Micromachining Techniques for Fabrication of Integrated Light Modulating Devices

Serhat Sakarya
Stellingen

behorende bij het proefschrift

MICROMACHINING TECHNIQUES FOR
FABRICATION OF INTEGRATED
LIGHT MODULATING DEVICES

door

Serhat Sakarya

Delft, 31 maart 2003
These propositions are considered defendable and as such have been approved by the promotors Prof. dr. P.J. French and Prof. dr. ir. J.H. Huijsing.

1. When direct deposition is unfeasible, indirect thin-film transfer techniques can be used as a Micro-Opto-Electro-Mechanical (MOEM) processing tool to deposit highly-planar reflective layers on a range of different bases. Examples are periodic grid structures and viscoelastic bases (chapter 5).

2. The dynamic performance of a spatial light modulator (SLM) depends on switching time and on the number of greyscale values. This means that a continuous SLM may have equal performance as a discrete SLM switching at a much faster rate (chapters 4 and 5).

3. Phase-only modulators using deformable reflective surfaces can provide similar or better performance than SLMs that modulate intensity directly, given that they are placed in the right optical setup (chapters 4 and 5).

4. It is possible to gain technological and economical advantages by incorporating part of the packaging steps into the entire process to ensure optimal protection of the SLM both during fabrication and later during operation.

5. The best experimental results are generally obtained with devices using the least amount of processing steps and the least amount of work. However, a huge time investment is often required to find the optimal minimum set of steps.

6. If researchers throughout history had not attempted things "proven" to be impossible, many of the achievements taken for granted today would never have existed.

7. Many of the most common phenomena in biology are often the most difficult to explain or emulate in a technological framework [1].

8. The combination of mentality and dedication to succeed in one area will positively influence non-related activities as well. Compromise in one area will carry the risk of setting the tone for all other areas.

9. A new idea formed as a combination of existing ones may yet produce something totally revolutionary.

10. Anything that encourages hate towards others should be subjected to re-evaluation.

11. Any social system that relies on the suppression of fundamental aspects of human nature denies its own long-term stability.

12. Internal politics naturally exists in any group of people.

Deze stellingen worden verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren Prof. dr. P.J. French en Prof. dr. ir. J.H. Huijsing.

1. Wanneer directe depositie niet mogelijk is, kunnen indirecte dunne-film overzettingstechnieken worden toegespast als een Micro-Opto-Electro-Mechanisch (MOEM) processing middel om zeer vlakke reflecterende lagen op een variëteit aan verschillende substraten aan te brengen. Voorbeelden zijn periodieke grid structuren en viscoelastische ondergronden (hoofdstuk 5).

2. De dynamische prestaties van een spatial light modulator (SLM) hangen af van de schakelsnelheid en van het aantal weer te geven grijswaarden. Dit betekent dat een continue SLM gelijkwaardige prestaties zou kunnen leveren als een discrete SLM die op een veel hogere frequentiesnelheid schakelt.

3. Modulatoren die alleen de fase aanpassen door middel van vervormbare reflecterende oppervlakken kunnen even goed of beter presteren dan SLMs die direct de intensiteit aanpassen, aangenomen dat ze in de juiste optische opstelling worden geplaatst (hoofdstukken 4 en 5).

4. Het is mogelijk om technische en economische voordelen te behalen door packaging stappen te integreren in het gehele proces, zodat de SLM zowel tijdens fabricage als tijdens operatie optimaal beschermd blijft.

5. De beste experimentele resultaten worden over het algemeen behaald met devices die het minimum aantal processing stappen en de minimale hoeveelheid werk nodig hebben. Er is echter vaak een aanmerkelijke investering nodig om de optimale minimum set van stappen te vinden.

6. Als onderzoekers in het verleden niet dingen hadden geprobeerd, die "bewezen" waren onmogelijk te zijn, dan zouden veel van de verworvenheden die vandaag de dag voor lief worden genomen, nooit hebben bestaan.

7. Veel van de meest algemene fenomenen in de biologie zijn vaak het moeilijkst uit te leggen of te emuleren in een technologisch kader [1].

8. De combinatie van mentaliteit en toewijding die nodig is om in een gebied te slagen zal ook andere activiteiten positief beïnvloeden. Door compromis in één gebied, bestaat het risico dat dit de toonzetting van alle gebieden wordt.

9. Een nieuw idee dat wordt gevormd als combinatie van bestaande ideeën kan toch tot iets compleet revolutionairs leiden.

10. Alles wat aanzet tot haat jegens anderen moet worden onderworpen aan herevaluatie.

11. Elk maatschappelijk systeem dat afhangt van de onderdrukking van fundamentele aspecten van de menselijke natuur, ontkent haar eigen stabilititeit op lange termijn.

12. In elke groep mensen bestaat natuurlijkerwijs interne politiek.

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PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. dr. ir. J.T. Fokkema,
voorzitter van het College voor Promoties,
inhet openbaar te verdedigen op maandag 31 maart 2003 om 10.30 uur

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University of Edinburgh, UK
University of Durham, UK

Printed by: [OPTIMA] Grafische Communicatie, Rotterdam
ISBN: 90-6734-196-7

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PRINTED IN THE NETHERLANDS
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Chapter 1

Introduction

1.1 Micro-Opto-Electro-Mechanical Systems

Recent years have seen increasing commercial interest and investment into the field of miniature optical components that are fabricated on a microscale for a wide variety of purposes ranging from optical elements in mobile devices [1] to projection displays and to optical communication networks. Since each field by itself comprises a billion-dollar market [2], the combined potential justifies academic exploration into approaches toward a uniform technology applicable within a large context.

In order to allow for mass deployment of these components beyond just several specialized custom-designed applications, they will have to meet a number of stringent requirements in the areas of reproducibility, quality, performance and especially low per-unit fabrication and maintenance costs [3].

The designer must obtain an optimal compromise within a set of mutually conflicting demands in three main technology domains: optical, electrical and mechanical, using various means of interaction between each. For example, electrostatic attraction between two electrodes produces relevant forces on a microscopic scale [4] and can result in mechanical movement of a reflective membrane that in turn leads to a phase variation in an optical wavefront. Additionally, for commercialization of the developed technology, issues such as long-term stability, production yields and packaging form important points of attention [5].

Devices that are designed to operate within the overlapping regions of optical, electrical and mechanical domains are typically referred to as micro-opto-electro-mechanical systems (MOEMS) [6] as depicted in Fig. 1.1.

In the last decades there has been an increasing interest in using silicon as a
mechanical material for both sensors and actuators [7] and the past decade saw an increasingly widespread interest in micro-mechanical systems, followed by a similarly increasing allocation of research budgets to these diverse fields. [8].

![Diagram of energy domains]

Figure 1.1: Overview of the three energy domains (optics, electronics and mechanics) in which MOEMS operate simultaneously.

To realize general requirements such as control of production cost and complexity, currently available IC compatible processes for fabrication should be used, since that decision allows for the use of already existing infrastructure. Non-compatible steps that would contaminate this type of process line are either done after processing or they are performed independently and merged later on in an offline process.

MOEMS allow the modulation of different properties of a light beam, such as intensity, phase and polarization as a function of electrical or optical input signals. These input signals can be controlled by e.g. a processor in response to measurements of the wavefront.

With regard to light, we consider three basic operating modes: transmissive, reflective and emissive mode. In the first case, all light passes through, in the second case, light is reflected from the active surface and in the last case, the light is generated by the modulator itself.
1.1 Micro-Opto-Electro-Mechanical Systems

This thesis regards only the first two categories, also often referred to as "light valves" [9]. The first examples of light valves are cinema projectors, and as requirements evolved, the need for electronically controllable valves led to the research of a wide range of concepts, most notably the Eidophor projector as early as in 1939 [10, 11].

For MOEMS, the following features are attainable:

- A highly accurate degree of control over the wavefront, ranging in the orders of 10ths to 30ths of a wavelength. This accuracy is often expressed in the form of e.g. $\lambda/20$ [12].

- Potentially very small feature size, from several micrometers up to several centimeters.

- Capability of integration with electric circuits on the same chip and/or in the same process line [13].

- Potentially high switching speeds, up to several MHz.

The spectral region of interest usually lies in the range covering visible, infrared and ultraviolet light, with wavelengths in the region of 250 to 1600nm [14]. For most common applications, the visible light range is sufficient, but the other ranges become important if it concerns applications such as optical lithography and communications.

Examples of such devices include arrays of tilting mirrors [15], deformable membrane mirrors [16], optical switches [17] and optical scanners [18, 19] in diverse application areas such as optical communication networks [20], projection displays, on-chip optical communication and adaptive optics [21]. Also, higher-definition spatial light modulators (SLMs) are becoming available, and an interesting emerging application for these is optical lithography, where such a dynamic image modulator could replace the expensive static optical masks [22].

Within the scope of this thesis, two general ends of the implementation spectrum within MOEMS are of interest:

- Spatial light modulators that perform localized alterations to the wavefront, typically with many points of control, but with few degrees of freedom per modulating element. Given a uniform and scalable technology, a large number of application areas can be facilitated such as light modulators for projection displays, components in optical information processing systems, dynamic lenslet arrays and chip-to-chip optical links.
Adaptive optics for global correction of wavefronts. The number of controlling elements is relatively low compared to the active area, but the total degrees of freedom is greater. Applications lie in wavefront correction of aberrated light beams through imperfect media, such as the atmosphere, through which the stars are observed from ground-based telescopes [23, 24] or when viewing the retina of a human eye for diagnostic purposes.

The overall aim of the project is to focus on the fabrication technology of a silicon based SLM, where an optimum of design simplicity and optical quality is sought. This technology can then be extended to fit other design concepts as well.

1.2 Objectives of the project

This project started under the title “High-definition micromachined display”, supported by the STW foundation, project code DEL.44.3945. Its goal was to create a high-resolution projection display based on known micromachining technologies. An immediate approach was already suggested based on pixelated nitride membranes, an extension of adaptive mirror technology.

During the course of the research, it was found that the initial approach would be unable to yield pixel sizes lower than 50μm while essential properties were maintained such as a high effective fill ratio, relatively high sensitivity, production yield and stability. As a result, large chip areas in the order of 5x5cm would have to be used to produce high resolution images.

However, it was found that such devices can offer interesting solutions for laser applications that can benefit from their excellent optical properties, but do not require very high resolutions.

A step forward into the technological aspects was taken and it was decided to broaden the research into both high- and low-resolution types of optical components, since a good basic understanding of the underlying technology will not only make it possible to fabricate the originally intended set of modulators, but also to provide insight in possibilities to fabricate a much larger range of MOEMS components with standard low-cost processes.

This thesis considers micromachining techniques that are usable for the fabrication and design of silicon-based SLMs. It will be seen that even with relatively different approaches, several common technologies can be developed and used. Special attention needs to be paid to packaging after fabrication, often an under appreciated aspect. Several techniques are considered to integrate the packaging aspect into the entire fabrication procedure.
1.3 Organization of the thesis

The first chapter gives a brief introduction to the thesis and motivation for the research and describes the organization of the thesis.

The second chapter gives basic theory on wavefronts, spatial light modulators and their operating context. The emphasis is on phase modulation. It gives a number of commercially available examples of several modulation principles and ends with a blueprint for the practical research done in the project, which is used as a roadmap for the following three chapters.

The general technology and packaging aspects of fabricated chips are discussed in chapter 3. After a brief introduction into micromachining, the chapter describes custom meta-technology that had to be developed to aid the actual research. It will show how integration of the packaging aspect can facilitate processing.

The next two chapters give an in-depth description of our SLM approaches: pixelated membranes and viscoelastic layers. Each chapter will analyse on approach more specifically and provide information on the technical choices and experimental results. In this analysis, elastic materials are considered for encapsulation, active deformable layers and packaging materials.

Chapter 6 discusses alternative applications employing elastomer-based optical components for the use in adaptive optics. It discusses several technological issues and possible solutions for fabrication.

Finally, chapter 7 gives conclusions on the project and thesis and gives recommendations for future work in this field that uses the technologies developed within the scope of the research project.
Chapter 2

Theory and background on spatial light modulators

2.1 Introduction

The generic term “light modulator” describes a broad class of devices that can alter one or more properties of light under the influence of user-controlled input signals. The term “spatial” narrows it down to a class that has the ability to modulate one part of the wavefront without disturbing the other, in one or two dimensions.

Fig. 2.1 shows several areas of propagation of the inputs to the final altered output: the input signals are first converted into internal actuation signals, which impose a change in the optically active area and then this area creates the final wavefront change.

![Diagram showing the process of light modulator](image)

Figure 2.1: Areas of transduction in a generic reflective surface-based spatial light modulator (SLM).

This chapter describes light modulators by the different areas of transduction. First an introduction to basic theory of the modulation of optical wavefronts is given, then types of modulation are discussed, followed by practical methods of achieving these and finally, the layout for the practical research is given by selecting
the approaches to be realized.

Applications such as projection displays, adaptive optics and information processing systems are studied to provide insight in the context within which any design should function.

2.2 Properties of the coherent optical wavefront

Light can be expressed as electromagnetic waves traveling at a speed \( c_0/n \) through a medium, where \( n \) is the index of refraction. The conditions for the electric and magnetic components of these waves are given by Maxwell’s equations. In the case of free space, these can be concisely written in vector form as [25]:

\[
\nabla^2 \mathbf{E} = \epsilon_0\mu_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}, \quad \nabla^2 \mathbf{B} = \epsilon_0\mu_0 \frac{\partial^2 \mathbf{B}}{\partial t^2},
\]

where the electric permittivity \( \epsilon_0 = 8.85 \times 10^{-12} \text{F/m} \) and the magnetic permeability \( \mu_0 = 4\pi \times 10^{-7} \text{H/m} \). The speed of light in free space can be expressed as:

\[ c_0 = \frac{1}{\sqrt{\epsilon_0\mu_0}} \approx 3 \times 10^8 \text{m/s}. \]

A solution to the equation (2.1) for the electric component traveling in the \( x \) direction can be written as:

\[
\mathbf{E}(z, t) = \mathbf{E}_0 e^{i(kz-\omega t+\epsilon)} = \mathbf{E}_0 e^{i(\kappa z + \epsilon)} e^{-i\omega t}
\]

where the wave number \( k = 2\pi/\lambda \) and angular frequency \( \omega = 2\pi c_0/\lambda \) and \( \epsilon \) is the relative phase offset. The first two terms of the right-hand side equation denote the complex amplitude and direction of the field in which both phase and intensity are represented, while the second part specifies the time dependent oscillating component.

Given a linear and isotropic medium, any linear combination of solutions to equation (2.1) satisfies the given conditions. A wavefront is defined as a surface of all points which have equal phase, \( \phi = kz + \epsilon \). Over this virtually defined surface, the intensity profile may vary.

The type of interaction of the incident light beam with the active area can be expressed in terms of manipulation of the complex amplitude as shown in Fig. 2.2. For intensity modulation, \( |\mathbf{E}_0| \) is changed and for phase modulation, \( \phi \) is modified.

2.2.1 Quantitative definitions

The direction of the power flow of the electromagnetic wave is expressed as the Poynting vector and can be written as \( \mathbf{S} = c^2 \epsilon_0 \mathbf{E} \times \mathbf{H} \) for isotropic media. By
2.2 Properties of the coherent optical wavefront

Figure 2.2: Graph showing light modulation in the complex plane, where phase is given by \( \text{atan}(\text{Im/Re}) \) and intensity by the square of the vector length.

taking the time average of this vector, one can calculate the \textit{intensity}, also called the \textit{irradiance}. This time-averaged radiant flux density is expressed in \( W/m^2 \) and defined as:

\[
E \equiv \langle S \rangle_T = \frac{c \varepsilon_0}{2} |E_o|^2 \tag{2.3}
\]

From such formulas, we can derive several other quantities relevant to quantizing intensity related light beam properties.

**Radiometric quantities**

The \textit{radiant flux} \( \Phi \) [W] is defined as the radiant energy per time unit [25] over the entire spectral range. One wants to know this radiant flux with respect to the steradian or surface area.

The energy output per area, \textit{radiant flux density} \( E \) [W/m\(^2\)], the \textit{radiant intensity} \( I \) [W/sr] and \textit{radiance} \( L \) [W/sr m\(^2\)] can be written as [14]:

\[
E = \frac{d\Phi}{dA_O}, \quad I = \frac{d\Phi}{d\Omega}, \quad L = \frac{d^2\Phi}{d\Omega dA_L}, \tag{2.4}
\]

where \( A_O \) is the area normal to the light source and \( A_L \) is the surface of an extended light source.
Photometric quantities

Radiant quantities cannot be used to compare different light sources by means of the human eye, since it perceives according to a non-uniform spectral sensitivity \( V(\lambda) \). To relate these types of quantities, luminous flux \( \Phi_v \) can be expressed as:

\[
\Phi_v = K \int_{380}^{760} V(\lambda) \frac{dP(\lambda)}{d\lambda} d\lambda,
\]

where luminous efficacy \( K = K(555\text{nm}) = 680\text{lm/W} \).

Similarly, we define **illuminance** \( E_v \) [lm/m\(^2\)], **luminous intensity** \( I_v \) [lm/sr] and **luminance** \( L_v \) [lm/sr m\(^2\)] as:

\[
E_v = \frac{d\Phi_v}{dA_O}, \quad I_v = \frac{d\Phi_v}{d\Omega}, \quad L_v = \frac{d^2\Phi_v}{d\Omega dA_L}
\]

The unit lm/sr is often written as cd (candela), whereas lm/m\(^2\) is often written as lux or lx [14].

### 2.2.2 Figures of merit

Using the definitions (2.4) and (2.6), we can express several intensity relationships for light beams interacting with a modulator surface. The incident intensity is \( I_i \), the reflected intensity is \( I_r \) and the transmitted intensity \( I_t \).

Reflectance \( R \), transmittance \( T \) and absorptance \( A \) are then defined as:

\[
R \equiv I_r/I_i, \quad T \equiv I_t/I_i, \quad A \equiv 1 - (R + T)
\]

The amount of energy that is absorbed is usually converted into heat.

A figure of merit for SLMs in display applications is the **contrast ratio** \( C \), which gives an indication of the ratio of intensities between the brightest and the darkest pixel states. Possible definitions include:

\[
C_1 = \frac{L(\text{max}) + L_A}{L(\text{min}) + L_A}, \quad C_2 = \frac{L(\text{max}) - L(\text{min})}{L(\text{max}) + L(\text{min})}, \quad C_3 = \frac{L(\text{max})}{L(\text{min})},
\]

where the \( L_A \) term indicates the ambient luminance, which is relevant to real-world viewing, especially for projection displays. In our case, we use definition \( C_1 \). Inherent contrast ratios (without the ambient term) of 30:1 are considered good and range up to 100:1 for high-quality displays.
2.2.3 Basic forms of interaction

Three different processes of incident light beam interaction can be considered for both reflective and transmissive mode. These are shown schematically in Fig. 2.3.

![Basic forms of interaction](image)

Figure 2.3: Schematic representations of ways of interaction for phase changes (a,d), intensity variations (b,e) and scattering or diffraction (c,f) for both transmissive and reflective modulators.

In the case of phase modulation, the total intensity is kept constant and is either completely specularly reflected or transmitted ($R$ or $T$ approach 100% ideally). Examples of static phase modulators can be found in solid optical components such as spherical mirrors and lenses.

For modulation of intensity, the phase is generally fixed while the intensity $I$ or $I_t$ is adjusted as a function of location $(x,y)$ by e.g. absorbing segments. In practice the phase often also changes along with the intensity, but this change is not observable by the viewer. An illustration is found in slide projectors, where the degree of incident light absorption determines the on-screen intensity.

Finally, diffraction or scattering of the incoming light beam can be used. In this case, much of the information of the original light source is lost and effectively, it appears as though the output light emanates from point sources on the plane of the modulating surface. A form of this type of modulation is performed by this piece of paper: all text (black) regions absorb light and the rest (white) scatters the light. The light source is the ambient light.

The difference between reflective and transmissive mode operation can be further observed when considering the optical path length (OPL) and its approxima-
tion in the incident $z$ direction for a material or medium with refraction index $n$:

$$OPL = \int_S n(z)dz \approx n\Delta z$$  \hspace{1cm} (2.9)

It can then be said that for reflective mode phase modulation, $\Delta z$ is modulated by physically moving the location of local mirror elements. In the case of transmissive mode, such as for some liquid crystal devices [26], $n$ is modulated.

### 2.3 Phase and diffraction modulation

Modulating only the wavefront phase rather than its intensity gives several advantages when implemented on a micro-scale, such as less concentrated heat dissipation at the light valve area and a higher light handling capacity due to fewer inherent losses such as polarization. This section explores several issues regarding this type of modulation.

#### 2.3.1 Schlieren imaging systems

In many cases, such as for projection displays, an intensity-modulated image is required, while still using a phase modulator as the active component. For these cases, phase-to-intensity mapping optical setups exist, which are based on two major principles: a) the direction of output light is changed (tilt/convergence/etc) and b) the integrating property of the imaging lens is used.

Well-known methods use Schlieren bars, derived from the German term for “light stops” and were first used in Eidophor projectors [27]. Basically, we distinguish between two main principles: dark-field Schlieren systems and bright-field Schlieren systems as exemplified in Fig. 2.4.

In the case of dark-field Schlieren projection, the Schlieren lens, SL, focuses all light on an absorbing target located in front of the lens. By activating a pixel $D$, a divergent reflecting light beam will result, most of which will pass the optical stop and enter into the projection lens, which images it to the screen to form a projected pixel $D'$.

For bright-field systems, all light by default enters the projection lens through an aperture. When a pixel is modulated, the aim is to move a maximum of light out of the default plane state and make it hit the absorbing stop surrounding the aperture. This will result in a dark spot $D'$ at the image plane.
2.3 Phase and diffraction modulation

![Diagram of optical system](image)

Figure 2.4: Diagrams for dark-field (top) and bright-field (bottom) systems, where the SLM changes the direction of incident light, showing no modulation (dashed lines), some modulation (dotted lines), and maximum modulation (solid lines).

In principle, greyscale projection is said to be possible as the final pixel intensity is a function of the total amount of light entering the projection lens, which is in turn a function of deformation of the mechanical pixel.

If we assume an intensity profile at the plane of the stops, then we can approximate the effect on contrast as:

$$C = \frac{\iint_A I_{actuated}(r, \phi) dA}{\iint_D I_{default}(r, \phi) dD}, \quad (2.10)$$

where the area $D$ defines the area of the blocked light at the optical stop and $A$ is the area of light that passes through. In the case of dark-field imaging, the limiting issues are given by:

- The extent to which the light source (ideally a point source) is imaged completely onto the optical stop, which should be as small as possible. This directly affects contrast.
The limitation on resolution at mid-actuated state when only part of the full lens aperture is filled. The smallest cone of light giving an activated pixel will give the lower limit of resolution.

For a bright-field system, these factors are mostly similar, but with some minor differences:

- Contrast is highly dependent on the degree of modulation of the light out of the acceptance cone of the projection lens.

- A higher degree of modulation may be required to achieve optimal use of the projection lens.

For bright-field systems, it is vital to modulate as much of the light out of the aperture as possible. If e.g. 90% of the light energy can be modulated, then the contrast (ratio between brightest and darkest states) is 10:1, which is very low quality. A similar type of modulation for dark-field systems can result in much higher contrast ratios.

The next section takes a look at the modulator that can be used in this setup.

### 2.3.2 Modulators for Schlieren systems

We consider phase-only spatial light modulators (also called POSLM [28]) based on reflective pixels. Given the previous analysis, we distinguish between four practically implementable forms:

- Tilt modulation: light is either reflected back into the projection lens or tilted out of the aperture by angle $\theta$ (either dark- or bright-field Schlieren imaging are suitable).

- Piston: the phase is adjusted by imposing a delay $\varepsilon = 2d$ [29]

- Curvature modulation: pixels are curved by $\Delta$ to impose a component of focus, resulting in a light beam that passes the absorbing stop (dark-field imaging).

- Diffraction/scattering: light reflected from active pixels are scattered into different directions, within the acceptance cone of the projection lens (dark-field imaging).
2.3 Phase and diffraction modulation

![Diagram of modulation types](image)

Figure 2.5: Overview of common reflective-mode modulation types: tilt (a), piston (b), curvature (c) and scattering/diffraction (d).

Fig. 2.5 gives an overview of these methods of modulation for a one-dimensional array of 3 pixels, where the middle one is actuated.

We define the fill factor as the ratio of the surface area covered by pixels. In the case of rotating (tilting) pixels, this is determined from $P/(P + \Delta P)$. For curvature modulation, using continuous membranes, this factor approximates 100% since conceptually, all light is reflected.

Even though the entire surface may be reflective (and thus completely "filled"), not all regions are active in modulating the image, i.e. they stay fixed regardless of pixel state. The effective fill factor defines the ratio of the active deforming area to the entire area. Usually such a figure is in the range of 80-90%.

Apart from the two extreme states "on" or "off", the modulator can be characterized by whether it allows intermediate states, in this context called greyscales. If this is not possible, then this effect can be simulated by duty-cycle modulation of the input signal. Assuming $N$ degrees, we get as a minimum requirement:

$$F_{\text{switch}} = N \cdot F_{\text{frame}} \quad \Delta_{\text{cycle}} = \frac{1}{N} \cdot T_{\text{frame}},$$

(2.11)

which means that for 256 values and 25 frames/second, the maximum switching time should be around 150$\mu$s.
Commercially implemented examples of the given principles are found in literature. The next few sections give an overview.

**Liquid Crystals (LCD)**

The term “Liquid Crystals” refers to substances that exist in a state between an isotropic liquid and a crystal, but exhibit properties similar to both. These materials can be classified in three main categories: nematic, smectic and cholesteric. The nematic types are the simplest and most often used. These crystals are generally organic with elongated shapes, which gives them an anisotropic dielectric constant, which in turn makes them controllable under the influence of external electric fields.

Several effects of interest for displays are: a) possibility to align molecules of a dye with LC molecules according to a guest-host principle, b) dynamic scattering effect which can switch pixels from transparent to scattering (white).

Nowadays, transmissive twisted nematic LCDs (TN) are common. These have higher contrast and higher reliability than dynamic scattering based devices. The liquid is contained between two glass plates that are coated with transparent electrodes. Orthogonal alignment layers on the top and bottom plates cause the liquid crystals to ”twist” by 90° while going from one plate to the other. If no electric field is applied, the light passes through undisturbed and if an electric field is applied, the light is blocked by the exit polarizer.

LC technology is being used to modulate light in almost every possible way, including phase, intensity and scattering. However, several issues exist, including: a) switching speed of nematic crystals is in the order of tens of milliseconds, causing image lag, b) low contrast ratio and viewing angle, c) long-term stability issues and d) 50% polarization losses. Much research is being done on mitigating these issues by e.g. dual frequency driving.

**Digital Micromirror Device (DMD)**

Texas Instruments has developed and commercialized the Digital Micromirror Device, using micromachined tilting mirrors on a chip. This research has taken place for at least a decade [15, 30] and is currently becoming successful. The display consists of a 2D array of tilting micro-mirrors similar to Fig. 2.5a. that are used to steer beams.

Pixel sizes down to 14µm with a ΔP of 1µm have been reported. Electrostatic forces generate the mechanical motion. Since the device is tilt-only and knows
only two stable states, the light can be steered by ±20 degrees, which is sufficient for high-contrast operation. Switching times are in the order of 15μs, enough for greyscale operation or even for time-multiplexing three colour components.

Research exists in finding use in alternative applications such as lithography, telecommunications, holography and medical systems [31].

**Pixelated membranes (curvature modulators)**

In 1982, two-dimensional arrays of individually controlled membranes were proposed by L. Hornbeck [32], where the curvature of each pixel determines the extent of light passing the stops. Due to technological considerations at the time, this method was initially abandoned in favour of tilting digital micro-mirrors (DMDs). Starting from 1998, the concept was picked up as part of this research work, but using more modern fabrication technologies and materials [33] and was partially inspired by existing work using nitride membranes for adaptive optics [16].

By using a continuous membrane, gaps between pixels can be avoided, so that more light can be handled and the amount of stray light falling onto the silicon driver chip is minimized. Effective fill factors are approximately 83% at experimental contrast ratios in the order of 30:1.

Greyscale modulation is possible, thus allowing static images. Operating speeds in the order of at least 1kHz can be expected. Drawbacks are the relatively large pixel sizes of at least 50μm and mandatory mechanical boundaries at each pixel perimeter.

A more detailed explanation of the technology is given in chapter 4.

**Grating Light Valve\(^\text{TM}\) (GLV)**

Micromachined grating light valves can modulate light by means of diffraction and have been commercialized under the name Grating Light Valve by Silicon Light Machines [34, 35]. Such a modulator can be used in a dark-field Schlieren setup. Basically, it consists of a number of reflective "ribbons" per pixel (conceptually similar to Fig. 2.5d).

Pixel dimensions reported are 20μm with a ribbon pitch of 5μm. Of the 4 ribbons, 2 are static and 2 are deformed electrostatically to switch the pixel to the scattering state.

Switching speeds are said to be 20ns for a 130nm deflection. Fill ratios are mentioned of 67.5% with contrasts of up to 200:1. The promise of high switching speeds and high contrast ratios make it interesting for future projection displays,
but the relatively low fill factor as well as unintended diffraction effects may limit its application in other areas.

**Eidophor projector**

One of the most famous and earliest electronic projection displays is the Eidophor projector [27, 36]. It is one of the first implementations of electronically controlled light valve technology. Since its first commercialization in the early 1950s, it has had commercial success due to its high output quality at considerable levels of brightness.

It is based on a thin oil-film layer spread on a conducting spherical mirror. The layer is addressed by an electron beam which deposits a charge pattern on it, causing local deformations on the oil, which results in diffraction of the reflected light, making these parts pass the Schlieren bars, as shown in Fig. 2.6.

![Diagram of Eidophor projector setup](image)

**Figure 2.6: Setup for Eidophor projection system.**

In spite of the reported high light outputs (10000 lumens) and very high contrast ratios of up to 300:1, the complexity and low reliability of the technology has prohibited more widespread and commodity use.
2.4 Modulator characteristics

Considering the mechanical interface, we distinguish between two main types of modulators: global and spatial ones. The difference lies in the way the placement of a signal on an actuator influences the mechanical deformation of the surface. This location-dependent deformation \( w_z(x, y) \) can be described in general form:

\[
 w_z(x, y) = w_0(x, y) + \sum_{i=1}^{n} W_i f_i(x, y),
\]

where \( w_0(x, y) \) is the base shape, in this case a planar one. The influence function of each actuator is integrated over the entire area and weighted by the actuator-controlled factor \( W_i \).

Fig. 2.7 shows side-view graphs of deformable-membrane-based modulators. Application of a signal on each actuator results in a deflection of the membrane according to the corresponding influence function. In the first case, the influence functions are overlapping and result in global deformation, where the peak deformation is near the actuator location.

![Graph showing examples of influence functions for a global modulator (left) and a spatial light modulator (right). The dotted lines indicate actuated state.](image)

In the case of spatial modulation, the boundaries of the functions \( f_i \) are limited to a fixed place, denoted in the figure by periodic supports. The resulting deformation will be localized to their respective membrane segments. Ideally, the
influence of one element on another, called crosstalk, is negligible. This crosstalk has a quality-diminishing effect and is influenced by every transduction.

Usually, the size of the individually controlled elements of a spatial light modulator (SLM) will be in the order of 20-100μm, where the diameter of globalized deformable mirrors can differ up to several centimeters. Another key property of these mirrors is that the deformations will generally be larger if the influence of each actuator is integrated over a larger area.

2.4.1 Methods of micro-scale actuation

The relationship between the factor $W_i$ and the amplitude of the input signal is directly dependent on the transduction method. In general, it is highly preferable to avoid time-dependent relationships or hysteresis effects, since they add a degree of complexity and unpredictability to the operation.

We consider several actuation methods known to be implementable on micro-scale and possible to integrate on a silicon chip.

Electrostatic attraction

Common actuation methods in the micro-scale regime use electrostatic forces, which are generated directly by placing a potential difference between two conductive plates. This type of actuation has also been used in MEMS at least since the 1970s for deflections of 100x25μm sized cantilevers [18].

The electrostatic pressure is a square function of the distance $d$ and the potential difference $V$:

$$ P(x, y) = \frac{\epsilon \varepsilon_0 V(x, y)^2}{d(x, y)^2} $$  \hspace{1cm} (2.13)

This pressure distribution can be used to calculate the exact deformation resulting from a potential $V_i$ on an actuator, and generally (as will be seen in chapter 4), the quadratic relationship will hold.

Electromagnetic actuation

These fields are generated by coils that have to be integrated on the chip, through which current has to pass. Ideally, these coils have to be formed in a multilayered structure, at the cost of complicating fabrication. The other drawback is that a constant amount of current is required to maintain actuation states.
2.5 Context of operation

Mechanical movement can be performed in conjunction with an external field, which has been done for fabrication of optical 2x2 bypass switches [19].

Piezoelectric actuation

In these actuators, mechanical strain results from an applied field due to an voltage \( V_s \). The resulting mechanical deformations can be used for a range of MEMS purposes. The relationship between the strain vector \( S \) and applied field vector \( F \) is given by:

\[
S \approx D F,
\]

where \( D \) is a matrix specific for the material. Such actuators have been made in e.g. quartz wafers [37], but appear difficult to integrate on a silicon-based chip. More recent work uses a cantilever with a contracting piezoelectric layer, on top of which a 97 \( \mu \)m sized mirror is placed, so that a vertical movement \( \delta \) is translated into a mirror rotation of \( \alpha \) [38].

Thermal actuation

Thermal actuators are sometimes used on a micro-scale to achieve relatively large deflections of up to 10 \( \mu \)m and forces around 5 \( \mu \)N, which can only be reached if that the actuators lie in regions that are sufficiently thermally isolated from one another to prevent crosstalk [39, 40].

Basically, the actuator resistive material is heated by e.g. a driving current and elongates accordingly. This results in a mechanical force. Switching speeds of up to 300Hz appear possible [41].

Given the generally good conductivity of heat of many materials, it is not practical to use this actuation method for individually controllable densely packed structures, such as SLMs.

2.5 Context of operation

Different types of modulators and modulation principles have been discussed. This section looks into the larger scope of their application.
2.5.1 Projection displays

We define a display as a device that visualizes information to observers. These can be classified into three main categories: direct-view displays, virtual displays and projection displays. The first type inherently produces the image on its own surface, e.g. by local stimulation of a phosphor layer by an electron beam such as in CRT displays. Virtual displays directly project images into the observer’s eyes, thus forming a virtual image. Finally, projection displays are characterized by being a two-component solution in the sense that the image generator and the surface from which the image is observed are separate entities.

Projection displays form the area of interest within the scope of our research. These can be further classified into front-projection systems (slide projectors, cinema, etc) and rear-projection systems for e.g. HDTV sets [42]. For further analysis, we define a projection display as consisting of a number of individual components. Table 2.1 gives an overview of requirements.

- Light source: generates all light available in the system. The total light output of the projector can never exceed that of the light source and will usually be significantly less.

- Condenser: necessary for uniform and optimal illumination of the image generator so as to maximize image quality and efficiency.

- Image generator: modulates the light from the light source to form the image displayed on the screen.

- Projection lens: images the modulator plane to the projection screen.

- Projection screen: provides a diffusing surface for display of the projected image to the human observer. Important properties include the angle of view and gain.

A typical projector has two main parts: the condenser lens system and the projection lens system; the first illuminates the light valve and the second images it to the projection screen.

A simplified schematic diagram of a projector system using a transmissive-mode light valve is shown in Fig. 2.8. We assume a light emitting area as a source that is mapped to completely fill the projection lens. This light is modulated and imaged by the projection lens to the screen. The distances involved can be easily calculated by using the simple thin-lens formula: $s_0^{-1} + s_p^{-1} = f_p^{-1}$.
2.5 Context of operation

<table>
<thead>
<tr>
<th></th>
<th>optical</th>
<th>electrical</th>
<th>mechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light source</td>
<td>small, stable</td>
<td>low-power input</td>
<td>small, robust long lifetime</td>
</tr>
<tr>
<td>Condenser</td>
<td>uniform illumination of modulator, large NA</td>
<td>high thermal load capacity</td>
<td></td>
</tr>
<tr>
<td>Image generator</td>
<td>perfectly reflecting or blocking, large output pupil, low loss</td>
<td>low voltages and power input</td>
<td>very long lifetime</td>
</tr>
<tr>
<td>Projection lens</td>
<td>large entrance pupil, minimal absorption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projection screen</td>
<td>gain of 1.0, diffusion of incoming light</td>
<td></td>
<td>robust light</td>
</tr>
</tbody>
</table>

Table 2.1: Requirements of each of the main components of a projection display in the optical, electrical and mechanical domains.

The magnification factor of the image size at the projection plane to modulator size can be determined as: \( M = \frac{s_p}{s_o} \). Another measure often used for projectors is the throw ratio, which is commonly defined as: \( TR = \frac{s_p}{S_p} \) and gives an indication of the capability of projecting large images at short distances, e.g. a throw ratio of 0.5 means that at a distance of 5m, an image of 2.5m in width can be projected on the screen.

Table 2.2 gives an overview of different types of projectors and modulation principles used.

<table>
<thead>
<tr>
<th></th>
<th>Intensity</th>
<th>Polarization</th>
<th>Diffraction</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cinematic film</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil film (Eidophor)</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Viscoelastic layers</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Liquid Crystals</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Grating Light Valve</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Deformable membranes</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Tilting mirrors (DMD)</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 2.2: Overview of modulation methods.
Figure 2.8: Schematic of a projection system, showing the light source, condenser lens system, modulator and projection lens. Dotted and dashed lines denote two different two ray paths from the modulator. Arrowed lines indicate boundaries of the total light beams.

**Light source**

The light source of the system converts electrical energy into optical energy, the degree of which is defined by the *efficacy* [lm/W] and is typically in the range of 25-100 lm/W. This light source, with the help of the condenser lens system, has to illuminate the light valve optimally and at the same time get a maximum amount of light into the projection lens.

Defining features are the size of the light source and the emitted light spectrum. Ideally, one wants to have a perfect point source which emits a uniform spectrum in the visible light range and no energy in the UV or IR ranges, since this will limit performance or damage components.

Common lamps sold commercially can be classified into two main categories: a) incandescent lamps, using thermal radiation from a heated tungsten filament, either in a vacuum or in e.g. halogen gas and b) luminescence lamps, where a short discharge arc excites a fill material such as Xenon or Mercury [43]. The latter are characterized by arc sizes which are typically in a 1-5mm range.

Because of their high efficacy and colorimetry, usually arc (luminescence) lamps are used as projector lamps [44]. Drawbacks of these are their finite arc size (instead of being an ideal point source), possibly high-pressure environments (resulting in unsafe situations) and their spectral emission lines.

Improvements can be made geometrically by so-called Orthogonal Parabolic
2.5 Context of operation

Reflectors, which are dimensioned to focus the light of a linear light source to a single spot, thus better approximating the ideal point source [45, 46].

Projection screen

The purpose of the projection screen is to provide a diffusing surface onto which the projector image is cast and to form passive optical elements. There are two variations: front and rear projection screens [42, 47].

The projection screen has a relative gain in the sense that it can be optimized to reflect most of the light into the particular directions where the viewers are expected, i.e. not at the ceiling. Angles are usually set within a +/- 60° range.

2.5.2 Adaptive optics

The term adaptive optics refers to optical systems that adapt themselves to compensate for distortions imposed on an object image by the medium through which the light travels. Ideally, it will appear as if the distortions are not even present [21].

Application areas are generally found in astronomy, where adaptive optics compensates for atmospheric turbulence to generate sharper images, focusing elements in scanners, fiber switches [20] and wavefront shaping. The most common elements for these systems are deformable mirrors.

Micromachined deformable-membrane mirrors

Figure 2.9 gives a photograph of two mirrors, where one mirror membrane is broken to reveal the underlying hexagonal electrode structure [16]. The metallized membrane is electrostatically attracted as a result of a potential difference between the membrane and the electrodes, as shown in the schematic.

The fabrication method and design philosophy allow for a low-cost implementation with a very high membrane quality. Such devices formed the initial inspiration for the project upon which this thesis is based, and similar philosophies are employed for their fabrication.

Figure 2.10 shows a possible setup for an adaptive optical system, where a membrane mirror is used to compensate an aberration in the beam path. A CCD camera is used to qualitatively observe the resulting beam shape. Beam splitters BS1, BS2 and BS3 are used to sample the light beams.

Initially, the system is calibrated using a self-referencing optimizing feedback loop: a high-quality divergent beam with an optimal spherical wavefront is generated by a 1-200μm pinhole PH and is reflected back by the adaptive mirror DM
through the pinhole onto the photodiode PD. The signal of the photodiode is proportional to the coupling efficiency. The problem of finding an ideal mirror shape for referencing is thus reduced to optimizing a single feedback value as a function of an N-dimensional vector, where N corresponds to the degrees of freedom of the adaptive mirror. Several algorithms can be used for such purposes, such as genetic algorithms and the simplex method. However, this is a generally slow step, but required for calibration of the faster wavefront detection loop.

Once the reference data is found, the incident wavefront can be sampled by the wavefront sensor. This sensor is based on the Hartmann-Shack method, where the Hartmann mask HR produces an array of light spots on the CCD camera. When the wavefront changes shape, the set of spots will be displaced according to the local wavefront tilt. In the future, integrated wavefront sensors using high-speed integrated CMOS-based sensors will replace such setups in the future.

The data on relative spot displacements can be used to calculate the approximate wavefront shape and thus directly gain knowledge about the nature of the aberration. With this information, the mirror can be adjusted to compensate for it, e.g. by introducing a "focus" or "tilt" term on its surface. Using this approach, the effects of the aberration can be greatly reduced or even completely eliminated.

2.6 Blueprint for practical research

Based on the analysis given previously and the interest in using MOEMS technology, the following three key approaches are of interest for further scientific exploration in our research:
2.6 Blueprint for practical research

Figure 2.10: Setup of an adaptive optical system featuring a self-referencing calibration loop (Optimizing feedback), a wavefront detection based correction loop (Wavefront reconstructor) and an intensity distribution viewer (CCD far-field).

- The first uses pixelated reflective continuous membranes, where square deformable membrane segments act as pixels. Using a Schlieren-based optical setup, one can convert the phase modulation resulting from the local curvature into an intensity-modulated pixel at the projection screen. Pixel sizes are in the order of 50-400 μm.

- The second approach uses viscoelastic layers supporting a reflective continuous metal layer. Period deformation of this layer results in phase gratings, the modulation method used by Eidophor projectors. Pixels are in the range of 20-100 μm.

- Various transmissive elastomer optical components, usable for larger scale optical signals and deformation depths.

The binding factor of the first two technologies is their use of a continuous reflective surface that can be flexible in terms of materials used, thus allowing its function in a wide optical range, even at high powers. The latter technology complements the set of ideas into a wide range of devices.
By having chosen these three approaches, the total research covers a relatively wide scope in terms of the number of modulator concepts and implementations. These concepts and their corresponding fabrication technologies will be studied extensively in the following chapters.

2.7 Conclusions

The generic layout of a spatial light modulator (SLM) was shown, in which several areas were distinguished: the direct modulation of an optical wavefront, the mechanism of actuating the modulator, and actuation signals.

An introduction to some details on the optical wavefront and common definitions were given and the basic forms of interaction were presented: changes in phase, changes in intensity and scattering or diffraction.

From these, the chapter proceeded by discussing phase and diffraction modulation by looking at ways to map phase variations into intensity variations with Schlieren imaging systems. These systems use changes in deflection of the modulator to selectively block part of the light. The light that does pass the blocks is integrated by the imaging lens into a visible image.

Next, the focus was on micro-scale modulators for such systems, summarized as tilt, piston, curvature and diffraction/scattering modulators.

Several forms of actuation were described such as using electrostatic forces, electromagnetic fields, piezoelectrics and thermal actuation. It was concluded that for this application, electrostatic actuation is the most practical principle on a micro-scale, since it generally shows no hysteresis, has fast response times and has low energy consumption. This principle will be used in subsequent chapters.

For a further application context, projection displays and adaptive optical systems were described. For the first, the modulators mentioned previously can be used, optionally within a Schlieren-based setup. Requirements on practically implementable SLMs such as contrast ratios, switching speeds and pixel size can be extracted from this context.

Adaptive optics is a field in which MOEMS have been used extensively and successfully. A setup is described for correction of aberrations in light beams.

Finally, a layout is given for the practical research and two approaches were selected: pixelated reflective membrane and viscoelastic layers. Although these concepts have been previously explored in literature, new approaches in a technological sense based on modern materials and techniques can contribute to being able to implement high-quality modulators at low production costs.
Chapter 3

Micromachining and encapsulation technology

3.1 Introduction

This chapter first gives an introduction to basic micromachining techniques and properties of materials that will be used as part of procedures mentioned in subsequent chapters and then it describes a set of specific technologies developed within the project [48] to aid custom fabrication steps.

Aspects such as packaging and encapsulation are often seen as an independent final step in the complete process. It is important to note that packaging often amounts to 75% of the total product cost for optical components [49]. It is possible to gain technological as well as economical advantages by incorporating these into the fabrication procedure, so that there is overall integration. This allows for potentially higher yields and reduced overall complexity.

A flexible encapsulation technology that was developed in the framework of this Ph.D. work is presented that is used to protect the chip from chemical etchants during processing and then to protect it during operation. Although more steps are required to provide the “final touch”, it can be seen that such an approach can provide an optimal protection of MEMS during their entire operational lifetime.

3.2 Standard micromachining techniques

Micromachining refers to a set of technologies which enable the fabrication of three-dimensional structures with a dimension in the order of micrometers. The
most prevalent material used is silicon due to its mechanical and electrical properties. The technology for fabricating microelectronics on silicon is well developed, making silicon an excellent material for integrated microsystems. Additionally, the use of silicon simplifies integration into IC compatible processes, which are commonly required to provide driving electronics for actuation structures.

Commonly, etching techniques are used to remove the material [50]. A combination of etchants and materials is used to make the etching process selective to one region or orientation, while protecting another. We differentiate between anisotropic etchants that depend on the crystal orientation and isotropic etchants that do not. Another differentiation is between surface and bulk micromachining, depending on how the mechanical layers are grown and etched.

The challenge for the designer to address is to find the correct set and order of process steps to solve any cross-incompatibilities. For example, materials such as gold are popular as optical coatings, but give problems in clean-room processing, for which reason they can only be used as one of the later process steps or they must be included in a post-process treatment.

Required thicknesses of optical coatings and the choice of material are also important considerations as they can also strongly influence the mechanical properties of e.g. deformable layers, where ideally a minimum thickness is used to get a maximum flexibility.

### 3.2.1 Materials

Common materials such as aluminum, gold, silver or stacks of dielectric layers can be used as reflective coatings to meet optical requirements. The spectral dependency of its reflectivity is used as a guideline for application. Gold will typically have a high reflectivity in the 550-2000nm range, silver is highly reflective starting from $\lambda = 400$nm and aluminum has reasonable overall reflectivity over a wide range, including UV.

Aluminum has the advantage of having a good reflectivity, around 90% in the visible light range, it is compatible with standard processes and has good adhesion to many base materials. It can be evaporated on flat surfaces. Gold has the advantage of better chemical resistance, but it is generally not compatible with standard processes and requires an additional adhesion layer (commonly a thin layer of Cr).

As a base layer for membranes, we typically use nitride [51], since it is a relatively strong material that is compatible with standard processes and shows high selectivity to etchants such as KOH, thus minimizing the surface damage when used as an etch stop. The material is insulating, so it can be used as a form of
passivation as well [52]. If used as a mechanical layer, then it can provide a safety control if it is located between two electrodes (membrane and actuators) to prevent short-circuits.

Optimization and precise control of involved process parameters makes it possible to accurately and reproducibly deposit very high-quality nitride layers on polished silicon substrata, giving it a high initial flatness that is increased once the membrane is released (after etching of the bulk silicon) and the tensile stress stretches out the membrane or membrane segment.

### 3.2.2 Wet etching of silicon

Wet etching covers the techniques that remove materials by immersing the sample in an etch bath that contains the liquid chemical etchant. These techniques offer relatively fast etch rates at low cost, making it the method of choice for our applications. Commonly, these etchants can be divided in two categories: isotropic etchants and anisotropic etchants.

Isotropic etchants etch the material uniformly in all directions, whereas anisotropic etchants etch at different rates in different crystallographic orientations, giving more control over the resulting shape. Figure 3.1 shows cross sections for both of these types of etchants. Note that isotropic etching results in undercutting of the etch mask.

![Masking layer](image)

**Figure 3.1:** Side-view schematic showing etching profiles for an isotropic etchant (left) and an anisotropic etchant (right).

The features and etching depth of the sample can be determined in a number of ways. Since the etching rates are known, the process can be stopped after a predetermined time period. A more precise way is to use etch stops. These depend on the combinations of materials used which necessarily include materials that are etched much more slowly than the material to be etched, e.g. by a factor of 1000.

A popular anisotropic etchant is KOH [50, 53], given its high etch rate, selectiv-
ity, low cost and low toxicity. Common etch masks for KOH are nitride and oxide, although nitride is better for longer etching periods. Table 3.1 gives a comparison of commonly used anisotropic etchants.

<table>
<thead>
<tr>
<th></th>
<th>KOH</th>
<th>TMAH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etch rate of silicon(100) [(\mu\text{m}/\text{h})]</td>
<td>50-150</td>
<td>20-70</td>
</tr>
<tr>
<td>Etch rate of Aluminum</td>
<td>high</td>
<td>low (with Si)</td>
</tr>
<tr>
<td>Selectivity SiO(_2)</td>
<td>1:100 - 300</td>
<td>1:10(^2) - 10(^3)</td>
</tr>
<tr>
<td>Selectivity SiN</td>
<td>1:10(^4)</td>
<td>1:150 - 200</td>
</tr>
<tr>
<td>Quality of etched surfaces</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>CMOS compatible</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Toxicity</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Deployment cost</td>
<td>low</td>
<td>medium</td>
</tr>
</tbody>
</table>

Table 3.1: Comparison of different anisotropic etchants.

TMAH etchants may be usable for passivation of aluminum layers provided that it is saturated with silicon. Experiments based on 25 wt% TMAH solutions and various temperatures are reported [54, 55] to exhibit full protection of the aluminum, but at the cost of lower silicon etch rates. A drawback of this method are the pyramidal shaped structures following the crystallographic lines due to imperfect etching.

### 3.2.3 Surface and bulk micromachining

With surface micromachining, thin layers are formed as a stack on the wafer surface and this stack becomes the active part of the chip, whereas bulk micromachining uses the whole depth of the wafer and also involves removing significant portions of the substrate material.

The principle is shown in Fig. 3.2. In the case of surface micromachining, the mechanical layers are typically formed on top of sacrificial layers that are subsequently removed. This procedure allows for fabricating e.g. cantilevers as is shown in the figure. On the other hand, the bulk micromachining example shows a membrane material layer (e.g. nitride) deposited on a flat and polished bulk silicon substrate, which is then removed. This mechanical structure can then be placed on an independently processed chip to form an assembled device.

The specific set of advantages of each approach with regard to reflective light modulators is given in table 3.2.
Figure 3.2: Schematic overview of surface micromachining steps for a single element (left) and bulk micromachining for a full-chip design (right).

Note that the table applies specifically to our approaches. The formation of a layer directly on the substrate will generally be higher than that made on less planar/polished stacks of surfaces. Furthermore, it is difficult to provide large continuous released surfaces, since etching techniques would require access channels to the underlying sacrificial material.

Based on the comparison and other implementation-specific issues, bulk micromachining enables simplification of fabrication processes while retaining high optical qualities, thus making it the preferred method for the fabrication of our spatial light modulators, as will be further explained in following chapters.

### 3.3 Flexible encapsulation technology

In our experiments and early fabrication attempts, we repeatedly ran into problems with regard to etching steps and subsequent handling and experimentation. A special chip-protection technology had to be developed to address a number of essential process requirements:
## Micromachining and encapsulation technology

<table>
<thead>
<tr>
<th></th>
<th>Surface micromachining</th>
<th>Bulk micromachining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integration with</td>
<td>Direct integration is possible</td>
<td>External chips required</td>
</tr>
<tr>
<td>electronics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality of the</td>
<td>Medium due to accumulation of errors</td>
<td>Potentially very high</td>
</tr>
<tr>
<td>reflective layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing compatibility issues</td>
<td>More issues due to higher integration</td>
<td>More flexibility with regard to coatings</td>
</tr>
<tr>
<td>Overall complexity</td>
<td>Medium due to need for finer tuning of process</td>
<td>Possibly low, given good bonding technology</td>
</tr>
</tbody>
</table>

Table 3.2: Comparison of surface and bulk micromachining for reflective layer based light modulators.

- Part of the samples should be exposed to the etchant and the rest left completely protected.

- A minimum of stress must be placed on the chips and sensitive membranes to avoid breaking.

- Simple post-removal must be possible without any damage to the samples.

- Procedure should work for both samples (order of 10mm) and full wafers (order of 100mm).

The necessity to completely shield parts of the samples are often encountered with wet etching and commonly solved by using static Teflon holders that press insulating rubber rings onto the chip surface to isolate the etch regions. Common problems resulting from this approach are leakage of the etchant in spite of the insulation and localized pressure through the rings that gives an undesirable non-uniform stress distribution, rendering this method unsuitable for our applications.

The problem was addressed by using a novel elastomer-based concept [48] using a common elastomer called polydimethylsiloxane (PDMS) to partially encapsulate the samples, while leaving the rest exposed to the etchant. These elastomers are often used to protect electronics and microstructures [5] in a packaging context.

The schematic comparison of the two approaches for pixelated membrane-based SLMs (chapter 4) is shown in Fig. 3.3. In this case, the sample consists of two chips bonded together, with a size in the order of 25mm. The same approach can, however, be used for full wafers as well. Material properties and relevant
data on elastomers used are given in chapter 6, which discusses the use of such elastomers for optical components.

![Sample](image1)

![Teflon holder](image2)

![Flexible holder](image3)

Figure 3.3: Static Teflon holder with two inner O-rings and one outer O-ring (top) and flexible elastomer encapsulation (bottom) for a sample comprising two bonded chips about 20mm in size.

It can be seen that the flexible package places fewer requirements on the actual design and provides a more equal balance of the already minimal force over the active surface. The next section describes the exact fabrication steps that need to be taken to make such a package.

### 3.3.1 Fabrication procedure

The fabrication procedure is illustrated in Fig. 3.4, showing schematically the following steps for either chips or full wafers:

- The base and agent components of the elastomer (PDMS - see chapter 6) are cross-mixed in a 1:10 weight ratio and de-gassed for 30-60 minutes (depend-
ing on total volume) in a vacuum chamber before use.

- A 1mm layer is poured in a plastic container and pre-cured for 8 minutes at 50°C to serve as a carrier layer.

- The samples are placed on top of the carrier layer, optionally on an additional non-cured layer to prevent air bubbles under the sample.

- An adhesive layer (Sylgard 527 or 1200 OS primer) is applied to the regions adjacent to the parts to be exposed to the etchant, either by dipping the chip into the primer, spin-coating the primer on the chip/wafer or by using a brush.

- Another 1.5mm layer of elastomer is added for complete encapsulation and cured for at least 4 hours at 50°C.

- Parts are cut out of the elastomer with a sharp knife, exposing regions on the sample to be etched.

- The package is lifted out of the container and is ready for use.

After fabrication, the encapsulated samples can be immersed into a KOH solution and the selected regions will be etched.

Figure 3.4: Fabrication procedure for flexible encapsulation showing the container with base layer (a), introduction of samples on the base (b), application of an optional adhesive layer (c), complete encapsulation (d), removal of etch regions (e) and final package (f).
3.3 Flexible encapsulation technology

The elastomer has the property of having poor adhesion to aluminum, silicon and nitride, which allows for simple post-process removal of the elastomer. Since any stress is distributed over a larger area, this method will impose little stress on the samples. The fact that no external pressure is required to enforce the isolation further strengthens this effect.

Figure 3.5 shows a processed package containing 5 samples of viscoelastic SLM chips (chapter 5) under slightly different angles, where all selected regions have already been etched and the reflective membrane as well as the slopes typical for anisotropic etching are visible.

![Etch windows](image)

Figure 3.5: Top-view photograph of 5 encapsulated samples.

These encapsulations have been used in 33 wt% KOH solutions up to 85°C for 6 hours without significant damage, showing a very high selectivity. The transparency of the elastomer facilitates good real-time visual verification of the samples during the etch process.

To remove the elastomer, the material can be etched in 100% HNO₃ or 70% HF solutions. In general, it can be assumed that even though most etchants will etch the protective material to some extent, the etch rate will be low enough for the time frame required.

To successfully fabricate an elastomer encapsulation of this sort, just a few requirements need to be met: a) the elastomer should be resistant to the etchant for at least the duration of the etching period, b) it is preferably transparent, c) it can be made to have good or bad adhesion in specific regions, d) it is non-conductive (thus both electrically and chemically insulating) e) and it should be chemically
neutral so as not to contaminate either the etchant or the contained samples.

If it is problematic for the protected regions of the sample to contact the elastomer (as is the case for thin membranes), then they can be shielded prior to encapsulation. This protective material functions as a sacrificial contact layer and need not meet any chemical requirements with regard to the etchant.

3.3.2 Practical applications of the encapsulation technology

The technology proposed by the author was applied outside the direct scope of research and used for several other projects done by other researchers as well. It is noted that in all cases, yield improved considerably, which makes this technology generically useful. Several example applications follow.

Through-wafer copper interconnects

In the first external application, done by dr. V. G. Kutchoukov, the aim is to provide through-wafer interconnects in a chip by forming a grid of conductive copper-plated paths in vertically etched trenches ranging up to 200μm in depth [56]. The procedure is shown in Fig. 3.6.

![Diagram of through-wafer copper interconnects](image)

Figure 3.6: Different stages of fabrication: chip with trenches (a), after passivation and metallization (b), filling of gaps with material (c) and etching until bumps appear (d).

After etching and passivation of the trenches, a thin Cr layer is deposited, followed by the deposition of a conductive material, e.g. a 200nm copper layer (which is further electroplated), creating electrically isolated conductive paths through the bulk silicon.
3.3 Flexible encapsulation technology

Access to these paths is obtained by etching the bulk silicon in e.g. a KOH or TMAH solution until the copper bumps protrude.

The trenches must be protected from the etchant, as this is the side where any sensitive layers (photoresist, electronics, etc) may be placed. In principle, the copper bump forms only a thin membrane without additional filling of the trenches. This trench filling (see Fig. 3.6c) is necessary as large pressure differences in different process steps can result in damage to this membrane. To give it initial strength, the trenches can be partially filled with a thin film of polymide or photoresist.

The trenches can be further filled with the elastomer material to provide integral protection on top of any initial protective coatings. In this case, an additional degassing step is necessary as there is obvious air entrapment during this step. After this step is completed, the sensitive side is already practically well protected.

Adhesives had to be applied to the sidewalls and part of the top side of the chip, after which the same procedure as described in the previous section is followed.

Fig. 3.7 shows a photograph where the grid pattern that is formed by the copper bumps is visible after the final etching step and before removing the sample from the protective material.

![Figure 3.7: Top-view photograph of an etched chip, showing the grid structure.](image)

Note that the top side of the chip does not contain any patterning for the formation of etch windows, so in this case it is the sealing material that determines the approximate location for side-wall formation.

Positive results obtained with this technology have been published in [57].
Galvanic etch stop in KOH

The second practical application of the approach is found in research on galvanic etch stops in alkaline solutions by Dr. E. Connolly [58]. This research deals with finding an optimized method that can be used in KOH rather than just in e.g. TMAH solutions at reasonable process parameters. In this case, this is achieved by introducing small amounts of NaOCl into the solution.

Fig. 3.8 shows a side-view diagram of a galvanic cell. This type of etch stop depends on the properties of the pn junction, which is formed by the n-type epilayer. This section will omit an analysis of process-specific parameters such as current flow, etching rates and biasing, which are described in much more detail in the references given.

![Schematic side-view diagram of a galvanic cell using a protective elastomer encapsulation.](image)

Figure 3.8: Schematic side-view diagram of a galvanic cell using a protective elastomer encapsulation.

Prior to etching, the samples are placed in the protective elastomer and an opening is cut at the silicon side, similar to the general method described earlier. The presence of the elastomer does not only give a chemical and mechanical protection in this case, but it also helps prevent “stray” currents from the sides of the samples and thus has a measurable positive influence on the predictability of the process.

The side with the gold was kept sealed, so as to protect it during the most part of the etching, except for the final stage. Without the elastomer, the sides would be more easily attacked and problems could arise with adhesion of the gold layer.

Results with this method have been reported [59].
3.4 Mask prototyping

Full wafer encapsulation

As an experiment, silicon wafers were used one side of which contained nitride and aluminum patterns. This sensitive side was covered by the elastomer, while the other side was exposed to KOH. To decrease the chances of internal leakage, adhesives were applied to the edges and a 2mm part of the exposed side was covered as well.

Results showed that for a well-encapsulated wafer, after 8 hours of etching in KOH at 85°C, there was no damage damage on the protected side. On wafers without an additional side layer, some damage could be observed.

3.4 Mask prototyping

With the encapsulation technology, regions are defined to be exposed and on-chip etch windows (usually by silicon nitride in KOH solutions) provide the local fine definition of the exact etch shape. This leads to an interesting additional application: omit the on-chip layers and just use the definition of the elastomer shape as the final etch region, at the cost of accuracy. This is illustrated in Fig. 3.9.

![Diagram](image)

Figure 3.9: Flexible elastomer mask (top) and hard mask plus elastomer intermediate layer (bottom).
This method can provide fast and relatively good results for experimental purposes. It was found experimentally that under optimal conditions, the elastomer definition can be followed with an inaccuracy of ±75\(\mu\)m provided that good adhesion takes place.

Two possible configurations are considered (Fig. 3.9). The first one uses the encapsulation itself as the defining layer and the second uses a more accurately defined hard mask. In both cases, the elastomer provides the contact to the bare silicon substrate.

Underetching of the elastomer due to insufficient adhesion can lead to high inaccuracies, in the order of 1\(\mu\)m; minimizing adhesion problems will thus automatically lead to higher accuracies. Using optimized adhesives or applying pressure on the flexible layer is an option. Another option is using well-defined hard masks resting on a thin intermediate elastomer layer (at most 200\(\mu\)m thick). The intermediate layer resolves any non-uniformities on the silicon surface.

Good results have been obtained with anisotropic etchants as shown in figure 3.10. Compared to the ideal shape as provided by integrated masking layers, the peak-to-peak inaccuracy could be minimized to 100\(\mu\)m, provided that a hard mask was used.

Figure 3.10: Photographs of two chips, each with an etched sidewall on the left and a membrane segment on the right. The left chip was produced using a flexible mask and the right chip with a nitride mask.

Figure 3.11 gives a SEM photograph of an etched sidewall with part of the elastomer still present. It also shows some minor underetching effects due to imperfect adhesion.

After removal of the elastomer, the resulting structure can be made free of any physical masking layers, allowing further processing and patterning. However,
3.4 Mask prototyping

Figure 3.11: SEM photograph of a silicon sidewall etched with elastomer masks, where the sidewall has a roughness within a 75\textmu m range.

depending on the etching steps and cleaning procedure, the sample may not be able to re-enter clean-room processing.

It is possible to use this technology to define patterns on a full wafer scale by defining the etch regions in a metal mask, pressed on top of the bare silicon with an intermediate elastomer layer. After etching, this mask and protective layer can be removed, leaving a patterned silicon wafer. These steps can be repeated with different masks, potentially making limited formation of stepped 3D structures possible.

The roughness as seen in the figure is different for each sample. In many applications, smoother and more reproducible patterns would be required. This process is viable, however, for experimental and some production purposes where the roughness of the sidewalls of the mechanical structure is not a point of concern for operational reasons.

The development of this method is an example of how packaging technology can be incorporated as an integral part of the total process and even lead to a drastic simplification in some cases where highest accuracies and specialization are not a strict requirement.

The following chapters give more details on the direct application of these methods and specifically the elastomer-based encapsulation technology as necessary tools for processing.
3.5 Conclusions

The chapter gave an introduction to several standard micromachining techniques and relevant properties of materials for the devices to be developed in the following chapters. Based on a comparison between surface and bulk micromachining, it was decided to use bulk micromachining for the fabrication of mechanical layers, since this gives a higher degree of flexibility in the process as well as higher optical quality of the reflective layers. A drawback is that a more complicated assembly procedure is required.

A flexible encapsulation technology was developed within the research project to solve certain problems specific to wet bulk etching steps common in micromachining. This technology directly showed its generic applicability to several other non-related research projects.

The method employs chemically resistant elastomers to protect the samples during both processing and operation, thereby forming a completely integrated packaging solution. The transparency, resistance to common anisotropic etchants, form flexibility and overall low stress on the samples, make it an ideal experimental processing and encapsulation technology.

A further extension is found in using elastomers for prototyping micromachining, where arbitrary etch regions can be defined, significantly reducing complexity at the relative cost of inaccuracy. It can be concluded that integration of packaging into the entire process, rather than using it as a final and separate step, opens up many useful possibilities.
Chapter 4

Pixelated membranes

4.1 Introduction

Curvature modulation can be implemented on a micro-scale by means of a continuous membrane that is pixelated by an underlying support structure. The aim is to find a technology that is optimized for both quality and fabrication simplicity and dimensioned for integrated electronics.

Fig. 4.1 shows a schematic representation with 3x3 columns that define a 2x2 pixel structure, where the bottom-right pixel has been deformed due to activation of its underlying actuator.

Figure 4.1: Schematic view of a 2x2 pixelated membrane SLM with one deformed membrane segment.

Deformable-membrane-based spatial light modulators were first proposed by L.J. Hornbeck in 1982 for optical signal processing [32]. These were based on a technology that involves casting a nitrocellulose film on a flat water surface,
followed by metallization steps and placement of the film on a wall structure with an integrated address circuit.

Pixelated membrane modulators with a 128x128 pixel array were demonstrated that employed electrostatic attraction as an actuation mechanism. The curvature of each deformed membrane segment can be mapped to an intensity value using darkfield Schlieren optics.

Because of limitations on the technology, this approach was then abandoned in favour of tilting microstructures, which is currently being commercialized. In recent years, membrane technology has been optimized for use in adaptive deformable mirrors [16, 60].

For such designs based on bulk micromachined surfaces, membranes with a diameter in a 1 to 5cm range are suspended at their perimeter over an electrode array. This type of technology has been optimized for high optical quality (order of \( \lambda/10 \)), high reflectivities over the spectral range of choice and capability to handle high optical loads.

By redimensioning the membranes appropriately so that the diameter lies around 50\( \mu \text{m} \), a single-pixel design results that can be deformed sufficiently (in the order of 200nm to 1.0\( \mu \text{m} \)) at low enough potentials to allow integrated CMOS driver electronics. A full-scale modulator is achieved by replication of this type of pixel in a 2D plane.

The type of modulation per pixel is based on a single focus term, so that the number of electrodes per pixel can be reduced to 1, 2 or 4. By deforming the central region of the pixel by value \( \Delta \) and assuming a pure parabolic shape, the focal point \( F_p \) is moved from infinity (planar mirror) to one in front of the pixel, approximated by:

\[
F_p = \frac{a^2}{16\Delta}, \tag{4.1}
\]

where \( a \) is the pixel size. This basic relation is used to connect the requirements from the different domains.

The concept of pixelated membranes is explored using modern processing technologies and materials, while aiming for a simple fabrication procedure.

### 4.2 Concepts and theory

The modulator consists of a continuous reflective membrane that rests on a column structure, which effectively subdivides it into individually controllable segments as shown in Fig. 4.2.
4.2 Concepts and theory

The fill factor is said to be 100% since all light is reflected from the active region. However, the effective fill factor is limited to 80-90% by a) the static areas caused by the columns and b) the non-ideal deformation due to the stiffness of the mechanical layer.

![Diagram of control voltages on two electrodes]

Figure 4.2: Schematic diagram of control voltages on two electrodes.

Because of the continuous membrane, there are no gaps around each pixel, which means that there is less power incident on the substrate and unwanted diffraction effects are mitigated. The membrane consists of a thin nitride carrier layer and a reflective metal layer, which can be chosen according to spectral region and optical load of interest.

In principle, the technology can be scaled to facilitate pixelated SLMs with a wide range of pixel sizes and mechanical layer types.

4.2.1 Modulation concept

The phase of the wavefront is altered, while the light intensity remains equal to that of the incoming beam entering the SLM aperture. This is called curvature modulation (see chapter 2). However, it only alters the phase of the wavefront and not the intensity profile, so a phase-to-intensity mapping setup as provided by a dark-field Schlieren imaging system is required. This is shown in Fig. 4.3.

If the pixel is planar, all light is focused on the target in front of the projection lens. By curving the pixel, the focal point is relocated and a portion of the light passes the stop.

For an intensity distribution $I_B(r, \phi)$ of the reflected light beam at the area of the stop, the intensity going into the aperture of the projection lens is expressed as:
Figure 4.3: Schematic diagram of an optical setup for single-pixel curvature modulator.

\[ I = \int_{R_S}^{R_B} I_B(r, \phi) dr d\phi, \quad (4.2) \]

where \( R_S \) is the radius of the stop and \( R_B \) that of the beam. The assumption is that the beam fits into the projection lens: \( R_B < R_P \). Polar coordinates \( r \) and \( \phi \) are used at the plane of the mirror, parallel to the projection lens and projection screen; \( r = 0 \) defines the axis passing through the center of the projection lens. If we assume a uniform intensity distribution, then the equation can be simplified to:

\[ I = I_0 \left\{ 1 - \left( \frac{R_S}{R_B} \right)^2 \right\} \quad (4.3) \]

It follows from equation (4.3) that the ratio \( R_S/R_B \) should be minimized to achieve maximum efficiency. The bottom limit of \( R_S \) is determined by the size of the focal spot on it, since all light in the “off” state should be blocked for maximum contrast.

4.3 Theoretical model of a single pixel

In order to optimally couple a deformed pixel to the projection lens in the “on” state, the numerical aperture of the pixel \( A_p \) should equal that of the projection lens. Assuming a pure parabolic deformation (which is a good approximation for
very thin membranes), the numerical aperture of the deformed membrane can be expressed as:

\[ A_p = \frac{a}{F_p} = \frac{16\Delta}{a} \]  \hfill (4.4)

Therefore, the required deflection \( \Delta \) as a function of \( A_p \) in an optical system is a simple linear function that illustrates the necessary deflection of an individual pixel as a function of its pixel size:

\[ \Delta = \frac{aA_p}{16}, \]  \hfill (4.5)

so for example, for a \( A_p \) of 0.3 and pixel size of 100\( \mu \)m, the required deformation would be 1.88\( \mu \)m and for a 20\( \mu \)m pixel size, it would be 375nm. Similarly, for an \( A_p \) of 0.1, the values would be 626nm and 125nm respectively. Deflections of up to 300-600nm should be achievable.

There are two major conditions which the mechanics of the pixel should satisfy:

- All deformations should lie in the linear region; plasticity is not allowed.
- The electrostatic pressure to produce the necessary deformation should be available at low control voltages for integrated electronics.

Membrane thickness, pixel size, air gap and the control voltage of a pixel can be estimated based on these two principles. We assume a square membrane with all edges built in. Taking into account various parameters, one must consider the following:

- Is the influence of the thickness of the membrane negligible? (ideal)
- What are the boundary conditions at the edges for membranes with stiffness: are the edges horizontal (clamped) or bent (simply supported)?

Fig. 4.4 shows two main types of deformation: a) infinitely thin membrane hinged by its boundaries, deforms in a parabolic shape and b) clamped plate with finite thickness \( h \) influencing the deformation shape.

In both cases, the downward electrostatic force \( P(x, y) \) for position \([x, y]\) in the active area is given by:

\[ P(x, y) = \frac{\varepsilon \varepsilon_0 V(x, y)^2}{d(x, y)^2} \rightarrow P = \frac{\varepsilon \varepsilon_0 V^2}{d^2}, \]  \hfill (4.6)
Figure 4.4: Two boundaries within the model: infinitely thin membrane (top) and clamped plate with thickness $h$ (bottom).

where $V$ is the potential difference between the membrane and the electrode, which are separated by the spacer distance $d$. A uniform pressure $P$ is assumed, which is an accurate approximation for $\Delta \ll d$.

4.3.1 Thin-membrane model

An ideal infinitely thin-membrane model is assumed with zero stiffness and uniform pressure $P$ causing deformation that depends only on the pixel size $a$ and uniform surface tension $T$. This can be considered the ideal theoretical limit for practical implementations.

The $Z$-component of the pixel deflection $S(x, y)$ in the linear case is described by the Poisson equation:

$$\Delta S(x, y) = \frac{P}{T}$$  \hspace{1cm} (4.7)

These equations must be supplied with a set of boundary conditions that describe the shape of the membrane contour: $S_c = F(x, y)$. Since an analytical solution of the equations (4.7) and (4.6) is complicated for arbitrary pixel contours, numerical estimation is used to calculate the approximate pixel deformation shape.

To obtain a numerical solution to the Poisson equations, we determine functions $S$ and $P$ on a square grid separated by steps of equal size $\delta$ in the $X$ and $Y$ directions. The grid nodes are indexed as $i$ and $j$ for $X$ and $Y$ directions correspondingly. The grid approximation of the Laplace operator has the form which is given by:

$$\Delta S \approx \frac{S_{i+1,j} + S_{i-1,j} + S_{i,j+1} + S_{i,j-1} - 4S_{i,j}}{\delta^2}$$  \hspace{1cm} (4.8)
Using this form, we can write the grid analogue of the Poisson equation (4.7) in the following form:

\[
\frac{S_{i+1,j} + S_{i-1,j} + S_{i,j+1} + S_{i,j-1} - 4S_{i,j}}{\delta^2} = \frac{P_{i,j}}{T}
\]  \hspace{1cm} (4.9)

The system of linear equations provided by (4.9) can be solved by a direct method of Gauss elimination, but it leads to a very large matrix of coefficients that makes it prohibitively difficult to solve for a large number of nodes due to inherent storage requirements even in modern computers.

A computationally less intensive approximation can be derived by using the open form of the expression for membrane deformation \( S_{i,j} \) by rewriting equation (4.9) in this form:

\[
S_{i,j} = -\frac{1}{4} \left( \delta^2 \frac{P_{i,j}}{T} - S_{i-1,j} - S_{i+1,j} - S_{i,j+1} - S_{i,j-1} \right)
\]  \hspace{1cm} (4.10)

The expression (4.10) can be used to solve the Poisson equation iteratively when the right-hand side of (4.9) \( P_{i,j}/T \) is known and the boundary conditions \( S_{i,j} \) are explicitly given.

By continuously iterating, the solution converges to a final state and the iteration can be halted once the error margin threshold is reached and can be plotted in a figure.

The typical solution of the membrane equation is shown in Fig. 4.5. Here, the underlying electrode structure has been supplied with a uniform potential on 3 electrodes that result in deformation on the corresponding membrane segments.

The solution can be directly used for the membrane optical figure to build a model of a simplified optical system of a dark-field Schlieren projector. The intensity distributions for “off” and “on” states are shown in Fig. 4.6.

### 4.3.2 Clamped-plate model

A plate model is assumed for square pixels with edge size \( a \), membrane thickness \( h \) whose edges are all clamped at the boundaries. In the analysis, the influence of the nitride membrane is modeled and that of the metal layer is neglected.

This type of problem has been studied in several forms for generalized pressure \( P \) [61, 62] and has resulted in an accurate approximation for determining central deflection \( \Delta \):

\[
\Delta = 1.26 \cdot 10^{-3} \frac{Pa^4}{D},
\]  \hspace{1cm} (4.11)
Figure 4.5: Membrane response to a voltage distribution where 3 pixels are uniformly attracted.

where $D$ is the flexural rigidity of the material, given by:

$$D = \frac{E h^3}{12(1 - \nu^2)}, \quad (4.12)$$

where the Young’s modulus $E$ and Poisson’s ratio $\nu$ are assumed to be 360GPa and 0.30 respectively for low-stress nitride [51]. By substituting $D$ and $P$ in (4.11), it follows that:

$$\Delta = 13.8 \cdot 10^{-3} \frac{\epsilon \epsilon_0 V^2 a^4}{E h^3 d^2}, \quad (4.13)$$

where $V$ is the potential difference, $a$ is the pixel size, $d$ is the spacer distance and $h$ is the membrane thickness. For a theoretical reference, we can choose: $a = 100\mu m$, $d = 1\mu m$, $h = 250nm$, $V = 1V$. Then for further analysis, we use $\alpha, \delta, \phi$ for the relative pixel size, spacer distance and potential difference respectively. By further substituting known numerical values, we obtain the following simplified equation:

$$\Delta = 2.172 \cdot 10^{-9} \frac{\phi^2 \alpha^4}{\delta^2} \quad (4.14)$$
4.3 Theoretical model of a single pixel

Figure 4.6: Calculated “off” intensity distributions in the screen plane (not in scale) and intensity distribution produced by the voltage distribution on 3 electrodes.

The equation predicts that for a standard pixel with spacer distance 3µm and a potential difference of 30V, the deformation will be approximately 217.2nm and will increase as a square function of the potential. This helps in making biased operation possible, since the incremental influence scales linearly with the increasing potential.

The square relationship between potential and pixel size for constant deformation illustrates the influence of the stiffness of the membrane, making it difficult to use pixel sizes smaller than 50µm at low control voltages (including bias term).

Decreasing the thickness of the membrane \( h \) will improve the response, but this option is limited by issues such as yield and minimum mechanical strength. A safe margin for standard-processed nitride layers is in the order of 250nm.

Table 4.1 gives an overview of several parameter choices and the resulting maximum central deformation. Note that for some values in the table the condition \( \Delta << d \) does not apply, but it does give an indication of the control range.

To examine the relationships graphically, we plotted the potential \( V \) that is required to obtain deformations of 250 to 500nm with a step size of 50nm as a function of pixel size for a pixel of 25 to 100µm, a spacer distance of 1.4µm and a membrane thickness of 250nm.

Included in the figure is the incremental potential to achieve relative deformation from 250 to 500nm, as would be the case in biased mode.

Once the deformation is known, shape approximations can be scaled accordingly to fit the central deflection.
Table 4.1: Numerical approximations of maximum central deformation for several different sets of parameters.

### 4.3.3 Dimensions for practical designs

The two models present the theoretical limits on the deformation, which ideally follows a membrane approximation that predicts a high effective fill factor. In reality, the second model will be more valid. A few additional complicating factors need to be taken into account:

- The compressive stress of e.g. an aluminum layer on top of the nitride layer. Such a layer needs a minimum thickness in the order of 75nm to be reflective.

- The dielectric properties of the nitride layer when the ratio of nitride layer thickness and the air gap is relatively large. While this influence is negligible when $h << d$, a change in this condition will have noticeable effects.

- If air is used in an enclosed chamber, the resulting deformation (assuming it is non-negligible) will create a counter-pressure that lowers the actual deformation and also lowers the speed of response.

- The column width has an increasingly negative influence on the fill factor as the pixel sizes decrease, since a minimum width in the order of 2-5μm will most likely have to be achieved for high-yield processes and mechanical stability.

- Even in the thin-membrane (ideal) situation, using a square-shaped aperture instead of a circular one (to improve fill factor) causes the near-edge deformations to deviate strongly from an ideal parabolic shape.
In practice, these factors do not necessarily affect performance significantly and if they do, they can be minimized by appropriate technological choices. For example, minor a deviation from pure parabolic deformation does not decrease the contrast in a dark-Schlieren-based projection setup as long as no rays will miss the stop in the planar state.

Dimensional ranges for implementations are given in table 4.2.

4.4 Technology and fabrication procedure

The procedure has to be optimized for two specific goals: a) high local quality of the optical surface (at most 40nm RMS deviation) and b) minimization of fabrication complexity. Various different approaches have been explored.

The first choice was between using bulk micromachining techniques or surface micromachining. With the first, the result is having to use two separate chips and with the second, all can be done on a single chip. Table 4.3 gives a brief overview of relevant arguments.

For separate processing, two chips are used: one with the mechanical layer and
Table 4.2: Design range for each dimensional variable.

<table>
<thead>
<tr>
<th>Dimensional variable</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacer distance $d$ [μm]</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Column width $c$ [μm]</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Pixel size $a$ [μm]</td>
<td>100</td>
<td>900</td>
</tr>
<tr>
<td>Window size $w$ [mm]</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Membrane thickness $h$ [nm]</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Coating thickness $h_c$ [nm]</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Pixel rows/lines per chip</td>
<td>16</td>
<td>128</td>
</tr>
</tbody>
</table>

Table 4.3: Comparison of using separate and integrated fabrication.

<table>
<thead>
<tr>
<th>Separate processing</th>
<th>Integrated fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>High optical quality due to bulk micromachining techniques</td>
<td>Relatively low optical surface flatness (quality) with surface micromachining</td>
</tr>
<tr>
<td>Possible yield problems during assembly</td>
<td>Complete process run, without manual assembly</td>
</tr>
<tr>
<td>Best of two technologies and chip productions can be used</td>
<td>Total assembly depends on success of one run</td>
</tr>
<tr>
<td>Larger spacer distances are possible</td>
<td>Maximum spacer distance is lower</td>
</tr>
</tbody>
</table>

one with the driver electronics. This has the advantage that each process can be optimized individually without compromise.

Surface micromachining uses several stacks on top of each other, after which etching of sacrificial layers is necessary. Therefore, it inherently makes it harder to fabricate continuous membranes, while the surface is rougher due to accumulation of errors.

The first techniques were chosen, where a 250nm stretched SiN layer forms the membrane, similar to the case for the larger-scale adaptive mirrors. Further choices are related to the column structure and metal coatings.

The process is outlined here:

1. The top bulk silicon chip is coated with a 250nm SiN layer on the polished side. The other side contains an etch window.
2. The bottom driver chip is formed with an NxM electrode array.

3. Both chips are brought in contact and bonded together.

4. The bulk silicon of the top chip is etched, until the resistant SiN layer is reached.

5. Metal and/or dielectric layer stacks are coated on the freed nitride membrane to make it both reflective and conductive.

6. Final mounting and packaging.

The following challenges need to be addressed:

- Sufficient bond strengths need to be achieved with minimal damage to either chip.
- Finding an optimal etching process.
- Finding a spacer material that can easily be integrated.
- Minimizing any stress on the fragile membranes during bonding, etching and mounting steps.

The first two steps in the procedure set the maximum temperature range to 200°C so as to avoid any damage to the membrane. Initially, it was considered to glue the top frame over a column array at the perimeter of the bottom chip, but the result was poor. Better results were achieved when the fragile membrane was directly supported by the underlying column structure.

4.4.1 Experimental designs

The primary interest is on the optimization of the mechanical layers, so that base chips without independent control can be used (i.e. all pixels are deflected equally). After optimization of the process, the base chips can be interchanged with electronic drivers.

Designs for periodic grids of cross-shaped structures were made for a 4” full wafer. The masks used for the top and bottom chips can be seen in Fig. 4.8. The closeup view shows that each pixel perimeter is defined by a cross-shaped structure at each of its four points.
Figure 4.8: Full wafer design for the top carrier chip (left), design for for a bottom chip with 5 fully usable chips with varying pixel sizes (center) and closeup view of a single bottom chip (right).

In this design, the intention is that the wafers are first diced, and then for each modulator, the 20x20mm top chip is placed over the 25x25 bottom chip. Given the round shape of the wafer, part of the corners of 4 chips will be cut off.

Cross-shaped structures were chosen to allow lateral air flow and thus minimize the influence of air damping due to the possible presence of air or other gasses in otherwise enclosed chambers.

The etch windows determine the centrally usable area and were set from 3x3 to 8x8mm. Pixel dimensions were set at 100μm to 900μm over a 10x10mm area. The column width is constant at 10μm, to guarantee that there will be no direct mechanical crosstalk between membrane segments.

The pattern for the spacers can be applied to either surface.

4.4.2 Bonding process and spacer material

For bonding, two possibilities were considered. When a polysilicon grid structure is patterned on the top chip, it can be bonded by coating the bottom surface with a thin layer of bonding material, then the two are connected and the surface is heated - see Fig. 4.9. In the second case, the bonding material is present at the grid structure which gives higher precision.

Photoresist has been chosen as the bonding material, since it is relatively simple to apply and integrate in current processes. The bond strength was determined experimentally by measuring the force necessary to separate two bonded surfaces. Ideally, the top chip will give way at a large value of L in Fig. 4.10.

If additional adhesives are applied to the sides, then it should be guaranteed to
Figure 4.9: Cross section of the top and bottom chips prior to bonding, using photoresist as a bonding material coated on the bottom chip (left) or on the column structures (right).

Figure 4.10: Schematic view of a test setup showing the separation of two chips bonded together with a photoresist layer.

not shrink during curing, so as to avoid any preset deformations.

For spacer materials, we considered polysilicon and photoresist, requiring one of the following procedures:

- A 3μm layer of polysilicon is deposited on the SiN layer and patterned. A thin 1.3μm thick photoresist layer is spin-coated on the bottom chip. The two are then connected and baked at 150°C for 15 minutes.

- A 1.3μm layer of photoresist is patterned and functions both as the bonding layer and the spacer material, eliminating one extra step. The chip with the SiN layer contains no structures. After baking at 150°C for 25 minutes, they are bonded.

The possible process flows are shown schematically in Fig. 4.11. In the first flow, the approach with the polysilicon grid structure is used and in the second one, the photoresist grid structure is used. In both cases, etching takes place as a final step. As a variation, the bulk silicon can be etched before the bonding step so that a frame with a thin film is pressed upon the grid structure prior to any bonding steps.
Figure 4.11: Approaches toward fabrication: (a) Polysilicon grid structure, (b) Photoresist grid structure, (c) pre-etched die with photoresist structure.

Using photoresist structures for a dual function instead of polysilicon gives the follow points of interest:

- Alignment problems of the two chips are relaxed from an order of 5-10μm to 100μm, because the column structure is integrated with electronics.

- Reduction of complexity and costs because patterning of polysilicon structures can be omitted.

- Bonding has to happen relatively shortly after fabrication of the resist patterns due to longer-term hardening of resist that may make reflow difficult at higher temperatures.

- Cleaning and etching procedures can be slightly more difficult due to compatibility issues with resist patterns. Encapsulation technology provides solutions in this area.

Different reflowing/curing schemes were tried, where the reflowing of the photoresist was assured. A temperature of 150°C for 15-20 minutes provided good
results. For more stable processes, 110°C for 50-60 minutes is suitable. After a
longer reflow/curing time, the photoresist began to smear laterally.

Fig. 4.12 shows two closeup views of cross-shaped photoresist structures after
bonding, visible through the transparent SiN layer. The first structure shows less
than 5% lateral smearing as a result of heating at 150°C for 15-30 minutes.

Figure 4.12: Closeup views of a single cross shaped structure fabricated with a
pre-etched die approach (left) and a structure where smearing occurred due to a
step shift during the bonding process (right).

Imposing a step shift results in an intermediate break of the columns, showing
adequate adhesion to both surfaces. Taken together with the maintenance of defini-
tion, it proves the feasibility of the approach using reflowed photoresist structures.

Fig. 4.13 shows photographs of a test implementation made with the pre-etched
die approach. The interference fringes at the sides show stretching of the membrane
as a result of having only pressure applied on the frame during bonding.

4.4.3 Etching methods

The bulk silicon was etched anisotropically for approximately 5½ hours in a 33wt%
KOH solution at 85°C, using the SiN layer as an etch stop.

The sensitive parts such as contact pads were protected using the encapsulation
technique from chapter 3. Conventional etching techniques using Teflon holders
with KOH resistant O-rings caused too much pressure between the chips, resulting
in very low yields and any success was reached with only 3x3mm window sizes.

By encapsulating the entire sample, it was possible to remove requirements
with regard to the dimensions of the top frame and the yield was greatly improved.
Figure 4.13: Closeup view of a chip using pre-etched membranes on a resist cross-shaped column structure before coating.

4.4.4 Metal coatings on the membrane

The metal layer can be placed at three locations: on the top, on the bottom and on both sides of the membrane - see Fig. 4.14. A top-side coating is preferred for maximum reflectivity. The following requirements have to be satisfied: the coating has to:

- be optimally reflective for operational spectral range → 75μm.
- be conductive to serve as a counter-electrode for electrostatic attraction. Nitride is dielectric, so that cannot be used.
- have a minimal mechanical influence; ideally it is infinitely thin.

All requirements can be met by using one top-side evaporated coating on the SiN layer after etching. Alternatively, stacks of metals and dielectrics can be used to obtain the desired optical properties, but at the cost of increased membrane stiffness and thus lower sensitivity to the control voltages.

It was observed experimentally that hysteresis effects can occur due to the presence of the intermediate SiN layer, especially when h/d is not negligible. A bottom-side metal screening layer eliminates the problem and can be used in addition to a top-side coating.

The metal layer can be either sputtered or evaporated. For top-side coatings that are performed after bonding of the two chips, evaporation was the only option available that did not require unacceptable temperatures or have issues with cleanroom incompatibilities.
4.5 Mounting and packaging

Figure 4.14: Options for coatings: top side (a), bottom side (b), both sides (c).

4.5 Mounting and packaging

Fig. 4.15 shows a photograph of an SLM using polysilicon support structures prior to coating. A closeup view shows the shape of the support structure around 300x300μm sized pixels. The window size is 8x8mm.

Figure 4.15: Photographs for polysilicon grid structure, prior to coating (left) and closeup view showing the cross shapes defining the pixel boundaries (right).

There are two main contacts for test chips: membrane and substrate. Wires can be attached to both with conductive glue and then everything can be encapsulated
in one package, so that any post-process handling will take place at a safe distance from the mechanical interface. Similar approaches can be used for integrated electronics, where some of the wires can be bonded before encapsulation.

The openings at the sides provide problems when external fluid materials are present, such as the elastomer before curing - see Fig. 4.16.

Figure 4.16: SEM photographs of an elastomer inside a capillary channel, where the original top-side cover has been removed.

These effects can be countered by either closing/removing of these holes or by curing at an optimized temperature regime so that the elastomer advances to the active region before full curing.

4.6 Operation and electronics

The dimensions have been scaled to allow low actuation voltages in the order of 0-15V (after biasing) necessary for deflection, so as to facilitate the fabrication and construction of control electronics. The electronics should provide an NxM matrix of electrodes on which voltages can be set semi-statically. CMOS SRAM designs are of interest as an electrode array, but bipolar processes can also be considered.

It is possible to effectively change the potential working range by biasing the membrane to a set voltage relative to the electronics, thus achieving ranges of, e.g., 30-45V without changes to the electronics, which still operates in the 0-15V range.

The maximum driving frequency is mostly limited by air damping effects. These are reduced slightly by using cross-shaped support structures instead of fully enclosing column structures, so that lateral air movement is allowed within the cavity and at the perimeter. In order to further reduce these effects, holes can be made either in the pixel surface or in the backplane.
For the electronics substructure, a 2D electrode array is required on which potentials can be applied to introduce the electrostatic fields. Provided that certain types of photoresist are used to fabricate the column structure, its fabrication can be integrated into that of the electronics chip, which reduces alignment problems to that of aligning the entire frame (order of 100μm).

Addressing modes normally found in practice are passive-matrix addressing and active-matrix addressing. Passive addressing is the simplest, but for better performance in terms of pixel density, active-matrix addressing is preferable. Fig. 4.17 shows a simplified example design for a 3x3 pixel actuator array using a sample-and-hold system.

![Diagram of active-matrix addressing circuit](image)

Figure 4.17: Overview of active-matrix addressing circuit for a 2D contact actuator array (left) and a closeup for a single pixel (right).

In this scheme, all transistors of a single row are switched on by a high row potential, upon which the capacitors are charged to the potentials supplied on the column lines. After this step, the next row is read in, until the entire frame is completely updated.

In this case, analogue values are set on the pads. In other designs, some of which are optimized for obtaining higher potentials (in the order of 50V), only discrete operation is possible.

However, binary operated electrode can also be used if switching speeds are sufficiently fast. The relatively slow membrane will act as a mechanical low-pass filter, so that analogue operation is still provided optically.
4.7 Experimental results

This section describes some of the experiments done on fabricated devices to verify technological aspects as well as response functions resulting from the application of potentials. Given the set of advantages for processing, the technological approach using photoresist is taken as a standard and is used for further experimentation.

4.7.1 Technological verification

The first experiments concentrated on verification of the definition of the photoresist patterns after the critical bonding steps, since possible smearing or even evaporation of the photoresist could have been expected. The silicon bottom chips with photoresist patterns were bonded to transparent glass plates rather than to the normal top chip, which is opaque in the visible light range.

This makes it possible to observe a) to what extent the pattern definition would be affected and b) whether a sufficiently strong bond would result. After baking for about 25 minutes at 150°C, the patterns showed less than a 10% lateral increase, giving similar results to experiments done on chips with etched membranes as shown in Fig. 4.12.

The bond strengths were found to be sufficient in the sense that adhesion took place and the chips could only be separated using with non-trivial lateral forces.

4.7.2 Experiments on single pixels

In the early stage of the project, dr. G. Vdovin fabricated and characterized single-pixel implementations with pixel sizes of 500, 1000 and 4000μm. These membranes were mounted 20μm over the electrode with a potential difference of up to 250V.

The pixel was illuminated by a collimated He-Ne laser beam, and the reflected beam was imaged by a 5cm lens onto the spatial filter. The transmitted light was then measured with a photodiode.

Between “on” and “off” states, contrast ratios of 30:1 could be measured. A removable ambient term was introduced by the diffraction effects due to the non-continuous boundaries of the pixel.

Linearity of the on-screen response could be measured by linearly increasing the potential difference as shown in Fig. 4.18. As is seen, there was initially almost no response until the effective switching threshold, after which the response is nearly linear.
4.7 Experimental results

Figure 4.18: Pixel brightness as a function of linear potential differences (left) and switching time (right).

The thresholding effect is a result of the square relationship given by equation (4.6) between deformation and applied potential.

Similarly, the figure shows the response for a step-wise change of the input signal. Several conclusions that can be drawn from the measurements:

- A bias can be placed on the membrane to give it a constant deformation around the threshold point. Integrated electronics can then provide additional voltage for effective switching.
- After the threshold is passed, the response is nearly linear, making greyscale operation possible at contrast ratios of at least 30:1.
- There is a 200μs response time, thus potentially allowing a 5KHz framerate.

4.7.3 Fabricated multi-pixel chips

In experiments with Al coated membranes, the primary interest was in determining the range of voltages required for actuation. The membrane was grounded and a voltage was applied to the substrate, thus deflecting all pixels equally, as shown in Fig. 4.19.
Figure 4.19: Experimental setup: voltage is applied between the substrate and the Al layer, deforming all pixels.

The schematic overview of the experimental setup is shown in Fig. 4.20. Since all pixels deform equally, the spot on the screen will consist of the superposition of all pixel influences, each e.g. 100μm apart. In principle, this effect can be neglected so that we can practically consider the spot on the screen as the influence of a single pixel.

Figure 4.20: Overview of the experimental setup for both deformed and non-deformed states.

**Measured responses**

A modulator with a top-side Al coating, a 400μm pixel size, 3x3mm window and 1.4μm spacer distance was mounted in this setup and illuminated with a 1mW laser beam produced by a He-Ne laser source.

The following considerations exist:
4.7 Experimental results

- Of interest are the response time $T$ and deflection $\Delta$ as a function of potential $U_S$. From equation (4.14), we expect a square relationship.

- It was not possible to directly measure $\Delta$ without damaging the membrane, so it had to be derived indirectly by measuring the spot size and using it in formula (4.4). The deflection is proportional to this spot size.

The potential was increased from 0 to 25V, measuring the spot size of the projection of the reflected beam. Figure 4.21 shows pictures of the projection for 5V and 25V.

![Intensity plots of mirror projection for: 5V (left) and 25V (right). The right distribution is typical for the far-field scattering pattern caused by a deformed square plate.](image)

A photodiode was placed in the center and a rectangular pulse with an amplitude of 20V was placed at $U_S$ and the response was measured - see Fig. 4.22. In this experiment, about 60% of the light was moved out of the planar state.

It was observed that around 22V, there is a rapid increase in spot size, which indicates the effective threshold point around which switching can occur. However, the spot gradually decreases in size if the potential is kept at 22V, an effect that is clearly not desirable.

To investigate this effect further, a graph was made for the measured spot size as a function of the applied potential, which was increased at 2V/s. This is shown in Fig. 4.23 for two sweeps: 0 - 30 - 0V and 0 - 40 - 0 - 40V, with each graph showing slightly different results.

It is seen from this experiment that there is a significant amount of hysteresis present during operation; combined with the instability over time, these effects make behaviour quite unpredictable and render normal operation difficult.
Figure 4.22: Central response as a function of a rectangular input signal.

The reason for this can be found in the trapping of charge by the dielectric layers between the conductive plates (nitride and oxide) by the electric field, which is very high, even at low control voltages due to the small spacer distance (1.4μm). In large-area deformable mirrors with a gap in the order of 35μm and higher potentials (order of 250-300V), this effect is not as large because the charge potential is low compared to the control voltage.

Theory predicts a deformation behavior $\Delta \propto V^2$, approximately similar to the figure in the upward slope, but the conditions leading to hysteresis effects were not present in the model.

The positive result is that the active range for effectively switching a pixel from the “off” to “on” state lies within a 10-20V potential band, which is likely to stay within the same order for smaller pixel sizes. This shows that biasing can be used to offset potentials provided by integrated electronics.

**Elimination of hysteresis**

Initially, given the existing experience with larger deformable mirrors, evaporated top-side coatings were the first to be experimented with in this project. In a next iteration, bottom-side coatings were used, which effectively removed the influ-
Figure 4.23: Spot size versus applied voltage, for 0-30-0V sweep (left) and for 0-40-0-40V sweep (right).

ence of the dielectric layers between the conductive plates. These basically form a screening layer.

The relocation of the metal layer provided similar results, but the presence of hysteresis and time-variant behaviour has been eliminated. The only intermediate materials in this case are air and the non-deforming patterned photoresist layer.

The maximum observed spot size was 13cm at a projection distance of 1.5m – this gives a numerical aperture of 0.043 or an f-number of 11.6. Assuming that the deformation is approximately parabolic, we used equation (4.4) to determine pixel deflection: 1.08μm, which is very close to the maximum possible deflection.

4.8 Conclusions

The chapter presented a concept for an SLM based on metallize nitride membranes suspended by a column structure that pixelated it into individually controllable segments. Electrostatic forces generated by a potential difference between a membrane segment and its underlying electrode result in local deformation.

Applications such as projection displays require intensity-modulated images, so that Schlieren-based optical setups are necessary to map phase variations due to on-chip curvature modulation to an on-screen change in intensity.

Theoretical analysis considers an idealized thin-membrane model and a clamped-
plate model in which the influence of the membrane thickness is not neglected. Practical dimensions for applications that follow indicate a spacer distance $d$ of 1 to 3 $\mu$m and pixel sizes of 100 to 900 $\mu$m at SiN thicknesses in the order of 250 nm.

For fabrication of the modulator, surface or bulk micromachining processes can be used. The advantage of the first approach is that all processing is integrated, while the second approach requires separate processing but has an inherent advantage in terms of optical quality. The procedure chosen uses a chip containing the mechanical layers (SiN and Al) and a driver chip with the controlling electrode array. The two were connected and the bulk silicon of the carrier was etched away, resulting in a freed membrane.

The column structure can be based on two approaches: polysilicon patterned on the carrier chip or patterned photoresist integrated with electronics. The advantage of polysilicon lies in perfect adhesion to the membrane, but the second approach provides simplicity since it reduces alignment problems and eliminates a process step. Experiments using photoresist in a dual function as both a bonding and a spacer material showed that this material has good adhesion to both surfaces and less than 5% lateral smearing during the entire process.

Experiments with single-pixel designs with 500 $\mu$m pixel sizes show an approximate linear response after a threshold value is passed at response times in the order of 200 $\mu$s. Experiments with pixelated membranes showed deformation of up to 1 $\mu$m at potential levels around 25 V, where the modulation from the “off” to “on” state occurred in a 10 V range, so that biased operation makes integrated electronics possible. Initially, hysteresis was found caused by the presence of the SiN layer, but bottom-side coatings removed this effect.
Chapter 5

Metallized viscoelastic layers

5.1 Introduction

One of the things that gave the motivation to research a spatial light modulator based on deformable viscoelastic layers is that these can be used as a solid-state alternative for the modulating element of the Eidophor projector and offer a very high image quality. As mentioned previously in chapter 2, the technology of Eidophor projectors had progressed to the point where light output levels of up to 10000lm and contrast ratios in the order of 300:1 were possible. Unfortunately, high fabrication and maintenance costs, which are due to its complexity, have prohibited mass deployment [63].

Given the theoretically excellent optical characteristics of the Eidophor projector, it is thus attractive to explore such an alternative that would eliminate the need for oil films and vacuum chambers, resulting in much lower costs. One such concept is based on using metallized viscoelastic layers. Much research has been done in this field over the past decades [64, 65, 66, 67, 68], but but without much further commercial exploration.

Fig. 5.1 shows the principle of operation: a 5-10μm thick viscoelastic layer supports a 80nm reflective metal film over a periodic electrode structure. This surface is normally flat and acts like a planar mirror. When alternating potentials are applied (V+ and V-), the top metal layer is electrostatically attracted to the active electrodes (V+). This creates a local phase grating with a peak-to-valley distance of approximately 150nm.

Usually potentials in the order of 250V would be required, but the non-linear response of the deformation with respect to potentials allows for using a bias voltage $V_0$ to offset the point of operation to the active region, so that integration of
electronics becomes feasible.

The structure shown in the figure represents a single pixel. This structure has to be replicated on a (x,y) plane to form the complete 2D viscoelastic spatial light modulator (VSLM). Practical pixel dimensions are in the order of 20-50\(\mu\)m.

![Diagram](image)

Figure 5.1: Schematic side-view diagram for a single pixel without (left) and with (right) alternating potentials applied on the electrodes.

Well-known approaches as found in literature use spin-coated and planarized elastic layers [69] upon which the metal film is evaporated in a vacuum chamber, which contributes to possible instabilities.

This chapter presents technological approaches in which all deposition, polishing and other optimization steps take place on an independent static carrier instead of on the less stable elastic surfaces. Methods are described to transfer the processed metal layer onto the pre-cured elastic layer. This is complemented by a flexible encapsulation method that allows for low-stress processing of almost all possible sample shapes.

### 5.2 Concepts and theory

The conceptual analysis of the modulator will be done from the perspective of a projection display application using a Schlieren imaging system as described previously in chapter 2. The general boundary conditions are:

- All modulation is possible at low enough potentials (order of 15-20V) to allow integration of electronics; a high bias potential \(V_0\) may be present.
- Processing can be done in standard facilities.
• Contrast ratios of at least 50:1 must be achieved.
• Switching speeds are least 100Hz for 2D modulators and $N_{\text{vertical}} \times 100$Hz for 1D scanning modulators.
• Mechanical stability over large periods of time is required.

5.2.1 Modulation principle

The modulation effect is similar to that of modulated oil films in Eidophor projectors and a similar optical setup can be used to map the modulated wavefront that is reflected from the active surface area to an intensity modulated image at the screen location.

In Fig. 5.2 an incoming light beam is reflected from the Schlieren bars into the lens in front of the VSLM. These bars are imaged onto themselves and will block all reflected light from a planar mirror. By sinusoidally deforming this surface, several reflected beam paths result and some of these will pass the stops and enter the projection lens, which images the VSLM pixel to a screen.

![Diagram](image)

Figure 5.2: Operating principle for a single pixel in non-actuated state (dashed lines) and in actuated state (solid lines).
By shifting optical power out of the blocked beam to the other beams, one can modulate the power that enters the projection lens directly in an analogue manner and translate it to greyscale operation. As long as the passed beams are within the projection lens aperture, they will be integrated into a single intensity value at the image plane.

**Diffraction gratings**

To better understand the operating principle, we take a closer look at diffraction gratings in general. These are periodic structures of diffracting elements that alter the wavefront phase and/or amplitude. An example is a slit array for transmissive diffraction gratings. In this case, we are interested in a reflective diffraction grating.

Fig. 5.3 shows a simplified schematic of a diffraction grating. Assuming that there is a periodic set of coherent waves, each set offset by the grating period \( a \), a number of waves emerge, where each point has the same relative phase. These are denoted with 0th order for the zero order, \( \pm 1 \) for the first order, \( \pm 2 \) for the second order and so on.

![Diagram](image)

**Figure 5.3:** Schematic overview of a diffraction grating.

By looking at the optical path difference, we can determine the places where constructive interference will take place and thus the order angles \( \theta_n \), for example
\( \theta_2 \) for the +2 order in the figure. The grating equation is given by [25]:

\[
\sin \theta_n = n \lambda,
\]

where \( a \) is the grating period, \( \theta_n \) is the order angle, \( n \) the diffraction order and \( \lambda \) the wavelength of the coherent light source used.

### 5.2.2 Deformation behaviour of the elastic layer

The deformation of an incompressible viscoelastic layer resulting from electrostatic forces has been studied extensively in the literature [64, 70, 71, 72], which can be used as the basis for our analysis.

We assume a single pixel as shown in Fig. 5.4 with sinusoidal deformation behaviour, elastic layer thickness \( h \), amplitude \( a \), period \( D \) and a total number of periods \( N \).

![Diagram of elastic layer](image)

Figure 5.4: Side-view schematic of a highly deformed elastic layer. The periodic electrode structure has been abstracted into a potential distribution \( V(x) \).

On the electrode plane \( z = 0 \), assume a potential distribution given by:

\[
V(x) = V_0 + V_S \cos(2\pi f_s x),
\]

where \( f_s = 1/D \) is the spatial frequency, \( V_0 \) is the bias voltage (to provide the offset to the operational range) and \( V_S \) is the signal voltage. The sinusoidal approximation is used for simplification. Under the condition of \( V_S/V_0 \ll 1 \), the deformation may be assumed to be expressed as:

\[
\Delta(x, t) = a(t) \cos(2\pi f_s x),
\]
Metallized viscoelastic layers

where $a(t)$ is the deformation amplitude. The behaviour of the viscoelastic layer can be analyzed using the Voigt model, whereas for the behaviour of the top metal layer (the counter-electrode), a strongly bent plate is assumed.

An approximation for the stationary amplitude is given as [71]:

$$a_0 \approx \frac{\varepsilon_1}{h} \frac{V_0 V_S e^{-2\pi f_s h}}{G + \frac{E(2\pi f_s \delta)^3}{24(1-\nu^2)}} - \frac{\varepsilon_1}{2} \left(\frac{V_0}{h}\right)^2 \propto V_0 V_S e^{-2\pi f_s h} \frac{1}{h E \delta^3 (2\pi f_s \delta)^3}, \quad (5.4)$$

where the elastic layer is characterized by dielectric constant $\varepsilon_1$, thickness $h$, shear modulus $G$ and viscosity $\eta$. The properties of the metal layer are expressed in Young's modulus $E$ and Poisson ratio $\nu$. The viscosity $\eta$ determines the speed at which the layer will deform to its static shape.

The main conclusions following from literature are:

- The ratio of layer thickness $h$ and period $D$ should be small: $h/d < 0.10$ to maximize deformation and to prevent very non-uniform electric field distributions.

- Low signal voltages in addition to a bias voltage allow sufficient contrast in operation.

- The response time depends strongly on the viscosity $\eta$ and the metal-layer thickness $\delta$, which are both minimized in the ideal case. Response times down to $25\mu s$ are possible for very specific situations, but can be expected to be in the order of several milliseconds for the general case.

- The ratio $h/D$ determines spatial frequency response: lower periods require thinner viscoelastic layers.

To achieve maximum deformation and fastest response, a set of optimized parameters can be given by grating periods $D$ between 10 and 50$\mu$m and viscoelastic layer thicknesses in the order of 5-10$\mu$m.

5.2.3 Deformation required for optimal efficiency

In a Schlieren-based configuration, the zero order corresponds to the planar state and is thus blocked. To maximize efficiency, power must be moved from this order to the other orders. Also, the specific orders to use or block must be chosen. For
these gratings, we can express the \( n^{th} \) order diffraction efficiency \( \eta_n \) of each order \( n \) as follows [68, 73]:

\[
\eta_n(\theta) = J_n^2(\theta), \quad \theta = 4\pi a/\lambda,
\]  

(5.5)

where \( J_n \) is the \( n^{th} \) order Bessel function and \( a \) is the deformation amplitude. The square of the Bessel function \( J_n^2 \) gives the relative intensity and can be added linearly for the total relative intensity of transmitted orders. This function \( \eta_n(\theta) \) is plotted in Fig. 5.5 for orders 0, 1, 2 and 3 [74]. The zero order decreases rapidly around \( \theta = 2.4 \) and shows several small maxima after that.

![Figure 5.5: Relative efficiencies of different positive orders \( J_n^2(\theta) \).](image)

Taking both \( n \) and \( -n \) orders, the cumulative efficiency for non-zero orders up to \( N \) is written as:

\[
\gamma_N(\theta) = \sum_{n=1}^{N} J_n^2(\theta) + J_{-n}^2(\theta)
\]  

(5.6)

For the extreme case of using all non-zero orders, we obtain:
\[ \gamma_{max}(\theta) = \lim_{N \to \infty} \gamma_N(\theta) \] (5.7)

Fig. 5.6 gives plots for the cumulative efficiency \( \gamma_N \) for different values of \( N \). As more orders are included with increasing \( n \), the graph more closely approximates that of the theoretical maximum. Since the sum of all relative efficiencies is 100%, it follows that \( \gamma_{max}(\theta) = 1 - \eta_0(\theta) \).

![Graph showing relative efficiencies for different orders](image)

Figure 5.6: Relative efficiencies \( \gamma_N(\theta) \) for: (a) first order, (b) first and second orders, (c) first to third orders, (d) first to fourth orders and (e) all orders except zero order.

The challenge is to obtain a maximum efficiency with a minimum number of orders at a minimal amplitude. Taking the sum of the first two +/- orders at \( \theta = 0.6\pi \), a theoretical efficiency of 90% is reached.

In terms of response, it is observed that \( \gamma_N(\theta) \) is nearly linear for \( 0.2\pi < \theta < 0.55\pi \) for \( n \geq 2 \), so that modulating \( a_{max} \) will result in a linear modulation of corresponding intensity.

From equation (5.5) it follows that \( a_{max} = 0.15\lambda \), meaning a total peak-to-valley deformation of 0.30\( \lambda \). This is about 150nm for the visible light range.
5.3 Practical designs

Two types of designs are considered: a) a single-pixel modulator and b) a 2D VSLM. In the first case, a linear array of interdigitated electrodes is used to mimic a single pixel. Practical data such as optimal dimensions can be obtained to improve designs for the second design, which will eventually incorporate an NxM array of individual replicas of single pixels.

As an intermediate step and proof of concept, a single-frame implementation is chosen where the picture is hard-wired into the design. Then, standard CMOS technologies can be used for a completed VSLM.

5.3.1 Experimental single-pixel design

The design consists of: a) an interdigitated electrode array on which alternating potentials can be applied and b) a corresponding silicon chip with an etch mask on top and the mechanical layers on the bottom facing the electrodes.

Designs with electrode widths ranging from 10\(\mu\text{m}\) to 1000\(\mu\text{m}\) have been fabricated to cover a large experimental spectrum. The space between electrodes is set at 10\(\mu\text{m}\) and the thickness of the deposited layer is 0.6\(\mu\text{m}\). For flexibility, spacers are included in a later process step rather than in the base design.

![Diagram of experimental single-pixel design](image)

Figure 5.7: Top membrane (left) and bottom electrode (right) chips for experimental chips.

Global chip dimensions were determined to be 10x15mm, where the active area is 6x6mm and the rest of the space is used for contact pads or as a safety margin.

The initial purpose of the top chip was to protect the entire bottom chip, where etch windows provide access to the active area and contact pads. Then, only the sidewalls need adequate protection.
Further improvement of etching techniques using total encapsulation provide the ability to fully protect any part of a design, so such measures were found to be no longer necessary. However, having a well-defined etch window for the active region remains a good choice in terms of quality.

The exact implementation for the top chip is relatively flexible and newer designs made in parallel to optimization of the process have included covering only the active region rather than also the contact pads. As a base coating, all designs use a thin nitride layer, but the metal layer (generally aluminum) is relatively implementation independent.

A direct application for this design beyond experiments is to use them as a depth-modulated diffraction grating for e.g. spectrography or to use them as a form of light switches for communication networks.

### 5.3.2 Static grating-encoded image

As a proof of concept design, a single-frame layout of activated pixels can be made that are controllable with just a few contact pads. Fig. 5.8 illustrates the basic design for an 'N' shape.

Each grating is provided with two alternating voltages $V_+$ and $V_-$. The places with "off" pixels are left empty. Proceeding to the actual realization of integrated electronics from this point will then be a relatively small step.

If all lines of equal potential are interconnected, the full frame can be driven by just two contact pads in addition to the ones for the silicon substrate and the membrane counter electrode.

The full-wafer design features various resolutions and grating parameters as given in table 5.1.

<table>
<thead>
<tr>
<th>Dimensional variable</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of frame [mm]</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Number of pixels per frame</td>
<td>25</td>
<td>680</td>
</tr>
<tr>
<td>Pixel size [$\mu$m]</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>Electrode width [$\mu$m]</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Inter-electrode space [$\mu$m]</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Electrodes per pixel</td>
<td>4</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 5.1: Table with tunable parameters for grating arrays

The further technology and design for the top chip stay principally the same as
that for the single-pixel design, except for the change in window size.

5.4 Technology and fabrication procedure

The fabrication procedure is conceptually independent of the driving array, be it a single pixel or a full frame. For all designs and practical approaches, the main technological issues to be taken into account are:

- Shrinkage of the elastic material during the polymerization sequence. The volume of the finalized layer is typically less than that of the material, usually by a factor of 1-5%, resulting in surface tension.

- Thermal expansion coefficients that may be one or two orders of magnitude greater than that of e.g. aluminum or gold, complicating the use of thermally cured elastomers.
• Imprinting effects of long-term deformations when the potential distribution on the electrode array remains static. This can be solved by driving the electronics in AC mode.

• Compatibility with existing processes when post-production steps are taken to prevent contamination of process lines.

The shrinkage and expansion effects of the viscoelastic layer cause problems during both construction and operation. These limit the use of processes that either require high temperatures or a vacuum. To avoid these problems, the following choices were made:

• All processing of the mechanical layers is done on an independent static carrier chip. Technology has to be developed to transfer this to the viscoelastic base.

• It must be possible to carry out the complete procedure at room temperature, with the exception of selected parts for shorter processing times.

With these choices, a different path is taken from that in literature, where the metal layer is evaporated on spin-coated elastic layers, which form non-optimal supports. The outline of our fabrication process is shown in Fig. 5.9, depicting the following steps:

1. The elastic material is cross-mixed, filtered and de-gassed before use, so that no large particles or air bubbles remain in the solution that can limit operation or damage the membrane.

2. A droplet of the elastic material is deposited on the bottom chip and optionally de-gassed again.

3. The top chip is placed on top of the droplet and pressed down until it reaches the spacers, thus planarizing the viscoelastic layer.

4. The silicon of the top chip is removed, commonly by etching it away, resulting in a freed membrane.

5. Post-process mounting and packaging steps for completion.

The only post-process step that is directly dimension dependent is the one concerning spacers. In the fourth step, the top carrier chip can be removed in several different ways:
Figure 5.9: Schematic overview of the fabrication process: after deposition of a droplet on the bottom chip (a), pressing together the chips (b), curing the elastic layer (c) and etching the bulk silicon (d).

- Etch away the bulk silicon completely, using an etch stop in the top mechanical layer. Elevated temperatures may be required.
- Use an intermediate sacrificial material between the bulk carrier and mechanical layers, then use lift-off to free these layers. Various methods are available for room temperature processing.

The relevant dimensions for the procedure are listed in table 5.2.

<table>
<thead>
<tr>
<th>Dimensional variable</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacer distance [$\mu$m]</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>Nitride thickness [nm]</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Aluminum thickness [nm]</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Electrode width [$\mu$m]</td>
<td>10</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 5.2: Dimension ranges for experimental implementations.

Various possibilities had to be explored for the exact process parameters and will be given detailed attention in the next few sections.
5.4.1 Carrier and driver chips

The assembly requires two chips: the carrier chip for mechanical layers and the driver chip with the electrode array.

Driver chip with electrode array

A 600nm aluminum layer is patterned on a silicon substrate coated with an 800nm insulating layer of oxide. Directly on top of this aluminum layer, the viscoelastic layer will be formed.

Optionally, to remove or lessen the possibility of a short-circuit or break-through, an additional oxide layer can be formed on top of the active area as shown in Fig. 5.10. The profile will follow that of the patterned aluminum structure.

![Diagram of oxide coating and contact pads](image)

Figure 5.10: Schematic side-view diagram of an oxide coating electrodes and contact pads showing all relevant layer thicknesses and profile.

These chips form the base for the elastic layer and similar pre-processing can be applied to different structures with full-frame modulators or electronic silicon substrates.

If necessary, solder bumps on top of the contact pads can provide conductive paths for external electrical connections to the electrode structure if wirebonding is either complicated or not an option.

Mechanical carrier chip

On the top carrier chip, the mechanical layers are formed. The exact configuration depends on the approach taken. Fig. 5.11 shows the schematic of a typical layer stack, with a nitride layer (for an etch stop and mechanical support), aluminum layer (for reflectivity and as a counter electrode) and optional protective layers.

A nitride etch window can be created to improve definition, but it is not required. A 50-100nm thick LPCVD low-stress nitride layer is grown on the pol-
5.4 Technology and fabrication procedure

![Diagram of top chip layers](image)

Figure 5.11: Schematic side-view diagram of the top chip showing different possible layers.

ished side. On top of this, a 60-100nm thick metal layer (aluminum or gold) is either evaporated or sputtered.

The protective layers are necessary to prevent damage during dicing and handling. Initially, a polysilicon layer was used, but removal with anisotropic etchants caused artefacts - see Fig. 5.12. This problem was alleviated by first immersing the chips for 50-80 minutes in a 100% HNO₃ solution. Better results were obtained with isotropically etched protective layers.

![SEM photograph](image)

Figure 5.12: SEM photograph of an unetched orientation-dependent remnant due to initial dirt on the sacrificial surface.

In the first approach, where the top chip fully covered the driver chip, we evaporated the aluminum layer as it offered higher flexibility in the choice of coated area, however, this caused adhesion problems. Full encapsulation technology al-
metallized viscoelastic layers

lows for full-chip sputtered coatings.

5.4.2 Properties and preparation of the elastic layer

A number of conditions need to be met by the elastic material that is to be used, such as low viscosity, sufficient adhesion (or means to achieve it) and good dielectric properties to sustain high electric fields. Various such materials exist and the elastic material that will be considered here is “Sylgard 527 Silicone Dielectric Gel” that has properties such as being relatively soft and not very viscous, thus allowing deformation at low externally applied mechanical forces.

Such materials are generally polymerized by UV light, crosslinking of two components, thermal or by exposure to air. In this case, the process starts after mixing of parts A and B and can be accelerated thermally. Relevant properties are shown in table 5.3 for 25°C.

<table>
<thead>
<tr>
<th>Product</th>
<th>Sylgard 527</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity [mPa.s]</td>
<td>425</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.97</td>
</tr>
<tr>
<td>Curing time at 100°C [min]</td>
<td>200</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.4074</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>2.85</td>
</tr>
<tr>
<td>Dielectric strength [kV/mm]</td>
<td>15.1</td>
</tr>
<tr>
<td>Volumetric resistance [ohm.cm]</td>
<td>$7.0 \times 10^{15}$</td>
</tr>
<tr>
<td>Potting time [h]</td>
<td>1.5</td>
</tr>
<tr>
<td>Mix ratio by weight</td>
<td>1:1</td>
</tr>
<tr>
<td>Adhesion to flat surfaces</td>
<td>moderate</td>
</tr>
</tbody>
</table>

Table 5.3: Relevant parameters of Sylgard 527 Silicone Dielectric Gel.

The exact preparation process for this viscoelastic material is outlined as:

1. Components A and B are thoroughly mixed in a 1:1 volume ratio. Properties can be altered by changing the ratios.

2. The resulting liquid is filtered through a teflon filter with a pore size of 0.2µm in order to remove the larger particles.

3. Optionally, small glass balls with a diameter in the range of 5-10µm are inter-mixed in the solution for spacer purposes.
4. The filtered substance is de-gassed in a vacuum chamber.

A point of concern was the introduction of air bubbles when forming the layer between two flat surfaces. It was checked whether bubbles were introduced by using a transparent glass plate as a top chip. Careful analysis revealed no inherent introduction of air bubbles as a result of the procedure, provided that the droplet shape is convex.

5.4.3 Internal and external spacers

The spacer distance between the chips and thus the thickness of the viscoelastic layer can be achieved in three ways:

- Integrated spacers in the process for the driver chip.

- Introduction of 5-10μm sized glass balls into the solution at the cost of random defects over the surface.

- External spacers placed at the edges, about 15-35μm thick.

The first method will be used for larger scale production, while for experimental purposes, the last two can be considered to fit both high and low spacer regimes. For the approach with glass balls, commercially available products were used. For the case with external spacers, diced thinned silicon chips were found suitable. Various wafer thinning methods were researched [75, 76], but we developed a more simple approach: using a successively approximated timed etch stop.

A process wafer was immersed in a 33 wt% KOH solution at 85°C and etched at about 170μm per hour. The results are thicknesses of e.g. 23 ± 2μm, which is accurate enough for this purpose. Accuracy can be improved by better pre-polishing of the wafer and the use of lower etching temperatures.

The process method is as follows:

1. Place the (initially) 525μm thick wafer in the 33 wt% KOH solution at 85°C.

2. Etch both sides for 114 minutes to approximately 200μm, measure actual thickness and calculate time $T_e$ needed to reach 100μm.

3. Etch for $T_e$ minutes (in the order of 30-40) to reach 100μm. Calculate time $T_{e2}$ for reaching 50μm.
4. Etch for $T_{e2}$ minutes (approximately 15-20) and calculate time $T_{e3}$ for reaching the final thickness.

5. Etch for $T_{e3}$ minutes, remove wafer from etchant and carefully clean for 30 minutes in water.

The resulting thinned wafer is flexible and can be carefully removed from the solution. Then, it is diced into small fragments. These are then used at the perimeter of the driver chip. Matching of these fragments over the statistical spread ensures increased accuracy.

### 5.4.4 Thin-film transfer using bulk etching steps

In the first approach, the sacrificial material is removed by dissolving it directly after bonding the active layers to the viscoelastic carrier. Here, the carrier chip should feature a top layer that is resistant to the etchant. For some metals such as aluminum, an additional protective layer such as nitride is required.

As a first test we used, top chips coated with only a 50nm layer of nitride and after the etching step, a 80nm layer of aluminum was evaporated on the freed nitride surface. However, expansion and shrinkage effects during the evaporation, which took place in a vacuum chamber, caused folding of the membrane (Fig. 5.13). As can be seen, the non-coated regions over the electrodes were still intact.

![Figure 5.13: Photographs of a top-side-coated membrane (left) and non-coated contact electrodes (right).](image)

Since the nitride area over the electrodes was measured and was relatively smooth and the coating step significantly deformed the active area, it can be concluded that although elevated temperatures were used in the etching step (up to
85°C), this will not lead to permanent deviations if the metal layer is not formed on the elastic layer while the latter is still expanded due to the influence of heat.

The logical next step was to eliminate the post-etch evaporation step and to coat the metal layer on the bottom side of the 50nm thick nitride membrane, so that the 80nm aluminum (or other metal) layer directly contacts the elastic layer. However, it is already perfectly formed on the nitride layer, corresponding to the shape at operational temperature. Fig. 5.14 shows a diagram of this setup.

![Diagram of Si chip + SiN and Al coatings](image)

Figure 5.14: Schematic diagram of the experimental design prior to deposition of the elastic layer.

The thickness of the nitride layer is at least 50nm, to avoid the risk of punch-through during etching, which could damage the metal layer. It is found that in these instances, the underlying electrode structure remains intact.

Fig. 5.15 shows several close-up views of bottom-side-coated membranes after the etching step. A surface deviation in the order of 0.10λ was measured in the center. A spherical deformation in the order of several wavelengths was observed over the entire aperture, for which purpose a standard Twyman-Green based interferometry measurement setup was used. This deviation was most noticeable at the frame perimeter.

Considering all issues explained above, we designed the following film-transfer procedure:

1. A droplet of the elastic material, while still in liquid phase, is deposited on the bottom chip.

2. The top chip containing the active membrane is pressed on the droplet and spreads it out without introducing air bubbles.
Figure 5.15: Photographs of a bottom-side coated membrane and a corresponding interferogram.

3. The elastic layer is cured either at room temperature (in the order of 72 hours) or at elevated temperatures.

4. The sample is encapsulated and the etch regions are determined, either defined accurately with a nitride mask or less precisely by an elastomer mask.

5. The exposed regions are etched for 6 hours in a 33 wt% KOH solution at 85°C and then cleaned in demi-water.

5.4.5 Thin-film transfer using lift-off

To simplify the procedure, etching steps can be avoided by using a lift-off approach. This has the additional benefit of not requiring elevated temperatures.

Instead of forming the layers directly on a bulk silicon base, the layers are formed on an intermediate sacrificial material or on a base to which they have poor adhesion. The mechanical layer is removed either by removing the sacrificial layer or by lifting off the base carrier.

Methods to consider are:

- Spin-coating 5-10μm thick photoresist sacrificial layers on silicon which are then coated with an aluminum layer. Acetone removes the layer.

- Use of a gold layer coated on a silicon or SiN coated substrate. The thin Cr adhesive layer is omitted so that the gold layer has poor adhesion to the base.

In both cases, the elastic layer is cured against the top chip with sacrificial material, resulting in a directly deposited metal layer on top of the 5-35μm thick viscoelastic layer.
5.4 Technology and fabrication procedure

Fig. 5.16 gives the outline where the formation of the sacrificial layer and metal stack follows the known thin-film transfer method. The first 3 steps may have to take place at higher temperatures if e.g. photoresist is used to force it to reflow and provide good adhesion.

![Diagram of fabrication steps](image)

(a) (b) (c) (d) (e) (f)

- **Bulk silicon**
- **Metal layer**
- **Elastomer**
- **Sacrificial material**

Figure 5.16: Procedure showing transfer of an optimized layer to the sacrificial layer (a,b,c) and subsequent transfer to the viscoelastic layer (d,e,f).

Any processing requiring higher temperatures can be done on materials less prone to high thermal expansion coefficients. The first two steps in the figure are optional as a means of improving surface quality. The last three steps are conceptually the same as in the previous outline, but different approaches may use different means of removing the sacrificial material.

5.4.6 Mounting and packaging

Several options exist with regard to what is done to the encapsulation:

- After etching and cleaning, the encapsulating elastomer is completely removed. The contact pads, substrate and membrane are directly accessible and can be wirebonded to the PCB.

- After etching, the encapsulant is just partially removed near the contact pads and the remainder serves as protective packaging.
Prior to encapsulation, wires are attached to the pads and these wires are already present during etching. At a safe distance from the mechanical interface, the wires are released and bonded.

Fig. 5.17 shows a photograph in which the encapsulation has been partially removed and bond wires connect the pads to the PCB.

![Figure 5.17: Partially encapsulated sample on a PCB carrier.](image)

Use of mechanical force must be minimized near the fragile interface between the two chips, so the first option is undesirable and the last option provides the best results. Additionally, electrical connections are simpler.

The schematic diagram of a typical configuration with the four main contacts is shown in Fig. 5.18.

Encapsulation steps are only necessary for processes requiring etching steps. When using lift-off, they can be directly mounted on the PCB.

### 5.5 Experimental results

Experiments are described here that were conducted in parallel to ongoing research. Since the technology itself is very experimental, the first aim was to be able to produce flat surfaces and secondly, it was seen if these could be adequately deformed.
5.5 Experimental results

Figure 5.18: Schematic diagram of an assembled chip, showing the four contact points.

5.5.1 Measurement setup

Optically, there were two things of interest to measure:

- Information about surface shape and deformation, to be obtained from an interferogram.
- Far-field diffraction pattern as a result of applied potentials.

Fig. 5.19 shows a diagram of a Twyman-Green-based setup, where the spatially filtered light (through a $20\mu$m pinhole) of a He-Ne laser beam is collimated and split to both the active surface and a flat reference mirror (at least $\lambda/20$ accuracy). The reflected beam of the reference mirror passes through the beam splitter and the beam of the measured surface is reflected from it. The combined beams will then produce the interferogram.

To view the far-field diffraction pattern, the reference beam has to be blocked and the imaging lens removed. The distance of the modulator to the screen is a constant 2.47m.

5.5.2 Single-pixel modulators

The types of configurations to experiment with are:

- Non-etched samples based on lift-off, $5\mu$m viscoelastic layer thickness and only a metal layer.
Figure 5.19: Schematic representation of the experimental setup.

- Samples with etched carriers and, a layer thickness of 5μm, additional 50nm nitride layer over the metal.

- Same type of samples, but with a thickness of 25-35μm and nitride.

- Stack of materials including 250nm of SiN and thickness set at 35μm.

Gold coated lift-off chips

A 125nm thick gold surface was transferred directly to a 5μm viscoelastic layer using the lift-off technique in which the bad adhesivity of the metal layer to the carrier is used. In this case, the entire 10x10mm upper area of the driver chip was coated, in which 6x6 is optically active.

The membrane and first electrode contact were grounded and on the other pad, a potential $V_S$ was applied. This would correspond in Fig. 5.1 to $V+$ being set to $V_S$, while $V-$ and $V_0$ are both grounded. In the experiment, $V_S$ was gradually increased producing the interferograms shown in Fig. 5.20. The vertical line pattern
that emerged follows that of the electrodes and increases in modulation depth with increasing potential.

Figure 5.20: Interferograms for $V_S = 0\text{V}$ to $V_S = 200\text{V}$.

Observing the corresponding diffraction pattern, we obtain Fig. 5.21. The centers of each order are each spaced at 7.2mm, meaning a first-order angle of 2.91 mrad. It is seen that the power distribution in the non-zero orders follow those as predicted by the Bessel functions.

Figure 5.21: Far-field diffraction pattern for increasing $V_S$ up to 200V and back again to 0V.

Clearly observable diffraction was found already at $V_S = 50\text{V}$. The static regions surrounding the active area cause the large bright spot in the picture and are the reason for the brightness in the zero order in spite of modulation. The
Diffraction pattern and spacing are consistent with theoretical expectations.

Response time was measured by placing a photodiode in the third order and applying a periodic pulse to $V_5$ as shown in Fig. 5.22.

![Figure 5.22: Intensity response to a rectangular input signal pulse.](image)

When only one channel is used, the rise time is very fast (order of 1-5ms), while the return time is considerably longer, owing to passive relaxation of the elastomer. In principle, this can be countered by alternate driving of the contacts.

Fig. 5.23 shows the response in a dark-Schlieren type optical setup.

![Figure 5.23: Graph of response times to a rectangular signal pulse on $V_5$.](image)

A lens with $f=15\text{mm}$ is placed in the light path and an absorbing target is placed in the focal spot. A projection lens images the modulator surface to the
5.5 Experimental results

projection plane, where a photodiode is placed.

At the screen, a bright pixel results if modulation takes place causing the non-zero orders to pass the stop as shown in Fig. 5.23. Frame rates of up to 75Hz can be achieved before optimization.

Bulk-etched top chips with a thin viscoelastic layer

We carried out measurements on a modulator with a 5μm viscoelastic layer, 56 electrodes over the active region and a 50nm SiN layer coated with an 80nm aluminum layer. The membrane was unconnected, while a potential difference \( V_D \) was applied between the electrode pads.

The potential \( V_D \) was increased up to 300V, and the resulting deformation was observed from the diffraction pattern given in Fig 5.24.

![Diffraction Patterns](image)

Figure 5.24: Photographs of the far-field diffraction pattern of a semi-actuated pixel at \( V_D=230\text{V} \) (top) and an actuated pixel at \( V_D=300\text{V} \) (bottom).

As the potential increased, power shifted out of the zero order into the other orders. The centers of maxima were 13mm apart. In this case, it is seen that power was still present in the zero order, which is due to the effect of the nitride layer in addition to the scattered light of the packaging.

Measurements with 100 electrodes give similar results, except that the maxima are spaced apart by 14.4mm and more power is modulated out of the zero order. As seen, higher spatial frequencies \( f_s \) on the electrode structure will result in higher first-order diffraction, which will have a positive impact on contrast.

Since the mechanical layer thickness is greater (an Al-SiN stack is used), the responsivity is less than for a modulator with just a 125nm gold layer.
Bulk-etched top chips with a thick viscoelastic layer

To see the influence of thicker viscoelastic layers, we used these in the same configuration, except with a 23µm spacer distance and 30 electrodes over the active area. In this case, all contacts were grounded except for one electrode pad, on which up to 300V was applied.

Fig. 5.25 shows interferograms of the surface under increasing potential. The quality of the surface is not optimal, because of incomplete etching at the bottom right corner and partially due to the greater layer thickness.

![Interferograms](image)

Figure 5.25: Interferograms of a surface with thick viscoelastic layer under increasing $V_D$ up to 300V.

It can be seen that a periodic sinusoidal shape is present corresponding to the electrode structure with an amplitude that increases with $V_D$.

The viscoelastic layer thickness and spatial frequency $f_s$ are not in the ideal theoretical range and this is reflected in the diffraction pattern under high potential: only one order was visible and most power remained in the zero order.

Experiments on other devices with equal thicknesses yielded similar results. This confirms the predicted requirement for thinner films that are in the 5µm range.

Stack of materials on a thick layer

An adaptive mirror with a 15mm diameter, 500nm SiN layer and a stack of metals was filled with a 35µm thick viscoelastic layer and cured. All underlying electrodes were connected to potential $V_S$ and the membrane was grounded.

Increasing $V_S$ up to 300V leads to visible modulation of the wavefront in the order of 200nm. To obtain data on the response time, a step-shift was introduced to $V_S$ and the settling time of the diffraction pattern was measured. In this case, it was 100ms, meaning that a 10Hz driving frequency is possible. Given the configuration, this figure can be considered a lower bound in the operational sense.
5.5.3 Conclusions from the experiments

Experiments were done with different modulators using both technological approaches and covered several parameter sets. It is seen that the behaviour improved as the device parameters were closer to those predicted by theory.

It was, however, not the direct goal to reach the theoretical limit, as first the challenge of finding a reliable fabrication technology had to be met. This is why relatively safe parameters had to be used with a viscoelastic material known to provide acceptable results.

As confirmed by the experiments, thicker layers and lower spatial frequencies result in worse performance in terms of the modulation, as seen in the diffraction pattern. In terms of response times, theoretical expectations were in the order of several milliseconds. This expectation was met for the active flanks, but not when response depended on relaxation of the elastic layer to return to its original shape.

The conclusion that can be draw from the current experiments is that the modulators based on lift-off are most promising since they give best response times and modulation characteristics even at non-optimized parameters, while at the same time being most straightforward to fabricate.

5.6 Conclusions

Approaches were presented to the previously researched ideas of using elastomer-based deformable reflective surfaces as solid-state alternatives for the modulators in Eidophor projectors, which are known for their high light output and image quality.

The VSLM consists of a mechanical set of layers resting on a 5-35μm thick viscoelastic layer over a periodic electrode structure. By applying alternating potentials, the surface is deformed sinusoidally. Schlieren imaging systems can be used to map the phase change to an intensity modulation.

Theoretical analysis showed that for maximum efficiency, total deformations in the order of 0.30λ are necessary.

The mechanical layers are formed independently on a static carrier chip and optimized before being transferred to a thin viscoelastic layer. Approaches for this transfer technology were investigated: in the bulk-etching technique, the carrier was etched away and for lift-off, it was removed by dissolving a possible intermediate sacrificial layer.

The process was optimized to work in a 25-85°C temperature range with the metal surfaces reaching local accuracies in the order of 0.10λ. Using encapsulation
technology, the procedure can be further simplified by omitting etch windows on the top chip.

Designs were made for a single-pixel design consisting of a linear array of interdigitated electrodes in sizes of 10 to 1000μm. These are driven by two electrode contact pads and a membrane contact.

Spacers were introduced independently, either as a random distribution of glass balls in the solution or as thinned wafer fragments at the perimeter. Spacer distances of 5 to 35μm were employed. The mechanical layer consisted of 50nm SiN and 80nm aluminum.

For mounting, three options were considered: the flexible encapsulation could be completely removed, partially removed or not removed at all. In the last case, wires have to be incorporated prior to etching, but this approach has the advantage of higher mechanical stability.

Experiments with at least one implementation of each approach are described. In the case of gold coatings on 5μm sized elastic layers, diffraction was observed starting from 50V which increased in strength around 200V. Rise times to the modulated state were in the order of 5ms, but longer times were necessary to return to unmodulated state. Using a basic Schlieren type imaging system, frequencies in the order of 75Hz could be obtained. We expect that these can be improved by driving alternate electrodes for each subsequent frame.

For bulk-etched top chips, similar results were found, but the presence of the SiN layer appeared to have a positive effect on fall times. With thicker elastic layers, the depth of modulation is larger, but the total response time is lower. When a 500nm SiN layer was used and a stack of metals on a 35μm viscoelastic layer, response times in the order of 100ms were measured at $V_S=300V$. 
Chapter 6

Elastomer optical components

6.1 Introduction

Given the sub-micron precision attainable with certain elastic materials, it is interesting to investigate a new class of adaptive optical components: elastic optical components. These are macroscopic oriented and rely mostly on direct mechanical deformation as a means of actuation. Deformation can be induced by e.g. piezoelectric or thermal principles.

The elastic layer is cast against a static mold, which is usually pre-treated with a release agent to prevent adhesion. After curing and post-treatment, the layer is released from the mold and a freestanding flexible component results as seen in Fig. 6.1.

Using such technology, it is possible to make very precise and low-cost replicas of microstructures. Commonly, elastomers are used as a flexible mold into which materials are poured with suitable mechanical and optical properties (such as some epoxies and optical adhesives). Deviations from ideal surfaces have been reported in literature in the range of 0.13λ [77], which is sufficient for most optical applications.

In this chapter, we will consider using elastomers for fabricating the following component types:

- Flat surfaces: a reflective coating on the elastomer generates a deformable mirror surface.

- Curved surfaces: flexible positive lenses of up to 10cm in diameter and focal lengths in the order of 50cm.
- Flexible diffraction gratings with periods in the range of 1 to 10\( \mu \text{m} \) and a 600nm height.

- Square and hexagonal microlens arrays with pitches in the order of 300\( \mu \text{m} \) and focal lengths of 30mm.

To fabricate these components, one can use already optimized static masks as molds, such as polished flat surfaces, periodic structures or hexagonal and square micromirror arrays fabricated in silicon [78]. We fabricated elastomer diffraction gratings with periods of 10\( \mu \text{m} \) and a step height of 0.6\( \mu \text{m} \) in this fashion.

![Diagram of fabrication process](image)

Figure 6.1: Schematic overview of the fabrication process for deformable optical components before/during curing steps (left) and after curing (right).

Once fabricated, the flexibility of the resulting structure allows it to be deformed and attached to non-standard surfaces, such as cylindrical ones or into non-convex shapes, which are more difficult to create using standard casting methods.

### 6.2 Material properties

The adhesive properties of these materials can be modified by using special adhesives or release agents, and therefore the initial adhesivity to the substrate is not always a limiting factor. Sometimes, the presence of a natural lack of adhesivity can even be used to omit the use of release agents, which can further increase surface quality.

A very common commercially available elastomer is polydimethylsiloxane (PDMS), which we obtained under the name “Sylgard 184 Silicone Elastomer” manufactured by Dow Corning. This material has desirable dielectric properties
and is resistant to a range of chemicals (as observed in chapter 3), thereby providing both mechanical and electrical protection. Table 6.1 gives a list of relevant parameters.

<table>
<thead>
<tr>
<th>Product</th>
<th>Sylgard 184</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity [mPa.s]</td>
<td>3900</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.03</td>
</tr>
<tr>
<td>Thermal expansion coefficient [μm/m°C]</td>
<td>310</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>6.20</td>
</tr>
<tr>
<td>Curing time at 100°C [min]</td>
<td>60</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.430</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>2.7</td>
</tr>
<tr>
<td>Dielectric strength [kV/mm]</td>
<td>21.2</td>
</tr>
<tr>
<td>Volumetric resistance [ohm.cm]</td>
<td>$1.2 \cdot 10^{14}$</td>
</tr>
<tr>
<td>Potting time [h]</td>
<td>2</td>
</tr>
<tr>
<td>Mix ratio by weight</td>
<td>1:10</td>
</tr>
<tr>
<td>Adhesion to flat surfaces</td>
<td>poor</td>
</tr>
</tbody>
</table>

Table 6.1: Relevant parameters of Sylgard 184.

Interfacing elastomers with other materials (such as a reflective metal layer) involves a number of problems:

- Thermal expansion coefficients differ by at least one order of magnitude, causing expansion and shrinking effects.
- Final flatness of a relatively large reflective layer over a long period of time and a wide temperature range.
- Imprintining of patterns due to any irregularities in the underlying structure, due to shrinkage of the elastomer.
- Long-term stability of the metal layers.

These problems are similar to those for VSLMs, but can be larger because equal relative deformation will result in a larger absolute deformation if the layer thickness is increased from 5-10μm to 2-5mm. This effect is partially a result of a non-planar substrate base as illustrated in Fig. 6.2. As a worst-case approximation, it can be assumed that the peak-to-valley deformation on the top surface will be in the same order as that of the periodic structure.
6.3 Elastomer-based deformable mirrors

It may be interesting to provide elastomers with an optically very flat reflective metal coating, given that the elastomers themselves can be made to accurately planarize on surfaces that are not ideally smooth within specific tolerance ranges.

Literature study suggests various methods being researched on casting large optical components from polymers or glass (order of 9-10μm) without using predefined surfaces, but by using physical properties of the material in liquid phase e.g. while it is being spun to achieve initial shapes that can subsequently be polished further if necessary [79, 80, 81].

Direct evaporation of the metal on the elastomer is not possible, as is verified with experimental examples. Fig. 6.3 shows a SEM photograph of an initially flat elastomer surface after evaporation in a vacuum chamber. A possible solution to this problem is to form intermediate layers that have averaged mechanical and thermal properties [69].

An approach that is explored in more detail in this thesis uses direct transfer of pre-metallized sacrificial surfaces to elastomer layers. Commonly, a 50-250nm thick SiN layer is grown on a silicon wafer, after which it is coated with a 80-100nm thick aluminum layer. The aluminum coated side of the wafer is then attached to the host material, such as a pre-cured elastomer solution. After curing and corresponding alignment to the flat top chip, the silicon can be bulk etched, stopping on the nitride layer.

Another approach is based on curing elastomers or UV cured optical adhesives (Norland 61) against gold-plated silicon chips and using the bad adhesivity of evaporated gold to the silicon carrier chip. Due to the inherent shrinkage effects, the
6.4 Elastomer lenses

resulting surface of the metal is deformed. Ways to counter this can be found in creating a stack of 100\(\mu\)m thick layers on the gold surface, where the bottom layer is a thin layer of cyanoacrylate glue.

To test the surface roughness experimentally, we measured a 2mm thick elastomer cured against a planar chip in several places with an alpha stepper. This equipment carefully positions a needle toward the test surface until it detects contact. A typical graph of such a measurement is shown in Fig. 6.4, where it can be seen for example that over a 200\(\mu\)m range, the peak-to-valley roughness is about 90nm, with an average deviation of 15nm.

6.4 Elastomer lenses

For the fabrication of transmissive elastomer lenses, positive lenses were considered to be of most interest.

As one of the initial experiments, an NaCl water solution was used whose relative density was equal to that of the elastomer. Then, floating rings were placed on the surface and the liquid-phase material was deposited inside, resulting in naturally shaped high-quality positive lenses.

Practical problems occurred, however: strongly reduced curing at the interface of the elastomer and the solution, even after heating or the use of longer curing
times. To solve this, solutions would have to be used that are chemically non-interacting with the elastomer.

A better overall solution was found in using a static mold, such as high-quality concave mirrors. The elastomer is poured into this mold while in liquid state, resulting in the top side being flat (except at the outer edges) and the bottom side having the same radius \( R \) as the mirror.

The focal distance of the elastomer lens can then be approximately calculated using a thin lens assumption as [25]:

\[
\frac{1}{f} = (n_t - 1) \frac{1}{R}
\]  

(6.1)

Filling in the refraction index of 1.4 for the elastomer from table 6.1 yields the
practical formula: $f = 2.5R$.

As an experiment, the central 3.5mm of an elastomer lens was measured with a Hartmann-Shack-based wavefront sensor. An optical power of approx. 4.5 diopters was measured. The deviation from the ideal shape was $0.375\lambda$ at an RMS value of $0.075\lambda$. Fig. 6.5 shows surface graphs for both the normal and the deformed state.

![Surface graphs showing wavefront deformation](image)

**Figure 6.5:** Graphs of the wavefront shape after passing a lens in the non-deformed state (left) and the same lens in cylindrically deformed state (right).

The resulting interferograms were calculated and are shown in Fig. 6.6.

![Interferograms showing wavefront deformation](image)

**Figure 6.6:** Calculated interferograms for a non-deformed lens (left) and a deformed one (right).

It can be concluded that at least in the central region, the surface accuracy is very high and at least one type of deformation is possible with reasonable accuracy.
6.5 Flexible diffraction gratings

Initially, as a test for the casting precision of the elastomers, these were cured against chips containing 600nm thick repetitive aluminum patterns, spaced apart by 10μm.

After fabrication, the diffractive effects could be seen by observing a bright white light source through the transmissive grating. Several increasingly diminishing diffraction orders could be seen, where in each order the different colour bands were separated.

Fig. 6.7 shows the diffraction pattern of the collimated He-Ne laser beam. The distance between each order was measured to be 73mm at a total distance of 2.2m, meaning an angle of 33 mrad for the first order.

In the spot for the zero order, parts of the surrounding packaging can be seen. The first, second and fourth orders are clearly visible, while the third order is diminished.

![Diffraction pattern](image)

Figure 6.7: Diffraction pattern for a flexible diffraction grating in normal state (top) and in deformed state (bottom).

Modulation takes place by means of e.g. compressing, stressing or bending the flexible grating. In the figure, a cylindrical deformation was imposed. Possible applications include scanning spectrography. These structures can be easily integrated with standard silicon chips and can be incorporated as part of the packaging.

6.6 Microlens arrays

As a more small-scale implementation of the positive lens with diameters up to several centimeters, one project in the Electronics Instrumentation Lab has em-
ployed elastomers (and also other materials) to form transmissive microlens arrays by curing a very thin layer of the elastomer against a micromirror array.

As a support, small transparent glass plates were used. The fabrication technology and more details are described in detail in literature [78]. Fig. 6.8 shows a photograph of an hexagonal microlens array with a 300μm pitch that was used as a mold.

![Microlens array molded in an elastomer.](image)

Figure 6.8: Microlens array molded in an elastomer.

It was reported that such arrays can be employed in Hartmann-Shack wavefront sensors leading to a λ/60 rms aberration of the reconstructed wavefront.

### 6.7 Conclusions

In the previous chapters, elastomers were used either to aid processing or for support. In this chapter, several possibilities were explored to use them as flexible optical components. Four different areas are described: flat surfaces, curved surfaces, diffraction gratings and microlenses. Direct mechanical actuation is the most likely deformation mechanism.

Technological issues that must be taken into account include thermal expansion of the material, shrinkage during curing and adhesivity of any metal layers.

Elastomer-based deformable flat mirrors were fabricated. After it was found that direct evaporation was not possible on a macroscopic scale, thin-film transfer techniques were used to achieve central deviations in the order of 90nm over a
200\(\mu m\) range. As an alternative, UV cured optical adhesives were used as a base, resulting in specularly reflecting surfaces when using a multi-layer approach.

Elastomer lenses were made by curing them against existing molds. Measurements showed RMS deviations from ideal spherical shape in the order of 0.075\(\lambda\) at strengths of 4.5 D. Cylindrical deformation of the lens was measured as well.

Flexible diffraction gratings illustrate the high sub-micron precision that can be obtained with some elastomers, by creating a 6x6mm wide transmissive grating with a 10\(\mu m\) pitch at a 600nm step. Different diffraction orders could be seen with a He-Ne laser beam, where the first order deviated by 10.5 mrad. This effect is maintained during e.g. cylindrical deformation. Possible applications include spectroscopy.

Finally, microlens arrays were created by casting them from already existing silicon molds. These can be used in various applications, such as a Hartmann-Shack wavefront sensor to obtain reconstructed wavefronts with an aberration down to \(\lambda/60\) rms.
Chapter 7

Conclusions

7.1 Introduction

In this thesis, an introduction was given to MOEMS technology and several application areas, such as projection displays and adaptive optics. The interest of research is to be able to make suitable low-cost modulators based on deformable reflective layers to accommodate a number of applications, some belonging to the mainstream and others to niche markets.

Two methods were described in chapters 4 and 5 for making spatial light modulators: a) pixelated membranes, where each pixel curves corresponding to the intended intensity value and b) viscoelastic layers with metal coatings that use diffraction to turn pixels on or off.

Elastomers were used for three different purposes: a) custom encapsulation technology to both integrate packaging and to facilitate processing steps, b) act as a mechanical support layer for VSLMs and c) elastic optical components.

It can be concluded that a diverse range of MOEMS and optics related applications is possible using elastomer materials.

7.2 Discussion of results

7.2.1 Comparison of pixelated membranes and VSLMs

It was found in the research that by using the concept of pixelated membranes, the goal of realizing commercially viable high-resolution devices would not be possible as the pixel sizes would be 3-4 times larger than that of state-of-the-art devices, which prompted a deeper step into the fabrication technology to find a
broader basis and to find a larger area of application, where for example larger pixel sizes are favourable e.g. for high-power laser applications.

The devices based on viscoelastic layers are potentially more suitable for projection systems as the pixel sizes can theoretically be sized down to 20μm and there is the attractive possibility of having a solid-state alternative for Eidophor projectors, a proven but expensive technology.

We can compare different aspects of the two approaches as shown in Table 7.1. Note that the values mentioned are theoretically possible ones for this choice of materials, e.g. Sylgard 527 as the viscoelastic material.

<table>
<thead>
<tr>
<th>Method</th>
<th>Pixelated membranes</th>
<th>Viscoelastic layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum pixel size [μm]</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Typical response time [ms]</td>
<td>&lt;1</td>
<td>5-20</td>
</tr>
<tr>
<td>Effective fill factor [%]</td>
<td>83</td>
<td>90</td>
</tr>
<tr>
<td>Possible deformation depth [nm]</td>
<td>&gt;500</td>
<td>300</td>
</tr>
<tr>
<td>Type of modulation</td>
<td>curvature</td>
<td>grating</td>
</tr>
</tbody>
</table>

Table 7.1: Comparison of several parameters of PSLM and VSLM technology.

Modulators using pixelated membranes offer advantages in applications where potentially large deformations are required and flexibility with regard to coating steps is essential. The fill factor is limited by the required wall structure, which causes parts of the reflective surface to remain static.

Devices based on viscoelastic layers are more suitable for applications where their low pixel sizes and diffractive properties are a requirement, but they can also be considered for e.g. multi-channel light-switching applications.

### 7.2.2 Comparison with other modulators

Two currently commercially available technologies in the projection display market are modulators based on liquid crystals and modulators based on arrays of tilting mirrors. Assuming a fully developed PSLM or VSLM technology, we can consider the following points:

- Analogue operation is possible, so that an equal throughput (greyscale pixels switches per second) can be provided at much lower switching speeds. This also gives a an image that is free of artefacts, unlike binary operated SLMs.
7.2 Discussion of results

- The surface is fully reflective over the entire active range and has no gaps, which results in better control of the amount of energy on the substrate.

- The relative simplicity of the mechanical layers potentially results in much higher yield during production and higher stability during operation.

- The optical setup and calibration can be more complicated since a fine-tuned dark-Schlieren imaging system is required.

- There is minimal absorptance. All light is reflected by the active surface, regardless of modulation state.

- Theoretical efficiency is in the order of 90% and is also limited by metal reflectivity. There are no losses due to e.g. polarization filters.

7.2.3 Limiting factors and stability

The properties of the viscoelastic layer in VSLMs give these limiting factors:

1. The relaxation time in single-mode driving is long (order of 30-50ms).

2. Imprinting of the electrode pattern over longer time periods, which can be fixed by using better materials.


4. Effect of e.g. deep-UV light passing through the reflective layer.

Points 1 and 2 can be countered by using active driving: the odd and even electrode phases in the grating are driven alternately, so that all switching is done on active flanks. The third point can be mitigated by resetting the shape in the form of a “maintenance mode” every period of time, e.g. 1-2 weeks. The fourth point is an issue that depends on how the elastic material responds to long periods of exposure to the deep-UV light that is not fully reflected by the metal layer. This may limit the application to spectral ranges that do not influence the material.

In terms of response time, it was seen experimentally that on the active flank, short enough response times are possible to allow full-greyscale framerates of up to 100Hz. Better response times are already possible for pixellated membranes.

The thermal stability is of more concern to VSLMs than to pixellated membranes. About the latter type, more data is known from related deformable mirror technology and it is known to be very stable both in time and temperature. The relatively high thermal expansion coefficient of the elastic layer in VSLMs can result
in a variation of deformation depths and thereby of the image quality. In this case, it is advisable to control the device temperature if either the ambient temperature or the incident optical energy fluctuates (or builds up) over time.

7.3 Recommendations for future work

The greater part of this research has focused on the fabrication and optimization of the mechanical layers. Working modulators with 5-35μm thick layers, using both the bulk micromachining and lift-off techniques have been manufactured and demonstrated. For future research, the approach using viscoelastic-based technology is most promising.

Much research has already been done on VSLMs, but because the complicated route was taken where the metal is formed on top of the viscoelastic layer, such efforts have been abandoned. By taking a different technological approach, such modulators can still prove viable. For improvement of current results, the following is suggested:

- Thorough study of the properties of the viscoelastic layer and finding the optimal cutting-edge material with the more suitable parameter set.
- Optimization of current thin-film transfer process, especially the lift-off technique.
- Study of all possible long-term effects and appropriate methods of compensation that do not cause long interruptions of operation.
- Fabrication of electronics for driving the 2D grating array to achieve individual pixel control.

Once those areas are researched and under control, a modulator can be made that could provide a solid-state Eidophor alternative and find large-scale application and deployment.
Bibliography


[31] D. Dudley, W. Duncan, and J. Slaughter


Summary

In this thesis, several aspects of light-modulating devices are explored and implemented to reach the objective of developing technology necessary for fabrication of these devices in a high-quality and low-cost manner using standard processes. Presented below are short summaries of each chapter.

Chapter 1 gives a brief introduction into the general field of application of the modulators intended and the objectives and historical background of the project itself. Outlined is the general direction and scope of the thesis.

Chapter 2 gives an overview of current technologies for the different application areas, namely projection displays, optical information processing and adaptive optics. Based on this analysis, two types of spatial light modulators are selected to be implemented: pixelated membrane- and elastomer-based modulators. These will be described in subsequent chapters.

Chapter 3 describes the technologies as required for the practical implementation, such as a novel flexible encapsulation technology that imposes a minimum of stress during fabrication and can also be used for packaging purposes, thereby integrating the packaging aspect into the entire fabrication lifecycle. As a result, different rapid-prototyping possibilities exist for quick fabrication of demonstrator samples.

Chapter 4 researches an implementation using a continuous reflective surface that is effectively subdivided into separately controllable pixels by an underlying grid structure. By applying a potential difference between membrane element and underlying electrode, electrostatic attraction results, which causes the element (pixel) to curve. This causes the phase modulation of the incoming wavefront. Using a dark-Schlieren based setup, this phase modulation can be converted into an intensity modulated projected image. Several fabrication approaches and design considerations are described. Experiments with fabricated devices reveal different effects, such as hysteresis or linear operation depending on positioning of the metal layer relative to the nitride carrier layer.
Chapter 5 further explores a spatial light modulator concept based on viscoelastic layers. The device consists of a high-quality metallized viscoelastic layer that is deformed electrostatically under application of potentials on its underlying electrode structure. This deformation leads to a sinusoidal diffraction grating, causing incoming light to be diffracted into different directions, an effect which can be used for various purposes such as optical communication. In an almost similar setup as in the previous chapter, the depth of modulation influences the intensity at the projected image plane. Given the different mechanical properties of the elastic layer and metal layers, the challenge is to deposit these layers in a stack. Several approaches to achieve this end are described. Experimental results with both SiN-Al and Au coatings show deformation as a result of applied potentials.

Chapter 6 continues the idea of using elastomers in micro-optical processes, but at a larger scale where electrostatic deformation is no longer a viable means of actuation but rather mechanical (or thermal) actuation is required. As examples of elastic optical components, flexible lenses, diffraction gratings and lenslet arrays are described.

Chapter 7 draws conclusions over the entire project and compares the characteristics of the devices implemented, providing insight in their strong and weak points in overlapping application areas.
Samenvatting

In dit proefschrift worden verschillende aspecten onderzocht en toegepast van licht modulerende devices, teneinde een technologie te ontwikkelen die kan worden gebruikt voor de fabricage van zulke modulatoren die zowel over goede optische eigenschappen beschikken als eenvoudig (en dus goedkoop) te fabriceren zijn met behulp van standaard processen. Hieronder wordt een samenvatting gegeven van elk hoofdstuk.

Hoofdstuk 1 geeft een korte introductie tot het algemene toepassingsgebied van de beoogde modulatoren en ook de doelstellingen en historische achtergrond van het project zelf. Er wordt hier ook een overzicht gegeven van het algemene doel en de reikwijdte van het proefschrift.

Hoofdstuk 2 geeft een overzicht van huidige technologie voor verschillende toepassingsgebieden, zoals projectiedisplays, optische informatieverwerking en adaptieve optica. Gebaseerd op deze analyse worden twee types "spatial light modulators" gekozen om te worden gemaakt: die gebaseerd op gepixelleerde membranen en die gebaseerd op vervormbare elastische lagen. Deze zullen worden beschreven in volgende hoofdstukken.

Hoofdstuk 3 beschrijft de technologie die nodig is voor praktische implementatie, zoals een nieuwe flexibele encapsulatietechnologie die minimale stress uitgeoefent op de samples gedurende fabricage en die ook voor packaging doeleinden gebruikt kan worden, waardoor het packaging aspect geïntegreerd wordt in de gehele fabricagecyclus. Als voortvloeiSEL hieruit zijn ook verschillende snelleprototyping mogelijkheden ontwikkeld voor snelle fabricage van prototypes.

Hoofdstuk 4 behandelt een toepassing die gebruik maakt van een continu reflecterend oppervlak dat effectief in afzonderlijke pixels wordt onderverdeeld door een onderliggende gridstructuur. Door te zorgen voor een spanningsverschil tussen het membraanelement en de onderliggende electrode ontstaat elektrostatische aantrekking, waardoor het element (pixel) zal krommen. Dit zorgt voor de verandering in fase van het binnenkomende golffront. Door een dark-Schlieren opstelling te ge-
bruiken, kan deze fase-modulatie worden omgezet in een intensiteitsmodulatie op het projectiescherm. Verschillende fabricagemethoden en ontwerpaspecten worden behandeld. Experimenten met geïmplementeerde devices laten verschillende effecten zien, zoals hysterese of lineaire operatie, afhankelijk van de positionering van de metaallaag ten opzichte van de dragende nitridelaag.

Hoofdstuk 5 behandelt een SLM concept gebaseerd op viscoelastische lagen. In het concept wordt een dunne gemetalliseerde visco-elastische laag elektrostatisch vervormd onder invloed van potentialen op zijn onderliggende electrodestructuur. Deze vervorming zorgt voor een sinussvormig diffractietralie, dat er op zijn beurt weer voor zorgt dat het inkomende licht verschillende kanten op wordt gestuurd. Dit is een effect dat voor verschillende doeleinden gebruikt kan worden, zoals voor optische communicatie. Er wordt gebruik gemaakt van eenzelfde opstelling als in het vorige hoofdstuk, waar de modulatiediepte de intensiteit van de pixel op het scherm beïnvloedt. Vanwege het verschil in mechanische eigenschappen van de elastische lagen en metaallagen ligt de uitdaging in het nauwkeurig aanbrengen van deze twee op elkaar. Verschillende benaderingen hiervoor worden beschreven. Experimentele resultaten met zowel SiN-Al en Au lagen laten vervorming zien als resultaat van toegepaste spanningen.

Hoofdstuk 6 werkt het idee van het gebruik van elastomeren voor micro-optica toepassingen verder uit, maar op een grotere schaal. Hier kan elektrostatische aan- trekking niet langer gebruikt worden voor aandrijving, maar is mechanische (of thermische) actuatie nodig. Als voorbeelden van elastische optische componenten worden flexibele lenzen, diffractietralies en "lenslet arrays" beschreven.

Hoofdstuk 7 trekt conclusies betreffende het gehele project en vergelijkt de karakteristieken van de geïmplementeerde devices en geeft zodoende inzicht in hun sterke en zwakke punten op overlappende toepassingsgebieden.
Acknowledgements

The research described in the thesis spanned a period of more than four years, during which many things have happened, both in my professional and personal life. I would like to thank all the people who have shared this period of my life and helped shape it.

I wish to thank dr. Gleb Vdovin for guiding me both through the Ph.D. work and the graduate work prior to it. His insights, constructive comments and ability to distinguish positive results were very valuable and have been important for the successful completion of this work.

I am grateful to prof. Paddy French and prof. Han Huijsing for being my promotors and for maintaining a friendly and warm atmosphere in the Electronic Instrumentation group.

The Dutch technology foundation STW supported the project, under code DEL 44.3945, which made the project possible in the first place. I thank the members of the users committee who have attended the progress meetings and shared their insights.

Writing and organizing a thesis is a fair amount of work, the quality of which depends on people willing to read it and provide comments. I thank all the members of the committee for taking the time to read it thoroughly and being part of the final defence. Mirjam Nieman has been very nice in giving many corrections and suggestions for the English part of this thesis.

The cover design has proved to be an interesting exercise. I thank the people willing to give their opinions and comments, especially Dafina Tanase and Vladimir Kutchoukov.

Going to conferences and giving presentations there is a mandatory part of Ph.D. work. This has given me the opportunity to see and experience different parts of the world such as the US and China. I remember fondly the experiences shared with the various colleagues that accompanied me on these international trips over the years.
Acknowledgements

My colleagues in the group have mostly been very kind and were often very interesting to have conversations with, both on professional topics and on more philosophical ones.

I would like to thank the staff members of the group, especially Willem van der Sluys, Inge Egmond and Evelyn Sharabi for their kind help with many financial and other administrative issues.

I thank my roommates that I have had throughout time: Frederic Laugere, Miki Djurica, Orla O’Halloran, Wijnand Lubking, Luis Rocha and Eamon Connolly. I am also grateful for having worked with the other colleagues in the micro-optics group: Davies de Lima Monteiro, Michael Loktev and Oleg Soloviev. They have each in different ways contributed greatly to making the lab a nice place to be. Special thanks goes to Ourang Akhzar-Mehr, who has helped very constructively and enthusiastically with the development of the VSLM technology.

Much of the practical work has taken place in DIMES Technology Center. Prof. Lina Sarro has been very helpful in discussions for new designs and processes and is very knowledgeable about all processing details. For technical support, Wim van der Vlist and Ruud Klerks have often helped me with dicing and bonding of my chips. Alex van den Boogaard has helped with some creative methods for patterning oxide layers. Arjan Driessen and Martijn Tijssen have always been helpful with aluminum coatings. Charles de Boer has been very friendly and has helped with essential work on getting gold coatings done.

For experimental work and setups, Jeroen Bastemeijer, Maureen Meekel, Ger de Graaf and Piet Trimp have provided me with invaluable help.

In my spare time, I have gotten positive insights by being involved in several interesting projects, one of which being the Knowledge Explosion Network (KEN), which showed me how a very diverse group of people can work together in a creative and positive manner.

Several years ago, I started taking Wing-Chun Kung-Fu classes from the school headed by Rob Vogel. In my experience, these activities have been useful both physically and mentally and have contributed positively to my life and thus indirectly to my ability to write this thesis.

Finally, I wish to thank my family and friends for their continuing support and guidance throughout time. Thanks to them, life is more pleasant and interesting.
List of publications


S. Sakarya, G. Vdovin and P.M. Sarro, "Technology for integrated spatial light


About the author

Serhat Sakarya was born on the 25th of March 1975 in Ankara, Turkey. After an internationally oriented primary school education in different countries, he moved to The Netherlands permanently and in 1993 completed his secondary education at the Gymnasium Haganum in The Hague. Then he went to Delft Technical University to pursue a study in Electrical Engineering. As part of his graduation project, he joined the Electronic Instrumentation Lab in 1997, where he worked on control algorithms for an adaptive optical system using micromachined deformable mirrors (MDMs). After receiving his MSc, he continued in the lab as a PhD student, where his work entails the development of micromachined spatial light modulators.