move the reticle until the wafer marks are centered with respect to the reticle marks. As alignment is performed by symmetry, changes in wafer line width during the process do not affect accuracy. In the event of an epi shift, a software feature enables alignment for a particular asymmetry ratio.

In principle, the evaluation of three composed mark images is sufficient. The software can be programmed to skip the fourth image or to use it to correct in a first approximation for in-chip distortion by making a best fit to four. If more than two marks are lost, the alignment is carried out taking the lacking information from the preceding field.

Using through-the-lens, step-by-step alignment, temperature effects are minimized. Consequently, the machine is less sensitive to temperature variations in its environment. Also machine-to-machine match is highly improved.
3.6 Focusing and leveling
No additional hardware for signal generation is needed for focusing. The focal position of the wafer is derived from the intensity profiles by calculating the slope of the curves as shown in Figure 7. The measurement and calculation of up to four points on the image field provides sufficient information for determining the ideal level position.

Figure 8 shows a chart recording of two actual intensity profiles of the same image composition a) in focus, and b) out of focus by 10 micron. The wafer mark is a line, etched 0.5 micron deep and 4 micron wide into a gate oxide layer, covered with a 1.5 micron thick layer of AZ 1350 photoresist. The reticle window is 400 micron wide. The imaging wavelength is 547 nm. Appropriate z1, z2 and z3 alignment commands are given to the three positioning elements of the wafer stage. Again, when some marks are missing in the image field, the corresponding values of the preceding fields are used. A software feature permits the operator to select an offset between the measured focal plane and the exposed focal plane, which can be important at process levels with high substrate steps.

This direct through-the-lens focusing and leveling method, which adjusts the entire image field for actual focal plane, is a major improvement over indirect distance measuring methods, which focus at a presumed distance between the wafer and a reference plane because reference plane position can vary with temperature. Such variations become more critical as the numerical aperture of the imaging system increases and depth of focus decreases.

3.7 Wafer stage system
The wafer stage is a low mass mechanism, supported by air bearings. Maximum productivity is maintained during the wafer load/unload cycle with vacuum and quick-venting atmospheric bleed channels. Motion in x and y directions is provided by servo motors, which are controlled by a positive closed-loop microprocessor system. The wafer substrate is held in a temperature controlled wafer chuck, which provides flat backing support. A three point support of the wafer stage effects the required leveling for optimum image replication and maintains proper focusing over the full image field.

3.8 Reticle stage system
The reticle stage system incorporates several features to ensure high resolution and registration while effectively eliminating reticle defects. The 6" x 6" or 5" x 5" reticle glass is held in the stage with the image surface facing vertical. A cover glass can be provided to prevent particles from adhering to the reticle surface in the focal plane. The reticle together with its cover glass is pre-mounted and pre-aligned in a special frame (see Figure 9).
Manipulation of the reticle frame is accomplished by servo motors, controlled by a positive closed-loop microprocessor system. The reticle is aligned to the previously created marks on the wafer (except for the first level) by manipulation at the reticle plane taking advantage of the beneficial leverage provided by the 10x optical reduction.

Up to 15 different reticles can be stored under controlled ambient conditions in the reticle library and can be automatically recalled and inserted into the reticle stage. Reticle transfer requires approximately 8 seconds.

3.9 Environmental controls
The unit is mounted on a self-contained anti-vibration table to provide protection from low-frequency vibrations that could negatively impact its performance. The pre-alignment system and the wafer stage are enclosed in an environmental system of their own. The photograph Figure 10 shows how the wafer handling mechanics (i.e. load/unload cassettes pre-alignment stage, wafer stage) are enclosed in a protective pressurized chamber. The unit requires temperature control that is within acceptable limits for normal semiconductor photoresist areas (+/- 2 degree C). No bulky environmental chamber or other space-consuming support equipment are needed, although a Class 100 laminar flow module is recommended for optimum operating conditions on this or any V.L.S.I. instrument.

3.10 Throughput
Although wafer stepper throughput data appears inferior to those of total-field exposure systems in terms of total wafers per hour, the number of good devices per hour can prove to be higher with step-by-step aligning/focusing and leveling. Device throughput further improves when the higher resolution that is achievable with a stepping system is taken into consideration.

The time required for each step consists of the time needed to move the wafer, align the exposure field, and expose the wafer. In the described system, a short step time is achieved with high-speed, fast-accelerating servo motors. Alignment times are minimized by high scanning frequencies used to locate the imaged alignment mark (moving the reticle requires practically no time because of the small displacements). A powerful illumination system results in short exposure times.

As exposure area increases, the number of steps required to cover the whole substrate area decreases. Thus, a certain flexibility in the exposure fields is needed to maximize throughputs with a variety of die formats (see Figure 11). To obtain this flexibility, the system has an illumination field which is larger than necessary to print the largest possible square and accommodates reticles as large as 6" x 6" to maximize the illumination area (130 mm x 102.5 mm). Of course, smaller reticles could be used at the expense of throughput.
The diagrams in Figure 12 demonstrate how throughput depends on die format. Assuming 4" wafers and a die aspect ratio of 1:1 (squares), optimum coverage of the exposure field - and maximum throughput - is achieved with a 400-mil die. As die size decreases to 200 mils, throughput drops to 15 wafers per hour, unless more dice could be simultaneously exposed in the region below 250 mils. The unfavorable regions near the minima can still be avoided by altering the die aspect ratio during the design process. The throughput diagrams for different die aspect ratios are calculated for a 1 micron-thick layer of AZ 1400 on a "typical" substrate, assuming a time of 0.8 sec to translate, align and expose one image field, and simultaneously exposing 1, 2, 3, 4 or more dice. The die area at which it is possible to progress from a curve with a low number of exposures to a higher one is determined by the die aspect ratio. Thus, die design plays a key role in ultimate throughput of wafer step-and-repeat exposure systems.

4. SYSTEM PERFORMANCE

4.1 Test reticle
A 10 x hard surface reticle has been developed for testing various performance characteristics of the described system. The reticle corresponds to SEMI standards. The size of exposure field is 10 mm x 10 mm on the wafer. The layout of the test reticle is shown in Figure 13.

4.2 Resolution pattern
The resolution pattern consists of an array of rectangular lines and spaces of increasing line width. The patterns are arranged in pairs of positive and negative arrays and located
a) in the center,
b) in the corners of a 5 mm x 5 mm square on the wafer,
c) in the corners of a 7 mm x 7 mm square on the wafer,
d) at a distance of 5 mm from the center on the wafer,
e) at a distance of 6.5 mm from the center on the wafer.
The lines printed on the wafer are increasing in width from .5 micron to 2.5 microns in increments of .25 micron and from 2.5 microns the lines are as wide as 3, 4, 7 and 10 microns.

4.3 Alignment verniers
The alignment verniers are similar to those as described in Reference (1). The alignment vernier patterns consist of a reduced scale (female half) matching a normal scale (male half) enabling visual read-out of alignment with an accuracy of 0.1 micron by means of a microscope. There are three vernier pairs X1, X2 and Y on the reticle, the Y-pair being located in the center, and the X1, X2-pairs being located at a distance of 4 mm from the center on the wafer. The X1, X2 pairs serve for reading out X and Z alignment.
4.4 Test procedure
In a first exposure the test pattern is projected onto the resist coating of the wafer and developed. For the second exposure the wafer is shifted by an offset distance of 0.55 mm and aligned to the wafer alignment marks laid down with the first exposure. The male vernier halves of the first exposure fit into the female halves of the second exposure and vice versa. Alignment accuracy is controlled by microscopic evaluation of the vernier match. Focussing capability over the full field as well as lens resolution is checked by inspection of the resolution patterns.

4.5 Resolution results
First results obtained with the new N.A. = 0.35 lens are demonstrated by the scanning electron micrographs Figure 14. Blank silicon wafers were coated with 1.2 micron of Shipley AZ 1470 positive photoresist and baked at 90 degree C for 30 minutes. The wafers were exposed in the new SRA system under typical fabrication conditions (fastest stepping sequence) with an exposure time of 300 ms and developed in 1:5 diluted Shipley AZ 351 at 20 degree C.

The pictures are showing positive and negative resist images of the finest features in the resolution patterns located at the periphery of the image field. It can be seen that the 0.75 micron lines are appearing clearly resolved with nearly vertical walls in both the positive and negative images. The pictures also demonstrate that the focusing and leveling system is operative, that the antivibration system is working satisfactorily and that the settling time of the stepping table is short enough allowing for high stepping frequencies.

4.6 Alignment accuracy
The alignment accuracy was checked by aligning the test reticle to the resist image of the first exposure and visually reading out the alignment verniers. The histogram Figure 15 is showing the X-alignment error occurring on one wafer (36 fields). It is evident that the design goal of +/- 0.1 micron is achieved. The constant mean value of the alignment position can be electronically zeroed by an offset command to the terminal. The alignment time for all six parameters X, Y and θ and z1, z2, z3 (full-field focusing) was less than 300 ms.

5. SUMMARY
A photograph of the step-and-repeat alignment system is shown in Figure 16. Here is a summary of the ability of the system to meet the criteria established above for routine, high-volume V.L.S.I. circuit fabrication.
5.1 Working sub-micron resolution
The proprietary new N.A. = 0.35; 14.5 mm field diameter lens and matching illuminator represents a fundamental cornerstone for attaining submicrometer resolution. Other concepts contributing to superior resolution include:

a) Through-the-lens focusing and feedback control ensure ultimate image quality for each die.
b) Autoleveling each step allows sharp images, even for wafers with complicated geometry.
c) Vibration isolation technology filters out all frequencies that could cause degradation in image quality.

5.2 Alignment accuracy
Alignment Accuracy is specified to +/- 0.1 micron and is automatically performed for each exposure. Through-the-lens alignment follows images already present on the wafer and compensates for distortion in image arrangement, permitting cross-matching to other machines and eliminating systematic alignment errors caused by temperature effects.

5.3 Productivity
Productivity is typically in the range of 60 wafer substrates of 100 mm diameter per hour. Automatic, microprocessor-controlled functions ensure optimum throughput for a large variety of die formats. Factors contributing to high productivity are:

a) Wafer handling from magazine to chuck and back, is completed in 4 seconds.
b) Each alignment can be carried out to an accuracy of +/- 0.1 micron in 300 milliseconds or less.
c) Automatic exposure and focus minimize loss of productivity from out-of-specification exposure dose or focal distance and ensure exposure times of 300 milliseconds/die or less.
d) Acceleration, deceleration and maximum velocity of the wafer-chuck transport are all programmed to minimize wafer-stage translation time.

5.4 Defect density reduction
Several features contribute to achieving this goal.

a) Reticles are stored in a dust-free, temperature controlled chamber.
b) Automatic change minimizes contamination and operator-induced damage.
c) Reduction at 1/10X reduces sensitivity to defects, which are reduced by the same factor.
d) 10X magnification facilitates fabrication of defect-free reticles and alleviates pattern to alignment mark tolerance.
e) A reticle cover glass can be attached to to keep particles out of the focal plane.
f) With no front-side contact with the wafer substrate, photoresist damage is minimized.
g) Automatic handling of each wafer from magazine to chuck and return reduces exposure to human contaminants.

h) In an ionized Nitrogen blow-off station particles are removed from the wafer surface prior to exposure.

i) Wafer processing is performed in a self-sustained, controlled environmental chamber, permitting operation in most normal work areas.

Reference:

a) global alignment match  

b) local alignment match

Figure 1: Principal advantage of local alignment

Figure 2: Schematic of the step-and-repeat alignment system

Figure 3: Schematic of the illumination system
Figure 4: Arrangement of alignment marks on the reticle and on the wafer resp.

Figure 5: Schematic of the alignment system
Figure 6: Explanation of the intensity profile of the composed reticle and wafer mark image. In the left column the wafer marks are misaligned to the reticle marks. The right column shows the aligned situation.

Figure 7: Principle of autofocusing / autoleveling. Wafer is in focus when the slope of the intensity profile is a maximum.
Figure 8: Actual intensity profiles (recorder plots) of composed alignment marks images a) in focus, b) out of focus by 10 micron

Figure 9: Reticle pre-align and pre-mount frame showing a reticle with cover glass attached
Figure 10: Top view on wafer handling and processing units in the protective enclosure

Figure 11: Die format flexibility allows for high wafer throughput at different die aspect ratios
Figure 12:

Typical throughput diagram for different die sizes and aspect ratios. Assumed process parameters: 0.8 sec per field; 70 fields and 4 sec overhead time per wafer.

Figure 13: Lay-out of the test reticle
Figure 14: Scanning electron micrographs of the (a) positive and (b) negative resist image of the resolution pattern showing nominal 1.0, 0.75 and 0.5 micron lines (left to right)
Figure 15: Histogram of x-alignment accuracy

Figure 16: View of the step-and-repeat alignment system
AN ADVANCED STEP AND REPEAT ALIGNER FOR VLSI

Jim Dey, Karl Johannsmeier

1. INTRODUCTION

Semiconductor devices with minimum feature sizes of 1-3 µm are now being manufactured in rapidly increasing volumes. It has now become clear that these products can be manufactured most effectively through the use of step and repeat exposure directly on the wafers. The first generation of production wafer steppers has proven the viability of the technique. There is no longer any question about the ability to produce high quality, high resolution images on wafers. There is no longer any doubt that the technique results in substantial yield increases and improved device performance. However, there is concern about the ability of these first generation machines to fit comfortably into a manufacturing environment and to have the versatility to handle the multitude of day-to-day problems that are encountered in production.

Optical technology is not the problem. The second generation of wafer steppers must attack the problems of throughput, alignment, flexibility, and suitability for production environments. The Optimetrix Model 8010 has been designed to address these problems. This paper discusses some of the unique ways in which these problems have been solved.

2. DESIGN PHILOSOPHY

Five major types of requirements dominated the design of this system.
- Comfortable margin of performance for 1.25 µm features. This implied not only good optical performance, but adequate registration as well. It also placed stringent requirements on vibration isolation and cleanliness. In order to perform comfortably at 1.25 µm, it must be able to perform reasonably at sub-micron dimensions.
- High throughput. Throughput directly affects the economics of wafer stepping.
- Ease of operation. High volume manufacturing requires the use of relatively unskilled operators who can be trained quickly.
- Suitability for a production line environment. This requires the system to be rugged, and relatively insensitive to environmental fluctuations such as temperature, humidity, and barometric pressure. The system should occupy as little space as possible.

+The authors are with Optimetrix Corp., Mountain View, CA, USA
floor space as possible.

- The system must possess enough versatility to be able to handle a wide range of production problems that are not always anticipated, but that always seem to happen. The system must impose the least possible number of restrictions on the rest of the manufacturing process.

3. OPTICAL SYSTEM

The basic optical system is shown schematically in Figure 1. Principal components of this system include an on-axis split field microscope, a beam splitting prism, and the 10x lens. The beam splitting prism is an integral part of the design of the 10x reduction lens, and therefore causes no distortion or aberrations in the image. The on-axis microscope permits the operator to view the superimposed images of the reticle and the wafer through the main lens. By moving the on-axis microscope in x and y the operator can view any location within the image field of the 10x reduction lens.

An auxiliary white light microscope is mounted parallel to the main lens and allows off-axis alignment with white light in those cases in which interference fringes prevent the effective use of the narrow band on-axis microscope. This auxiliary microscope is also used in conjunction with the on-axis microscope for direct measurement of the system base line and for coarse alignment of the wafer.

The illumination system contains separate light sources for alignment and exposure. The design of the illuminator allows the operator to control the size and format of the exposure field and to view on axis without damaging the wafer. These features will be discussed in more detail later.

The 10x reduction lens is available in two different versions and can be corrected for the g- and h-lines of mercury (436 nm and 405 nm) or for only the g-line (436 nm). Either version of the lens has a maximum field of 14.1 mm diameter (10X10 mm
square field) at the image plane. Rectangular fields with a maximum elongation of 13 mm x 5.6 mm can be exposed. Specifications for the reduction lens are shown in Table 1.

| REDUCTION RATIO | 10:1     |
| WAVELENGTH      | 436 nm or 436 plus 405 nm |
| MAXIMUM IMAGE FIELD | 10 X 10 mm to 5.6 X 13 mm |
| DISTORTION      | Matched to ± 0.1 um |
| NUMERICAL APERTURE | 0.27 N.A. @ Full Field |
|                 | 0.32 N.A. @ 9 mm Ø Field |
| ILLUMINATION UNIFORMITY | ± 3% |

Table 1. Optics Specifications.

4. ALIGNMENT

Wafer to reticle alignment can be accomplished in several different modes—each of which can be done automatically or with manual back-up. These alignment modes are:

- On-axis die-by-die alignment (blue light)
- On-axis zone alignment (blue light)
- On-axis global alignment (blue light)
- Off-axis global alignment (green light)
- Off-axis global alignment (white light)

On-axis die-by-die alignment is used when the best possible registration is required or when non-linear distortion of previous patterns is severe. Non-linear distortion might result from high temperature wafer processing or from the use of another type of imaging system such as a contact printer or a large field projection printer. Die-by-die alignment results in some loss of throughput, and therefore is not always used unless its ultimate accuracy is required.

Zone alignment is an operational procedure in which on-axis alignment is performed at several locations on the wafer, and these locations are used as reference points for blind stepping of nearby areas. Zone alignment offers a compromise between the accuracy of die-by-die alignment and the high throughput of global alignment.

On-axis global alignment provides high throughput for those applications in which non-linear distortion is small enough to be ignored, or for which the higher accuracy of die-by-die or zone alignment is not required. The use of blue light provides some advantage in accuracy over the use of green light, but at the cost of having to provide expendable global
alignment marks for each exposure level. The use of green light for on-axis alignment requires the use of an auxiliary corrector lens that results in a small reduction of alignment accuracy.

Off-axis global alignment, using white light from which the ultraviolet has been removed, provides a back-up capability that can be used in those instances in which interference fringes prevent the use of narrow band on-axis alignment. The principal disadvantage of most off-axis alignment systems is that they are dependent upon the stability of the hardware in maintaining a constant distance between the off-axis microscope and the optical axis of the main reduction lens. In the Optimetrix Model 8010, this disadvantage has been eliminated by providing the ability to periodically update the baseline to compensate for mechanical drift. The white light global alignment procedure that provides this capability also serves as the coarse alignment procedure to position the wafer within the acquisition range of the fine alignment targets. The ability to correct for changes in baseline will be discussed later.

4.1. Functions of the off-axis and on-axis microscopes.
The auxiliary off-axis microscope serves three functions: it is used for establishing the base line for off-axis alignment, for coarse alignment that is to be followed by a more precise on-axis alignment, and as the primary microscope for off-axis global white light alignment. The value of the off-axis microscope is due to the fact that it provides excellent resolution when used with broad band, non-actinic light. It is not affected by interference fringes, and it does not expose the resist. The on-axis microscope provides a means for viewing the image of the reticle directly on the wafer plane without any subsequent alteration of the optics or the mechanical position of the stage. When used together, these two microscopes can provide capabilities that would not otherwise be possible.

4.2. Reticle alignment and self-correcting base line.
The reticle alignment and self-correcting base line functions are explained with the help of Figure 2. Reticle alignment is begun by mechanically positioning the reticle onto the reticle alignment stage. The wafer is then moved to a home position under the reduction lens. The image of the first reticle alignment mark is projected onto the wafer stage and is aligned to a mark that is permanently engraved into the stage. The stage is then moved along the x-axis, and the image of the second reticle mark is aligned to the stage mark. During this second alignment, x-axis corrections are made by moving the stage and y-axis corrections are made by rotating the reticle about an axis that passes through the first mark. This procedure assures that the reticle is aligned parallel to the x-axis motion of the stage, and the locations of the
reticle alignment marks are determined relative to the position of the stage. The stage is then moved to the off-axis position, and the stage mark is aligned to the off-axis microscope. This establishes a baseline between the off-axis microscope and the images of the alignment marks on the reticle. The baseline is referenced to the image of the reticle, not to the optic axis. This eliminates a major source of cumulative error that is present in other off-axis alignment systems. A new baseline is established each time the reticle is changed, but it is not necessary to change reticles in order to check the baseline. Base line can be checked and corrected at any time with very little effort.

4.3. Off-axis alignment. The off-axis alignment procedure can be used to perform coarse alignment and off-axis global alignment. These functions can be explained with the help of Figure 3. Coarse alignment is accomplished with the use of alignment targets that are located near the extreme right-hand and left-hand edges of the wafer. For coarse alignment, the mechanical positioning of the wafer on the chuck is sufficient to assure that the alignment marks can be recognized and measured. The wafer stage moves so that the positions of the wafer marks are detected and measured by the automatic off-axis alignment system. For coarse alignment, the wafer is not actually positioned to align accurately with the off-axis microscope, but the positional errors are measured. The wafer is then moved on-axis with whatever corrections are required to compensate for the measured off-axis errors to assure that the fine-alignment targets can be located for final on-axis alignment.

For off-axis global alignment, the preceding coarse alignment procedure is followed, but the wafer is actually moved to the calculated alignment position and is rechecked for
accuracy before it is moved to the on-axis position for blind stepping.

4.4. **On-axis global alignment.**

On-axis global alignment can be done with either blue or green light. Green light global alignment uses the same targets that were used for the off-axis alignment described in the previous paragraph. These targets are exposed onto the periphery of the wafer during the processing of the first wafer level, and are preserved during all subsequent levels. Automatic masking shutters, which are built into the reticle framing apertures, protect these global targets from being exposed during processing of the second and subsequent levels. The algorithms and procedures that are used for green on-axis global alignment are essentially the same as those used for white light off-axis global alignment. Green on-axis alignment requires the use of an auxiliary corrector lens to bring the mercury e-line (546 nm) into focus.

Blue light on-axis alignment requires a separate set of alignment targets because the exposure that occurs during alignment causes the targets to be destroyed. The targets that are used for blue global alignment are similar to the targets that are used for die-by-die alignment. The design of the alignment illuminator makes it possible to illuminate these marks without exposing the resist in other areas of the die.

4.5. **Die-by-die alignment.**

Die-by-die alignment uses expendable wafer marks (Figure 4,) that are normally placed in the scribe lines outside the active area of the die. A separate mark is required for each wafer level because each mark is destroyed after it is used. However, only the marks that are actually used are destroyed. Adjacent marks, intended for alignment of subsequent levels, are not damaged prematurely. Therefore, it is possible to minimize cumulative errors by laying down several wafer marks at one time and referencing subsequent alignments to a single layer or to any particular critical layer.
Figure 4. Alignment Marks for Die-By-Die Alignment.

Figure 5. Special Features In The Illumination System That Provide Control Of Alignment Illumination And Reticle Borders.
The reticle alignment marks consist of "v" shaped windows that correspond to the wafer marks. Each reticle contains only the reticle mark that is to be used for that particular wafer level, thus preventing the other wafer marks from being destroyed. The image of the reticle alignment mark is projected onto the wafer, and the superimposed images of the wafer and reticle marks are viewed through the on-axis microscope. A TV camera that is coupled into the microscope scans the superimposed marks and measures their relative alignment. Alignment corrections in X and Y are accomplished by moving the wafer stage and then rechecking the alignment of the marks. A programmable X-Y offset bias can be used to compensate for known systematic errors caused by process variations, e.g. shift, reticle errors, etc.

Repeatability of automatic die-by-die alignment has been found to be better than ±0.05um at one standard deviation. In typical usage, approximately eighty percent of the alignments on wafers lie within a total range of 0.2 um, and approximately ninety-five percent lie within a range of 0.3 um.

5. ALIGNMENT MARK ILLUMINATOR

When using blue light for on-axis alignment it is necessary to prevent the light from exposing the resist in areas outside the immediate vicinity of the alignment mark. This is accomplished through the use of a moveable field stop in a secondary branch of the illuminator. See Figure 5. This field stop contains a small masking aperture that is electro-mechanically linked to the on-axis microscope. The mechanical movement of the aperture tracks the movement of the microscope so the operator can see the area that is being illuminated. The image of the alignment masking aperture is sharply focused on the reticle so only a small rectangular area is exposed. The operator can move this illuminated rectangle to any desired position within the image field. During automatic alignment, the alignment spot is driven to the required locations by computer control.

6. RETICLE MASKING APERTURES

The reticle area that is illuminated by the exposure light source is determined by the positions of four opaque blades that form the reticle border masking apertures. This aperture functions in a manner similar to the alignment mark masking aperture. The image of the reticle aperture blades is focused onto the surface of the reticle so that only the clear area between the blades receives any exposure. By moving the positions of the blades, the exposed area of the reticle can be controlled. Independent adjustment of the x- and y-aperture blades makes it possible to vary the size and aspect ratio of
the exposure field. See Figure 6. Asymmetric movement of the y-axis aperture blades makes it possible to off-set the exposure field in a vertical direction—thus making it possible to select two or more exposure fields on the same reticle. This ability to select different fields on the same reticle makes it possible to insert test patterns without having to change reticles. This capability is explained with the aid of Figure 7. The principal die pattern and the test pattern are both contained on the same reticle. By moving the reticle aperture blades, it is possible to uncover either of these patterns independently. The principal die patterns are exposed by uncovering the reticle areas around the die pattern and stepping and repeating in the normal manner. When the stepper comes to a wafer position that is supposed to receive a test pattern image, the aperture blades are moved to cover the die pattern and to uncover the test pattern. Movement of the aperture blades can be made without any loss of registration or any danger of damaging or contaminating the reticle. The only restrictions in the use of this capability are that the principal die pattern and the test pattern must both be contained within a 14.1 mm diameter and that their total aspect ratio must be contained within the limits of the 10x10 mm and 13x5.6mm extreme formats.

7. GRID PLATE X-Y STAGE METERING

The Optimetrix Model 8010 is available with either a laser metered stage or with a grid-plate metered stage. In this paper we will discuss only the grid-plate metered version. A quartz grid plate, Figure 8, is mounted beneath the stage directly under the optic axis of the 10X reduction lens. The motion of the grid plate is detected by an optical analyzer that sends an electronic position signal to the microprocessor that keeps track of the stage position. The optical analyzer detects the average position of a large number of grid elements, and is insensitive to changes in barometric pressure and other factors that influence laser detection systems. Since the grid plate is made of optical quality quartz, it is virtually insensitive to changes in temperature. The small temperature sensitivity is compensated by a linear correction that is made during initial global alignment.

The main advantages and disadvantages of the use of a quartz grid plate are shown in Table 2. Grid plate metering is well suited to the day-to-day requirements of high volume production lines. It provides a high degree of reproducibility with only a small loss of absolute accuracy. Laser metering provides the absolute ultimate in accuracy, but requires a degree of environmental control that is not practical in most production lines. Linear variations in the accuracy of the grid plates can be compensated in the software of the wafer stepper.
Figure 6. Variable Format Provided By Reticle Masking Apertures. Maximum size of square field is 10x10 mm. Maximum elongation of field is 13 mm x 5.6 mm. Independent control of y-axis blades allows exposure field to be off-set from optic axis.

AUTOMATIC INSERTION OF TEST PATTERNS

Figure 7. Use of Reticle Masking Apertures to Expose Test Patterns and Principal Die Patterns From a Single Reticle.
Non-linearity, which cannot ordinarily be compensated, is about ±0.15 μm. In production use, grid plate performance is comparable to laser metered stages without the need for bulky environmental chambers.

**ADVANTAGES**

- Tolerant of environmental changes
- Excellent precision under production conditions
- High signal-to-noise ratio
- Compact
- Reliable
- Easy to maintain

**DISADVANTAGES**

- Dependent upon accuracy of Secondary Standard
- Grid plates are difficult to make
- Requires careful mounting and testing to assure accuracy
- Psychological prejudice

Table 2. Advantages and Disadvantages of Grid Plate Metering

8. SUMMARY

Optical performance is not the primary limiting factor for production wafer steppers. The major limitations are registration, throughput, suitability for production line environments, and the versatility to accommodate a wide range of real life production situations. By adequately addressing these needs, the second generation of wafer steppers will become the standard technique for high volume production of semiconductor devices with 1-3 μm geometries.

![Quartz X-Y grid plate generated by laser-controlled stepping table.](image)

**Figure 8. Quartz Grid Plate.**
CHARACTERIZATIONS OF THREE WAFER STEPPERS, AND USER IMPLICATIONS

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Abstract: Three wafer steppers (GCA, Electromask and Optimetrix) are characterized for two-level overlay misalignment. Pattern uniformity across an exposure field and across a slice are reported for the GCA stepper. Vector maps and contour maps are presented.

INTRODUCTION

Direct Stepping on Wafers (DSW) promises to be a workhorse lithography for the decade. Three equipment vendors (GCA, Electromask, and Optimetrix) have already delivered steppers, and several other prototype DSW machines have been reported or announced. The DSW systems are extremely expensive, and the opportunity to make disastrous decisions in lithography was never higher. To reduce the margin for error in the costly decision, it is important that the DSW systems be characterized as they become available. This paper reports characterizations of alignment accuracy, uniformity, and repeatability for the three American-made steppers which are commercially available.

The characterization methods we use include vector maps of misalignment, and contour maps of resolution uniformity, following the techniques reported by Perloff. The basic technique utilizes resistor patterns delineated on the silicon wafer by the stepper. These resistor "monitors" are then probed electrically using automated test equipment and the electrical data are analyzed and displayed by the computer as maps of the wafer.

Figures la and lb illustrate the two test monitors used at Signetics. Figures lc and ld illustrate how the resistors are formed by processing the silicon slice. Contour maps for resolution and uniformity are obtained by fabricating fineline resistors (Figure la) and measuring the line widths or spaces Wx and Wy over the wafer. The vector maps are slightly more complex, in that two levels of lithography are required; the monitor is basically a voltage divider, with the center taps patterned by the second exposure. If the center tap were exactly at midpoint of the van der Pauw square resistor, the misalignment in that direction is zero; if the tap is displaced from midpoint by ΔX, the displacement of ΔX is measured electrically (i.e., from the sum and difference of the resistor values on either side of

the center tap). The voltage-divider test patterns are generated at 118 positions across the wafer. By fitting the displacement data to a theoretical model using linear least squares analysis(1) it is possible to determine the translation, rotation and expansion of the second stepped array with respect to the first. Upon subtracting the calculated values of misalignment from the measured values, one obtains the residual errors. These residual errors represent the random, rather than global sources of error over the wafer. From control structures which are fabricated with every exposure step, it is possible to determine measurement and process contributions to the total error. This highly-automated measurement technique has demonstrated accuracy to 0.02µm.

STEPPER CANDIDATES

The GCA-4800 wafer stepper has been commercially available for approximately two years. A variety of characterizations has been reported on the GCA machine during that time. We are the first to report the vector maps and a statistical breakdown of the component sources of net error. We believe our alignment characterizations to be the most complete to date.

The Electromask and Optimetrix DSW machines have only become available this year; the characterizations we give here are the first reported. The data should be considered preliminary, because the wafer samples were stepped on prototype machines at the manufacturers' facilities; the experimental conditions were less than optimal. The data, however, were quite good.

GCA-4800

Figure 2 illustrates the alignment strategy of the GCA machine. The 10X reticle is aligned to the column; the wafer is aligned to a split-field filar microscope mounted on the column; the laser-controlled stepping stage then moves the wafer under the column, and image stepping begins. There are, thus, three primary independent sources of alignment error:(2) 1) reticle alignment, 2) wafer alignment, and 3) stage stepping error. Superimposed on those errors are other systematic errors, operator errors, or variational errors caused by environmental factors.

Since the baseline between the microscope axis and the column axis is designed to be a fixed distance, an incremental change in the baseline

can result in a substantial alignment error. Another occasional source of error is the microscope itself; in particular, the distance between the two filar marks in the split-field optics can change due to thermal or mechanical disturbances. A change in that distance would be interpreted by the operator as "runout" (i.e., in-plane distortion). The distance between the filar marks is designed to be 63.5mm, exactly equal to the distance between alignment marks on the wafer. When the distance between alignment marks changes (or appears to change, as measured relative to the filar marks), the operator activates a software routine which modifies the stepping distance to correct for the apparent runout. When it is the microscope that has changed, instead of the silicon slice, the operator has inadvertently introduced alignment distortion via the software.

Figure 3a characterizes a full-wafer manual alignment. The vector map illustrates global misalignment (a linear translation in X and Y) and a linear expansion (runout); rotation is negligible. For this wafer a scale marker for 1-μm is shown above the vector map. The magnitude of misalignment error is equal to the length of the vector at each site. The amount of translation and expansion in X and Y are printed out at the left of the map. The average vector length and the standard deviation are printed near the bottom of the data column.

The average vector length (~0.3μm) can be somewhat misleading from the user point of view, since a large fraction of the vectors are on the order of 0.5μm. The user would have to ascribe a 0.5μm alignment tolerance in order to obtain an acceptable yield for a complex IC fabrication.

The computer can subtract the linear components of the global misalignment and expansion point-by-point, leaving the random and non-linear residual vector components. The vector map of residuals is presented in Figure 3b; notice the changed scale marker above the plot. The residuals in this plot represent the stage stepping errors, because this particular silicon slice had not been subjected to a high-temperature process between exposures. Most of the residual vectors are on the order of 0.05μm, but many are on the order of 0.15μm. The local correlations of directionality of the residual vectors suggest acceleration or retardation of the stage at specific locations along its path; however, at a given location, summed over many wafers, the vectors are found to be random.

Figure 4 illustrates some of our recent and better data on the GCA machine. The average vector length is ~0.329μm, and is essentially uniform across the wafer. The vector map of residuals is more random than the earlier data shown in Figure 3b, and the average vector length is smaller, ~0.05μm. These data suggest that the stage is under better control and that the machine environment is more stable now than earlier.
Figure 5 presents an independent and direct measurement of stage-stepping error. For this experiment a single reticle was used to expose both levels of the monitor pattern for misalignment; that is, the reticle had patterns with both levels, and only a software shift was required to overlay the patterns on the wafer. Neither wafer nor reticle was removed from the machine during the experiment. The first level was blind-stepped, and after a software shift, the second level was blind-stepped. The vector pattern shown in Figure 5a is similar in nature and magnitudes to the residual map shown in Figure 4b. Figure 5b shows histograms of stage shift error (which includes any possible reticle rotation). This error is 0.155 μm for x and y combined.

The data shown in Figures 3, 4, and 5 indicate the net misalignment and the stage-stepping errors. The third error component, reticle-translation error, was investigated by independent measurements. Statistical data on reticle-placement error were obtained by changing reticles while leaving the slice fixed (after the first exposure). This laborious task was repeated some 30 times, and using several operators. Figure 5c shows histograms of the total error which is 0.149 μm. Since the stage shift and die-rotation component was measured to be ±0.155 μm, the reticle-translation error component is small enough to be neglected.

Other GCA characterizations included contour maps of fineline pattern uniformity across the 1-cm² exposure field, and across a 3" wafer. Figure 6 presents contour maps of fineline pattern uniformity across the 1-cm exposure field. These data represent direct measurements of the upper limit on lens distortion; slice leveling, illumination uniformity, and focusing are also included in the pattern exposure. The pattern uniformity in both X and Y are exceptional, and the standard deviation is near the noise level of the experimental measurements. These data infer chip sizes near 1-cm on a side, with design rules near 1 μm are feasible. Across the 3" wafer a uniformity of ±0.08 μm (2σ) was measured; the test patterns used were at the center of the exposure field. This uniformity is excellent, and suggests a pattern standard for plasma etching comparisons, and similar applications.

GCA SUMMARY

Net misalignment error (2σ value) at any given location was measured to be 0.40 - 0.4 μm. The stage-stepping error component of that net value was measured to be ~0.1 μm. The reticle-placement error component was estimated to be near zero. The operator full-wafer alignment error was measured to be 0.25 - 0.30 μm. The data reported here should be representative, but are not necessarily statistical; systematic errors crept into some measurements, and the total data base was accumulated over a long time.
Resolution of fineline patterns across the 1-cm² exposure field and across a 3" wafer was extremely uniform (better than ±0.1μm). These unique data indicate large chips with fineline geometries are feasible.

OPTIMETRIX 8010

The Optimetrix wafer stepper is an interesting case study; its design was not an outgrowth of an earlier mask-making system. It is a compact machine and has through-the-lens through-the-reticle automatic alignment. The machine can perform automatic die-by-die alignment or full-wafer alignment. For multi-die reticles, where the scribe street is at the center of the exposure field, it is possible to use on-axis alignment. The basic system does not use a laser-controlled stepping stage, although that is an available option; an optical-encoder system controls the stage-stepping.

Signetics does not own an Optimetrix machine; the two-level-overlay characterizations reported here were performed on demonstration models (or units to be shipped to customers) at the manufacturer's facility. Two iterations of characterizations were run several months apart. The first iteration indicated die-by-die alignment of ±0.4μm across a 3" wafer using different steppers for each exposure. The second (current) iteration done on one machine indicates both full-wafer alignment and die-by-die alignment on the order of ±0.3μm. The residual errors indicate the stepping stage using the optical encoder can be accurate to better than 0.1μm (1σ), which is not significantly different from a laser-controlled stage.

The detailed machine description and alignment strategy are presented in another paper in this session. The net alignment strategy is:

1) The reticle is optically aligned (through the lens) to several marks engraved in the wafer stage; this alignment sets Θ (rotation), because each die on the wafer will be aligned only in x & y.

2) The silicon slice is manually pre-aligned off axis, in an arrangement similar to the GCA system (Figure 2), and is then moved onto the stage; the slice is then given a full-wafer autoalignment through the reticle and through the lens. If only full-wafer alignment is required, the stage steps and exposes (open loop) under control of the optical-encoder system.

3) If die-by-die alignment is required, the silicon slice receives full-wafer autoalignment as described in step 2, but is then stepped and autoaligned die-by-die under closed-loop control.
Figure 7a presents a vector map of full-wafer alignment. Some rotation error and expansion is evident from a global inspection. The translation error is nominally 0.33μm in x and -0.17μm in y. The expansion is -0.07μm/cm in y and -0.055μm/cm in x; since the slices did not receive a thermal subjection between exposures, the expansion is most likely stage-stepping error or an ambient temperature change. The vector map is reminiscent of Figure 2, where large portions of the slice had misalignments twice the average. The average vector length is 0.236μm, which can be somewhat misleading to a user; a user would allow for ~0.3 - 0.4μm overlay tolerance, in order to obtain reasonable yield over many levels of alignment.

Figure 7b presents the residual random and systematic errors, after the linear global errors have been subtracted point-by-point from the vector map in Figure 7a. Aside from a few artifacts, the residual data compare favorably to the stage-stepping error of a laser controlled stage.

Figure 8a presents data of die-by-die autoalignment. A global inspection indicates the average vector length is equal to the nominal vector length everywhere. There is negligible rotation and expansion. There is however, a linear offset of ~0.26μm in x and -0.08μm in y. This fixed offset may be an electrical offset in the closed-loop alignment, an optical or mechanical offset in the closed loop (such as a tilted mirror), a reticle mark-placement error, or some other systematic error in the machine or experiment. One thing is clear, a linear offset of this nature can be found and corrected by the manufacturer.

The residual vector map in Figure 8b indicates a random distribution with average vector length near 0.06μm, and with standard deviations near 0.034μm. This value of standard deviation is within a factor of two of the noise level of the experimental control monitors (~0.015 - 0.25μm), so the repeatability of the autoalign is very good.

OPTIMETRIX SUMMARY

Characterizations of Optimetrix steppers in the machine manufacturer's facility yielded excellent data, considering the non-optimal environment. Full-wafer alignment and die-by-die autoalignment was very precise and yielded standard deviations on the order of our measurement noise.
The Electromask stepper has through-the-lens through-the-reticle alignment. The optical elements which allow the TV camera viewing through the lens are fixed in place near the edge of the reticle; hence the marks are always viewed slightly off the column axis. Die-by-die automatic alignment is offered and has been demonstrated. Our initial characterization (on a demonstration system at the manufacturer's facility) utilized full-wafer manual alignment; reticles with autoalign marks are now in preparation. The environment of the experiment was non-optimum, and so the data should be considered preliminary. The first iteration of alignment data was good, however.

Details of the alignment system are presented in another paper in this session. The net alignment strategy is:

1) The reticle is automatically aligned to the column; this alignment is not independent and not critically important, however, since the silicon slice is to be aligned to the reticle. It does however, set the rotation, since the wafer will be aligned only in x and y.

2) The silicon slice is mechanically pre-aligned to the stage by a video edge-finding technique which looks through the reticle and through the lens.

3) The silicon slice receives a full-wafer alignment through the reticle and through the lens.

4) For die-by-die alignment, the alignment marks in the scribe streets of the silicon wafer are viewed through-the-reticle and through the lens slightly off axis. The autoalign sensing system measures the misalignment, and the laser-controlled stage makes one open-loop step to position the die center under the optical axis. The stage typically moves 1-2mm, but for large die with the scribe streets near the edge of the reticle, it is possible to design the reticle set so no stepping after alignment is necessary.

5) For the general case, the net alignment error is the sum of the alignment-sensing error and the stage-stepping error (as it moves the few mm to position the die on axis).

Figure 9a presents preliminary vector-map data of the Electromask full-wafer manual alignment. The average vector length is 0.3μm, and a global inspection indicates that nearly all of the vectors are 0.3μm. The linear translation error is printed out to be -0.18μm in x and -0.275μm in y, which alone indicates a vector length near 0.3μm.
This value of error is typically operator-alignment error for manual full-wafer alignment (based on our more extensive GCA experience). Hence it is clear that additional data are required to establish the accuracy limits of the Electromask machine; in particular, we are now having reticles fabricated for the autoalign system.

The Electromask stage is laser-interferometer controlled and rides on air bearings; one might expect that the stage stepping precision would be similar to the GCA machine. Figure 9b presents the residual vector map, which should be essentially the stage stepping error since the silicon slice had no heat treatment between exposures. The average vector length is 0.069μm, which is similar to the GCA machine data. There appears to be a systematic error near the center of the slice, which may be a result of the stage stepping format.

**ELEGTROMASK SUMMARY**

Preliminary data on manual full-wafer alignment were obtained from a demonstration system at the manufacturer's facility. Alignment accuracy of ~0.3μm was obtained, with a standard deviation of 0.065μm (10). Test reticles with marks for autoalignment have been fabricated, and characterizations are in progress.

**SUMMARY OF THE THREE STEPPER CHARACTERIZATIONS**

It is apparent from data presented that all three steppers evaluated meet the practical near-term requirements for pattern resolution and overlay accuracy. All three steppers have demonstrated delineation of patterns with 1μm resolution, with better than 0.5μm overlay registration across a wafer. In production, of course, larger tolerances would improve yield (especially with slice runout). In addition, wafer throughput as a function of alignment tolerance would have to be characterized for a given product mix.

Alignment strategies which allow viewing wafer marks through the reticle and through the lens perform best, as indicated even on preliminary data obtained under non-optimal conditions. Die-by-die alignment indicates a lower standard deviation than full-wafer alignment, as might be expected. Standard deviations are typically less than 0.1μm (10) for all of the steppers.

The Zeiss lens in our GCA stepper exhibited remarkable pattern uniformity across the full 1-cm² exposure field. Contour maps of 1-μm test structures indicated standard deviations (10) of 0.027μm in x and 0.065μm in y. Similar contour maps are not yet available for the Optimetrix unit (Tropel lens) and the Electromask unit (Zeiss lens). The unique data demonstrated by these contour maps include nonuniformities in the resist and in pattern etching, in defocussing caused by
poor slice leveling, and in reticle pattern nonuniformities. In short, these data represent the bottom line to the user. The data indicates that large chips (~1cm square) with 1-μm design rules may be practical in the short term.

Contour maps of pattern uniformity across a slice were found to have standard deviations near 0.035μm (1σ); these stepped patterns were at the center of the exposure fields. Hence stepped resolution patterns make excellent standards for evaluating plasma etchers, etc.

In general, additional characterizations under controlled conditions are needed on the Optimetrix and Electromask steppers. The current alignment data is good, additional data should only be better.
a) Resistor pattern for electrical probing of resolution/uniformity.

b) Van der Pauw test pattern for measurement of sheet resistivity and alignment.

c) Thin-film resistor cross section (polysilicon or metal).

d) Doped-silicon resistor cross section (implanted or diffused).

Figure 1. Test Patterns for Resolution and Alignment
**Figure 2.** Illustrative Schematic of GCA-4800 Alignment Strategy

**Figure 3.** Vector map for GCA-4800, illustrating

a) global misalignment and expansion, and

b) residual errors.
Figure 4. Recent Vector-map Data on GCA-4800

Figure 5. Stage-Shift Accuracy and Reticle Rotation
Figure 6: Lens Distortion; Contour Maps of Fineline Resolution/Uniformity Across 1-cm² Exposure Field
Figure 7. Optimetrix Full-Wafer Automatic Alignment

Figure 8. Optimetrix Die-by-die Autoalign
Figure 9. Electromask Stepper; Full-wafer Manual Alignment
THE CHARACTERIZATION OF OPTICAL LITHOGRAPHY*

Michael C. King**

INTRODUCTION

Appreciating the status of today's optical lithographic technologies requires an understanding of how attitudes toward lithographic characterization have changed over the past 10 years. As late as 1970, it was customary to evaluate lithographic exposure tools by the term "resolution"; that is, "this machine is a 10-μm machine", or "that one does 5 μm". Resolution meant the smallest achievable linewidth under ideal exposure conditions. In time, IC industry engineers began to realize that minimum resolution did not relate to performance under manufacturing conditions. In response, they began referring to the "minimum feature size", or "minimum working feature". This referred to the smallest feature with which devices could be fabricated with satisfactory yield.

By 1975 devices were being fabricated with features smaller than 4.0 μm. At this level a single descriptive parameter proved insufficient to describe lithographic performance. It was often found that the exposure technology that provided the highest resolution with acceptable yield did not necessarily provide the best performance for larger features. At about the same time, requirements for linewidth control and overlay accuracy began to exceed the performance provided by some of the available lithographic exposure equipment. At this juncture the expression "minimum feature size of x micrometers" took on the added meaning that the exposure tool provided all the characteristics required by an x-micrometer design rule.

The single parameter "minimum feature size," with its implied meaning was an adequate description of lithographic exposure tools until the advent of 2.0-μm design rules in 1979. At this level it became impossible to judge lithographic performance without considering nonhardware aspects of the technology. With overlay requirements in the submicrometer region and linewidth control tolerances under 0.2 μm, the role of the photoresist and subsequent processes cannot be ignored. It is partially because of these factors that different IC manufacturers with identical exposure equipment, manufacturing identical types of devices (NMOS for example), achieve minimum features ranging from as small as 1.5 μm to as large as 3.0 μm.


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The analytical characterization of optical lithographic performance requires a four step evaluation. First the optical imagery must be examined independent of effects related to resist, process and substrate. This requires information regarding the image modulation and the shape of the aerial image. Second the shape of the image profile formed in the developed resist must be investigated. The important characteristic is the slope of the profile at the resist-substrate interface. Third the consistency of the imagery over the entire wafer needs to be determined. This involves changes in feature size resulting from variations in exposure, process, focus and substrate. Fourth one needs to examine how the etch process affects linewidth control.

In this paper we will examine the special case where the mask consists of equal lines and spaces of spatial frequency \( \nu \), where \( \nu \) approaches the practical performance limit of the exposure tool (60-70% MTF with incoherent illumination). It is assumed that the imaging system is aberration free with the exception of a focus error. Under these conditions we derive a set of closed-form equations for the case of incoherent and coherent illumination that describes (1) the slope (\( \tan (\theta) \)) of the resist profile at the resist-substrate interface, (2) the fractional change in linewidth (\( \Delta L/L \)) that results from variations in exposure, process and substrate conditions, and the effects of dry etching and (3) the depth of focus. These expressions are expanded about the exposure value that produces equal lines and spaces on the wafer (the edge of the feature is defined as the position where the resist thickness goes to zero).

THE AERIAL IMAGE

The aerial image is the light intensity distribution that reaches the wafer. The aerial image is depicted in Figure 1 which shows an idealized lithographic system. It is a complex function of the mask pattern, the F/number (F) of the projection optics, the wavelength \( \lambda \) of the actinic radiation, the degree of coherence of the illumination, and the distance of the wafer from the plane of best focus. It is also a function of aberrations and fabrication errors in the optical system.

The shape of the aerial image is strongly influenced by the coherence of the illumination. For a review of this subject the reader is referred to articles by Reynolds and DeVelis, Offner and King. For photolithographic applications it is desirable to compromise between the attributes of coherent and incoherent imagery. This is achieved by partially filling the pupil of the projection optics. The condition thus created is called partial coherence. It is characterized by the parameter, \( S \), the ratio of the numerical aperture of the illuminator and the numerical aperture of the projection optics. A coherent system is characterized by \( S = 0 \) and an incoherent system by \( S = \infty \), implying that the pupil is overfilled. The difference between \( S = \infty \) and \( S = 1 \) is small.
Figure 1. Idealized photolithographic system.
The response of a lithographic projection system to a mask pattern consisting of a sinusoidally varying transmittance of spatial frequency \( \nu \) is characterized by the modulation transfer function (MTF)\(^2\),\(^4\). The MTF is a plot of image modulation as a function of \( \nu \). It is assumed that the modulation of the mask pattern is 1.0.

From the standpoint of lithographic imagery, MTF provides a reasonably complete characterization of an optical system. In the case of incoherent illumination \((S = 0)\) the projection system has a linear response to intensity. Given the MTF the aerial image can be predicted for a given mask pattern.

Analyzing the behavior of a partially coherent imaging system is difficult because the functional relationship between the object and image spectral components is nonlinear. However, it is possible to measure the image modulation for a partially coherent system. It is also possible to calculate it. But, because of this nonlinearity, the concept of MTF is invalid. There is no transfer function from which one can predict the exact imagery that will result from a given mask pattern.

In spite of this difficulty it has become common practice to use "MTF" curves to describe the quality of performance even when the system is illuminated in a partially coherent manner. This may trouble the purist, but there is good justification for maintaining the tradition. For fine-line lithographic applications, the exposure tools are used near the limits of performance. In these cases only the fundamental frequency of the mask pattern reaches the image plane. In the sections that follow, we will demonstrate how many useful characteristics of the lithographic image can be predicted by knowing only the modulation of the fundamental frequency. When the mask features are so large that many spatial frequency components are imaged, the partially coherent "MTF" ceases to be meaningful. This poses no problem since lithographic performance is nearly perfect for these large features and performance is predictabie without resorting to the "MTF" concept.

Offner\(^2\) has calculated a series of "MTF" curves based on diffraction considerations as a function of partial coherence \( S \). These curves are plotted in Figure 2 as a function of the normalized spatial frequency \( \frac{\nu}{F} = \nu \lambda F \). The curve for the incoherent MTF for a circular pupil is approximated by the expression

\[
M_{\text{I}}(\nu) \approx 1 - \frac{4}{\pi} \sin (\nu \lambda F) \tag{1}
\]

for all but the highest spatial frequencies.*

---

*To distinguish between various forms of illumination we will use the subscripts \( C, I \) and \( P \) for coherent, incoherent and partial coherence.
The "MTF" curves in Figure 2 represent an idealized optical system maintained in perfect focus. Today's lithographic projection optics are derived from sophisticated optical designs and are fabricated to very high tolerances. For this reason, the values obtained from Figure 2 are in very close agreement with the values measured on available lithographic equipment.

In practice, neither the mask nor the wafer is perfectly flat, so the effects of focus must be noted. By convention, we measure defocus in units of $2\lambda F^2$, referred to as the "Rayleigh unit." Offner has calculated the effect of defocus on the incoherent MTF as a function of spatial frequency. This is represented by the curve $D^2$ in Figure 2. When the optical system is defocused by $R$ Rayleigh units, the MTF can be calculated by subtracting $RD^2$ from the focused MTF value. The depth of focus of an optical system is usually designated as $\pm 1$ Rayleigh unit. However, as we shall discuss under Focal Tolerance, the effective depth of focus for a lithographic system can be smaller or many times larger than the Rayleigh unit depending on the feature being imaged and the resist process employed.

When the mask pattern is an odd periodic function of position with equal lines and spaces of spatial frequency $\nu$, it can be written as an infinite Fourier series

$$\text{Mask Pattern}(x) = a_0 + \sum_{k=1}^{\infty} a_k \sin(2\pi k \nu x)$$

where the constants $a_0, a_1, \ldots, a_n$ are the Fourier coefficients of the pattern on the mask. When the optical system is illuminated with incoherent light, the system is linear in intensity. From the definition of MTF the Fourier coefficients of the aerial image are simply those of the mask pattern weighted by the MTF of the lithographic tool. Thus,

$$I(x) = a_0 + \sum_{k=1}^{\infty} \text{MTF}(k \nu) a_k \sin(2\pi k \nu x)$$

In order to simplify the discussion, we will now state some basic restrictions that will hold throughout the remainder of this paper. First, we will only consider the case in which the mask consists of equal lines and spaces of period $p$ ($\nu = 1/p$) extending over the entire mask surface. Second, we will consider lithographic systems performing near their limiting capability, where only the fundamental spatial frequency of the periodic pattern plays a significant role. In Eq. (3) we will set $\text{MTF}(k \nu) = 0$ for $k > 1$. The above restrictions lead to tractable solutions of a simple form that give clear insight into the performance of lithographic systems.

By applying these two restrictions to Eq. (3) and using the fact that $\text{MTF}(0) = 1$, we can derive the following expression for the incoherent aerial image intensity:
Figure 2. "MTF" for imaging system with partial coherence. S is the ratio of the numerical aperture of the illumination system to that of the projection optics. The incoherent modulation (S = ∞) is reduced by R^2 D^2 when the system is defocused by R Rayleigh units (from Offner^2)
I(x) = \frac{I_{\text{max}}}{2} \left[ 1 + M_\alpha (\nu) \frac{4}{\pi} \sin \left( 2\pi \nu x \right) \right] \tag{4}

where $I_{\text{max}}$ is the intensity of illumination that would occur in a large unpatterned area. The term $4/\pi$ in Eq. (4) is a consequence of the square wave intensity pattern of the mask.

By applying the same restrictions to the case of coherent imaging, one can derive the following equation for the amplitude of the aerial image.

$$A(x,z) = \frac{A_{\text{max}}}{2} \left[ 1 + \frac{4}{\pi} e^{i\phi(z)} \sin \left( 2\pi \nu x \right) \right] \tag{5}$$

The phase angle, $\phi$, can have many values originating from various aberrations within the optical system. For our purposes, we will continue to assume that the exposure system is nearly perfect so that the phase term is only dependent on the focus condition. In this case, $\phi$ can be approximated by the expression:

$$\phi(z) = \frac{\pi z \lambda}{2 p} \tag{6}$$

where $z$ is the distance from the plane of best focus. A coherent imaging system characteristically has a magnitude of modulation of 1.0, but there is an additional phase dependency. The intensity of the coherent aerial image is given by $I(x) = |A(x)|^2$,

$$I(x) = \frac{I_{\text{max}}}{4} \left[ 1 + \frac{8}{\pi} \cos (\phi) \sin \left( 2\pi \nu x \right) + \left(\frac{4}{\pi}\right)^2 \sin^2 \left( 2\pi \nu x \right) \right] \tag{7}$$

Equations (6) and (7) are equally valid for projection printers with coherent illumination and contact/proximity printers using collimated illumination. In the latter case, parameter $z$ is replaced by $y$, the separation distance between the mask and wafer.

Comparing Eq. (7) to Eq. (4) we note that, for a given $I_{\text{max}}$, the average light intensity with incoherent illumination is twice the average intensity that will occur in the coherent case. In the sections that follow we will observe that this factor of 2 plays a major role in explaining differences in profile angle and linewidth control.

**RESIST PROFILE**

Having derived the shape of the aerial image for incoherent and coherent imaging, we are now ready to examine the shape of the resist profile that will result with a specific resist-process-substrate combination. Specifically, we want to know the position and the slope of the profile at the point where the resist thickness falls to zero. The characteristics of the resist profile in this region ultimately determine the quality of the image transfer for either wet or dry etching processes.
A most useful characterization of a photoresist is obtained by measuring the percentage of resist remaining after development as a function of exposure. By plotting this "characteristic curve" on a semilog scale, we can obtain information about the resist that allows us to predict the quality and consistency of the lithographic imagery. Figure 3 shows the basic features of a characteristic curve for a typical positive resist. In region A there is a range of low level exposures for which the solubility of the resist is unmodified. A loss of approximately 10% of the resist thickness in this region demonstrates that the resist has a finite solubility even when no exposure takes place. In region B the solubility begins to increase with exposure. In region C the curves become linear with \( \log(E) \) indicating that light is being absorbed within the resist layer. It is customary to identify two parameters, \( E_0 \) and \( \gamma \), with the characteristic curve. \( E_0 \) is the minimum exposure needed to remove completely the photoresist during development. It is called the "threshold exposure" and is a measure of the sensitivity of the process. \( \gamma \) is the slope of the characteristic curve as measured in region C. We define it by the expression

\[
\gamma = \left[ \log_e \left( \frac{E_0}{E_1} \right) \right]^{-1}
\]

where \( E_1 \) is the exposure corresponding to the intersection of the tangent drawn at \( E_0 \) and the ordinate at 100% resist thickness before development. This definition of \( \gamma \) and \( E_0 \) differs from previous definitions in three important ways. First, in previous treatments \( \gamma \) has been defined by drawing the tangent at the point on the characteristic curve corresponding to 50% thickness. In this paper we have drawn the tangent at the point where the resist thickness goes to zero. This has been done since our main interest is in the behavior of the resist profile near the resist substrate interface. Second, \( \gamma \) has been defined to the base e. This has been done to simplify many of the equations that follow. Third, in the past \( E_0 \) and \( \gamma \) were considered to be solely a function of the resist type and the processing conditions. For our purposes, this description is too restrictive because it overlooks the fact that \( E_0 \) and \( \gamma \) are also functions of resist thickness, the optical properties of the underlying substrate, and the spectral composition of the actinic radiation. It is the primary purpose of this paper to describe the basic functional relationships that connect the resist process and exposure parameters with lithographic performance. For this reason it is necessary to expand the meanings of \( E_0 \) and \( \gamma \) to include all the parameters on which they are functionally dependent. To achieve this, we will redefine \( E_0 \) and \( \gamma \) to mean the exposure and slope at threshold as determined from a characteristic curve as measured with a specific exposure tool, development process, resist thickness, and substrate composition. This expanded definition is consistent with a definition first proposed by McGillis and Fehrs. Table I lists some representative values of \( \gamma \) measured on 7000Å of oxide on silicon wafers.
Figure 3. Characteristic curve for a positive resist. Threshold exposure is \( E_0 \). \( \gamma \) is defined by drawing tangent at \( E_0 \). The log scale is to the base \( e \).
### Table I. Photoresist $\gamma$

Measured values of $\gamma$ (as defined in text) for F/3 reflective projection printer. Substrate is silicon wafer, coated with 7000 A of wet oxide. Resist thickness is 1.0 $\mu$m with standard processing.

<table>
<thead>
<tr>
<th>Exposing Bandwidth (Å)</th>
<th>Resist</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3400 - 4400</td>
<td>AZ-1370</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>AZ-2400</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>HR-204</td>
<td>1.43</td>
</tr>
<tr>
<td>3000 - 3300</td>
<td>AZ-2400</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td>Kodak 809</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>AZ-1370</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>HR-204</td>
<td>1.0</td>
</tr>
<tr>
<td>2800 - 3300</td>
<td>AZ-2400</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>AZ-1370</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>HR-204</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Consider the case of a resist profile similar to that shown in Figure 1 where the resist is $T_0$ micrometers thick and where the resist, process, substrate, and exposing wavelength combination is characterized by a specific $\gamma$ and threshold $E_0$. To calculate the slope of the resist profile, we follow the approach of Blais by expressing the slope of the resist profile as the product of two partial derivatives.

$$\frac{dT}{dx} = \tan(\theta) = \left(\frac{\partial T}{\partial E}\right)\left(\frac{\partial E}{\partial x}\right)$$  \hspace{1cm} (9)

where $T$ is the resist thickness after development and $E$ is the exposure. The first term $\frac{\partial T}{\partial E}$ is mainly dependent on the process. The second term $\frac{\partial E}{\partial x}$ is the slope of the aerial image and is a function of the exposure tool and the mask pattern.

Following the approach of Bruning and Shankoff, the process-dependent term can be calculated from the characteristic curve. From the definition of gamma in Eq. (8) the resist thickness remaining in the vicinity of the threshold for $E < E_0$ is given by

$$T(E) = T_0 \gamma \log_e \left(\frac{E_0}{E}\right)$$  \hspace{1cm} (10)

where $T_0$ is the unexposed resist thickness, and $E(x)$ is the exposure at position $x$. By differentiating with respect to $E$, the slope is given by

$$\frac{\partial T(E)}{\partial E} = -\frac{T_0 \gamma}{E}$$  \hspace{1cm} (11)

The second term in Eq. (9) can be obtained from Eq. (4) for the case of incoherent imaging. By multiplying both sides of the equation by the exposure time, we can write Eq. (4) in terms of exposure

$$E(x) = \frac{E_M}{2} \left[1 + \frac{4}{\pi} M_1(\nu) \sin(2\pi x)\right]$$  \hspace{1cm} (12)

Here the term $E_M$ corresponds to what we normally refer to as the "exposure". This is the exposure that would occur from a large clear area on the mask. From this expression we obtain

$$\frac{\partial E}{\partial x} = 4E_M \nu M_1(\nu) \cos(2\pi x)$$  \hspace{1cm} (13)

Substituting Eqs. (11) and (13) into Eq. (9)

$$\tan_1(\theta) = 4\gamma T_0 \left(\frac{E_M}{E(x)}\right) \nu M_1(\nu) \cos(2\pi x)$$  \hspace{1cm} (14)

Recall that Eq. (12) is a function of a series representing a pattern of equal lines and spaces. The position $x = 0$ corresponds to the point of transition between a clear and an opaque region on the mask. When exposure $E_M$ is adjusted such that $E(0) = E_0$, the resist pattern will delineate equal lines and spaces on the wafer. From Eq. (12) we see that this will occur when $E_M = 2E_0$. Under these conditions we obtain
\[ \tan_I(\theta) = 8 \gamma T_0 \vee M_I(\nu) \] (15)

Equations (14) and (15) have been found by the author to give excellent agreement with experiment. As discussed under Linewidth Control Over Steps the product \( \gamma T_0 \) is independent of \( T_0 \) when \( T_0 \) is large (typically greater than 0.5 \( \mu \text{m} \)). However, \( \gamma T_0 \) becomes proportional to \( T_0 \) for very thin resist layers. For this reason, steep profile angles are easier to obtain when the resist is thick. A similar result has been reported by Tigreat. Note that the feature size enters Eq. (15) only in the product \( \vee M(\nu) \). By setting \( E(x) = E \) in Eq. (14) we see that \( \tan_I(\theta) \) to the first order is proportional to the exposure \( E_0 \).

Starting with Eq. (7), similar expressions for the resist profile angle can be derived for the case of coherent illumination:

\[ \tan_c(\theta) = 4 \gamma T_0 \left( \frac{E_M}{E(x)} \right) \gamma \cos(2\pi \nu x) \left[ \cos \phi + \frac{4}{\pi} \sin(2\pi \nu x) \right] \] (16)

and

\[ \tan_c(\theta) = 16 \gamma T_0 \vee \cos(\phi) \] (17)

when the exposure is adjusted to obtain equal lines and spaces on the wafer, which occurs when \( E_M = 4E \). Comparing our results for coherent and incoherent illumination, we conclude that the slope of the resist profile at the resist-substrate interface is more than a factor of 2 greater and proportional to the spatial frequency (assuming perfect focus) in the case of coherent illumination.

Calculating the resist profile angle for the case of partial coherence is beyond the scope of this chapter. However, it is useful to take an heuristic approach by writing

\[ \tan_p(\theta) = 8Q \gamma T_0 \vee M_p(\nu) \] (18)

in place of Eq. (15). Here \( M_p \) is the modulation obtained from the "MTF" curves in Figure 2, and \( Q \) is equal to the ratio \( E_M/2E_0 \) when \( E_M \) is the exposure found to achieve equal lines and spaces on the wafer. The value of \( Q \) is found to monotonically increase from 1.0 to 2.0 with increasing coherence.

**FEATURE SIZE CONTROL**

To preserve device yield it is essential to maintain the correct width of the feature not only over the entire wafer, but for all wafers in a lot, and from lot to lot. Indeed, the ability to control linewidth is usually the factor that determines the limiting feature size. It depends on variations in exposure energy, changes in the resist threshold and departures from perfect focus. Numerous authors have calculated linewidth variations that occur under specific conditions of exposure, wafer composition, and process. With the use of computer
modeling it is possible to predict accurately the changes in resist profile that occur as a result of specified changes in exposure, substrate, development, etc. In this section, we will use our simplified model to derive the functional relationships that exist between feature size control and the lithographic variables.

**Linewidth Control with Incoherent Illumination**

In order to determine the linewidth dependence on each lithographic parameter, for the case of incoherent illumination, we can solve Eq. (12) for $x$ and calculate

$$
\frac{\Delta L}{L} = \frac{2}{L} \left( \frac{\partial x}{\partial E} \right) \Delta E_M + \frac{2}{L} \left( \frac{\partial x}{\partial E} \right) \Delta E + \frac{2}{L} \left( \frac{\partial x}{\partial M} \right) \Delta M
$$

(19)

We will again limit our analysis to the simplified case of imaging an equal spaced grid of spatial frequency $v$, where only the fundamental frequency plays a significant role. Considering the fractional change in linewidth for a resist pattern corresponding to an opaque feature on the mask, we evaluate Eq. (19) at the position $x = 0$.

$$
\frac{\Delta L}{L} = \frac{1}{M_I} \left( \frac{D M}{E} \right) + \frac{1}{2M_I} \left( \frac{\Delta E}{E} \right) - \frac{1}{2M_I} \left( \frac{2E - 1}{EM} \right) \left( \frac{\Delta M_I}{M_I} \right)
$$

(20)

When the exposure is adjusted to obtain equal lines and spaces on the wafer, $E_M = 2E_0$ and $E(0) = E_0$. Substituting these values into Eq. (20) we obtain

$$
\frac{\Delta L}{L} = -\frac{1}{2M_I} \left[ \left( \frac{\Delta E_M}{E_M} \right) - \left( \frac{\Delta E_0}{E_0} \right) \right]
$$

(21)

The first term in Eq. (21) describes the functional relationship between modulation, nonuniformity of the illumination, and variations in the linewidth. For example, if our exposure tool has a nonuniformity of illumination of $\pm 10\%$ and we require a $\pm 10\%$ linewidth control, we are restricted to features for which the modulation is greater than $50\%$.

The second term in Eq. (21) describes the functional relationship between modulation, variations in resist threshold exposure, and variations in linewidth. As previously defined, $E$ is a function of all the process- and substrate-related parameters. As in the case of exposure nonuniformity, the greater the modulation, the greater the latitude for process variations.

The third term in Eq. (20) does not appear in Eq. (21) because it vanishes when $E(0) = E_M/2$. This expression describes the variations in linewidth that will occur when the optical system departs from optimum focus. The functional dependence of $\Delta M/M$ on focus can be calculated from Eq. (1) and Figure 2. More importantly, we see that by choosing
the exposure to be twice the resist threshold (which is the same condition for equal lines and spaces) the ability to control linewidth becomes independent of focal position. This can be verified experimentally, as shown in Figure 4, where $\Delta L$ is measured as a function of focal position and exposure. Here, as predicted by Eq. (20), the linewidth becomes insensitive to focus for exposures that reproduce the nominal linewidth. Also note that the slopes of the curves for exposures greater than and less than $2\Delta E$ are correctly predicted. The existence of operation points at which linewidth can be maintained independent of focus was first described by Cuthbert by calculating the image of a step function under various conditions of focus and partial coherence.

By combining the rms values from Eq. (21) we obtain

$$\frac{\Delta L}{L} = \left[ \frac{\Delta E}{E_m} \right]^2 + \left( \frac{\Delta E_o}{E_o} \right)^2 \right]^{1/2}$$

for the fractional linewidth variation caused by variations in exposure and processing. This expression demonstrates clearly that large image modulation is the most important factor in achieving good linewidth control. Increasing the modulation can reduce the effect of exposure and processing variations. Likewise, when smaller features are imaged, linewidth control becomes more difficult by virtue of the lowered modulation. Equation (22) points out the various tradeoffs that can be used to obtain the necessary linewidth control. For example, to achieve $\pm 10\%$ linewidth control at 60% modulation with a nonuniformity of exposure of $\pm 10\%$ leaves a $\pm 6\%$ allowable variation for the processing. Similarly, if we increase the modulation to 80% and assume a 5% nonuniformity of exposure, the tolerance for process variations is increased to 15%.

Equation (22) contains a subtle relationship between focus and linewidth control. By exposing at the operating point and dropping the third term in Eq. (20), the expression is still dependent on focus as a result of $M$ in the denominator. When the system becomes defocused, the modulation decreases, which leads to less latitude for exposure and process variations. As established below under Focus Tolerance, a practical focal tolerance is a depth of focus that maintains the modulation above 40%.

Linewidth Control with Coherent Illumination

Starting with Eq. (7) and substituting the various partial derivatives into Eq. (19) we can calculate the fractional variation in linewidth that will occur when using coherent illumination. With the same mask pattern used in the previous discussion, we obtain

*In the general case when $L \neq p/2$, the exposure for nominal feature will differ from the operating point exposure by the multiplicative factor $\left(1 + \frac{4}{\pi} M \cos \frac{\pi L}{p}\right)$ for incoherent illumination and $\left[1 + \frac{8}{\pi} \cos (\phi) \sin \left(\frac{\pi L}{p}\right) \right]$ for coherent illumination.
Figure 4. Change in linewidth as a function of exposure and focal position. Feature size was a 2.0-μm line and space on the mask. The exposure system was an F/3 1:1 projection printer, $\lambda = 3900 \text{ Å}$, $S = 0.857$, exposing in 1.0 μm of AZ-1370 resist. Note that the feature size is insensitive to focus for the exposure that achieves the nominal feature size.
From Eq. (7) we note that equal lines and spaces will occur on the wafer when the exposure $E_M$ is adjusted such that $E(0) = E$, which implies that $E_M = 4E_0$. Substituting these values into Eq. (23) we obtain

$$\left( \frac{\Delta L}{L} \right)_c = -\frac{1}{4\cos(\phi)} \left( \frac{\Delta E}{E} \right) - \frac{1}{4\cos(\phi)} \left( \frac{E_0 - 1}{E_0} \right) \frac{\Delta \cos(\phi)}{\cos(\phi)}$$  \hspace{1cm} (23)$$

Comparing the fractional change in linewidth using coherent illumination to the situation that occurs with incoherent illumination, we observe three major differences. First, with coherent illumination the operating point is at $E_M = 4E_0$, which is twice the exposure required for incoherent illumination. Fortunately, this is also the exposure value required to maintain the nominal linewidth. Second, the modulation has been replaced by $\cos(\phi)$ which has the value of 1.0 for perfect focus but decreases with focal error. Third, there is an additional value of 2 in the denominator, which implies that for the same exposure and process tolerances a coherent imaging system will exhibit half the percentage change in linewidth that would occur with incoherent imaging. This last difference is most significant. It points out the key advantage of contact printing and explains why the transition from contact printing to projection printing has often required major improvements in processing before an increase in yield can be realized.

**Linewidth Control with Partial Coherence**

In the real world, we are interested in projection systems that have a certain degree of partial coherence. Calculating linewidth control as a function of partial coherence is beyond the scope of this paper. Again, we will take an heuristic approach by writing

$$\left( \frac{\Delta L}{L} \right)_p = \frac{1}{2} Q \frac{M}{M_p} \left[ \left( \frac{\Delta E}{E} \right)_p^2 + \left( \frac{\Delta E}{E_0} \right)_p^2 \right]^{1/2}$$  \hspace{1cm} (24)$$

where $Q$ is the ratio of the measured operating point exposure with partial coherence to the operating point exposure with incoherent illumination. The operating point occurs at the exposure $E_M = 2Q E_0$. The relationship between linewidth control and partial coherence has been treated in detail in a paper by Lacombat and Dubrocoucq. Their results agree quite well with those predicted by Eq. (25).

**Linewidth Control Over Steps**

An important aspect of the linewidth control problem is the situation that occurs when imaging over steps. In general, the resist thickness will undergo large fluctuations whenever there are sharp changes in substrate topography. This makes it difficult to control the width of the resist profile, for example, when it passes from a thick to a thin oxide layer. The origin of this effect can be understood from Figure 5, which is an "inverted characteristic curve" for AZ-1300 resist. From
Figure 5. Inverted characteristic curve for AZ-1300 resist. From this data, $\gamma$ can be calculated for a given resist thickness.
this curve, \( \gamma \) can be obtained for any specified resist thickness. The slope of the curve is constant over the range \( 0.5 \mu m \leq T_o \leq 2.0 \mu m \). If the resist thickness is maintained in this range, \( \gamma T_o \) is a constant, which implies

\[
\frac{\Delta \gamma}{\gamma} = - \frac{\Delta T_o}{T_o} \tag{26}
\]

From Eq. (8)

\[
\frac{\Delta E_o}{E_o} = - \frac{1}{\gamma} \left( \frac{\Delta \gamma}{\gamma} \right) \tag{27}
\]

Substituting Eqs. (26) and (27) into Eq. (25) we obtain

\[
\left( \frac{\Delta L}{L} \right)_p = \frac{1}{2 M_p Q \gamma T_o} \Delta T_o = \frac{2 \Delta T_o}{L \tan_p (\theta)} \tag{28}
\]

From this expression we see the importance of having steep profile angles when imaging over steps. This emphasizes the need for good modulation, large \( \gamma \), and using partial coherence when variations in resist thickness are expected. The same conclusion was found by Widmann and Binder\(^{12}\) using a different approach to the problem.

This treatment has ignored the effect of standing waves. When the substrate reflects a large percentage of the illumination and the change in resist thickness allows more or less light to become coupled into the resist film, substantial changes in \( E_o \) can occur. Cuthbert\(^5\) has calculated this effect for a number of cases.

Linewidth Control with Dry Etching

In the previous section we developed the functional relationship between the key lithographic parameters and the control of the resist profile width at the resist-substrate interface. For device fabrication, we are ultimately interested in the uniformity of the etched pattern. When the resist is impervious to the etch, as in the case of wet etching, the relationships presented in Eqs. (22), (24), and (25) are adequate.

Consider the situation depicted in Figure 6 where an anisotropic etch removes a resist thickness \( h \) during the process of image transfer. As we see in the figure, the edge of the resist profile will move by an amount

\[
u = h/\tan(\phi) \tag{29}\]

and the width of the resist profile will be narrower by the amount \( 2u \). In order to etch the nominal linewidth into the substrate we will plan to underexpose by an amount necessary to compensate for the loss in
Figure 6. Schematic of a resist profile before and after an anisotropic etch. Removing the resist by the amount, $h$, results in an edge loss $u$. 
feature size. This is accomplished by requiring that the resist thickness \( T \) remaining at \( x = 0 \) (location of the nominal feature edge) be equal to \( h \), the resist removed by the etch. From Eq. (10)

\[
h = \gamma T_o \log_e \left( \frac{E_o}{E(x)} \right)
\]  

(30)

By solving this expression for \( E(x) \), substituting the value into Eq. (30) for the incoherent aerial image, and solving for \( x \) to the first order, we obtain

\[
x = \frac{L}{4 M_I} \left( \frac{2 E_o}{E_M} e^{-h/\gamma T_o} - 1 \right)
\]  

(31)

The fractional change in linewidth is given by

\[
\left( \frac{\Delta L}{L} \right)_I = \frac{2}{L} \left[ \frac{-L}{4 M_I} \left( \frac{2 E_o}{E_M} e^{-h/\gamma T_o} - 1 \right) \Delta M_I \right] + \frac{L e^{2 E_o e^{-h/\gamma T_o}}}{2 M_I E_M} \Delta E_o
\]  

\[
- \frac{L e^{-h/\gamma T_o}}{2 M_I E_M} \Delta E_M - \frac{L e^{2 E_o e^{-h/\gamma T_o}}}{2 M_I \gamma T_o E_M} \Delta h
\]  

(32)

from which we obtain

\[
\left( \frac{\Delta L}{L} \right)_I = \frac{1}{2 M_I} \left( \frac{\Delta E_o}{E_o} - \frac{\Delta E_M}{E_M} \right) - \frac{2 \Delta h}{L \tan \theta}
\]  

(33)

We have assumed that \( \Delta \gamma T_o = 0 \). Evaluating Eqs. (31) and (33) at \( x = 0 \), we obtain

\[
E_M = 2 E_o e^{-h/\gamma T_o}
\]  

(34)

for the correct exposure, and Eq. (33) reduces to

\[
\left( \frac{\Delta L}{L} \right)_I = \frac{1}{2 M_I} \left( \frac{\Delta E_o}{E_o} - \frac{\Delta E_M}{E_M} \right) - \frac{2 \Delta h}{L \tan \theta}
\]  

(35)

where

\[
\tan (\theta) = 4 T_o \gamma \vee M_I \left( \frac{E_M}{E_o} e^{-h/\gamma T_o} \right) = 8 T_o \gamma \vee M_I
\]  

(36)

is the slope of the resist profile.

Comparing Eq. (35) to Eq. (21) we see that under the stated conditions the fractional change in linewidth is equal to the change associated with the lithography alone plus an additional etch-dependent term that is dependent on \( \Delta h \) but independent of \( h \). This expression stresses the need for steep profile angles when etching small features.
From this analysis we conclude that underexposing to maintain the nominal feature size is of critical importance for achieving good linewidth control. Under this exposure condition the first term in Eq. (33) vanishes allowing us to maintain the full focal tolerance (see below).

FOCAL TOLERANCE

The allowable depth of focus for a lithographic exposure system depends on our criteria for acceptable performance. The deciding factor is determined by the ability to maintain a desired degree of linewidth control. In the presence of nonuniformities in process and exposure, we can relate the depth of focus to the minimum value of the image modulation or \( \cos \phi \), which will allow us to maintain a 10% linewidth control. Assuming that exposure is at the operating point, from Eqs. (21) and (24) we can write

\[
\cos \phi \geq \frac{1}{0.4} \left[ \frac{(\Delta E_M)}{E_M} \right]^2 + \left( \frac{\Delta E_o}{E_o} \right)^2 \right]^{1/2}
\]  

(37)

for coherent illumination, and

\[
M_I \geq \frac{1}{0.2} \left[ \frac{(\Delta E_M)}{E_M} \right]^2 + \left( \frac{\Delta E_o}{E_o} \right)^2 \right]^{1/2}
\]

(38)

for incoherent illumination.

Considering today’s level of process control, 40% is usually accepted as the minimum allowable modulation, \( M_I \), which enables one to maintain 10% linewidth control. From Figure 2 and Eq. (1) we can calculate the depth of focus for an incoherent system. By fitting a linear curve to \( D^* \) in Figure 2, assuming the unaberrated MTF to be greater than 60% for a periodic feature of period 2L, and allowing the modulation to fall to 40%, one can show (Appendix) that the depth of focus \( \delta_I \) is given by

\[
\delta_I = \pm 1.85 FL \]

(39)

We conclude that for incoherent illumination the depth of focus is proportional to the F-number, \( F \), and the feature size, \( L \), but independent of wavelength. A physical interpretation of the independence of the incoherent depth of focus on wavelength has been previously discussed by King.

Assuming the same level of exposure and process control for coherent illumination we obtain

\[
\cos(\phi) \geq 0.2
\]

(40)

substituting this value in Eq. (6) we obtain the depth of focus for a coherent optical system.
Here we find that the depth of focus is a function of the wavelength and feature size but independent of $F$. For contact/proximity printers, $\delta_c$ is the maximum proximity gap, $z$, that will allow one to obtain minimum features of dimension $L$. In practice, the allowable proximity gap would be less as a result of a decollimation of the illumination.

A similar calculation for partial coherence is beyond the scope of this chapter. From Eqs. (39)-(41) the effects of partial coherence can be inferred. By increasing the partial coherence, the depth of focus becomes more dependent on $\lambda$ in a favorable way, less dependent on $F$, and more dependent on the feature size in an unfavorable way.

In Figure 7, the depth of focus is plotted for coherent and incoherent illumination as a function of feature size for three values of $\lambda$ for coherent illumination, and three values of $F$-number for incoherent illumination. The spread between the coherent depth of focus for a given $\lambda$ and the incoherent depth of focus for a given $F$ is an indication of the benefits that can be achieved with partial coherence. The reader is cautioned that Figure 7 contains $F$ and feature size combinations for which the unaberrated MTF falls below 60% and are therefore invalid for consideration. As a guideline, the point where the coherent and incoherent curves cross is a 40% modulation, which is outside the range of interest.

Our calculation of depth of focus is based on the assumption that the minimum allowable modulation for incoherent imaging is 40%. Assuming that process control will improve by the use of multilevel resist technology, it is useful to examine how far the modulation can be allowed to fall. A reasonable limit is imposed by requiring that the resist thickness not be diminished as a result of low profile angles. This requires that $\tan \theta \geq 2T/L$. From Eq. (14) we obtain

$$ M_I \geq \frac{1}{2\gamma} $$

for incoherent illumination, and

$$ M_P > \frac{1}{2QY} $$

with partial coherence. We therefore conclude that greater depth of focus can be achieved by using resist systems with large $\gamma$. Unfortunately, the use of multilayer resist technologies with thin layers of conventional resist involves low $\gamma$ systems. The use of multilayer resist technologies with inorganic photosensitive layers may offer some relief.
Figure 7. Calculated depth of focus for small features as a function of coherence. The depth of focus is independent of $\lambda$ for incoherent systems and independent of F-number for coherent systems. This figure only gives correct values for feature size, F-number, and wavelength combinations that provide a modulation greater than 60% in the focused state as determined from Figure 2.
CONCLUSION

The equations developed in this paper describe the functional relationship between the key lithographic parameters and lithographic performance. Results derived for a mask pattern with equal lines and spaces lack the generality afforded by computer modeling techniques. On the other hand, the closed form solutions provide an understanding of the lithographic process that is missing in numerical approaches.
APPENDIX
Effect of F-Number and Wavelength on the Incoherent Focal Tolerance
by
Abe Offner

In a system in which the unaberrated MTF is greater than 0.6,
\[ M_o = 1 - 1.22 \nu \lambda F \]
where \( M_o \) is unaberrated MTF
\( \nu \) is spatial frequency
\( \lambda \) is wavelength
\( F \) is f/number

in such systems, \( \nu \lambda F \lesssim 0.33 \)

For defocus = \( z \), we have
\[ R = \frac{z}{2F^2 \lambda} \] (A-1)

where \( R \) is the defocus in units of the Rayleigh tolerance. The decrease in MTF due to the defocus \( z \) is equal to \( R N^2 (nu \lambda F) \)

For \( \nu \lambda F \leq 0.33 \)
\[ R^2 (\nu \lambda F) = \frac{\nu \lambda F}{3} \] (A-2)

The value of the MTF when the focus error is \( z \) is given by
\[ M(z) = M_o - R^2 N^2 (\nu \lambda F) = 1 - 1.22 \nu \lambda F - \frac{z^2}{4F^2 \lambda^2} \left( \frac{\nu \lambda F}{3} \right) \] (A-3)

\[ M(z) = 1 - 1.22 F - \frac{z^2}{12F^3 \lambda} \] (A-4)

There is a minimum value, \( M_{\text{min}} \), of the MTF which is required for recording. For \( M(\delta) = M_{\text{min}} \), we have
\[ \frac{\delta^2}{12F^3 \lambda} = 1 - M_{\text{min}} - 1.22 \nu \lambda F \] (A-5)

\[ \delta^2 = 12 (1-M_{\text{min}})^2 \left[ \frac{F \nu}{\nu} - \frac{1.22}{1-M_{\text{min}}} \frac{F^2 \lambda^2}{\lambda} \right] \] (A-6)
For \( M_{\text{min}} = 0.39 \)

\[
\delta^2 = 12 \left( 1 - M_{\text{min}} \right) \frac{F^2}{\nu^2} \left[ F \lambda \nu - \frac{1.22}{1 - M_{\text{min}}} F^2 \lambda^2 \nu^2 \right]
\]  
(A-7)

where \( F \lambda \nu < 0.33 \)

In practical systems for imaging feature sizes less than 2 \( \mu \text{m} \),

if \( 2000 \leq \lambda \leq 4358 \) then \( 0.15 \leq F \lambda \nu \leq 0.33 \)

The maximum value of \( F \lambda \nu (1 - 2F \lambda \nu) \) is reached at \( F \lambda \nu = 0.25 \). For other values of \( F \lambda \nu \) in this range, the variation of the value of \( F \lambda \nu (1 - 2F \lambda \nu) \) is quite small as can be seen from the table.

<table>
<thead>
<tr>
<th>( F \lambda \nu )</th>
<th>( \sqrt{F \lambda \nu (1 - 2F \lambda \nu)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33</td>
<td>0.335</td>
</tr>
<tr>
<td>0.25</td>
<td>0.354</td>
</tr>
<tr>
<td>0.20</td>
<td>0.346</td>
</tr>
<tr>
<td>0.15</td>
<td>0.324</td>
</tr>
</tbody>
</table>

In a practical unaberrated system, the focus error that reduces the MTF to 0.39 for a feature size \( L = \frac{1}{2\nu} \) is given by the expression

\[
\delta_I = 1.85 FL
\]  
(A-9)

The permissible focal error for a particular feature size is thus independent of the wavelength and directly proportional to the \( F/\text{number} \) for systems in which

\[
L \leq 2 \mu \text{m} \\
0.2 \mu \text{m} \leq \lambda \leq 0.436 \mu \text{m} \\
0.15 \leq F \lambda \nu \leq 0.33
\]
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RECENT ADVANCES IN LIQUID METAL ION SOURCES

Lynwood Swanson *

1. INTRODUCTION

Field emission phenomena provide the means of attaining high brightness sources for both ions and electrons. In recent years successful modes of operating both field electron (FE) and field ion (FI) sources have been developed and evaluated with respect to their use in microprobe (i.e. focussed beams less than ~ 0.9 µm) applications. With respect to gas phase FI sources it is well known that kinetic supply of ionizable gaseous particles to the high field region of a conically shaped emitter provides an ultimate limit to the emitted current density. This limit can be removed if a liquid film reservoir of the ionizable material is formed in the high field region of the emitter and supplies the emitting area via diffusion or viscous flow. Increased FI currents due to film formation have been reported for low temperature FI of hydrogen and room temperature FI of water.

In the case of sufficiently thick conducting films it has been shown that a further enhancement of the FI current can be realized through the formation of a field stabilized cone of the liquid film supported on an underlying solid emitter structure. It was shown by G. Taylor that a balance between surface tension and electrostatic stress leads to the formation of a liquid cone of half angle 49.3° where the onset of cone formation occurs at a critical voltage (typically 5-10 kV) which depends on the surface tension and electrode geometry. As the cone forms, the apex radius decreases sufficiently to enable field emission to occur. If a negative field is applied to the emitter, field electron emission occurs when the local apex field reaches typical field emission values (0.1-0.5 V/A), while field desorption or field ionization occurs when the polarity is reversed and the local apex field reaches values ≥ 1 V/A. For the case of electron emission it was found that the cone elongation and concomitant rapid increase in field emission led to pulsed mode emission whereas for ion emission a dc current is obtained.

Gomer has investigated the mechanism of ion formation and concludes that at the onset of formation of the so-called "Taylor cone" ions are generated by field desorption, while at higher current considerable heating takes place resulting in vaporization of the liquid metal and concomitant field ionization of thermally evaporated atoms. An interesting feature of Gomer's analysis was the occurrence of space charge effects even at onset currents which are the order of 1 µA. Without space charge, electrostatic forces would decrease the apex radius until disruption of the cone occurred.

Stable and exceedingly bright liquid metal ion sources of long life (> 100 hours) have been developed using this technique. Ion emission has been obtained for Ga, Au, Hg, Woods Metal, alkali metals, and others. Typically

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for Ga, ion currents of 1 to 100 μA may be obtained, corresponding to source angular intensities of up to $10^{-4}$ A/sr which is approximately 100 times greater than the gas phase FI sources.

In view of the unique features of the liquid metal ion (LMI) source a number of potential applications can be envisaged. For example, sub-micron focussed ion beams may be employed in such microcircuit fabrication processes as resist exposure, ion implantation, pattern formation by microsputtering and circuit interconnection. In surface analysis applications such as SIMS sub-micron ion beams can greatly increase lateral resolution. Because of the high total current capabilities of such sources broad beam applications can also be considered. At this juncture it appears that the variety of applications will expand greatly as the variety of ionic species suitable for the LMI increases.

In this article we discuss some of the important considerations in source design and operation along with the way in which charge-to-mass ratio affects pertinent source emission characteristics. Typical expectations for focussed beam applications will also be presented.

2. SOURCE DESIGN CONSIDERATIONS

The LMI source configurations generally employed fall into two categories: pointed emitter or nozzle types. Figs. 1(a) and (b) illustrate two variants of the pointed emitter type where the supply of liquid to the emitter tip occurs through flow along the emitter shank. The Fig. 1(a) structure consists of a heatable reservoir with a pointed emitter of 5 to 10 μm radius protruding from the reservoir. A simpler structure, which is reminiscent of a field emitter and shown in Fig. 1(b), relies on a thick (10 μm) film of the liquid metal coating the 0.13 mm diameter solid emitter and filament support. In both types (a) and (b) an important key to success is proper wetting so as to allow adequate supply to the emitter tip where the field stabilized liquid cone is formed. Longitudinal grooves along the emitter shank from the wire drawing process provide a capillary effect which enhances supply to the emitter tip.

The nozzle type structure shown in Fig. 1(c) also requires proper wetting so that flow to the ~0.05 mm diameter nozzle occurs uninterrupted. Types (a) and (c) are employed when long term emission at high current (> 10 μA) level is required. The more convenient type (b) structure is employed when operation at low current (< 10 μA) is anticipated or when a high melting point liquid film, e.g., Au, is being utilized. In structures (a) and (b) the flow along the smooth conical section adjacent to the emitter tip is usually the critical region. In this region the thermodynamic motive for flow given in terms of hydrostatic pressure $\Delta P$ is

$$\Delta P = \left(\frac{K \rho^2}{8 \pi}\right) - \frac{\gamma}{r}$$

where $F$, $\gamma$, $r$, and $K$ are respectively the electrostatic field, surface tension, local radius of curvature and film dielectric constant. If $\Delta P$ is negative the flow motive is away from the emitter, thus the condition

$$F > \left(\frac{8 \pi \rho}{Kr}\right)^{1/2}$$

(2)
must be met along the emitter shank in order for flow to occur toward the emitter. Preferential etching so as to expose grain boundaries along the emitter cone can also be helpful in providing a favorable capillary effect.

The nozzle or emitter material must not be overly attacked by the liquid film, but must be wetted, i.e. contact angle < 90°. Tungsten has proved to be a good nozzle or emitter material for liquid films of Ga, In, Au and Cs. For a Bi ion source nichrome emitters have been successfully employed.\textsuperscript{12} In addition to proper wetting, the liquid film must not be overly volatile, i.e. $P < 10^{-4}$ torr, at the melting point in order to conserve the liquid film supply. Highly volatile or high melting point materials can be made compatible by forming a low melting binary or ternary eutectic mixture. For example boron cannot be used as a pure element as a LMI source, however a 40% B/60% (atomic) Pt mixture forms a eutectic which melts at 830°C.

3. SOURCE EMISSION CHARACTERISTICS

The emission characteristics of the LMI sources are important both from the standpoint of predicting performance in various applications and understanding the mechanism of operation. The $I(V)$ characteristics for various metal films of a well wetted emitter of the type shown in Fig. 1(b) are similar. Fig. 2 shows both the total and probe (i.e. on axis current through a 1.13 mr half angle aperture) for an In source at 410 K of the Fig. 1(b) type. Notice the rapid decrease in transmission as the total current increases. The value of $dI/dV$, which is very large for well wetted emitters, decreases as the flow rate to the emitter is reduced due to poor wetting.

Typically a threshold voltage is required to initiate emission such that a lower limit on the total current of 0.5 to 1.0 mA is observed for most LMI sources of the Fig. 1(b) type. That the threshold voltage is generally found to increase with the emitter radius can be justified from Eq. (2) by noting that $F = kV/r$; thus, the condition for net flow toward the emitter is

$$V > \left(\frac{8\pi yr}{K}\right)^{1/2}/k$$

This relationship has been verified experimentally for a Au LMI source.\textsuperscript{13} Another common experimental observation is the increase in total current $I_T$ with temperature. A typical result is shown in Fig. 3 for a Ga LMI source plotted according to $\ln I_T$ vs $1/T$. An interesting result is the temperature independence of $I_T$ for $T < 375$K, and $V > 3.32$ kV. This latter result so far appears unique for Ga, whereas the generally decreasing slope (given in terms of an activation energy) of $\ln I_T$ vs $1/T$ with increasing voltage for $T > 375$ K is a result observed for other LMI sources.

A comparison of the mass dependency of several other emission characteristics will be described in the following section.

3.1 Mass Spectra

Table 1, which summarizes the relative intensities of the various mass species for the Ga, In and Bi sources, shows that $M^+$ is the major species in each case at a total current $I_T$ of 10 mA. As will be shown, the energy spread $\Delta E$ of the ions not only depends on current but also depends on ionic charge $n$ and mass $m$.\textsuperscript{9}
This leads to a differing degree of broadening of the mass peaks as shown in Fig. 4 for the various Bi species. Thus, it is important to measure the total area under each mass peak rather than peak height when determining relative abundance ratios since $\Delta E = (\Delta m/m)E$. Because the mass scale in Fig. 4 is the voltage due to a Hall effect probe in the swept magnetic field, it is nonlinear. Nevertheless, the relative energy broadening determined from the full width half maximum (FWHM) of the mass peaks (corrected for the nonlinear Hall voltage probe) versus $m/ne$ was found to vary in the following fashion:

$$M_3^+ > M_2^+ > M^+ > M_{3+} > M_{4+}$$

In each case peaks were observed to broaden with increasing value of $I_T$ and the doubly charged entity of each mass gave a narrower FWHM than the corresponding singly charged species. This latter effect was observed by other workers using an Au LMI source.\(^{14}\)

The temperature dependence of the Ga mass peaks given in Table 2 at $I_T = 10 \mu A$ shows an increasing contribution of the dimer and trimer species with increasing temperature. Other workers\(^{15}\) have shown that the Ga\(^{2+}\) and Ga\(^{+}\) peaks increase relative to the Ga\(^{++}\) with increasing $T_T$.

### 3.2 Beam Angular Intensity Distribution

By sweeping the beam across a small aperture the distribution of the current density with beam angle was measured for Ga, In and Bi LMI sources. The results plotted in Fig. 5 as current/solid angle vs beam angle for Ga show that the distribution is extremely flat, i.e. uniform current intensity over the solid angle subtended by the emitting area. In addition the results show an increasing beam divergence with $I_T$ and an angular intensity of 60 $\mu A$/sr at $I_T = 25 \mu A$. Similar results were observed for other LMI sources such as In and Bi, although a smaller value of angular intensity with increasing mass was obtained at a specific value of $I_T$.

A summary of the results with Ga, In, Bi is given in Fig. 6 where the FWHM of the beam angular divergence vs $I_T$ is plotted for each species. At a specific value of $I_T$ the beam angular divergence increases linearly with mass. Interestingly, when extrapolated to $I_T = 0$ the curves suggest a common value of 325 mr (18.6°) for the beam angular divergence.

The mechanism for the current dependent increase in beam divergence is believed to be due to coulomb interactions within the beam that become more manifest with increasing $I_T$ and mass. A more detailed analysis of this mechanism will be published later.

### 3.3 Beam Energy Spread

The total energy distribution (TED) measurements for Ga, In and Bi were carried out using a focusing meshless filter lens arrangement.\(^{12,16}\) The input aperture to the retarding analyzer subtended a $6.0 \times 10^{-6}$ sr solid angle at the emitter. Fig. 7 shows the variation of the TED shape with $I_T$ while in Fig. 8 the variation of the TED FWHM value and beam angular intensity with $I_T$ is given for an In LMI source. The TED measurements for Ga and Bi exhibited similar trends with $I_T$; however an important effect of mass was noted as can be surmised from Fig. 9. Fig. 10 shows the effect of mass on both the TED FWHM and shift of the TED peak.
to smaller energy deficit $D$ (where $D = -eV_{\text{RETARD}}$) at $I_T = 3 \, \mu\text{A}$.

To summarize, (1) the FWHM values increase significantly with increasing $I_T$; (2) the TED peak shifts to smaller (even negative) energy deficits with increasing $I_T$; (3) both of the latter effects increase with mass; and (4) the FWHM values are relatively insensitive to source temperature. The experimental values of $D$ extrapolated to $I_T = 0$ are given in Table III. At large values of $I_T$ a significant portion of the ions arrive at the retarding collector with a negative energy deficit due to the TED broadening and shift.

The value of $D$ for a field evaporation mechanism of ion formation due to an applied field $F$ is given by

$$D_n = I_n - n\phi_c + H_n - Q(F),$$

where $I_n$ is the ionization potential of an $n$-fold charged ion, $\phi_c$ is the effective work function of the retarding electrode, $H_n$ is the vaporization energy, and $Q(F)$ is the field-dependent activation energy of field evaporation. The measured value of $\phi_c$ in this study was 3.8 eV and based on the Fig. 3 results a value of $Q(F) \sim 0$ is justified. In addition, from the Table I mass spectrometer results, the singly charge ($n = 1$) species is dominant for the LMI sources investigated here. Thus, values of $D$ can be calculated from Eq. (4) and are tabulated in Table III. The reasonable agreement of the latter values with the experimental results lends support for a field evaporation mechanism involving $n = 1$ as the dominant species.

If a field evaporation mechanism is operative, one would anticipate even a smaller energy spread $\Delta E$ than the 1-2 eV value observed for gas phase field ionization. This conclusion follows from the spatial localization of the surface metallic atom in its potential well during ionization. In view of the much larger values of $\Delta E$ and their sharp increase with current, we conclude that coulomb interactions within the beam,\textsuperscript{1,17} are responsible for this observation. A more detailed analysis of this effect will be published later.

Of critical concern for microprobe application is the value of $\Delta E$ at a particular angular intensity. Fig. 9 shows this relationship for the three LMI sources investigated. Clearly, the lower mass Ga source will provide the best performance based on the maximization of the paraxial value of $\Delta I / (\Delta\theta \Delta E)$.

### 4. BEAM CURRENT FLUCTUATION

Of considerable importance in a variety of microprobe applications is the amplitude of the beam current fluctuation or noise. Such investigations have been carried out both for Ga and Bi LMI sources.\textsuperscript{12} The rms noise amplitude $\Delta I$ over a small frequency interval $\Delta f$ plotted in terms of the noise spectral density function $\Delta I^2 / \Delta f$ vs $f$ is given in Fig. 11 for the Bi source. An almost identical result was obtained for the Ga source.

The Fig. 11 results show that the spectral density function over the frequency range 1 to 5000 Hz is only slightly above the shot noise limit. Over the same frequency range the mean signal to noise ratio is 333. Little effect of $I_T$ or source temperature on the noise amplitude was observed. This remarkably low
noise value for the LMI sources appears to be a general result and bodes well for microprobe applications where a high signal to noise ratio is required.

5. FOCUSED BEAM APPLICATIONS

A typical microprobe column containing two electrostatic lenses, beam blanking at a crossover and deflection is shown in Fig. 12. For such a system the beam current vs spot size is given in Fig. 13 at beam voltages of 20 and 60 kV for a Ga LMI source. Based on the Fig. 9 results values of $dI/d\Omega = 20 \mu A/sr$ and $\Delta E = 5 eV$ were used. A virtual source size of 0.03 \( \mu m \) was assumed.

The upper lens of the column is a physical and voltage asymmetric lens which accelerates the beam to its final voltage. This lens has been described in detail elsewhere and is employed here because of its low value of chromatic aberration at low accelerating ratios. The lower projector lens is a symmetrical einzel lens that transfers the crossover image to the target plane. The overall magnification of the column is 2.1 and 1.1 at 20 and 60 kV respectively.

The Fig. 13 results show that a current density at the target $J_n$ in excess of 10 $A/cm^2$ of Ga$^+$ can be achieved in a 0.1 \( \mu m \) focussed spot with deflection aberrations included for a $1 \times 1 \text{ mm}$ deflection field. At a beam size of $\sim 0.05 \mu m$ $J_n = 5 A/cm^2$ for the 60 kV beam. The larger value of beam diameter at 20 kV is due in part to a larger system magnification and increased contribution of chromatic aberration.

A critical assumption in this analysis is a virtual source size $d_g$ of 0.03 \( \mu m \). Several results and theoretical expectations support this assumption. First, Seliger, et al., have experimentally demonstrated a focussed Ga beam size of $< 0.05 \mu m$ which, by virtue of their optics, implied $d_g < 0.05 \mu m$. Second, from consideration of the electric field required to stabilize the Taylor cone, one can show that the cone apex field $F_c$ is

$$F_c = 3322 \left( \gamma/r_a \right)^{1/2} (V/cm) \tag{5}$$

where $r_a$ is the cone apex radius in cm and $\gamma = 700 \text{ dyne/cm}$ is the surface tension of Ga. Since it can be shown from field evaporation theory that $F_c \sim 1.6 \times 10^8 \text{ V/cm}$, one calculates from Eq.(5) that $r_a \sim 30 \AA$. Third, measurements in this laboratory of a Bi "frozen in" Taylor cone in a high-resolution SEM have shown that $r_a < 600 \AA$.

Further work will be necessary to narrow the uncertainty of $d_g$. Nevertheless, 300 \( \AA \) is probably a conservative value at low values of $I_n$. Thus, for microprobe application the LMI source gives an impressive performance.

6. CONCLUSION

The results of existing investigations of the LMI source have provided a number of insights concerning its mechanism of operation and the effect of current and particle mass on various emission characteristics. Direct and indirect evidence suggest a very small radius (e.g. $< 0.05 \mu m$) of the emitting point of the Taylor cone. This implies an even smaller virtual source size, which, in light of the measured axial angular intensity of $20 \mu A/sr$ for Ga$^+$ at threshold, means a source
brightness in excess of $10^7 \text{A/(cm}^2 \text{sr)}$. An energy spread and beam angular divergence of 5 eV and 20° are associated with this value of beam brightness.

Increasing the particle mass leads to an increase in both angular divergence and energy spread at constant total current. Thus, with respect to microprobe applications, best performance will be realized as the particle mass is decreased.

Preliminary analysis of the results suggest that coulomb interactions within the beam are responsible for both the current and mass dependent increase of energy spread and beam divergence.

From energy deficit measurements and the mass distribution, a field desorption mechanism of ion formation appears most plausible. At higher current levels where various heating mechanisms may come into play, thereby increasing the local metal vapor pressure, gas phase field ionization and other electronic excitation mechanisms become increasingly important. Justification of this view is partially based on the observed increasing intensity with current of visible radiation localized in front of the emitter.

In view of the nearly flat distribution of current density with beam angle the LMI source also has potential for a variety of broad beam applications. Multi-emitter or slit LMI source structure have already been successfully demonstrated where very large area beams or large total currents (e.g. $> 1 \text{mA}$) are of interest. In fine focussed applications using state-of-the-art electrostatic lenses the LMI sources can easily achieve 1 to 10 $\text{A/cm}^2$ of current density in 0.1 $\mu\text{m}$ beam sizes. Further investigation will undoubtedly expand the variety of metals capable of use as LMI sources. For nonmetals (e.g. B) or excessively volatile (at their melting point) metals binary or ternary alloy combinations can be used in order to obtain ion currents from otherwise inaccessible species.

Acknowledgments
This work was supported by a grant from the M. J. Murdock Charitable Trust Foundation.

References

<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative amount of the various mass species at ( I_T = 10 \mu A ) for the Ga, In and Bi liquid metal ion sources.</td>
</tr>
<tr>
<td>( \text{Ga}^+ )</td>
</tr>
<tr>
<td>( \text{In}^+ )</td>
</tr>
<tr>
<td>( \text{Bi}^+ )</td>
</tr>
<tr>
<td>( \text{Ga}^{++} )</td>
</tr>
<tr>
<td>( \text{In}^{++} )</td>
</tr>
<tr>
<td>( \text{Bi}^{++} )</td>
</tr>
<tr>
<td>( \text{Ga}_2^+ )</td>
</tr>
<tr>
<td>( \text{In}_2^+ )</td>
</tr>
<tr>
<td>( \text{Bi}_2^+ )</td>
</tr>
<tr>
<td>( \text{Ga}_3^+ )</td>
</tr>
<tr>
<td>( \text{Bi}_3^+ )</td>
</tr>
<tr>
<td>( \text{Bi}_5^+ )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation of mass peak area ratios with source temperature</td>
</tr>
<tr>
<td>at ( I_T = 10 \mu A )</td>
</tr>
<tr>
<td>( T(k) )</td>
</tr>
<tr>
<td>300 K</td>
</tr>
<tr>
<td>361 K</td>
</tr>
<tr>
<td>432 K</td>
</tr>
</tbody>
</table>
TABLE III

Calculated and experimental (in parenthesis) values of the energy deficit $D_n$ in eV for single ($n = 1$) and double ($n = 2$) charged ions.

<table>
<thead>
<tr>
<th></th>
<th>Ga</th>
<th>In</th>
<th>Bi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$</td>
<td>4.9 ($3.4 \pm 1$)</td>
<td>5.8 ($3.2 \pm 1$)</td>
<td>6.0 ($4.7 \pm 1$)</td>
</tr>
<tr>
<td>$D_2$</td>
<td>15.5</td>
<td>17.4</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Figure 1. Schematic diagrams of various source configurations. (a) indirectly heated pointed emitter type; (b) directly heated pointed emitter type; (c) indirectly heated nozzle type.
Figure 2. Current/voltage characteristics for both probe and total current. Dotted line represents transmission and $\Omega$ is the solid angle of the probe.

Figure 3. Total current plotted in $I_T$ vs $1/T$ at the indicated voltage. Values of the slopes $m$ of the straight line portions of each curve given as $Q(F) = mk$ in $eV$ units.
Figure 4. Typical mass spectrum of the LMI Bi source. The mass scale is nonlinear.

Figure 5. Lower curves show the angular current intensity vs beam angle ($0\,\text{mr}$ is the emitter apex direction) at the indicated total source currents $I_T$ for Ga. The upper curve shows the FWHM values of the lower curves versus $I_T$. 
Figure 6. Curves show the variation of FWHM values of the angular beam divergence vs total current for the indicated LMI sources.

Figure 7. Curves of the TED for the In LMI source at the indicated values of total current and temperature.
Figure 8. Upper graph shows the variation of angular intensity with total current through a $4 \times 10^{-6}$ sr aperture; lower graph shows the variation of full width at half maximum of TED curves vs total current for the indicated temperatures.

Figure 9. The FWHM values of the TED curves are plotted versus angular intensity for the indicated LMI sources.
Figure 10. Upper curve shows the TED FWHM values and lower curve shows the energy shift in the peak of the TED vs atomic mass of the LMI source.

Figure 11. Plot of the spectral density function vs frequency for a Bi LMI source for $\Omega = 4.0 \text{ sr}$. 
Figure 12. Schematic drawing of a two lens microprobe system incorporating a LMI source. Typical electrode voltages are indicated for a 60 kV beam voltage.

Figure 13. Theoretical plot of focused beam diameter vs beam current for a Ga LMI using the Fig. 12 optical system. Source parameters are indicated. Curves are calculated for 20 and 60 kV beam voltages. The dashed curves include the chromatic deflection aberrations due to deflection of the beam by ± 0.5 mm.
Use of metal alloys has been investigated to fabricate B, As and Si field ion sources, and various basic characteristics such as voltage vs current characteristics, an energy distribution, an angular ion current intensity and mass spectra have been measured. B-Pt-Au-Ge alloys, Au-Si eutectic alloys and Pb-Sn-As alloys were used. It was found that these alloy field ion sources gave an angular ion current intensity of more than 30 µA/sr for \( ^{11}B^+ \), 11 µA/sr for \( ^{28}Si^+ \) and 0.3 µA/sr for As and were stable at least for 10 hours.

1. INTRODUCTION

Liquid metal field ion sources have a very high brightness and can be expected to provide an intense fine focused beam.[1, 2] Such an intense fine focused beam has been desired for applications to maskless ion implantation, microfabrication and various ion beam microanalysis. Therefore there has been an increasing interest in developing various field ion sources and fine ion beam apparatus.

Up to now various metal field ion sources have been built for Ga[2-4], Au[5, 6], Bi[4], In[7], and others[7, 8]. These are limited to elements which have relatively low melting points and low vapor pressure at melting points and which wet emitter tips without any significant reaction.

For various applications, many important elements have high melting points or high vapor pressure, which make it impracticable to build field ion sources. Ionization of B, As and Si by field ion sources, for example, is desirable for a maskless ion implantation in Si and a maskless self-ion sputter etching, but it is very difficult to build field ion sources for these elements because they have a high melting point (B, Si) or a high vapor pressure at a melting point (As). Among various dopants for Si, only Ga field ion sources have been built.[2-4]
The importance of a field ion source increases explosively if ionization of other important elements is achievable.

There are many metal alloys which have significantly lower melting points than that of the constituent elements, and consequently have a low vapor pressure at the melting point enough to operate a field ion source. An alloy field ion source may produce various ion species but desirable ion can be easily obtained by mass-separating the ion beam. We proposed to use such alloys and showed the usefulness of a metal alloy field ion source by building Au-Ge and Au-Si eutectic alloy field ion sources and measuring their basic characteristics.[9]

In the present paper, basic characteristics of B, As and Si field ion sources are presented. A significant amount of B, As and Si ions was obtained by the present field ion sources and the ion sources were stable for a long time. We believe that this is the first report on B, As and Si field ion sources using metal alloys. The present results clearly indicate that use of metal alloys surmount limitations and extend the applicability of a field ion source over various important elements.

2. EXPERIMENTAL PROCEDURES

Alloys used were B-Pt-Au-Ge for B, Sn-Pb-As for As and Au-Si eutectic alloy for Si. The atomic ratio of these alloys are shown in Tab. 1. The melting point was 650 ± 100°C for B-Pt-Au-Ge, ~200°C for Sn-Pb-As and 370°C for Au-Si. The source configuration consisted of a field emitter tip spot-welded to a tungsten or tantalum helical loop which could be used to resistively heat the emitter and act as the liquid metal reservoir. The fabrication process of the field emitter tips are described in the previous paper.[9] The fabricated ion source is shown in Fig. 1. The emitter tip and heater assembly is mounted on a ceramic

Fig. 1 A photograph of the fabricated metal alloy field ion source. The extraction aperture was 1 mm of a diameter.
hermetic feedthrough and is plugged in the heater terminal posts. The ion source was operated at a pressure less than \(10^{-6}\) Torr. The emitter temperature was set slightly above a melting point by adjusting the heater current. The mass spectra of the metal alloy field ion sources were measured by mounting the sources on an ion implantation apparatus which employs a \(15^\circ\) sector magnet. To measure an energy distribution of the ion beams obtained, a filter-lens-type retarding potential analyzer[10] was used. The angular ion current intensity was measured by using a Faraday cup.

3. RESULTS AND DISCUSSION

Typical current-voltage characteristics for the Si alloy field ion source is shown in Fig. 2. The ion source turned on at a threshold voltage of 4.0 kV and the ion current increased rapidly with increasing the extraction voltage. The threshold voltages for the B and the As alloy sources were 4.2 and 4.4 kV, respectively. These threshold

![Fig. 2 Typical current-voltage characteristics for the Au-Si eutectic alloy field ion source.](image)
voltage varied within 10% among different ion sources, probably due to the slight difference in the alloy composition, surface contamination or a source configuration. The current flow through the extraction electrode was negligible. The probe current measured, $I_p$, is that emitted in a half angle of $0.5^\circ$ as shown in the inset and the fraction of $I_p$ to the total ion current, $I_t$, decreased with increasing the total ion current at $I_t < 7 \mu A$ and saturate at larger $I_t$. This suggests that the beam angular divergence increases with increasing the ion current. The similar behavior was also observed for Ga and Bi ion sources [4]. This may be due to a space charge effect which causes a spread in a beam angular divergence and an energy distribution.

The energy distribution curves for the Si and the B alloy field ion sources are shown in Figs. 3a and b, respectively, as a function of the source ion current $I_s$. The ion beam was not mass-separated and therefore the observed distribution curves are a convolution of distribution curves for various ion species. The width of the distribution curves increased and the peak position shifted towards the higher energy with increasing $I_s$. It was also found that the distribution extends to the lower energy and a long energy deficit tail appears at the large $I_s$.

From the curves shown in Figs. 3a and b, the FWHM values and the peak position of the energy distribution curves are replotted in Figs. 4a and b, respectively. As can be seen from Fig. 4a, the FWHM values vary with the square root of the source current except for $I_s < 10 \mu A$ for the B alloy source. This square root dependence can take as an indication that a space charge broadening effect is dominant on determining the energy distribution width. The peak position shifted towards the higher energy with increasing $I_s$ and the variation with $I_s$ was larger for the Au-Si alloy source.

The observed mass spectra for the B alloy, the As alloy and the Au-Si eutectic alloy sources are shown in Figs. 5a, b and c, respectively. As can be seen from the observed spectra, ion beams of each element were dominant and those of inter-metallic compounds were absent. These may be due to a weak metallic bonding between the constituent metallic elements. For the B ion current, the intensity ratio of $^{11}B^+$ and $^{10}B^+$ ion current was in good agreement with the isotope ratio and singly charged ions were dominant. The fraction of the $^{11}B^+$ ion flux intensity (not the current intensity) was 32.1% of the total ion flux intensity (the contributions of a doubly charged ion beam and a diatomic molecular ion beam to the total ion flux intensity are half and twice of the observed ion current intensity, respectively), and the angular current intensity of $^{11}B^+$ was $\sim 30 \mu A/\text{sr}$ at a FWHM value of 20 eV, a value which is comparable to a Ga field ion source [4]. The alloy composition used, which is shown in Tab. 1, was not optimized and more current may be expected by the optimization. For Ge ions, the doubly charged ion flux was slightly higher than the singly charged ion flux.
Fig. 3 The energy distribution curves for the B alloy field ion source (a) and the Au-Si eutectic alloy field ion source (b) as a function of the source current.
Fig. 4 The FWHM and the peak position of the energy distribution curves as a function of the source current, for the B alloy and the Au-Si eutectic alloy field ion sources.

For the As alloy field ion source (Fig. 5b), the fraction of As ion flux was only about 1% of the total ion flux, and much improvement is necessary to obtain practical field ion sources. For Sn and Pb, the singly charged ion flux intensity was more than 2 times of the doubly charged ion flux.

For the Au-Si eutectic alloy field ion source (Fig. 5c), the fraction of the singly charged Si ion flux was about 12% of the total ion flux and an angular current intensity of about 11 μA/sr at a FWHM value of 20 eV was obtained. The amount of the doubly charged Si ion flux was almost the same with that of the singly charged Si ion flux. This fact
Fig. 5 Mass-spectra of ion beams for the B alloy field ion source (a), the As alloy field ion source (b) and the Au-Si eutectic alloy field ion source (c).
is very attractive for a high energy implantation in GaAs because an ion energy of twice of the acceleration voltage is obtained by using the doubly charged ion. For Au, the singly charged ion flux was 20 times larger than the doubly charged Au ion flux.

Table 1 shows the summary of the observed mass spectra and the composition of the alloys used. The ion flux fraction is obtained from the spectra shown in Figs. 5 a, b and c. These ion sources could be operated for more than 10 hours without any significant change in ion current intensity and source operation temperature, and no reactions between the emitter tip or the helical heater coil and the liquid alloys were observed.

Tab. 1 The alloy composition and the observed ion flux fraction. Refer to text for the normalization.

<table>
<thead>
<tr>
<th>Source material composition (a/o)</th>
<th>ion flux fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11B+ 10B+ 10B++ 11B++ 10B+ 11B2+ Ge+ Ge++</td>
<td></td>
</tr>
<tr>
<td>32.1 7.0 0.3 0.6 4.1 6.4</td>
<td></td>
</tr>
<tr>
<td>Au+Pt+ Au++Pt++ AuGe+PtGe+</td>
<td></td>
</tr>
<tr>
<td>36.8 10.5 2.2</td>
<td></td>
</tr>
<tr>
<td>As+ As++ As+++ Sn+ Sn++ Sn2+ Pb+ Pb++</td>
<td></td>
</tr>
<tr>
<td>0.4 0.1 0.1 44.8 20.3 12.9 14.4 5.1</td>
<td></td>
</tr>
<tr>
<td>Pb2+</td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Au Si</td>
<td>Si+ Si++ Si2+ Au+ Au++ AuSi+</td>
</tr>
<tr>
<td>69 31</td>
<td></td>
</tr>
<tr>
<td>12.2 12.0 1.9 60.9 2.9 10.1</td>
<td></td>
</tr>
</tbody>
</table>

The variation of the mass spectra with the source ion current was measured for the Au-Si eutectic alloy source. The result is shown in Fig. 6. The fraction of the ion flux is normalized to the singly charged Si and Au ion flux. The ion beam composition changes slightly with $I_s$ and the ratios of the doubly and the singly charged Au ion fluxes to the singly charged Si ion flux decrease with increasing $I_s$. It was also observed that the ratio of the doubly charged ion flux to the singly ion flux both for Au and Si decreased with increasing $I_s$. At present, the ionization mechanism is not clear but these compositional changes and the variation of peak position (Fig. 4b) with $I_s$ may reflect a complex process such as a charge exchange process or ionization collisions etc. occurring in a high density space charge region [5].
Fig. 6 Variation of the ion beam composition with the source current for the Au-Si eutectic alloy field ion source.

4. SUMMARY

Various metal alloy field ion sources have been fabricated and their basic characteristics have been measured. The observed results clearly indicate that significant amount of various important ion beams can be obtained by field ion sources using metal alloys, and such metal alloy field ion sources are very promising for applications to maskless implantation, micromachining and microanalysis.

REFERENCES

RESIST INVESTIGATION FOR ION-BEAM LITHOGRAPHY

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ABSTRACT

The ion sensitivity of several positive and negative e-beam resists obtained from different manufacturers was measured. The resists were irradiated with hydrogen, helium, and argon ions with energies of 40, 80, and 120 keV at doses from $10^{11}$ to $5 \times 10^{14}$ cm$^{-2}$. The thickness of the removed layers after developing was measured using a mechanical profilometer. It was found that the positive resists are more sensitive by two orders of magnitude in comparison to e-beam exposure, whereas for negative resists the gain in sensitivity is only about a factor of ten.

INTRODUCTION

Recently, ion-beam lithography has been the subject of much interest [1-5], because photoresists are more sensitive to ions than to electrons or X-rays [3, 5]. Therefore, the need for the development of more sensitive resists is strongly reduced, and resists such as polymethylmethacrylate (PMMA), which have a high contrast but are not extremely sensitive, can be used. Moreover, in contrast to electrons, ions produce only low energy secondary electrons, and are less sensitive in regard to magnetic stray fields. This results in the possible exposure of structures with submicron dimensions without any proximity effects. Structures with dimensions of less than 1000 Å could be successfully fabricated [1].

There are two different ways of applying ions in lithography. Using recently-developed field emission sources with high brightness [1, 6, 7], writing of structures similarly to electron-beam lithography can be done with a great increase in writing speed, due to the higher sensitivity of the resists (about a factor of 100) to ions and the reduced computing time due to the absence of the proximity effect. This technique can be used for mask making and direct exposure of the wafer. As a technique for mass production, ion-projection exposure is an alternative to X-ray exposure [8]. This technique uses the mask technology well known in X-ray lithography, and can advantageously use the channeling effect to enhance mask stability and contrast [2, 9].

The sensitivity of electron-beam resists was investigated in two recent studies. Komuro et al. [3] investigated the exposure behavior of one PMMA resist with a molecular weight of $1.85 \times 10^{9}$ as well as a
polydimethylsiloxane (PDMS) negative resist, using argon and helium ions with different energies. They found that the exposure process in PMMA is primary due to electronic stopping, whereas in PDMS it is due to electronic and nuclear stopping. Hall et al. [4] studied the exposure behavior of various positive and negative resists at 1.5 MeV using hydrogen, helium and oxygen ions. The deposited energy per unit volume required to expose a resist was found to vary by up to a factor of ten between electrons and ions. A model accounting for the variation of the energy distribution around the particle track in connection with the number of sites required to produce the exposure showed that all electron resists have to be re-evaluated for the case of exposure with ions, since their behavior cannot be predicted from their electron sensitivity.

In this investigation, the exposure behavior of positive and negative resists with different molecular weights from 25000 to 875000 was measured. No attempt has been made up to now to compare these results with the models of Komuro et al. and Hall et al. [3, 4].

**EXPERIMENTAL TECHNIQUES**

Different positive resists (mostly PMMA) and negative resists from different manufactures, having different molecular weights were used for the experiments. In Table 1, a list of all investigated resists is given. The resist films were prepared by conventional spin-coating of oxidized silicon wafers. After the exposure with ions, the resists were developed as shown in the table for different periods of time.

**Table 1. Investigated Photoresists.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Polymer</th>
<th>Molecular Weight</th>
<th>Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elvacite 2008</td>
<td>pos.</td>
<td>PMMA</td>
<td>25000</td>
<td>1 MIBK:1 IPA, 17°C</td>
</tr>
<tr>
<td>Elvacite 2041</td>
<td>pos.</td>
<td>PMMA</td>
<td>350000</td>
<td>1 MIBK:1 IPA, 20°C</td>
</tr>
<tr>
<td>Esschemical</td>
<td>pos.</td>
<td>PMMA</td>
<td>678000(meas.)</td>
<td>1 MIBK:1 IPA, 20°C</td>
</tr>
<tr>
<td>EPMF 1</td>
<td>pos.</td>
<td>PMMA</td>
<td>875000(meas.)</td>
<td>1 MIBK:1 IPA, 20°C</td>
</tr>
<tr>
<td>OEBR 100</td>
<td>neg.</td>
<td>PGMA</td>
<td>90000</td>
<td>OEBR-DEVELOP. 23°C</td>
</tr>
<tr>
<td>OEBR 1000</td>
<td>pos.</td>
<td>PMMA</td>
<td>600000</td>
<td>OEBR-DEVELOP. 25°C</td>
</tr>
<tr>
<td>OEBR 1010</td>
<td>pos.</td>
<td>PMMA</td>
<td>750000</td>
<td>OEBR-DEVELOP. 20°C</td>
</tr>
<tr>
<td>COP</td>
<td>neg.</td>
<td>PGMA-co-EA180000</td>
<td>COP-DEVELOP. 26°C</td>
<td></td>
</tr>
<tr>
<td>XXL-15</td>
<td>neg.</td>
<td>PMMA</td>
<td>Butylacetate, 20°C</td>
<td></td>
</tr>
</tbody>
</table>

At periodic intervals, the samples were removed from the developer, rinsed in isopropyl alcohol and blown dry with purified nitrogen. The thickness of the unexposed and exposed areas were measured using a Talystep. The exposure with ion beams was done in an ion implantation system using shadow masks. Hydrogen, helium and argon ions at energies of 40, 80 and 120 keV were used with doses varying from $10^{11}$ to $5 \times 10^{14}$ cm$^{-2}$. A shutter aperture was used to allow different dose exposures on the same wafer.

RESULTS AND DISCUSSION

Figure 1 shows the thickness of the removed photoresist depending on ion dose and exposure time for argon implantations into the PMMA resist from Esschemical. The thickness of the unexposed resist was 1 µm. Depending on the dose used, a thickness of 240 nm ($10^{12}$ cm$^{-2}$) up to 320 nm ($3 \times 10^{13}$ cm$^{-2}$) is sufficiently exposed and can be completely developed within 5 min. No dark removal rate was found with the developing procedure used. The resist is extremely sensitive to ions, approximately a factor of 300 more sensitive in comparison to electron-beam exposure; however, only thin layers of less than several hundred nm can be exposed. This, though, is sufficient for photomask exposure.

![Fig. 1. Dissolution characteristic of Esschemical PMMA resist at 20°C after exposure with different doses of argon ions at 120 keV.](image)

The developing characteristics of helium-ion exposed resist layers are given for different energies and doses as a function of the development time in Fig. 2. Depending on the energy used, the total removable thickness varies between 500 nm at 40 keV to 1000 nm at 120 keV. The resist is less sensitive than in the case of argon exposure,
but much thicker layers can be exposed due to the larger range of helium. Therefore, thick resist layers such as those which are required for step coverage and etching procedures in silicon technology can be exposed. The same is true for hydrogen, which has an even smaller mass than helium (Fig. 3). Therefore, also the sensitivity of the resists is likewise lower than with helium and argon ions but still more than a factor of 100 higher than with electrons.
As can be seen from Figs. 1 to 3, exposure time and developing time are mutually exchangeable to a certain degree. Usually, however, a developing time of 2 min has been used, and all further reported experiments have been restricted to this fixed time.

A comparison of the normalized resist thicknesses after exposure with different doses of hydrogen ions is given for six different positive resists in Fig. 4. In this figure the sensitivity and the contrast of the resists may be seen of these resists, Elvacite 2008 and XXL-15 are the most sensitive, and OEER 1010 is the least sensitive. The highest contrast is obtained using EPMF 1.

![Fig. 4. Exposure characteristics of different positive resists irradiated with hydrogen ions at 120 keV.](image)

Corresponding results for the negative resists investigated are shown in Fig. 5. The sensitivity is about a factor of 10 higher than those of the PMMA resists. The most sensitive resist is COP, the least sensitive is ROJ 1989. The contrast is much less than with all positive resists; only ROJ 1989 shows a reasonable gradation. This is well known from the case of electron-beam exposure.

In Table 2, the sensitivity of all resists exposed with 120 keV hydrogen ions is listed and compared to electron sensitivities taken from the literature. The positive resists are more sensitive, approx. by a factor of 100, the negative resists only by approx. a factor of 10. The reason for this different behavior is not yet well understood. Since optimized developing procedures have been used for all different resists, no clear correlation to the molecular weight can be established. According to theory, the resist of the same type with the highest molecular weight should show the highest sensitivity [3].
Fig. 5. Exposure characteristics of different negative resists irradiated with hydrogen ions at 120 keV.

Table 2. Ion sensitivity (120 keV hydrogen) of different positive and negative resists in comparison to electron sensitivity.

<table>
<thead>
<tr>
<th>Resist</th>
<th>Ion Sensitivity (C/cm²)</th>
<th>Electron Sensitivity (C/cm²)</th>
<th>Lit.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>5x10⁻⁵</td>
<td>5x10⁻⁵ (1)</td>
<td>/10/</td>
</tr>
<tr>
<td>Elvacite 2008</td>
<td>4.5x10⁻⁷</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elvacite 2041</td>
<td>5.8x10⁻⁷</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esschemical</td>
<td>7.4x10⁻⁷</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPMF1</td>
<td>6.7x10⁻⁷</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OEBR 100</td>
<td>5.5x10⁻⁸</td>
<td>5x10⁻⁷ (2)</td>
<td>/12/</td>
</tr>
<tr>
<td>OEBR 1000</td>
<td>5.3x10⁻⁷</td>
<td>5x10⁻⁷ (2)</td>
<td>/12/</td>
</tr>
<tr>
<td>OEBR 1010</td>
<td>9.6x10⁻⁷</td>
<td>6x10⁻⁷ (2)</td>
<td>/12/</td>
</tr>
<tr>
<td>COP</td>
<td>4.8x10⁻⁸</td>
<td>3x10⁻⁷ (1)</td>
<td>/11/</td>
</tr>
<tr>
<td>ROK 1989</td>
<td>1.1x10⁻⁷</td>
<td>8x10⁻⁷ (1)</td>
<td>/11/</td>
</tr>
<tr>
<td>XXL-15</td>
<td>4.5x10⁻⁷</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) 10 keV, (2) 20 keV

Only EPMF 1, Esschemical and Elvacite 2041 can be compared because they were all developed in one part MIBK:one part IPA at 20°C. Although the molecular weight is the highest for EPMF 1, followed by Esschemical and Elvacite 2041, the sensitivity shows no correspondence, since Elvacite 2041 is the most sensitive resist followed by EPMF 1 and Esschemical.
Table 3. Resist sensitivity for different ions and energies in units of $10^{12}$ cm$^{-2}$; resist Elvacite 2041, thickness 0.3 μm

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>H</td>
<td>3.4</td>
</tr>
<tr>
<td>He</td>
<td>2.4</td>
</tr>
<tr>
<td>Ar</td>
<td>1.5</td>
</tr>
</tbody>
</table>

A comparison of the sensitivity of an 0.3 μm thick PMMA resist (Elvacite 2041) for hydrogen, helium and argon ions at energies of 40, 80 and 120 keV is given in Table 3. At higher energies, the resist shows a higher sensitivity for all three ion species. This can be explained by the increased stopping power together with increasing energy in this energy range [13]. The resist is approximately a factor of 2 or 3 more sensitive to helium or argon, respectively, than to hydrogen for energies of 80 and 120 keV. For 40 keV, the sensitivity to argon is smaller due to the limited range of argon ions. These results can only be explained assuming that, in the case of argon exposure, the nuclear stopping is as effective as the electronic stopping. For helium and hydrogen, only electronic stopping is important.

An example of a vertical step obtained in a 1 μm thick resist layer (PMMA Elvacite 2041) exposed with $3 \times 10^{12}$ hydrogen/cm$^2$ at 120 keV is shown in Fig. 6. The proximity distance between mask and wafer was approx. 25 μm. The developing time is not a critical parameter for obtaining vertical walls, as is the case with electron-beam exposure.

Fig. 6. Profile of 1 μm PMMA (Esschepmethyl) exposed through a shadow mask with a dose of $3 \times 10^{12}$ cm$^{-2}$ hydrogen at 120 keV.
CONCLUSIONS

It has been shown that all investigated electron-beam resists are well suited for ion-beam lithography. The sensitivity of positive resists is approx. a factor of 100 higher for hydrogen ions, 200 for helium ions, and 300 for argon ions in comparison to 10-20 keV electrons. For negative resists, the enhancement of the sensitivity is less pronounced. For hydrogen, a factor of approx. 10 has been measured. Vertical slopes in the photoresist layers are producible without a critical developing procedure.

ACKNOWLEDGEMENT

Part of the work was supported by the Bundesministerium fuer Forschung und Technologie of Germany. The authors wish to thank K. Hoffmann, B. Schmiedt, and M. Podstowka for their helpfull advice and assistance during the course of this work.

LITERATURE

[12] Tokyo Ohka Kogyo Comp., data sheet
APPLICATION OF ION CHANNELING AND DECHANNELING IN THE FABRICATION OF HIGH-RESOLUTION RESIST STRUCTURES

L. Csepregi, F. Iberl and P. Eichinger*)

ABSTRACT

A new masking technique for ion-beam shadow printing has been developed, employing the dechanneling effect of a thin metal layer as well as the difference in energy loss between the random and channeling directions.

1. INTRODUCTION

Ion-beam lithography is the subject of increasing interest, due to its advantageous features such as the high energy-deposition density in the resist and the small range of the scattered electrons (1). Another significant feature is that relatively inexpensive ion sources with high intensities are already available (2). The exposure techniques under development at present include direct writing with a focused ion beam (2, 3) and large-area exposure through a mask (4, 5). The main advantage of the second technique is the considerably shorter exposure time. The question of finding an appropriate masking method, however, still presents a problem. Employing self-supporting masks requires, in most cases, the splitting of the pattern into two complementary masks (6), therefore doubling the exposure time. A different method employs a hyperthin Al₂O₃ support membrane (2, 4) 1000 to 2000 Å thick, in order to minimize the angular scattering of the ions in the foil. A further technique is based on ion channeling, i.e., a thin single-crystal silicon foil covered with an absorbing pattern is aligned with the incident ion beam in order to reduce the angular dispersion of the transmitted beam (4). All of these masking concepts are based on absorption in a heavy metal layer, which is usually gold having a thickness of 0.5-1 μm. The role of the amorphous or single-crystal foil is limited to the support of the absorbing pattern, and therefore it is fabricated as thin as possible.

The fabrication of the thick absorber pattern and the mechanical and dimensional instability of the mask lead to a number of difficulties.

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The results presented in this paper are connected with the use of a different masking concept (7). This method is based on the fact that particles traversing a single crystal in the channeling or in the random direction exhibit a significant difference in energy losses and ranges (8). The method exploits this feature by employing a relatively thin metal pattern (Au thickness less than 1000 Å) whose role is primarily the dispersion and dechanneling of the beam. Furthermore, the energy of the incident beam is selected so that the dispersed and random portion of the beam has a very small probability of transmission through the membrane. This principle is shown in Fig. 1. As indicated in the experimental scheme, the channeled particles still have the necessary energy and small enough angular spread after traversing the single-crystal silicon foil so that they can expose the resist layer. The role of the single-crystal silicon foil is not only "passive"-supporting- but also "active", since it absorbs the particles deflected by more than about 0.5° from the incidence direction.

2. EXPERIMENTAL PROCEDURES

The fabrication of the ion beam "channeling masks" is almost identical with the fabrication of silicon X-ray masks. Highly boron-doped 2-7 μm thick epitaxial layers were deposited onto <110>-oriented silicon wafers. This orientation provides the greatest difference between energy losses in the channeling and random directions (8).

For the dechanneling method, the wafers to be exposed were always smaller than the thin membrane area. This can be avoided if the dispersive pattern is fabricated on the etched back-side of the membrane, or if a support ring is attached to the wafer on the side of the metal pattern. In the following step, the whole wafer is etched down to the necessary thickness. The thinning was done in the commonly-used anisotropic selective etchant (a mixture of ethylenediamine, pyrocatechol and water). The ion-beam experiments were performed on a 2.5 MeV van de Graaff accelerator. The thin mask membranes and wafers to be exposed were mounted on a goniometer. Large-area exposures were performed by scanning the wafer and the mask together. Typical beam currents were 1-50 nA, with a collimation of 0.05° and a diameter of 0.5-1 mm. Spin-coated high-molecular-weight PMMA X-ray resist was used, with thicknesses in the range of 0.5-3 μm. The exposed films were developed in a 1:1 MIBK-ethyl-alcohol solution at a temperature of 17°C.

Fizeau interference measurements were used to study the flatness distortion (9) induced by radiation damage in the mask.
3. ENERGY RANGE

The mean energy of the emerging helium particles was calculated after traversing a single-crystal silicon foil in the channeling direction. This energy can be derived by numerical integration, using the energy-loss data of Eisen et al., according to the formula:

\[
E = E_i - t \int_0^t \frac{dE}{dx} \, dx
\]

where \( E_i \) is the incidence energy, \( t \) is the thickness of the membrane, and \( \frac{dE}{dx} \) is the energy loss in the channeling direction. The results of such calculations are shown as a function of incidence energy for <110>-orientation, and for different silicon foil thicknesses. The energy region where the random part of the beam has a projected range greater than the foil thickness is indicated by a dashed line. On the right-hand vertical axis, the exposable PMMA resist thickness is shown, corresponding to the mean energy of the transmitted helium ions (3). According to this figure, the silicon foil thickness necessary to expose a 1 μm thick PMMA resist layer is in the range of 3.5-4 μm, with a corresponding incidence energy of 1 MeV.

4. CONTRAST

Considering contrast, two factors are of significance. One is the energy of the incident ions, and the second is the thickness of the gold pattern necessary to disperse and de-channel the ions. The ratio of ion fluxes transmitted in the channeling and the random directions was determined as a function of incident ion energy, employing a large-area surface barrier detector placed directly behind the silicon foil, and an extremely low beam current. The result of this measurement, shown in Fig. 3, was obtained by simply counting the number of transmitted particles and disregarding their energy distribution. This means that the values shown are worst-case values, and refer only to the resist surface. Still, contrast values higher than 20 can easily be achieved.

In order to determine the thickness of the metal layer necessary for the dispersion of the beam, the experimental results of Rimini et al. (10) have been used. They have shown that for 1.8 MeV \(^4\)He incident along the <110> axis of a silicon crystal, a 1000 Å thick Au layer increases the random component of the beam to above 80 percent.

5. ANGULAR DISTRIBUTION

The angular divergence of the transmitted particles is one
of the most important factors limiting the distance between mask and wafer. A simple way to measure the angular profile of an exposed and developed thick resist layer, is shown in Fig. 4.

Here, a 1.6 μm thick resist layer was exposed through a 5.8 μm thick silicon foil. The initial energy of the ⁴He beam was 1.47 MeV, and the maximum energy of the transmitted particles was about 230 keV. Following development, the thickness profile of the resist was measured, employing the $^{12}$C(d,p)$^{13}$C nuclear reaction (11) and a focused 1.05 MeV deuterium beam. The halfwidth of the distribution is about 0.5°. Knowing the required replication accuracy as well as this angle, the maximal mask-wafer distance can be estimated.

As a different way of measuring this angular distribution, a masked (diameter 0.3 mm) detector was scanned at a large distance from the membrane, perpendicular to the direction of the incident beam. Such measurements give the energy spectra of the transmitted particles as a function of the angle, as shown in Fig. 5.

6. DAMAGE

The ion beams traversing a thin silicon foil create damage, resulting in a macroscopic distortion of the membrane, which is often described as a "dimple" (12). This deformation is interpreted as expansion induced by radiation. Fig. 6 shows distortion measurements on a 6 μm thick membrane. The 1x1 cm² area shown in Fig. 6b was exposed to 1.6 MeV ⁴He ions with a dose of $10^{17}$ ion/cm², equivalent to about 10,000 PMMA exposures. It can be seen that noticeable distortion of the foil flatness occurs only between the non-irradiated and the irradiated areas. Such distortion also appears inside the irradiated area if the irradiation dose is nonuniform. This is important since it is not the damage itself, but rather the induced distortion of the membrane, which causes significant dechanneling, thus increasing exposure time and limiting the accuracy of replication.

7. REPLICATED RESIST PATTERNS

Fig. 7 shows resist structures for which the diameter of the exposed spot was 1 mm. A 5.8 μm thick silicon foil and a 1.47 MeV ⁴He beam were employed with a current value of 2 nA and an exposure time of 10 sec. The gold pattern for dispersion was 1000 Å thick. The proximity distance between the foil and the wafer was about 20 μm. In Fig. 8, a line pattern can be seen which was replicated with the help of
using this method. The grating period is 1 µm.

8. SUMMARY

It has been demonstrated that the active, or dispersive, channeling mask concept described, can be effectively used for the replication of submicron structures. The main advantages of the method are the easy fabrication of the metal pattern due to the fact that only a very thin dispersive layer is necessary, and the mechanical stability of the mask because of the thick single-crystal membrane.

Although the effectiveness of the masking concept has been demonstrated employing a helium beam, the use of lower-energy protons would be advantageous from the view points of mask heating as well as angular distribution.

9. ACKNOWLEDGEMENTS

The authors wish to thank Prof. I. Ruge and A. Heuberger for many helpful discussion.

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Fig. 1. Schematic diagram showing the principle of the masking method.

Fig. 2. Mean energy of the $^4\text{He}$ particles transmitted through silicon foils in the $<110>$-direction.
Fig. 3. Channeled/random flux ratio as a function of incidence energy of the $^4$He beam.

Fig. 4. Angular profile of the resist after exposure and development, measured with the $^{12}$C$(d,p)^{13}$C nuclear reaction.
Fig. 5. Angular and energy distribution of 1.6 MeV $^4$He, transmitted through a 6 μm thick silicon crystal in the <110> direction.

Fig. 6. Distortion measurements on a 6 μm thick membrane with the Fizeau interference method ($\lambda = 5350 \text{ Å}$):

a) unirradiated membrane
b) membrane irradiated with 1.6 MeV $^4$He, dose $10^{17}$ ion/cm².
Fig. 7. Replicated resist pattern:
  a) exposed spot with a diameter of 1 mm
  b) magnified picture of the resist pattern with a minimum linewidth of 1.5 μm and a thickness of 0.5 μm

Fig. 8. Replicated grating pattern with a period of 1 μm.
AN X-RAY LITHOGRAPHY ALIGNMENT SYSTEM

W.D. Buckley, G.P. Hughes, D. Kittell, J.L. Kreuzer and M.P. Eisenberg

A full field, short exposure time X-ray lithography system which is capable of submicron lithography on silicon wafer is described. The optimum system configuration is outlined and the exposure system performance when used with a high flux tungsten source is highlighted.

INTRODUCTION

X-ray lithography is a candidate technology for the fabrication of silicon integrated circuits with submicron minimum feature size. The lithographic performance of an X-ray lithography system is determined by the interaction of the exposure source, the aligner, the mask technology and the photoresist. (Figure 1) This paper discusses an approach to one such system and reports its performance including evaluation of radiation damage.

The system is based on an electron beam generated X-ray source with a water cooled rotating anode. Exposures are performed in helium at atmospheric pressure, and a thin Be window separates the source vacuum chamber from the exposure chamber. A compatible mask technology has been developed based on titanium mask membranes and gold absorbers. The fabrication, patterning and stability of these masks is described in reference 1. Similarly an optical aligner has been developed compatible with optically opaque or transparent masks. This paper will present X-ray Lithography performance data obtained for the system as a whole.

System Considerations

In any lithography system, the parameters of practical interest are the resolution, linewidth control, exposure time and overlay capability. In an X-ray lithography system these dependent parameters are controlled by the independent parameters, source diameter(s), mask to wafer distance (d), exposure distance (D) and source power (P). System design consists of optimizing the geometric factors to satisfy the conflicting requirements of high resolution and short exposure time.

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Figure 1. X-Ray Lithography System (Schematic). The mask and wafer are carried in a cartridge which fits in turn over the alignment and exposure system.

The optimum exposure distance \((D = 15 \text{ cm})\) is determined by the consideration of exposure flux uniformity and the exposure time. Since the wafer is illuminated by a quasi-point source of X-rays, the exposure flux at the wafer decreases radially. In order to ensure an exposure uniformity within \(\pm 5\%\) across the wafer it is necessary that the exposure distance be greater than three times the wafer radius. For the 15 cm exposure distance used here, the flux uniformity is \(\pm 3\%\).

The optimum source spot diameter is determined by the desired resolution and by the maximum permissible linewidth variation. In order to provide process latitude for 1 \(\mu\)m lithography, and to have the capability of extending to the sub-micron regime, a penumbral resolution limit of 0.5 \(\mu\)m was selected. This requires a 1.5 mm spot diameter, a 15 cm exposure distance and 50 \(\mu\)m mask to wafer separation.

Deliberate variations in the gap are part of the alignment procedure. These variations cause linear magnification changes at the image plane due to the inherent nature of point source imaging. The magnitude of the change is given by the relation \(\Delta R/R = \Delta d/D\). For the system geometry chosen this results in a magnification change of about 0.25 \(\mu\)m per \(\mu\)m of gap variation at the periphery of a 3 inch wafer. This effect can be used to compensate for linear magnification changes in the mask or wafer which can occur due to thermal or wafer processing effects (2). It can also compensate for linear magnification changes in the mask and, in so doing, considerably relax mask stability requirements.
Uncontrolled variations in the gap between exposures can result in image distortions which will limit the overlay precision. The magnitude of these distortions is given by the relation above and amounts to about 0.25 μm per μm of uncontrolled gap variation at the periphery of a 3 inch wafer. In order to minimize this effect a 'bed of nails' wafer chuck was used. This reduces the chance of particle entrapment by simultaneously reducing the total contact area between the chuck and wafer and distributing this area over an array of small studs. The chuck surface was polished flat and served as a reference surface for the back of the wafer. In this manner the front surface profile of the wafer was controlled.

As a result of these considerations we have chosen the geometrical parameters of the system as d = 50 μm, D = 15 cm and s = 0.15 cm. The source power is the only unspecified independent parameter. Its value is determined by the maximum permissible power input to the specified source size for the anode material chosen.

Tungsten has been chosen for its high input power capability and its medium energy X-ray M line (7A) (3). A water cooled tungsten anode, 250 mm in diameter and rotating at 8000 rmp can dissipate 20 KW of input power in a 0.15 cm spot.

It is informative at this point to compare this system with conventional lithographic tools. It is customary to describe the performance of lithographic tools by the vague term resolution. However, King and Goldrick (4) have shown that the modulation transfer function (MTF) is a more useful concept in describing the performance of photolithographic tools. MTF is a plot of the image modulation as a function of the spatial frequency of the mask pattern. Current practice is to associate an MTF value of 60% with the minimum feature size achievable in production.

Rao has presented a method for calculation of the MTF of an X-ray lithography system (5). Figure 2 compares the MTF of a F3 projection aligner and the X-ray lithography system described above. The large improvement in MTF obtained with the X-ray system is apparent. However, it is important to remember that the overall system MTF is determined by the product of the MTF of the mask and the MTF of the imaging system. For an optical system, with a high contrast mask, the mask MTF is essentially 100% and the system MTF dominates. For the X-ray system the mask contrast is less and the mask MTF dominates for features larger than about 0.5 μm.

The MTF of the exposure system is determined by the geometric parameters s, d and D. Consequently these parameters can be changed to enhance the MTF at the desired feature size. Figure 2 illustrates the system MTF for two different sets of geometric parameters as indicated by the penumbra.
Figure 2. A comparison of the MTF of an optical Lithography System (F3 Projection Aligner) with the MTF of the Proposed X-Ray Lithography System. Depending on the system geometries the X-ray MTF can be modified yielding a 1 μm or a 1/2 μm penumbra.

System Performance

The experimental system consisting of a tungsten anode X-ray source with a ring cathode electron gun is shown in Figure 3. For this system the source power is limited to 10 Kw by a low anode rational speed (200 rpm). This system has operated reliably at Perkin-Elmer for more than a year. A similar system at a major semiconductor manufacturing facility has experienced less than 2% down time. The exposure time is longer than predicted since a nonoptimum exposure distance (D = 17 cm) was used at 10Kw beam power. For COP resist an exposure time of about 1 minute is typical. With a fast experimental resist such as Eastman Kodak EK88, exposure times are approximately 30 seconds.
The use of a tungsten anode simplifies the electron gun design. Since tungsten deposition on the anode from the gun filament is not an issue, direct line of sight from the filament to the anode is acceptable. Consequently we have constructed a ring cathode electron gun by adapting the design of a linear cathode gun from a conventional X-ray tube. This configuration is not optimized for X-ray lithography and is presently limited to a minimum spot size of about 3 mm. Although larger than our ultimate goal of 1.5 mm, this spot size results in a 1.0 μm penumbra when used with a 50 μm gap and a 1/2 μm penumbra when used with a 25 μm gap.

The resolution of the system has been studied with several X-ray resists. In Figure 4, a high gamma resist (PMMA) was used in three different resolution regions. The first SEM photo represents a contact print to the mask and thus has a penumbra of 0.1μm (i.e., a 100% MTF at 0.1 μm). The second and third micrographs were of wafers exposed using the high power X-ray system in its intended proximity mode. The mask to wafer gaps were 25 μm and 50 μm, respectively, thus providing a penumbra of 0.5 μm and 1.0 μm (i.e., a maximum MTF of 0.5 μm and 1.0 μm), respectively. In all cases the 1 μm lines are resolved.
Figure 6 illustrates X-ray lithography of 3 μm lines in 1 μm of PMMA over a surface with 0.8 μm oxide steps because there is virtually no exposure difference between the top of the resist and the bottom, the resist line width is constant over the step.

3 μm LINE IN 1 μm PMMA OVER 8000 Å STEPS

Figure 6. X-ray exposed PMMA images in 8000 Å of resist over 8000 Å steps of silicon dioxides. Because of the uniform X-ray exposure there are no linewidth variations in the images over the step.

Radiation damage evaluation has been performed by a major semiconductor manufacturer using both discrete MOS devices and MOS integrated circuits. X-ray lithography was simulated by exposing completed MOS devices 1, 3 and 10 times the PBS exposure dose. All devices exhibited parametric changes but the differences for the different doses were small. Discrete device results indicate that radiation effects are removed by a conventional aluminum alloy process anneal for all exposure doses. Similar experiments were performed on an integrated circuit chosen for its expected sensitivity to radiation damage. Radiation effects were removed by an additional aluminum anneal of the finished circuits. No significant behavior difference was observed between the irradiated devices and a control group.

Alignment System

We have described an X-ray lithography exposure system capable of submicron lithography. In order to fully exploit this capability an alignment system with an overlay accuracy of one half to one third the minimum feature size is required. In addition the alignment system must be compatible with the overall lithography system and mask technology. The use of a titanium mask membrane technology mandates that the aligner be capable of aligning optically opaque masks.
Since X-ray lithography is based on point source projection imaging, the gap between the mask and wafer results in a magnification of the mask pattern. The image on the wafer is enlarged by an amount $\Delta = \frac{Rd}{D}$ where $d$ is the mask to wafer gap, $R$ is the radial distance from the wafer center and $D$ is the exposure distance. Consequently, in order to minimize magnification changes between consecutive exposures the mask to wafer separation must be controlled.

The overlay error of one level relative to another will be influenced by in plane wafer distortions. However, recent studies have shown that these changes manifest themselves principally as a linear change in wafer dimensions (6). Similar changes will result from thermal differences between exposures. Consequently, the magnification of an X-ray system can be used to advantage if the proximity gap can be fine-tuned to compensate these effects.

An alignment system based on optical detection and an optical alignment transfer standard can satisfy all of these requirements. The basis of the approach is illustrated in figure 7. The center of the wafer alignment target is located in space on the axis of an optical alignment channel by means of precise lateral and vertical alignment positioners. The wafer is then displaced a known distance, typically 50 $\mu$m, in order to provide the mask to wafer separation. Next the mask is inserted and the alignment procedure is repeated. Since the location of the wafer alignment target is retained in the transfer standard at the optical axis location, it is not necessary to view the wafer during mask alignment. Therefore either transparent or opaque masks can be aligned. In order to locate the mask parallel to the wafer, three alignment channels are used.

![Figure 7. Simplified single-channel alignment procedure. Three channels are needed to set the mask and wafer parallel as shown on the right.](image_url)
Figure 4. High resolution images using PMMA with our exposure-aligner system.

Figure 5 illustrates high aspect ratio lines using a tri-level process where the top layer was PBS. In this case 0.8 μm lines and spaces were delineated with a 1.0 μm penumbra system. This is compatible with the theoretical MTF curve as shown in Figure 2.

Figure 5. A trilevel resist process with an X-ray exposed top layer of PBS and the system configured for a 1 μm penumbra distortion. This resolution is constant with the MTF predicted for the system.
The optical system detects both lateral and vertical position of the alignment target simultaneously by means of a combined interferometer objective. A point in space is thus defined along the optic axis which serves as an alignment transfer standard and permits the alignment of opaque or transparent masks.

Figure 8 shows a schematic diagram of the system we have developed to test these alignment concepts.

Figure 8. Schematic diagram of the alignment cartridge. Mask and wafer are aligned separately to three optical channels (two of which are shown). In order to expose, the cartridge is removed together with the mask and wafer, and placed over the exposure source.

The alignment procedure requires that the optical head be first aligned to the wafer. Next, the cartridge is removed to permit installation of the mask, and the mask is then aligned to the optical channels. Since the alignment transfer standard is the axis of the optical channels, they are not disturbed after the first alignment. Subsequent alignments are by means of the mask stage position controls. Successful alignment requires accurate replacement of the cartridge after loading the mask. This can be done within an RMS error of less than 0.05 μm. Exposures are performed by placing the cartridge containing the mask and wafer over the exposure source.
Aligner Evaluation

The aligner evaluation was performed using oxidized silicon wafers and a titanium X-ray mask. A double exposure technique was used. The wafer was first coated with COP resist and the aligner was used to set the mask to wafer spacing and center the mask over the wafer. After exposure by means of the X-ray source, the resist image was developed and the underlying oxide etched. The resist was then stripped and the wafer was recoated. In subsequent experiments, the mask was aligned to the image defined in the oxide and then exposed. After development, the position of the resist image relative to oxide image was used to determine the overlay performance of the aligner.

Since the same mask was used for the overlay, the evaluation was independent of the mask-to-mask distortions. In addition, since the wafer was not subject to high-temperature processing after the oxide etch, wafer distortions did not affect the results. In order to read the overlay errors a vernier mask pattern was used. Overlay was achieved by shifting the mask laterally 300 μm to produce an overlay image. The central vernier pattern had a resolution of 0.2 μm.

Figure 9 is an example of a double exposure overlay on a three inch wafer. The dots on the wafer represent the location on the wafer where the vernier patterns were read and the vectors represent (to the scale drawn) the magnitude and direction of the measured misalignment. In this example, the mask was misaligned toward the lower left. However, the displacement vectors lie on diameters with a common center to within the measuring accuracy. This is an indication that the mask is undistorted and stable. Figure 10 summarizes the results for 7 wafers. Each plotted symbol represents the displacement vector at that location for a particular wafer. The boxes are ± 0.7 μm scale references.

Figure 9. Overlay Performance using Titanium Mask. The arrows represent (to scale) the displacement vector at each location. The dashed lines are diameters with a common center. All the vectors lie in the lines indicating that the mask is stable, i.e. behaving as a rigid body.
The alignment precision can be estimated from figure 11 which is a histogram of the overlay errors at 17 data points on each of seven wafers. The curve illustrates the cumulative overlay error and thus, the percentage of data points within a particular overlay error.

Both the histogram and the curve indicate that the alignment accuracy has a standard deviation of less than 0.3 μm. In these experiments no attempt was made to control the temperature or to vary the mask to wafer gap to compensate for scale changes.

Figure 10. Composite of Double Exposure Overlays for 7 three inch wafers. The symbols each represent a single wafer. The boxes are consistent with an alignment error with a standard deviation of less the 0.3 μm.
Alignment Error Analysis

X-ray lithography alignment consists of aligning a mask to a wafer each of which has six degrees of freedom. Assuming the mask and wafer are rigid bodies, errors in alignment can be represented by a set of rigid body alignment error terms as shown in Figure 12.
These errors include translational errors ($\varepsilon X$, $\varepsilon Y$), mask to wafer spacing error ($\varepsilon Z$), in plane rotational errors ($\varepsilon \theta_x$, $\varepsilon \theta_y$), and mask to wafer tilt ($\varepsilon \theta_x$, $\varepsilon \theta_y$). The rigid body errors act in combination to produce overlay errors ($\Delta X$, $\Delta Y$) on the wafer. At any coordinate (X,Y) the total displacement error on the wafer due to the rigid body error terms is given by:

$$\Delta X = \varepsilon X + \frac{X}{D} \varepsilon Z + \frac{X \cdot Y}{D} \varepsilon \theta_x + \frac{X^2}{D} \varepsilon \theta_y - Y \varepsilon \theta_z$$ (1)

and

$$\Delta Y = \varepsilon Y + \frac{Y}{D} \varepsilon Z + \frac{X \cdot Y}{D} \varepsilon \theta_x + \frac{Y^2}{D} \varepsilon \theta_y + X \varepsilon \theta_z$$ (2)

(where the center of the wafer is the center of the coordinate system)

Figure 12. Rigid body misalignment errors. These terms are used to evaluate aligner performance.

Using these equations and the overlay displacement errors a best fit set of rigid body terms can be computed for each overlay wafer. Figure 13 represents the result of subtracting the vectors determined by the best fit overlay data from the measured overlay error vectors. The standard deviation of the X and Y components of these residuals is $\pm 0.1 \, \mu m$ which is the reading error of the vernier targets. Thus the alignment errors as shown in Figure 9 can be represented, within our measuring accuracy, by the rigid body error terms, implying that there is no measurable wafer or mask distortion.
Another measure of the alignment performance is represented in Table 1 which details the mean and standard deviation of the rigid body error for the wafer overlays in Figure 10.

The effect of these rigid body terms on the edge of a 3" wafer is also included. Note that the mean values are all small and thus represent no systematic alignment error. The standard deviation is consistent with the histogram of figure 11. It is important to observe that all rigid body alignment errors, except for the translational errors, increase linearly with distance from the wafer center. Consequently that data of Table 1 represents the worst case result at the wafer edge. In contrast the translational errors approximate the results obtained at the wafer center.
TABLE 1
ALIGNMENT PERFORMANCE OF SEVEN WAFERS

<table>
<thead>
<tr>
<th>Rigid Body Error Terms</th>
<th>Calculated Error on Wafer at 1.5&quot; Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Translation</td>
<td></td>
</tr>
<tr>
<td>εX (µm)</td>
<td>+ 0.13</td>
</tr>
<tr>
<td>εY (µm)</td>
<td>- 0.02</td>
</tr>
<tr>
<td>εZ (µm)</td>
<td>- 0.65</td>
</tr>
<tr>
<td>Rotational</td>
<td></td>
</tr>
<tr>
<td>θx (arc-sec)</td>
<td>- 0.6</td>
</tr>
<tr>
<td>θy (arc-sec)</td>
<td>+ 5.5</td>
</tr>
<tr>
<td>θz (arc-sec)</td>
<td>- 0.36</td>
</tr>
</tbody>
</table>

The alignment system has demonstrated overlay performance with a standard deviation of less than 0.3 µm, using optically opaque X-ray masks and 3 inch silicon wafers. This performance presently is limited by the aligner and not by mask or wafer stability. Readily implemented improvements including a temperature controlled environment, high resolution viewing optics and linear magnification change compensation should result in an overlay standard deviation of better than 1/8 µm.

Conclusion:

An X-ray proximity lithography system with a well developed source, mask, and alignment system has been described. The fundamental problems of X-ray lithography have been addressed and shown to be tractable. The use of a high brightness X-ray source with conventional E-Beam resist has reduced exposure time to less than a minute. Experimental resists result in exposure time comparable to optical lithography systems. The use of ductile titanium masks with gold absorber layers has yielded high contrast, low distortion, overlays. The masks and bright exposure source in conjunction with an optical alignment system have been used to demonstrate the feasibility of X-ray lithography as a high resolution tool. Experiments which simulated MOS and integrated circuit fabrication by X-ray lithography indicate that the exposure system is compatible with current fabrication processes.
REFERENCES


X-RAY LITHOGRAPHY MASK TECHNOLOGY

W.D. Buckley, J.F. Nester, H. Windischmann

A high yield process will be described for fabricating large area free standing membranes for use as an X-ray lithography mask substrate. The choice of material and method of preparation will be discussed. Techniques for generating X-ray absorber patterns with sub-micron feature size are reported. Measurements of the patterning distortion and temporal dimensional stability of a completed X-ray mask are reported.

1. INTRODUCTION

X-ray lithography is a proximity mask replication technique that permits the definition of submicron features on silicon wafers or other substrates. Like its counterpart, U.V. proximity printing, it utilizes a patterned photomask. However, because soft X-rays are the exposing radiation there are significant differences in the photomask technology (1,2). The ideal X-ray mask should meet many difficult, seemingly contradictory, criteria. It should be relatively thin, yet rugged, flat and dimensionally stable, have a low atomic number and a favorably located absorption edge relative to the source wavelength; be fabricable in large area with low defect density and uniformly thin; have isotropic mechanical properties, be optically transparent, relatively inexpensive and impervious to process chemicals commonly encountered in the semiconductor industry. In addition the absorber must be deposited with low intrinsic stress so not to induce pattern distortions.

Since X-ray lithography permits the choice of a range of exposing wavelengths the mask technology must be selected in the context of the overall system selection. In this paper a mask technology is described which is compatible with the X-ray exposure system described in reference 3 and the alignment approach described in reference 4. The X-ray lithography mask chosen consists of a thin (∼1 μm) titanium membrane stretched on a support ring. The desired pattern is defined on the membrane by a gold absorber.

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In order to be useful for submicron lithography the membrane must be dimensionally stable in order to permit overlay of sequential mask patterns. In addition the membrane must have a smooth surface morphology to permit submicron absorber definition and to avoid defects. These requirements constrain the choice of fabrication process and pattern definition technology. In the following discussion, membrane fabrication, tensioning, patterning and dimensional stability are described.

2. MEMBRANE FABRICATION

Titanium membranes are produced by electron beam evaporation onto a glass substrate. In order to ensure membrane dimensional stability the deposition conditions are chosen to produce bulk strength films (5) of uniform thickness with isotropic physical characteristics, zero intrinsic stress and smooth surface morphology. Films are deposited onto 12.5 cm diameter photomask quality soda lime glass. This glass is chosen because of the close match of its thermal expansion coefficient with titanium and because the high quality surface minimizes defects. The combination of high rate (100 Å/sec.), high deposition temperature (350°C) and matched expansion coefficient produces large area bulk strength films with low intrinsic stress. The evaporation system geometry is chosen to ensure membrane thickness variations of less than 2% across a 8.6 cm active diameter.

A gold parting agent is used to facilitate separation of the titanium membrane from the glass substrate. The choice of parting agent, its thickness and deposition temperature are critical to the membrane fabrication process and to the membrane surface morphology. Because gold has a relatively low recrystallization temperature (150°C) it must be deposited at low temperature to minimize grain growth which has a deleterious effect on the titanium surface morphology. Similarly a thin gold film (< 500 Å) is used to minimize the effect of grain growth during titanium deposition. A titanium surface with features smaller than 0.2 μm is obtained by minimizing the heating cycle. The lower limit of gold parting layer thickness is determined by the interdiffusion kinetics of the Au-Ti system. It has been observed (6 and 7) that the Au-Ti system is susceptible to significant intergranular diffusion at temperatures above 300°C. Furthermore, the diffusion rate is ambient dependent. Faster diffusion occurs in vacuum than in air possibly due to oxide formation at the titanium grain boundaries which act as interdiffusion barriers (8). Therefore, to assist peeling, it is necessary to minimize the elapsed time in vacuum after the completion of titanium deposition. The use of a gold parting layer results in a peeling yield of greater than 90% for 1 μm thick titanium films 12.5 cm in diameter. We have demonstrated that films as thin as 0.4 μm can be peeled.
successfully by this technique.

The titanium film is removed from the glass by mechanical peeling as illustrated in figure 1. A thin flexible ring is attached to the titanium by means of double sided adhesive tape. Peeling proceeds under water until the membrane is free standing on the flexible ring. The water acts as a surfactant to reduce peeling forces at the film-glass interface. Separation occurs at the weakly bonded gold glass interface and a titanium-gold film is obtained. The gold surface replicates the original glass substrate and is featureless at 10 KX magnification in an SEM. This surface is used for subsequent lithography and patterning. After separation the membrane is slack on its mounting ring indicative of the absence of stress. The peeled films have a pin hole density of 1-2 per cm² as determined by optical transmission measurement.

The peeled membrane is tensioned and attached to a support ring.
Figure 2 is a photograph of a 1 μm thick tensioned membrane and support ring with an 8.6 cm unsupported diameter suitable for exposing 7.5 cm diameter silicon wafers. Figure 3 illustrates schematically the tensioning procedure. The membrane (M) mounted on its peeling ring (P) is placed symmetrically over the smoothly machined rim (A). Weights (W) are added at the periphery to apply a known tension to the membrane and the permanent support ring (T) is expoxied in place. Membranes are typically tensioned to approximately 10⁶ psi.
To maintain a constant geometric distortion for various mask levels it is critical to maintain a repeatable gap between the mask and wafer. This requires that the front surface of the wafer always gets pulled down to the same shape and that the mask-to-mask flatness be within .07 μm. That is, the X-ray mask must be fabricated flat and remain flat to within 1/2 wave (λ = .63 μm) over its useful lifetime in order to avoid mask-to-mask misregistration of 0.1 μm. By using a polished support ring and decoupling the epoxy bond between the Ti membrane and the support ring from the plant of the mask we are able to achieve an rms flatness of 1/5 wave across a 7.6 cm diameter circle on the Ti X-ray mask. The flatness of the X-ray mask was measured with a phase-measurement interferometer capable of resolving a flatness of 1/100 wave. Figure 4 shows a plan and isometric view of the mask flatness. Each fringe in the top view represents an out-of-flatness of .31 μm. The data shows that within a 7.6 cm diameter circle the mask is flat to better than λ/2.
Figure 4. Phase Measurement Interferogram of the flatness of a 1 μm thick titanium X-ray mask: 1 fringe = $\lambda \cdot \frac{.31 \text{ μm}}{2}$

3. MASK PATTERNING

The tensioned membranes described above serve as substrates for the subsequent generation of a completed masks with the desired absorber pattern. Unlike optical photomasks the absorber in an X-ray mask may have significant transmission. The X-ray transmission may be minimized by increasing the absorber thickness. However, the patterning process becomes progressively more difficult as the absorber thickness increases. Therefore, a practical compromise is necessary between the conflicting requirements of thick absorbers to produce high contrast and thin absorbers to facilitate high resolution patterning.

The choice of absorber thickness is influenced by the overall system configuration. For a $W_m$ lithography system a contrast of 4:1 (analogous to that achieved by an optical system operating at 60% MTF) mandates a gold absorber thickness of at least 0.5 μm as shown in figure 5. In practice, gold thickness of about 8000Å is used corresponding to 8:1 contrast.
Submicron patterning of the absorber has been achieved by both additive and subtractive processing. Both of these processes require photoresist thickness comparable to the absorber thickness. Submicron resist pattern generation was achieved by electron beam lithography using a MEBES instrument.

Figure 5. Contrast and MTF Dependence on Gold Absorber Thickness. The dashed line indicates an M.T.F. of 60% a value generally used to define the minimum feature size for practical lithography using optical systems.
Since it is difficult to achieve submicron pattern features in thick electron resist we have used tri-level or stencil processes. The additive stencil process is shown in figure 6. The tri-levels consist of 1 μm of PMMA on the membrane which is coated by 0.1 μm of evaporated Cr (or Al) on top of which is a 0.4 μm layer of electron resist (PBS). The PBS is electron beam patterned and the developed resist serves as an etch mask for patterning the metal layer. The PBS is then stripped in an oxygen plasma and the metal stencil is transferred to the PMMA by deep U.V. exposure. After developing the PMMA in MIBK, and removing metal by etching, the gold absorber is electroplated onto the thin parting layer which is used as a plating base. The final process step is removal of the PMMA in acetone. This process is attractive when Cr is used as the metal stencil since the electron beam resist patterning and metal etching use established photomask fabrication technology.

![Figure 6. Additive Absorber Definition Process. The Pattern is defined in the Upper Resist by Electron Beam Lithography. This pattern is transferred to the Thick Lower Resist by U.V. Exposure. Subsequent Absorber Definition is by Low Stress Gold Plating.](image-url)
The electroplating process takes advantage of the conductivity of the titanium membrane. The plating apparatus is shown schematically in figure 7. In this scheme the entire mask is surrounded by an insulated housing with both surfaces of the membrane exposed to a conducting liquid solution. An internal electrode is placed in close proximity to the back surface of the membrane. In this configuration gold plating occurs onto the front surface of the membrane through openings in the PMMA resist pattern. Since the current flow is perpendicular to the membrane plane current distribution problems are avoided and uniform absorber thickness is obtained independent of position on the membrane surface. Figure 8 is a scanning electron micrograph of 1 \( \mu \text{m} \) lines and spaces produced by this process.

![Figure 7. Apparatus for Electroplating a Titanium Mask Membrane](image)

![Figure 8. 1 \( \mu \text{m} \) Features x 1 \( \mu \text{m} \) Thick Electroplated Gold Test Patterns on Titanium X-Ray Mask.](image)
For an X-ray exposure system using a relatively short source to mask distance and a thick absorber, geometrical shadowing effects may result in linewidth variations as illustrated in figure 9. However, in the process described above, if a point deep U.V. source is located at the same source to mask distance as in the X-ray exposure system, then a leaning pattern is produced in the PMMA. Electroplating faithfully reproduces this profile in the absorber and eliminates the shadowing effects as illustrated in figure 9.

![Figure 9. Absorber Definition Technique which Eliminates Shadowing Effects](image-url)
During exposure, X-rays absorbed in the titanium membrane produce photoelectrons which can cause spurious exposure of the X-ray resist. In order to minimize this effect a 1 µm thick coating of low atomic number material, such as PMMA, is applied to the unpatterned surface of the membrane. Figure 10 is a photomicrograph of a finished patterned X-ray mask.

The subtractive version of the mask patterning process is similar to that described above except that a thick layer of absorber is deposited before stenciling layers are applied. Absorber patterning proceeds by sputtering or ion etching.

In its present state of development a finished mask has an optically-visible defect density of less than 20 cm⁻². Straightforward improvements in cleanliness and process techniques are expected to lead to a notable improvement.

4. MASK DIMENSIONAL STABILITY

A practical X-ray lithography system mask must permit accurate overlay of successive mask layer. The dimensional stability of the overall mask structure is thus critical, including not only distortions introduced by the mask patterning process but also those associated with the temporal stability of the membrane, bond and base support.

Figure 10. Titanium X-Ray Mask with Gold Absorber Pattern.
In order to measure these distortions we have fabricated X-ray masks with vernier test patterns. These masks were patterned by means of a Micralign™ projection printer using a quartz master photoplate. The X-ray mask was subsequently compared with the original photoplate by using the optomechanical alignment system of the projection printer to read the vernier patterns. A patterned silicon wafer was also measured periodically to insure against changes in the measurement system. Using these methods the precision of our measurement technique was estimated to be ± 0.25 μm.

The X-ray alignment system (4) permits the detection and compensation of small linear scale changes in the X-ray mask by adjustment of the mask to wafer distance. Therefore, our major concern is with random or nonlinear dimensional changes remaining after a single linear magnification correction. We have analyzed our dimensional stability data in terms of linear and non-linear distortions.

Figure 11 illustrates the average linear scale change of a 7.5 cm diameter mask with time. The data indicates a small continuous shrinkage of the mask pattern with time. However, most of the shrinkage occurs in the first 1000 hours. This suggests that patterning of the stretched membrane after an initial aging should result in no further scale change. (Although the small scale change illustrated in figure 11 is, in fact, well within the compensating capability of the system.)

![Figure 11. Average Linear Magnification Change as a Function of Time for a 1μm Thick Titanium Mask Membrane.](image-url)
Figure 12 illustrates the temporal variation of the residual non-linear distortion term. It can be seen that this random term is small and within our measuring uncertainty at all times. It is important to note that this data includes pattern distortions introduced by the fabrication process.

![Graph](image)

Figure 12. Nonlinear Dimensional Change as a Function of Time at a Fixed Location on a Titanium Mask Membrane.

An X-ray multiple exposure technique was also used to measure the temporal stability of the X-ray mask. The X-ray lithography system was used to expose a silicon wafer and the pattern was etched in silicon dioxide. A second exposure using the same mask created an image in a new resist coating. The second exposure was offset from the first so that a vernier mask pattern could be used to measure misregistration. The vernier measurement uncertainty was approximately 0.1 μm. Misregistration was measured at seventeen locations in the wafer. The linear alignment errors were removed
mathematically and the residual non linear errors are shown in figure 13. This figure summarizes the data for 6 wafers with an elapsed time of 7 weeks between exposures. The data shows that to within the measuring precision there is no non linear error.

Figure 13. Nonlinear Dimensional Change after 7 Weeks for 6 Wafers and a Single Mask. The Data Scatter is of the same magnitude as the Measuring Uncertainty.
5. CONCLUSION

Using a unique combination of materials and novel processing techniques we have developed a fullfield X-ray mask fabrication process. The masks are rugged, have a relatively high X-ray transmittance, stable and sufficiently blemish-free to be suitable for device fabrication.

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RESIST PROFILES IN X-RAY LITHOGRAPHY

J. R. Maldonado,† J. M. Moran†

A detailed study is made of the effect of the mask feature edge on the resist profiles when exposure is carried out with a PdLα X-ray source. Both wet and dry developed resists are considered.

1. INTRODUCTION

The achievements of the X-ray exposure system¹-⁴ currently being used for producing high resolution features has been substantial. At present, X-ray lithography is being used to pattern features as small as 1.0 μm for silicon integrated circuit devices.⁵ The success of such a device technology depends in part on how accurately the lithography can reproduce 1.0 μm features from wafer to wafer.

Recent advances in plasma developed X-ray resist make this resist a promising contender for use with X-ray lithography. This resist provides exposure times of under 1 min and 0.5 μm resolution capability using our 4 kW stationary Pd target X-ray source. This brings the sub-micron features closer to reality in terms of manufacturing of devices. Such being the case, it is of interest to study the limitations on feature resolution as they are affected by the source, mask and resist. In addition, the effect of the slope at the edge of the mask features on the developed resist profile is examined in this paper.

2. MASK CONTRAST

In this section we present calculations and experimental results towards a better understanding of the resist profiles obtained in our X-ray lithography system.

In order to calculate the resist profiles we need to know: i) the X-ray spectrum and spot size of the X-ray source, ii) the X-ray absorption of the mask materials, iii) the geometry of the features on the mask, iv) the mask-to-wafer gap, and v) the X-ray absorption and contrast characteristics of the resist.

The contrast properties of the X-ray resist DCOPA have been described by Moran and Taylor,⁴ and the X-ray mask structure and its fabrication was described by Maydan et al.² A cross section of the boron nitride X-ray mask structure is shown in Fig. 1A where the mask absorber is depicted as a combination of three film layers (300Å of Ta, 6000Å of Au and 800Å of Ta). Sputter etching is used to pattern features in the absorber. Due to the isotropy of the sputter etching process, the edge of the feature has a slope of about 67° from the horizontal as is shown schematically in Fig. 1A. An SEM photograph of the absorber profile for the present mask structure is shown in Fig. 1B.

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Fig. 1A  Schematic cross section of X-ray mask.

Fig. 1B  Photograph of mask absorber profile.
The mask contrast is defined as:

\[
\text{Mask Contrast} = \frac{\text{resist dose under "clear" area of mask}}{\text{resist dose under "opaque" area of mask}}.
\]  

(1)

The mask contrast can be more rigorously written as

\[
\text{Mask Contrast} = \frac{\int f(E)T_C(E)\alpha_R(E)\,dE}{\int f(E)T_C(E)T_0(E,t_A)\alpha_R(E)\,dE}
\]  

(2)

where \(E\) is the photon energy, \(f(E)\) is the X-ray incident spectrum from the source, and \(T_C(E)\) is the transmission of the clear areas of the mask; \(T_0(E,t_A)\) is the transmission of the opaque areas of the mask, \(t_A\) is the thickness of the absorber materials, and \(\alpha_R(E)\) is the absorption/unit length of the X-ray resist; \(t_R\) is the thickness of the resist which cancels out from Eq. (2) if we assume uniform X-ray absorption through the resist thickness and is included only for completeness. The sums are performed taking into account the absorption edges of the mask materials and the resist.

The X-ray spectrum used for our calculations for 25 kV electrons exciting the PdLa line is given by

\[
f'(E) = C_1eI\delta(V-V_L) + C_2eI\left(\frac{V_{\text{max}}}{V} - 1\right), \text{joules/ster/sec}
\]  

(3)

where \(\delta(V-V_L)\) is a delta function at the characteristic PdLa line at \(V_L = 2.84\) kV.

\[
C_1 = 4 \times 10^{15} \text{ (coulomb-ster)}^{-1}
\]

\[
C_2 = 1.2 \times 10^{14} \text{ (coulomb-ster)}^{-1}
\]

\[
V_{\text{max}} = 25 \text{ kV}
\]

\[
I = \text{current in amperes.}
\]

The above spectrum is consistent with our experimentally observed energy efficiency for the PdLa line at 25 kV and the observed relation

\[
\frac{\text{number of photons of PdLa}}{\text{total number of photons (char. + continuum)}} \bigg|_{25 \text{ kV}} \approx 0.4.
\]  

(4)

The second term in (3) has the functional relationship given by Kramers\(^7\) for the continuum spectrum.

After passing through a Be window 50 \(\mu\)m thick we get

\[
f(E) = f'(E)\exp(-4.9/V^3).
\]  

(5)

where \(V = E/e\), is given in kilovolts.

Figure 2 shows values for the X-ray absorption of several materials from which \(T_C(E)\), \(T_0(E)\), and \(\alpha_R(E)\) can be obtained.
Fig. 2  X-ray absorption of several mask materials in dB/μm. The resist absorption is shown. The resist absorption was measured in a free-standing resist film (a few micrometers thick). The film was obtained by depositing the resist on a glass slide. The glass slide was treated with a surfactant to prevent resist adhesion. The film thickness was controlled by a doctor blading technique.
The integration of (2) is then performed with a computer and the results are presented in Fig. 3. Figure 3 shows the calculated mask contrast vs. thickness of mask absorber for several absorber materials.

Using the definition of mask contrast given by (1), we can check our calculations by fabricating a step mask made of gold and exposing resist. This was done with various gold thicknesses and the X-ray resist, DCOPA. After exposure the final resist thickness was measured. Plotted in Fig. 3 are the mask contrast for the characteristic only of Au and Ta and the mask contrast for the total spectrum which includes the continuum. The exposure characteristics of this resist were previously determined so that the developed resist thickness could be translated into the corresponding incident dose, which in turn, can be used to calculate the mask contrast. We observe from Fig. 3 that the calculated mask contrast for a pure gold absorber agrees very well with the measured values. This results tells us that the values used for the source spectrum and X-ray absorption coefficients of resist and mask materials are valid. Therefore, we can now proceed to calculate the expected resist profiles close to the feature edge.
Fig. 4 Resist dose vs. gold thickness. The contribution for the continuum radiation is shown.

However, before we do that, it is interesting to plot the resist dose as a function of the thickness of Au absorber [denominator of (2)]. The contributions of the characteristic line and the continuum spectrum are shown in Fig. 4. We observe from the figure that more than 30% of the resist dose, when no absorber is present, is due to the continuum spectrum. This calculation shows the need to include both the continuum and the characteristic radiation when specifying an X-ray resist sensitivity.

Calculation of the Resist Profiles
In order to simplify the calculations the following assumptions were made:

1. The X-ray source spot was assumed a slit 3 mm wide and negligible width.
2. The X-ray photon flux was assumed uniform over the source. The non-Lambertian properties (target absorption) of the source were neglected.
3. The slope of the feature edge was assumed 67° from horizontal.

Figure 5 shows the relevant geometrical factors. The incident dose \( D(\xi) \), at the coordinate \( \xi \) in the resist plane, is a sum of contributions from each elemental area of the source which in turn must be summed over all energies from the source.
Fig. 5  Geometry used in the linewidth profile calculations.

\[ D(\xi) = \int_{E_{\text{min}}}^{E_{\text{max}}} \int_{-\infty}^{\infty} \left[ U(x - \xi + \frac{\Delta}{2}) - U(x + \xi - \frac{\Delta}{2}) \right] f(E) F(E, x, t_A) \alpha(E) dE dx \]  

(6)

where \( U(x) \) is a step unit function, \( \Delta = \frac{a}{D} S \) (from Fig. 5), \( f(E) \) is the X-ray spectrum from the source; \( F(E, x, t_A) \) is the transmission of the mask (absorber and transparent regions); and the zero for the \( x \) coordinate is defined as the mid-point of the slope of the gold absorber as shown in Fig. 5. For \( a = 3 \text{ mm}, D = 50 \text{ cm}, s = 40 \mu\text{m} \) and \( \Delta = 0.25 \mu\text{m} \), then

\[ F(E, x, t_A) -> T_A(E, t_A), \quad x \geq 0.125 \text{ \mu m} \]

where \( T_A(E, t_A) \) was defined in Eq. (2) as the ray transmission of the mask absorber and

\[ F(E, x, t_A) -> T_C(E), \quad x \leq -0.125 \mu\text{m} \]

\( T_C(E) \) is the transmission of the clear areas of the mask defined in Eq. (2).

\[ F(E, x, t_A) = e^{-\mu_A(E) s_A(x \tan \alpha + t_A^2/2)}, \]

for \(-0.125 < x < 0.125 \mu\text{m}\)
where \( \mu_A(E) \) is the X-ray absorption coefficient of the mask absorber; \( \rho_A \) is the density of the mask absorber; and \( \tan \alpha \) is the slope of the feature edge.

The results are shown in Fig. 6 for a 0.6 \( \mu \)m thick gold film which is the present thickness of gold used as an X-ray absorber. We observe from Fig. 6 that the dose increases to the clear area value at about 0.250 \( \mu \)m from the edge, as expected from the source spot size of 3 mm and a 40 \( \mu \)m gap between mask and wafer that is (50 cm from the source). The feature edge is defined as the point where the feature thickness is half the nominal thickness. The dose under the feature edge is mainly determined by the source spot size and the feature slope. The dose decreases to the minimum value at about 0.15 \( \mu \)m from the edge.

The contrast and the gel point of the resist are determined by the ambient in which exposure takes place. The results for exposure in a pure \( \text{N}_2 \) atmosphere and a mixture \( \text{N}_2/\text{O}_2 \) atmosphere between the mask and the wafer are shown in Fig. 7. This figure shows the normalized resist thickness vs. dose in minutes of exposure.
It is interesting to note, from Fig. 3, that the mask contrast for a 0.6 \( \mu \)m thick Au absorber is about 5.6:1. This contrast, although relatively low when compared to the contrast produced by the characteristic PdL\( \alpha \) alone (Fig. 3), is adequate to leave no resist residue under the Au away from the feature edges when the exposure is adjusted to give a developed resist thickness under clear areas of the mask equal to half the initial resist thickness. This can be seen from the contrast characteristics of the resist shown in Fig. 7. The gel point of the resist occurs at a higher dose than 1/5.6 of the dose that produces 50% remaining thickness of resist \( D_g^{0.5} \).

![Graph](image)

**Fig. 7** DCOPA negative X-ray resist contrast characteristics for \( \text{N}_2-\text{O}_2 \) and \( \text{N}_2 \) atmospheres.

Utilizing the curves of Figs. 6 and 7, we can now calculate the expected profile of the resist. In terms of the use of \( \text{N}_2 \) or an \( \text{N}_2-\text{O}_2 \) atmosphere, the change in profile was found small and only the \( \text{N}_2-\text{O}_2 \) profile is shown in Fig. 8 where the mask edge is schematically presented for reference. We observe from the figure that for a \( \text{N}_2-\text{O}_2 \) atmosphere the resist thickness cuts off approximately a little over half way under the sloped edge. This indicates that a 0.64 \( \mu \)m gap at the feature base will be replicated in the device resist as a linewidth of 1 \( \mu \)m.

However, in the case of a wet developed resist such as DCOPA, there is considerable swelling during development when the solvents are removed and the resist pulls back to its original size. Therefore, one would expect surface forces to cause a small stretching out of the resist edge. As a result, the expected profile would not be as steep as the calculated profile. Figure 9 shows the actual resist feature. It is seen that the slope is not as steep as expected.
Fig. 8  Expected resist profile obtained from Fig. 6 and Fig. 7. A straight gold absorber is also shown with its corresponding resist profile. Note that the zero of coordinates is different from Fig. 6.

Fig. 9  Photograph of an actual DCOPA resist feature obtained in our X-ray lithography system. Resist thickness is 0.35 μm and it has been wet developed.
Although the swelling of wet developed resist does tend to make resist profiles more shallow, this is not true of the dry developed resist. Basically, the dry developed resist is "developed" by selective reactive ion etching of the exposed and unexposed portions of the resist. As a result, the exposure alone will affect the resist shape.

Figure 10 shows the exposure curve for a dry developed resist presently under evaluation. Again, utilizing this curve and the calculated resist dose curve of Fig. 6 for the present mask structure, a resist profile can be calculated. The expected profile is shown in Fig. 11. Clearly the expected resist profile is very sharp for the top half of the resist but has a very shallow profile for the rest of its length. In addition, our calculations show a very thin layer of resist in the expected "clear" area under the Au absorber. There is definitely a loss of definition and a large increase in linewidth. This is confirmed by experimental measurements which produce a 0.42 μm thick resist layer when the resist in the "unexposed" region just clears and when the initial resist thickness is 1.0 μm. However a nominal 2 μm trench is closed, which can be predicted by these calculations. There may also be some microloading due to the reactive ion etching of small features which may enhance this effect. However, the profile is predictable.

When the "developing" of the dry etched resist (i.e., etching away more material) is continued to a thickness of ~0.27 μm, the resolution of 0.5 μm features is excellent. This can also be seen from the calculated resist profile in Fig. 11 (the top half has a very steep slope).
Clearly, in the case of wet developed resist and even more so in the case of dry developed resist, some improvements are called for. There are many possibilities such as a smaller diameter source or a better contrast resist or an improved positive resist. However, these possibilities are very difficult to obtain. There are cooling problems with the source which preclude reduction in size if the exposure time is to remain short. The development of new, improved resists with all the desired properties takes years and may not be fruitful.

One area that can be considered as a more practical solution is in the alteration of the mask profile. A rectangular mask profile would greatly improve things and can be possible with either electroplating, lift-off or reactive ion etching. It is even possible to consider other metals (see Fig. 3), such as tungsten or tantalum, which may have excellent reactive ion etch properties.

Fig. 11 Expected resist profile for dry developed resist. The dry developed resist X-ray absorption was assumed to be the same as the DCPA. In practice the difference is about 6% less absorption for the dry developed resist at the characteristic PdLα line. Note that the zero of coordinates is different from Fig. 6.
Figures 8 and 11 show the expected profiles for the wet developed and dry developed resists given a rectangular absorber profile. There is definite improvement in the profile of the feature in both cases. The dry developed resist could use a thicker absorber for further improvement; however, only a small amount of overetch should produce a feature with good definition and a steep profile.

3. CONCLUSIONS

In this paper we have presented a detailed study of the effect of a sloped X-ray absorber on the X-ray resist profiles. Both wet-developed and dry-developed resist profiles were shown to improve significantly with a vertical walled X-ray absorber profile. Furthermore, in the case of a dry-developed resist, a vertical profile will provide final resist thicknesses of 0.42 μm.

Based on the above results we recommend that more effort be made to improve the gold absorber edge profile over its present structure so that submicron features will be available for new device development. A vertical edge for mask features could be obtained with either electroplating, lift-off or reactive ion etching using perhaps other metals such as W or Ta.

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REFERENCES


MULTILAYER RESIST TECHNIQUES FOR HIGH RESOLUTION DEVICE PATTERNING

J. M. Moran

In the course of developing technology for patterning devices with increasingly fine features, several important problems have been identified. One problem is with linewidth variations that occur as the resist goes over different topologies. A second problem is the resist erosion that occurs when the resist pattern is transferred into the substrate using dry plasma etch techniques. Finally, there is a resolution limitation due to unwanted resist exposure. This may be caused by back-scattering in the case of electron beam exposure and by standing waves resulting from reflected light in optical exposures.

To get around these problems, researchers have resorted to using multi-layer resist techniques in which only the top layer is sensitive to the exposure radiation, and a large choice of materials can be used for the underlying resist.

This paper discusses the advantages and applications of various multi-layer resist techniques as they are being used in X-ray, photo and electron beam lithography since the multi-layer resist techniques permit finer lines to be patterned than would be possible with single-layer resists.

1. INTRODUCTION

In the future, design rules will use micron and sub-micron technologies for VLSI circuits.

The options available for achieving micron and sub-micron lines in lithography are optical and U-V projection printing, X-ray proximity printing and direct writing with an electron beam. With all of these approaches there are difficulties in obtaining good linewidth control, high resolution and good step coverage simultaneously without sacrificing writing speed. Good step coverage can be obtained with thick resist but there is a loss of resolution. On the other hand, high resolution is more easily achieved using a thin resist. This is true for all resists, both positive and negative.

Considering these specifications, we will discuss various techniques which can achieve both high resolution and also maintain a thick resist structure. In addition, we will discuss this in light of the problems that are encountered by each of the lithographic techniques that are available. Each of these techniques are constrained in different ways and the problem must be addressed in terms of the nature of the mask pattern, the type of exposure tool, the resist properties and the topographical layout present on the wafer. The advantages for each of these lithographic techniques has been discussed enough times that we will avoid repeating them here.

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2. PROBLEM DEFINITION

2.1. X-Ray Lithography

X-ray lithography proposes to be a proximity printing system which uses a metal mask pattern.\(^{(1)}\) One exposure system\(^{(2)}\) currently in use at Bell Laboratories has a 25 kV, 4 kW electron beam exciting the 4.37 Å characteristic Pd\(_{\text{L}}\) radiation from a stationary, water cooled anode. One class of negative resists which meets the sensitivity requirements for this system is the poly (chloroalkyl acrylates).\(^{(3)}\) In particular, poly (2,3-dichloro-1-propyl acrylate) mixed with poly(glycidyl methacrylate-co-ethyl acrylate)\(^{(4)}\) was found to exhibit the best overall properties for our exposure system.

This negative working resist, denoted as DCOPA, presents some problems for device wafer patterning. In order to achieve 1.0 \(\mu\)m and sub-micron lines with good linewidth control, it is necessary to use initial resist thicknesses on the order of 0.7 \(\mu\)m and expose to 50% thickness. This is due to the severe stresses encountered during the swelling and contraction processes of development. The profile of the spun on resist, before exposure, is shown in Figure 1. This SEM profile photo shows 1 \(\mu\)m polysilicon (light rectangular sections) covered over with 1.0 \(\mu\)m of flowed phosphosilicate glass. The dark area on top is the spun down resist which varies from 0.5 \(\mu\)m on top of the feature to 1.2 \(\mu\)m in the valley between features. It is seen that as the resist goes over features that are 1.0 \(\mu\)m high, there is a variation in resist thickness.

This presents no great problems from an exposure point of view since X-rays have virtually little scattering or standing wave problems so that linewidth control is well maintained.\(^{(3,4)}\) Figure 2 shows 1 \(\mu\)m and 2 \(\mu\)m lines and spaces exposed over this type of topography. The problem arises in attempting to transfer the pattern to the phosphosilicate glass. For most high resolution applications, some form of plasma or reactive ion etching is needed. This requires the resist to be either totally plasma resistant or to be thick enough to not break down during the subsequent etch of the glass. In both cases, the DCOPA resist does not stand up. To indicate the severity of the problem, Figure 3 is a profile SEM photo of the 1.0 and 2.0 \(\mu\)m lines going over a step. The 1.0 \(\mu\)m lines are in the foreground. The resist thickness goes from 0.4 \(\mu\)m below the step to 0.15 \(\mu\)m on top of the step. This will cause resist breakdown during etching which will erode the P-glass. As a result, it would be desirable to have a flat surface and some intermediate type of mask structure so as to transfer the X-ray resist pattern to the P-glass.

2.2. Electron-Beam Lithography

Although many high quality positive electron beam resists are available with good resolution in thick resist, they are too slow to be considered, at the present time, for direct writing. This approach requires a very expensive machine which must be economically justified with sufficient throughput. As a result, some of the faster resists available, such as PBS\(^{(5)}\) and GMC\(^{(6)}\) suffer from the same problems as outlined in the X-ray section. That is, they must be applied in a very thin layer (<0.5 \(\mu\)m) and will not stand up very well to plasma processing.

The exposure is also sensitive to resist thickness which must be controlled fairly accurately or there will be a variability in feature size. The exposure is also dependent on substrate material since high atomic number material will generate secondary electrons that can further expose the resist. The direct writing is also sensitive to charging which can vary from wafer to wafer and depend on the conductivity of the substrate material directly below the resist.
2.3. Optical and U-V Projection Printing

This approach, while not offering the ultimate in resolution, does present itself as a well practiced art. Both direct and demagnifying optics are well established technologies. However, there are problems with the resist which are not easily solved.

The spin coating of a positive photoresist, such as HPR-204, produces the same type of step coverage as shown in the X-ray section. In this case, the resist is more sensitive to standing waves, scattering of light from edges and also in terms of type of substrate material. The thin resist will get over-exposed while the thickest resist section is being correctly exposed. As a result, there can be a variation in feature size as the resist traverses a step which is generally a necking down due to over-exposure. There are standing waves (see Figure 4) which depend on the resist thickness and the reflection of the substrate below the resist and there is a variable exposure setting for each level which is also dependent on the substrate reflection. Finally, there can be a problem with maintaining focus which can cause a variation in feature size over a wafer.

3. PROBLEM SOLUTIONS

3.1. Bi-Level Techniques

Many lithographic problems can be eliminated by using a multilayer resist structure. The base layer is usually an organic polymer that is thick compared to the steps that it has to cover on the wafer so that it flows and forms a relatively flat top surface over the device topography. In a bi-level or two-layer technique, the top layer is a thin resist material which can be applied to the flat surface of the bottom resist. The top resist is appropriately patterned and then the pattern is transferred to the bottom resist. This thick bottom layer is then used as a mask for either etching or metal lift-off.

In considering the use of a bi-level technique, several factors have to be considered, (i) the bottom layer must have good adherence as well as acceptable processing properties, (ii) the two layers must be compatible and (iii) the top layer must adhere well and not appreciably affect the properties of the bottom layer.

Several schemes for bi-level techniques have been proposed. Lin(7,8) used a combination of electron beam and deep U-V exposure to create a conformal mask structure. The bottom layer is PMMA and the top layer is AZ-1350J. The AZ-1350J is exposed with either an electron beam or near U-V and then developed. The AZ-1350J serves as a deep U-V mask for exposing the PMMA layer. A tri-level system is also possible in which there is an intermediate layer of metal film when higher e-beam currents may have to be used and one does not want the PMMA to be exposed. Either of these techniques offers the advantage of using a thin top resist layer which gives higher resolution as well as producing a planar top surface to pattern on. This technique was tried using HPR-204 photoresist (0.3 μm) for the top layer and PMMA (2.0 μm) for the bottom layer as illustrated in Figure 5. Figure 6 shows the absorbance of the two layers as a function of wavelength and Figure 7 shows the resultant patterns. It is seen that there is some undercut due to the sloping edge of the top masking resist allowing some exposure to occur under the mask. However, the technique does show promise for geometries on the order of 2 μm.

Haller and his co-workers(9) also produced a bi-level structure in which an electron beam exposure is done on both layers of resist. The structure is developed such that the bottom layer develops faster than the top layer. This produces an undercut resist profile which is suitable for metal lift-off, with the degree of undercut controlled by development time.
A novel use for the bi-level technique was developed by Howard and his co-workers\(^{10}\) in which 0.12 \(\mu\text{m}\) of PMMA was spun on top of a more sensitive 0.4 \(\mu\text{m}\) thick e-beam resist \(\text{P(MMA/MAA)}\),\(^{9}\) a copolymer of polymethylmethacrylate and methacrylic acid. For a given dose of electrons, the lower layer develops more rapidly and can produce a well defined undercut and bridging of resist. The use of this technique by Howard \textit{et al.}\(^{10}\) is for two purposes. The first is an increase in resolution since the thin upper layer minimizes forward scattering while the thick lower layer reduces backscattering.\(^{11,12}\) Secondly, the bridge of upper resist makes an excellent shadow mask for metal deposition at oblique angles. Using lift-off and the bi-level technique, they were able to produce superconducting tunnel junctions as small as \(10^{-10}\) cm\(^2\).

Tai and his co-workers\(^{13}\) also used a bi-level technique which used an inorganic resist for the top layer and \(\text{O}_2\) reactive ion etching to transfer the image to the bottom layer of polymer. In this case, a Ge-Se inorganic resist, doped with Ag, serves as the top layer and is patterned using U-V exposure. The resist is a high contrast material with very high resolution in a thickness of 0.3 \(\mu\text{m}\). The Ge-Se is resistant to \(\text{O}_2\) plasma so that the bottom layer can be reactive ion etched with the top layer as the mask. An example of the feature resolution is shown in Figure 8. The features are well defined and the conformal coating of the bottom topography as well as the flat top surface of the thick resist layer are clearly evident.

### 3.2. Tri-Level Techniques

This technique follows, in essence, the same principles as the bi-level technique except there is an intermediate layer inserted between the top and bottom resists. This intermediate layer must be compatible with both resists as well as possess the properties necessary for pattern transfer.

One technique for this is that of Hatzakis and co-workers.\(^{14}\) They utilize two resist layers and an intermediate layer of metal for the purpose of generating a hybrid (e-beam/X-ray) exposure system. The top 0.5 \(\mu\text{m}\) thick layer is an electron beam resist (Shipley AZ-2400) that is more sensitive than PMMA which is the bottom resist layer. Sandwiched between the two is a 600 Å thick metal layer. The top resist is exposed and developed and 2500 Å of gold is deposited and lifted off. The bottom PMMA is then X-ray exposed and the PMMA developed. This pattern is then used for subsequent wafer processing.

Another tri-level approach is that of Moran and co-workers.\(^{15,16}\) This is the technique presently being used for VLSI development at Bell Laboratories in Murray Hill. The present process consists of spinning down a thick organic layer of material (2.5 \(\mu\text{m}\) thick) which conforms to the topology of the wafer and produces an essentially planar surface at the resist top. On top of the thick resist is a plasma deposited 0.12 \(\mu\text{m}\) thick layer of \(\text{SiO}_2\). What one now has is a surface that is both flat and constant in substrate properties. This is the ideal surface to pattern a resist on since the resist will spin down more uniformly and a large choice of thin, high speed resists can be considered.

In addition, the \(\text{SiO}_2\) layer is always the same which means that the adhesion problem need be solved only for the one surface. Furthermore, the \(\text{SiO}_2\) is reactive ion etched which means the adhesion requirements for the top resist are minimal for such a mild dry etch process.

As an illustration, see Figure 9 which schematically represents the sequence of operations. A 2.6 \(\mu\text{m}\) thick layer of photoresist (HPR-204) is spun down on a silicon wafer. An intermediate layer of 0.12 \(\mu\text{m}\) of \(\text{SiO}_2\) is deposited and a 0.8 \(\mu\text{m}\) thick layer of DCOPA X-ray resist is spun down and exposed on top of this structure. Reactive ion etching is used to transfer the pattern from the thin resist to the thick resist with no perceptible loss in linewidth.
For X-rays, the only processing the X-ray resist has to withstand is a reactive ion etch of 0.12 μm of SiO₂. This does not perceptibly degrade the resist and a pattern obtained using X-ray resist for the top layer is shown in Figures 10a and b which indicates excellent linewidth control for 1 μm features.

For electron beam resist, again, the only requirement is that it hold up for reactive ion etching of the 0.12 μm of SiO₂. A further advantage of tri-level is that the thick organic is of low atomic number and offers very little scattering. A Monte-Carlo computer program has been used to investigate the effects of various composite target structures on the proximity effect. In all the calculations, the resist layers sandwiching the intermediate layer were chosen to be the negative electron beam resist COP. This has been done because the electron scattering properties of most organic polymer resists should be very similar. Hence, the results from COP should be indicative of what one would expect from other polymer resists.

In Figure 11, we present the most significant results of our theoretical investigations. The simulated exposure pattern consists of two identical arrays of Gaussian lines separated by a 1 μm gap. The arrays are each 3.96 μm wide. The center-to-center line spacing a₀ and the incident beam’s Gaussian radius σ₀ are as shown. The incident electron energy is 20 kV. The quantity R plotted in this figure is the ratio of the energy dissipation density per unit line dose E(y,z) to its value at the center of either array bounding the gap. The results obtained from simulations of three different tri-layer systems are compared with that obtained from a straight resist-on-silicon system. All the results are evaluated at a depth Z = 5000Å. The noticeable reductions in the levels of unwanted energy dissipation inside the gap region afforded by the tri-layer systems are readily apparent in Figure 11. The one problem area is in charging since the thick organic plus the SiO₂ are dielectrics which will charge. One solution for this would be a conducting layer replacing the SiO₂ which could eliminate charging effects.

For optical lithography, the flat surface and minimal requirements for plasma etching resistance allow the use of a thin resist (≤0.8 μm) for potentially higher resolution. The SiO₂ and thick organic layers also offer a good match and an absorbing layer for the exposure light so that the substrate surface plays no role in scattering or standing waves. Figure 12 shows a 1.25 μm feature resolved in developed photoresist which was exposed with a Perkin-Elmer projection printer on top of the tri-level structure with no standing waves apparent as seen in Figure 4. Figure 13 shows a comparison between the type of features obtained with tri-level (Figure 13a) and single level resist (Figure 13b). The tri-level resist does not provide a solution for the depth-of-focus problem in projection lithography. This has to be solved by either a much higher contrast resist or better focus tracking devices on projection cameras.

4. DEVICE PROCESSING

The tri-level technique presented here has to also be compatible with device processing, both wet and dry. In this case, again there are some advantages. In the case of adhesion, the thick bottom resist layer is baked so that it is desensitized to being exposed by light. The baking at high temperatures also promotes adhesion so that subsequent processing does not lift the resist.

The thick resist has been used as an implant mask and for reactive ion etching of phosphosilicate glass, SiO₂, aluminum and polysilicon. Figure 8 has shown the step coverage of the thick resist over steps. The resist linewidth has no perceptible variation for the different step geometries encountered. Figure 14 shows the tri-level process being used as a mask for etching of aluminum. The resist pattern and the aluminum form almost a continuous wall.
One additional advantage of the tri-level process is that it permits the use of resists which have very poor plasma resistance. One good example is PBS(5) electron resist which erodes quite quickly in plasma. Figure 15 shows a PBS pattern which has 0.5 μm lines and spaces with the large areas having a thickness of 0.35 μm and the 0.5 μm lines being much thinner and tapering to the edge of the resist. It is obvious that proximity effects are still a consideration even though they are much reduced by the tri-level technique. This resist pattern was used as a mask to transfer the pattern to the SiO₂ which in turn was used to reactive ion etch the thick resist. The result is shown in Figure 16 which reveals 0.5 μm lines and spaces in 1.2 μm thick HPR-204 resist with total linewidth loss of less than 0.08 μm. As a result, one can now consider using PBS resist and the tri-level technique in X-ray mask processing where the high resolution requirement is essential. Figure 17 shows a pattern produced in 0.9 μm of gold using the tri-level resist as a plating mask. Here the steep wall is extremely important for good edge definition of a mask structure.

5. CONCLUSION
Multilayer resist techniques such as tri-level or bi-level offer many potential advantages and applications to all phases of lithography. Sub-micron resolution features with better linewidth control and good step coverage are possible. It allows much more flexibility in considering new lithographic systems, greatly relaxes resist requirements and also permits another generation of devices to be made using conventional projection photolithography for resolving small features.

REFERENCES
Fig. 1  Resist coverage over device topography (SEM photograph).
Fig. 2  X-ray exposure of 1 \( \mu m \) and 2 \( \mu m \) resist lines and spaces traversing steps (SEM photograph).
Fig. 3  Profile of 1 μm and 2 μm resist lines traversing a step. Note the severe thinning out of the resist as it goes over a device feature (SEM photograph).
Fig. 4  Standing waves generated in photoresist exposed with Perkin-Elmer projection printer (SEM photograph).
Fig. 5  Schematic of the two-level photoresist process. Top level of visible sensitive resist is patterned using a projection aligner and normal development (a). The pattern is transferred to the lower, UV sensitive resist by flood exposure with 215 nm radiation (b). The final structure after developing the lower layer (c).
Fig. 6  UV absorption of HPR-204 and PMMA in the 200-300 nm region.
Fig. 7 Typical structures produced with the two-level resist process (SEM photograph).
Fig. 8  Bilevel resist features, 1 μm in width, shown traversing steps on a device wafer. No linewidth variation is observed as the resist feature crosses a step (SEM photograph).
REACTIVE ION ETCH

1000 Å
SiO₂

4000 Å PHOTO, ELECTRON, OR X-RAY RESIST

2-3 μm THICK PHOTORESIST

VLSI SUBSTRATE

REACTIVE ION ETCH

SiO₂

PHOTORESIST

VLSI SUBSTRATE

SCHEMATIC PRESENTATION OF THE VARIOUS STEPS REQUIRED TO DEFINE A STEEP PROFILE RESIST PATTERN.

FIG. 9
Fig. 10  (a) High resolution linewidth control of 1 \( \mu \)m lines and spaces going over steps. The linewidth variation is not detectable (SEM photograph).

(b) Profile of Figure 10(a), showing flat top surface and conformal coating of bottom features (SEM photograph).
Fig. 11  Theoretical energy distribution in the electron beam resist using Monte-Carlo calculations.
Patterned optical resist (HPR-204) using a Perkin-Elmer projection printer. No standing waves are seen, as in Figure 4, since it was exposed on a tri-level structure (SEM photograph).
Fig. 13 (a) Pattern exposed with photolithography using a tri-level technique to transfer the pattern to a thick resist.

(b) Same pattern, as in (a) except using a single 1.0 μm thick layer of resist. Note the standing waves and loss of resolution.
Fig. 14  Etched 1.0 μm thick aluminum (1/2% copper) using a thick tri-level (2.4 μm) as a mask. The break between the aluminum and the resist can just be seen.
Fig. 15  SEM photograph of 0.5 μm lines and spaces in 0.35 μm thick PBS electron beam resist.

Fig. 16  SEM photograph of 0.5 μm lines and spaces in which the PBS resist pattern has been transferred to the thick resist pattern using the tri-level technique.
Fig. 17  X-ray mask absorber pattern produced using a tri-level resist pattern as the mask for electroplating.
TANTALUM ON GOLD
PATTERNED WITH PBS TRILEVEL PROCESS

FIG. 18
A TWO LAYER RESIST SYSTEM FOR EFFICIENT LIFTOFF IN VERY HIGH RESOLUTION ELECTRON BEAM LITHOGRAPHY


1. INTRODUCTION

The definition of metal patterns by lift-off demands vertical or undercut resist walls otherwise there is a danger that bridges will form between the metal layers on the undissolved resist and those on the substrate, causing lift-off to fail when the resist is removed. Profiles which meet these requirements may be obtained in solid substrate electron beam lithography by exploiting the electron scattering pattern in the resist. This is undercut in form, so that if sufficient exposure is given and development conditions are correctly chosen, the resist will develop away to an undercut edge.

As this technique lacks sensitivity, two layer resist methods have been devised. These involve the coating of two films of different sensitivity, a higher sensitivity layer underlying a layer of lower sensitivity. On exposure and development the lower layer dissolved away laterally more quickly than the upper, giving rise to a well-defined undercut, the extent of which depends on the relative sensitivities of the two films.

In very high resolution electron beam lithography the conditions for producing undercut profiles in single resist layers do not prevail. Electron scattering is minimised by reducing the thicknesses of both the resist and substrate so that there is on average only about one elastic scattering event within the resist and a negligible amount of backscattering. We have developed a very high resolution electron beam lithography system which relies on lift-off for the transfer of a developed PMMA pattern into metal. Although we have successfully used this technique to write patterns of 16nm lines on 50nm centres we find that the maximum permissible thickness of metallisation for successful lift-off is only about one-third of the resist thickness. Applications of the technique involving thicker metallisation than we have hitherto been able to lift off (about 20nm) necessitate much thicker resist layers which are detrimental to resolution. For example, in order to ensure adequate X-ray contrast for printing by Carbon Kα radiation, 45nm of gold is needed on the mask. Using a single layer resist this would require a resist thickness of 140nm and a very high aspect ratio (8.5:1) for say 16nm lines.

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Consequently we have devised a two-layer resist system to enable us to fabricate 45nm thick structures without loss of linewidth or pitch resolution. This second constraint implies that whilst the sensitivity ratio of the two layers must be adequate to develop an undercut, or at least to sharpen up the profile, it must be small enough to prevent adjacent patterns from running into one another leaving, in some circumstances, the upper layer freely suspended over the substrate(7). A further implication is that other factors limiting resolution, such as resist adhesion, must not be adversely affected by the choice of resist combination. We therefore chose to examine a system comprising two layers of dissimilar PMMAs. This method has been used before in solid substrate electron beam lithography, where sensitivity was gained at the expense of resolution(3).

2. EXPERIMENTAL DETAILS

We chose two PMMAs from different manufacturers (Aldrich Chemical Co. and BDH Chemicals Ltd.). The relative sensitivities of the two layers were measured at 25kV and 50kV by electron beam exposing 200nm thick films of each, spin-coated onto silicon substrates. After development in a 3:1 mixture of IPA and MIBK the loss of thickness in areas given different exposures was measured by ellipsometry. Results are shown in Fig.1. Defining the sensitivity by the exposure required to clear the resist under the prevailing development conditions, we obtained a sensitivity ratio of 1.3-1.4 for the two materials, Aldrich polymer having the lower sensitivity.

PMMA sensitivity is influenced by a number of factors including molecular weight, heterogeneity and tacticity(8). The polymers in question were analysed by gel permeation chromatography (GPC) to measure the first two of these parameters. The GPC spectra show the Aldrich PMMA ($M_w=452,000,x=2.4$) to have higher molecular weight and dispersion than the BDH material ($M_w=138,000,x=1.8$), which is consistent with the sensitivity measurements. However, without NMR data we cannot attribute the sensitivity differences wholly to these characteristics.

The process sequence used to make thin samples for very high resolution lithography is broadly similar to that described elsewhere with a few detailed differences. Fig.2 is a step-by-step illustration of the process. Briefly, a clean glass slide is spin-coated with a 5% solution of poly(vinyl alcohol) in water to form a smooth 100nm thick film which is baked for 1-2 hrs at 95°C. Onto this a 20-40nm thick film of carbon is evaporated from an arc struck between pointed graphite rods. This forms the resist substrate. We are using carbon rather than silicon nitride, for example, because of its strength and ease of production in thin film form, and also because its transparency to its own characteristic radiation favours its use as a soft X-ray mask substrate. After carbon coating the samples may be stored in a dessicator until required. Next, a film of BDH PMMA is
spin coated from solution in MIBK and baked for 1 hr. at 150°C, before
the Aldrich PMMA coating is applied. Although the solubility rate of
BDH resist in MIBK is low, we take the precaution of allowing as
little time as possible to elapse from the application of solution to
commencement of the spin. Good results are also obtained by start­
ing the spinner and applying just one drop of solution to the surface.
The entire sample is given a further 20 min. bake at 150°C.

Having divided the films into squares with a diamond scribe, the
carbon/PMMA sandwich is stripped by dissolving the PVA layer in water,
allowing the films to float off as it does so. They are then picked
up on individual 3mm microscope grids and exposed in a Philips PSEM
500 scanning electron microscope fitted with a microprocessor
controlled scan generator and STEM facilities. Most patterns are
written with an 8mm nominal diameter spot at 50kV.

The exposed resist layers are developed in a continuous stream of
drops of 3:1 IPA:MIBK for 45s at 23°C, rinsed in IPA for 30s, dried
and then metallised. The specimens to be discussed in this paper
were mostly coated with Au/Pd as it is easier to evaporate thick
films of this material from a well collimated tungsten basket source
than it is to deposit the finer-grained, higher melting point mater­
ials such as Pt/Pd. Finally, lift-off is carried out by 'shooting'
methyl ethyl ketone at the specimen immersed in a bath of methanol.

3. RESULTS

The technique has met our objective of successfully lifting off thick
metal without a commensurate increase in resist thickness. Fig. 3
shows a pattern of 20nm wide lines defined from a 45nm thick deposit;
the resist combination used for this consisted of 30nm of BDH PMMA
underlying 50nm of Aldrich PMMA, both supported on a 40nm carbon
substrate. Exposure was 2.8x10^-9c/cm. The lines are continuous
and appear uniformly thick in this electron micrograph. At a
slightly lower dose of 2.4x10^-9c/cm the lines narrow to 16nm (Fig. 4)
but now a number of lines are missing where adhesion of the gold/
palladium has failed. Some indication of the metal structure can be
obtained from the line which has collapsed flat onto the substrate.
Its thickness profile is very ragged, and there appear to be a few
long needle-shaped crystallites around which thinner material has been
deposited.

Fig. 5 shows part of a pattern of 16nm lines on 50nm pitch formed in
the same resist combination. Thinner metallisation (about 16nm) has
been applied and lifted off to confirm that both linewidth and pitch
resolution have been preserved relative to a similar total thickness
of single layer PMMA.

We have also been able to define extremely narrow lines using the two­
layer system. Fig. 6(a) is a pattern of Au/Pd lines defined by single
layer resist with an exposure just above the critical value required
to develop the resist down to the substrate. Under these conditions
the resist profile is very sensitive to variations in dose and develop-
ment so that, although the lines formed are only about 10nm wide on
average, they are badly broken up and have poorly defined edges. In
two layer resist (40nm Aldrich PMMA on 30nm BDH PMMA) under similar
exposure conditions continuous 10nm lines with excellent edge control
have been defined (Fig. 6b). These are the narrowest reported
structures written in polymeric resist.

4. ACKNOWLEDGEMENTS

We thank R.A. Pethrick of Strathclyde University for undertaking the
GPC analyses; the Department of Natural Philosophy, Glasgow
University for provision of TEM facilities; and J.V. Crichton for
carrying out all our pattern exposures. Financial support for this
work is provided by the United Kingdom Science Research Council.

5. REFERENCES

ed. R. Bakish (Electrochem Soc. Princeton, to be
published).
Fig. 1. Sensitivity measurement curves. Graph shows loss of thickness of resists as a function of exposure at 25kV and 50kV. PMMA developed in 3:1 IPA:MIBK.

Fig. 2. Sequence of process steps used to make very high resolution metal patterns by lift-off.
Fig. 3. Gold-palladium lines 20nm wide, 45nm high defined by a two-layer resist pattern. Exposure: 2.8x10^{-9} C/cm, 8nm spot, 50kV.

Fig. 4. 16nm wide gold-palladium lines. Resist exposure: 2.4x10^{-9} C/cm, 8nm spot, 50kV.

Fig. 5. Pattern of 16nm wide, 15nm thick gold-palladium lines on 50nm pitch.
Fig. 6a. Lines formed by gold-palladium lift-off from single layer PMMA exposed close to the critical dose.

Fig. 6b. 10 nm wide gold-palladium lines formed by lift-off from two-layer PMMA.
THE USE OF POLYMER DISPERSIONS TO IMPROVE THE SENSITIVITY OF ELECTRON RESISTS

David R. Cowley*, Colin Price*, and Christopher J. Hardy†

1. INTRODUCTION

Poly(methyl methacrylate) (PMMA) has been extensively used as a resist in electron beam lithography1,2. The substrate to be pattern-delineated is usually first covered with a PMMA film by spin-coating from a molecular solution of the polymer. By the term molecular solution we refer simply to a mixture of individual (unassociated) polymer chains and solvent molecules. The coated substrate is selectively irradiated by a focused beam of electrons and the degraded polymer is removed with the aid of a selective solvent to form a positive image. A number of polymers (e.g. poly(butene-1-sulphone)3 are now known to be considerably more sensitive as electron resists than PMMA. The latter is still widely used in the fabrication of microelectronic devices however because of its merits with regard to other required properties.

In the present contribution we compare the electron resist properties of films spin-cast from colloidal dispersions of PMMA in hydrocarbon media with films formed in the conventional manner from solutions of PMMA in methyl isobutyl ketone (MIBK).

2. MATERIALS

2.1. Dispersion 1

This was prepared in our laboratories by polymerizing methyl methacrylate monomer in heptane with the aid of a free-radical initiator, azo-bis-isobutyronitrile, in the presence of a poly(styrene-ethylene/propylene) block copolymer. Heptane is a non-solvent for PMMA. The block copolymer was introduced as a stabilizing agent and during and after polymerization served to hold PMMA in colloidal suspension in heptane. The block copolymer was provided by Shell Research Ltd. It had been prepared by hydrogenating the polyisoprene block of an anionically synthesized polystyrene-polyisoprene block

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copolymers. The poly(styrene-co-ethylene/propylene) block copolymer had a weight-average molecular weight of \((1.06 \pm 0.11) \times 10^5\) g mol\(^{-1}\), the ratio of its weight-average to number-average molecular weight \((\overline{M}_w/\overline{M}_n)\) was 1.14, and it contained \((38.5 \pm 3.0)\%\) by weight polystyrene.

The dispersion polymerization was carried out in three stages. The system was rigorously stirred throughout the reaction programme. The composition of the reaction mixture used in the first stage (a seeding stage) and the composition of the two feeds, one added before the second stage and the other before the third stage are given below:

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Parts by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>First stage</td>
<td></td>
</tr>
<tr>
<td>monomer</td>
<td>10</td>
</tr>
<tr>
<td>initiator</td>
<td>0.15</td>
</tr>
<tr>
<td>stabilizer</td>
<td>4.75</td>
</tr>
<tr>
<td>heptane</td>
<td>42</td>
</tr>
<tr>
<td>First monomer feed</td>
<td></td>
</tr>
<tr>
<td>monomer</td>
<td>20</td>
</tr>
<tr>
<td>initiator</td>
<td>0.5</td>
</tr>
<tr>
<td>stabilizer</td>
<td>3</td>
</tr>
<tr>
<td>Second monomer feed</td>
<td></td>
</tr>
<tr>
<td>monomer</td>
<td>20</td>
</tr>
<tr>
<td>initiator</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The poly(styrene-co-ethylene/propylene) stabiliser was always dissolved in heptane before being added to the other reagents. In the first stage of polymerization the reaction mixture was heated to 70-80°C for two hours. The temperature was then raised to 80-85°C whilst the two feeds were added. The first stage lasted for 120 minutes. The first feed was added over a period of 90 minutes and then after waiting for a further 30 minutes the second feed was added over a second 90 minute period. The reaction was then maintained at a temperature of 80-85°C for a period of time to allow it to go to completion.

At the end of the polymerization the dispersion was filtered after being allowed to cool. It was then centrifuged at 10,000 r.p.m. for 15 minutes. The supernatant liquid was poured off and exchanged for fresh heptane. After the polymer particles had redispersed in the heptane the centrifugation/exchange process was carried out two more times. These cycles served to remove unconverted monomer, unattached block copolymer, and initiator residues from the dispersion system. The percentage conversion of monomer to polymer was found to be 26%. 
The polymer particles were examined using an A.E.I. 6G electron microscope operating at 80 kV. Drops of the diluted dispersion were dried on a carbon substrate supported on a copper grid. Specimens were shadowed with platinum/carbon. Particle sizes were determined from measurements on enlarged prints. The number-average particle diameter, \( \bar{D}_n \), was found to be 0.3 \( \mu \text{m} \) and the ratio of weight-average to number-average particle diameter, \( \bar{D}_w/\bar{D}_n \), was found to be 1.1. These values must be considered as rough estimates only however, since during the drying process the spherical particles became somewhat flattened. From these estimates however it can be concluded that each particle contained many PMMA chains. In the colloidal state the PMMA chains would have been slightly swollen with heptane. The poly(styrene-co-ethylene/propylene) stabilizer was probably attached to the particles through its polystyrene block since heptane is a non-solvent for polystyrene. The polyethylene/propylene blocks would have sterically stabilized the particles by forming a flexible fringe around the particles.

The PMMA chains making up the dispersion particles were characterized by gel permeation chromatography in a good solvent for the polymer. Heptane was removed from the samples by vacuum drying and a solution of the residual polymer was made up in tetrahydrofuran. Analysis of the chromatograms showed the weight-average molecular weight of the PMMA to be 508,000 g mol\(^{-1}\) and the ratio \( \bar{M}_w/\bar{M}_n \) was 2.42.

### 2.2. Dispersion 2

The second PMMA dispersion was kindly supplied by Imperial Chemical Industries, Paints Division, Slough. The dispersing medium was iso-octane, a non-solvent for PMMA, and the stabilizing agent was a graft copolymer consisting of a poly(methyl methacrylate) backbone and poly(12-hydroxystearic acid) grafts. As supplied the dispersion consisted of 60% involatile content by weight and 15% plasticizer. The copolymer molecules were presumably attached to the colloidal particles of PMMA by their backbones leaving the soluble graft units to form an outer protective fringe that prevented the particles from coagulating. The particles of dispersion 2 were very difficult to characterize by electron microscopy because they tended to undergo gross distortion during the isolation procedure. A very rough estimate gave a number-average particle diameter, \( \bar{D}_n \), of 0.2 \( \mu \text{m} \). For the individual chains gel permeation chromatography in tetrahydrofuran gave \( \bar{M}_w = 292,000 \) g mol\(^{-1}\) and \( \bar{M}_w/\bar{M}_n = 4.39 \).

### 2.3. Solutions of PMMA

The solutions used were prepared from samples of PMMA supplied by British Drug Houses (BDH) and Du Pont. The solvent in both cases was methyl isobutyl ketone. The gel permeation studies of the polymers in tetrahydrofuran showed that BDH’s High Molecular Weight PMMA had a \( \bar{M}_w = 188,700 \) g mol\(^{-1}\) and a \( \bar{M}_w/\bar{M}_n \) of 2.28, whilst Du Pont’s Elvacite 2041 had a \( \bar{M}_w = 457,000 \) g mol\(^{-1}\) and a \( \bar{M}_w/\bar{M}_n \) of 2.96.
3. FILM FORMATION AND PROCESSING

The operations described below were carried out in a horizontal laminar flow cabinet which was located in a clean room.

After being passed through a depth prefilter and a 1 μm absolute filter, the dispersion or solution was flooded onto a chromium/glass substrate. The thickness of the chromium layer was 350 nm. The substrate was spun at high speed to produce a resist thickness of 500 nm. The concentration and spinning speed required to produce a film of the required thickness for each sample are given below:

<table>
<thead>
<tr>
<th>Dispersion 1</th>
<th>Dispersion 2</th>
<th>BDH PMMA</th>
<th>Elvacite 2041</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration/10^{-2} g cm^{-3}</td>
<td>8</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>Speed/rev s^{-1}</td>
<td>50</td>
<td>86.6</td>
<td>83.3</td>
</tr>
</tbody>
</table>

Residual solvent and spinning strains were removed by placing the substrate on a hot plate. In the case of the dispersion-based resists this step also served to ensure the formation of a contiguous film. Specimens of the dispersion-based resists needed to be baked for 20 minutes at 130°C, whilst specimens of solution-based resists required baking at 170°C for 30 minutes. The polymeric resists were then tested with a beam of energy 20 kV and a width of 0.25 μm. The beam current was measured, by a Faraday cage, before and after each series of exposure patterns. Each exposure pattern consisted of a series of sub-patterns built up from an array of spots. For each series of patterns within the overall exposure pattern the spot exposure time was varied from 4 μs to 998 μs. A resolution test pattern was also included with each exposure pattern.

The developing cycle, which followed the exposure of the resist, consisted of (i) a 2 minute soak, (ii) a 30 second spray with a developer followed by, (iii) a 2 minute soak, (iv) a 30 second spray in isopropyl alcohol, (IPA), to remove all traces of the developer. The developer used was a 3:1 mixture of IPA and MIBK, except for dispersion 1 which gave better results with a 9:4 mixture of IPA to cyclohexanone. After development the specimens were baked at 130°C for 30 minutes, except for dispersion 1 which did not require this treatment. The chromium was then etched by an acidic ceric sulphate solution and finally the resists were removed by soaking in a suitable solvent.
4. RESULTS AND DISCUSSION

The sensitivities of the various films studied are recorded in the Table 1. The sensitivity was taken to be the minimum electrical charge per unit area required for complete development of an exposed area. In each case the film thickness was 0.5 \( \mu \text{m} \).

<table>
<thead>
<tr>
<th>Resist</th>
<th>Charge Density/ C m(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion 1</td>
<td>min. 0.31</td>
</tr>
<tr>
<td></td>
<td>max. 0.35</td>
</tr>
<tr>
<td>Dispersion 2</td>
<td>min. 0.28</td>
</tr>
<tr>
<td></td>
<td>max. 0.38</td>
</tr>
<tr>
<td>B.D.H. PMMA</td>
<td>min. 0.86</td>
</tr>
<tr>
<td></td>
<td>max. 1.04</td>
</tr>
<tr>
<td>Elvacite 2041</td>
<td>min. 0.89</td>
</tr>
<tr>
<td></td>
<td>max. 0.99</td>
</tr>
</tbody>
</table>

**TABLE 1.** The sensitivities of the four samples of P.M.M.A.

The results show that in general dispersion-based resists are considerably more sensitive than solution-based resists. Since the molecular-weight characteristics of the PMMA samples are fairly similar, these differences cannot be attributed to the well-known dependence of sensitivity and molecular weight. Instead we tentatively attribute the improved sensitivity to the lack of any strong adhesion between neighbouring particles in the dispersion-based films. We believe that the particles retain their identity even after baking. When a significant fraction of chains within a particle have been degraded the particle can be easily dislodged and washed out by the solvent. The choice of solvent will of course affect the strength of this adhesion between particles. It should be pointed out that the adhesion will be strongly influenced by the nature of the stabilizer since this will be still located at the particle boundaries. Some support for this weak-adhesion theory was provided by an experiment carried out on dispersion 2-based films. This showed that when the films were prebaked at 170\(^0\)C for 30 minutes they became less sensitive, although still remaining more sensitive than solution-based films by a factor of 2. Presumably heating to 170\(^0\)C instead of 130\(^0\)C allowed greater interpenetration of the particles and therefore better adhesion. In the case of solution-cast films the PMMA chains are uniformly entangled throughout the film and therefore not subject to the same development mechanism.
Another advantage offered by dispersions is that for a given PMMA molecular weight and concentration they have much lower viscosities than polymer solutions. During the formation of resist layers the dispersions are therefore generally easier to handle. Problems arising from premature evaporation of solvent and hence poor distribution of resist can be more readily avoided.

The electron beam we used in the investigation was too broad to enable measurements to be made of the limiting line-widths which could be obtained from the systems. In future studies we hope to carry out tests with a finer beam. In general however the resolution patterns produced in the present work from dispersion-based resists had equally good or better definition than those produced from solution-spun resists. In order to obtain the highest possible resolution from the dispersion systems we believe it will be necessary to use colloidal particles with diameters < 1000 Å. Synthetic work is presently underway in our laboratory to produce such systems.

5. ACKNOWLEDGEMENTS

We thank the Science Research Council for providing a research studentship for D.R.C. and for general support of our research programme on polymers. We thank I.C.I. Paints Division, Slough for the supply of dispersion 2.

6. REFERENCES


AZ 1350 AS A NEGATIVE ELECTRON RESIST BY IMAGE REVERSAL

E. Hieke, W.G. Oldham

The use of AZ 1350 photoresist as negative resist using an e-beam exposure for patterning is described. A flood UV exposure is used for image reversal. The resist contrast is 1.3, sensitivity is about 25 μC/cm². Useful resolution is demonstrated to be 0.5 μm.

1. INTRODUCTION

The properties of the present day menu of electron resists have been reviewed by Bowden /1/. Some of the most common negative resists are represented in Fig. 1. While resists with high resolution, high sensitivity, and high etch resistance are reported, these properties are never combined in one resist. It is particularly a problem in negative resists where resolution is limited by swelling as is shown in Fig. 2. Shaw and Hatzakis /2/ have shown that a number of positive photoresists may be used as positive electron resists. They display moderate sensitivity, high resolution, and high etch resistance. We demonstrate here that the AZ 1350 family may be alternatively processed as negative electron resists and as such display equal sensitivity, resolution, and etch resistance. Hiraoka and Gutierrez /3/ showed that AZ 1350J can yield negative e-beam images if the dose exceeds 600 μC/cm² (overexposure). Because of this high dose and the fact that formation of negative resist structures is proximity dependent, this method is unattractive.

There is another mechanism given in the literature: Pacansky and Lyerla /4/ studied the chemistry of the exposure of the AZ 1350 resist family. They showed that water plays a key role on the photo-initiated processes. UV exposure in the presence of water leads to the destruction of photo active compound (PAC) and the production of 3-indene carboxylic acid (Fig. 3). This compound enhances solu-
bilitation of the resin in alkaline developer solutions, resulting in positive resist behavior. If the resist is water free during UV exposure, e.g. as in a vacuum environment, the destruction of the PAC produces an ester and somewhat cross-linked base resin. The dissolution enhancing acid species is absent. Thus a negative resist process is possible in which the PAC is first selectively destroyed in vacuum exposure, and a subsequent flood UV exposure in a wet atmosphere converts the remaining areas into a highly soluble state.

2. EXPERIMENTS, RESULTS AND DISCUSSION

The e-beam process described here differs from the negative photoresist process above only in the use of electronic energy to destroy the PAC in the first patterning exposure. In Fig. 4 the image reversal process is described. On the left the imaging characteristics, on the right the schematic of the developing rate as a function of the absorbed dose within the resist for both positive and negative imaging are given. In these experiments 1.5 µm of AZ 1350 H was spun on the wafers and prebaked at either 65 or 100°C. After e-beam exposure at 20 keV in a Thomson CSF 102 EPG/CNC 330 ES vector scan system (1/8 µm address structure), the wafers were flood UV exposed to an integrated dose exceeding 500 mJ/cm². They were developed in various AZ:H₂O mixtures for 5-30 s; typically the development time was chosen to be about 25% greater than the time for large unexposed areas to clear.

The resist behavior after e-beam exposure is shown in Fig. 5, which plots the normalized remaining thickness against log exposure dose. We observed a threshold sensitivity of 3 to 7 µC/cm², and contrasts in the range 1 to 1.5. Using a 1:2.6 mixture of AZ:H₂O developer, the contrast is 1.0, and 80% of the original thickness remains at an exposure of 20 µm/cm². A higher contrast may be obtained at the expense of either lower sensitivity (1:1 developer) or poorer adhesion during development (65°C prebake).

Typical resist line edges are shown in Fig. 6 for the conditions of 100°C prebake temperature and development in a AZ:H₂O = 1:2.5 mixture. The substrate was a sputtered Al film, and the excellent coverage properties of the resist are evident as one can see by the 1 µm resist line in (b). The resist edge slope is approximately 65° for an exposure dose of 24 µC/cm².

The change in linewidth ΔW relative to the nominally written linewidth is shown in Fig. 7 as a function of dose for three different linewidths. The very large sensitivity to backscattered electrons (intraproximity effect) is evident.
in the nearly 1.0 \( \mu \text{m} \) difference in \( \Delta W \) for 10 \( \mu \text{m} \) and 1 \( \mu \text{m} \) features. Nevertheless it is possible to reproducibly write 0.5 \( \mu \text{m} \) lines by adjustment of exposure and development conditions.

After a 1000\(^\circ\)C post-development bake, the resist is adequate to mask the etching of 0.8 \( \mu \text{m} \) thick Al-Si-Ti films in a CCl\(_4\)-He plasma. Fig. 8 shows the cross-sections of an array of lines after etching (resist not removed). Resolution below 1 \( \mu \text{m} \) is observed. Fig. 9 shows 1.5, 1.0 and 0.5 \( \mu \text{m} \) wide etched Al (Ti, Si) lines after stripping (Fig. 9a). The steep sidewalls of the Al lines indicate an excellent etch resistance of the final resist film (Figs. 9a, b, c).

The authors thank I. Ahlbrink, J. Schmid and W. Beinvogl for performing resist and etching procedures. The work has been supported in part by Joint Services Electronics Program.


Fig. 1 Sensitivity curves for some common negative e-beam resists. $d_0$... original resist thickness, res... resolution; hatched area indicates working area with useful remaining thickness.
Fig. 2 Example of typical Electron Negative Resist after exposure.

Fig. 3 PAC + e-beam exposure results in ester with no increased solubility; PAC + H₂O + light exposure results in acid with increased solubility. The ester does not change under exposure in moist atmosphere and leads to a difference in development rates although its solubility is increased. cf. J. Pacansky, S.R. Lyerla; IBM J. of Res. and Dev. 23, 42 (1979).
Fig. 4 Schematic of image reversal process with AZ 1350J.

Fig. 5 The normalized remaining resist thickness versus log dose for a 1.5 μm AZ 1350 H film developed as a negative resist in an AZ developer: H₂O solution. Sensitivity for developer dilutions and two prebake temperatures are shown.
Fig. 6 Scanning electron (SEM) micrographs of developed resist lines in a resist film of 1.5 μm initial thickness. The substrate is a sputtered Al film on Si. (a) Nominal linewidths of 1.5, 1, 0.5 μm exposed at 28 μC/cm², prebaked at 100°C, and developed in an AZ: H₂O = 1:2.5 solution. (b) Close up of a 1.0 μm line.

Fig. 7 The change in linewidth ΔW with respect to the nominal written linewidth as a function of the exposure dose. The initial resist thickness was 1.5 μm, prebaked at 65°C, and developed in AZ: H₂O at a 1:2.5 dilution. Linewidth control is shown for 3 nominal linewidths.
Fig. 8 Cross-section of three plasma-etched Al lines using the AZ 1350 H resist as etch mask.

Fig. 9 Plasma-etched Al(Ti, Si) pattern with AZ 1350 H mask generated by image reversal.
Plasma-Developed X-ray and Photoresists

Gary N. Taylor* and Thomas M. Wolf*

High resolution, high sensitivity x-ray resists developed by oxygen plasma etching are described and compared to photoresist analogues. Advantages and disadvantages of these materials are summarized.

1. INTRODUCTION

One of the fundamental problems of high resolution lithography using polymeric negative resist materials is the limit to resolution caused by swelling of the polymeric resist during solution development of the exposed pattern.\(^1\) Swelling is a necessary consequence of the development process and can be minimized by a judicious choice of developer and rinsing solvents and conditions.\(^2\) However, resolution is generally limited to about \(1\ \mu m\) in \(0.5\ \mu m\) thick films. Thus, new methods and materials are being sought which minimize or eliminate the distortions introduced by solution development.

One promising approach to the problem posed by swelling was recently reported by Hofer, Kaufmann and Kramer. They described a polymeric material which formed a charge-transfer salt upon X-ray or electron irradiation.\(^3\) Because swelling upon solution development is minimized by the ionic species present, resolution in these resists was approximately \(0.1\ \mu m\) in \(0.5\ \mu m\) thick films.

Herein we report materials and processes for x-ray and photolithography which avoid the use of solutions during the development process. Instead, a combination of post-exposure baking (fixing) and oxygen plasma development are used to develop negative resist images. The materials are mixtures of a host polymer and a moderately volatile monomer which is locked into the host by the impinging radiation. For photolithographic exposures a sensitizer is included in the composition. A similar process has recently been described for photoresist compositions by workers from Motorola.\(^4\) However, no chemical details of their process have been described.

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2. EXPERIMENTAL

2.1. Materials
Poly(vinyl chloride) (Aldrich), polychloroprene) (Dupont) and poly(epichlorohydrin) were used as received. Poly(butene-1 sulfone) was used as a 4% solution from Mead Chemical Co. All chlorinated and brominated acrylates and methacrylates were prepared in-house using techniques analogous to those previously described. Mono­mers were obtained from either Aldrich Chemical Co., Monomer-Polymer Labora­tories, or Polysciences except for 2-(l-naphthyl)ethyl acrylate and methacrylate which were prepared in-house via standard Fisher esterification techniques.

2.2. Procedures
The polymer, monomer and sensitizer needed for photolithographic exposures, were dissolved in a suitable solvent. The solution was used to spin-coat silicon wafers to provide uniform spun films ranging in thickness from 1-3μm. The coated wafers were exposed to radiation and were immediately fixed by heating at 70-100°C for 1 hr in a vacuum oven maintained at 0.1-0.3 torr. Then the resist pattern was developed by treatment with an oxygen plasma generated in either a Dionics, Inc. model 2005T plasma etcher or a planar plasma etcher of in-house design. Operating conditions ranged from 0.4-1.0 torr and 25-100 watts without causing major changes in results. Trilevel processing was conducted as described by Moran and Maydan.

2.3. Equipment
X-ray exposures were conducted using the Pd_{La} exposure system which was previously described. X-ray masks consisted of 6000Å Au and 1000Å of La patterned on either polyimide or boron nitride membranes. Exposures were conducted under a nitrogen atmosphere. Photolithographic exposures were conducted on a Kasper model 2001 contact printer. The mask and wafer were flushed with nitrogen in proximity prior to expo­sure. Additional samples were exposed on a Perkin Elmer Model II1 projection printer with optics modified to permit exposure at 3100Å. UV spectra were measured on a Cary 17 UV-visible spectrometer. Relative film thicknesses were measured on a Nanometrics, Inc. Model 10-0174 Nanospec automatic film thickness guage.

3. RESULTS AND DISCUSSION

The process which we have developed using all dry processes is outlined in Figure 1. In a first exposure step the spun film containing polymer host P and monomer guest m is subjected to radiation which causes locking of monomer m presumably by radiation grafting and polymerization (P-m and m-m bonds, respectively). Fixing by application of a moderate vacuum (0.1 torr) and heat removes unlocked (unreacted) monomer which results in formation of a weak negative relief image (<1500Å) the height of which is dependent upon composition, radiation dose and fixing conditions. Then in a final step negative tone patterns are obtained by treatment with an oxygen plasma which removes the unexposed regions faster than the exposed regions. Tone inversion by use of other plasma conditions (plasma B) can be achieved when the exposed
regions are removed at a higher rate than the unexposed regions.

This process was based on work by Broers and coworkers who demonstrated very fine line formation by electron beam writing with "monomers" present as contaminants in high vacuum systems, the work of Chandross and coworkers who made optical waveguide circuits by photolocking monomers into polymeric hosts, and by the observation that rates of oxygen plasma removal of polymers are dramatically influenced by the molecular structure and constituent atoms of the polymer. Some selected examples are presented in Table 1 for polymers mainly degraded by ionizing radiation and in Table 2 for polymers mainly crosslinked by ionizing radiation.

Experimental realization of the processes outlined in Figure 1 are shown photomicrographically in Figure 2 for an 80:20 mixture by weight of poly(2,3-dichloro-l-propyl acrylate) DCPA and N-vinyl carbazole NVC exposed to 2.5 \((7.25 \text{ mj/cm}^2)\) of \(\text{Pd}_{11}\) \(\text{x-radiation}\). Typical sensitivity curves for the 85:15 mixture of DCPA and NVC are shown in Figure 3 for negative tone patterns only. \(\text{NT}_R\) refers to the normalized thickness of the relief image after fixing and \(\text{NT}_D\) is the normalized thickness of the completely plasma developed image. For each point in the lower curve, resolution of 0.5\( \mu \text{m} \) lines and spaces was achieved. Thus, the etching times for each point are different and increase with increasing dose.

The sensitivity of plasma developed resists is highly dependent on composition and is determined by the monomer locking efficiency measured by \(\text{NT}_R\), and by the differential removal rate of the exposed and unexposed regions in an oxygen plasma. This is called \(\text{RD}\) and is given by

\[
\text{RD} = \frac{\text{NT}_D - \text{NT}_R}{t}
\]

where \(t\) is the plasma etch time.

Selected examples which show the dependence of \(\text{NT}_R\) and \(\text{NT}_D\) on monomer type and amount are summarized in Table 3 for a common \(\text{x-ray absorbing polymer host, poly}(2,3\text{-dichloro-l-propyl acrylate})\). Values of \(\text{NT}_R\) and \(\text{NT}_D\) are given for a single exposure time to minimize complications in the comparisons. In Table 3, data is presented for those monomers expected to be locked by primarily cationic processes (examples 1-5) and for those monomers locked primarily by free radical processes (examples 6-10) single entries are approximately optimum results for that particular example. In each case 1\( \mu \text{m} \) initial thickness films were used. Etch times were 4 ± 1.0 min.

Note that the locking efficiencies judged by exposure time and \(\text{NT}_R\) differ broadly. N-vinyl carbazole is most sensitive. Similar variations are observed for the differential removal rates judged by the \(\text{NT}_D\)-\(\text{NT}_R\) values assembled in the last column of the Table. As expected, the highest differential removal rates are obtained for the largest amounts of locked monomers (see examples 5, 9, and 10). This is observed for each example listed and for many others that have been tested including acryloyl carbazole,
diphenyl acrylamide, 1- and 2-naphthyl acrylate, and trimethylolpropane triacrylate. Nearly every composition containing monomer having aromatic functionality exhibits a substantially higher removal rate in the unexposed region. Optimum results were obtained for N-phenyl maleimide, 2-vinyl naphthalene, and acenaphthalene. Conversely, low differential removal rates were obtained for the difunctional methacrylate esters and for the highly chlorinated acrylic esters. With the exception of hydroquinone dimethacrylate, these results agree with expectations derived from the study of relative rates of polymer film loss in an oxygen plasma by Taylor and Wolf.\textsuperscript{11}

The efficient locking of N-vinyl carbazole makes it the preferred monomer in DCPA host. Sensitivity curves for plasma developed patterns are shown for various compositions in Figure 4. Note that sensitivity increases with composition and that normalized thickness reaches a maximum at high doses which does not increase further with incremental dose. This would be expected if all monomer were locked at high dose. However, only a major fraction is locked. This suggests that some monomer resides in unreactive sites.

Unlike N-vinyl carbazole, 2-(1-naphthylethyl) methacrylate and acrylate are locked with decreasing efficiency at the highest monomer concentrations. This phenomenon appears to be quite general. In Table 3 a similar trend is noted for N-phenyl maleimide. The sensitivity curves shown in Figure 5 for N-phenyl maleimide in DCPA host emphasize this phenomenon. Sensitivity is optimum at 10 wt % monomer. Thus at high concentrations, monomers locked by free radical mechanisms are self inhibiting.

The polymer selected as host also plays a major role in determining sensitivity. One important property is that the host contain atoms with high mass absorption coefficients. In addition when the host is irradiated, species must be produced which efficiently initiate locking of the monomer. Finally, the host polymer must be removed at a rapid rate upon plasma development such that the differential development rate is optimized.

We have studied the influence of host structure and atomic composition only for N-vinyl carbazole monomer. The results for ten polymeric hosts are compiled in Table 4. Approximately optimum values are given for NT\textsubscript{R}, NT\textsubscript{D}, and NT\textsubscript{D}-NT\textsubscript{R} at selected exposure times. With the exception of poly(2,3-dibromo-1-propyl acrylate) the examples are listed in order of increasing sensitivity. Polymers containing mainly chlorine were studied since chlorine has a K absorption edge which is resonant with the 4.37Å Pd\textsubscript{La} radiation. One example each for bromine and sulfur containing polymers also is included.

The first entry for poly(vinyl chloride) is included to indicate the problem of compatibility that is often encountered with the monomer-polymer mixtures. In Table 3 we have also alluded to this by the "monomer crystallized" entries for acenaphthalene, N-vinyl carbazole, and hydroquinone dimethacrylate. For the remainder of the examples in Table 4 we note a greater than 10 fold variation in sensitivity. For the first three
Examples IocIcing is inefficient (low NT_R values for long exposure times). Differential removal rates appear favorable with both poly(butene-1 sulfone) and poly(epichlorohydrin).

Examination of the remaining halogenated acrylic examples in Table 4 reveals the subtle influence of host structure. Differences mainly arise from changes in locking efficiency. The influence of phase is emphasized by a comparison of the poly-methacrylate and acrylate esters of 2,3-dichloro-L-propanol. The glassy methacrylate is approximately four times less sensitive. Differences in differential removal rate are less important except for poly(2,3-dibromo-L-propyl acrylate). In this case the removal rate is greater in the exposed regions thus leading to a partial inversion of the tone. We have not been able to determine the cause of this anomaly.

The last four examples in Table 4 probe the dependence on the type of aliphatic C-Cl bond functionality. From the limited data available, it appears that the ability to stabilize a carbonium ion on the side chain may be the most important factor. Thus, poly(2,3-dichloro-L-propyl acrylate) may be most sensitive because it can form a more stable secondary carbonium ion by heterolytic cleavage of a secondary C-Cl bond. The greater stability of such a species could provide efficient locking of the vinyl carbazole by cationic polymerization. If a free radical mechanism were involved one would have expected poly(2,2,2-trichloroethyl acrylate) to exhibit the most favorable locking efficiency.

From the results described above, we can summarize those properties of the monomer and polymer which are important in optimizing the properties of plasma-developed x-ray resists. The monomer should have moderate volatility so that it neither exudes too rapidly or slowly from the film. It should be capable of being locked by a chain mechanism to realize gain. It should be removed slowly (as polymer) in an oxygen plasma. Finally, it should contain absorbing atoms and have polarity similar to that of the host to insure compatibility.

The polymer host must contain x-ray absorbing atoms and must be removed rapidly in an oxygen plasma in order to optimize the differential removal rate. It also must be capable of providing species upon irradiation which efficiently initiate locking.

3.1. Poly(2,3-dichloro-L-propyl AcrylateN-vinyl Carbazole X-ray Resist Mixtures
In the previous sections we see that highest sensitivity is achieved for mixtures of poly(2,3-dichloro-L-propyl acrylate) and N-vinyl carbazole. We find that an optimum composition contains 81 wt % DCPA and 19 wt % NVC. At monomer concentrations greater than 19 wt % crystallization of monomer occurs for long standing times. A sensitivity curve is given for the 81:19 mixture in Figure 6. An exposure time of 1.5 min affords a normalized final thickness of 0.2. This is normally too thin to be of use in the trilevel processing steps required for fabricating devices. However, as Figure 7 shows the final thickness is linearly dependent on initial thickness. Typically we use an initial
thickness of 1.5μm. This provides us with 2700-3000Å final thickness for a 1.5 min exposure time. This is 4 times faster than the x-ray resist mixture described previously by Moran and Taylor. Some typical scanning electron micrographs of patterns obtained with the DCPA-NVC mixture are shown in Figure 8 where the final resist thickness is 3000Å.

This plasma-developed resist can not be used directly on topographic features. On such features resist patterns in valleys will be underdeveloped when the features are properly developed on plateaus. Thus, multilevel processing schemes are required to planarize topographic surfaces. Consequently, the ultimate resolution test should be made on multilevel processed wafers. In Figure 9 we present the results of such a test. Here we compare three trilevel processed resist patterns consisting of HPR-204, SiO₂, and plasma developed resist layers with the exact mask structure from which they were copied. Careful examination of the micrographs shows that defect structures on the poorly resolved 1.0 and 0.5μm features on the mask are copied with good integrity in the resist patterns. By matching identical features, the resolution limit can be approximated as 0.3μm. Loss of plasma-developed resist during reactive ion etching of the 1200Å intermediate SiO₂ layer was 300Å thus providing sufficient processing latitude for pattern transfer of submicron features.

3.2. Photolithographic Comparison
A comparison of the x-ray reexposure results obtained above with photolithographic results obtained when 2.6 wt % phenanthroquinone sensitizer is added to the 81:19 composition is enlightening. This sensitizer presumably functions by quenching N-vinyl carbazole excited states thereby producing cation radical intermediates which initiate polymerization. Sensitivity curves for contact-printed patterns are compared in Figure 10. Two curves (a) and (b) are observed for ≥2μm features and 1.0μm features, respectively. Both indicate a sensitivity intermediate to presently used negative and positive photoresists.

At high doses, curves a and b diverge. Longer plasma development time is required to resolve the fine features. This leads to severe linewidth losses for larger features. At low doses, all feature sizes ≥1.0μm are resolved. Photomicrographs of some typical patterns are shown in Figure 11. High resolution patterns can only be obtained for normalized thickness <0.25.

We believe these results can be attributed to exposure by diffracted light. Slightly off contact and projection exposures exhibit lower resolution. Conversely, x-ray exposures which are not subject to diffraction at the 1.0μm dimension, do not exhibit variations with feature size even though the print is made in proximity with the mask-wafer separation of 40μm. Resolution of photolithographically printed patterns in this type of plasma-developed resist is therefore inferior to x-ray patterns because of the apparently low MTF of the resist. Further comparisons with electron-beam-written patterns can not be made because the moderately volatile carbazole monomer is lost in the ultra high vacuum of the electron beam exposure system.
3.3. Processing Parameters

In the previous section we have shown that DCPA-NVC plasma-developed x-ray resist has both high resolution and sensitivity. These advantages are supplemented by others which include the independence of radiation locking and plasma development from polymer molecular weight. This is a significant advantage because the sensitivity of most other negative the positive resists is critically dependent on molecular weight. We also indicated the requirement of multilevel processing for these resists. Considering that some form of multilevel processing will probably be required for all very high resolution materials, this does not appear to constitute a disadvantage. The serious disadvantages are encountered mainly in the plasma development step. These disadvantages result from the extremely uniform coating, development and end point control during plasma development that are required to realize submicron features with proper linewidth tolerances. For good linewidth control of submicron features the process must have a final resist thickness uniformity across the wafer of about ±200Å. The barrel and planar plasma etchers described in the experimental section are not capable of providing the required uniformity because of the well known loading affect encountered upon plasma etching in oxygen. Batch processing is also ruled out because of the loading effect. Consequently, new processes are being investigated which should be capable of providing the required uniformity. Foremost among these is oxygen reactive ion etching. Initial results meet the uniformity requirements. However, sensitivity is reduced because differential etch rates are lower under reactive ion etching conditions.

4. CONCLUSIONS

We have described novel materials and processes which provide high speed and high resolution negative x-ray resists sensitive to Pd Lα x-rays. This is accomplished by radiation locking moderately volatile monomers in x-ray absorbing host polymers, fixing by heating in vacuum to remove unlocked monomers, and plasma development in an oxygen plasma. A variety of compositions have been evaluated for sensitivity and resolution. Sensitivity is critically dependent on the structure of the monomer guest and polymer host. Cationically-locked monomers are more sensitive than free-radically-locked monomers. The latter exhibit self inhibition at high monomer concentrations.

The most sensitive material investigated contains 81 parts by weight poly(2,3-dichloro-l-propyl acrylate) and 19 parts by weight N-vinyl carbazole. In a 1.5 min exposure time, 0.3 μm thick patterns with submicron resolution are obtained. The final patterns are sufficiently resistant to conditions for reactive ion etching of SiO2 to permit use in multilevel processing schemes. Comparison of multilevel processed patterns with the exact mask patterns from which they were copied reveals a limiting resolution of about 0.3 μm.

Compositions of the DCPA-NVC resist containing phenantraquinone sensitizer are sensitive to UV radiation. However, diffraction affects limit resolution to about 1.0-1.25 μm in 2500Å final film thickness. Such limitations are not encountered when the material is used as an x-ray resist for which diffraction affects are negligible. This resist finds no application as an electron resist due to rapid monomer loss in the high vacuum
exposure system.

The advantages of this plasma-developed x-ray resist are increased speed, higher resolution, and independence of these properties from molecular parameters of the host. Since wet development is not used, adhesion requirements are reduced. Multilevel processing is required since final resist thickness is low. The major disadvantage with plasma-developed resists is the stringent development uniformity requirements needed to maintain adequate linewidth control at micron and submicron dimensions. Presently used plasma development methods will not meet the uniformity requirements. Initial results suggest that these requirements can be met using oxygen reactive ion etching to develop the final patterns. However, under these conditions some sensitivity is lost because differential removal rates are reduced considerably.

5. ACKNOWLEDGEMENTS

We thank E. A. Chandross, D. Maydan and C. J. Mogab for helpful discussions and M. B. Goldrick for experimental assistance.

References

Figure Captions

Figure 1 - Schematic diagram of plasma-developed resist showing the resist film composed of polymer host P and moderately volatile monomer m. The three processing steps are a) exposure which locks monomer in place by grafting and polymerization b) fixing which removes unlocked monomer from all regions c) plasma development where plasma A is an oxygen plasma. Plasma B will be described elsewhere.

Figure 2 - Photomicrographs of plasma-developed resist patterns in 80 wt % poly(2,3-dichloro-l-propyl acrylate) and 20 wt % N-vinyl carbazole at various processing stages a) immediately after exposure for 2.5 min b) after fixing at 90°C and 0.1 torr for 1 hr c) 2500Å negative-tone image after O₂ plasma treatment of magnified 1 and 2µm lines and spaces d) 6400Å positive-tone image obtained after treatment with plasma B e) corresponding features on the mask.

Figure 3 - Sensitivity curves for 85:15 mixture by weight of poly(2,3-dichloro-l-propyl acrylate) and N-vinyl carbazole. The top curve plots normalized relief image thickness after fixing NTₐ versus log exposure time (dose). The lower curve plots normalized thickness of the plasma-developed image versus exposure time.

Figure 4 - Sensitivity curves for mixtures by weight of poly(2,3-dichloro-l-propyl acrylate) and N-vinyl carbazole.

Figure 5 - Sensitivity curves for mixtures by weight of poly(2,3-dichloro-l-propyl acrylate) and N-phenyl maleimide.

Figure 6 - Sensitivity curves for a mixture by weight of 81 parts poly(2,3-dichloro-l-propyl acrylate) and 19 parts N-vinyl carbazole.

Figure 7 - Plot of plasma-developed resist thickness versus initial film thickness for the resist mixture detailed in Figure 6.

Figure 8 - Plasma-developed resist patterns obtained with 81:19 DCPA-NVC in 3000Å thick resist after exposure for 1.5 min and plasma development. Initial thickness was 1.5µm. Fully-developed patterns are shown in (a), (b), and (c). A 2000Å thick partially developed pattern is shown in (d).

Figure 9 - Comparison of trilevel resist pattern resolution in 2.0µm thick resist obtained from a plasma-developed resist top layer (a)(b)(c) to the exactly corresponding mask patterns in 7000Å thick Au (d)(e)(f). The limit to resolution seen by matching up the sharpest edges in the resist and mask patterns is about 0.3µm.

Figure 10 - Sensitivity curves for exposure of 81:19 DCPA-NVC to which 2.6 wt % phenanthraquinone was added. Curves (a) and (b) are for features
Figure 11 - Photomicrographs of 0.24 μm thick patterns in DCPA-NVC-PQ resist contact exposed for 3 sec a) 1 and 2 μm lines and spaces and 2 μm oblique lines b) 1 and 2 μm windows c) 0.5, 1.0 and 2.0 μm isolated lines d) 0.5, 1.0, and 2.0 μm isolated gaps.

Table 1

<table>
<thead>
<tr>
<th>Polymer</th>
<th>k_rel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly(α-methylstyrene)</td>
<td>1.11</td>
</tr>
<tr>
<td>Poly(methyl methacrylate)</td>
<td>2.37</td>
</tr>
<tr>
<td>Poly(isobutylene)</td>
<td>3.56</td>
</tr>
<tr>
<td>Poly(butene-1 sulfone)</td>
<td>7.11</td>
</tr>
</tbody>
</table>

a. Relative to poly(styrene) having a removal rate of 270 Å/min.
Table 2
Relative Rates of Oxygen Plasma Removal for Selected Polymers Crosslinked by High Energy Radiation

<table>
<thead>
<tr>
<th>Polymer</th>
<th>$k_{rel}$</th>
</tr>
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<tr>
<td>Poly(N-vinylcarbazole)</td>
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</tr>
<tr>
<td>Poly(acenaphthalene)</td>
<td>0.63</td>
</tr>
<tr>
<td>Poly(vinylidene fluoride)</td>
<td>0.83</td>
</tr>
<tr>
<td>Cyclized cis-poly(isoprene)</td>
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<tr>
<td>Poly(4-vinylpyridine)</td>
<td>1.70</td>
</tr>
<tr>
<td>Poly(4-bromostyrene)</td>
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</tr>
<tr>
<td>Poly(4-chlorostyrene)</td>
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</tr>
<tr>
<td>Poly(2,3-dibromo-1-propyl acrylate)</td>
<td>3.04</td>
</tr>
<tr>
<td>Poly(vinyl acetate)</td>
<td>5.46</td>
</tr>
<tr>
<td>Poly(2,3-dichloro-1-propyl acrylate)</td>
<td>12.22</td>
</tr>
<tr>
<td>Poly(vinyl chloride)</td>
<td>12.96</td>
</tr>
<tr>
<td>Poly(vinyl bromide)</td>
<td>13.70</td>
</tr>
<tr>
<td>Poly(epichlorohydrin)</td>
<td>21.50</td>
</tr>
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</table>
Table 3
Properties of Poly(2,3-dichloro-1-propyl Acrylate) — Monomer Mixtures

<table>
<thead>
<tr>
<th>Monomer</th>
<th>State</th>
<th>Wt % Monomer</th>
<th>Exposure Time (min)</th>
<th>NT&lt;sub&gt;R&lt;/sub&gt;</th>
<th>NT&lt;sub&gt;D&lt;/sub&gt;</th>
<th>NT&lt;sub&gt;D&lt;/sub&gt;—NT&lt;sub&gt;R&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 9-Vinylanthracene</td>
<td>s</td>
<td>15</td>
<td>2.5</td>
<td>trace</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>2. N-Vinyl Phthalimide</td>
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<td>2.5</td>
<td>0.05</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>3. Acenaphthalene</td>
<td>s</td>
<td>20</td>
<td>2.5</td>
<td>0.04</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td>Monomer Crystalized</td>
</tr>
<tr>
<td>4. 2-Vinylphenanthrene</td>
<td>l</td>
<td>15</td>
<td>2.5</td>
<td>0.05</td>
<td>0.17</td>
<td>0.12</td>
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<tr>
<td>5. N-Vinyl Carbazole</td>
<td>s</td>
<td>5</td>
<td>1.0</td>
<td>0.03</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>1.0</td>
<td>0.04</td>
<td>0.11</td>
<td>0.07</td>
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<td></td>
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<td>1.0</td>
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<td>1.0</td>
<td>0.07</td>
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<td>0.11</td>
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<tr>
<td></td>
<td></td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td>Monomer Crystalized</td>
</tr>
<tr>
<td>6. Ethylene Glycol Dimethacrylate</td>
<td>l</td>
<td>20</td>
<td>2.5</td>
<td>0.04</td>
<td>0.04</td>
<td>0.0</td>
</tr>
<tr>
<td>7. Hydroquinone</td>
<td>s</td>
<td>12.5</td>
<td>2.5</td>
<td></td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td>Monomer Crystalized</td>
</tr>
<tr>
<td>8. Pentachlorophenyl Methacrylate and Acrylate</td>
<td>s</td>
<td>25</td>
<td>2.5</td>
<td>0.10</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>9. 2-(l-naphthyl)-ethyl Methacrylate and Acrylate</td>
<td>l</td>
<td>10</td>
<td>2.5</td>
<td>0.05</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>2.5</td>
<td>0.02</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>2.5</td>
<td>trace</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>10. N-phenyl Maleimide</td>
<td>s</td>
<td>5</td>
<td>2.5</td>
<td>0.02</td>
<td>0.12</td>
<td>0.10</td>
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<td>10</td>
<td>2.5</td>
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<td>0.02</td>
<td>0.15</td>
<td>0.13</td>
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<td></td>
<td></td>
<td>30</td>
<td>2.5</td>
<td>trace</td>
<td>0.10</td>
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Table 4
Influence of Polymer Host on the Properties of Plasma Developed Negative X-ray Resist Containing N-Vinyl Carbazole Monomer

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Phase</th>
<th>Relative Plasma Removal Rate</th>
<th>wt% Monomer</th>
<th>Exposure Time (min)</th>
<th>NT_R</th>
<th>NT_D</th>
<th>NT_D−NT_R</th>
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</thead>
<tbody>
<tr>
<td>Poly(vinyl chloride)</td>
<td>G</td>
<td>12.96</td>
<td>20</td>
<td>Incompatible</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly(chloroprene)</td>
<td>R</td>
<td>13.33</td>
<td>20</td>
<td>9</td>
<td>.01</td>
<td>.02</td>
<td>.01</td>
</tr>
<tr>
<td>Poly(butene-1 sulfone)</td>
<td>G</td>
<td>7.11</td>
<td>25</td>
<td>9</td>
<td>.02</td>
<td>.07</td>
<td>.05</td>
</tr>
<tr>
<td>Poly(epichlorohydrin)</td>
<td>R</td>
<td>21.50</td>
<td>20</td>
<td>9</td>
<td>.04</td>
<td>.12</td>
<td>.08</td>
</tr>
<tr>
<td>Poly(2,3-dibromo-1-propyl acrylate)</td>
<td>R</td>
<td>3.04</td>
<td>20</td>
<td>9</td>
<td>.12</td>
<td>.04</td>
<td>-.08</td>
</tr>
<tr>
<td>Poly(2,3-dichloro-1-propyl methacrylate)</td>
<td>G</td>
<td>12.96</td>
<td>20</td>
<td>4</td>
<td>.06</td>
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<td>.07</td>
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<td>Poly(2-chloroethyl acrylate)</td>
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<td>.16</td>
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<td>R</td>
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<td>20</td>
<td>1.0</td>
<td>.07</td>
<td>.18</td>
<td>.11</td>
</tr>
</tbody>
</table>

a.  G = glass and R = rubber.

b. Relative to the removal rate for poly(styrene) in an oxygen plasma (270Å/min) at 35°C.
Figure 1
Figure 2
SLOPE = 0.18

Figure 7
Figure 9
Figure 10
Figure 11
PLASMA DEVELOPMENT PROCESS FOR THE SUBMICRON RESIST IMAGE


Negative resist materials are newly formulated for the plasma development process for the submicron resist image. The properties of the resists and the submicron dry etching process on the 3 inches wafer by the resist was presented in details.

1. INTRODUCTION—The Importance of the Dry Development Process of the Resist Image in the Submicron Lithography

In all the lithographic processes, i.e. the photo-, the electron beam-, the X-rays-, the Deep UV- and the ion beam-lithography, the resist images are produced by the wet development process, where an exposed resist coating is immersed in the developer solvent, and the resist images are developed by the dissolution of the exposed (in the case of positive resists) or unexposed (in the case of negative resists) area by the solvent developer.

As is well known, the negative resist is highly sensitive but is not suitable for making fine patterns, and the positive resist gives fine patterns readily but is unsatisfactory in its sensitivity. Since the highly intense sources of electron beam, X-rays, and Deep UV light have not yet been obtained, highly sensitive and fine pattern giving resists are expected as the key materials in the submicron lithography.

Then, what is the origin of the antinomy between the sensitivity and the resolution of resist materials? How can we explain the phenomena that the negative resist is highly sensitive but gives a low resolution and the positive resist, vice versa? The negative resist is crosslinked by the exposure of light or electron beam and becomes developable, provided that only one crosslink is formed for one polymer chain.[1]

Therefore, there is no difference on the affinity for the developer solvent between the exposed and unexposed area of the resist coating. When the unexposed area absorbs much solvent and is dissolved, the exposed (crosslinked) area also absorbs much solvent and swells. This phenomenon is confirmed by the microscope picture. (Fig.1)

On the other hand, the positive resist is easily soluble in its solvents because it is a linear polymer. So, the developer solvent of a positive resist should be a non-solvent of the polymer. The fact means that no swelling occurs during the development process of a positive resist coating. Therefore, in the case of a positive resist the degradation of the polymers or the sensitive materials must proceeds enough in the exposed area that a non-solvent for the unexposed area can acts as a developer. This requisite means that much dose of light
Fig. 1. Photoresist Images in the Wet Development Process (Window Pictures)
(a) Immediately after Development
(b) Half dried
(c) After Rinsing

Fig. 2. Photoresist Images in the Wet Development Process (Island Pictures)
(a) Immediately after Development
(b) Half dried
(c) After Rinsing
or electron beams is required for a positive resist coating in order to become developable. So, we must evaluate that the positive resist is low sensitive although the real sensitivity, a quantum yield, of a positive resist is comparable to that of a negative resist.

These few years we have investigated the Deep UV lithography in order to perform the submicron pattern fabrications. The submicron pattern is easily obtained by the Deep UV lithography when we use a positive resist, a sensitized PMIPK, which was newly formulated by our research group.[2] However, when we use a negative resist, which have also been newly formulated by our research group, it is very difficult to obtain the submicron pattern, especially in the cases of window patterns(Figs. 3 and 4). As will be discussed later, it is clear that the nature of the low resolution of the negative resist arises from the swelling in the wet development process. Therefore, we must overcome the swelling phenomena in the development process if we hope to utilize the highly sensitive negative resist for obtaining the submicron image. This is the importance of the dry development process of the resist image in the submicron microfabrication technology.

2. Swelling Phenomena in the Wet Development Process

2.1 Photoresist
The picture of Fig. 1(a) shows a case of a usual negative photoresist comprised of an aromatic azide and a cyclized rubber. Immediately after the development, the windows of the resist picture of lines and spaces are completely closed even in the case of 5 \( \mu m \) width. The 0.5 \( \mu m \) pattern is lost completely in this picture. Following the vaporization of the developer from the resist, the windows of the resist picture gradually open as shown in Fig. 1(b). After rinsing, the normal window picture is obtained. However, the windows are not open in the cases of those narrower than 2 \( \mu m \)(Fig. 1(c)). This picture is consistent with the common-sense that the 2 \( \mu m \) width is the limit of the photolithography.

In the case of the island picture the situation seems to be improved. Fig. 2(a) is the island picture immediately after the development. Fig. 2(b) is the island picture half dried. Fig. 2(c) is the island picture after rinsing. This picture shows, however, the situations is not improved. The island are isolated only in the cases of those wider than 2 \( \mu m \). The fine patterns narrower than 1.5 \( \mu m \) are not isolated. Here, we have to consent the limit of 2 \( \mu m \) in the photolithography.

2.2 Deep UV Resist
The picture of Fig. 3(a) shows a case of a negative Deep UV resist. Immediately after the development, the windows of the resist picture of lines and spaces are completely closed even in the case of 5 \( \mu m \) width. Fig. 3(b) is the picture after rinsing. These pictures show that 0.5 \( \mu m \) pattern is completely lost and the useful patterns are those wider than 1.5 \( \mu m \). Figs. 4(a) and 4(b) show the case of the island patterns. Although 0.5 \( \mu m \) pattern was obtained in this case,
Fig. 3. Deep UV Resist Images in the Wet Development Process (Window Pictures)
(a) Immediately after Development
(b) After Rinsing

Fig. 4. Deep UV Resist Images in the Wet Development Process (Island Pictures)
(a) Immediately after Development
(b) After Rinsing
the practical usefulness will be in those patterns wider than 1.5 μm. Fig. 4(a) is immediately after development and Fig. 4(b) is that after rinsing.

From the foregoing discussions, we must conclude that the submicron fabrication is impossible when we use the negative resist, even in the case of the Deep UV lithography.

3. Negative Resists for the Dry Development Process

There are many patent literatures on the dry development of the resist image[3]. However, in some cases the resist compositions are obscure and we cannot trace them, and in other cases where the ordinary resist materials were used, the experimental results are not realistic. Therefore, we have investigated new resist materials and succeeded in the formulations of the plasma developable negative resists for the photolithography, the Deep UV lithography and the electron beams and X-rays lithography, respectively, where the line narrower than 0.3 μm wide by the electron beam lithography and the line of 0.5 μm wide by the Deep UV lithography were easily obtained. In this paper, we shall focus on the Deep UV lithography.

3.1 Experimental procedure

Resist was coated on the 3-inches wafer by the spin coating machine (20 sec) and dried in the heat chamber with warm blow for 30 min at 60°C. The resist thickness is 1 μm. The Deep UV pattern transfer was carried out by the PLA-520F aligner, a product of Canon(Exposure:10sec) and the electron beam patterning by the HHS-2R, a product of Hitachi, respectively. Post baking was made at 140°C for 30min. Dry development was carried out in the plasma etching machine, OAPM-301B, a product of Tokyo Ohka, by the oxygen gas plasma, where the chamber was pumped up to 0.1 Torr in 5 sec, the gas was changed in 5 sec, the RF power (100W) was on for 3 min at 100°C (Table Temperature) at 1.0 Torr of the gas pressure and the pumpdown and the backfill were carried out in 5 sec. The time for the RF power on was varied, as shown later, depending upon the RF power, the table temperature, the gas pressure, etc. The fine pattern resist images were obtained uniformly over the 3-inches SiO2 or Si wafer surface.

The dry etching of Si was performed by CF4-O2 plasma for 3 min at 100°C (Table temperature) for the etching depth of 3500 Å, succeeding the dry development by the replacement of the etching gas only. The wet etching of SiO2 was performed in NH4F (85%) and HF (15%) etching solutions for 5 min at 23°C for the etching depth of 6700 Å. In the case of the wet etching, an application of the pre-etch bake is preferrable at 170°C for 5 min in order to avoid the creeping of the etching solution under the resist coating. After the etching, the resist images were removed by the plasma resist ashing. This process was successively carried out in the case of the dry etching by the replacement of the reacting gas only. Therefore, the complete dry microfabrication process was performed in the case of Si, as shown in Fig. 5.
ALL DRY MICROFABRICATION PROCESS (IN THE CASE OF Si)

1. Si
2. Resist Coating
3. Exposure with Photon or Electron Beam
4. Development with O₂ Plasma
5. Etching with C₆F₆ Plasma or Ion Beam
6. Ashing with O₂ Plasma

Fig. 5. The Complete Dry Microfabrication Process in the Case of Si

Fig. 6. The Table Temperature Dependence of the Etching Ratio of the Unexposed and the Exposed Area of the Resist Coating and the Resist Thickness of the Resist Image after the Complete Development.
4. The Properties of the Resist Formulated for the Dry Development Process

4.1 Etching ratio of the resist coating

The etching rates of the resist materials depend upon the table temperature of the plasma apparatus, the gas pressure in the plasma chamber and the RF power applied to the plasma atmosphere, respectively. Usually, the etching rates were enhanced following the elevation of the table temperature, the decrease of the gas pressure and the increase of the RF power. However, in the dry development process, our interests are focused on the etching ratio between the exposed area and the unexposed area of the resist coating. The absolute etching rate concerns the development time only.

The change of the etching ratio between the unexposed and the exposed area of the plasma development resist for the Deep UV lithography was shown in Fig. 6 following the elevation of the table temperature of the plasma apparatus. The change of the resist thickness of the resist image after the complete plasma development performed was also shown. There is a little difference between the peaks of these two curves. From this result, the best temperature was selected to be 80°C-100°C.

Fig. 7 is the gas pressure dependence of the etching ratio and the resist thickness of the resist images after the complete dry development. We chose 1.0-1.5 Torr of the reactive gas pressure for the best condition. The RF power dependence of the etching ratio and the resist thickness of the resist images after the complete dry development were shown in Fig. 8. The best RF power will be 75-125 W.

4.2 Characteristic curves for the Deep UV exposure

The characteristic curves depend upon the conditions of the plasma development. From the results of Fig. 6-Fig. 8, we have decided the standard experimental conditions as already shown in the part of the experimental procedure. Under the standard procedure, the characteristic curves were obtained in the various RF power atmosphere. (Fig. 9) It is clear that the characteristic curves are substantially the same between 75-125 W, which is in accordance with the results of Fig. 8. The similar experiments were carried out under the variation of the reactive gas pressures. (Fig. 10) Although there is a little fluctuation, the ideal curves are obtained in the cases of 0.8, 1.0 and 1.5 Torr, respectively. This result is very similar to those of Fig. 7.

5. Resist, Si and SiO₂ Images Obtained by the Dry Development Process

5.1 The resist images

Fig. 11(a) is the window patterns of the resist images obtained by the plasma development. We should compare this patterns with those of Fig. 1(c) and Fig. 3(b). The advantage of the dry development is clear. Fig. 12(a) is the island patterns. The effectiveness of the plasma development is also reconfirmed when we compare this picture with Fig. 2(c) and Fig. 4(b).
Fig. 7. The Gas Pressure Dependence of the Etching Ratio and the Resist Thickness of the Resist Image after the Complete Development.

Fig. 8. The RF Power Dependence of the Etching Ratio and the Resist Thickness of the Resist Image after the Complete Development.
Fig. 9. The Characteristic Curves obtained by the Plasma Development under the Various RF Power Atmospheres.

Fig. 10. Characteristic Curves obtained by the Dry Development under the Various Gas Pressures.
5.2 Si images
The resist images formed on the Si wafer were etched by the CF$_4$-O$_2$ plasma. The results were shown in Fig. 11(b) and Fig. 12(b). The complete dry micorfabrication process were performed in this case, which is shown in Fig. 5.

5.3 SiO$_2$ images
The resist images formed in the SiO$_2$-Si wafer were etched by the NH$_4$F-HF aqueous solutions. The results were shown in Fig. 11(c) and Fig. 12(c). The side etch was observed in this case, especially in the island patterns. This result comes from the uniform etching usually observed in the cases of the chemical etching and is not specific for the resist images obtained by the dry development.

REFERENCES

Fig. 11. Resist, Si and SiO₂ Images obtained by the Dry Development Process (Window Patterns)
(a) Resist Image: O₂ 100% Pressure 1.2 Torr; RF Power 100W; Table Temperature 100°C.
(b) Si Image: CF₄:O₂=95:5 Pressure 0.3 Torr; RF Power 200W; Table Temp. 100°C; 3 min etch, depth 3500 Å.
(c) SiO₂ Image; NH₄F:HF=6:1; 23°C/5 min etch depth 6700 Å.

Fig. 12. Resist, Si and SiO₂ Images obtained by the Dry Development Process (Island Patterns)
(a) Resist Image
(b) Si Image
(c) SiO₂ Image
The experimental conditions of (a), (b) and (c) are the same as those of Figs. 11(a), (b) and (c), respectively.
SINGLE STEP OPTICAL LIFT-OFF PROCESS

M. Hatzakis, B. Canavello and J. M. Shaw*

Abstract: *A process is described which allows the use of the lift-off metallization technique with uv exposure of a single layer of AZ type photo resist. The process consists of soaking the AZ resist layer in chlorobenzene or other aromatic solvents before or after exposure for a pre-determined time. After development, resist profiles with overhang are obtained suitable for lift-off metallization.*

Introduction

Optical lithography is still used as the main tool in microcircuit fabrication and it is very likely that it will continue to be used for at least the next ten years even though the minimum linewidth that can be reproduced reliably is about two micrometers. Even at this line width metallic conductor patterns with metal thickness of about one micron can not be produced reliably by conventional wet etching techniques.

Although reactive ion etching (RIE) methods may prove useful, additional process development is required before such methods can be introduced in the manufacturing environment.

An additive metallization technique, known as the "lift-off" technique (1), was developed with the advent of electron beam lithography in the late 1960's which allows metallization after resist exposure and development. This technique utilizes the fact that electron scattering in the resist and backscattering from the substrate creates a pear-shaped energy absorption profile in the resist, which results in an undercut profile after resist development. With this undercut in the resist image, metal can be evaporated over the entire surface and a discontinuity maintained between the metal on the substrate and the metal over the resist, as illustrated in Fig. 1. During resist removal in a suitable solvent the metal over the resist is also removed and a clean and faithful reproduction of the image is obtained in metal. This technique has been used with PMMA electron resist in IBM and many other companies for the fabrication of devices and circuits with minimum dimensions down to 700 Å.(2,3,4,5)

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An additional advantage of the lift-off technique is that multilevel metal structures can be formed. In fact any material or combination of materials that can be evaporated, can be used.

**Application of the lift-off process to optical lithography**

One of the main reasons for the success of the lift-off process in electron beam lithography is the fact that the energy absorption in the resist film during exposure is not linear but reaches a maximum at about two-thirds of the beam penetration range.\(^{(6,7)}\) This ensures that, with proper exposure and development undercut resist profiles can be easily obtained.\(^{(8)}\)

In optical (UV) exposure of photoresists, however, energy absorption is highest at the top of the resist film and lowest at the interface between resist and substrate due to the uv light attenuation in the resist. In addition, standing wave effects created by the light reflected off the substrate further complicate the situation as it was shown by Dill et. al.\(^{(9)}\) These exposure conditions make it impossible to obtain undercut or even vertical resist profiles with normal uv exposure of AZ\(^{(10)}\) type positive photoresists.

A technique, that has been used successfully in electron beam lithography to increase resist sensitivity while maintaining the undercut feature of the developed resist, consists of coating two or more resist layers with widely different solubilities. After electron beam exposure, a developer is chosen that develops the top layer at least ten times slower than the bottom layer. Alternatively two mutually exclusive developers can be used for the successive development of the two layers\(^{(11)}\). Both of these approaches result in resist profiles suitable for lift-off metallization. With optical AZ type resists, however, it is difficult to spin-coat two distinct layers without excessive mixing at the interface, due to the low prebake temperatures allowed for these resists between coatings. Electron resists such as poly-methyl-methacrylate (PMMA) can be baked at up to 170°C without deterioration, while AZ resists should not be baked above 90°C. At this low temperature the resist film retains a large amount of solvent and can therefore be easily redissolved by the application of the second layer.

Work in IBM Research has concentrated on methods of obtaining undercut profiles with a single layer of uv exposed AZ photoresist by surface modification before or after exposure. This work has lead to the development of the chlorobenzene soak process with AZ1350J photoresist.

The basic process consists of coating wafers with AZ1350J photoresist, at a thickness of at least one and one-half times higher than the required metal thickness, prebaking at 70-80°C for 15 minutes exposing the required pattern then soaking in chlorobenzene for 5-15 minutes and developing in a mixture of one part AZ1350 developer to one part water. An alternative of this process is to soak in chlorobenzene before
exposure to uv, and this alternative was also tried initially with equal success although it required a longer soaking time.

**Experimental**

In order to fully characterize the process, and determine the sensitivity to variations of such parameters as prebake temperature and time, soaking time, exposure density, developer concentration, e.t.c., tests were run on silicon wafers using Shipley-1350J photoresist.

The effect of soaking time in chlorobenzene to the modified AZ layer thickness was measured by coating silicon wafers with photoresist to a thickness of 1-2 microns, prebaking at a certain temperature and time and exposing a pattern in a contact printing system through a chrome mask. After exposure the wafers were soaked in chlorobenzene for various time periods, developed for a fixed time, and prepared for SEM observation. The thickness of the modified layer (overhang) was measured in the SEM for every sample at the point where it joins the profile of the main resist layer.

Figure 2 shows the modified layer thickness for Shipley-1350J prebaked at 70°C for 15 minutes and developed in 1:1 AZ1350J developer, versus chlorobenzene soaking time. Note that the resist modification rate is almost linear with time with an approximate value of 800 Å/minute. The modification rate was also verified in the Film Thickness Analyzer (FTA) which measures resist thickness as a function of time in the developer.

Figure 3 shows solubility curves obtained in the FTA for the same resist and conditions as in Figure 2. The first curve on the left of figure 3 shows the unsoaked resist development characteristics, the second curve is for a five minute soak in chlorobenzene and the third for a ten minute soak. These curves indicate that the development rate of the modified layer, even in the exposed regions of the resist, proceeds very slowly until the interface between that and the unmodified layer of resist is reached. At this point development proceeds at the normal rate of the non-soaked resist.

Figure 4 shows SEM and optical photos of metallized structures before and after lift-off using the process with a 5 minute soak in chlorobenzene. Figure 5 shows the effect of exposure dosages on the profile shape of Shipley-1350J soaked in chlorobenzene for 5 minutes after exposure of the pattern. Note that at higher exposures the main resist profiles (bottom layer) become more vertical while the overhang is not affected.

Figure 6 shows the process employed in the lift-off of a one micron thick aluminum metal with a 1.5 micron thick resist including the overhang layer.
Other solvents tried initially with Shipley-1350J and AZ developer include the following with the indicated results: (5 minute soak)

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trichloroethylene</td>
<td>no effect on profile</td>
</tr>
<tr>
<td>Benzene</td>
<td>straight edges, no overhang</td>
</tr>
<tr>
<td>Toluene</td>
<td>very small overhang</td>
</tr>
<tr>
<td>Methyl-cyclohexane</td>
<td>no effect</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>no effect</td>
</tr>
<tr>
<td>Chloroform</td>
<td>no development possible</td>
</tr>
<tr>
<td>Cyclohexanone</td>
<td>dissolves resist</td>
</tr>
<tr>
<td>Ethyl-Acetate</td>
<td>dissolves resist</td>
</tr>
<tr>
<td>Kerosene</td>
<td>no effect</td>
</tr>
</tbody>
</table>

Of these solvents only toluene and benzene showed some effect although not in any case approaching that obtained with chlorobenzene.

Soaking in chlorobenzene before uv exposure was also tried with Shipley-1350J and 1:1 AZ developer. The results showed that good overhang can be obtained, although the soaking time has to be doubled for the same overhang thickness as obtained by soaking after exposure.

The chlorobenzene soak or Single Level Optical Lift-off process has been practiced in Yorktown with Shipley-1350J and a contact printing exposure system as well as a Perkin-Elmer 100 series Micralign, and good repeatability has been obtained with both exposure systems.

The process can also be used to enhance the contrast of an optical exposure system by taking advantage of the non-linear response of the chlorobenzene soaked photoresist, and thus obtain high resolution, high aspect ratio resist patterns with ordinary contact printing equipment. Figure 7 shows SEM profiles of 1.5 micron lines and spaces developed in 3.5 micron thick AZ 1350J resist, chlorobenzene soaked and exposed in a contact printing system. Aluminum, 1.5 micron thick has been evaporated over the resist to illustrate the high aspect ratio of metal lines that can be obtained with the process.

Further Investigation of the Surface Modification Process

The fact that the thickness of the modified AZ layer, after soaking in chlorobenzene or other aromatic solvents, depends on the soaking time tends to indicate that the process is controlled by the diffusion rate of the solvent in the AZ layer. This hypothesis is also supported by the fact that the modified layer thickness depends on the resist prebake conditions for at higher prebake temperatures the resist molecules are more tightly packed and the solvent diffusion rate is reduced. Figure 8 shows the modified resist layer thickness (overhang) as a function of soaking time for three resist prebak-
ing temperatures. Note that at 66°C prebake for 30 minutes the diffusion rate is three times higher than the 80°C bake for any soaking period. Figure 9-a shows the overhang thickness as a function of prebake time at a constant temperature of 75°C and constant soak time of 17 minutes. Figure 9-b shows the same thickness as a function of prebake temperature with a constant soak time of 17 minutes in chlorobenzene. All these curves demonstrate the linear dependence of the modified resist layer thickness to soaking time, prebake temperature of the resist and baking time. The very strong dependence on prebake temperature is illustrated by the steep slope of the curve on figure 9-b.

In order to test the chlorobenzene diffusion theory further, the assumption was made that if similar solvents to chlorobenzene are used but with smaller and larger molecule sizes than chlorobenzene, the diffusion rate should be higher with the smaller size solvent. A test was run to this end with two other solvents, fluorobenzene and bromobenzene. The results are seen in the SEM photos of figure 10 together with toluene and kerosene. Surprisingly it can be seen that the opposite is true, that is that bromobenzene with the largest size molecule produces a thicker overhang that fluorobenzene with the smallest molecules. Also toluene for AZ1350J and 1:1 AZ developer produces similar overhang to fluorobenzene. Figure 11 shows SEM photos of toluene soaked AZ1350J for 10 minutes, developed in 1:1 solution of AZ developer at resist prebake temperature varying from 65°C to 100°C for 10 minutes. As it can be seen from these photos, the length and thickness of the overhang is decreased as the prebake temperature increases. These results are consistent with chlorobenzene soaking except for the fact that longer soaking time is required to produce the same overhang thickness with toluene.

Additional efforts to explain the phenomenon were undertaken by studying the two AZ resist components, PAC and Alnoval resin separately. Infrared spectra of the two components were obtained separately before and after soaking in chlorobenzene for up to 16 hours. No detectable differences were observed in any case, except for some residual chlorobenzene. Also no significant shift or intensity change in the OH absorption in either the PAC or the resin could be detected due to possible H⁺ bonding of the resist components and the chlorobenzene.

In order to test the effects of soaking on the AZ resin without the PAC, solutions of both 429K Alnoval resin and Varcum resin were prepared in both AZ thinner and diglyme. These polymeric solutions were coated on silicon wafers and developed using AZ 1:1 developer solutions in the FTA. Another group of wafers were soaked prior to development in toluene for 15 minutes then developed in the FTA. The normal development time for the unsoaked Alnoval resin in both AZ thinner and diglyme was approximately 120 seconds for a 7000 Å thick film. When soaked in toluene there was no thickness loss during development for 7 minutes, then the film lifted off the surface of the wafer due to poor adhesion. The normal development time of the Varcum resin was slightly faster (~75 seconds). The toluene soaked samples showed
no thickness loss for 3.5 minutes of development, or half of the time required for AZ resin. These results indicate that the resin may be at least partly responsible for the effects of soaking with AZ resists in chlorobenzene or other aromatic solvents.

**Conclusions**

A new process has been proposed and tested which makes it possible to obtain undercut profiles suitable for lift-off metallization with uv exposure systems and AZ type photoresists.

The process has been tested with Shipley 1350J photoresist and chlorobenzene soaking followed by development in 1:1 AZ developer.

Process variations include the use of toluene as the substitute for chlorobenzene, and soaking in chlorobenzene before uv exposure.

Efforts are continued to explain and understand the mechanism of the process. These include the use of mass spectrometry on chlorobenzene soaked AZ samples and the use of radioactive tracers. Studies conducted so far indicate that the chlorobenzene removes residual solvent and low molecular weight resin from the modified layer thereby reducing the solubility of the layer in the developing solution.
References


10. "AZ" is a registered trademark of the Azoplate Division of American Hoechst Corp., Somerville, N. J. 08876; the material was supplied by Shipley Co., Newton, MA.


Fig. 1 Illustration of the lift-off process.

Fig. 2 Surface modification rate of AZ-1350J photoresist in chlorobenzene.
Fig. 3  Development rates of AZ-1350J obtained in the Film Thickness Analyzer (FTA).

1. No Soaking
2. Five minute soak in chlorobenzene
3. Ten minute soak in chlorobenzene

Fig. 4  Shipley 1350-J photoresist, 1.5 microns thick, baked at 70°C for 15 minutes, exposed in a contact printer for one minute, soaked in chlorobenzene for five minutes and developed in 1:1 solution of 1350 developer:water. 5000 Å aluminum evaporated.
Fig. 5  Shipley 1350J photoresist profiles at exposures of 0.5, 1 and 2 minutes with constant soak and development times.

Fig. 6  Lift-off of one micron thick aluminum metallurgy with optically exposed AZ-1350J soaked in chlorobenzene for 5 minutes, prior to development.
Fig. 7 Profiles of 3.5 micron thick AZ 1350-J resist chlorobenzene soaked, exposed in a contact printing system and developed in 1:1 AZ developer solution. Shown after evaporation of 1.5 micron thick aluminum, prior to lift-off.

Fig. 8 Modified resist layer thickness as a function of chlorobenzene soaking time for three resist prebake temperatures.
Fig. 9-a  Overhang thickness as a function of resist prebake time at 75°C.

Fig. 9-b  Overhang thickness as a function of resist prebake temperature and constant baking time of 30 minutes.
Fig. 10  Profiles of Shipley 1350-J photoresist soaked in various aromatic solvents for 10 minutes and developed in 1:1 solution of AZ developer in water.
Fig. 11 Profiles of Shipley 1350-J photoresist prebaked at various temperatures for 10 minutes, soaked in Toluene for 10 minutes and developed in 1:1 AZ developer solution.
SYNCHROTRON X-RAY LITHOGRAPHY
EXPOSURE AND DEVELOPMENT MODELS

E. Rammos, V. Chalmet

1. INTRODUCTION

As the density of integration of I.C.s increases continuously, several lithographic methods are investigated in order to obtain submicron geometries. Among these, X-ray lithography seems one of the most attractive for very fine patterns (ref. [1]). For the development of this method, the source problem is one of the most difficult to solve. The synchrotron radiation, whose emission is very intense in the soft X-ray range, is one of the possible solutions because of its high intensity and collimation (ref. [2]). We choose it as a research tool and we use the radiation of the ACO storage ring in Orsay (cf ref. [3]).

Since the spectrum and the intensity of the radiation vary with the elevation angle (angle of the emission with the orbital plane), the total absorbed energy density in the resist layer depends on the position on the sample (and on the depth in the resist). After development, only a given zone of the resist is completely developed as indicated on figure 1. The width of this zone depends on the exposure and development parameters. To forecast and to explain the results of this phenomenon, an exposure and a development computer models have been built up.

2. EXPOSURE MODEL

The aim of this model is to compute the incident, absorbed and transmitted energies at every point of a lithographic system. As regards the source, we have computed the Synchrotron Radiation flux \( P(\Psi, \lambda) \) by the classical formula (cf ref. [4]):

\[
P(\Psi, \lambda) = \frac{8\pi^2 e^2 \gamma}{2\pi m^3 R^5} \left( \frac{\lambda c}{\lambda} \right)^4 \beta^8 \left[ 1 + \left( \frac{\beta \Psi}{\lambda} \right)^2 \right]^2 \left[ K_{1/2}(\gamma) - \frac{(\beta \Psi)^2}{1 + (\beta \Psi)^2} \right] \left\{ K_{1/2}(\gamma) \right\} \]

with \( \lambda c = \frac{4\pi R}{3} \beta^{-3} \), \( \beta = \frac{E}{m c^2} \) and \( \gamma = \frac{x c}{\lambda} \left[ 1 + \left( \frac{\beta \Psi}{\lambda} \right)^2 \right]^{1/2} \).

\( E \) is the orbiting energy and \( \Psi \) the elevation angle.

A subroutine computes the fractional Bessel functions \( K_p(\gamma) \) with a good accuracy (better than \( 10^{-8} \)) for \( 0 \leq \Psi \leq 1 \) and \( 0 \leq \gamma \leq 12.5 \).

For each layer crossed by the X-ray beam, we assume an exponential attenuation at each wavelength. Diffusion and backscattering are negligible compared to the photoelectric effect. This assumption is widely true in this soft X-ray range (5 to 100 Å). Each layer is characterized

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by its absorption coefficient, given as a function of the wavelength, and by its thickness.

This program computes the input, absorbed and transmitted powers at each level, the mean wavelengths \( \bar{\lambda} \) and \( \bar{\lambda}' \) and the contrast \( C \), as indicated on figure 2, through the formulas:

\[
\bar{\lambda} = \frac{\int_{0}^{\infty} \lambda N(\psi, \lambda) \, d\lambda}{\int_{0}^{\infty} N(\psi, \lambda) \, d\lambda}, \quad \bar{\lambda}' = \frac{\int_{0}^{\infty} \lambda' N(\psi, \lambda) \, d\lambda}{\int_{0}^{\infty} N(\psi, \lambda) \, d\lambda}, \quad C = \frac{P_D - P_R}{P_D + P_R}
\]

The number of photons \( N(\psi, \lambda) \) is also computed from formula (1) by

\[
N(\psi, \lambda) = P(\psi, \lambda) \frac{\lambda}{hc} \quad (cf \ [3]).
\]

This program is accurate, flexible and easy to use. The values of all needed classical absorption coefficients are stored in data files and there are special procedures for easier input. The data used for the synchrotron are the radius \( R \), the current \( I \) and the electron energy \( E \). The user must only give the natures and thicknesses of the successive layers in a given configuration. We used the parameters of the synchrotron ACO, but other synchrotron parameters can be easily introduced.

As an example of the results, we give in figure 3 the absorbed energy density, \( \mathcal{E} \), in a resist layer (PMMA) as a function of the position \( x \) on the sample and of the depth \( z \) in the resist after integration of wavelength. The position on the sample \( x \) is related to the elevation angle \( \psi \) by the relation \( x = \psi \cdot D \) (\( D \) being the distance between the source and the sample). As \( D \) is 10 m, 1 mrad \( \approx 10 \) mm. Other curves are given in ref. [3] and [5]. The non-uniformity of these absorbed doses is evident. The dashed lines give the ratios of \( \mathcal{E} \), at the surface and at the indicated depth. This shows that the non-uniformity in depth increases with the elevation angle, and this corresponds to the fact that X-rays become softer when the elevation angle \( \psi \) increases.

3. DISSOLUTION RATE

As we have seen above, the exposure dose is not homogeneous over the whole volume of the resist (variations with \( \psi \) and \( z \)). These variations of the absorbed energy give detectable variations of thickness after development.

The variations of the resist thickness during development are related to the variations of exposure through a dissolution rate. The knowledge of this dissolution rate for each pair developer-resist is necessary for any forecasting or explanation.

To take into account the non-uniformity of the irradiation, we measure the thickness variation of the resist as a function of the position on the sample (cf [3]). It is easy to determine the thickness dissolved by a developer in a positive resist (under some given development conditions), by measuring after development, the depth of the holes produced in a resist exposed through a two-dimensional periodic pattern (vidicon grid). This depth can be measured with a good accuracy either by optical (interferometer), or mechanical (Tallysurf) means. For a given exposure and development time, a scanning of the sample along a line perpendicular to the orbital plane gives a complete set of depths
corresponding to various exposure conditions (cf figure 3). So using several samples with the same resist coating and various development times for the same exposure time, it is possible to establish a set of curves like that given in figure 4. The slope of these curves at the origin gives the dissolution rate near the surface. The different distances to the orbital plane correspond to different mean wavelengths and different absorbed energy densities given by the exposure program. In our case, PMMA (Evacite 2041) is used as a typical positive resist because of its good reproducibility and stability in time. Using a set of such curves with various exposure times and incident spectrum (with or without a 3.5 \,\mu m Mylar filter) and using the values of \( \mathcal{E} \) given by the exposure program, it is possible to find the dissolution rate \( S \) a function of \( \mathcal{E} \).

These results are given on figure 5 for two different developers. These curves show that the dissolution rate does not depend on the mean wavelength but only on \( \mathcal{E} \). Three points corresponding to the results obtained by Spiller at Desy \[2\] confirm these results.

A mathematical expression of dissolution rate is:

\[
S = S_i + S_r \left( \frac{\mathcal{E}}{\mathcal{E}_r} \right)^\gamma
\]

The nature and values of these parameters are given in table 1:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nature</th>
<th>MIBK</th>
<th>MIBK:IPA 1/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>Dissolution rate (Å/s)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( S_i )</td>
<td>Initial dissolution rate</td>
<td>1.67 Å/s</td>
<td>0</td>
</tr>
<tr>
<td>( \mathcal{E} )</td>
<td>Absorbed energy density (J/cm(^3))</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \mathcal{E}_r )</td>
<td>Reference absorbed energy density (J/cm(^3))</td>
<td>500</td>
<td>1300</td>
</tr>
<tr>
<td>( S_r )</td>
<td>Corresponding reference dissolution rate (Å/s)</td>
<td>1.67</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Gamma</td>
<td>2.13</td>
<td>3.5</td>
</tr>
</tbody>
</table>

4. DEVELOPMENT MODEL

For the development model, we assume that the resist is etched only at the interface resist/developer and that the dissolution products do not affect the reaction. These assumptions are generally accepted for positive resists and especially PMMA (e.g. \[6,7\]).

The thickness dissolved (or the depth \( z \) in the resist) after a given development time \( t_d \) is a function of the dissolution rate \( S \) and of the development time \( t_d \)

\[
z = f(S, t_d)
\]

The dissolution rate \( S \) is a function of \( \mathcal{E} \), given by the relation (2):

\[
S = h(\mathcal{E})
\]
\( \xi \) is, as we have seen in part I, a function of the position \( \gamma \) on the sample and of the depth \( z \) in the resist

\[ \xi = \gamma (\gamma, z) \]  

(4)

So, the depth \( z \) can be expressed as:

\[ z = g \left( t_d, \{ \xi [\gamma, z] \} \right) \]  

(5)

Such a system of equations cannot be solved analytically, especially in this case where \( \xi \) is a complicated function of the position in the resist; thus we used a numerical step by step method as indicated below:

\[
\begin{align*}
Z_0 & \rightarrow \xi_0 \rightarrow S_0 \rightarrow dz_0 = S_0 \cdot t_{\text{step}} \\
S_1 & \rightarrow z_1 \rightarrow \xi_1 \rightarrow S_1 \\
& \vdots \\
S_0 & \rightarrow z_0 \rightarrow dZ_0 = S_0 \cdot t_{\text{step}} \\
\end{align*}
\]

For a given position on the sample (i.e., a given dose distribution) at the surface \((z_0 = 0)\) we have an absorbed energy density \( \xi_0 \) given by the exposure program. This value, \( \xi_0 \), gives a dissolution rate \( S_0 \) (equation (2)) and during an elementary time \( t_{\text{step}} \), a thickness \( dz_0 \) is removed with:

\[ dz_0 = S_0 \cdot t_{\text{step}} \]  

(6)

This elementary dissolved thickness leads to a depth \( z_1 \)

\[ z_1 = z_0 + dz_0 \]  

(7)

At this depth \( z_1 \), the absorbed energy density is \( \xi_1 \) giving a dissolution rate \( S_1 \) and a new dissolved thickness \( dz_1 \) during the time \( t_{\text{step}} \) and so on...

To take into account the transmission characteristics of the periodic mask used for the depth measurements, the computation of the development depth is done for the resist parts under the transparent and absorbing parts of the mask. The difference of these two depths, which is the experimentally measurable quantity is plotted as a function of the distance to the orbital plane.

As an example, figure 6 shows the calculated depths as a function of the position \( x \) on the sample. The fit with the experimental points is good. The influence of various parameters can be studied. For example on figure 7, we draw the depth as a function of the position \( x \) for two development times and three values of \( \gamma \) showing the interest of having a high \( \gamma \) resist. Figure 8 shows the depths obtained for the same development times as in figure 7, but three masks of different constitution and contrast are used. It can be seen that even a low contrast mask can be used, if the exposure and development conditions are adequate. The contrast of the first mask is only 0.55 and that of the third is 1 and the results are similar. So it would not be necessary to use a very thick absorbant for the mask.
5. CONCLUSION

Using these programs, it is possible to predict the results of a given lithographic experiment. For practical use, it is easy to draw up charts relating the main experimental parameters. For example, figure 9 gives the development time versus the resist thickness for two completely developed widths and various exposure times. Figure 10 gives the half completely developed width versus the development time for various exposures. And last, figure 11 gives the exposure time versus the development time for various completely developed widths. So, with such charts and fixing one parameter, it is possible to choose the others, or it is possible to determine possible compromises. As 11 layers can be considered in the programs, a wide variety of configurations can be computed. By modifying the subroutine giving the synchrotron radiation in the first program, it is possible to adapt all the computation to any other X-ray source and then to predict the results.

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[6] K. UBERREITER,

FIGURES

**FIG. 1** SYNCHROTRON RADIATION DISTRIBUTION ON A SAMPLE

**FIG. 2** CONFIGURATION OF THE LITHOGRAPHIC SYSTEM AND CORRESPONDING COMPUTED VALUES

**INPUT RADIATION**
- FILTER 1
- FILTER 2
- FILTER 3
- Mask substrate
- Absorbent layer
- Resist
- Substrate

**COMPUTED VALUES**
- **SOURCE**
  \[ P(x, y), P(y), \bar{P}(x), \bar{P}(y) \]
- For each layer (including mask and resist)
  \[ P(x, y), P(y), \bar{P}(x), \bar{P}(y) \]
  \[ \bar{P}(x), \bar{P}(y) \]
  \[ P_1(x, y), P_1(y), \bar{P}_1(x), \bar{P}_1(y) \]
- For the Mask
  \[ C_0(x, y), C_0(y) \]
- For the Resist
  \[ C_0(x, y), C_0(y) \]
  \[ \bar{P}(x, y), \bar{P}(y) \]
FIG. 3 ABSORBED ENERGY DENSITY IN PMMA AS A FUNCTION OF POSITION AND DEPTH IN THE RESIST AND RATIOS OF $\xi(0)$ TO $\xi(2)$

FIG. 5 DISSOLUTION RATE VERSUS ABSORBED ENERGY DENSITY IN PMMA FOR TWO DEVELOPERS (MIBK PURE AND MIBK : IPA, 1/3)

FIG. 4 MEASURED DEPTH VERSUS DEVELOPMENT TIME FOR VARIOUS POSITIONS (PMMA • MIBK : IPA, 1/3)
FIG. 6
$S_i = 167 \text{ A/s}$
$\phi = 500 \text{ J/cm}^2$
$\delta = 2.13$

MASK: MYLAR 3.5 pm
GOLD 2.5 pm
RESIST: PMMA

$T_{exp}(s) = T_{dev}(s)$
$\circ 159$
$\Delta 167$
$\triangledown 60$
$\triangle 30$
$\checkmark 15$

FIG. 7
$S_i = 167 \text{ A/s}$
$\phi = 500 \text{ J/cm}^2$

MASK: MYLAR 3.5 pm
GOLD 2.5 pm

$T_{exp} = 159 s$

FIG. 8
$S_i = 167 \text{ A/s}$
$\phi = 500, \delta = 2.13$

DEVELOPER MIBK (pure)

$172 \text{ mJ/cm}^2$

FIG. 9
$S_i = Sr = 1.67$
$\phi = 500 \text{ J/cm}^2$

MIBK
pure
FIG. 9 DEVELOPMENT TIME VERSUS PMMA THICKNESS FOR 2 DEVELOPED WIDTHS AND 6 EXPOSURE TIMES (PMMA + MIBK, IPA, 1/3)

FIG. 10 COMPLETELY DEVELOPED WIDTH VERSUS DEVELOPMENT TIME FOR VARIOUS EXPOSURE TIMES (PMMA + MIBK : IPA, 1/3)

FIG. 11 EXPOSURE TIME VERSUS DEVELOPMENT TIME FOR VARIOUS COMPLETELY DEVELOPED WIDTHS (PMMA + MIBK : IPA, 1/3)
When the dimensions of artificial structures approach or become smaller than certain characteristic distances (e.g. grain size, domain size, wavelength, mean-free-path, coherence length, molecular size) it becomes possible to access phenomena or manipulate materials in new and different ways. The present and future impact of submicrometer structures on electronic devices, studies of physics at small dimensions, imaging, spectroscopy, graphoepitaxy, manipulation of organic molecules and catalysis is briefly discussed with emphasis on the connection between dimensions of structures and characteristic distances.

INTRODUCTION

Figure 1 compares a 1 μm distance scale with a relief grating in SiO₂ and three biological items. The relief grating was fabricated at MIT Lincoln Laboratory a few years ago using a process that included soft x-ray lithography and reactive ion etching.¹ Figure 2 depicts, at a tenfold magnification relative to Fig. 1, the same relief grating together with some results of recent work at the forefront of micromachining technology.²-⁴ Figures 1 and 2 show artificially fabricated structures having dimensions that are smaller than objects of our common experience and even the smallest living particles, and that approach the size domain of the organic molecules. When the dimensions of artificial structures approach, or become smaller than, certain characteristic distances, such as grain size, domain size, wavelength, mean-free-path, coherence length, molecular size, etc. it becomes possible to access phenomena and manipulate materials in new and different ways. For these reasons, we can anticipate that structure fabrication technology will have a pervasive impact on a wide variety of research areas and applications. In this article I will discuss a few of these, attempt to illustrate the connection between dimensions of structures and characteristic distances, and speculate on some future directions for submicrometer structures technology and applications. The treatment is selective and very brief, and hence cannot give appropriate coverage to all of the work going on in this exciting and rapidly moving field.

*The Lincoln Laboratory portion of this work was sponsored by the Department of the Air Force and the Defense Advanced Research Projects Agency.
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The ability to fabricate artificial structures with submicrometer dimensions is not entirely new. Thin films with control of thicknesses to less than 1 nm, monolayers, deposits of materials in the form of discrete nuclei < 1 nm in size, fine powders, photographic emulsions, fine surface finishes, fibers and many other forms of artificial micro-structures have been available for many years. In most cases, however, such artificial structures are characterized by a certain randomness. With modern techniques, on the other hand, both lateral and thickness dimensions are controllable, and structures have a predetermined pattern that can be reproduced at will.

DEVICES

Conventional semiconductor electronic devices can be scaled to submicrometer feature sizes, and in the case of discrete GaAs devices this has been done to advantage. However, for the majority of conventional devices and circuits there may be limited advantage in scaling to the submicrometer. For certain new types of devices, on the other hand, submicrometer structures are essential. An example is the permeable base transistor (PBT) developed by Bozler, et al. and illustrated in Fig. 3. The openings in the tungsten grating that is buried within an epitaxial film of GaAs must be smaller than the zero-bias depletion width of the Schottky barrier formed between the tungsten and the GaAs. Moreover, the device characteristics depend critically on the size of the opening in the grating. For the case of a 0.32 μm period grating, as shown, the opening width should be controlled to about ± 10 nm for reproducible device performance. Analysis indicates that the maximum frequency of operation of the PBT should be several hundred GHz.

There is considerable current interest in investigating electron devices that employ ballistic transport. Here, the dimensions of structures must be comparable to, or only slightly larger than, the electron mean-free-path. For GaAs and Si these distances are about 150 nm and 20 nm respectively. Studies of the physics of transport over small distances and experiments on new devices based on ballistic transport are feasible by virtue of modern microfabrication techniques. Flanders has pointed out that certain simple structures, such as lines, gaps or interdigital patterns, suitable for basic studies or single devices, can be fabricated by oblique shadowing methods, either directly on substrates or through the use of x-ray lithography. For more complex structures and circuits, electron beam lithography is required for pattern generation.

PHYSICS AT SMALL DIMENSIONS

A number of researchers have observed that the Raman scattering of molecules (e.g., pyridine, benzene, CN-) is enhanced by several orders of magnitude if the molecules are adsorbed on suitably roughened metallic surfaces. Some have speculated that the Raman enhancement is caused by large local fields at optical frequencies that are associated with plasmon resonances in small metallic particles < 100 nm in diameter. Such particles, which have been produced by several
techniques, exhibit a variety of shapes and sizes and are randomly distributed over a surface. In order to determine if the shape and size of metallic particles is responsible for the enhancement and to investigate the Raman enhancement effect in a controlled and quantitative way, Liao, et al. have fabricated matrices of roughly ellipsoidal shaped silver particles with approximately 50 nm linear dimensions. The fabrication procedure involved holographic lithography and reactive ion etching to produce a relief grid of conical shapes, followed by oblique evaporation of silver to produce the desired silver particles. The expected Raman enhancement was observed and correlated with the particle shape. These experiments are an example of fundamental measurements in physics made possible by virtue of submicrometer structures technology. The fact that the silver particles formed a regular array of identical shapes, whose dimensions could be controlled, greatly simplified the analysis, and leads one to speculate on further studies and perhaps applications.

Recent studies, by a number of investigators, of transport in conductors with diameters of a few tens of nanometers are another example of how microfabrication techniques have permitted experimental investigations to be extended into previously inaccessible domains. Laibowitz, et al. have studied the properties of Josephson microbridges with approximately 10 nm linewidths. These structures were fabricated in niobium using STEM lithography and ion beam etching. Feuer and Prober have made variable-thickness Josephson microbridges in which both the length and width of the bridges were comparable to the superconducting coherence length. A "two-dimensional shadowing" technique was used that consisted of evaporating metal at an oblique angle onto a substrate into which orthogonal steps had been etched. They believe the technique is capable of producing device sizes of 10-20 nm.

A number of groups have investigated a theoretical prediction of Thouless that any conductor whose cross-sectional area is sufficiently small that it can be considered one dimensional, and whose impurity resistance exceeds $10^{14}$ ohm, will behave like an insulator at very low temperature due to Anderson localization of electrons. Below a certain critical temperature the resistance will increase with further decrease in temperature. To produce wires of sufficiently small cross-sectional area to test this prediction, Giordano, et al. deposited a metal film onto a relief step in a glass substrate and then ion beam etched the metal at an oblique angle such that only metal in the corner of the steps, protected from the ion beam, remained behind. Wires of 30 nm width were produced. White and Flanders evaporated metal onto a relief step at an oblique angle and removed excess metal by ion beam etching. Wires as small as 15 nm width were produced. Chaudhari and Habermeier made measurements on conductors produced by electron beam lithography and ion beam etching. Increase in resistance with decreasing temperature was observed by both Giordana et al. and Chaudhari and Habermeier.
Fresnel zone plates and phase plates provide a means of forming images with short wavelength radiation, such as deep UV, soft x-rays and thermal neutrons. In the absence of aberrations, the resolution in the first order image is approximately equal to the width of the outermost zone. Both holographic lithography and scanning electron beam lithography have been used to generate the pattern of circular zones. The holographic method required special optics to correct for the spherical aberration that results from using an exposure wavelength that differs from the wavelength used for imaging. When scanning electron beam lithography is used for pattern generation, distortion in the electron scan raster must be corrected. This is most conveniently done by a moiré technique using a holographically generated reference grid.

With Fresnel zone plates or phase plates it may be possible to obtain soft x-ray images of living cells and cell organelles with a resolution of the order of 10 nm. The potential for gathering information not available through either optical or electron microscopy makes this a particularly exciting application. The focusing of x-rays with zone plates could also be useful in materials and surface analysis.

Reflective optical elements for soft x-rays, that would consist of multilayer films of alternating high and low atomic number materials, are also under development. The layer thicknesses and surface figure must be controlled to less than 1 nm, making this a very challenging technology.

P. D. Kearney et al. have formed Fresnel zone structures in copper 2.4 μm thick, which is sufficient to produce a differential phase shift of π for thermal neutrons. Using such Fresnel phase plates, images have been formed with 2 nm wavelength neutrons. Chromatic aberration limited the spatial resolution to about 50 μm.

Diffraction gratings with spatial periods less than 100 nm are important for research in the far UV and x-ray regions. It is very difficult to use holographic techniques to expose high-quality gratings with periods in this range due to limitations in the available laser sources and certain practical problems. Flanders, et al. have described a "bootstrapping" technique, called spatial-period-division, that in principle should enable grating periods down to about 20 nm to be exposed. Soft x-rays are passed through a "parent" grating of period p and, under the appropriate circumstances, an interference pattern of period p/n (where n is an integer) is present in the near field and could be used to expose a grating of this finer period. Exposure of a grating pattern in a resist is, of course, only a part of the task. The lines of a grating must be sufficiently thick to produce the required differential absorption or phase shift. This is generally a difficult task and depends on detailed understanding and control, on a microscopic scale, of processes such as plating and etching. There is a clear need for research on these issues.
GRAPHOEPISTAXY

Graphoeptaxy is a process in which an artificial pattern at a surface is used to induce or control orientation in a film. In order to exercise such control one or more dimensions of the artificial pattern must be small compared to the grain or domain size that characterizes the film. For the case of solid crystalline films, the patterns used to date have been grating relief structures, and the objective has been to achieve uniform orientation. However, the concept of control via artificial patterns is itself more general. Researchers have known for many years that accidental scratches or pits in a substrate surface have a profound effect on the formation and orientation of a film. In a sense, graphoeptaxy seeks to turn this generally detrimental effect into a means for control. In the future, artificial structures will probably be used very broadly to manipulate the properties of crystalline films.

Our initial work on graphoeptaxy was directed at manipulating and controlling nucleation, coalescence and recrystallization in the early stages of the growth of a solid thin film. To accomplish this it was necessary to first develop techniques for fabricating submicrometer surface relief structures with precisely controlled dimensions and profiles. The development of such techniques, and studies of the influence of artificial structures on the early stages of film growth, continue to be important areas for research. Orientation via graphoeptaxy has been demonstrated for KCl and silicon. The silicon work involved crystallization of amorphous silicon, or recrystallization of polycrystalline silicon, deposited over 3.8 \( \mu \text{m} \) period relief gratings in amorphous SiO\(_2\). Figure 4 is a TEM micrograph of a graphoeptaxial silicon film recrystallized in a strip-heater oven. At the present time, the mechanism of orientation is not understood. Transistors have been fabricated in the films and showed electron surface mobilities of 300–460 cm\(^2\)/V sec at a doping level of 6 \( \times 10^{15} \) cm\(^{-3}\). Further improvements in graphoeptaxial silicon to make it suitable for integrated electronic devices will depend on developing a basic understanding of the orientation mechanism.

Sheftal and coworkers have, for many years, propounded a theory that crystal growth can occur through the formation of free individual micro-crystals which attach themselves to a growing crystal face. They found support for this in the tendency of NH\(_4\)I crystals, precipitated from solution, to align relative to a diffraction grating. Sheftal and Klykov have proposed that microcrystal attachment to artificial relief structures could be used to obtain continuous oriented films.

Liquid crystals are quite readily oriented by artificial surface patterns. The mechanism is believed to be minimization of elastic deformation energy. Early work used abrasive and oblique evaporation techniques to produce relief structures suitable for inducing
orientation. Relief gratings fabricated by planar techniques produce superior orientation\(^{31,38-40}\) and permit a more precise control than is possible with quasi-random structures. Moreover, forms of manipulation other than uniform orientation appear feasible\(^{29,39}\) and could have very novel and important applications.

Shaver has demonstrated orientation of a liquid crystal layer using a grating pattern of a surfactant on a SiO\(_2\) surface.\(^{39}\) The surfactant locally altered the angle between the liquid crystal director and the surface plane. Since the thickness of the surfactant pattern was negligible (\(\approx 1\) nm), the mechanism of orientation is quite different than in the case of a relief structure.

**MANIPULATION OF ORGANIC MOLECULES AND CATALYSIS**

H. P. Zingsheim has reported experiments in which a STEM was used to write grating patterns in an insulin monolayer on a thin carbon membrane.\(^{4}\) The lines were 4 nm wide and the distance between lines was 50 nm. The beam writing modified the insulin in such a way that after immersion in an electrolyte solution ferritin molecules adsorbed preferentially on the lines by about a factor of 20. Zingsheim postulated that the preferential adsorption was due to surface charging that took place in the electrolyte. In this experiment organic molecules were directed to attach themselves to an artificial pattern having some dimensions comparable to the size of the molecule. Although the original motivation was to explore the possibility of creating two-dimensional molecular assemblies that would facilitate low-dose electron microscopy, the implications of such molecular manipulation are no doubt much broader. One can envision other means of attaching molecules or exploiting their site specific properties, and further improvements in "nanofabrication" that would yield more complex patterns with finer linewidths and spacings. We have only to look at the microscopic details of living systems and the complex functions performed, such as sensing, synthesis, energy conversion, to appreciate some of the implications of artificial molecular manipulation. Very likely, synergistic connections will develop: artificial structures will be used to manipulate molecules and molecular manipulation will provide improved fabrication techniques.\(^{31}\)

Catalysis frequently depends on extremely small particles and edge effects. If the size, shape, separation, mobility, etc. of catalytic sites are directly controlled by means of nanostructure technology it may be possible to gather fundamental information about catalysis or influence catalytic processes. Here, as in the case of molecular manipulation, there is considerable opportunity for exploratory research.
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Figure 1. Drawing, approximately to scale, of the cross section of a human hair, a human chromosome, a bacterium (depicted with considerable artistic liberty) and the cross section of a relief grating etched into SiO₂.

Figure 2. Drawing, at ten times the magnification of Fig. 1, of the relief grating etched into SiO₂ in Fig. 1, and the results of research on nano-fabrication at three laboratories. In the work at MIT Lincoln Laboratory, a T₄-phage virus is shown adjacent to a pattern of 20 nm wide lines exposed in PMMA by x-ray lithography. The IBM work is a grid of 8 nm wide lines of PdAu produced on a carbon foil by STEM lithography and ion beam etching. The work at the Max Planck Institute used a STEM to write 4 nm wide lines in an insulin monolayer on a carbon foil. Thereafter, ferritin molecules (shown as spheres) could be made to selectively attach to the written lines.
Figure 3. Permeable base transistor. The grating, which is made of tungsten, is embedded in epitaxial gallium arsenide. The electrons flow from emitter to collector through the openings in the tungsten grating.

Figure 4. Transmission electron micrograph of a graphoepitaxial silicon film crystallized in a strip-heater oven. The lines of the surface relief grating run diagonally. The other lines and bands are bend contours. The fourfold symmetry and orientation of the bend contours confirm that the <100> direction is aligned with the grating axis. The micrograph is of a single crystallite free of line defects, as indicated by the absence of discontinuities in the bend contours.

"The U.S. Government assumes no responsibility for the information presented."
E-BEAM LITHOGRAPHY IN JOSEPHSON TECHNOLOGY

Theodor Forster, Albertus Oosenbrug, Peter Vettiger and Henry Wohltjen

This paper discusses the application of e-beam lithography for fabricating Josephson circuits. Circuit designs require a margin of ±10% in the Josephson current of individual devices, implying geometrical tolerances that are difficult to obtain using standard optical lithography. Therefore we explore the use of electron-optical lithography at the critical levels.

1. INTRODUCTION

Digital devices based on the phenomena of superconductivity and electron pair tunneling through an insulating barrier offer fast switching at extremely low power levels. The delay-power product of Josephson devices is orders of magnitude below that of semiconductors. The feasibility of the circuit and fabrication technology has been sufficiently well demonstrated to warrant efforts towards realization of a computing-system prototype based on Josephson Technology.1

2. JOSEPHSON DEVICES

A Josephson tunneling device is fabricated by subjecting a silicon substrate to a number of thin-film processing steps to form the superconducting electrodes and control metallization (Nb- and Pb-alloy films) and the insulating layers (SiO).2,3 Key in the process is the formation of the thin tunnel barrier (30-50 Å thick) on top of the base electrode (Nb- or Pb-alloy) in an rf sputter oxidation process (Fig. 1). The tunnel junction areas are determined by windows which are opened in a SiO film (12Å level). Once the tunnel barrier has been formed, the Pb-alloy counterelectrode is vapor-deposited in situ. All metal and insulator layers are patterned by lift-off except the Nb ground plane and Nb junction base electrode, which are both patterned by subtractive plasma etching.

3. LITHOGRAPHY REQUIREMENTS

The most important circuit-design parameter is the maximum Josephson current which can be carried by a junction (Fig. 2). The Josephson tunnel current density is exponentially dependent on the tunnel barrier

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height, exclusively determined by the rf oxidation process. For small junctions, the total Josephson current is linearly proportional to the junction area as determined by the lithographic process. The circuit design, currently used, requires a ± 10% margin on the design value of the Josephson current. Thus, typically used junction areas of 7 × 7 μm or smaller require line-width control of ± 0.3 μm or better. In addition, very high pattern fidelity-rounding-off errors of < 0.5 μm are required to obtain the desired electrical properties in the shaped Josephson junctions, recently introduced for logic applications.

4. E-BEAM EXPOSURE SYSTEM

It is difficult to obtain the required geometrical precision by using standard optical lithography. Therefore we explore the use of electron-optical lithography for the critical or possibly for all levels in the fabrication of Josephson circuits. The system used for this purpose is a Vector-Scan (VS) system. An electron beam generated by a lanthanum hexaboride e-gun is focused to a spot size of 0.1-0.2 μm on the substrate level by means of two magnetic lenses and one final lens. A double deflection coil assembly provides magnetic beam deflection; 16,000 points can be addressed along both X and Y axes. The substrate is mounted on a stepper motor-driven, laser interferometer controlled stage, which permits laser-directed stitching. By using this option, we can address 16,000 × 16,000 points over small – typically 1.6 × 1.6 mm – subfields and stitch these subfields in a 4 × 4 array to a large (6.4 × 6.4 mm) chip together. This leads to negligibly small deflection distortion and high resolution across the entire chip. Pattern data are created in a postprocessor, which translates CAD-created data into VS data. Calibration, registration and beam deflection during exposure are under the control of an IBM 1130 computer. Recently developed techniques support automatic registration for stitched patterns. While scanning four target marks, any rotation of the wafer with respect to the laser/stage axis, is calculated. At the same time, any isotropic change across the wafer is compensated by an equivalent scaling. This procedure allows the system to move the stage under laser control into the center of the chip/subfield. Scanning chip marks at each chip site allows correction of the electron-optical deflection system according to the measured chip rotation. The capability to recalibrate at each chip site reduces stitching errors due to wafer flatness variations. This technique and its excellent performance for stitching within a level as well as overlay between two stitched levels made the Vector-Scan system a very versatile tool for our program.

5. RESIST PROCESS

For the fabrication of actual devices with minimum line widths down to 1.5 μm, we use PMMA (2041, 10% in chlorobenzene) at all levels. Because
the electrical characteristics of Josephson devices change on annealing, we use the lowest possible temperature to bake the resist. With PMMA 2041 baked at 110°C, good lift-off profiles are obtained for the deposition of SiO and Pb-alloy films with an exposure of \( Q = 2.5 \times 10^{-4} \text{ C/cm}^2 \). A dose \( Q = 1.5 \times 10^{-4} \text{ C/cm}^2 \) is adequate if this resist is used as etch mask in a \( \text{CF}_4 + \text{O}_2 \) plasma etching step.

In order to evaluate the influence of the kind of resist being used while forming the junction oxide, other resists are being investigated.

6. REGISTRATION MARKS

Electrons backscattered from scanning across marks provide calibration and registration signals. Fabrication of the calibration mark - a narrow single-cross - is actually the first lithographical step. The cross is etched into the Nb groundplane and is used to calibrate the deflection system and the laser interferometer servo gain. Target marks and chip registration marks, used for correction of the rotation, orthogonality, field size and offset of the deflection fields, are fabricated simultaneously with the first device level. Because of the many lift-off levels, we cannot use a single-cross mark approach to preserve the same set of marks throughout the entire process, as reported by other investigators: subsequent depositions will cover the marks if clearing boxes are used, and without the use of clearing boxes, cross-linked resist will disturb the registration signals of next levels (Fig. 3). The change of the mark profile during the whole process is shown in Fig. 4. The corresponding averaged registration signals for various levels are shown in Fig. 5. It demonstrates that the signal received from the M3 level is about 6-7 times weaker than from the M1 level. It was found that the registration precision is poor and not reliable after deposition of any Pb-alloy level (\( \geq 3,000 \AA \)). Therefore the multi-pair mark approach is proposed which requires chip area for two additional marks but solves the problem of registration for Pb-alloy lift-off processes. Three marks are required for the whole process because the first mark is not usable after M3 metalization, and the second unusable after M4. All other lift-off levels in the present structure do not create any problems for registration. The process sequence for a complete device structure is summarized in Fig. 6.

7. LSI APPLICATIONS

Present ground rules for the technology demand a minimum linewidth of 2.5 \( \mu \text{m} \). This can be achieved by standard optical lithography. However, the required geometrical precision for the critical levels (e.g., tunnel junction area) does require precise area control. The VS system with its inherent capability of high resolution and precision is used
to write these critical levels directly onto the wafer. The system overlays these levels by registering on marks which have been deposited in a previous optical level. Figure 7 shows a comparison between a shaped Josephson junction exposed optically and with e-beam. There is a clear rounding error at the endpoints of the junction in the case of the optical exposure. Also visible are some noticeable residues of SiO (a few hundred Å thick) within the junction area due to the lift-off stencil of the AZ 1450 J C.B. resist. The residues prevent any junction oxide being formed with these areas, resulting in badly defined junction areas. This is not clearly visible in the case of the e-beam exposure with the PMMA 2041. The standard chip size for these applications is 6.4 × 6.4 mm and all levels are being written in the stitched mode with a 4 × 4 subfield array.

8. EXPLORATORY APPLICATIONS

The high degree of flexibility for any design changes and the short turn-around time from design to exposure makes the VS system a very versatile tool for exploratory kinds of designs. A 2 × 2 mm field size is being used for the active circuit design area. In order to use the standard measurement jigs for the 6.4 × 6.4 mm chips, the 2 × 2 mm design interfaces with a 6.4 × 6.4 mm peripheral chip (pads and lines). Registration is performed at marks located in the four corners of the 2 × 2 mm design. As mentioned above, there are three pairs of marks required on a chip for a full structure design from M1 to M5. The approach has proven its flexibility and requires a minimum CAD effort because the peripheral mask designs have to be designed only once and can be reused for other designs without any changes.

9. CONCLUSIONS

Due to the many lift-off processes in Josephson technology (specifically Pb-alloy levels), there are three pairs of marks required at each chip site. The use of three different marks does not show any influence on overlay performance. Experience gained so far, showed that good junction-area definition can be achieved through e-beam lithography. This demonstration of the current capability of electron-beam technology looks very convincing and may help promote further advances in Josephson technology.

ACKNOWLEDGEMENTS

We would like to acknowledge the many stimulating discussions and the support of E. Bretscher and D.F. Moore, who postprocessed and designed all the data being used for this work. We also gratefully acknowledge the support of K. Dätwyler, H.P. Dietrich, L. Perriard and G. Sasso for preparing the wafers, and the encouragement received from E.J. Van Derveer.
Many thanks also to all the members of IBM Yorktown Research E-Beam Group for their support during the training and installation period of the vector-scan system.

REFERENCES


Fig. 1. Structure of a Josephson circuit
JOSEPHSON JUNCTION

1962 JOSEPHSON EFFECT PREDICTED BY B.D. JOSEPHSON

Fig. 2. Josephson device characteristic
APPRAOCH USING CLEARING BOXES

CLEARING BOX
100 x 100 μm

SCAN FIELDS
FOR
REGISTRATION

CLEARING BOX
COVERED WITH
NEXT LEVEL

Fig. 3. Clearing boxes
Fig. 4. Mark profiles during process
Registration for 2500 Å Nb on SiO₂

Reg. Error

Registration for 3000 Å SiO on Nb/SiO₂

Reg. Error ≤ 0.4 BS

Registration for 3500 Å Pb-alloy on SiO/SiO/Nb/SiO₂

Reg. Error > 1.5 BS
Usually not successful

Fig. 5. Registration signals
### SEQUENCE OF PROCESS STEPS

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<tr>
<th>LEVEL</th>
<th>PROCESS</th>
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<td>M1 GROUND PLANE</td>
<td>Evaporate Nb PMMA stencil Plasma etch anodize remaining Nb</td>
<td>Target Marks Registration Marks M1 Pattern Ev. opt. Exposure</td>
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<td>I1 INSULATION</td>
<td>PMMA stencil evaporate SiO lift off</td>
<td>Registration Mark 1 I1 Pattern Ev. opt. Exposure</td>
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<td>M5 CONTROL LINE</td>
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Fig. 6. Sequence of process steps
Fig. 7b. E-beam and optical lift-off profiles
Fig. 7a. E-beam and optically exposed sine shaped logic gates
MICROSTRUCTURE PATTERN REPLICATION FOR ADVANCED PLANAR GaAs LSI/VLSI

B. M. Welch, Y. D. Shen and W. P. Fleming

LSI/VLSI compatible processes for producing micron resolved geometries have been developed and applied to the fabrication of planar GaAs ICs. Use of dry pattern replication techniques, along with unique high yield planar microstructures have resulted in the recent fabrication of GaAs LSI (>1000 gates circuits).

1. INTRODUCTION

During the past several years the development of GaAs integrated circuits has been making rapid progress [1]. Currently, several GaAs IC technologies have achieved MSI status and are expected to impact near term high speed signal processing applications which are already beyond the scope of available Si ICs. However, the trend of modern electronics dictates that for GaAs IC technology to make a serious impact on future electronic systems, it must be capable of LSI/VLSI complexities. GaAs fabrication approaches and processing techniques must be selected that are extendable and fully compatible with the yield and reliability demands of high density complex LSI/VLSI. GaAs technology demonstration at the MSI level does not necessarily indicate that MSI processes will be extendable to LSI/VLSI levels. In that context, the fabrication approaches and processing techniques are critical factors in determining whether GaAs ICs can achieve LSI/VLSI status.

This paper describes a fabrication technology that was specifically designed and developed to satisfy LSI/VLSI requirements [2]. Key elements of this technology are use of ion implantation for individual device active layers, reduction projection photolithography for 1 μm geometries, and dry microstructure pattern replication techniques. Rapid progress over the last twelve months has seen this technology progress from an MSI (60-100 gates) level to the current LSI (>1000 gates) level.

2. ADVANCED PLANAR GaAs MICROSTRUCTURES

The microstructure pattern replication techniques described in this paper combine plasma etching with metal lift-off techniques resulting in precisely aligned circuit patterns within dielectric openings on

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GaAs. These processes are integrated into a unique fabrication approach resulting in the totally planar multi-level GaAs IC structure illustrated in Fig. 1. As illustrated in the upper portion of Fig. 1, this fabrication approach results in a smooth metal/dielectric surface after the first level metalization steps, leading to a planar multi-level interconnect crossover structure. Planar crossovers greatly enhance the yield of multi-level interconnects as compared to conventional crossover structures shown in the lower portion of Fig. 1. Also shown in Fig. 1 is the use of "filled" vias interconnecting the first level metal to the second level metal. Since there is no step coverage consideration for filled vias, higher yield, denser multi-level interconnect structures are possible. In the following discussions the processes used to fabricate these planar microstructures will be described.

2.1. Enhanced Lift-off Technique
Photoresist lift-off techniques have been commonly used in fine line lithography applications for many years. However, when direct photoresist lifting is used for defining metal patterns, excellent edge acuity of the photoresist profile is required. Normally, in practice, excellent edge acuity (vertical side walls) is not always attainable and limited process yield is typically experienced. This is particularly true using reduction projection photolithography techniques where resist images and profiles are often difficult to control due to the small depth of focus (typically ±1.5 μm for 1 μm resolution) of this optical technique combined with large wafer flatness variations commonly experienced. Therefore, in order to insure high yields from lift-off processes, enhanced lift-off techniques are commonly used [3]. Two examples of enhanced lift-off techniques are shown in the upper portion of Fig. 2 with the plasma etched dielectric intermediate layer method used in this work shown at the bottom of Fig. 2. The key principle used in both the multi-level mask or intermediate layer methods is use of evaporation shadowing. Mask structures are formed with resist ledges (multi-mask techniques) or under cut resist/dielectric structures (intermediate layer) that allow convenient shadowing of the evaporated metal, thus insuring an extremely high yield lift-off process.

The enhanced lift-off method described here was developed specifically for GaAs IC applications. This process approach has taken into account the inherent differences between processing on GaAs versus Si. For example, in this work the substrate is semi-insulating (the Si analogy would be insulating sapphire substrates in SOS technology), therefore, the first level interconnects may be fabricated directly on the substrate without the usual constraints associated with isolation and stray capacitance common to Si. Additionally, the commonly used freon based plasma etching techniques used for etching Si₃N₄ and SiO₂ do not etch GaAs. These two unique features of GaAs has motivated the development of the plasma etched dielectric intermediate layer enhanced lift-off technique shown in Fig. 2. The
The structural advantage of the intermediate layer enhanced lift-off method can be seen in the scanning electron micrograph of Fig. 3. The intermediate dielectric layer is first plasma etched, then the appropriate metal is evaporated to a thickness less than or equal to the dielectric thickness (as shown in Fig. 3). The processed microstructure has no continuity between the metal deposited in the dielectric window and the metal deposited on the top and side wall of the photoresist pattern. This structure allows solvents to easily penetrate and readily dissolve the photoresist. This process is easy to implement, very reproducible and extremely high yield.

The key difference between this approach and other intermediate layer lift-off approaches is that plasma etching techniques have been developed providing micron resolved dielectric profiles with minimum resist degradation resulting in the precisely aligned metal/dielectric structure shown in Fig. 4. Optimization of the plasma etching parameters for near (~75° slope) anisotropic dielectric profiles allows the metal to actually seal the dielectric opening (see Fig. 4) This is advantageous for GaAs IC processing since critical, lightly doped, thin GaAs FET channel active layers are sealed and isolated from subsequent process steps. Future refinements in these processes will include better differential etch rates between photoresist and dielectrics and between Si$_3$N$_4$ and SiO$_2$.

### 2.2. Planar Crossovers

As shown in Fig. 1, having fabricated the first-level metal within dielectric windows, and maintaining the metal thickness close to the dielectric thickness results in a smooth planar surface greatly facilitating the fabrication of complex multilayer interconnects. Figure 5(a) shows an actual cross section of the planar crossovers resulting from these process approaches. Figure 5(b) shows a top view of a similar structure. The process used to fabricate the planar multilayer structure is described as follows: a ~5000Å plasma enhanced CVD silicon nitride (plasma nitride) layer is deposited on the ICs. Via Windows are then reactively ion etched (RIE) through the nitride in order to interconnect the first-level metal to the second-level metal. A second-level metal composed of Ti/Au is deposited over the second-level dielectric and is subsequently defined by ion milling, completing the process.

The planar crossovers eliminate any potential for crossover problems such as shorts between first- and second-level interconnects, and high-resistances or open interconnects resulting from poor step coverage. Another very important advantage is that these planar structures allow both thinner metal and dielectric films to be used which results in less film stress, positively impacting yield and reliability. We also believe that these planar approaches have real potential for extension to three levels of interconnects which will greatly impact the optimization of future complex VLSI.
2.3. Filled Via Development

Currently in development, but not yet fully implemented into our process, is the planar second-level via interconnect shown in the schematic of Fig. 1. A similar process to the enhanced lift-off method already described is used to fill the via windows with intermediate metal between the first and second level interconnects.

Figure 6(a) shows a 4500Å thick Ti/Au film precisely aligned within a 5000Å thick plasma nitride via window. In this process reactive ion etching is used to etch an anisotropic via window with metal subsequently being evaporated into the window. Any small voids or gaps (~500Å) between the intermediate via metal and the dielectric is easily filled during the deposition of the second-level metal. Figure 6(b) shows a SEM cross section of a filled via window along with the planar second-level interconnect. The motivation for developing this process is illustrated in Fig. 7 which contrasts two different via interconnect layouts both having a common via hole cross-sectional area (1.5 μm x 1.5 μm). Conventional processing and layout designs call for isotropic via sidewalls which require larger geometries for the second level interconnects and tight alignments for insuring adequate step coverage. However, filled vias do not require any step coverage; therefore, smaller second-level interconnects with relaxed alignment tolerances may be utilized. The capability for achieving higher densities with increased process yields is evident. These via approaches are expected to positively impact future VLSI requirements.

3. SUMMARY AND STATUS

The microstructure pattern replication techniques described in this paper have been developed over the past three years. A key goal for this process development was to demonstrate the successful operation of a GaAs LSI circuit. This goal has been recently achieved through the successful fabrication and functional operation of the GaAs 8 x 8 bit parallel multiplier containing over 1000 gates shown in Fig. 8. Testing of this circuit has verified full functionality for all 64,000 possible multiplier combinations with gate delays of 150 ps having also been measured. This gate delay corresponds to a ~5 ns multiplication time to obtain a 16-bit product. These speeds are significantly higher than any currently available SI ICs.

Process capabilities have been clearly demonstrated at the LSI level as indicated by the component and feature count for this multiplier circuit shown in Table I. The gate count of 1008 corresponds to over 6000 individual devices, ~12,000 crossovers, and ~7,000 vias. Advanced planar GaAs LSI circuits have been made possible through the use of high yield planar microstructure fabrication techniques with future prospects for achieving GaAs VLSI appearing excellent.
REFERENCES


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ERC80-10579
Fig. 1 Schematic of a planar multi-level interconnect structure compared to conventional fabrication structures.

Fig. 2 Schematics of two commonly used enhanced lift-off methods, the multi-level mask and intermediate layer approaches in contrast with the plasma etched dielectric intermediate layer techniques described in this paper.
Fig. 3 Scanning electron micrograph showing the intermediate layer enhanced lift-off microstructure prior to lift-off.

Fig. 4 Scanning electron micrograph showing the planar self-aligned metal/dielectric structure resulting from use of the enhanced lift-off method described in this paper.
Fig 5  a) SEM cross section showing the planar multi-level interconnect structure illustrated in Fig. 1.  
b) SEM photo showing a planar second level interconnect overcrossing, isolated from the first level interconnect by plasma nitride.

Fig. 6  a) SEM cross section showing an Au filled via window in plasma nitride.  
b) SEM cross section showing the planar second level via interconnect method illustrated in Fig. 1
Fig. 7 Comparison of a conventional IC design via layout versus a filled via layout, illustrating the impact on density and alignment tolerance using these different approaches.

Fig. 8 Photograph of a planar GaAs LSI (1008 gates) 8 x 8 bit parallel multiplier.
1. INTRODUCTION

Ever since planar technology was first introduced into semiconductor manufacture it has been recognised that the processing steps can cause distortion of the silicon slice; the most obvious manifestation of this is the bowing of slices after furnace treatments. It is also recognised that slice distortion makes some contribution to the overlay misregistration of the various pattern layers in the fabrication process.

These difficulties in the lithography have usually been adequately overcome by stricter controls in the slice preparation and processing. But as progress is made to higher packing densities in IC's, through the use of finer device geometries, slice distortion becomes of greater significance in pattern registration and it becomes important to understand the nature and magnitude of the distortions that occur in the slice during the fabrication process.

Slice distortion can arise at various stages in the fabrication process and be caused in a variety of ways. It can be caused by stresses in the surface layers on the slice; by poor temperature control at the sequence of mask exposure stages; or by mechanical effects, such as occur, for example, when clamping the slice and mask during an in-contact pattern exposure.

This paper considers the importance of silicon slice distortions, due to grown or deposited layers on the surfaces of the slice, in relation to the required pattern registration in 1µm IC geometries.

2. IC DESIGN TOLERANCES

As a rough guide to the tolerable distortion for 1µm geometries, the overall tolerance in the position of the edge of a 1µm wide contact window in a 2µm wide diffused-region will be about ±0.25µm where, as is normally the practice in automatic-alignment exposure systems, each mask is aligned to the same marker pattern on the slice. Although, naturally, slightly different tolerances are adopted for different technologies. This overall tolerance covers errors from a number of sources: from pattern placement errors on

+ The authors are with
the mask; misalignment of the mask and slice at the exposure stage; the control on the resist exposure and development; the control on the oxide etch process; and of course, errors due to slice distortion.

Thus the errors due to distortion in the slice should be only a fraction of the total registration tolerance, say no more than a range of 0.15μm, corresponding to a change in the slice diameter of 0.3μm, that is a strain of 3.10⁻⁶ in a 100mm slice (or, incidentally, about the same distortion that is caused by a 1°C change in the slice temperature for the 100mm slice). Whilst already some exposure machines can make corrections for slice distortions which occur during the processing, the tolerance for 1μm geometry does give a useful comparison in the assessment of the general problem of distortion.

3. ELASTIC AND NON-ELASTIC DISTORTION

Distortion of the silicon slice can be elastic or non-elastic depending on whether the yield stress of the silicon is exceeded. The yield stress of silicon depends strongly on temperature as illustrated in Figure 1. (The values of yield stress in the indicated band have been taken from the literature (1-6)). At slice strains in the 10⁻⁶ range, which are appropriate to 1μm IC geometry, the diagram indicates that the slice itself will experience only elastic distortion. But, because the strain in the layer itself is 5 x 10² to 10³ higher than that in the silicon substrate the possibility of non-elastic distortion in some highly-stressed, deposited, layers cannot be ruled out and this may cause damage to the underlying silicon.

In the region of elastic deformation and for uniform isotropic stresses in the layers and the slice, the simple theoretical situation (7,8) is shown in Figure 2. For the slice with equally stressed layers on front and back surfaces, as occurs, for example in thermal oxidation, the stresses are balanced and the slice is deformed so that the diameter is either increased or decreased depending on whether the surface stresses are tensile or compressive. The change in diameter, ΔD, is;

\[ ΔD = \frac{D.2t_L. (1-\nu_s)S_o}{t_s E_s} \]

where, \( t_L \) and \( t_s \) are the thickness of layer and the substrate, \( S_o \) is the applied stress in the layer and \( E_s, \nu_s \) are the elastic constants of the silicon. With a single layer the unbalanced stress in only one surface of the slice causes the slice to bow with a magnitude \( Y \), given by:

\[ Y = \frac{1}{2} D^2 \frac{t_L (1-\nu_s)}{E_s^2} \frac{S_o}{E_s} \]
The magnitude of the layer stress depends, in general, on the layer material and the growth or deposition conditions. The elastic quantity \((1-v_s)/E_s\) is invariant, for silicon, for directions in both (100) and (111) planes (9).

The bow has circular symmetry and the variation of the curvature along a diameter is given by:

\[
y = \frac{3.\tau L_2}{t_s} \frac{(1-v_s)}{E_s} r^2
\]

where \(y\) and \(r\) are defined in Figure 2. The variation of curvature is parabolic.

When the bowed slice is flattened by a suitable frictionless chuck at a mask exposure stage, there is still a change of slice diameter from the unstrained value and this is half the value of the in-plane distortion for the slice with equal layers on both surfaces.

The ratio of the slice bow to the change of diameter of the flattened slice is:

\[
Y/\Delta D = \frac{3}{4} \frac{D}{t_s}
\]

The usual run of silicon slices have a diameter to thickness ratio, irrespective of diameter, of about 150 to 200 and the bow due to a stressed surface layer is expected to be 100 or 150 times the change of diameter (from the unstrained value) in the flattened slice. Thus for elastic deformation the measured changes of bow can be used to estimate the in-plane distortion and this is particularly useful where the diameter change is expected to be very small.

4. STRAINS IN OXIDISED AND DIFFUSED LAYERS

For interface stresses due to thermal oxide and diffused layers the strain in the slice can be calculated.

4.1 Thermal oxide layers

For a thermally grown oxide layer the strain in the silicon may be calculated from the differential thermal-contraction of the oxide and the silicon assuming that the layers are unstressed at the oxidation temperature (10,11) and that the stress is developed as the slice and oxide are cooled, from the oxidation temperature, over a range of, say, \(1000^\circ\text{C}\).

Figure 3 shows the calculated change in diameter of 100mm diameter, 500\(\mu\text{m}\) thick (100) silicon slice as a function of the thickness of
the thermal oxide. The basic expression for the change of diameter of the slice is:

\[ \Delta D = \frac{2t_L}{s} \frac{E_s}{E_s(1-v_s)} \frac{(\alpha_s - \alpha_L)T}{s} \]

where, \( E_s/(1-v_s) \) and \( E_L/(1-v_L) \) are the elastic moduli for the silicon and the silicon oxide, \( \alpha_s \) and \( \alpha_L \) are the thermal expansion coefficients and, \( T \) is the temperature range over which the slice strain is developed.

The experimental points were measured, for 505\( \mu \)m thick (100) slices, using a prototype Philips electron-beam writing machine. The agreement with the calculated line is satisfactory. Measurements on (111), 100mm, slices show lower distortion in agreement with the higher value of \( E_s/(1-v_s) \) for the (111) plane.

For oxide thicknesses up to say half a micron, that is, a total oxide thickness of 1\( \mu \)m, the change in diameter is less than 0.3\( \mu \)m - or a possible contribution to pattern misregistration of 0.15\( \mu \)m at the edges of the slice. This compares with the maximum allowable total distortion of 0.15\( \mu \)m for a 1\( \mu \)m IC geometry. So oxide could be a problem. However, the distortion is isotropic and in suitable equipment can be compensated for by magnification control in the exposure of the mask pattern.

When the oxide is removed from one side of the oxidised slice the slice begins to bow. Figure 4 shows the measured variation of slice bow, for a 100mm (100) slice, as the original 2\( \mu \)m layer of thermal oxide was incrementally removed from one surface. The full line is the calculated variation for the particular slice parameters. The change of bow is 45\( \mu \)m of bow per micron of oxide removed. (The initial oxide in this sample is, of course, considerably thicker than is usual for 1\( \mu \)m IC geometries).

Figure 5 shows the measured variation of bow over a slice diameter for the 2\( \mu \)m layer. The full line is a parabola fitted to the measured points.

The measured ratio of bow to change of diameter is very close to the calculated value of 150.

Thermally oxidised silicon slices follow closely the distortion behaviour predicted by the simple elastic theory.

4.2 Diffused layers

In diffused layers each dopant atom causes a local strain in the host lattice. The resultant strain in the silicon slice can be calculated
by summation over the dopant distribution as has been done by McQuae and Brown (13), to give the bow of the slice for diffusion into one side of the slice. Or, if we require the in-plane distortion for the flattened slice it can be calculated as if the total dopant concentration - due to layers in the back and front of the slice - is uniformly distributed through the slice. Figure 6 shows the calculated change in diameter for total dopant levels of various dopants for 100um, 500um thick, silicon slices based on lattice strain constants measured or estimated by various authors (14,15,16).

As device geometries are made smaller, the diffused layers become progressively shallower and for 1um geometries the dopant concentration will be about, or less than \(10^{16}\) atoms per square centimetre. The corresponding change in slice diameter (Figure 6) is less than 0.1um, or a pattern misregistration of half this, 0.05um, for these dopant species.

In common with other authors (17) we find significant variations in the measured strain due to diffused layers. For high surface levels in diffused phosphorus layers the strain depends on the deposition process and for a particular process the measured strain deviates from the predicted, direct proportionality with dopant concentration. For example, Figure 7 shows the strain in the flattened slice, obtained from bow measurements, for a deposition and drive-in, using a POCI source, into one face of 50mm silicon slices. However in the region of interest, that is below \(10^{16}\) atoms cm\(^{-2}\), the measured strains are close to the predicted line and less than 0.5 x 10\(^{-6}\) (The equivalent tolerable strain in 50mm slices for 1um geometries will be 6 x 10\(^{-6}\) for the allowable change in diameter of 0.3um).

5. DEPOSITED LAYERS

The slice strains generated by deposited layers are, in general, a combination of thermal and intrinsic strains. Figure 8 shows the variation of strain in the flattened slice (obtained from bow measurements) with the thickness of the layer deposited onto one side of the slice; for nitride and metal layers. The strains are both positive and negative. Even where the thermal strain is small, for example, CVD nitride - where the thermal expansion coefficients of the nitride and the substrate are very little different - the intrinsic strain can be very high (18,19). The strains can be very sensitive to the deposition conditions and so are not so readily calculable as thermal oxide or diffused layer strain.

The strains in some deposited layers reach high values of 10\(^{-6}\) for small thicknesses and particular attention needs to be paid to avoid excessive strains, at the mask exposure stage, following the deposition of some layers. Silox layers deposited at low temperatures show very little strain but the subsequent
densification heat treatment gives rise to differential strain. Figure 9 shows the increase of slice bow as silox layers, 0.8\mu m thick, are densified for 15 minutes at successively higher temperatures. At 1000\degree C the slice bow approaches the bow expected for a slice with the same thickness of thermal oxide on one side of the slice.

6. MISREGISTRATION DUE TO DEVICE PROCESSING

Pattern misregistration from slice distortion is due to a change in slice distortion between the two successive mask exposures. This change in distortion, in general, results from a combination of individual process steps each of which can make some contribution to the slice distortion.

For example, Figure 10 shows the measured change in slice bow, and the change in slice diameter (for the flattened 50mm slice) estimated from measurements of slice bow and oxide thickness due to an oxide pattern etch, a phosphorus diffusion and drive-in, the stripping of the oxide and re-oxidation before the next mask exposure.

The bow arises from the imbalance of stresses at the back and front of the slice. The change of diameter of the flattened slice is due to the sum of the stresses in the phosphorus layer and in the oxide layers on the front and back surface of the slice.

The changes in bow are readily explainable.

The initial increase in slice diameter (\Delta D), which is about 0.2\mu m, is due to the thermal oxidation, this distortion is approximately halved when the oxide on the back is etched away whilst the circuit pattern is being etched on the front of the slice. The further increases in diameter at the phosphorus deposition and drive-in are due to both the phosphorus and the accompanying increases in oxide thicknesses. After the masking and back oxide layers have been removed the strain in the slice is decreased and the residual strain of 0.2\mu m is entirely due to the phosphorus (in this case, due to the high surface concentration the layer produces a tensile stress) (17). There is a final increase in strain as the slice is re-oxidised. It is important to note that the in-plane distortion between the exposure stages, that is the oxidation stages, is in fact, only about 0.1\mu m.

In a similar way, the complete profile of the in-plane distortion throughout the whole IC fabrication process can be obtained and the contribution of distortion to the pattern misregistration can be assessed and if necessary the process modified to bring the distortion to acceptable levels.
7. SUMMARY AND CONCLUSIONS

Strains introduced as a result of processing in silicon slices could significantly affect the pattern registration of IC's designed with 1µm geometries.

Oxide layers present a particular problem as they are fundamental to planar technology. Thermal oxide up to about 1/2µm thick is probably acceptable, since some oxide will be present at each mask exposure stage. But for processes requiring thick oxides, such as oxide isolation, the distortion is likely to be significant.

Changes in lattice constant due to the incorporation of dopants is unlikely to be significant with the shallow layers used in most LSI processes. Any residual effects could be greatly reduced by avoiding diffusion into the back of the slice at intermediate stages in the schedule.

Due regard will have to be paid to very high strains in some deposited layers, although special techniques such as lift-off definition can probably reduce or avoid pattern misregistration.

Acknowledgements

The authors wish to thank their colleagues at Philips Research Laboratories who helped with some of the practical work and in particular, Mr. J.P. Beasley and his colleagues who provided the distortion measurements made on the electron beam pattern generator.

REFERENCES

Fig 1. Yield stress of Silicon

Equal surface stresses

**Equation:**
\[ \Delta D = D \frac{t_L}{t_s} \left( \frac{1-v_S}{E_S} \right) S_0 \]

One-sided stress

**Equation:**
\[ Y = \frac{3}{4} D^2 \frac{t_L}{t_s^2} \left( \frac{1-v_S}{E_S} \right) S_0 \]

**Equation:**
\[ y = 3 \frac{t_L}{t_s^2} \left( \frac{1-v_S}{E_S} \right) S_0 r^2 \]

Fig 2. Elastic distortion of the Silicon slice.
1.4

1.2

1.0

0.8

0.6

0.4

0.2

0.0

0.5 1.5 2.5 3.5 4.5

Total oxide thickness (μm)

100 mm (100) slice

500 μm thick

Fig. 3 Change of slice diameter with oxide thickness.

Fig. 4 Change of slice bow with reducing oxide thickness.
Fig 5. Silicon slice curvature.

Fig 6. Variation of slice diameter with dopant concentration.
Fig 7. Comparison of measured and predicted strain in diffused-phosphorus slice.
Fig 8. Measured in plane strain due to deposited layers.
Fig. 9 Change of slice bow due to 'silox' densification

Fig. 10 Change in slice distortion during phosphorus diffusion process.

Oxidation (0.36 μm)
Remove all oxide
Phosphorus drive-in (5Ω/□)(2 μm)
Phosphorus deposition (15Ω/□)
Pattern etch
Oxidation (0.4 μm)
Fresh slice

9 μm

0.06 μm

0 0.2 0.4

ΔD (μm)
A SIMPLE BUT PRECISE OPTICAL METHOD FOR THE DETERMINATION OF OVERALL LATERAL WAFER DISTORTION

N. Gellrich +

1. INTRODUCTION

One of the problems, which arise in VLSI circuit fabrication is wafer distortion resulting from elastic deformation. Elastic deformation of the wafer goes along for instance with the deposition of films. The resulting wafer distortion does severely affect the achievable overlay accuracy in VLSI circuit fabrication. To satisfy the need of having a simple method for the determination of wafer distortion, we will show that this problem can be solved by the determination of wafer curvature. This method is much less expensive and time consuming than direct measurements with aid of an electron beam microfabrication system /1/.

2. STRAIN DISTRIBUTION IN FILM AND SUBSTRATE

A film of thickness $t_f$ on a substrate of thickness $t_s$ is assumed to be in a plane stress state (fig.1). This stress can be described by a tensor $\sigma_{ik}^0 (x,y,z)$ with $i,k = x,y$, while the $z$ component of the tensor vanishes. This stress in the film causes deformation of the substrate and also of the film. The displacement vector, which describes this deformation is denoted by $u_x(x,y), u_y(x,y), u_z(x,y)$. Then the strain tensor including terms of second order are given by /2/

$$\varepsilon_{ik}(x,y,\xi) = A_{1k}(x,y) + \Delta A_{1k}(x,y) + \frac{\xi}{s} B_{1k}(x,y) \quad (1)$$

with

$$A_{1k} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_k} - \frac{\partial u_k}{\partial x_i} \right)$$

$$\Delta A_{1k} = \frac{1}{2} \left( \frac{\partial u_z}{\partial x_i} \right) \left( \frac{\partial u_z}{\partial x_k} \right)$$

$$B_{1k} = - \frac{\partial^2 u_z}{\partial x_i \partial x_k}$$

$\xi$ is the distance from the interface film/substrate after bending. Equation (1) can be solved using Hooke's law and conditions of equilibrium while the second term can be neglected for small deflection $u_z(x,y)$.

Considering a stress distribution which is homogeneous and isotropic in the $x,y$ plane ($\sigma_{xx}^0 = \sigma_{yy}^0 = \sigma_{xy}^0 = 0$)

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If the ratio of film thickness $t_f$ to substrate thickness $t_s$ is equal to or less than $10^{-2}$, a linear approximation of the solution of equation (1) is /3/:

$$A = -\frac{\frac{4}{3} t_f <\sigma^o>}{\nu t_s}$$

$$B = -\frac{\frac{6}{3} t_f <\sigma^o>}{\nu t_s^2}$$

with $<\sigma^o>$ averaged over film thickness and $\nu = \frac{E}{1-\mu}$, $E$ Young's modulus, $\mu$ Poisson's ratio.

If the stresses are isotropic and homogeneous the substrate surface is nearly spherical and then $B$ is given by the reciprocal of the radius of curvature. Inserting this in equation (2) yields

$$A = \frac{2}{3} t_s \cdot \frac{1}{R}$$

As the strain at the interface film/substrate is determined $\xi = 0$ and therefore

$$\varepsilon = \frac{2}{3} t_s \cdot \frac{1}{R}$$

Thus a simple formula is deduced from the Theory of Elasticity which allows for the calculation of wafer distortion, if substrate thickness and wafer curvature have been measured. After flattening by pure bending $\varepsilon$ decreases to

$$\varepsilon = \frac{1}{6} t_s \cdot \frac{1}{R}$$

but is still determined by the curvature measured before flattening.

Furthermore calculations show that this equation is still valid, if the wafer is covered with films of the same thickness $t_f$ on both sides resulting in a flat wafer. However, because the doubled thickness, $2 t_f$ instead $t_f$,

$$\varepsilon = \frac{1}{3} t_s \cdot \frac{1}{R}$$

if $R$ is measured with only one of the both surface layers of thickness $t_f$. 

\[
\begin{align*}
A_{xx} &= A_{yy} = A \\
B_{xx} &= B_{yy} = B \\
A_{xy} &= B_{xy} = 0.
\end{align*}
\]
3. MEASUREMENT OF WAFER SURFACE PROFILE AND CALCULATION OF WAFER CURVATURE

So far it has been shown, that the problem of determination of wafer distortion is equivalent to the problem of determination of wafer curvature. However, this problem is easily to solve after the surface profile is measured. Measurements are done with aid of a laser interferometer. Change in surface profile is visualized by fringes, which indicate height differences equal to half the wavelength of the light used, in our case to 316 nm (fig.2).

In this figure a 3"-Si-wafer is lying on a highly flat quartz plate. The wafer is still in the state as it was delivered by the producer and can be characterized as an extremely flat wafer. If the wafer exhibits a wedge shape the flat quartz plate is tilted such that the number of fringes is minimized and their shape is most close to circles. From these pictures we obtain the surface profile $\Delta h$ versus location along a diameter of the wafer (fig.3). $\Delta h$ is the relativ distance from an arbitrary plane, which is parallel to the reference mirror plane of the interferometer, to the wafer surface.

Surface profile $\Delta h$ obtained from this interferogram is plotted in fig.4. The wafer is extremely flat even though bow of the wafer was not prohibited by any flattening techniques, like inserting the wafer into a vacuum chuck.

This procedure has to be repeated after a processing step, which causes wafer bowing and consequently distortion. This profile is now fitted by a least square fit method to a circle of radius R. The result is given in fig. 5. The radii of curvature are 60 and 65.3 m parallel and perpendicular to the flat respectively. However, both radii should be equal, since in case of this $\langle 100 \rangle$-Si-wafer elastic constants are isotropic in the $\langle 100 \rangle$-plane. After taking into account the original nonflatness as seen in fig.4, the radii calculated are now 58.2 and 59.6 m respectively (fig.6). Correspondingly the fit is significantly improved, although there was only very little correction applied due to the original nonflatness of about 2 $\mu m$ peak to valley.

4. RESULTS OF MEASUREMENTS

These evaluations of curvature have been performed on many wafers, each with different oxide thickness. In fig. 7 the results are shown and it is seen that there is a linear relation between curvature and oxide thickness. This relation is expressed by

$$\frac{1}{\frac{R}{m^{-1}}} = (6.3 \pm 0.1) \cdot 10^{-2} \frac{t_f}{\mu m} . \quad (6)$$

If we insert equation (6) into equation (4) wafer distortion $\varepsilon_{eva}$-
Equation (7) for the flattened wafer:

$$\frac{\varepsilon}{\text{cm}} = (40.4 \pm 0.6) \frac{t_f}{\mu\text{m}}.$$  \hspace{1cm} (7)

For given processes formula like that allows to predict the distortion.

In another experiment gratings were etched into the SiO$_2$ film leaving SiO$_2$ patches and thereby the curvature was reduced. The gratings have been lines of width 1 mm and various distances between the lines. These gratings have been etched into the SiO$_2$ film and the influence of spatial SiO$_2$ coverage on wafer bow is seen in fig. 8. The gratings have been chosen to simulate an uniform distribution of SiO$_2$ patches. We expect that there is no dependence of the curvature on the orientation of the grating provided that percentage of area covered remains constant, since the elastic constants are isotropic in the <100>-plane. In fact in the experiments such dependence is not found. Instead the curvature is directly proportion to the percentage of area covered by SiO$_2$. That again indicates that a prediction of wafer bowing and distortion can be achieved.

5. COMPARISON WITH DIRECT MEASUREMENT BY EBMF II

The applied method of determining wafer distortion is an indirect and overall measurement technique, insensitive to local variations. So the results are compared to those of the direct measurements done with the electron beam machine. As an example 385 μm thick Si-wafers covered with SiO$_2$ are considered. For the measurements with aid of the electron beam machine the wafers were covered with 1.5 mm SiO$_2$ on both sides. In order to get corresponding results from measurements of curvature the SiO$_2$ hat to be removed from the back.

<table>
<thead>
<tr>
<th></th>
<th>Measurements of curvature</th>
<th>direct with aid of EBMF II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>to flat</td>
</tr>
<tr>
<td>$\varepsilon_{100}$</td>
<td>$(121 \pm 2)$ nm/cm</td>
<td>$(135 \pm 7)$ nm/cm</td>
</tr>
<tr>
<td>$\varepsilon_{111}$</td>
<td>$(95 \pm 2)$ nm/cm</td>
<td>$(90 \pm 7)$ nm/cm</td>
</tr>
<tr>
<td>$\frac{\varepsilon_{100}}{\varepsilon_{111}}$</td>
<td>$1.27 \pm 0.05$</td>
<td>$1.5 \pm 0.2$</td>
</tr>
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</table>
The results are different for <100> and <111> oriented wafers. The ratio of $E_{100}$ to $E_{111}$ determined by measurements of curvature is 1.27. This ratio has to be proportional to the ratio of $\nu_{111}/\nu_{100}$ with $\nu = \frac{E}{1-m}$, Young's modulus and $m$ Poisson's ratio. The estimated value is 1.3 in excellent accordance with those given by Brantley /4/.

The agreement is not of the same excellence for the direct measurements with the electron beam system. This is most probably due to the strong influence of small temperature variations on the accuracy of direct measurements. In case of the measurement of curvature temperature differences near room temperature do not affect the accuracy because the distance to the growth temperature of the oxide layers is great in any case. That is a further feature of the new measurement technique.

6. CONCLUSION

It is shown, that overall lateral wafer distortion can very exactly be determined by measurements of the radius of curvature. In contrast to direct measurements with an electron beam machine the measurements are not sensitive to temperature variations, and much easier and cheaper to perform. The measurements give rise to the statement, that lateral wafer distortion due to films deposited can be predicted from parameters like film thickness, film material, wafer thickness and orientation of the wafer surface.

Wafer distortion predicted in this way may advantageously be used in mask making to improve process yield especially if wafer diameter increases and minimum line width decreases.

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The author thanks Prof. Dr. H. Beneking for his encouragement. Furthermore thanks are due D. Stephani and E. Kratschmer for stimulating ideas and for many fruitful discussions.

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Fig. 1: System film-substrate

Fig. 2: Interferogram of a 3"-Si-wafer
Fig. 3: Determination of surface profile $\Delta h$

Fig. 4: Curvature of the bare wafer
Fig. 5: Curvature of an oxidized wafer

Fig. 6: Curvature of an oxidized wafer corrected in consideration of the curvature of the bare wafer
Fig. 7: Influence of SiO₂ thickness on wafer bow

Fig. 8: Influence of partial SiO₂ coverage on wafer bow
REACTIVE ION-BEAM ETCHING OF LiNbO₃

Shinji Matsui, Toshiya Yamato, Hiroaki Aritome and Susumu Namba

A reactive ion-beam etching technique using freon gas is developed for microfabrication in LiNbO₃. In particular, CHF₃ reactive ion-beam etching using AZ1350 photoresist mask is a very useful microfabrication technique for LiNbO₃. The ratio of the etching rate of LiNbO₃ to AZ1350 photoresist at normal incidence for CHF₃ gas is about 5 times as large as that for Ar gas. This high ratio is utilized to fabricate LiNbO₃ blazed gratings.

1. INTRODUCTION

For integrated optics, LiNbO₃ is an attractive material because of its high electro-optic and acousto-optic coefficients. The microfabrication technique of LiNbO₃ so far reported are mechanical grinding[1], Ar ion-beam etching[2], ion-bombardment-enhanced etching[3, 4] and CF₄ plasma etching[5]. However, the mechanical grinding method damages the surface of LiNbO₃ and put limitation on a surface geometry to be fabricated. In an Ar ion-beam etching, the accuracy of a wave-guide profile is limited by mask shrinkages during the etching because the ratio of an etching rate between LiNbO₃ and mask materials is very low. In an ion-bombardment-enhanced etching, the accuracy of the pattern width is better than that in an Ar ion-beam etching but the etched depth is limited by the projected range of the ion. The ion-bombardment-enhanced etching process must be repeated to etch to a depth of several hundred nm, which is necessary for a ridge waveguide. Plasma etching has the advantage that it does not attack mask. However, it is a completely isotropic etching and leads to a large degree of undercutting. In the case of a reactive ion-beam etching, it can be expected that the advantages of ion-beam etching and plasma etching are combined.

This paper reports, for the first time, the etching characteristics of LiNbO₃ by the reactive ion-beam etching and its application to fabricate blazed holographic gratings.

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2. EXPERIMENTS

The ion-beam etching apparatus, which was already reported in ref. (6), was used to measure the etching rates of LiNbO₃, Shipley AZ1350 photoresist and Cr for CHF₃, CF₄, and Ar gases. LiNbO₃ used in this experiment was Y cut and mirror finished by chemi-mechanical polishing.

Figure 1 shows the fabrication process of LiNbO₃ blazed gratings. Gratings were made holographically in the 0.13µm thick AZ1350 layer on the LiNbO₃ substrate by using a He-Cd laser of 325 nm.

Fig. 1 Fabrication process of LiNbO₃ blazed gratings by CHF₃ reactive ion-beam etching.
3. EXPERIMENTAL RESULT AND DISCUSSION

The measured etching rates for CHF$_3$, CF$_4$ and Ar gases are given in Table I. A number of interesting facts can be seen:

1. The enhancement of the etching rate of LiNbO$_3$ for CHF$_3$ and CF$_4$ reactive ion-beam etching is apparent. The etching rate of LiNbO$_3$ for CHF$_3$ and CF$_4$ gases is about 2 times larger than that for Ar gas. On the other hand, the etching rate of Cr is independent of gas species because of the nonreactive character of Cr.

2. AZ1350 photoresist shows very low etching rate for CHF$_3$ gas in comparison to those for Ar and CF$_4$ gases. Therefore a relatively thin layer of photoresist can act as a reliable etching mask for fabricating a deep structure.

3. The ratios of etching rates of LiNbO$_3$ to AZ1350 for CHF$_3$, CF$_4$ and Ar gases are 2.6, 1.2 and 0.44, respectively. The value for CHF$_3$ gas is about 5 times as large as that for Ar gas. CHF$_3$ reactive ion-beam etching is very useful technique for microfabrication of LiNbO$_3$.

4. The ratios of etching rates of LiNbO$_3$ to Cr for CHF$_3$, CF$_4$ and Ar gases are 2.6, 2.8 and 1.6, respectively. Cr film is also useful mask material for the reactive ion-beam etching.

Another useful method of microfabrication of LiNbO$_3$ using metal masks has been reported by Minakata[7]. He has shown that the maximum ratio of etching rate of LiNbO$_3$ to Ti obtained by admixing O$_2$ gas in Ar gas was about 5 at a total pressure of $1 \times 10^{-4}$ Torr and an acceleration voltage of 1.1kV. But, Ar+O$_2$ ion-beam etching is not a useful technique in the case of using etching mask of AZ1350 photoresist, because O$_2$ gas gives rise to an increase in the etching rate of AZ1350 photoresist. CHF$_3$ reactive ion-beam etching is particularly a useful technique in the case of using etching mask of AZ1350 photoresist.

Table I Etching rates for LiNbO$_3$, AZ1350 and Cr at normal incidence at a pressure of $8 \times 10^{-5}$ Torr. The acceleration voltage and the current density are 500 V and 0.4 mA/cm$^2$, respectively.

<table>
<thead>
<tr>
<th>gas</th>
<th>LiNbO$_3$ ($\AA$/min)</th>
<th>AZ1350 ($\AA$/min)</th>
<th>Cr ($\AA$/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHF$_3$</td>
<td>130</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CF$_4$</td>
<td>140</td>
<td>120</td>
<td>50</td>
</tr>
<tr>
<td>Ar</td>
<td>80</td>
<td>180</td>
<td>50</td>
</tr>
</tbody>
</table>
In the case of CF$_4$ plasma etching, it was reported[5] that a layer of dust was formed on the etched surface of LiNbO$_3$ and a rough surface and a decrease of etching rate were caused by this dust layer. However, such phenomena were not observed for the reactive ion-beam etching, since it includes not only a reactive chemical etching but also a sputtering.

Figure 2 shows the etching time dependence of the etched depth for LiNbO$_3$ using CHF$_3$ gas. This figure indicates that the etched depth of LiNbO$_3$ is proportional to the etching time for CHF$_3$ gas. The etched surface of LiNbO$_3$ for CHF$_3$ gas is very smooth.

![Graph showing etched depth vs. time for LiNbO$_3$ for CHF$_3$ gas at a pressure of 8x10$^{-5}$ Torr.](image)
Figures 3, 4 and 5 show the angular dependence of the etching rates for LiNbO$_3$, AZ1350 and Cr for Ar, CF$_4$ and CHF$_3$ gases at a pressure of $8 \times 10^{-5}$ Torr, respectively. The angular dependence of AZ1350 photoresist for Ar gas has a maximum value, but those for CF$_4$ and CHF$_3$ gases have not a maximum value. The angular dependence of LiNbO$_3$ also shows a similar tendency. The difference should have arisen because the etching mechanisms for CF$_4$ and CHF$_3$ gases include not only a sputtering but also chemical reaction. On the other hand, the angular dependence for nonreactive Cr is independent of gas species. The angular dependence for AZ1350 using CHF$_3$ gas is similar to that using CF$_4$ gas but the etching rate of AZ1350 for CHF$_3$ gas is very low compared with that for CF$_4$ gas.

Fig. 3 Angular dependence of the etching rates of LiNbO$_3$, AZ1350 and Cr for Ar gas.
Fig. 4 Angular dependence of the etching rates of LiNbO₃, AZ1350 and Cr for CF₄ gas.

Fig. 5 Angular dependence of the etching rates of LiNbO₃, AZ1350 and Cr for CHF₃ gas.
Figures 6 (a) and (b) show the SEM profiles of AZ1350J photoresist on LiNbO$_3$ after CHF$_3$ reactive ion-beam etching and Ar ion-beam etching. The etching masks of AZ1350J photoresist used in Ar ion-beam etching and CHF$_3$ reactive ion-beam etching were the same and the inclination angle of AZ1350J photoresist mask was about 45 degrees. Other etching conditions were also the same. The acceleration voltage, current density, gas pressure and etching time were 500 V, 0.4 mA/cm$^2$, 8x10$^{-5}$ Torr and 20 min, respectively. Figure 6 shows that the inclination angles of LiNbO$_3$ etched by CHF$_3$ and Ar gases are about 80 degrees and 15 degrees, respectively.

The relation between an inclination angle of mask and that of substrate can be calculated by using angular dependence of etching rates [8]. In the case of using AZ1350 photoresist mask with the inclination angle of 45 degrees, the calculated results for the inclination angles of LiNbO$_3$ using CHF$_3$ gas and Ar gas are 72 and 12 degrees, respectively. These calculated results agree approximately with the experimental results. From Fig. 6, it is also clear that the mask shrinkage for CHF$_3$ gas is very small compared with that for Ar gas. Figure 6 indicates that CHF$_3$ reactive ion-beam etching using AZ1350 photoresist mask is very useful microfabrication technique for LiNbO$_3$.

(a) After CHF$_3$ ion-beam etching  (b) After Ar ion-beam etching

Fig. 6 SEM profiles of AZ1350J photoresist on LiNbO$_3$ after CHF$_3$ reactive ion-beam etching and Ar ion-beam etching.
The Ar ion-beam etching technique has not been applied to a fabrication of LiNbO$_3$ blazed gratings, because the etching rate of LiNbO$_3$ is lower than that of AZ1350 photoresist etch mask. Figure 7 shows the SEM profile of a LiNbO$_3$ blazed grating with a period of 860 nm produced by the CHF$_3$ reactive ion-beam etching. The blaze angle can be controlled by changing the beam angle between the ion beam and the substrate. LiNbO$_3$ blazed grating is applied to produce a grating coupler with high efficiency.

![LiNbO$_3$ BLAZED GRATING \( \Lambda = 860 \text{ nm} \)](image)

**Fig. 7** Groove profile (SEM picture) of LiNbO$_3$ blazed grating produced by CHF$_3$ reactive ion-beam etching. The ion-beam angle is 60 degrees and the blaze angle obtained is 17 degrees.

4. CONCLUSION

Reactive ion-beam etching technique using freon gas was developed for microfabrication of LiNbO$_3$. This technique is very useful technique for microfabrication of LiNbO$_3$. The ratio of an etching rate of LiNbO$_3$ to AZ1350 at a normal incidence for CHF$_3$ gas is about 5 times larger than that for Ar gas. The CHF$_3$ reactive ion-beam etching technique using AZ1350 mask can be applied to a fabrication of LiNbO$_3$ blazed grating and various devices for integrated optics.

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EFFECTS OF EXCITATION FREQUENCY IN PLASMA ETCHING

R.H. Bruce and A.R. Reinberg

In Cl₂ discharges, an anisotropic etchant for silicon, etching is strongly affected by excitation frequency. Electrical and mass spectral measurements from 15 kHz to 27 MHz suggest that ions cease to respond to the high frequency fields.

INTRODUCTION

The excitation frequency is an interesting process parameter that can influence both the chemical and physical properties of a discharge. Commercially available plasma etching machines operate at several different frequencies and frequency dependent results have been reported in previous work (1-3). This paper presents a study of silicon etching by Cl₂ discharges along with diagnostic measurements of the discharge. Measurements of the electrical properties and ion energies are used to physically describe the discharge, and measurements of the ion composition suggest how these conditions relate to the plasma composition.

The study encompasses excitation frequencies from 15 kHz to 27 MHz. The etch rate and mass spectral measurements are made under identical conditions in equipment with commercial applications. The discharge composition sampled by the mass spectrometer is representative of that at the wafer surface.

EXPERIMENTAL METHOD

The apparatus, Fig. 1, used to make the diagnostic measurements consists of a parallel plate etching reactor connected by a pinhole to a differentially pumped chamber containing a mass spectrometer. The etching reactor is a typical system which has a top electrode attached to the RF generator and a lower grounded electrode on which the sample sits. Both electrodes can be

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water-cooled and are spaced 1 cm apart for this work. The upper electrode is 15 cm in diameter while the lower electrode is 7.5 cm in diameter. An insulating annulus surrounds the lower electrode to confine the discharge to the wafer. Etching gas is introduced through the top electrode and exits radially about the lower electrode through small holes in the insulation. A 16 cm diameter insulating cylinder forms the chamber wall. The total volume of the chamber is about 10³ cm³.

The RF power is coupled to the reactor with different circuits at high and low frequency. At high frequencies (above 1.0 MHz), a \(\pi\)(CLC) network is used, while at low frequency (below 1.0 MHz) a transformer is used. In both cases, the a.c. electrode is d.c. grounded. To insure that power delivered to the load is the same in both frequency regions, the emission from a 75 W light bulb is first calibrated using d.c. and then used as a standard to calibrate the RF power meters through the appropriate coupling circuits. The light bulb which simulates the discharge is connected in parallel to the reactor electrodes while the reactor is at atmospheric pressure, so no discharge is present.

The orifices connecting the reactor to the mass spectrometer chamber consist of several 0.04 mm diameter holes drilled in nickel foil 0.02 mm thick. Most of the work has been done at 0.3 Torr, where the mean free path for neutral molecules is 0.4 mm. Consequently the orifice diameter is much smaller than the mean free path, and collisionless flow through the orifices is dominant. The mass spectrometer chamber is situated below the orifices. This chamber is differentially pumped by a 100 l/sec turbomolecular pump and can be evacuated to the low 10⁻⁸ Torr range. The number of orifices used insures that the operating pressure in the mass spectrometer chamber is in the low 10⁻⁶ Torr range where the mean free path is tens of meters.

Ions pass through the orifice, and since the mass spectrometer is close and aligned to the orifice, the ion signal is quite strong and no additional collection optics are needed for detection. During ion detection, the mass spectrometer ionization chamber is switched off. To analyze the energy of the ions, three grids are inserted between the mass spectrometer and the orifices. A potential is applied to the middle grid, while the other grids are grounded to minimize the interference of this field with both the trajectory of the incident ions above and the entrance of the ions to the quadrapole analyzer below. This middle grid is made from two parallel 90% transmission grids to minimize field penetration.
MEASUREMENTS

Silicon Etching

Silicon etching has been investigated with pure Cl₂ at 0.3 Torr. The discharge is confined above a 3" wafer which covers the lower electrode. The wafers are masked with thermal oxide. Etch rates are determined by surface profiling. To insure reproducible results especially at high frequency, the wafers are dipped in buffered hydrofluoric acid to remove native oxide immediately prior to etching (4).

The effect of excitation frequency on etch rate at constant power is shown in Fig. 2. The etch rate is faster at frequencies below about 400 kHz. Vertical wall profiles are found in single crystal silicon independent of the frequency employed.

Electrical Measurements

Current and voltage measurements are made at the a.c. electrode where a coupling toroid centered on the power lead and a high frequency probe are used to sample respectively the alternating current and voltage which are displayed on a 50 MHz oscilloscope. The operating voltage is shown in Fig. 3 as a function of frequency. The current and voltage wave forms are shown in Fig. 4. The distorted current response at 100 kHz is representative of low frequency discharges while the more sinusoid shape at 13.56 MHz is representative of higher frequencies. The current and voltage are in phase at 100 kHz and about \( \frac{\pi}{2} \) out of phase at 13.56 MHz.

Ion Composition and Energy

The ion composition is measured by the mass spectrometer and is shown in Fig. 5 as a function of frequency. The signal due to Cl₂ appears to be independent of frequency while that from Cl appears to increase by a factor of 50 as the frequency is lowered from 27 MHz to 100 kHz. Note that the composition is measured after the ions pass through the sheath and consequently is not necessarily representative of the composition in the plasma because of additional ion-molecule collisions that may occur in the sheath, but it is representative of the ion composition striking the wafer.

The ion energy distributions determined by retarding potential measurements is shown in Fig. 6 for 100 kHz and 13.56 MHz. The incident ions have less energy at 13.56 MHz than at 100 kHz. In addition, at both frequencies the Cl ions exhibit larger concentrations at high energies than the Cl₂. This would be an expected result from charge exchange in the sheath, where the cross section
for resonant charge exchange between Cl$_2^+$ and the Cl$_2$ gas is expected to be larger.

**DISCUSSION**

A simple circuit diagram that describes the discharge is shown in Fig. 7a where $C_s$ is the sheath capacitance, $R_d$ is the discharge impedance and $R_S$ is a shunt impedance across the sheath. The diodes represent the high conductivity of electrons compared to ions. With the assumption that the plasma is highly conductive throughout the cycle and the electron response is fast compared to the oscillation frequency, the potential distribution across the reactor can be described by Fig. 7b (5). The equipotential plasma always assumes the most positive potential with respect to the rest of the system and oscillates coherently with the applied voltage.

The kinetic energy of an ion reaching the grounded electrode depends on whether it moves across the sheath slowly or quickly relative to the oscillating plasma potential. If the ions move quickly, then the maximum possible energy is the maximum plasma potential which is approximately equal to the amplitude of the operating voltage ($V_a$). If the ion is slow, then it will have a maximum energy equal to a time averaged value of the plasma potential. Since the plasma potential is pinned just above ground for the negative half cycle (Fig. 7c), the average potential is $V_a/\pi$ for a sinusoidal response during the positive half cycle. Fig. 8 shows the measured ratio of the ion energy to the operating voltage amplitude as a function of frequency. As can be seen, it goes from 1 to 0.32 as the ions respond directly to the a.c. field at low frequency and only to an average at high frequency. Therefore, by lowering the excitation frequency, the ion energy can increase through two mechanisms: first the operating voltage increases and second the ions begin to respond to the a.c. field and consequently the energy transfer becomes more efficient.

At high frequencies (13.56 MHz), the discharge responds via the sheath capacitance to the applied voltage and the phase shift between the current and voltage is about $\pi/2$ (Fig. 4). As the frequency is lowered, the operating voltage must increase to adjust for the increasing sheath capacitive impedance until the ions can traverse the sheath during part of a cycle. At this point the phase difference is zero because the discharge is resistive. This is equivalent to shorting the diodes in Fig. 7a with the resistors $R_b$, as now both ions and electrons can traverse the sheath.
To balance loss of electrons due to diffusion, electrons must be gained either by ionization in the plasma or from secondary emission at the surfaces. The contribution of gain from surface events should increase at low frequency as the energy of the bombarding ions becomes large. Secondary electrons produced at the cathode in these high fields can create avalanche breakdown (6), which would account for the distorted in-phase current response (Fig. 4).

The higher fields at low frequency could account for the increase in the Cl signal relative to the constant Cl$_2$ signal as the frequency is lowered. The ionization energies for Cl$^+$ and Cl$_2^+$ are 15 eV and 11.5 eV respectively, which indicates a larger concentration of high energy electrons at low frequency. This change in electron energy distribution could have other effects on the chemical composition which may influence etching.

The silicon etching is very anisotropic at both high and low frequencies with no observable undercutting (Fig. 9), and consequently appears to be a "bombardment" induced process with a negligible chemical contribution. The frequency dependence of the silicon etch rate is similar to that of the ion energies (Fig. 3 and 4) which suggests that the change in etch rate is related to the change in ion energy as has been found with CF$_4$-O$_2$ mixtures and silicon (7).

ACKNOWLEDGEMENT

The authors are grateful to D. Flamm, D. Smith and J. Taillet, for stimulating discussions and to R. Reed for his contribution to work reported herein.
REFERENCES


5. Bruce, R.H., Taillet, J., to be published.


7. Smith, D.L., to be published.
Fig. 1 - Schematic of experimental apparatus

Fig. 2 - Silicon etch rate

Fig. 3 - Operating voltage amplitude and ion energy
Fig. 4 - Operating voltage and current wavefronts for 100 kHz and 13.56 MHz excitation

Fig. 5 - $\text{Cl}_2^+$ and $\text{Cl}^+$ energy distribution

Fig. 6 - $\text{Cl}_2^+$ and $\text{Cl}^+$ current
Fig. 7 - a) schematic of discharge circuit, b) electric potential distribution, c) plasma potential vs. phase of applied voltage

Fig. 8 - Ratio of maximum ion energy to operating voltage

Fig. 9 - Etching profiles in single crystal silicon
THE USE OF SADDLE-FIELD ION SOURCES FOR ETCHING SEMICONDUCTOR MATERIALS

P.J. ReveIl
G.F. Goldspink

Etch selectivities, etch rates and the erosion of the source components have been measured using two sizes of saddle-field sources with reactive and non-reactive gases.

1. SADDLE-FIELD SOURCES

The concept of saddle-field ion sources originated with the work of McIlraith1 who proposed and constructed a charged particle oscillator. The device consisted of a pair of wire electrodes equally disposed about the axis of a surrounding metal tube. Electrons escaping from the cathode describe long, stable, oscillatory paths before coming to rest at one of the anodes. Using this configuration, efficient ionisation of gas within the source is accomplished without the use of a magnetic field. When +4 kV was applied to the wire anodes and the tube was maintained at earth potential, a discharge was observed within the tube, through a gauze set in one end. The symmetrical, double discharge was seen to have a central "pinched" region, known as the "saddle point".

Following the construction of a more robust version of the early particle oscillators, Fitch et. al2 were able to produce a stable ion beam and to measure the current density profile and perform some preliminary etching experiments using argon as the sputtering medium.

The work which has been carried out between 1970 and the present has led to a greater understanding of the mechanisms involved in the saddle-field source3-7, optimisation of their design8-13, and the widespread use of the sources particularly for the preparation of surfaces for optical and electron microscopy14-17.

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Middx.
Devices utilising the saddle-field principle have been used as ionisation gauges\textsuperscript{18,19} and time of flight molecular beam detectors\textsuperscript{20}. Self-extraction of positive ions occurs at the cathode, the resultant beam being defined by the anode system. Sputter erosion of the cathode aperture does not, therefore, affect the characteristics of the source.

Due to the low chamber pressures required for operating these devices (\(10^{-4}\) to \(10^{-5}\) torr), well-defined beams can be produced with minimal scattering. As the devices are cold-cathode sources, there are no filaments to burn out. Neutralisation filaments are not required for electron flooding, as the capture of secondary electrons at the cathode aperture by the emergent ions produces beams that are largely neutral. This characteristic is of great value when insulating materials are to be etched as charge accumulation does not occur.

1.1 Equipment Details

Work will be described which has been carried out with two sources manufactured by Ion-Tech Ltd., the B 21 and a B 93. Characteristics and operating parameters for the two sources are shown in Table 1.

<table>
<thead>
<tr>
<th>SOURCE TYPE</th>
<th>Total beam current equivalent (\mu\text{A})</th>
<th>Cathode aperture (\text{mm} \times \text{mm})</th>
<th>Beam area (\text{cm}^2) at (\text{mm}) distance</th>
<th>Chamber pressure (\text{torr})</th>
<th>Pumping speed required (\text{L/sec.})</th>
<th>Gas injected (\text{cc/min atmospheric})</th>
</tr>
</thead>
<tbody>
<tr>
<td>B21</td>
<td>100 (\mu\text{A})</td>
<td>Rectangular, 10 x 1.5</td>
<td>6.6 at 75</td>
<td>(5 \times 10^{-4})</td>
<td>150</td>
<td>1.0</td>
</tr>
<tr>
<td>B93</td>
<td>10 (\mu\text{A})</td>
<td>Carbon grid, 2.4 mm # holes in 25 mm # disc.</td>
<td>62.2 at 150</td>
<td>(8.5 \times 10^{-5})</td>
<td>500</td>
<td>30</td>
</tr>
</tbody>
</table>

Much of the present work has been done with the B 21 source set at 75 mm (cathode aperture to target) as 56\% of the area of a static 38 mm diameter silicon wafer is exposed to the beam. This source is normally allowed to attain thermal equilibrium without forced cooling of anode or cathode.

The beam of the B 93 source is virtually neutral, the maximum input power is 1 kW and the cathode is water cooled.

A larger source is being developed which has water cooled anodes and cathodes, which will accept an input power of 10 kW.
2. SAMPLE PREPARATION

Experimental work has been concerned with etching the major constituents of existing semiconductor processes:

Aluminium films: normally 1.2 μm thick, thermally or electron beam evaporated.

SiO₂: Steam grown layers to-date. Silox films will be etched later.

Si₃N₄: Deposited by C.V.D. process.

Si: Single crystal wafers to-date. Epitaxial layers to be investigated.

Resist Materials: Mostly Kodak Microneg 747 (negative) and PMMA electron beam resist.

3. ARGON ION BEAM SPUTTERING

The main problems with the direct ion milling of organic resist protected targets are:

1. Low selectivity between resist and target
2. Facet formation caused by etch rate dependence upon the angle of incidence of the beam
3. Redeposition of back-sputtered material²¹ ²²
4. Trench formation caused by reflected ion sputtering²¹.

3.1 Sputtering of Aluminium

Ion beam milling of aluminium is a notoriously slow and difficult process. The main difficulties are:

(i) Cone formation due to surface diffusion phenomena. Our own work confirms that of Kaufman & Robinson²³ - the efficient transfer of heat away from the surface undergoing bombardment is vital for the prevention of cone formation. The formation of cones is accelerated by the presence of surface films such as photoresist or pump fluid contamination. The critical temperature for the seeding process to be sustained is in the region of 400 °C²⁴. Equilibrium temperatures of 140 °C have been measured on specially constructed targets containing several thermocouples. It is not inconceivable, therefore, that the temperature of thin aluminium films on thermally isolated silicon wafers can exceed 400 °C.

(ii) The formation of low sputter-yield protective oxide films at low partial pressures of oxygen.
Experimental work by Mader & Hoepfner\textsuperscript{25} using a Kaufman source injected with argon (0.6 keV, 0.5 mA/cm\textsuperscript{2}) indicates etch rates of \( \approx 10 \) Å/min at oxygen partial pressures of \( 3 \times 10^{-5} \) torr and above. Etch rates in the region 100 - 400 Å/min are only achieved when the oxygen partial pressure is reduced below \( \approx 3.5 \times 10^{-6} \) torr. Experimental values of \( P_0 \) (transition oxygen partial pressure) for the system Al\textsubscript{2}O\textsubscript{3} - Al undergoing argon ion milling are \( 2.9 \times 10^{-6} \) torr at 0.5 mA/cm\textsuperscript{2} and \( 1.4 \times 10^{-5} \) torr at 1 mA/cm\textsuperscript{2} \textsuperscript{26}.

The typical etch rate of aluminium when exposed to a 75 µA/cm\textsuperscript{2} (ion equivalent) argon beam, is of the order 6 Å/min, which, although very low, suggests that the reaction is taking place at a pressure lower than the transition value.

(iii) Long etching times are required for the removal of normal thicknesses of the metal. As the etch rates of resists in normal use is vastly greater than that of aluminium under these conditions of oxygen partial pressure and beam current density, acceptable pattern transfer accuracy is virtually unobtainable. This then, is one suitable application for reactive ion beam etching, although it may be necessary to remake in stainless steel certain parts of the source currently made in aluminium. It is interesting to note the volume of research effort at present engaged in plasma etching of aluminium.

3.2 Sputtering of Si\textsubscript{2}O\textsubscript{3}

Similar problems of low etch selectivity between resist and target are encountered when Si\textsubscript{2}O\textsubscript{3} is argon beam etched with saddle-field sources, in common with ion milling with Kaufman sources\textsuperscript{29}. Unless judicious tilting of the specimen is carried out to increase the selectivity, the resist will be removed at rates similar to or even greater than that of the Si\textsubscript{2}O\textsubscript{3}.

Facetting of the resist leads to bevelled edges on the raised areas after etching. This in itself may not be a serious problem as subsequent metallisation may be less prone to film thinning at sharp edges. Protracted etching under these conditions leads to lateral etching and loss of line-width control.

Redeposition of sputtered material has not been observed after etching with a saddle-field argon beam on Si, Si\textsubscript{2}O\textsubscript{3} or Si\textsubscript{3}N\textsubscript{4} protected with Kodak 747 resist. Redeposition of sputtered debris has only been observed on argon ion beam etched Si\textsubscript{2}O\textsubscript{3} protected with PMMA electron beam resist. The quantity of redeposited material appears to be proportional to the wall: floor area ratio.
So far in this programme of work, no trench formation has been observed on any saddle-field argon beam etched sample, independently of resist used.

3.3 Sputtering of Si₃N₄

Silicon nitride films prepared by the CVD process have been etched with argon beams produced by saddle-field sources. Etch rate data is given in Table 2. No trench formation or redeposition has been observed on these samples. Due to the thickness of the films (generally less than 2000 Å), etch times have been shorter than has been the case with SiO₂ films and as a consequence facet formation has not been observed. See Table 2 on Page 6.

4. REACTIVE GAS ION BEAM ETCHING

As can be seen from the foregoing, there are a number of areas in which ion beam milling is unsatisfactory as an etching technique. As a result we are investigating the use of reactive ion beams.
In this context, we define "reactive" as any element or compound which, when used in conjunction with a saddle-field source, etches the target by primarily chemical means rather than by sputtering processes. By implication the chemical etching is accomplished by a directed beam, rather than by isotropic gas-phase mechanisms. Clearly there are many suitable etchants, some being toxic and corrosive in the natural state and others that are essentially inert.

Following the successes of many workers in the plasma etching field, we have decided to investigate the use of freons (fluorinated hydrocarbons) and other fluorine-containing compounds.

A number of workers, notably in Japan, have been investigating the etching characteristics of fluorocarbon beams produced by Kaufman-style sources. For example, an etch selectivity of 0.3 for SiO$_2$: AZ 1350 is quoted for an argon beam, whereas 2.8 for SiO$_2$: AZ 1350 using a CF$_4$ beam has been obtained$^{27}$. The maximum SiO$_2$ etch rate using CF$_4$ was 360 Å/min at 500 V and 0.4 mA/cm$^2$. Reported values$^{28}$ for C$_2$F$_6$ beam etching give a maximum selectivity of 6 for SiO$_2$: Si (400 Å/min SiO$_2$ etch rate) and show the selectivity dependence upon accelerating voltage.

Etching with reactive gases has been carried out with the small B21 and medium-sized B93 saddle-field sources. Using the small device, work has concentrated on etching SiO$_2$ with CF$_4$ beams. The larger source has been used with a number of different gases to etch different target materials.

### 4.1 Etching with Small Source

Use of this source has been mainly concerned with etching SiO$_2$ using beams produced by injecting CF$_4$ into the device. Increases in etch rate compared to results obtained for argon beam etching are shown in Table 2. A selective etch ratio of 2.8 for SiO$_2$: Si has been measured.
The etch rates of Si$_3$N$_4$ and Si are substantially unaltered by the choice of etchant. It is our intention to investigate more closely the chemical mechanisms involved.

Fig. II. SiO$_2$ etched by CF$_4$ beam
Etch time 300 min., 5 kV, 2 mA discharge current

This scanning electron micrograph shows a grating pattern etched to a depth of 5500 Å using a beam produced by the source injected with CF$_4$. The cathode to target distance was 75 mm and the beam was at normal incidence. The Kodak photolithist has been removed in an air plasma. There is no evidence of undercutting, facetting, redeposition or trench formation.

Etching of fine lines in SiO$_2$ has continued with an electron beam generated pattern in PMMA. Due to problems encountered with the pattern generation, the exposed areas are not well defined and have curved, instead of straight well-ends. The pattern, however, has been faithfully reproduced by etching with a CF$_4$ beam.

The PMMA resist has been removed in an air plasma. As with the previous example, the walls are vertical with no evidence of trenching at the base.
Fig. III. SiO$_2$ etched by CF$_4$ beam
Etch time 60 mins, 5 kV, 3 mA discharge current
1.0 and 0.5 μm wide trough etched to a depth of
1400 Å

4.2 Etching with the Large Source

Use of this source with reactive gases has been restricted so far to
obtaining etch rate data for different gases. The data are presented
in Table 3.

<table>
<thead>
<tr>
<th>Target</th>
<th>Etch rate, X/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ar</td>
</tr>
<tr>
<td>Si</td>
<td>13</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>28</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>17</td>
</tr>
</tbody>
</table>

*2.5 kV, †2.7 kV, ‡2.2 kV, °1.9 kV
All targets were 38 mm diameter silicon wafers; virgin, oxidised or nitrided as appropriate. A stainless steel mask with bevelled edges was clamped in intimate contact with each sample and a Talysurf instrument was used to measure the resultant step profile. In all cases the wafers were cooled, stationary and 150 mm from the source cathode, beam at normal incidence. The discharge current was 150 mA in all cases, the anode potential was 3 kV except where indicated.

Etch selectivity ratios for these materials are as follows:

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Ar</th>
<th>SF₆</th>
<th>CF₄</th>
<th>C₂F₆</th>
<th>C₃F₈</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂: Si</td>
<td>2.2</td>
<td>2.6</td>
<td>6.2</td>
<td>3.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Si₃N₄:SiO₂</td>
<td>0.61</td>
<td>1.2</td>
<td>0.65</td>
<td>2.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Si₃N₄:Si</td>
<td>1.3</td>
<td>3.2</td>
<td>4.1</td>
<td>7.1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

These results are intended as the basis for a more detailed investigation into the mechanisms of reactive gas ion beam etching rather than for an in-depth analysis at this stage.

5. EQUIPMENT OPERATION AND RELIABILITY

5.1 Sources

The B 21 source is made entirely of stainless steel and aluminium, with alumina high voltage insulators. No erosion of the components has been observed over approximately two hundred hours use with CF₄. Sputter-erosion of the cathodes occurs at a very slow rate, and is independent of the gas injected into the source. The source is normally used without forced cooling and body temperatures in excess of 180°C have been measured.

The B 93 source has a water cooled cathode plate with inset carbon grid. The anodes are not cooled. As with the small source, no degradation of the B 93 components has been observed.

5.2 Vacuum Systems

Conventional rotary pump backed oil diffusion pumps are normally used; the baffles are maintained at liquid nitrogen temperature.
We have observed no deterioration in pumping speed with either of the vacuum systems in use with these sources. Infra-red spectroscopic analysis of pump oils sampled over a period of months showed no absorption bands attributable to any breakdown product of the gases in use.

6. CONCLUSION

The ability of a small saddle-field source to etch line-widths down to 0.5 μm in SiO₂ has been demonstrated with CF₄ as etchant. Using a larger source with a number of fluorine-containing gases, etch rates have been measured for Si, SiO₂, and Si₃N₄ which suggest considerable potential in a commercial environment.

ACKNOWLEDGEMENT

The support of the Science Research Council in the form of a CASE award is acknowledged (PJR). The cooperation and support of Ion-Tech under the terms of this scheme are gratefully acknowledged.

REFERENCES

CHEMICAL REACTION MECHANISMS OF THE PLASMA DEVELOPMENT AND ASHING PROCESS OF RESIST MATERIALS

Minoru Tsuda, Setsuko Oikawa, Shigekazu Ohnogi and Atsuko Suzuki

The chemical reaction mechanisms of the plasma ashing and plasma development process of resist materials were theoretically investigated. It was elucidated how the resist materials are decomposed and vaporized in the oxygen gas plasma.

1. INTRODUCTION

The plasma ashing process of resist materials have been extensively investigated in the fabrication technology of microelectronic circuits and the plasma development process (the dry pattern etching of resists) is also researched recently aiming at the complete dry process.[1] The chemical reaction mechanisms, however, remain obscure in these processes and one cannot imagine how the resist materials are decomposed and vaporized in the oxygen gas plasma. In this paper the realistic reaction sequence in the plasma oxidation process will be clarified by the method of the theoretical calculations of the reaction co-ordinate.

2. THEORETICAL AND METHOD

The reaction co-ordinate is defined as the route connecting between the two minimum points on the 3N-6 dimensional adiabatic potential energy surface, which are corresponding to the initial (reactant) and the final (product) atomic configurations of the reaction system. N is the number of atoms comprising the reaction system. In order to obtain the adiabatic potential of the reaction system, the Schrödinger equation of the reaction system was solved under the adiabatic approximation, where the equation is separated into the equation of the electronic states and that of the states of the nuclei. The equation of the electronic states was solved by the molecular orbital method, where we used the MINDO/3 method[2] with the refinement by the configuration interaction. The eigenvalues of the electronic states at the fixed atomic configuration are the adiabatic potential energies of the states of the nuclei. Being the functions of the coordinates of the nuclei, in other words, the coordinates of the atoms comprising the reaction system, the eigenfunctions of the states of the nuclei have the 3N freedoms where N is the number of the atoms. Potential energy is the function of the 3N-6 independent variables because the nuclei have no kinetic energies under the adiabatic approximation and then the 6 freedoms of the transitions and rotations of the reaction system itself are excluded.[3]
2.1. Determination of the reaction coordinate
Chemical reaction is considered as the movements of atoms comprising the reaction system in the three-dimensional space where we are living. This movement can be expressed as the movement of a representative point on the $3N-6$ dimensional super-surface which is perpendicular to the potential energy axis, where $N$ is the number of the atoms comprising the reaction system. For the orthogonality among each of $3N-6$ axes the mass-weighted coordinate system was adopted. A reaction coordinate in question was determined in this paper as the minimum energy path-way of the representative point on the $3N-6$ dimensional super-surface defined above. The obtained reaction coordinate is substantially the same as is usually discussed in organic chemistry. The difference between our reaction coordinate and the usual reaction coordinate\cite{4} is that the former is measured by the scale which has an exact physical meaning and the latter has not any scale. Therefore, the real movements of atoms comprising the reaction system is clearly determined following the reaction coordinate in the former case and the process of the chemical reaction can be visually drawn (See Figs.). In the calculations, we determined at first the atomic configuration of the activation complex, the representative point of which is located at the maximum point of the $3N-6$ dimensional potential energy super-surface. Starting the maximum point the energy minimum pathway was determined stepwise by following the steepest descent. This is a intrinsic reaction coordinate (abbreviated as IRC hereafter) defined by Fukui et al.\cite{5} The method for the stepping is that developed by Morokuma et al.\cite{6} Correlation was given in each step in order that the center of mass and the three main axes of rotations of the reaction system were hold invariant throughout the reaction pathway, because the actual calculation were carried out in the $3N$ dimensional mass-weighted coordinate system and the stepwidth is not infinitesimal.

2.2. Determination of the atomic configurations at the potential minimum and maximum
The atomic configuration at the potential minimum was determined by the DFP (Davidon-Fletcher-Powell) method\cite{7} where the harmonic oscillator approximation is adopted at the minimum point. The maximum point at the $3N-6$ dimensional potential energy super-surface was determined by obtaining the minimum point of the $\sigma$-function\cite{8}, $\sigma=\frac{1}{2}(\frac{\partial E}{\partial Q_i})^2$, where $E$ is the potential energy and $Q_i$ is the $i$-th coordinate in the $3N$ dimensional mass-weighted coordinate system.

2.3. Model compound
Usually, in a theoretical investigation of polymers Bloch functions of the infinite periodical systems are used.\cite{9} However, we must investigate an oxidation reaction of polymers at a specific point by an atomic oxygen in this research, where the periodicity of polymer is lost completely. Therefore, the Bloch theorem was inadequate for our research and the investigation was carried out by using a model compound. Since resist materials contains mainly carbon and hydrogen, we choose a hydrocarbon molecule, n-pentane, as a model compound.
3. RESULTS AND DISCUSSIONS

3.1. Dissociation of an oxygen molecule in the oxygen gas plasma

The adiabatic potential curves in the dissociation reaction of oxygen molecule was shown in Fig.1[10]. Because oxygen molecules are electronically excited in the oxygen gas plasma, atomic oxygens in the singlet and triplet states are produced as a ultimate reaction species which reacts and decomposes resist materials. In this research only the singlet oxygen atom was considered because the reaction with the singlet one is produced on the potential surface on which the final oxidized products exist. The reaction with the triplet oxygen atom will be reported in future.

3.2. The primary oxidation of a resist molecule by an oxygen atom

Firstly, suppose that an oxygen atom approaches at the center of the linear resist molecule (n-pentane, as a model compound), one of the four hydrogen atoms nearly located to the approached oxygen is pulled by the oxygen atom, and a chemical bond $\text{O-H}$ (a triangle) is formed. The situation is shown in Fig. 2(a) and noticed by M. It should be noticed that the bond distance of O-H is the same as that of the final product and those of C-H and C-O are much different. (Fig. 2(c)) The potential energy of M is 6 eV higher than that of the final product (Fig. 2(b)). The reaction proceeds following the IRC, where $\text{O-H-C}$ becomes H-O-C by the exchange of the positions of hydrogen and oxygen. The details of the atomic motions following the reaction in progress were shown in Fig.2(c).

Another conclusion obtained by the IRC research is that no insertion reaction of an oxygen atom between C-C bond of the main chain occurs in the primary oxidation of a resist molecule. Whenever an oxygen atom approaches to a resist molecule from the area surrounded with the dotted lines, only an alcohol is produced, as illustrated in Fig. 3, where some examples are shown. This results obtained by the IRC research mean that an alcohol is the sole product in the primary oxidation of a resist molecule by an oxygen atom since all the area around the resist molecule is divided into the same small areas as that surrounded with the dotted lines if the molecule has a symmetry.

3.3. The second stage of the oxidation

In the second stage, another oxygen approaches to the primary oxidized CnH2n+1OH molecule and a gem-diol is produced as is shown (Fig. 4). This compound is known to be decomposed easily to $\text{C}=\text{O} + \text{H}_2\text{O}$ in room tempe-
The Initial Stage
\[ C_{n}H_{2n+1} + O \]

Reaction in progress

The Final Product (Alcohol)
\[ C_{n}H_{2n+1}OH \]

Fig. 2(a)
Schematic Interpretation of the Primary Oxidation of a Resist Molecule by an Oxygen Atom

nature. In this case other oxidation reactions for the formations of other diols, namely, a vicinal diol, \( \alpha, \gamma \)-diol, etc., also proceed. The product depends only upon the spatial position of the oxygen atom approaching the molecule. However, an insertion reaction between \( \text{C-C} \) bond of the main chain of the resist molecule never occurs in this case, too. The insertion between \( \text{O-H} \) bond to form \( \text{O-O-H} \) also does not occurs. Therefore, the resist material will be changed to \( \alpha, \beta \)-diketo compound, \( \sim \text{CO-CO} \sim \), with the progress of the plasma oxidation.
Fig. 2(b) Potential Energy Change following the IRC of the Oxidation Reaction of Resist Molecule (n-pentane as a model compound) by an Oxygen Atom.

Fig. 2(c) Details of the Atomic Motions following the Reaction in Progress.

Fig. 3
Some Examples in the Primary Oxidation of a Resist Molecule.
The IRC calculations showed that an alcohol is produced whenever an oxygen atom approaches to a resist molecule from any area surrounded with the dotted lines.
3.4. The third stage of the oxidation — The main chain oxidation

When a structure ~C=O—C=O~ is produced, another oxygen atom comes into between the C–C bond and forms ~CO–O–CO~ as is shown in Fig. 5(a), (b) and (c). This fact means the occurrence of the main chain oxidation. The potential energy change following the IRC of the oxidation of the main chain and the details of the movement of the atoms comprising the reaction system were also shown.

The ~CO–O–CO~ bond is stable and a bond cleavage does not occur. When OHC–CO–O–CO–CHO was used as a model compound, the activation energy calculated by the IRC technique is about 85 Kcal/mole for the bond dissociation reaction

\[
\text{HCO–CO–O–CO–CHO} \rightarrow \text{HCO–O}^* + \text{O–CO–CHO}
\]

as was shown in Fig. 6(b).

3.5. The fourth stage of the oxidation — The formation of peroxide for the main chain cleavage

Since the bond ~C=O–O–C=O~ is stable, the decomposition of the main chain of the resist material observed in the ashing or development process will occur in the advanced stage.

When another oxygen atom approached to the ~C=O–O–C=O~ bond, the peroxide ~CO–O–O–CO~ is easily produced as shown in Fig. 7, the result of the IRC calculations. The bond cleavage reaction requires 37 Kcal/mole, the value of which was obtained by the IRC calculation appeared in Fig. 6(a) for the model compound H–CO–CO–O–CO–CO–H.

These values are consistent with the experimental fact that the resist ashing occurs effectively when the table temperature is more than 100 °C of the plasma apparatus.

3.6. The reaction mechanism of the resist ashing and the dry development

The reaction sequence of the resist ashing or the dry development by the oxygen plasma are summarized as follows (Fig. 8): firstly, an oxygen atom attacks a hydrogen and forms an alcohol. The next attack forms a gem-diol which changes to a carbonyl group with the elimination
The Initial Stage

\[ \sim C \sim + O \]

Resist molecule

Reaction in progress

The Final Product

\[ \sim C \sim \sim O \sim \sim C \sim \sim O \sim \]

Fig. 5(a) The Main Chain Oxidation of the Resist Molecule. HO-\( \hat{O} \)-OH is used as a model compound.

of a water molecule. Following reactions forms 1,2-diketone and then an acid anhydride \( \sim C\sim O\sim C\sim \). Because the \( \sim C\sim O\sim C\sim \) bond is stable, the oxidation reaction proceeds to the formation of a peroxide, which is easily decomposed on heating (the activation is 37 Kcal/mole). The present theoretical research revealed that an oxygen atom has a nature of the insertion between the sigma bond. The nature is essential in the oxidation reaction progressing in the oxygen gas plasma which results in the vaporization of resist materials.
Fig. 5(b) Potential Energy Change following the IRC of the Oxidation of the Main Chain of the Resist Molecule by an Oxygen Atom. Oxalic acid was used as a model compound.

Fig. 5(c) Details of the Atomic Motion following the Reaction in Progress.

Fig. 6(a) Potential Energy Change following the IRC of the Main Chain Cleavage $\sim$CO-O$\cdot$ + $\cdot$O-CO$\sim$. HCO-CO-O-CO-CHO was used as a model compound.

Fig. 6(b) Potential Energy Change following the IRC of the Main Chain Cleavage $\sim$O$\cdot$ + $\cdot$O-CO$\sim$. HCO-CO-O-CO-CHO was used as a model compound.
Fig. 7. A Peroxide Formation for the Main Chain Cleavage of the Resist Molecule

![Diagram of a peroxy formation in a resist molecule]

Fig. 8. The Reaction Mechanism of the Resist Ashing and the Dry Development

![Diagram of a reaction mechanism involving bond cleavage]
3.7. Oxidation of aromatic ring
In the case of aromatic compounds, the IRC calculations revealed that
the oxidation reaction proceeds in two ways, i.e., an epoxide formation
and a hydroxyl group formation as shown in Fig. 9. It depends only
upon the spatial position of the oxygen atom approaching the molecule
which of these reactions occurs. When an oxygen atom approached to the
black part of a benzene molecule of Fig. 10, the product is an epoxide.
If the oxygen atom approaches to the white part, a phenol is produced.
Because the -C-O-H bond is stable, a -C-O-O-H bond should be produced
in order to decompose the -C-H bond. Since the -C-O-O-C- bond forma-
tion is required for the -C-C- bond cleavage, a benzene ring, C₆H₆,
consumes 36 oxygen atoms for the cleavages of all the bonds of itself
(Fig. 11). On the other hand, cyclohexane, C₆H₁₂, consumes only 24 oxy-
gen atoms. This result may explain partly the experimental fact that
the resist materials containing aromatic rings are stable to the oxygen
plasma and other oxidative plasma atmosphere, compared with the ali-
phatic polymer resists.

![Fig. 9. The Primary Oxidation of an Aromatic Ring by an Oxygen Atom.](image-url)
Fig. 10. The Primary Oxidation of Benzene Ring by an Oxygen Atom. When an oxygen atom approached to the black part, the product is an epoxide. If the oxygen atom approaches to the white part, a phenol is produced.

\[
\begin{align*}
\text{C}_6\text{H}_6 & + 36 \text{ (O)} \\
\text{C}_6\text{H}_{12} & + 24 \text{ (O)}
\end{align*}
\]

Fig. 11. Oxidative Decompositions of Benzene Ring in the Oxygen Gas Plasma.
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[3] Ref. 1, p.9


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