Title: FIELD EMISSION PHOTOCATHODE ARRAY COMPRISING AN ADDITIONAL LAYER TO IMPROVE THE YIELD AND ELECTRON OPTICAL IMAGING SYSTEM USING THE SAME

Abstract: An electron source provided with a substrate layer (17) and a semiconductor layer (16) with at least one tip (19), the substrate layer (17) being suitable for receiving light of a first wavelength and transmitting the light to the semiconductor layer (16) that is suitable to convert the light into electrons by a photo-electric effect, the substrate layer (17) being provided with a fluorescent layer (17(2)) to convert the light of the first wavelength into light with a second wavelength larger than the first wavelength.
FIELD EMISSION PHOTOCATHODE ARRAY COMPRISING AN ADDITIONAL LAYER TO IMPROVE THE
YIELD AND ELECTRON OPTICAL IMAGING SYSTEM USING THE SAME

Field of the invention

The invention relates to an electron source provided with a substrate layer and a
converter layer, the substrate layer being suitable for receiving light of a first wave-
length and transmitting said light to said converter layer that is suitable to convert said
light into electrons by a photo-electric effect.

The invention also relates to an electron optical system provided with such an
electron source.

Prior art

Electron sources are used in a wide variety of electron optical imaging systems,
like electron microscopes and lithography systems.

Field emission arrays as defined in the preamble of claim 1 are disclosed by
Schroder e.a., "The semiconductor field-emission photocathode", IEEE Transactions on
image tubes.

The use of electron sources in a lithography system is known from
WO98/54620.

Summary of the invention

One of the problems of the prior art arrangements is the yield. It is therefore an
object of the present invention to provide a field emitter photocathode array for a
lithography system that has an enhanced yield.

To that end, the invention as defined at the outset is characterized in that the
substrate layer is provided with a fluorescent layer to convert the light of the first
wavelength into light with a second wavelength larger than the first wavelength.

The second wavelength is tuned to the converter layer such that photons having
the second wavelength have a longer free path length in the converter layer than those
having the first wavelength. Thereby, the efficiency of electron generation in the con-
verter layer will be increased.

It is to be understood that "second wavelength" is not meant in a strict sense of
there being present only one single second wavelength. The fluorescent layer will normally produce photons of different wavelengths, as is known to persons skilled in the art.

The invention also relates to an electron optical system provided with an electron source as defined above.

Advantageous embodiments of the invention are defined in depending claims.

**Brief description of the drawings**

The invention will now be explained with reference to some drawings which are only intended to illustrate the invention and not to limit its scope of protection.

Figure 1 shows schematically a lithography system according to the prior art in which the field emitter photocathode array can be used;

Figure 2 shows an example of a scanning direction of pixels on a wafer to be lithographed;

Figure 3 shows a Scanning Electron Microscope image of a p-type silicon wafer with an array of tips;

Figure 4 shows schematically the operation of a semiconductor field emission array as shown in Figure 3 in a MAPPER setup;

Figure 5 shows a band energy scheme of a semiconductor field emission array as shown in Figure 3;

Figure 6 shows the current on a logarithmic scale flowing from a tip of a semiconductor field emission array as shown in Figure 3, as function of the inverse voltage across the tip.

Figures 7 and 8 show embodiments of the converter plate in accordance with the invention.

**Description of preferred embodiment**

For a better understanding of the invention, first of all, the use of electron sources in a lithography system will be explained with reference to Figures 1 and 2 which are also described in WO98/54620. The purpose of these converter elements is to provide a better resolution (0.1 μm or less) in such systems than was possible with prior art systems without such converters in which the resolution was entirely determined by the wavelength of the light beam used.
The background of the system described in WO98/54620 is as follows.

Imagine that there is provided a known deep-UV lithography tool (i.e., wavelength 193 nm or less) for the 0.13 μm generation with a "traditional" 4 x mask for obtaining the 0.1 μm generation. Then, at a wafer surface, each 0.4 μm "pixel" of a mask is focused to a spot of 0.13 μm. Since the distance between pixels at the wafer must be 0.1 μm, there is a mixing of information between neighboring pixels because the spots of 0.13 μm overlap each other. If we could sharpen up this 0.13 μm spot, this machine would be ready for the 0.1 generation. The sharpening up, or enhancement of resolution, cannot be done after the mixing of information has occurred.

According to one embodiment described in WO98/54620 only one pixel of the mask is illuminated. Then there is only an isolated spot of 0.13 μm at an imaginary wafer plane. At the location of the spot in the imaginary wafer plane a converter element, for example in the form of a photocathode of size 0.1 μm, or a photocathode with a metallic aperture of diameter of 0.1 μm on top, is positioned. Such a photocathode provides an electron source that may have a diameter of 0.1 μm. The photocathode that is obtained in this way is imaged with magnification factor 1 onto the wafer in a real wafer plane spaced from the photocathode. This can be done either with acceleration inside a magnetic field or with a small accelerating electrostatic lens. The next step is to move the mask, e.g., 0.4 μm in order to illuminate an adjacent pixel on the mask while, at the same time, moving the wafer 0.4/4 = 0.1 μm in order to have the adjacent pixel on the wafer written. In such a way, the mask pattern is transferred to the wafer with the required resolution.

However, it would take a long time to write a whole wafer with this single beam. Therefore, a multiple beamlet embodiment can also be used. In theory, the distance between separate beams at the wafer surface needs only to be as much as the point spread function. In practice, certainly when electrostatic focusing is used, the fabrication technology of the photocathode/lens array will determine the minimum distance. The number of beams is estimated to be in the order of 10⁴-10⁸.

Such a multiple beamlet embodiment shown in Figure 1. A light source (not shown) produces a light beam 13, preferably in deep UV. The light beam 13 impinges on a micro lens array 1 having lenses 2. The light beam 13 is as it were divided in beamlets 12, of which only one is shown for the sake of clarity. However, in practice
there may as much as 10^6 - 10^8 beamlets 12. The lens 2 focuses the beamlet 12 on a
mask 3 with spots of, e.g., 400 nm diameter. Each light beamlet 12 leaving the mask 3
passes a demagnifier 14, which is schematically indicated by lenses 4 and 5 and an
aperture 6. However, other types of demagnifiers known from the prior art may be used
instead. By the demagnifier 14 the beamlets 12 are focused on a converter plate 7 hav-
ing converter elements 8 of which only one is indicated. If, as disclosed by
WO98/54620, the converter plate 7 is constituted by a photocathode having a plurality
of apertures a plurality of electron beamlets 15 (only 1 being shown in Figure 1) is
generated. The electron beamlet 15 originates from the aperture and passes through
focusing means, indicated schematically by a lens 9. Finally, the electron beamlet 15
impinges on the wafer 10 in wafer plane 11.

The mask 3 may be moved in the direction of arrow P1 and the wafer in the
direction of arrow P2. If the mask 3 is, e.g., moved 0.4 μm the wafer must be shifted
0.1 μm. Pixels could be arranged at random on the wafer 10. In an embodiment shown
in Figure 2, the wafer pixels are arranged in lines and columns and the scanning direc-
tion SCAN differs from the direction of the lines of pixels.

The resolution is enhanced by sharpening up pixel by pixel, using a photo-
cathode with very many apertures. This known technology is called "Multiple Aperture
Pixel by Pixel Enhancement of Resolution" or "MAPPER" technology. It can be
thought of as traditional projection lithography in which the mask information is split
up and transferred to the wafer sequentially. It can also be thought of as multiple micro-
column lithography in which the electron sources are blanked by the mask.

The converter plate 7 according to the invention can be used in a system shown
in Figure 1, however, in principal, it can be used in any electron optical imaging sys-
tem.

In other types of lithography systems (not shown), the semiconductor field emis-
sion array 7 may, e.g., be illuminated by a single light beam 13. Then, no mask 3 and
demagnifier 14 are used. By illuminating the entire field emission array 7, all tips 19
will generate electrons simultaneously. By means of alignment deflectors, each electron
beam can be accurately positioned through a small blanking aperture on the object 10
to be processed. Blanking electrodes may be used to turn the individual electron beams
on and off at the vicinity of the object 10 in order to write a desired pattern on the ob-
ject surface. An example of such a multi-beam direct write electron beam lithography

In still a further embodiment, the light beamlets 12 may be modulated by electronically modulating the source(s) that produce them.

In the invention, the converter plate 7 comprises preferably a semiconductor field emission array as shown in Figure 3. However, other converters plates of other material may be used instead.

Figure 3 shows a plurality of tips on a p-doped silicon substrate. The image has been made by means of a Scanning Electron Microscope (SEM). The silicon wafer was sized 5 mm x 5 mm. 81 x 81 tips were etched on the wafer surface. The tips shown were spaced about 8 μm whereas their height was about 4 μm. Of course, these figures are only examples. To further enhance the resolution on the wafer 10 to be processed, it is envisaged that the tips may be located closer to one another than 8 μm.

The front surface from the tips, from which the electrons leave the silicon, have a diameter of preferably less than 100 nm, even more preferably less than 50 nm.

Figure 3 shows conically shaped tips. However, the tips may have a rectangle or other shaped cross section, or be shaped like a sphere.

A structure as shown in Figure 3 has been disclosed by Schroder e.a. referred to above. It has the following characteristics:

- field emission is limited by the availability of electrons in the operating regime;
- electrons are excited from the valence band in the conduction band by photons from the impinging beamlets 12;
- tunnel probability approaches 1;
- due to field penetration in the tips the sources are less sensitive for pollution than metallic emitters.

Figure 4 shows the operation of the semiconductor field emission array 7 in more detail. The array 7 comprises a supporting substrate 17. In accordance with the present invention this substrate 17 is designed such that the yield of the converter element 7 is enhanced. This will be further explained with reference to Figure 5 and 6, hereinafter. On top of the supporting substrate 17 a semiconductor field emission array layer 16 may be provided, preferably made of p-doped silicon.

The structure shown in Figure 4 is used in the transmissive mode, i.e., light
beamlet 12 impinges on the supporting substrate 17. The material used for the supporting substrate must be transparent to the wavelength of the light used. The photons from the light travel through the supporting substrate 17 and reach the semiconductor layer 16 where they will generate electrons.

The electrons leave the silicon layer 16 substantially at the front surface of the tips 19. An external (constant) electrical and magnetic field 18 accelerate the electrons and focus them on the wafer 10 to be processed. The electrical and magnetic fields are preferably directed in parallel from the silicon layer 16 towards the wafer 10 to be processed.

The generated electrons may be accelerated and focussed by other means, as is known to persons skilled in the art.

Figure 5 shows the energy bands of the silicon layer 16. The vertical axis shows the energy and the horizontal axis shows the position within the silicon layer 16. The most relevant energy bands are shown:

- \( E_C \) = energy of the conduction band;
- \( E_V \) = energy of the valence band;
- \( E_F \) = energy of the Fermi level, which is between \( E_C \) and \( E_V \).

The vertical line at the right hand side of the energy bands corresponds to the boundary of the tip 19 at the interface with the external vacuum. The most right bevelled line corresponds to the external electrical field. Its inclination is determined by the strength of the external electrical field.

When the conversion material is made from a semiconductor there are few electrons in the conduction band \( E_C \). By illuminating the semiconductor with light a photo-electric effect occurs within the semiconductor material. A photon excites an electron from the valence band \( E_V \) to the conduction band \( E_C \).

Figure 5 shows that the energy bands are curved at the outside surface of the tips 19. This is caused by the external electrical field that penetrates the semiconductor material. The curved energy bands cause electrons, indicated with "e", in the conduction band \( E_C \) to be accelerated towards the interface of tips 19 and the external vacuum. During their acceleration within the semiconductor material, these electrons may excite further electrons from the valence band to the conduction band. On the other hand, some of the electrons will fall back to the valence band. Including this latter effect, still an efficiency of 1 for the conversion of electrons per photon may be obtained. At the
same time, holes, indicated with "h", left behind in the valence band $E_v$ are accelerated in the opposite direction. When a high external electric field is applied there is a high change for electrons in the conduction band $E_c$ to tunnel from the material towards the external vacuum.

The electrical current thus generated by the impinging photons is mainly determined by the availability of electrons in the conduction band $E_c$ and less by the external electrical field strength.

Figure 6 shows the electrical current generated by the impinging photons on a logarithmic scale as a function of the voltage across the tips 19. The voltage is shown on an inverse scale, i.e., the voltage increases going from right to left.

Figure 6 shows that, starting at the right hand side of the curve, when the voltage increases above a certain first threshold the log current starts to deviate from a straight line and smooths to a more or less constant level. When the voltage increases further above a second threshold the log current increases sharply and returns to the original straight line.

In the region where the log current is smoothed the actual log current strength depends on, for instance, temperature and the amount of light in the beamlets 12. Therefore, in this region the current strength can be controlled by the impinging light. This effect is discussed in detail in the article of Schroder e.a. referred to above.

Preferably, light is used having a wavelength of 400 nm or less, e.g., 193 nm, since that allows masks 3 with very small pixels to be used and imaged on the object 10 to be processed.

However, many materials that would be suitable as converter material in converter element 7 show a high absorption factor for light of such small wavelengths. Therefore, it is proposed to design substrate 17 such that the efficiency of conversion of the beamlets 12 into electron beams 15 is increased.

In a first embodiment, as shown in Figure 7, the substrate 17 of the converter plate 7 comprises two sublayers 17(1), 17(2). Sublayer 17(1) is made of quartz and suitable to be transmissive for light with wavelengths in the UV range. Preferably, it is transparent to wavelengths of 400 nm or less, e.g., 248 nm. For still lower $\lambda$'s CaF$_2$ or BaF$_2$ lenses may be used instead of quartz. The sublayer 17(1) is indicated to be 500 $\mu$m thick, however, any other suitable thickness may be applied.

The sublayer 17(2) is made of a suitable fluorescent material selected to receive
light in the UV range and to convert the received UV photons into photons with larger wavelengths and thus less energy, for instance in the Infra Red range. A portion of these photons with larger wavelength will travel to the photocathode array 16 and will be less absorbed by the photocathode array material than the UV photons of the impinging light beamlets 12. Still, they will have enough energy to generate electrons within the photocathode array 16 by the photo-electric effect, as explained above. The photocathode array 16 may be made of a semiconductor material provided with tips 19, as shown in Figure 7 and 8. However, any other suitable material may be applied.

For instance, when the semiconductor material is silicon electrons may be generated by photons having a wavelength of up to 1.1 μm, whereas for germanium photons with a wavelength of up to 1.6 μm may be used (cf. Schroder, referred to above).

Thus, by applying a fluorescent sublayer 17(2) which converts photons having short wavelengths in the UV range to photons having larger wavelengths the efficiency of the converter element 7 can be improved in two ways:

1. the photons with larger wavelength will be absorbed less by the photocathode array 16 than the original photons;

2. The fluorescent material may be selected such that the generated photons with larger wavelength are in a range for an optimum photo-electric effect in the photocathode array 16. For instance, for p-doped (111) silicon, 10 Ω.cm, an optimum range for those latter photons may be 0.5 to 1.0 μm (cf. Schroder, Fig. 17).

The fluorescent layer 17(2) is indicated to have a thickness of 1-5 μm, however, if desired another thickness may be chosen. The thickness of the photocathode array 16 may be 20-30 μm, however, again this is just an example.

Figure 8 shows an alternative embodiment in which the fluorescent sublayer 17(2) and the transparent sublayer 17(1) have been interchanged. The sublayer 17(1) may be made of quartz, however, when the fluorescent sublayer 17(2) produces photons with wavelengths larger than those of UV light other materials can be used.

In figure 8 vertical lines are drawn in sublayer 17(1). These are to indicate that sublayer 17(1) may comprise glass fibres to avoid scattering of light produced by fluorescent layer 17(2).
Claims

1. An electron source provided with a substrate layer (17) and a converter layer (16), the substrate layer (17) being suitable for receiving light of a first wavelength and transmitting said light to said converter layer (17) that is suitable to convert said light into electrons by a photo-electric effect, characterized in that said substrate layer (17) is provided with a fluorescent layer (17(2)) to convert said light of said first wavelength into light with a second wavelength larger than said first wavelength.

2. Electron source according to claim 1, wherein said converter layer is a semiconductor layer.

3. Electron source according to claim 2, wherein said semiconductor is p-doped silicon.

4. Electron source according to any of the claims 1-3, wherein said electron source has at least one tip (19) with a front surface with a diameter of 100 nm or less.

5. Electron source according to claim 4, wherein said diameter is 50 nm or less.

6. Electron source according to any of the claims 1-5, wherein said semiconductor layer (16) comprises a plurality of tips (19).

7. Electron source according to claim 6, wherein said plurality of tips have intermediate spaces of less than 8 μm.

8. Electron source according to claim 6 or 7, wherein said plurality of tips have heights of 8 μm or less.

9. Electron source according to any of the claims 1-8, wherein said electron beam (15) is generated by an electric field and focused by a magnetic field.

10. Electron source according to any of the preceding claims, wherein said substrate
layer also comprises a transparent layer (17(1)) adjacent to said fluorescent layer (17(2)).

11. Electron source according to claim 10, wherein said transparent layer (17(1)) is made of quartz.

12. Electron optical system provided with an electron source according to any of the preceding claims.

13. Electron optical system according to claim 12, wherein said system is a lithography system comprising at least one microlens (2) to produce one light beamlet (12) directed to a mask (3) located in a mask location and an optical demagnifier (14) for demagnifying said light beamlet (12) by a predetermined factor and focusing the beamlet (12) on said electron source (7) for converting said beamlet (12) in at least one electron beam (15) directed towards and focussed on an object (10) to be processed.

14. Electron optical system according to claim 13, wherein said system comprises a plurality of microlenses (2) to produce a plurality of light beamlets (12), and said electron source comprises a plurality of tips (19) to produce a plurality of electron beams (15).

15. Electron optical system according to claims 14, wherein said system comprises between $10^6$ and $10^8$ microlenses (2).
Fig 3

Fig 4

Light

Magnetic Field

Electric Field

Electron beam

Silicon point array

Wafer
Fig 7
Quartz
Fluorescent layer
P-type semiconductor
17(1)
7
17(2)
16
19
500 μm
1 - 5 μm
20 - 30 μm

Fig 8
Fluorescent layer
Fibers
P-type semiconductor
17(2)
7
17(1)
19
1 - 5 μm
500 μm
20 - 30 μm
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01J1/34 H01J37/317

According to International Patent Classification (IPC) or to both national classification and IPC.

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of box C.

Further documents are listed in the continuation of box C. Patient family members are listed in annex.

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Date of mailing of the international search report
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Authorized officer
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