

SURFACE MICRO-MACHINED SU-8 2002 DEFORMABLE MEMBRANE
MIRRORS

by

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April 2011

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ABSTRACT

Imaging systems are continually decreasing in size, especially in applications such as microscopy and cell phone cameras. Much research is being done to increase focus control capabilities of these instruments. This paper describes a wet-etch release and a dry-etch release fabrication technique for SU-8 2002 surface micro-machined deformable mirrors for focus control and compensation of focus-induced spherical aberration. Producing a good quality SU-8 2002 membrane layer proved difficult and a detailed discussion of the recipe development is presented. A thorough review of both release processes is also included. The dry-etch release process has high yield and realizes larger mirrors with greater than a two-fold improvement in stroke, relative to the wet-etch release. This paper presents deflection vs. voltage plots, mechanical frequency response measurements, surface roughness and flatness, and intrinsic stress for the 750 μm – 4.24 mm nominal dimension circular and elliptical boundary membrane mirrors. The use of a 3 mm x 4.24 mm elliptical boundary mirror for 45° incidence focus control in microscopy is also demonstrated. The intrinsic stress of the film indicates that devices of similar size should be capable of 30 μm displacement in the future. This would allow for sufficient focus control in high NA microscopy applications, while the mirror or mechanism for such control could fit into an endoscopic sized imaging system.

INTRODUCTION

Focus Control for Miniature Devices

Arthroscopic surgeries provide a means for doctors to perform complex medical procedures while only making a small incision. Imaging systems in endoscopes and catheters create “eyes” for a physician to see what they are doing. While imaging systems have downscaled to address such needs, their focus control capabilities are still limited. Similarly, cell phone cameras and other miniature electronic devices also lack such capabilities. In the case of tissue imaging, introducing focus control would provide depth information to a normally two-dimensional image with the potential to improve disease diagnosis or better differentiate healthy from diseased tissues. In regard to cell-phone cameras, most currently do not offer true optical-focus control, thereby limiting picture resolution. Traditionally, focus control is achieved with motors and cams translating glass lenses, which are generally bulky and difficult to miniaturize. For significant improvement in focus control in millimeter-dimension optical systems, methods of focus control must be developed that not only meet size constraints, but are low cost and only require minimal power.

Instead of translating lenses in the system, investigators have explored the use of variable optical power elements. Examples include liquid lenses, spatial light modulators (SLM's), deformable mirrors (DM's), or a combination of such components. Focus control using liquid filled membranes that are actuated pneumatically, thermally, with optical curvature modification, and electromagnetically have been demonstrated [1-6].

Liquid lenses are typically capable of large changes in optical power, but suffer from limited ability to control the lens aberration and oftentimes require fluid handling and a pumping mechanism. Electrowetting liquid lenses control the contact angle of a fluid in order to adjust optical power [7, 8]. These do not require a pumping mechanism, but are also limited as far as fine control over the available liquid surface shape. A slightly different approach was taken by Commander et al. by immersing a microlens in a nematic liquid crystal for focus control [9]. They demonstrated a wide range of focus, but struggled to minimize negative effects of the microlens on the electric field and therefore aberrations. Martinez et al. created a zoom system using two spatial light modulators (SLM's) to mimic lenses [10, 11]. Generally, a SLM is limited to monochromatic imaging and is a pixellated modulator requiring a more complicated control interface to drive the lenses, thus adding complexity to the system. A thin camera with a magnetically actuated micromirror zoom lens was demonstrated by Kinoshita et al. [12]. This design was limited in that it only had two configurations; an inner wide-angle lens and an outer telescopic lens.

We and other investigators have explored the use of electrostatically actuated deformable micro-electro-mechanical systems (MEMs) mirrors for focus control and/or zoom while minimizing low-order spherical aberration induced by the deformation of such devices or arising from other elements in the optical system [13-19]. Because these mirrors are small and only require few electrical connections for a limited set of electrodes, they are particularly well suited for focus control in miniature imaging systems. Unlike varifocus liquid lenses, these mirrors have fast response times that allow

for novel capabilities such as high-speed focus tracking or scanning; an example is time-domain optical coherence tomography imaging [20].

Wavefront Modification for Focus Control

This section presents the basic concept of using a deformable mirror to focus rays. Deformable mirrors can alter planar wavefronts such that they become converging spherical waves. Figure 2 shows how a deformable mirror with parabolic curvature will focus a planar wave to a point by decreasing the pathlength of the rays around the perimeter of the mirror in comparison with the center, thereby creating a spherical wavefront. The Aberration Theory section in Chapter 2 covers ideal mirror shape for differing imaging configurations.

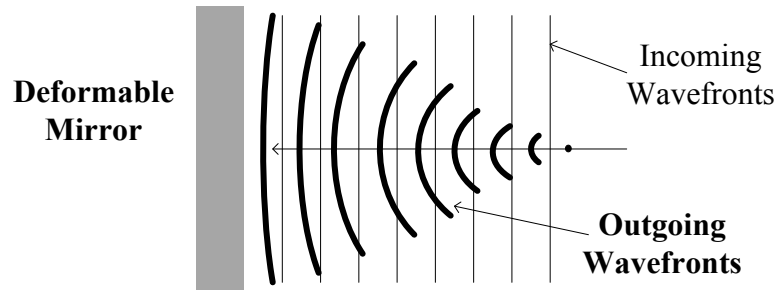


Figure 1: A deformable mirror for focus control. The deformable mirror imparts a slight curvature on the planar incoming wavefronts, resulting in a spherical converging wave focusing to a point.

Wavefront Modification for Aberration Correction

As a deformable mirror focuses light, it can potentially introduce spherical aberration. The induced spherical aberration can be minimized by controlling the shape of these mirrors. On a larger scale deformable mirrors (DMs) are utilized in adaptive optics for aberration compensation. In optical systems light can become aberrated due to

a variation of indices of refraction across an aperture. Because the phase velocity is inversely proportional to the index of refraction, this variation leads to phase differences across the aperture. Varying thicknesses of a lens across an aperture, temperature variations across a lens material, or imperfections in the lens can cause differing indices of refraction. To demonstrate how a mirror can correct for these aberrations, Figure 2 shows any isophase contour of a perturbed incoming wavefront reflecting from a deformable mirror that is deflected such that the outgoing wavefronts are planar. Portions of the incoming wavefront lead other portions and the mirror essentially creates delays for these sections, resulting in planar wavefronts reflecting off of the mirror.

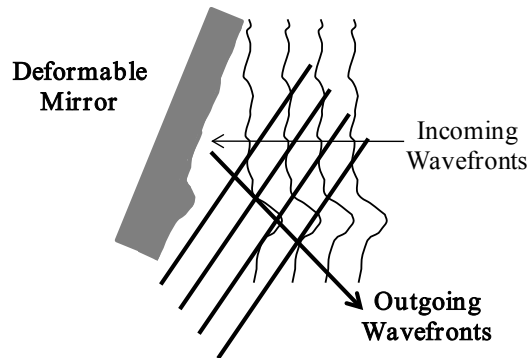


Figure 2: Perturbed incoming wavefronts corrected by a deformable mirror to be planar outgoing wavefronts. The wavefront lines represent any isophase contour of the wave.

The use of deformable MEMs mirrors or arrays of micromirrors as adaptive optics has been shown in adaptive scanning optical microscopy, multiphoton microscopy, coherent anti-Stokes Raman scattering (CARS) microscopy, and for interferometric nulling in space applications and beam steering with phase-distortion correction [21-25]. Zhao showed the feasibility of DMs for foveated imaging by demonstrating their ability

to increase the resolution of a specific section of an image in a broadband and wide field of view (FOV) system for space optics [26].

Previous MEMs Mirrors Designs

We are particularly interested in improving the design of single electrostatically actuated deformable membrane mirrors for focus control. Initially, silicon nitride surface micro-machined mirrors were fabricated for this purpose with effort to concurrently minimize induced spherical aberration [13, 27]. These devices maintained zero primary spherical aberration over a focal length range of 36 to 360 mm and could actively control two waves of spherical aberration at 660 nm. While they had a large bandwidth, greater than 100 kHz, their displacement stroke was practically limited to less than 5 μm . Extending the stroke beyond 5 μm is imperative for improving the focus control capabilities of miniature imaging devices and is further discussed in Chapter 2.

Surface Micro-machined SU-8 Membrane Mirrors

SU-8 2002 was used as the membrane layer for the mirrors presented in this paper due to its lower residual stress and elastic modulus relative to silicon nitride [28]. These mechanical properties suggest that it should be more pliable at lower voltages and better for achieving larger deflections. It is straightforward to fabricate because it is photopatternable, and the material requires lower temperatures for processing than low pressure chemical vapor deposition (LPCVD) membrane films. The low processing temperatures could make the implementation of these mirrors with other electronic

devices for MEMs applications more feasible in the future. Since SU-8 is inert to many etchants, it is a good candidate for surface micro-machining processes.

Although SU-8 is photopatternable, the soft bake temperature and other process parameters have proven to appreciably affect the quality of the film [29, 30]. Previously, investigators have performed an SU-8 surface micro-machining process to create micro valves, micro grippers, microfluidic channels, gearwheels, and chevron-type thermal actuators [31-35]. SU-8 deformable mirrors utilizing a bonded wafer technique have also been reported [36-38]. However, we have not seen free-standing millimeter dimension SU-8 membranes created using a surface micromachining process previously reported. This thesis presents a surface micro-machining technique to simplify fabrication and to reduce total fabrication time for free-standing millimeter dimension SU-8 membranes. These mirrors were also demonstrated for focus control in a microscopy optical set-up.

Thesis Organization

The Mirror Design section discusses the optical and mechanical design of the mirrors and presents an overview of their structure. The Fabrication Methods chapter provides a detailed discussion of the SU-8 recipe development and describes the other fabrication techniques used. Both the wet-etch and dry-etch release methods are explained in Release Methods. The mirrors are mechanically and optically characterized in the Characterization of Deformable Mirrors. The end of this section presents the microscopy demonstration. Finally, a Conclusion and Future Work section complete this thesis.

MIRROR DESIGN

The mirrors were specifically designed for focus control with an emphasis on minimizing self-induced aberrations. This section covers their optical and mechanical design. It also provides an overview of the devices and the fabrication processes.

Optical Design

The Aberration Theory section provides an introduction to aberrations and then further describes ideal mirror shapes for minimizing on-axis aberration for given imaging layouts. The first-order properties section describes how the geometry of the mirror leads to focusing of rays and presents optical requirements for these mirrors to benefit current imaging systems.

Aberration Theory

Although MEMs membrane mirrors can be used to reduce aberrations in a system, utilizing them for focus control can introduce additional aberrations. For an ideal optical system the wavefront leaving the exit pupil would be spherical and focus to a perfect point (Figure 3). In practice the actual wavefront deviates from this reference sphere by a pathlength error defined as the aberration function $w(x,y)$, where the pathlength error is determined by tracing a ray from the ideal image point to the exit pupil coordinates in the exit pupil plane. The exit pupil plane (x,y) and image plane (x',y') for an axially-symmetric optical system are shown in Figure 4. The five primary aberrations,

spherical a_s , coma a_c , astigmatism a_a , field curvature or defocus a_d , and distortion a_t compose the aberration function

$$w(x, y) = a_s r^4 + a_c r^2 (xx' + yy') + a_a (xx' + yy')^2 + a_d r^2 r'^2 + a_t (xx' + yy') r'^2 \quad (1)$$

and are based on the coordinate system shown in Figure 4. Since spherical aberrations only depend on a ray's location in the exit pupil plane and not the image plane, the shape of the mirror has a direct impact on spherical aberration. This means that deformable mirrors can introduce and/or compensate for spherical aberration, consequently, only spherical aberration will be discussed in detail for this thesis. One of the simplest configurations in which spherical aberration arises is when a spherical mirror is used for infinite conjugate imaging. A perfectly spherical mirror will reflect rays according to the law of reflection. This is shown in Figure 5 where the angle of the incoming ray is equal to the outgoing ray in relation to the surface normal. Also shown are infinite conjugate rays that cross the axis at a location shorter than the foci of the mirror, which is termed spherical aberration.

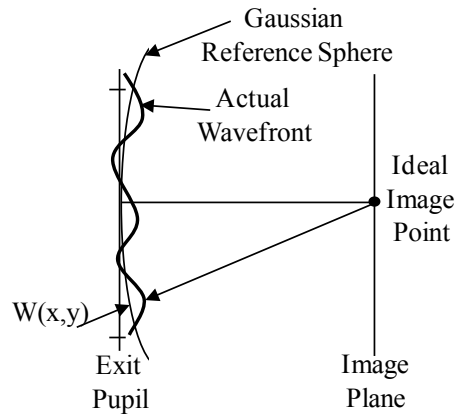


Figure 3: Gaussian reference sphere focusing to an ideal image point and actual wavefront for defining the aberration function $w(x,y)$.

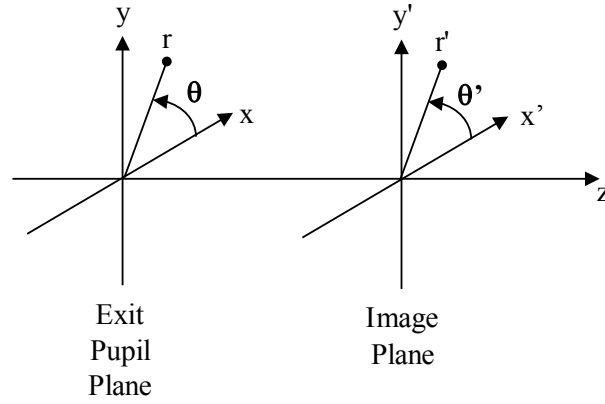


Figure 4: Coordinate system for wavefront aberration defined by Equation 6.

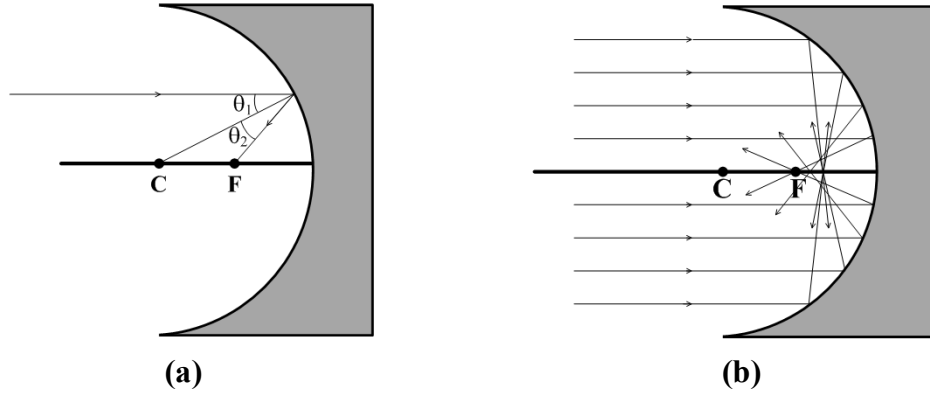


Figure 5: (a) Rays follow the law of reflection. The angle θ_2 is equal to θ_1 where the line between the two angles is normal to the surface of the mirror and extends to the center of curvature. (b) Infinite conjugate rays will have spherical aberration at the focal point of a spherical mirror. The rays cross the axis at different locations, where the incoming rays that are furthest from the center of the mirror cross furthest from the foci.

Figure 6 shows three imaging cases for focusing rays with a mirror; (a) infinite conjugate, (b) finite conjugate located at the center of curvature, and (c) finite conjugate located at a distance greater than the center of curvature of the mirror. For the infinite conjugate case, a paraboloidal mirror leads to zero aberrations. A spherical mirror would introduce spherical aberration due to larger angle rays crossing at a distance less than the distance to the focal plane, as previously discussed. For an object located at the center of

curvature of the mirror, a spherical mirror leads to zero on-axis aberration, whereas paraboloidal deflection causes spherical aberration due to the rays crossing at a distance greater than the focal plane. This case is useful for 1x magnification. In order to achieve magnification greater than one, finite conjugate object at a distance less than the center of curvature of the mirror can be used. Both spherical and paraboloidal shapes of the mirror lead to spherical aberration for this configuration, but an ellipsoidal mirror induces zero spherical aberration for finite conjugates not located at the center of curvature. Smaller magnification than 1x can be achieved by placing the object at a distance greater than the center of curvature.

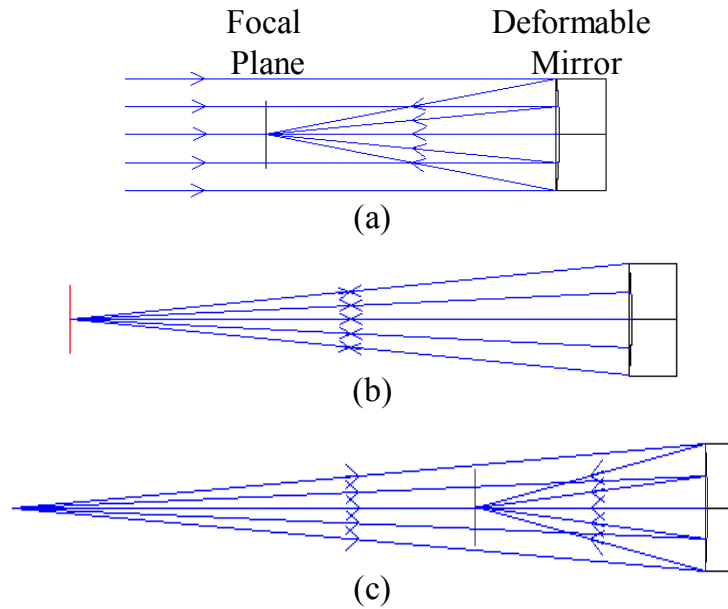


Figure 6: (a) Infinite conjugate with deformable mirror focusing rays at focal plane. A paraboloidal mirror provides zero spherical aberration in the image. (b) Finite conjugate with object located at the center of curvature where 1x magnification is achieved. Ideal imaging is with a spherically shaped mirror. (c) Object located at a finite distance greater than the center of curvature of the mirror. This creates a magnification less than 1x and in this case is 1/3x magnification. An ellipsoidal shape results in zero spherical aberration at the focal point.

With further displacement and greater focus control for these mirrors, more spherical aberration will be introduced due to difficulty in maintaining a paraboloidal shape. The mirrors presented here have three electrodes in order to better control the shape and minimize spherical aberrations with their increased stroke over the silicon nitride mirrors discussed in Chapter 1.

First Order Properties

We aim to deflect our mirrors with a paraboloidal shape, thereby creating an infinite conjugate optic while minimizing spherical aberrations. The equation for the parabola shown in Figure 7 is

$$z = cx^2 = \frac{\delta}{r_o^2} x^2. \quad (2)$$

where c is the quadratic coefficient, δ is the center displacement, and r_o is the radius.

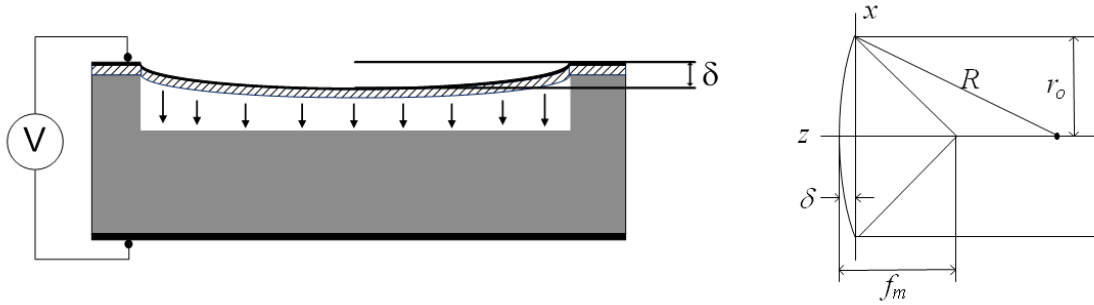


Figure 7: With an applied voltage V across the top and bottom electrodes, the mirror deflects to a center displacement δ . The membrane mirror has a radius of curvature R , radius a , and focal length f_m .

The focal length f_m of the mirror is

$$f_m = \frac{r_o^2}{4\delta}. \quad (3)$$

To achieve focus control in applications such as microscopy, a variable optical power element may be used in the front focal plane of an objective lens (Figure 8). The advantage of this location is that the NA in the image space remains constant. Furthermore, for telecentric systems the front focal plane is the location of the aperture stop for the system.

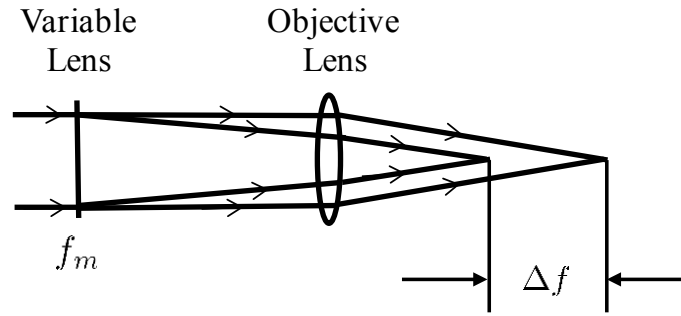


Figure 8: Variable lens in the front focal plane of an objective lens with a change in focal length Δf observed in the sample medium.

The paraxial imaging equation for the objective lens in Figure 8 is

$$\frac{F_F}{S_1} + \frac{F_R}{S_2} = 1, \quad (4)$$

where F_F is the front focal length of the lens, F_R is the rear focal length of the lens, S_1 is the distance to the object with positive distance in front of the lens, and S_2 is the location of the image with positive distance to the rear of the lens. The objective lens has a focal length of f_{0l} in air and the variable lens is located a distance f_{0l} in front of the objective lens. The medium between the two lenses is air with refractive index $n_{air}=1$. The sample medium behind the objective lens has refractive index n , making the focal length behind this lens $f_{02} = n * f_{0l}$. The relationship between the focal length of the variable lens f_m to the distance S_2 that the rays focus behind the objective lens is

$$\frac{f_{01}}{f_{01} - f_m} + \frac{f_{02}}{S_2} = 1 \quad (5)$$

This provides a change in focus within the sample

$$\Delta f = S_2 - f_{02} = -\frac{f_{01}f_{02}}{f_m} \quad (6)$$

The numerical aperture (NA) of the system for a ray angle in the sample medium θ_o , defined as $NA = n \sin(\theta_o)$, remains unchanged regardless of the focal shift for this optical layout. According to the sine condition, the height of the marginal ray at radius a has the relationship $a = f_{02} \sin(\theta_o)$. Using these relationships and Equation 3, Equation 6 can be expressed as

$$\Delta f = -\frac{4n\delta}{NA^2} \quad (7)$$

For confocal microscopy a typical index of refraction sample medium would be $n=1.33$ for water. For a $NA=0.9$ system a useful penetration depth would be $200 \mu\text{m}$ into the tissue. A membrane center displacement stroke of $30 \mu\text{m}$ would be needed to adjust focus over this penetration depth for these parameters [39]. The mirrors developed for this paper were intended to increase the stroke of such devices in order to improve their performance in applicable imaging instruments.

Focus Control in Optical Systems with Normal and 45° Incident Light

In optical systems circular boundary DM's can be used in the back focal plane of the objective lens by use of a beam splitter (Figure 9). The focal range for this configuration is the same as Equation 5.

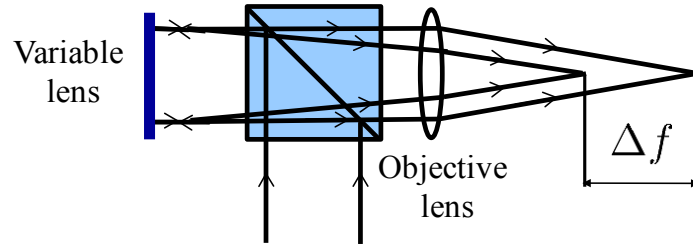


Figure 9: Circular boundary variable lens in the back focal plane of an objective lens with a beam splitter used to relay the light. This results in a change in focus Δf .

A variable lens can be used at 45° incidence in order to create a more compact optical system and/or to mitigate loss of light from the beam splitter. Figure 10 shows how the surface of a section of a paraboloid can reflect and focus infinite conjugate rays that are parallel to the paraboloid axis. Traditionally, off-axis parabolic mirrors are used for specific focal lengths and angles of incidence. Himmer proposed the use of deformable mirrors with elliptical boundaries as varifocus lenses at varying degrees of incidence for infinite conjugate rays [40, 41]. For 45° incidence the long axis of the elliptical boundary is a factor of $\sqrt{2}$ larger than the short axis to make the projection of the boundary circular at 45° incidence. This varifocus lens may be used both post-objective and pre-objective, as shown in Figure 11. The circular perimeter varifocus lens may also be used post-objective.

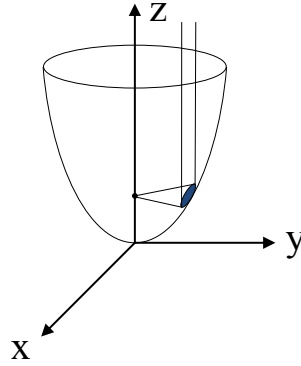


Figure 10: Infinite conjugate rays that are parallel to the paraboloid axis will reflect and focus at the paraboloid focus. Commercial off-axis parabolic mirrors can achieve this for specific angles of incidence and focal lengths. Elliptical boundary deformable membrane mirrors can replace off-axis parabolic mirrors (or equivalently the dark section on this paraboloid) and work as varifocus lenses for infinite conjugate rays at various angles of incidence.

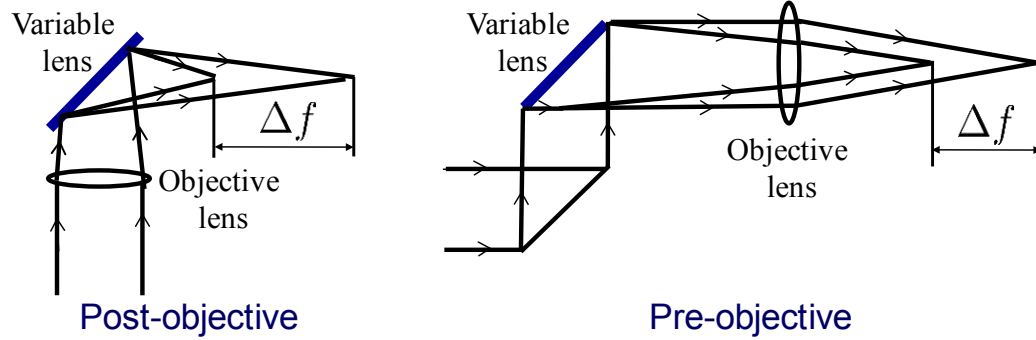


Figure 11: An elliptical boundary variable lens can be used in front of or behind an objective lens to induce a change in focus Δf .

The focus adjustment is

$$\Delta f = -\frac{4n\delta}{\sqrt{(2)NA^2}} \quad (8)$$

for the elliptical boundary variable lens in front of the objective lens at a distance equal to the focal length of the objective lens.

Membrane Model

Ulaby's *Fundamentals of Applied Electromagnetics* was used as a reference for the development of the membrane model [42]. Figure 12 shows the geometry of a circular boundary membrane with radius r_o , thickness h , and permittivity ϵ_l . In-plane tension T [N/m] suspends the membrane above a fluid medium with permittivity ϵ_2 . Two conductive films at the top and bottom support a voltage V and ground voltage $V=0$, respectively. The charge densities in the top conductive film and at the bottom of the membrane are $q_1(r)$ [C/m²] and $q_2(r)$ [C/m²], respectively. Deflection of the membrane into the initial air gap s_o is described by shape $s(r)$. Assume the membrane and fluid medium are non-conducting, the gap is small compared to the radial extent of the membrane, and the electric fields E_1 and E_2 are everywhere $\hat{z}$ directed.

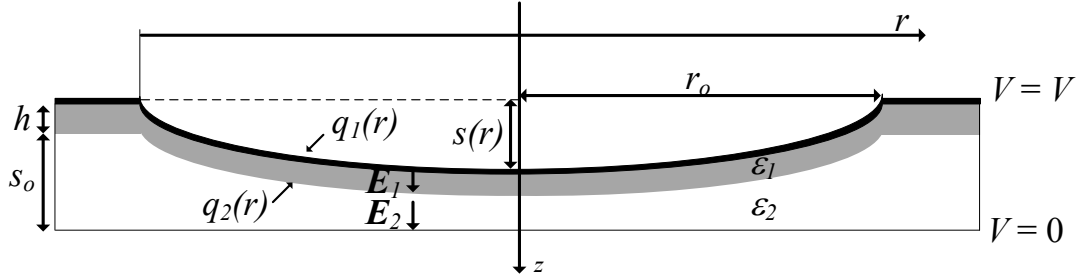


Figure 12: Membrane model schematic.

Using Gauss's law, where the total outward flux through the surfaces of a volume must equal the total charge enclosed, charge densities at the boundaries may be determined. The charge densities and applied voltage can be related to the electric fields as follows,

$$q_1 = \epsilon_l E_{1z}, \quad q_2 = \epsilon_2 E_{2z} - \epsilon_l E_{1z}, \quad V = h E_{1z} + (s_o - s(r)) E_{2z}.$$

Assuming that $q_2 = 0$ or that the membrane holds no charge,

$$\epsilon_2 E_{2z} = \epsilon_1 E_{1z} \quad \text{and} \quad V = h E_{1z} + \frac{\epsilon_1 (s_o - s(r))}{\epsilon_2} E_{1z}.$$

If the fluid medium is air, then $\epsilon_{r1} = \frac{\epsilon_1}{\epsilon_2}$. This provides

$$q_1(r) = \epsilon_1 E_{1z}(r) = \frac{\epsilon_2 V}{s_o - s(r) + \frac{h}{\epsilon_{r1}}} \quad [\text{C/m}^2]. \quad (9)$$

The equation for stored energy in a capacitor is $W_e = \frac{1}{2} Q^2 / C$ where C [F] is the capacitance and Q [C] is the charge. The equation for capacitance of a parallel-plate capacitor is $C = \epsilon A / d$, where A is the area of the plates and d is the distance between plates. Substituting in the series capacitance of the two dielectrics, the stored energy for the membrane with constant charge is,

$$W_e = \frac{1}{2} \frac{q_1^2 A}{\epsilon_1 \epsilon_2} [\epsilon_1 (s_o - s(r)) + \epsilon_2 h] \quad [\text{J}] \quad (10)$$

The electrostatic force equation is $\mathbf{F} = -\nabla W_e$ [N]. We are only concerned with the $\hat{z}$ -direction and will analyze the problem as a scalar. Taking the derivative with respect to $s(r)$ and dividing by A , the electrostatic pressure is $P(r) = q_1^2(r) / (2\epsilon_2)$ [N/m²]. In terms of the applied voltage this is

$$P(r) = \frac{\epsilon_2}{2s_o^2} \frac{V^2}{(1 - \frac{s(r)}{s_o} + \frac{h}{s_o \epsilon_{r1}})^2} = \frac{\epsilon_2}{2} \frac{V^2}{(s_o - s(r) + \frac{h}{\epsilon_{r1}})^2} \quad [\text{N/m}^2] \quad (11)$$

The equation of motion for a membrane is

$$T \nabla^2 s(r) + P(r) = \rho \frac{\partial^2 s}{\partial t^2} \quad (12)$$

where ρ [kg/m²] is the mass density of the membrane [43]. Tension is related to the intrinsic stress σ of the membrane as follows,

$$T = \sigma h. \quad (13)$$

The intrinsic stress of the membrane varies with process parameters. The area mass density for SU-8 2002 is $(1.2 \times 10^3 \text{ h}) \text{ kg/m}^2$. Under equilibrium conditions assuming $\frac{\partial^2 s}{\partial t^2} = 0$, the equation of motion for a membrane reduces to

$$\nabla^2 s(r) = -\frac{P(r)}{T}. \quad (14)$$

Substituting in the Laplacian $\nabla^2 = \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial r^2}$ for circular symmetry, the membrane motion may be described by

$$\frac{1}{r} \frac{\partial s}{\partial r} + \frac{\partial^2 s}{\partial r^2} = -\frac{P(r)}{T}. \quad (15)$$

Assuming small deflections $s(r) \ll s_o$ and a constant P for a given V , the coefficient c may be determined from Equation 2 by substituting in $s(r) = cr^2$ for a paraboloidal mirror shape. This relates the maximum displacement at the center of the membrane δ to the pressure and tension as follows,

$$\delta = |ar_o^2| = \frac{Pr_o^2}{4T} = \frac{\epsilon_2}{2} \frac{V^2}{(s_o + \frac{h}{\epsilon_{r1}})^2} \frac{r_o^2}{4T}. \quad (16)$$

Device Overview

Four main processes were done for fabricating the mirrors with two for wet-etch release (Process 1 and 2) and two for a dry-etch release process (Process 3 and 4). For Process 1 and 2, the mirrors consist of 150 nm gold for the reflective coating and top electrodes, 2.25 μm SU-8 2002 for the membrane layer, 150 nm sacrificial oxide (8 % phosphosilicate glass, psg), and 1 μm thermal oxide on a <100> silicon (Si) substrate. A

backside layer of 200 nm gold provides good electrical contact with the silicon, which serves as the counter electrode (Figure 13). 60 Å of chrome was used to promote adhesion of the gold layers. The oxides and silicon were wet-etched through 5 μm square vias. Process 3 and 4 devices have the same metallization as Process 1 and 2, but did not require oxide layers and are released in xenon difluoride (XeF_2) gas. Further details of the fabrication process are included in Chapter 3.

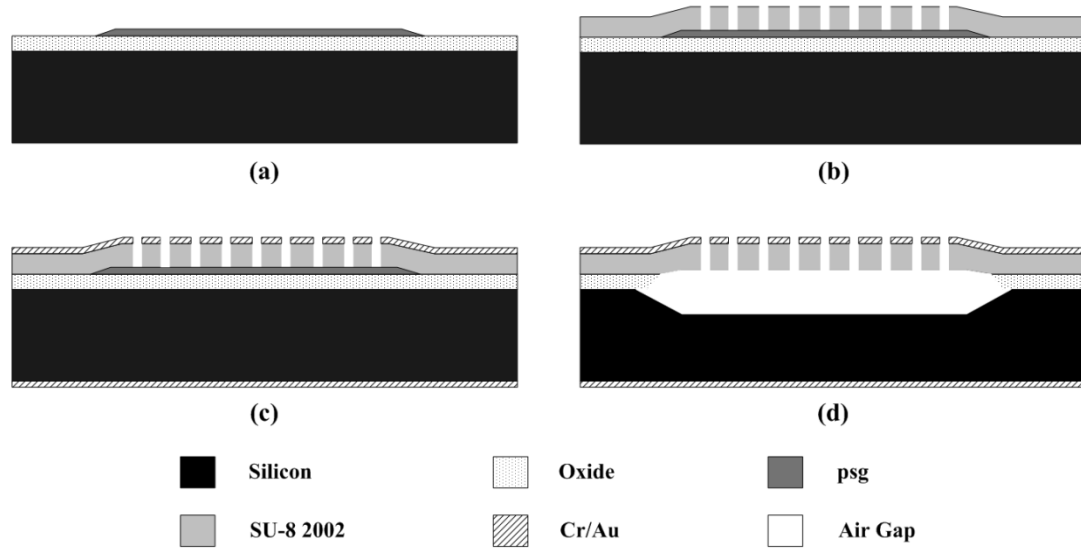


Figure 13: Cross section of the Process 1 and Process 2 SU-8 2002 mirrors, which were wet-etch released. (a) 1 μm thermal oxide and 150 nm psg were grown. (b) 2.25 μm of SU-8 2002 was photopatterned. (c) 60 Å chrome and 150 nm gold were evaporated as a reflective coating and to form the top electrodes. 60 Å chrome and 200 nm gold were evaporated onto the backside for the silicon counter electrode. (d) An air gap was created by wet-etching of the oxides and silicon through the small vias in the SU-8 and gold layers.

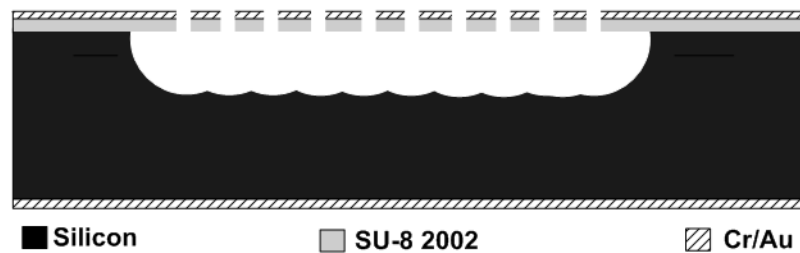


Figure 14: Cross section of the Process 3 and Process 4 SU-8 2002 mirrors, which were dry-etch released in XeF_2 .

The perimeters of the membranes were either fixed or segmented with 10 % or 20 % duty widths to emulate a simply supported boundary (Figure 15). 10 % duty width indicates 10 % of the boundary is supported by the membrane.

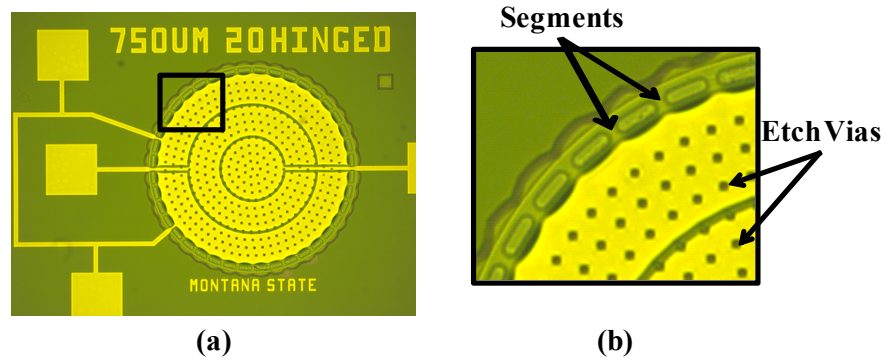


Figure 15: (a) Top view of a 750 μm diameter circular boundary SU-8 2002 mirror showing the three electrodes. (b) Smaller section of the mirror with 20 % duty width segments in the membrane layer to emulate a simply supported boundary. 5 μm square vias allow etchants to release the mirrors by creating an air gap.

FABRICATION AND RELEASE METHODS

This section begins with an overview of photolithography and all of the masks needed for fabrication of these mirrors. Next, the recipes used for the SU-8 2002 membrane layer, metallization and the wet-etch release of these mirrors are described. To improve yield and device size a dry-etch release process was then developed. Finally, the two main wet-etch release and two main dry-etch release SU-8 2002 processes are summarized.

Photolithography and Mask Overview

Photolithography was used for processing of the SU-8 2002 and to pattern Shipley S1813 photoresist (which served as an etch mask for several materials). Initially, a photo-sensitive material called photoresist is dispensed onto the center of a spinning wafer. The photoresist should form a uniform thickness layer on the wafer where the thickness depends on the spin speed and viscosity of the resist. Resists are typically composed of a resin (maintains physical structure of final film), a photoactive compound, and a solvent. The solvent keeps the resist in a liquid state during storage and coating of the wafers. Following the spin step, the wafer is placed onto a hotplate (or sometimes in an oven) to evaporate the solvent out of the resist. Next, the wafer is placed under a glass transparent mask with chrome geometric features for patterning with ultraviolet light. Exposure on a positive or initially crosslinked photoresist will uncrosslink the material rendering it soluble in the developer, whereas unexposed areas will remain crosslinked and insoluble. Conversely, exposure of uncrosslinked or negative resist leads to crosslinked and

insoluble material. For a negative photoresist, the portion of the resist that receives UV exposure generates the photoacid needed for crosslinking of the polymer. A post-exposure bake (PEB) is sometimes required to speed up the crosslinking reaction by increasing the thermal energy of the molecules. Resist also naturally forms an etalon where standing waves create areas of high and low concentration of the photoacid. The PEB minimizes the standing wave effects by aiding in the redistribution of the photoacid to increase uniformity throughout the exposed area. A developer completes the chemical reaction and removes the uncrosslinked material. A hardbake can be done to heal the material and/or to increase its ability to withstand certain thermal, chemical, or physical environments. Resists have a softening point or temperature. If this temperature is surpassed during the hardbake, then the film partially reflows and this can increase its connection to the substrate after it hardens again.

The fabrication processes discussed in this paper required masks to pattern the psg, SU-8, and metal layers. Figure 16 shows all three masks over one wafer with a close-up view of a few devices. Alignment marks are needed on opposite sides of the masks/wafers to ensure proper placement of features for each layer of material on the wafer. The alignment marks are shown in more detail in Figure 17. Squares are used for coarse alignment, whereas cross marks are used for fine adjustments.

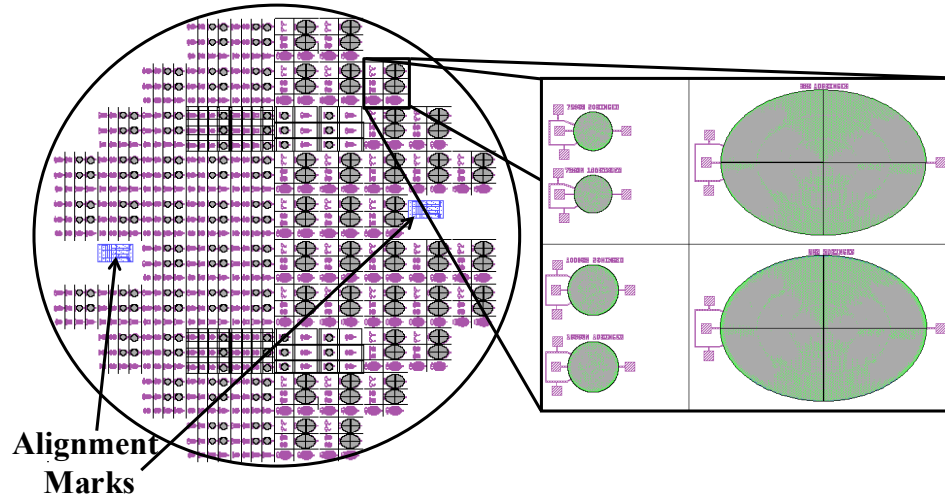


Figure 16: Left: 10 cm diameter wafer with three overlaying masks and the locations of the alignment marks shown. The left-hand side of the wafer has smaller diameter mirrors than the right-hand side of the wafer. Right: A close-up of six mirrors. Four have circular boundaries and two have elliptical boundaries.

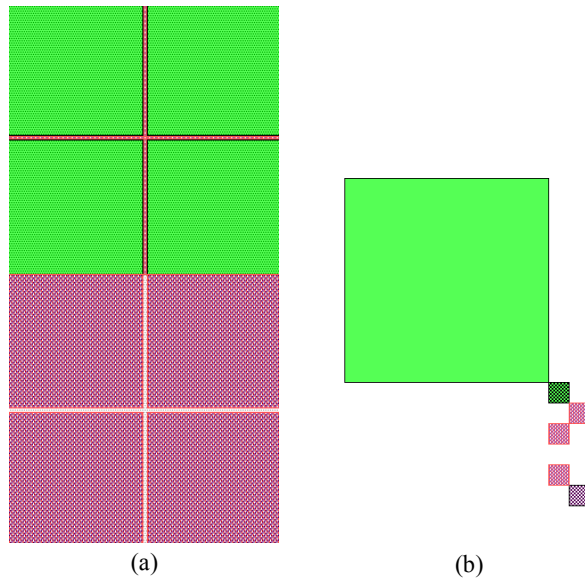


Figure 17: (a) Cross marks and (b) squares for alignment of the psg, SU-8, and metal masks. Coarse alignment is done by locating the large psg square and aligning the edges of the smaller squares below it. More fine alignment is done by the cross marks. The cross marks consist of a square of one material with slots for a $1.5\ \mu\text{m}$ wide cross for a different material to fit into or vice versa.

Wet-etch Process Development

Aside from the SU-8 2002 membrane layer (instead of a silicon nitride membrane layer), a different etch via pattern, and etch via windows; the structure of the wet-etch released mirrors is similar to Himmer's surface micro-machined silicon nitride membrane mirrors [27]. He developed appropriate thicknesses of oxide, psg, and the chrome/gold reflective layers and also presented information on wet-etch release processes [27].

Thermal Oxide and Phosphosilicate Glass

As shown in Figure 18, 1 μm of oxide was grown, followed by LPCVD deposition of 150 nm of sacrificial 8% psg. The silicon wafers were p-type <100> with a resistivity of 1-100 $\Omega\text{-cm}$ and 10 cm diameters. The psg layer was patterned to form a circular pad coincident with the boundary of the mirror. The purpose of the psg layer is to rapidly etch laterally between the vias, exposing the slower etching thermal oxide underneath and facilitating a rapid release of the membrane. A square psg pad was made in the upper right corner above the mirror. During the release process this provided a section of psg to monitor that was not hidden underneath the metal layer. 1 μm of oxide provided additional electrical isolation of the top electrodes from the silicon counter electrode.

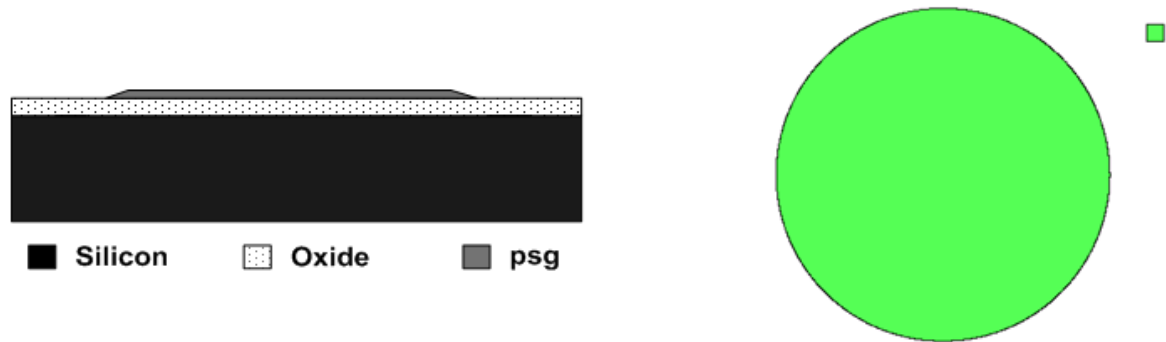


Figure 18: Left: Side view of the oxide and patterned psg. Right: The pattern for the mask was a circular psg pad. A square psg pad was made in the upper right corner to provide a view of the psg during release of the mirrors that was not concealed by the metal layer.

SU-8 2002 Membrane Layer for Wet-etch Processes

The SU-8 photolithography process consists of a dehydration, spin-coating, softbake, exposure, post-exposure bake, development, and a hardbake step. The dehydration, spinning, and exposure time parameters were 10 min at 115 °C, 30 s at 3250 rpm, and 4 s at 20 mW/cm², respectively. **All of the bake steps were performed on a hotplate using the automatic ramp rate (approximately 7 °C/min), unless otherwise noted. Intensity for exposure was 19-21 mW/cm² for all experiments.**

When developing the SU-8 2002 recipes for the wet-etch release process, the primary concerns were attaining well-defined features, ensuring the membrane could withstand the release process, and minimizing the intrinsic stress. Two main recipes (Process 1 and Process 2) were developed. Table 1 shows the development of Process 1 with each major change indicated as a Recipe Development Step. The majority of the experiments were done on bare silicon test grade wafers. Initially, Microchem's suggested recipe was followed. It consisted of a 1 min and 15 s 95 °C softbake, 6-7 s exposure, 2 min 95 °C PEB and development for 2-4 min. This produced a wrinkly and

granular SU-8 film. SU-8 has a high coefficient of thermal expansion (CTE) of 52 ppm/°C compared with 2.6 ppm/°C for silicon [44, 45]. Because the two materials expand at such different rates due to temperature changes and shrinkage of films can occur during crosslinking, it was suspected that the bake steps needed temperature ramps to more gradually expand and contract the materials to prevent delamination and wrinkles. Furthermore, the wafers stuck to the mask during exposure, so it was suspected that too much solvent remained in the resist following the softbake. An increase in the total softbake time to evaporate more solvent and to allow for ramping of the temperatures was tried on silicon test wafers for Recipe Development Step 2. The softbake regimen included ramping from 65 °C to 95 °C and holding for 5 min before removing from the hotplate and cooling to room temperature (RT). During Recipe Development Step 1, the 5 µm vias appeared smaller than expected, thus indicating overexposure of the negative resist. Because of this the exposure time was reduced to 5 seconds for these experiments. The PEB was still done at 95 °C, but was held for 5 min before cooling to room temperature (RT). Not enough solvent was evaporated for this recipe, as the wafer still stuck to the mask during exposure. This film appeared transparent in some areas and murky in other areas. Air pockets were also observed in the film, as shown in Figure 19.

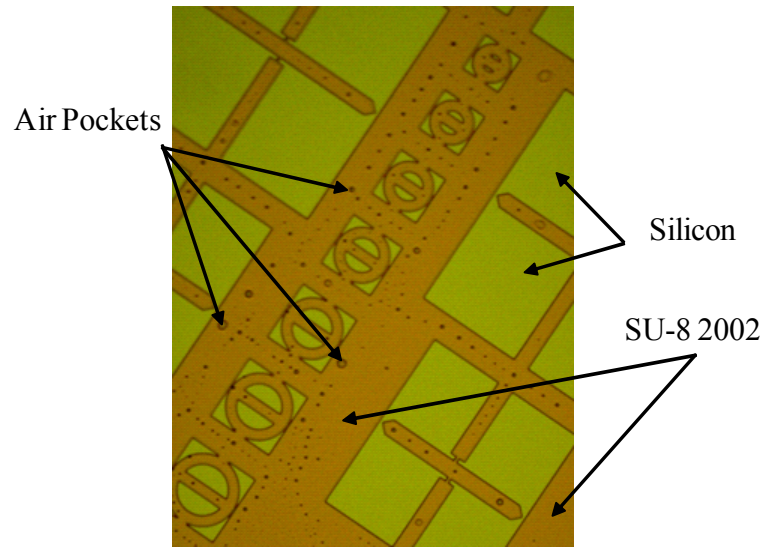


Figure 19: Air pockets observed in the SU-8 film with limited ramping for the softbake and no ramping for the PEB.

Recipe Development Step	Softbake	Exposure	PEB	Development	Hardbake	Results
1	1 min and 15 s at 95 °C	6-7 s	2 min at 95 °C	2-4 min, DI rinse		Wafer stuck to mask during exposure. Wrinkly and granular film.
2	65 °C ramp to 95 °C and hold 5 min, cool RT	5 s	5 min at 95 °C	2 min 20 s, DI rinse		Wafer stuck to mask during exposure. Bubbles in film. Some sections appeared clear and others murky. Cracking by vias.
3	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 95°C and hold 2 min, ramp to 45°C, cool to RT OR 45C hold 1 min ramp at 1C/min to 95C, ramp at 1C/min to 40C, cool RT	2.7-4 s	5 min at 95 °C OR At hotplates auto ramp rate - 45C hold 1 min, ramp to 65C hold 1 min, ramp to 95C hold 15 min, ramp to 45C, cool RT OR At hotplates auto ramp rate - 45C hold 1 min, ramp to 65C hold 1 min, ramp to 95C hold 2 min, ramp to 45C, cool RT	2 min 45 s, IPA rinse, DI OR 3 min 15 s, IPA rinse, DI rinse OR 2 min 45 s in ultrasonic cleaner, IPA rinse, DI rinse		Wafer did NOT stick to mask. Significant cracking. Unclear features. Development in ultrasonic cleaner improved clearing vias of SU-8
4	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 95°C and hold 2 min, ramp to 45°C, cool to RT	4 s	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 95°C and hold 2 min, ramp to 45°C, cool to RT	3 min 15 s, IPA rinse, DI rinse	45 C, ramp to 120, 130, 135, 140, 150, 160, 170, 175, 180, 200, 225 °C and hold 10-30 min, cool to RT on hotplate	Cracks were healed during hardbake. Higher hardbake temperatures showed less delamination in the TMAH mixture.
5	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 95°C and hold 2 min, ramp to 45°C, cool to RT	4 s	45C hold 1 min, ramp to 65C hold 1 min, ramp to 80C hold 10 min, ramp to 45C, cool RT	1 min in ultrasonic cleaner, IPA rinse, DI rinse		Clear features, some cracking, limited de lamination during development
6	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 80°C and hold 3 min, ramp to 45°C, cool to RT	4 s	45C hold 1 min, ramp to 65C hold 1 min, ramp to 80C hold 10 min, ramp to 45C, cool RT	1 min in ultrasonic cleaner, IPA rinse, DI rinse		Slight cracking, somewhat unclear features.
7	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 80°C and hold 3 min, ramp to 45°C, cool to RT	4 s	45C hold 1 min, ramp to 65C hold 1 min, ramp to 85C, immediately ramp to 45C, cool RT	1 min in ultrasonic cleaner, IPA rinse, DI rinse	45°C 1 min, ramp to 250°C and hold 30 min, ramp to RT	Slight cracking prior to hardbake, clear features. Hardbake healed cracks and allowed wafer to withstand release process.

Table 1: Process 1 recipe development overview. OR indicates procedures that were tried with all of the other procedures provided for that step (i.e. For Recipe Development Step 3, both softbake procedures were tried with all three of the PEB procedures.).

Silicon test wafers with thermal oxide were used for all future experiments, except when noted otherwise. For Recipe Development Step 3 an IPA rinse was done immediately following development and prior to the DI water rinse. The IPA rinse eliminated the wrinkly appearance of the film and was shown to be critical in all future experiments (i.e. omitting this step would ruin the entire process). SU-8 Developer is 98-100% propylene glycol monomethyl ether acetate or PGMEA, so an IPA rinse replaces the harsher PGMEA solvent prior to rinsing with DI water. The surface tensions of PGMEA, IPA and DI water are 26.9 dyne/cm, 21.15 dyne/cm and 72 dyne/cm, respectively [46, 47]. Since IPA has less surface tension than DI water, it should be a more gentle replacement of the PGMEA prior to a DI water rinse. Based on discussion and email communication with Dr. Yi Chiu (National Chiao Tung University), even slower ramp rates with intermittent temperature soaks for both the softbake and PEB were explored as a means to further reduce cracking and allow time for the film to rid itself of air pockets. A softbake procedure consisting of baking the wafer at 45 °C for 1 min, ramping to 65 °C and holding for 1 min, ramping to 95 °C and holding for 2 min, ramping down to 45 °C and removing the wafer from the hotplate to allow it to cool to room temperature (RT) prevented the wafer from sticking to the mask. Doing the same procedure, but with 1 °C/min ramp rates also prevented the wafer from the sticking to the mask. Various ramp rates and recipes for the PEB with a final temperature of 95 °C were tried with both of these softbake procedures. They all resulted in substantial cracking of the SU-8 film (Figure 20). Additionally, the developer did not appear to remove all of the resist where it should not have been cross-linked. As shown in Figure 21, vias and

segments had residual resist. To try and ensure that the features were fully cleared of resist, the development was done in an ultrasonic cleaner. This significantly helped, but did not completely remedy the problem. Features near the center of the wafer were most clear and became less clear toward the perimeter of the wafer, which might have been due to non-uniformity in intensity of the source or because the wafer might make better contact in the center of the mask during hard contact exposure.

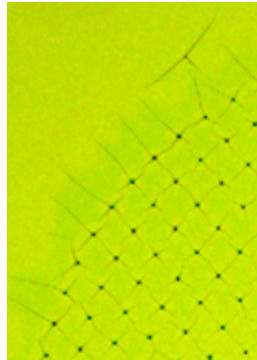
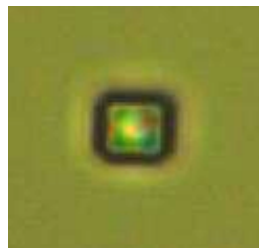
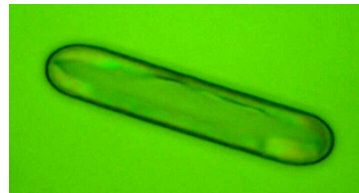


Figure 20: Cracking of the SU-8 film around the vias.



(a)



(b)

Figure 21: Resist not fully clearing a (a) via and (b) segment.

At this stage in the recipe development, the hardbake process was explored. As a side note, Microchem specifies the softening temperature of SU-8 as 210 °C, so any hardbakes above this temperature most likely resulted in some softening of the film [44]. Silicon wafers were prepared with the softbake and PEB done at 45 °C for 1 min,

ramping to 65 °C and holding for 1 min, ramping to 95 °C and holding for 2 min, ramping down to 45 °C and cooling to RT. For the hardbakes the wafers were scribed and broken, and different sections of the wafers were held for 1 min at 45 °C and ramped up to 120, 130, 135, 140, 150, 160, 170, 175, 180, 200, 225 and 250 °C and held for 10, 20, or 30 min before cooling to RT on the hotplate. The mirrors were released in 12.5% TMAH and 0.5% NCW-601 surfactant at 65 °C and observed at 10 min intervals. Higher temperatures and longer duration hardbakes resulted in the least amount of delamination during release. It was determined that 1 min at 45 °C, ramping to 250 °C and holding for 30 min before cooling to RT on the hotplate showed the least amount of delamination during release and also healed visible cracking in the film.

It seemed possible that the photoacid was diffusing into unexposed areas during the PEB, which would lead to crosslinking of the material and residual resist remaining in features. According to Keller, photoacid diffusion has more to do with the actual temperature than the amount of time spent at specific temperatures [30]. He and Li showed a strong increase in tensile stress in SU-8 2002 films with increasing PEB temperatures, most notably above 55-60 °C [30, 48]. Recipe Development Step 5 explored a lower PEB temperature to address these concerns. The softbake procedure that produced better results for Recipe Development 3 was used at 45 °C for 1 min, ramping to 65 °C and holding for 1 min, ramping to 95 °C and holding for 2 min, ramping down to 45 °C and cooling to RT. The exposure was now fixed at 4 s at 20 mW/cm² or 80 mJ/cm². The PEB consisted of baking the wafer at 45 °C for 1 min, ramping to 65 °C and holding for 1 min, ramping to 80 °C and holding for 10 min, and ramping down to 45 °C and

cooling to RT resulted in open features. However, this recipe caused some delamination of the film after development in an ultrasonic cleaner (Figure 22).

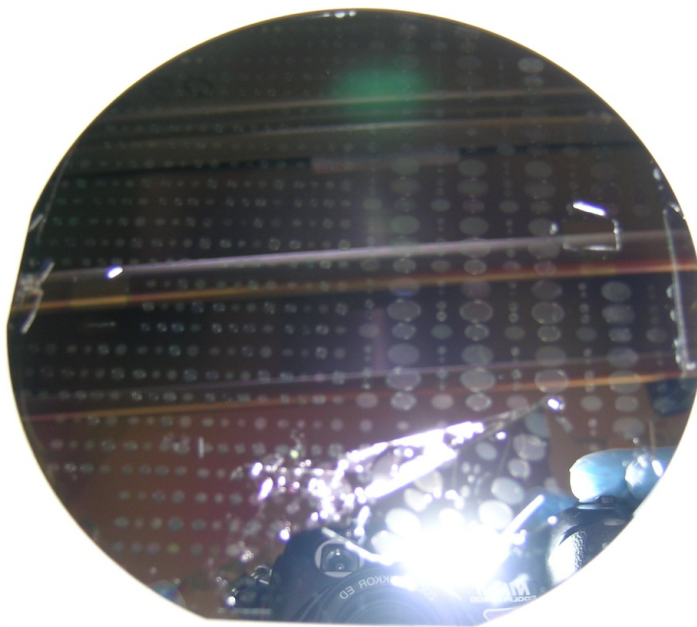


Figure 22: SU-8 2002 complete delamination on sections of the wafer. Delamination at the perimeters of the mirrors (circles and ellipses) is also present.

Anhoj showed lower crack density in 40 μm SU-8 films with lower softbake temperatures [29]. Thicker SU-8 films are composed of the same constituents as thinner SU-8 films – just in different ratios. So, it was assumed that a lower softbake temperature might lead to less cracking in the membrane and this was tried for Recipe Development Step 6. This produced less cracking than all previous steps. The PEB was then re-examined and optimized. The final softbake procedure for Process 1 consisted of baking the wafer at 45 °C for 1 min, ramping to 65 °C and holding for 1 min, ramping to 80 °C and holding for 3 min, ramping down to 45 °C and removing the wafer from the hotplate to allow it to cool to RT for 10 min. The PEB involved baking the wafer at 45 °C for

1 min, ramping to 65 °C and holding for 1 min, ramping to 85 °C and holding for 0 min, and ramping down to 45 °C and removing the wafer from the hotplate to allow it to cool to room temperature. The resist was developed in SU-8 developer for 1 min in an ultrasonic bath to ensure clear vias, rinsed with isopropanol (IPA) and finally rinsed with deionized (DI) water. Following the development step the wafer was hardbaked, holding the temperature at 45 °C for 1 min, ramping to 250 °C and holding for 30 min, and ramping down to room temperature on the hotplate. This recipe is termed Process 1 and is summarized at the end of this chapter in Table 6. The recipe steps yield a good quality film and well-defined features, where crisp segments and vias can be observed under a 50x objective microscope (Figure 23).

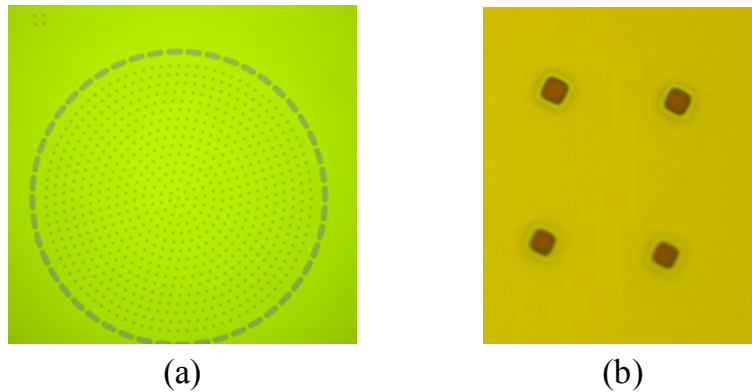


Figure 23: (a) Segmented mirror after development with Process 1 procedure. (b) The vias are crisp and square with the ability to clearly focus on the top surface of the SU-8 2002 and the silicon at the bottom of the vias under a 50X objective microscope.

After development and testing of Process 1 devices, the PEB and hardbake procedures were revisited in order to further reduce stress in the film. These tests were done on oxidized wafers. Keeping the softbake, exposure, and development parameters the same as Process 1, the PEB was switched to baking the wafer at 45 °C for 1 min,

ramping to 50 °C and holding for 1 h, ramping down to 45 °C and cooling to RT. Additionally, the same process to 70 °C was done, as well as the same process to 60, 65, and 70 °C with 1 °C/min ramp rates. 50 °C did not sufficiently crosslink the SU-8. The middle of the wafer had a murky appearance and the features did not form after development. The edges of the wafer also delaminated. The PEB to 60, 65, and 70 °C with 1 °C/min ramp rates produced good films after development. They all appeared to have less cracking than Process 1. Lower temperatures led to less visible cracking when observed with a 50X objective microscope. Various hardbake temperatures were investigated on the two 70 °C PEB temperature wafers (one done at the automatic ramp rate of the hotplate at approximately 7 °C/min and one at 1 °C/min). Each wafer was diced into 7 pieces. The pieces were ramped from 45 °C to 120, 150, 170, 180, 200, 225, and 250 °C. The hotplate was set to automatically shut-off after 1 h for all of the hardbake temperatures. The pieces were put into BOE 6:1 for 2 h followed by 2.5 h in 25% TMAH and 0.5% NCW-1000 at 75 °C. The pieces were visually inspected and rated in comparison with each other based on the percentage of the film per die that had delaminated post release. The rating system went from bad or film completely separated from wafer, fair, good, to excellent or no visible delamination. As shown in Table 2, a final temperature of 200 °C yielded the best results for both PEB's. 180 °C yielded the second best results.

Hardbake	Delamination Results*	
	PEB: 45°C 1 min, ramp to 70°C and hold 1 h, ramp to 45°C, cool to RT	PEB: 45 °C 1 min, ramp at 1 °C/min to 70 °C and hold 1 h, ramp at 1°C/min (limited by thermal mass of hotplate) to 45 °C, cool to RT
45 °C, ramp to 250 °C and hold 1 h, cool to RT on hotplate	bad	bad
45 °C, ramp to 225 °C and hold 1 h, cool to RT on hotplate	poor (half delaminated)	bad
45 °C, ramp to 200 °C and hold 1 h, cool to RT on hotplate	good (some delamination at edges)	good-excellent
45 °C, ramp to 180 °C and hold 1 h, cool to RT on hotplate	fair-good	good
45 °C, ramp to 170 °C and hold 1 h, cool to RT on hotplate	fair-good	good
45 °C, ramp to 150 °C and hold 1 h, cool to RT on hotplate	fair	good
45 °C, ramp to 120 °C and hold 1 h, cool to RT on hotplate	fair	bad

*Excellent indicates no delamination, whereas bad indicates the film completely separated from the substrate.

Table 2: Comparison of delamination after release of SU-8 membranes with different hardbake and PEB parameters.

The next PEB's tried were baking the wafer at 45 °C for 1 min, ramping at 1 °C/min to 60 °C and holding for 1 h, and ramping at 1 °C /min (potentially limited by thermal mass of hotplate) down to RT. The same procedure was done with 65 °C as the highest temperature. Both processes produced good films after development. They all appeared to have less cracking than Process 1. Again, lower temperatures yielded less visible cracking. Pieces of these wafers were ramped from 45 °C to 160, 170, 180, 190, and 200 °C at ramp rates of 230, 250, 270, 290, and 310 °C/h, respectively. These ramp rates brought the pieces to the appropriate temperature in ½ h. The hotplates

automatically shut-off after 1 h to allow ½ h at the final temperature before cooling down to RT. The pieces were put into BOE 6:1 for 2 h followed by 2.5 h in 25% TMAH and 0.5% NCW-1000 at 75 °C and evaluated for the severity of delamination during release (Table 3). A final temperature of 190 °C yielded the best results for both PEB's. Although a PEB temperature of 65 °C produced the best results, 60 °C was used for Process 2 in order to provide greater difference from Process 1 when examining the intrinsic stress of the two SU-8 2002 layers. Process 2 is the same as Process 1 except the highest PEB and hardbake temperatures reached were 60 °C and 190 °C, respectively (Table 6). Figure 24 shows the cross-sectional view of the 2.25 µm thick SU-8 with vias for wet-etching during the release process and the membrane pattern for a circular boundary mirror.

Hardbake	Delamination Results*	
	PEB: 45 °C 1 min, ramp at 1 °C/min to 60 °C and hold 1 h, ramp at 1 °C/min (limited by thermal mass of hotplate) to RT	PEB: 45 °C 1 min, ramp at 1 °C/min to 65 °C and hold 1 h, ramp at 1 °C/min (limited by thermal mass of hotplate) to RT
45 °C, ramp at 310 °C/h to 200 °C and hold 30 min, cool to RT on hotplate	good	good-excellent
45 °C, ramp at 290 °C/h to 190 °C and hold 30 min, cool to RT on hotplate	good-excellent	excellent
45 °C, ramp at 270 °C/h to 180 °C and hold 30 min, cool to RT on hotplate	fair	fair
45 °C, ramp at 250 °C/h to 170 °C and hold 30 min, cool to RT on hotplate	bad	good
45 °C, ramp at 230 °C/h to 160 °C and hold 30 min, cool to RT on hotplate	bad	bad

*Excellent indicates no delamination, whereas bad indicates the film completely separated from the substrate.

Table 3: Comparison of delamination after release of SU-8 membranes with different hardbake and PEB parameters.

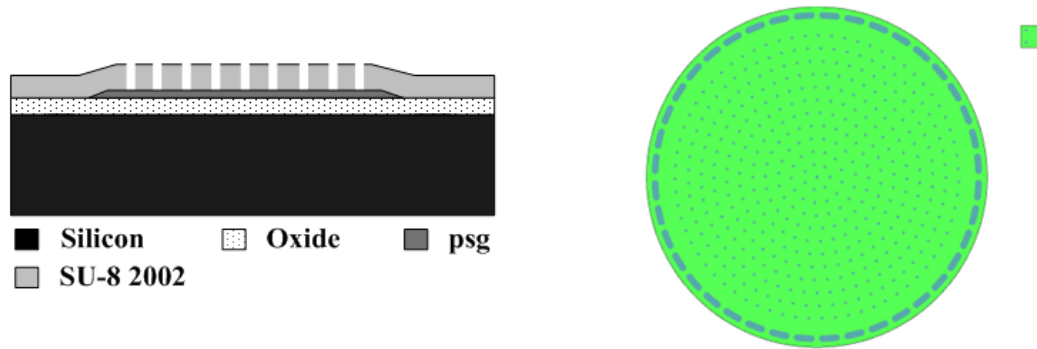


Figure 24: Left: Cross-sectional view of SU-8 2002 with 5 μm square vias for release of the membrane. Right: The vias were patterned at equally spaced radii with equal distance to all neighboring vias to ensure uniform release of the membrane and membrane perimeter.

Metallization for Wet-etch Processes

Gold (Au) provides sufficient reflectivity in the visible and excellent reflectivity in the infrared light region. It can also withstand TMAH for wet-etching of the silicon (unlike aluminum), so we used it with a thin chrome (Cr) adhesion layer for the optical surface. We sputtered 60 $\text{\AA}$ chrome and 150 nm gold onto the top side of the wafers and attempted to pattern it with S1813 with the intention of wet-etching the gold pattern. During patterning, however, S1813 remained in the bottom of the vias and segments (Figure 25). This meant that the Cr/Au etchants could not reach the metal layers in these locations and remove them as desired. S1813 is a positive resist, so it should become uncrosslinked with ultraviolet exposure and it was assumed that light was not reaching the bottom of these features. A longer exposure time, several short exposure doses, and repeated intervals of exposing and developing failed to remedy this problem. Instead of using metal etchants, the procedure switched to a metal lift-off process.

Metal lift-off sufficiently cleared gold out of the vias and led to repeatable results. 60 $\text{\AA}$ chrome and 150 nm gold were evaporated over patterned NR-1500PY Futurrex

negative resist for a metal lift-off procedure on the frontside of the wafers. In order to fully clear the 5 μm square etch vias, an ultrasonic bath with acetone was used for lift-off of the patterned metal. With this process thousands of 5 μm elongated square sections of Futurrex and Cr/Au are removed from the wafer. If these remain in acetone for too long, then the gold separates from the Futurrex. Oftentimes, these small gold peices will redeposit on the wafer. Agitating the wafer, removing it from the ultrasonic acetone bath, rinsing it with IPA, placing it in fresh acetone and replacing the ultrasonic bath with new acetone needed to be done every 30 s to prevent gold re-deposition problems. Additionally, the gold seemed to have an affinity for the stainless steel ultrasonic bath container. Forceful rinsing with acetone and IPA prior to replacing the acetone bath was also necessary. Lift-off was followed with an IPA rinse and DI water rinse.

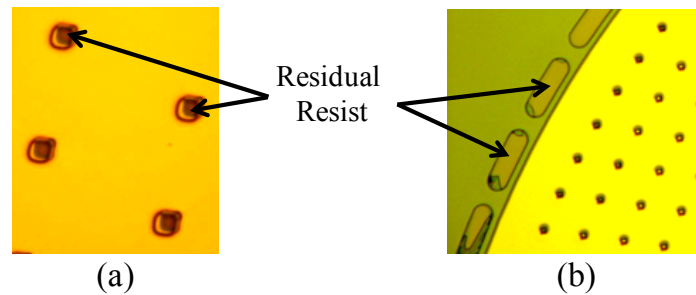


Figure 25: S1813 patterned for wet-etching of the gold and chrome layers. The red resist can be seen at the bottom of the (a) vias and (b) segments where no resist should remain.

As shown in Figure 26, the gold traces went out to 200 μm square electrode pads. Each of the three electrodes has one pad except for the outermost electrodes which are two separate sections due to other traces crossing the middle of the wafer. A protective layer of S1813 is spun onto the frontside before evaporating 60 $\text{\AA}$ chrome and 200 nm

gold onto the backside of the silicon wafer. Gold on the backside provides a solid electrical connection with the silicon counter electrode.

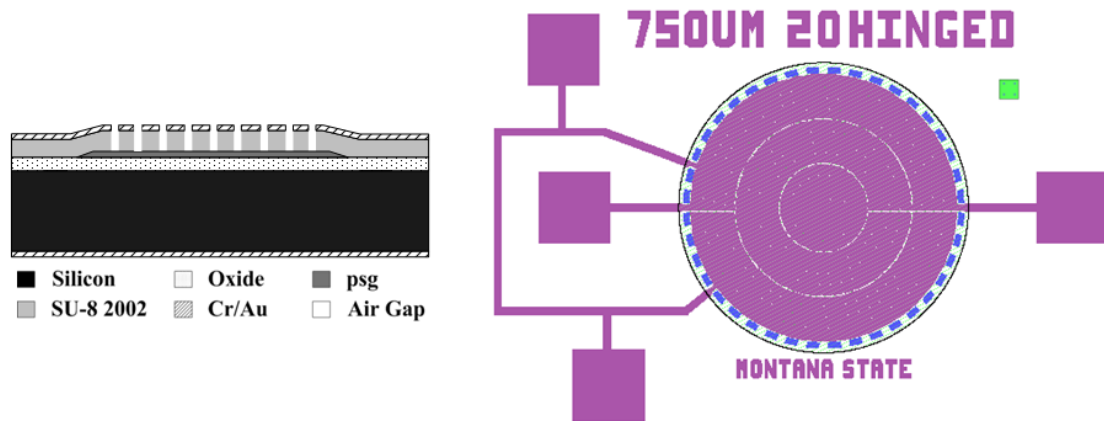


Figure 26: The top reflective Au layer also had etch vias for release of the membrane. The center and middle electrodes have one bond pad each. The outermost electrode has two bond pads, which are both connected to the top and bottom sections of the electrode.

Wet-etch Release

The release process consists of a cleaning, psg/oxide etch, and a silicon etch step. The cleaning step primarily removes the S1813 protective layer. SVC-175 at 70 °C for 90 min was compared with acetone, IPA, and a DI water rinse for cleaning. The acetone resulted in cleaner mirrors as visually inspected under a 10X-100X objective microscope.

Hydrofluoric acid (HF) readily attacks silicon dioxide and psg, while not having a strong affinity for gold or silicon. For these reasons it was chosen for etching the psg and thermal oxide layers in these mirrors. HF is frequently buffered with ammonium fluoride NH_4F in what is called buffered oxide etch (BOE). This can result in a more controlled and repeatable etch. Using the volume ratio of 40% NH_4F :49% HF, BOE 6:1 contains roughly 7-7.3% HF [49]. 8% phosphosilicate glass and thermal oxide have 6000 Å/min and 910 Å/min etch rates in BOE 6:1, respectively. The lateral spacing between vias was

30 μm , whereas the thickness of the oxide was 1 μm . The thin layer of psg created a sacrificial layer to quickly etch laterally between vias to fully expose the underlying thermal oxide layer for subsequent etching. In order to determine the best wet-etching mixture, the psg and oxide were fully etched in BOE 6:1, H₂O:HF 3:1, and 49% HF. As shown in Figure 27, the etch fronts beneath the vias were observed to determine full removal of the oxide. Visually observing the devices at 10 min etch intervals underneath 10X-100X objectives, the HF solutions caused the SU-8 2002 to delaminate more quickly than the BOE 6:1. The oxide was etched for 45-50 min in BOE 6:1 at room temperature for all future experiments, resulting in release of the membranes.

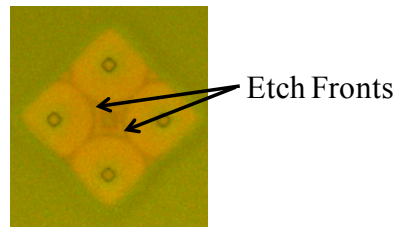
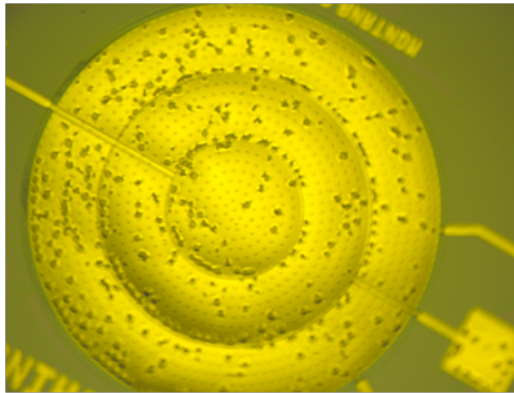


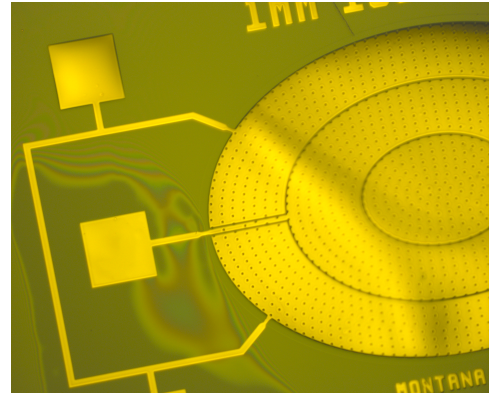
Figure 27: Every mirror has 4 reference vias without metal covering them. These are the etch fronts after 30 minutes in BOE 6:1. The oxide etch fronts laterally move away from the vias and approach each other. When the four fronts have converged completely, the silicon below the mirror surface is fully exposed for subsequent etching.

For the silicon etch we used tetramethylammonium hydroxide (TMAH) with a surfactant (NCW-1000, Wako Pure Chemical) to reduce surface tension and minimize bubble size for evolved hydrogen gas. Smaller bubbles can more easily escape from beneath the membrane through the vias and edge segments. Failure of the hydrogen gas to escape from beneath the membrane causes “pillowing” of the membrane and can result in delamination (Figure 28) and sometimes bursting (Figure 29). <100> silicon wafers were used to reduce undercutting of the edges of the mirror. When <100> planes

are etched in TMAH, the side surfaces of the etched features are $\langle 111 \rangle$ planes. $\langle 100 \rangle$ etches 30 times more quickly than $\langle 111 \rangle$, so the etch should primarily occur in the vertical direction during the wet-etching [50]. However, circular perimeters will not be undercut uniformly, with $\langle 011 \rangle$ directions undercut more than $\langle 001 \rangle$.



Evolved Hydrogen Gas



Delamination

Figure 28: Evolved hydrogen gas causes “pillowing” of the membrane and can lead to delamination of the SU-8 2002 from the silicon.



Figure 29: A burst membrane due to trapped evolved hydrogen gas.

Initially, a DI water rinse preceeded the TMAH etch, but this yielded inconsistent etch rates of the silicon. Most likely oxide formed on the silicon with the DI water rinsing

step, so for all of the following experiments the devices were taken directly from the BOE 6:1 bath and put into the TMAH bath. If the devices were observed in the middle of an etch process, then they were immersed in water for observation under the microscope. They would then be put into BOE 6:1 for 5 min prior to returning to TMAH to remove any oxide.

Several different concentrations of TMAH and NCW at various temperatures and time durations were tried on 10-20 mirrors for the release process (Table 4). We moved the mirrors with tweezers, so sometimes delamination was due to physical trauma. Because of this, qualitative observation of the mirrors often proved beneficial for determining the best recipe. No devices survived 25 % TMAH and 0.25 % NCW at 80 °C or 25 % TMAH and 0.5 % NCW at 80 °C. A few mirrors survived 25 % TMAH and 0.75 % NCW at 80 °C, 25 % TMAH and 0.25 % NCW at 70 °C, and 25 % TMAH and 0.5 % NCW at 70 °C, but many of these devices had delamination of the membrane. Recipes requiring long periods in the TMAH bath resulted in delamination and often lead to a granular appearance, as shown in Figure 30. A 25 % TMAH, 0.5 % NCW-601, and 75 % H₂O bath at 75 °C for 2-3 hr allowed for the silicon to etch 14-25 µm. A temperature of 70 °C for 7 hr resulted in a smoother and more even silicon surface with gaps of approximately 25-30 µm. These two recipes yielded the largest number of functional mirrors and the latter worked well for mirrors with a lower mirror area to die area ratio (i.e. delamination at the edges of the die did not affect the mirror).

TMAH (Total % concentration in H ₂ O)	NCW (Total % concentration in H ₂ O)	Temperature	Time	Results
25 %	0.25 %	80 °C	3 hr 35 min	No devices survived, SU-8 completely delaminated
25 %	0.25 %	70 °C	1 hr 20 min	Some devices survived. SU-8 partially delaminated
25 %	0.5 %	80 °C	1 hr 20 min	No devices survived, SU-8 partially delaminated
25 %	0.5 %	75 °C	2-2.5 hr	Best survival rate. Bubbles burst some membranes, but was improved with stir bar at 150 rpm
25 %	0.5 %	70 °C	7 hr 20 min	Some devices survived. SU-8 partially delaminated. Very smooth silicon surface.
25 %	0.75 %	80 °C	4 hr 10 min	Some devices survived. SU-8 partially delaminated. Silicon was very rough.

Table 4: Release process parameters tried for release of SU-8 membrane devices.

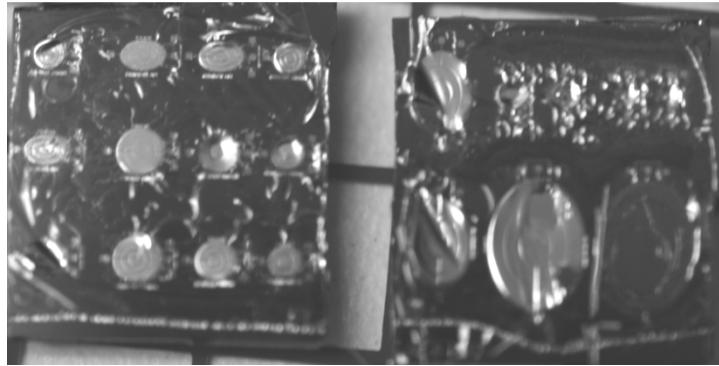


Figure 30: Long etch times in TMAH created a membrane layer that appeared granular and oftentimes delaminated the membrane from the silicon.

After the silicon etch, stiction needed to be avoided as the mirrors dried. The mirrors were rinsed in DI water, then IPA to decrease the surface tension of the liquid, and finally were covered on a 45 °C hotplate to evaporate off the IPA. Some mirrors were dried in a Tousimis critical point dryer (CPD), which did not yield consistent results. The

dryer sometimes caused delamination, which could have possibly been avoided by further exploration of the flow rate of the liquid CO₂.

Problems and Potential Improvements

Overall, only 10-20 % of the mirrors that underwent wet-etch release survived. Most failures were due to stiction and delamination issues. The largest devices realized were 1 mm circular boundary and 1 mm x 1.4 mm elliptical boundary mirrors. Maximum stable deflection observed was 6.8 μm for a 1 mm x 1.4 mm elliptical boundary mirror with an air gap of 14 μm . Chronis and Lee began with a wet-etch release for their SU-8 microgrippers, but switched to a xenon difluoride dry-etch release to mitigate stiction issues [35]. We elected to try XeF₂ as a completely dry-etch process to avoid the wet release problems that include bursting and delamination due to trapped hydrogen gas and stiction after drying.

Dry-etch Process Development

SU-8 2002 Membrane Layer for Dry-etch Processes

For the dry-etch release processes, SU-8 2002 was spun directly onto 0-100 ohm-cm resistivity silicon p-type test grade wafers. Initially, we tried Process 1. This generated extreme delamination and cracking of the film. The vias were well-defined 5 μm squares though. Compared to the wet-release process mirrors, the substrate beneath the SU-8 2002 switched from psg and oxide on top of silicon to bare silicon. Potentially, the oxides buffered the effect of the CTE mismatch between SU-8 and silicon. Also, the indices of refraction of oxide and silicon are approximately 1.4 and 3.4, respectively [51],

so reflected light may change, altering the exposure of the features. Additionally, all bake steps were performed on a hotplate, so the oxide layers could have limited the actual temperature of the SU-8 for Process 1 and Process 2, since oxides have roughly two orders of magnitude lower thermal conductivities than silicon [52, 53]. This could have affected the overall solvent level after the softbake and diffusion of photoacid during the PEB. Since the features appeared to be patterned well and an accurate development time proved important for Process 1 and Process 2, the development step was altered to improve the film. It has been shown that megasonic development generally works better than ultrasonic development due to exposed features becoming damaged or de-bonding [54], so it was assumed that the ultrasonic development may have been too strong and development without any agitation was tried. It appeared that the features developed immediately upon submersion in the SU-8 developer, but the wafer remained in the developer for 45 s total in an attempt to ensure clear vias. As shown in Figure 31, the film still had cracking and partial delamination. Potentially, the higher index of refraction in combination with a slightly higher PEB temperature of the actual SU-8 membrane led to faster crosslinking of the material on silicon in comparison with the oxides. The developer is a solvent, so once the un-crosslinked material is removed, it may also weaken exposed or crosslinked areas of the resist. Development times of 15 s and 5 s were then tried. 5 s yielded membranes with less delamination and cracking. In order to ensure clear etch vias and minimize cracking, 15 s development time was used.

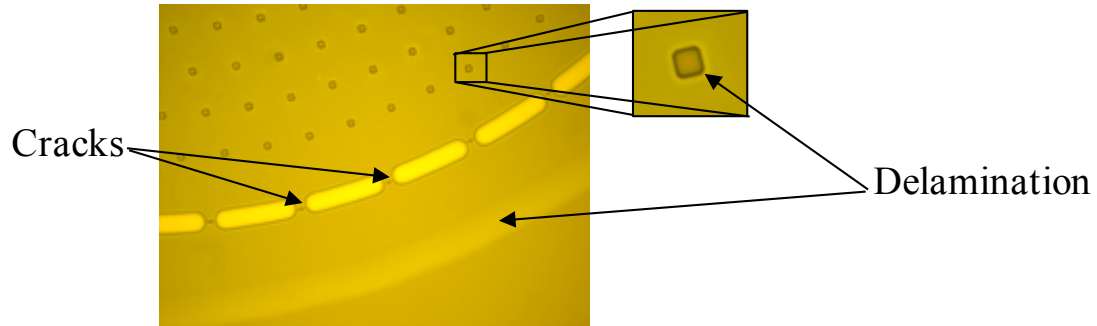


Figure 31: Pictures taken after 45 s in SU-8 developer. Severe delamination of structures from silicon occurred as indicated by the white rings around the perimeters. Cracking also exists between segments and around vias.

During testing of the wet-released wafers, the 5 μm vias in the SU-8 proved to be a problem. They were the same size as the vias in the metal and slight misalignment of the masks caused the metal to overhang the SU-8. During actuation or in the event of snapdown, this overhanging metal arced with the bottom silicon counter electrode and caused portions of the metal to be vaporized (Figure 32). Since the vias cleared more easily when the SU-8 was directly on silicon (in comparison with the SU-8 on psg for the wet-etch release), a mask with 3 μm vias for the SU-8 film was used for some Process 4 mirrors. Process 3 still used the 5 μm via mask in case diffusion of XeF_2 would be limited for the smaller vias.

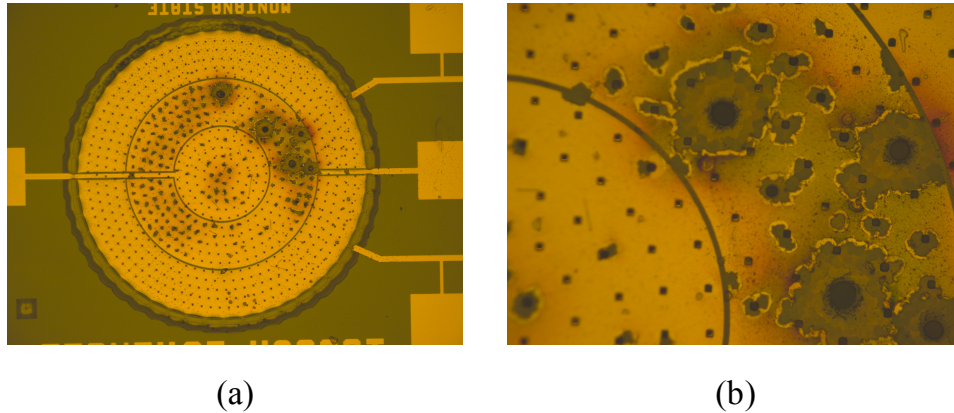


Figure 32: Pictures of Process 1-3 wafers with 5 μm gold vias slightly overhanging 5 μm SU-8 vias. This resulted in arcing with the bottom silicon counter electrode during actuation or snapdown and vaporized sections of gold.

Not only did Process 3 have the same via size as Process 1 and Process 2, but the hardbake temperature was the same as Process 1 at 250 $^{\circ}\text{C}$ to ensure it would survive etching in XeF_2 and to provide good comparison with the wet-etch release Process 1 (Table 6). The difference between Process 1 and Process 3 was that the resist was only developed in SU-8 developer for 15 s WITHOUT the use of an ultrasonic cleaner, rinsed with isopropanol (IPA) and finally rinsed with deionized (DI) water. As previously stated, Process 4 was the only process where some wafers had 3 μm vias in the SU-8 2002 film. Table 6 has the entire recipe for Process 4 and shows that it also only underwent 15 s in the developer. It had a lower final hardbake temperature than all other processes, where the hotplate temperature began at 45 $^{\circ}\text{C}$, ramped at 240 $^{\circ}\text{C}/\text{hr}$ to 165 $^{\circ}\text{C}$ and held for 30 min, and was ramped down to room temperature on the hotplate.

Metallization for Dry-etch Processes

The same lift-off process described in the Metallization for Wet-etch Processes section was used for the dry-etch processes. Cr/Au was used for metallization. However,

aluminum could have been used with the dry-etch process as a cheaper alternative. HF and TMAH etch aluminum, so it was not an option for the wet-etch processes.

Dry-etch Release

Xenon difluoride, a gas, was chosen to etch the silicon to create air gaps for these mirrors, because device size and stroke were limited by stiction and delamination issues with the wet-etch release processes. A Xactix XeF₂ etcher was used at 3 torr for 30 s per cycle for these experiments. As shown in Figure 33, the silicon etching could easily be observed under the un-metallized 4 via etching window. The left, middle and right picture has the 4 SU-8 vias, the high points of the merged etch fronts and the lowest points directly below the vias in focus, respectively. The silicon etch measurements are identified in Figure 34. The lateral distance etched A was measured with a digital ruler under a 50X objective to determine when the etch fronts had fully merged, resulting in release of the membrane. Xenon difluoride etches isotropically, so the distance DV below the vias should be roughly the same as A . The high points of the etch front DE were also of interest, because they could limit the stroke of the devices. We measured DV and DE by focusing on the silicon surface and the top of the SU-8 surface with a 50X objective and taking the difference. Larger diameter and smaller diameter (see device layout in Figure 16) Process 3 devices were etched for a total of 140 cycles and 120 cycles, respectively. The amount of silicon etched depends on the exposed silicon surface area of the sample, so quarter pieces of wafers were used to keep this parameter similar for all pieces. However, the larger devices etched more slowly, so they may have had more

silicon exposed for a quarter piece. All of Process 3 mirrors appeared to have etched to depths of $21\text{ }\mu\text{m}$ and $33\text{ }\mu\text{m}$ for DE and DV , respectively (Table 5).

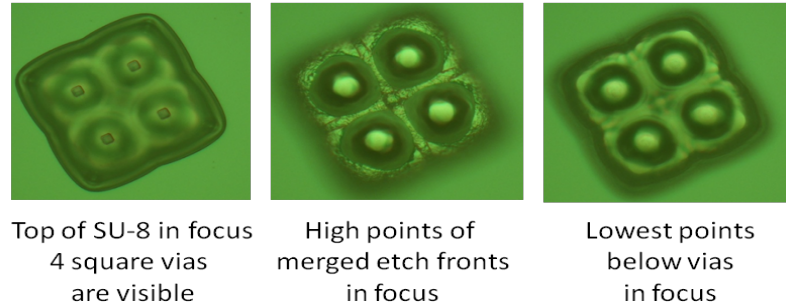


Figure 33: The SU-8 surface, high points of the merged etchfronts, and where the silicon etched the furthest below the vias were brought into focus under a 50X objective lens after the etchfronts had merged.

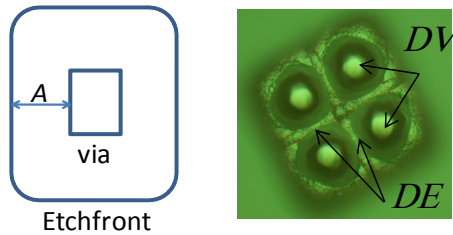


Figure 34: For the purposes of this experiment, A is the lateral distance the silicon has etched. DV is the depth directly below the via. DE is the depth below the merged etchfronts.

The bottom silicon topography after different numbers of cycles completed is shown in Figure 35. It begins to flatten out after 120 cycles, as evidenced by a more uniform appearance at one focal location of the objective lens. A profilometer trace of the bottom silicon counter electrode indicates approximately $10\text{ }\mu\text{m}$ variation in etch depths (Figure 36). The silicon profile in the profilometer trace did not appear to have purely periodic minimums and maximums or in other words lacked long-range uniformity. This is due to the way in which the patterned vias merge during etching, where some etch fronts merge more quickly than others. An image of the bottom surface with a Zeiss Supra 55VP field emission scanning electron microscope (SEM) also confirmed this

long-range non-uniformity (Figure 37). Figure 38 and Figure 39 show the etch rates in the horizontal and vertical directions. Both show a decrease in the etch rate with time. The depth etch graph may be somewhat less accurate than the lateral etch graph, since it relies on judgment of the user for the ideal focal point of the bottom silicon. However, the overall shape of the graph should be representative of the etching behavior and the etch depths should be within a couple of microns of the actual depth. The silicon etches vertically before lateral etching begins, because silicon needs to be exposed in the lateral direction before etching can occur. This can be observed by the slower etch rate for the lateral etching than the vertical etching.

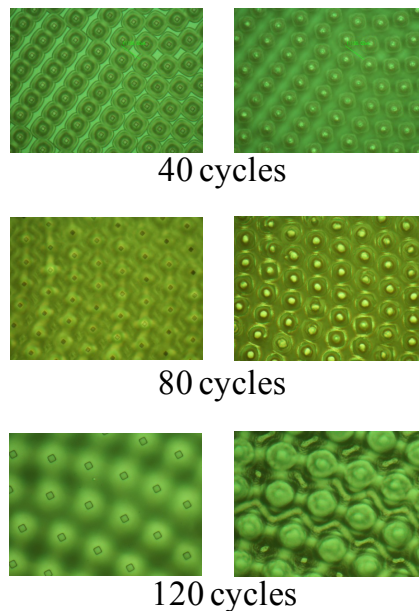


Figure 35: View of silicon topography with the top of the SU-8 layer in focus on the left and the deepest points of the silicon below the vias in focus on the right under a 50X objective microscope for 40, 80, and 120 cycles in the xenon difluoride.

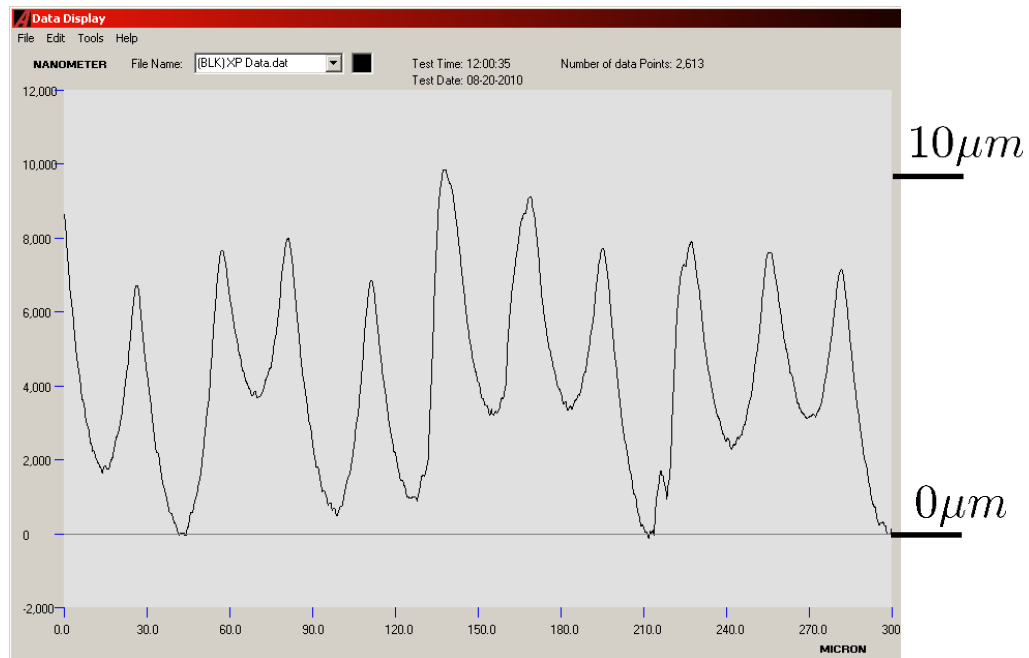


Figure 36: Profilometer trace on the bottom of xenon difluoride released mirrors. The variation in the depth of the silicon etch is approximately 10 μm. Long-range non-uniformity of the silicon counter electrode height can also be observed.

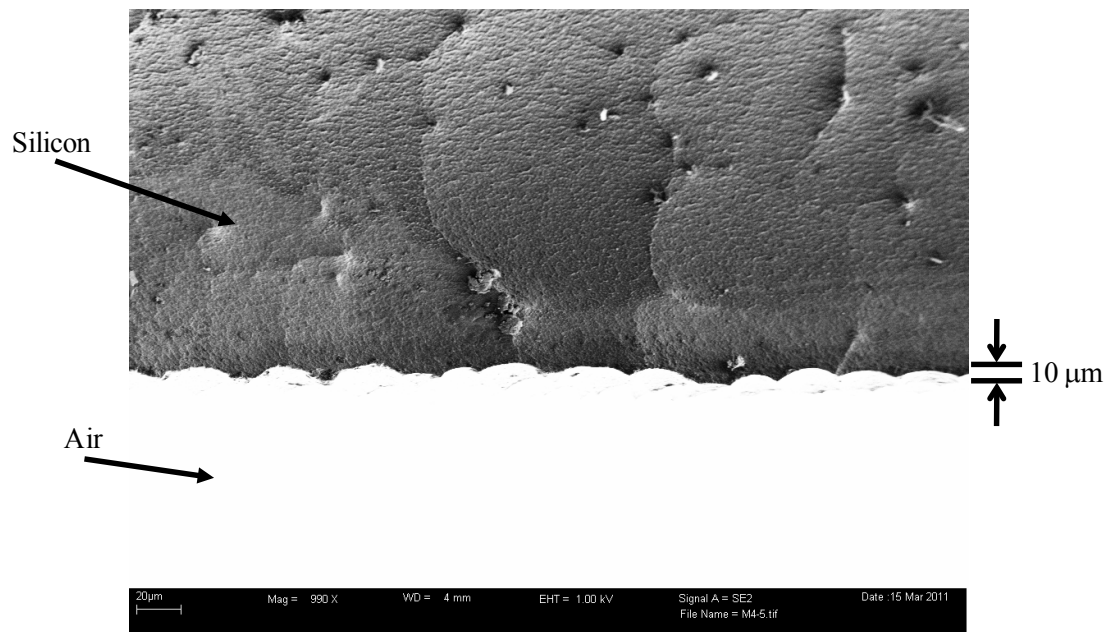


Figure 37: 990x SEM side view of the bottom silicon surface of Process 3 mirrors showing the aperiodic pattern of the etch depth of the silicon.

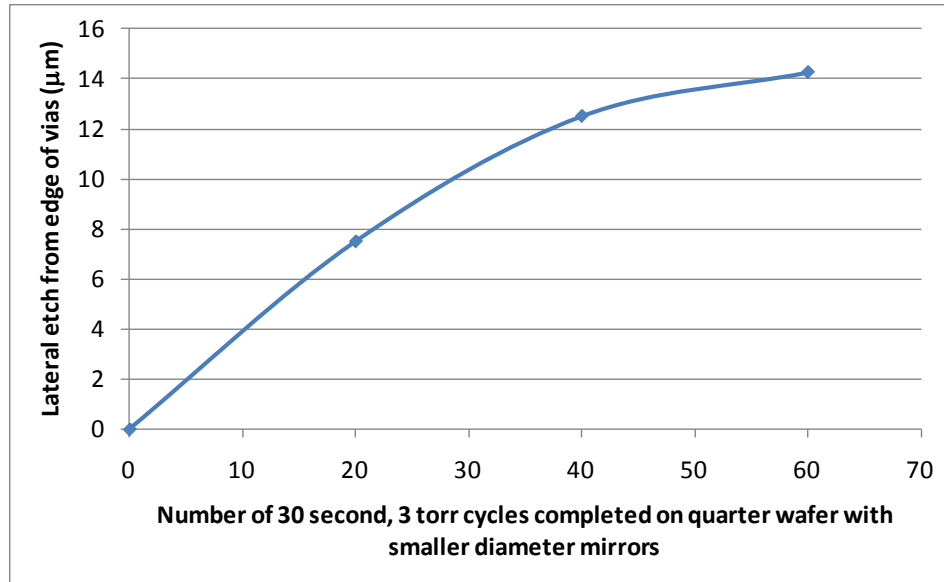


Figure 38: Lateral etch distance A vs. number of cycles completed on the quarter piece with smaller diameter mirrors. As more silicon becomes available for etching, the rate begins to slow.

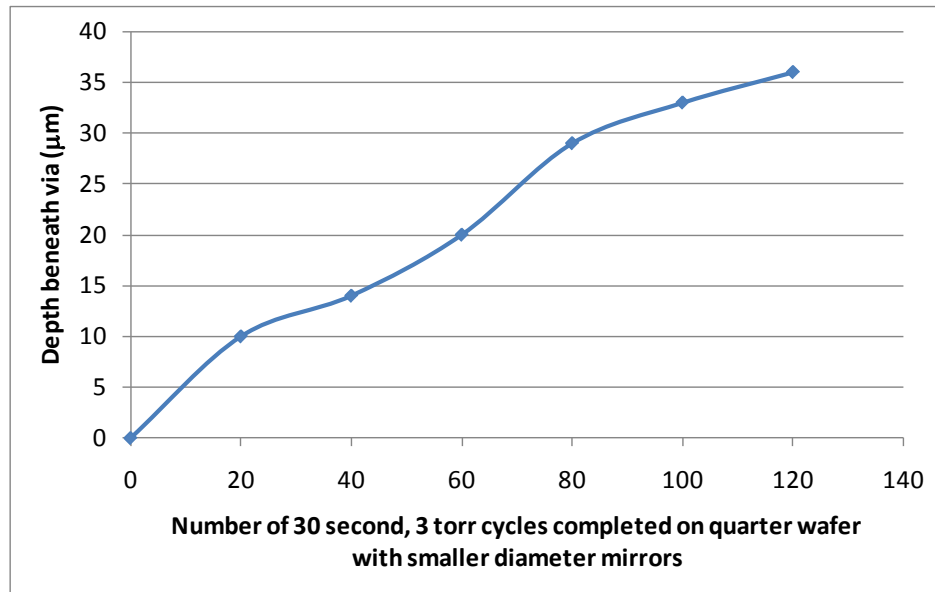


Figure 39: Depth of silicon etched beneath via DV vs. number of cycles completed on the quarter piece with smaller diameter mirrors. As more silicon becomes available for etching, the rate begins to slow.

The profile of the silicon counter electrode is shown in Figure 40 and Figure 41 where the high points of silicon are lighter in color than the low points. These images and the profilometer trace suggest that the gap depth has long-range non-uniformity. The

significance becomes more pronounced as the membrane deflects further since the non-uniformity becomes a greater percentage of the total air gap. The electric field is the voltage divided by the separation between the electrodes, so a varying gap depth suggests a non-uniform electric field across the membrane. Furthermore, the high points most likely exhibit fringing effects. The non-uniform electric field and the fringing effects could affect the shape of the membrane and lead to increased aberrations. Analysis of the actual electric field across the membrane would best be resolved numerically and will not be fully assessed in this paper.

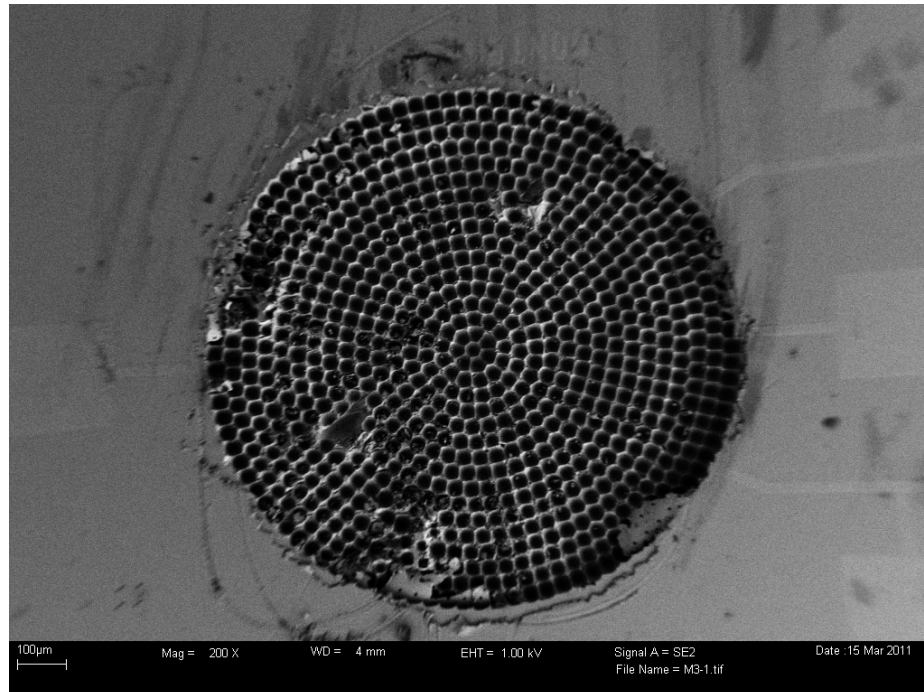


Figure 40: A 200x SEM image of a 1 mm fixed perimeter circular boundary Process 3 mirror after xenon difluoride etching. The membrane has been torn off of the top to provide a top view of the silicon substrate. The etch vias were above the centers of the numerous dark circles. The lighter gray areas are higher silicon peaks where the etch fronts merged.

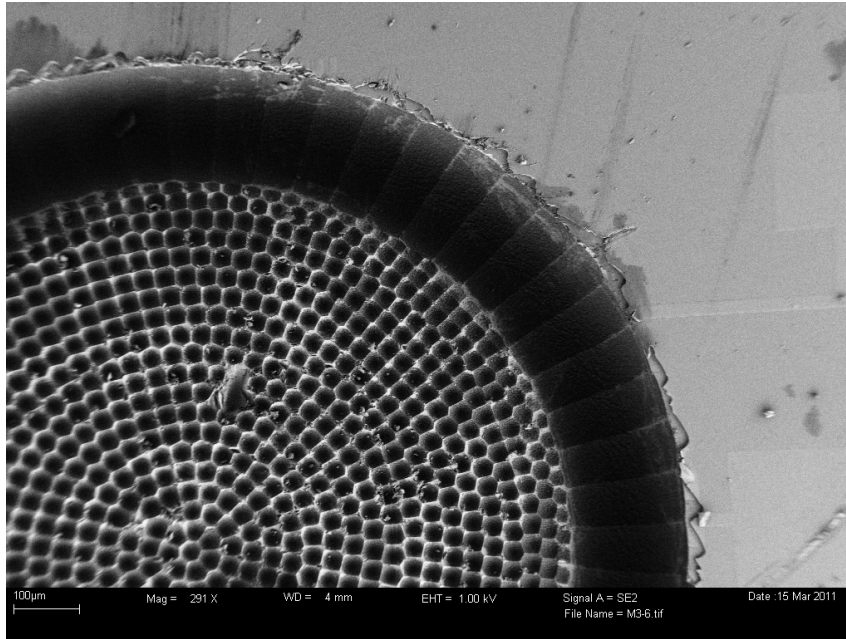


Figure 41: A 291x SEM image of a 1 mm 20% duty width support circular boundary Process 3 mirror. The segmentation around the perimeter creates lines of periodically spaced high (shown in gray) peaks of silicon.

Process 4 mirrors for the XeF_2 process were made at an even lower hardbake temperature of 165°C in an attempt to further lower the intrinsic stress of the membranes and since delamination during release was no longer a limiting factor. Some of these Process 4 mirrors were made with $3\text{ }\mu\text{m}$ etch vias to mitigate the problem of overhanging metallization contacting the bottom silicon counter-electrode (Figure 32). The via size, hardbake temperatures, mirror size on quarter piece, total number of etch cycles, and etch depths are summarized for both Process 3 and Process 4 mirrors in Table 5. First the $5\text{ }\mu\text{m}$ SU-8 via mirrors and then the $3\text{ }\mu\text{m}$ SU-8 via mirrors will be discussed. Quarter pieces with smaller and larger mirrors with $5\text{ }\mu\text{m}$ SU-8 vias were etched to depths of $20\text{ }\mu\text{m}$ and $30\text{ }\mu\text{m}$ for *DE* and *DV*, respectively. A smaller-mirror-quarter piece with $5\text{ }\mu\text{m}$ SU-8 vias was also etched to depths of $12\text{ }\mu\text{m}$ and $22\text{ }\mu\text{m}$ for *DE* and *DV*, respectively.

Furthermore, a larger-mirror-quarter piece with 5 μm SU-8 vias was etched to depths of 24 μm and 35 μm for *DE* and *DV*, respectively. These mirrors with the 5 μm SU-8 vias all etched similarly to the Process 3 mirrors (i.e. similar number of etch cycles for given depths). Two quarter pieces of the Process 4 mirrors with 3 μm etch vias were etched. One had smaller mirrors and was etched to depths of 15 μm and 33 μm for *DE* and *DV*, respectively. Following 920 cycles, a large-mirror-quarter piece with the 3 μm etch vias was etched to depths of 33 μm and 43 μm for *DE* and *DV*, respectively.

Process*	Process 3		Process 4					
Via Size (μm)	5	5	5	5	5	5	3	3
Hardbake Temperature	250°C	250°C	165°C	165°C	165°C	165°C	165°C	165°C
Large r or Smaller Sized Mirrors'	Smaller	Larger	Smaller	Smaller	Larger	Larger	Smaller	Larger
Total Number of Etch Cycles	120	140	100	120	140	180	Not recorded	920
<i>DE</i>	21	21	12	20	20	24	15	33
<i>DV</i>	33	33	22	30	30	35	33	43

*Refers to SU-8 2002 recipe Processes presented in Table 6.

'Wafers were diced into quarters prior to Xef2 etching. See Figure 16 for mirror size based on quartering of wafers.

Table 5: Summary of etch depths, via sizes, and hardbake temperatures for Process 3 and Process 4 mirrors.

The smaller-mirror-quarter piece with 3 μm SU-8 vias was the only piece that did not seem to etch laterally at the same rate as it etched vertically. Potentially, the lateral and vertical etch rates may be different for the smaller via size where diffusion is limited. Aperture sizes have been show to appreciably affect diffusion of XeF_2 and therefore, silicon etch rates [55, 56]. The total etch time of the larger-mirror-quarter piece with the smaller-etch vias demonstrated this, because it required 920 cycles for 33 μm and 43 μm for *DE* and *DV* etch depths, respectively. Furthermore, these mirrors took many more cycles to reach similar etch depths as the larger-etch-via Process 3 and Process 4 mirrors.

Reducing the etch via size appeared to increase the time for the XeF_2 gas to diffuse to the Si surface to allow full reaction of the XeF_2 gas, thus indicating that longer cycle times may have been needed. Another cause for slower etch rates can be misalignment of the metal layers with the SU-8 layers. Misalignment results in smaller nominal via sizes. Sometimes one quarter or one half of the wafer can have worse alignment than other sections of the wafer and this misalignment may also be responsible for minor discrepancies in etch times for all of the etches, both wet and dry.

Problems and Potential Improvements

The via pattern coupled with the use of an isotropic etchant, XeF_2 , led to long range non-uniformity of the silicon counter electrode. The impact of this on the electric field and resulting electrostatic pressure was not fully assessed. The membrane could have undesirable deviations in its surface profile from what a uniform air gap would produce. Furthermore, not enough mirrors were tested to determine where snapdown occurs relative to both minimum and maximum air gap depths. Snapdown could occur at approximately 50 % of the minimum air gap, but require a larger electric field than would be required for a uniform air gap. Furthermore, the silicon etched 100's of microns below the 20 % duty width perimeters. Both of these problems could be solved by creating lateral and vertical etch stops. Without the use of etch stops, the long range non-uniformity of the silicon could be remedied by having truly periodic etch vias.

SU-8 2002 Process Summary

All SU-8 2002 processes are shown in Table 6. Process 1 and Process 2 for the wet-etch release required wafers with 1 μm oxide and 150 nm psg. The dry-etch release allowed for simpler fabrication with the membrane layer being directly on silicon.

Substrate	P-type <100> Wafers with 1 μm oxide and 150 nm psg		P-type <100> Wafers	
Process #	Process 1	Process 2	Process 3	Process 4
Dehydration	10 min at 115 °C	10 min at 115 °C	10 min at 115 °C	10 min at 115 °C
Spincoat	30 s at 3250 rpm	30 s at 3250 rpm	30 s at 3250 rpm	30 s at 3250 rpm
Softbake	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 80°C and hold 3 min, ramp to 45°C, remove from hotplate and cool to RT	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 80°C and hold 3 min, ramp to 45°C, remove from hotplate and cool to RT	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 80°C and hold 3 min, ramp to 45°C, remove from hotplate and cool to RT	45°C 1 min, ramp to 65°C and hold 1 min, ramp to 80°C and hold 3 min, ramp to 45°C, remove from hotplate and cool to RT
Exposure	80 mJ/cm ²	80 mJ/cm ²	80 mJ/cm ²	80 mJ/cm ²
PEB	45 °C hold 1 min, ramp to 65 °C hold 1 min, ramp to 85 °C, immediately ramp to 45 °C, remove from hotplate and cool RT	45 °C 0 min, ramp at 1 °C/min to 60 °C hold 1 hr, ramp at 1 °C/min to RT	45 °C hold 1 min, ramp to 65 °C hold 1 min, ramp to 85 °C, immediately ramp to 45 °C, remove from hotplate and cool RT	45 °C hold 1 min, ramp to 65 °C hold 1 min, ramp to 85 °C, immediately ramp to 45 °C, remove from hotplate and cool RT
Development	1 min ultrasonic bath in SU-8 developer, rinse in IPA, rinse in DI water	1 min ultrasonic bath in SU-8 developer, rinse in IPA, rinse in DI water	15 s in SU-8 developer, rinse in IPA, rinse in DI water	15 s in SU-8 developer, rinse in IPA, rinse in DI water
Hardbake	45°C 1 min, ramp to 250°C and hold 30 min, ramp to RT	45°C 0 min, ramp at 290 °C/hr to 190°C and hold 30 min, ramp to RT	45°C 1 min, ramp to 250°C and hold 30 min, ramp to RT	45°C ramp at 240°C/hr to 165°C and hold 30min, ramp to RT

Note: Ramps were done at the automatic speed (roughly 7°C/min) of the hotplate unless otherwise noted. Ramp to RT indicates that the wafer was left on the hotplate and cooled at the rate limited by the thermal mass of the hotplate.

Table 6: The final recipe steps used for the SU-8 2002 membrane layer. For the wet-released wafers, Process 1 and Process 2 were done on top of oxide and psg. Process 3 and Process 4 were done directly on a silicon wafer for the XeF₂ release procedure.

PACKAGING

The wet-etch released mirrors were diced into individual mirrors or a couple of mirrors prior to release, thus making them small enough to fit onto a TO-8 or TO-5 header. The dry-etch release mirror were hand scribed and broken after release to prepare for packaging. The mirrors are mounted with conductive silver epoxy on TO-8 headers where a wire-bonder is used to attach the electrodes to the pins (Figure 42). The bonder used was a Model 4124 Universal Thermosonic Gold Ball Bonder by Kulicke and Soffa Industries, Inc. The bonder makes a ball connection on one end, pulls up wire and kinks to release tension, makes a wedge connection in a new location, pulls up and disconnects leaving a tail, and then the electric flame-off (EFO) arm strikes the wire to generate a new ball for the next bond cycle. Because the ball generally requires less force, it was initially used on the electrode (Figure 43). However, if the wedge bond fails, then the wire remains attached to the mirror electrode. The EFO arm strikes the wire and a large current surge evaporates the electrode gold pad. As a result, the ball bond is placed on the pin and the wedge bond connects the electrode.

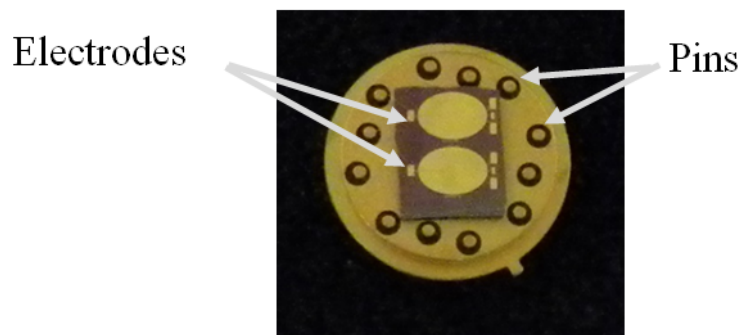


Figure 42: Two 3 mm elliptical boundary mirrors mounted on a TO-8 header. The mirror electrodes and the TO-8 pins are identified.

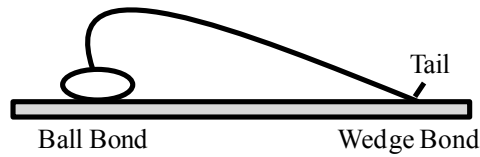


Figure 43: An ideal ball-wedge wire bond.

On the first mirrors, the bond pads had $60 \text{ \AA}$ Cr and 150 nm Au, applied with the metallization for the membrane. The metal delaminated from the SU-8 during the bonding process with this thickness of Cr/Au layers, so a bond pad mask was created. It was noted that the bonds worked best on a test piece with the thin 150 nm layer of gold on SU-8 where there was a larger area of gold. So, the surface area of the bond pad was increased for the new mask and thicker Cr/Au layers were used. An initial test with $60 \text{ \AA}$ Cr/ $0.5 \text{ }\mu\text{m}$ Au showed it could be wire-bonded without delaminating, but the bonds still pulled the gold off of the SU-8 membrane layer occasionally. Sameoto tested wirebonding on SU-8 for various metal layers and found that the best yield was for Cr/Au layers greater than $50 \text{ nm}/300 \text{ nm}$ thick, respectively [57]. To minimize cost while increasing adhesion, Process 4 wafers had 20 nm Cr and 800 nm Au evaporated onto them for the bond pads. Figure 44 shows the small square bond pads that are formed when metallization of the membrane is performed and the larger area bond pads with greater thickness. Figure 44 also shows that one of the bond pads had a smaller surface area than the other three. Wire bonding to this pad resulted in delamination of the bond pad from the membrane much more often than the other pads, so surface area may be important for adhesion of the Cr/Au to SU-8 2002.

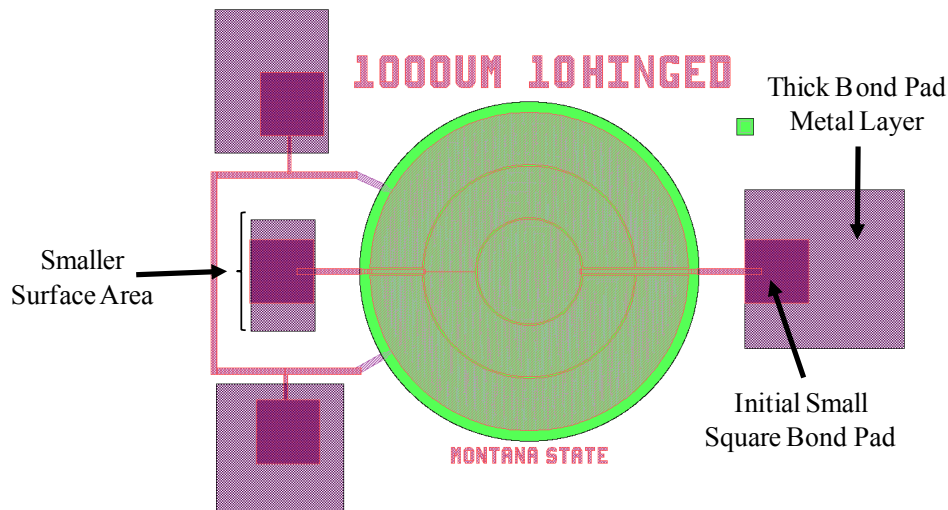


Figure 44: A bonding pad mask was made to create thicker Cr/Au layers and increase their surface areas.

Four main parameters can be changed on the ball bonder to ensure satisfactory bonds. These are the temperature, force, time, and power. A temperature of 95°C was recommended by the ball bonder manufacturer for our application. During bonding on the bond pads, however, it was noted that it worked best immediately after turning on the equipment and progressively got worse with time. Because temperature is the only bonding parameter that changes with time, the temperature was gradually turned down until good adhesion was restored. The ideal temperature for the bond pads was 55°C. The ideal temperature for the TO-8 mount was 95°C. Ideal means that the bond adhered more often and remained adhered for a longer period of time during device testing. Since silver epoxying a failed bond is easier on a pin than a bond pad, a temperature of 55°C was used. A force of approximately 6.5 worked for most bonds, but the wedge on the bond pad required a reduced force to prevent the capillary from piercing through the SU-8 and reaching the silicon counter electrode; thereby, shorting the top and bottom electrodes of

the device (Table 7). The ideal time and power for most of the bonds were approximately 4 and 4, respectively.

Bond Type	Substrate	Force	Time	Power
Ball	Bond Pad	6.5	3	3.5
Ball	Pin	6.5	4.5	4
Wedge	Bond Pad	3	4	4
Wedge	Pin	6.7	5.2	4.3

Table 7: Ideal bonding parameters for a given bond type and the substrate to which they are applied.

CHARACTERIZATION OF DEFORMABLE MIRRORS

The Device Characterization explains the interferometric set-up used for displacement measurements. It also covers the surface flatness and roughness, the diffraction pattern observed with 45° incident light on a 2 mm elliptical boundary mirror, electric field vs. deflection plots, the intrinsic stress results, and the mechanical frequency response of the devices.

Device Characterization

Deflection was measured with a Michelson interferometer ($\lambda=835$ nm), as shown in Figure 45. A spinning diffuser scatters collimated laser diode rays and is spinning at a rate faster than the scan rate of the CCD camera. This eliminates speckle in the image. A lens then condenses the rays. After passing through the Nikon 5x Michelson objective, the return beam from the interferometer reflects at 90° off of a beam splitter, passes through a focusing lens, and the image is captured by a CCD camera. Analyzing each interference fringe as $\lambda/2$ in depth difference, surface profiles across the membrane were generated (Figure 46).

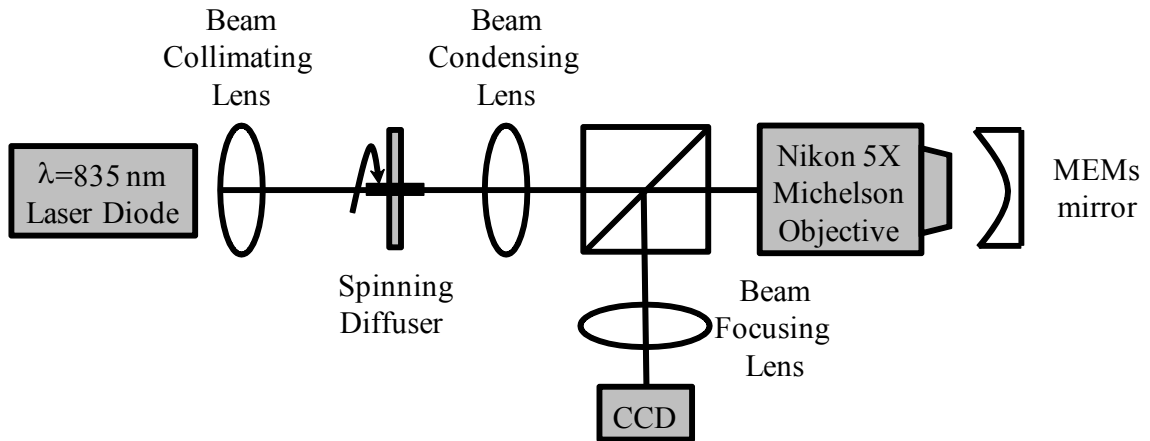


Figure 45: Interferometric set-up to measure deflection of the membrane under electrostatic actuation.

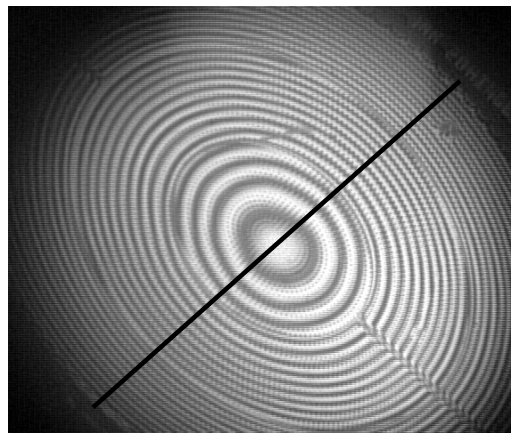


Figure 46: A 3 mm x 4.24 mm elliptical boundary mirror deflected to 11 μm . A line indicates the location of the surface profile.

This chapter discusses surface roughness, surface flatness, and surface profiles for specified deflections. The significance of deviations from the ideal flatness or membrane shape is dependent on the wavelength of light used for a given application. Since these mirrors are reflective, surface deviations induce twice their physical distance in phase to the optical system. The Strehl ratio is the irradiance value at the maximum of the point-spread function with aberrations divided by the maximum irradiance without aberrations [58]. For microscopy applications Rayleigh's quarter-wave rule is frequently used. This

rule derives from the relationship that the Strehl ratio will remain above 80 % for less than $\lambda/4$ aberrations in a system [58]. The $\lambda/4$ rule for aberrations will demand $\lambda/8$ surface accuracy in reflection. Some precision applications, such as interferometry, will often require less than $\lambda/10$ surface deviation.

Surface Flatness

Mirrors were tilted under the interferometer to get increased accuracy of small deflections across their surfaces. It was assumed that the largest mirrors would have the most natural sag, so both fixed perimeter (shown in Figure 47) and simply supported 3 mm x 4.24 mm elliptical boundary mirrors were analyzed across their short and long axes for flatness. Both showed less than 100 nm deviation pk-pk.

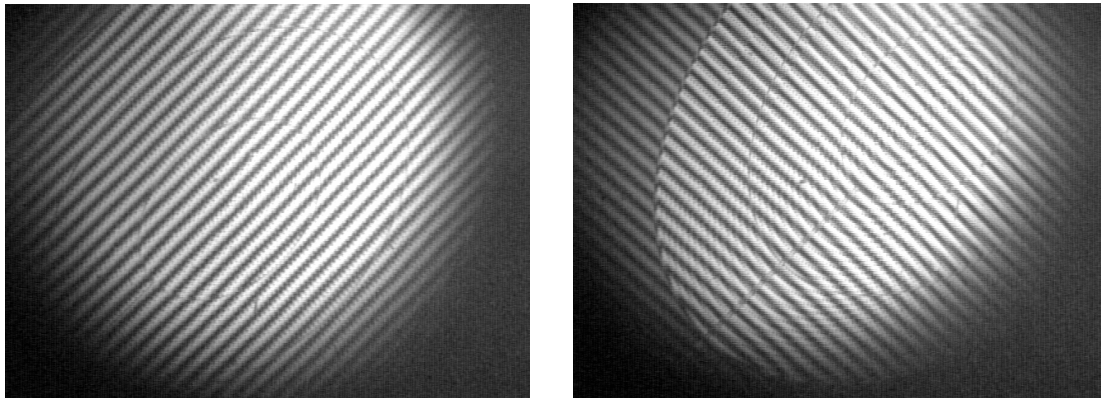


Figure 47: Process 4: 3 mm x 4.24 mm fixed perimeter elliptical boundary mirror used for flatness measurements. The sample was tilted to create parallel interferometric fringe lines for increased accuracy for the flatness measurements across the short axis (shown left) and long axis (shown right) of the mirror.

Surface Roughness

Surface quality is imperative for some imaging applications and is of concern when choosing membrane materials for deformable mirrors. The surface roughness of the SU-8 2002 membrane and the 150 nm gold layer was obtained for the Process 3 wafers both

prior to and after 140 etch cycles in xenon difluoride using the Veeco Multi-mode Atomic Force Microscope (AFM) with a NanoScope 5 controller and J scanner. A MikroMasch NSC36/AIBS tip C was used in tapping mode at a scan rate of 0.698 Hz. As shown in Figure 48, 40 μm by 40 μm square sections of SU-8 and gold in three different locations on both samples were scanned for a total of six measurements. A portion of the 40 μm by 40 μm square image was then selected using Nanoscope v7.20 software for the roughness measurement. The software does a statistical analysis on the pixel by pixel height data to determine the best plane for the roughness calculations. According to the software manual, the *Ra* value is the “Arithmetic average of the absolute values of the surface height deviations measured from the mean plane” [59]. The *Ra* values for the membrane and gold prior to etching were $1.26 \pm 0.217 \text{ nm}$ and $2.11 \pm 0.115 \text{ nm}$, respectively. The *Ra* values for the membrane and gold after 140 cycles in xenon difluoride were $4.45 \pm 1.69 \text{ nm}$ and $4.02 \pm 1.26 \text{ nm}$, respectively. The surface roughness did not significantly increase after etching in XeF_2 , but for considerably longer etch times or for certain applications where surface quality is of utmost importance, one might need to consider the effects of XeF_2 on the membrane and gold surfaces. The underside of the membrane is exposed to the etchant and this could also lead to varying thicknesses of SU-8 beneath the reflective coating, depending on distance from the etch vias (i.e. length of time the membrane is exposed to the etchant).

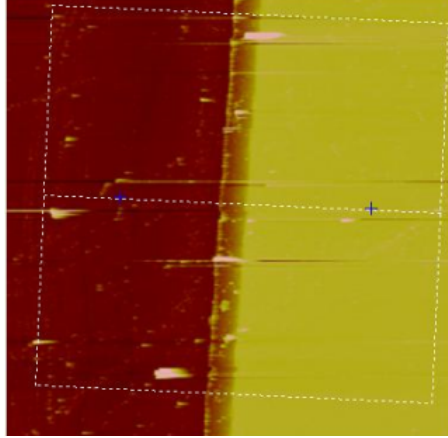


Figure 48: AFM image of the SU-8 2002 membrane on the left-hand side and 150 nm gold layer on a bond pad on the right-hand side. The entire image is 40 μm by 40 μm .

Diffraction at 45° Incidence due to Via Pattern

These mirrors have holes (or vias) periodically spaced 30 μm apart in the radial direction, which lead to diffraction. A periodically spaced grating with a period of Λ will produce maxima in intensity at an angle Θ from the grating (Figure 49). According to Huygens-Fresnel principle, at each aperture waves will propagate in all directions as they would from a point source. This makes it possible to find the angle at which the pathlengths of light will differ by $l\lambda$ (or $2\pi l$ radians of phase) where $l = 0, 1, 2, \dots$ and maxima in intensity will occur due to constructive interference. This occurs for this case when $\sin(\Theta) = n\lambda/\Lambda$ where $n = 0, 1, 2, \dots$. We will assume small angles, where $\sin(\Theta) \approx \Theta$.

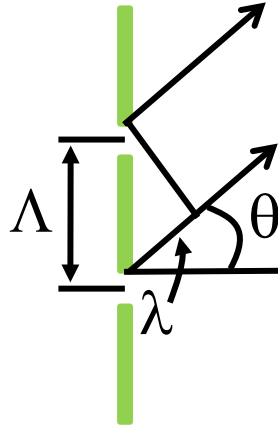


Figure 49: Diffraction pattern from periodically spaced grating. Waves have maxima when spaced in increments of λ apart or equivalently when they have increments of 2π phase delay, which happens when $\Theta \approx \lambda/\Lambda$.

Figure 50 shows the optical layout used to verify the diffraction pattern from a 2 mm x 2.8 mm mirror. A 635 nm wavelength laser was used, which provides a maxima or +/-1 order diffraction angle of $\Theta = 1.21^\circ$ for the vias spaced 30 μm apart. Using this angle and given an 8.8 mm x 6.6 mm sensing area on the CCD camera, a $f = 50$ mm lens was used to focus the rays onto the camera. As shown in Figure 51, the 0th order diffraction is the large central spot and the +/-1 diffraction orders form a bright ring with approximately a 2.1 mm diameter. The high frequency component bright vertical line can be attributed to the straight horizontal line created by the electrode traces.

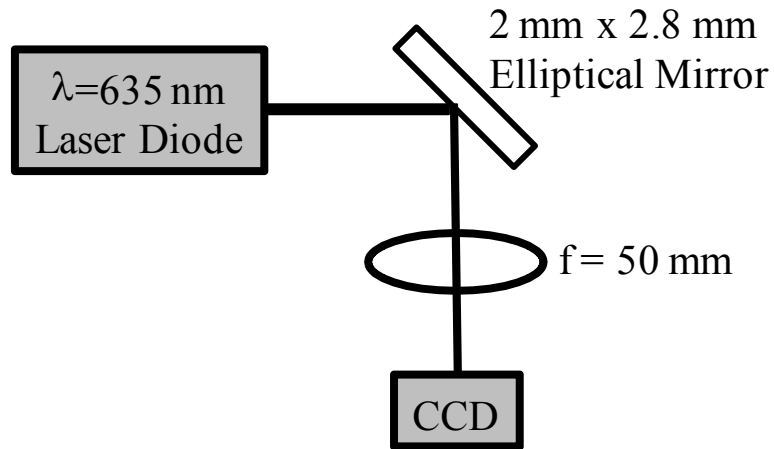


Figure 50: Optical layout for obtaining diffraction pattern from a 2 mm x 2.8 mm MEMS mirror.

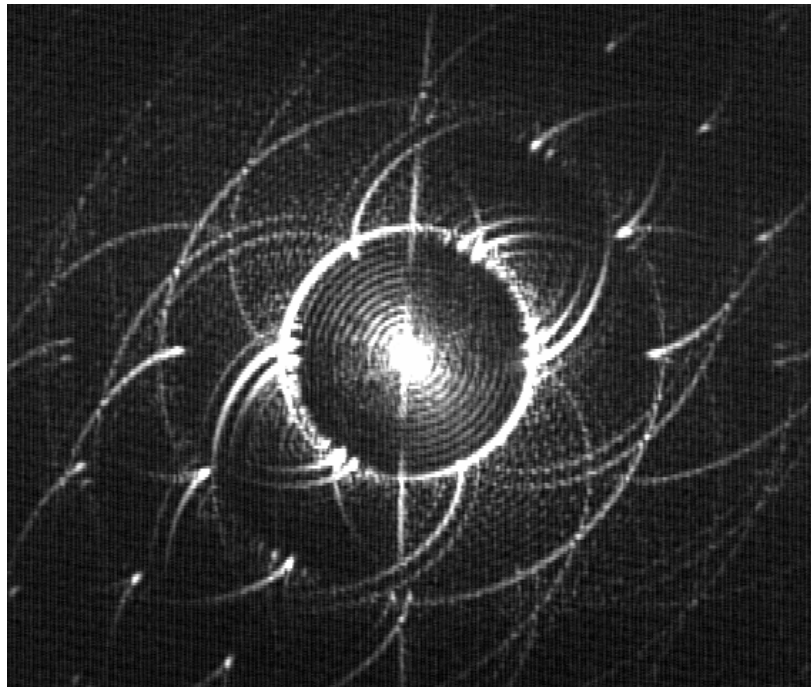


Figure 51: Diffraction pattern from 2 mm x 2.82 mm elliptical boundary mirror with 45° incident light.

Any imaging system that does not capture rays from the mirror greater than 1.2° , or essentially where a spatial filter has rejected the diffracted rays, will only see a small loss in throughput of irradiance. For instance, confocal microscopy uses a pinhole to limit ray collection to on-axis. With the current configuration of $5 \mu\text{m}$ square vias spaced

30 μm apart, the approximate loss of irradiance for these mirrors is $5^2/30^2 \approx 3\%$. Vias with increased periodicity would lead to a larger angle of diffraction and more uniform silicon counter electrode etching profiles with the tradeoff of greater irradiance loss.

Static Characterization

Figure 52 shows the electric field applied in parallel across all three electrodes of Process 1 circular boundary devices vs. the deflection of the mirrors. The larger mirrors required a smaller electric field for deflection and were able to reach further total deflection. The devices with 10 % and 20 % duty width membrane boundary conditions deflected further than the fixed membrane boundary devices.

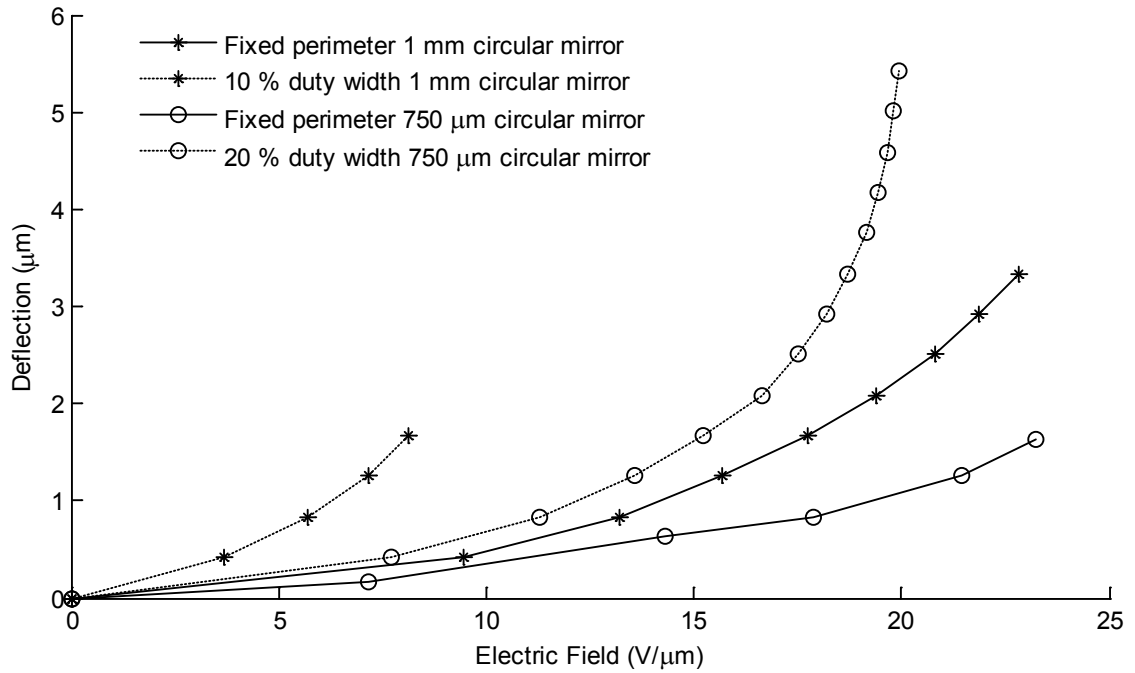


Figure 52: Electric field vs. deflection of Process 1 circular boundary devices. The fixed boundary membranes are more stiff than the simply supported devices and show less maximum deflection. Additionally, the larger mirrors had greater deflections for the same boundary conditions.

Two Process 4: 3 mm x 4.24 mm 20% duty width elliptical boundary mirrors with different air gaps were tested with equal potentials across all three electrodes. As shown in Figure 53, the 20 μm air gap took less voltage to achieve the same displacement as the 34 μm air gap device. The effective total deflection of the mirror is slightly less than these values presented for the entire membrane, since the reflective coating does not extend across the entire released membrane. The 3 mm x 4.24 mm dimension refers to metal region, but the silicon is undercut to a larger perimeter during etching, as can be observed near the segments shown in Figure 15. The maximum open loop displacement achieved was 16.7 μm at 320 V (not limited by the electric breakdown voltage of SU-8, but by snapdown phenomenon).

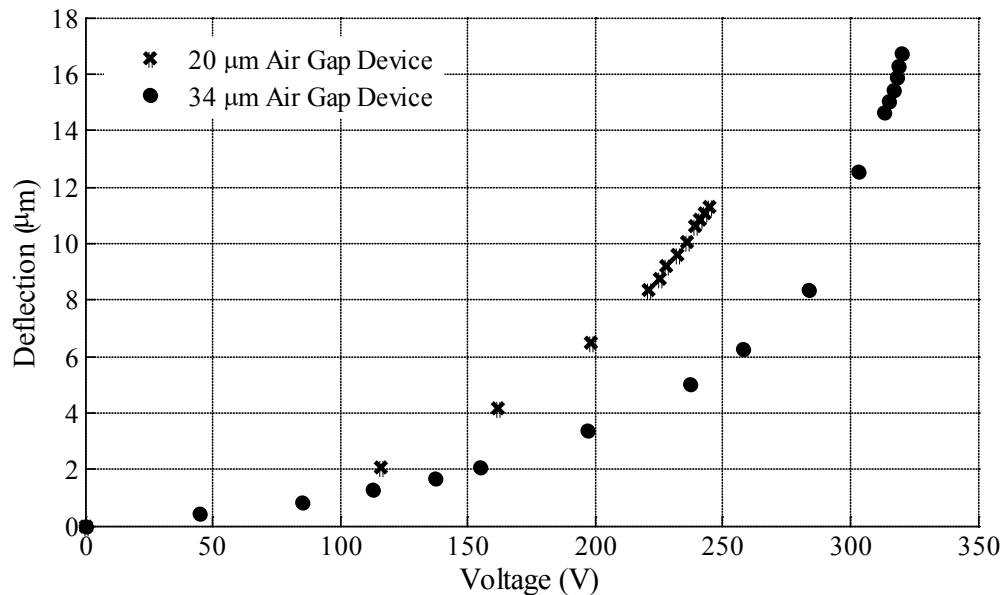


Figure 53: Voltage vs. deflection of Process 4: 3 mm x 4.24 mm elliptical boundary mirrors for 20 μm and 34 μm air gaps. The maximum displacement achieved was 16.7 μm . It should be noted that the effective total sag of the metalized mirror is slightly less than these values presented for the entire released membrane.

Surface profiles across the short axis of a Process 4: 3 mm x 4.24 mm ellipse are shown in Figure 54. The shape of the mirror was well represented by a 4th order polynomial curve fit at 3.9 μm of deflection and indicated 65 nm of peak-to-peak (pk-pk) spherical aberration when the quadratic term was subtracted. With 8.6 μm of deflection the mirror exhibited slightly more spherical aberration, requiring a 6th order polynomial to fit the measured shape and resulting in 255 nm pk-pk total spherical aberration after subtracting the quadratic term.

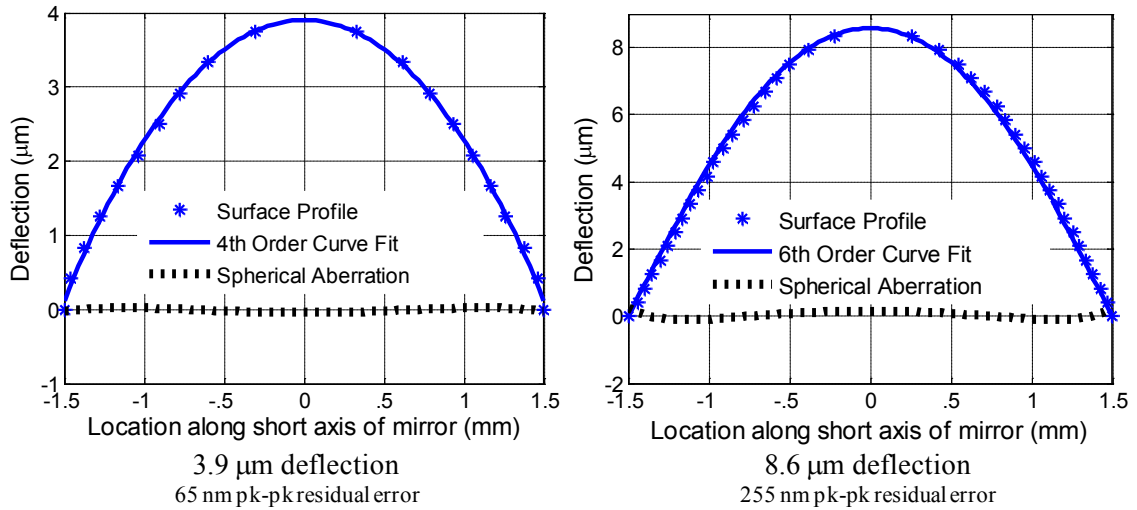


Figure 54: Surface profiles with all three electrodes at the same potential showing spherical aberrations of 65 nm and 255 nm (pk-pk) for 3.9 μm and 8.6 μm center deflections, respectively. The profiles are across the short axis of a Process 4: 3 mm x 4.24 mm 20 % duty width elliptical boundary mirror.

Intrinsic Stress

Using Equation 13 and Equation 16, it can be shown that the tension of the membrane is proportional to V^2/δ . For small displacements for fixed perimeter circular boundary mirrors, V^2 was plotted with respect to maximum deflection and the slope was

determined. Using this slope and relating Equation 13 and Equation 16, the intrinsic stress was calculated as follows,

$$\sigma = \left(\frac{\delta}{V^2} \right)^{-1} \frac{\epsilon_2}{2(s_o + \frac{h}{\epsilon_{r1}})^2} \frac{r_o^2}{4h}. \quad (17)$$

The depth measurement is more uniform for the wet released mirrors, so only the wet released mirrors were analyzed. The slope was found for the 750 μm and 1 mm fixed perimeter circular boundary mirrors shown in Figure 52 with gap depths of approximately 16.25 μm and 14 μm , respectively. Process 2 fixed perimeter 750 μm circular boundary mirrors were also analyzed where two had 14 μm air gaps and one had a 19 μm air gap. The curve fits with the smallest R-squared (square of the correlation coefficient) value for both processes are shown in Figure 55. Process 1 calculations indicated 22 MPa and 21 MPa intrinsic stress. Process 2 calculations indicated 8 MPa, 8 MPa, and 9.5 MPa. These values have a reasonably strong dependence on the actual air gap depth and this measurement as made under a 100x microscope objective can vary by 1-2 μm . Upon tearing off the membrane, profilometer measurements generally agree within 1-2 μm of the microscope objective measurements. Since delamination of the membrane along the perimeter can reduce stress values, care was taken to ensure there were no visual signs of delamination when these mirrors were viewed under a 100x microscope objective and under the interferometer.

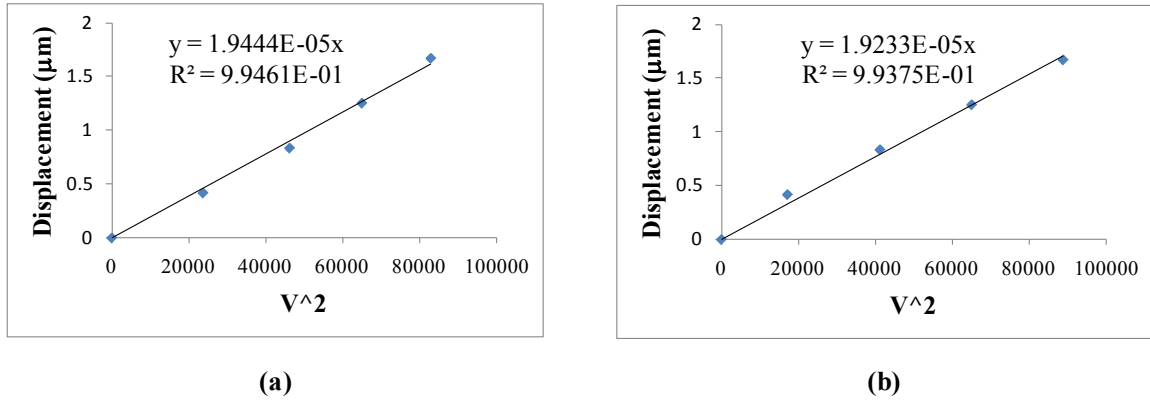


Figure 55: The linear curve fits with the smallest R-squared value for all devices analyzed for intrinsic stress for Process 1 (a) and Process 2 (b). Maximum displacement vs. voltage squared was plotted to determine the tension of the membranes using Equation 13 and Equation 16.

Dynamic Characterization

Dynamic measurements were taken using stroboscopic interferometry. As shown in Figure 56, the laser pulse and drive voltage are synchronized where the laser pulse takes a “snapshot” of the device for a small portion of its cycle (the test frequency is greater than the frame rate of the image capturing system, so the image is clear). A small AC component is added to a DC offset voltage. The phase response is determined by observing the relationship between the laser pulse and drive voltage signal where the maximum and/or minimum displacement is observed under the interferometer. Images of the maximum and minimum displacement using this technique are then used to determine the magnitude response.

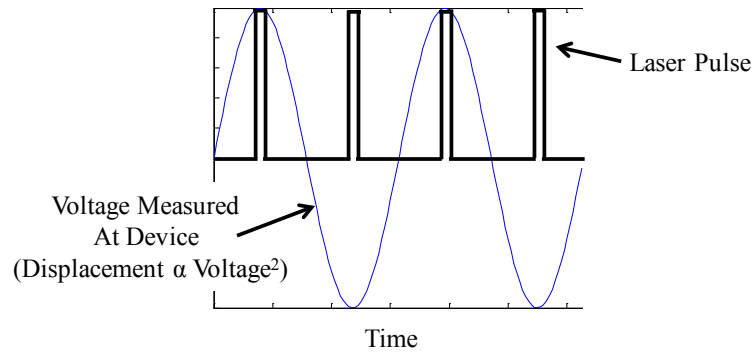


Figure 56: For stroboscopic interferometry, “snapshots” of the device are taken by pulsing the laser at the same frequency as the drive voltage. This frequency is faster than the frame rate of the image capturing system, so an interferometric image can be captured to determine the displacement. Since the laser pulse and voltage drive signal are synchronized, a specific phase can be introduced to the laser signal for comparison with displacement of the membrane. The phase difference between the voltage signal (driving the displacement) and the laser pulse can then be determined at maximum deflection.

The magnitude and phase response to frequency for two Process 1 mirrors are shown in Figure 57. The 3 dB cutoff frequency is approximately 20 kHz. The mechanical resonance appears to occur at a much higher frequency, in the neighborhood of 100 kHz, where the phase lag goes through -90° .

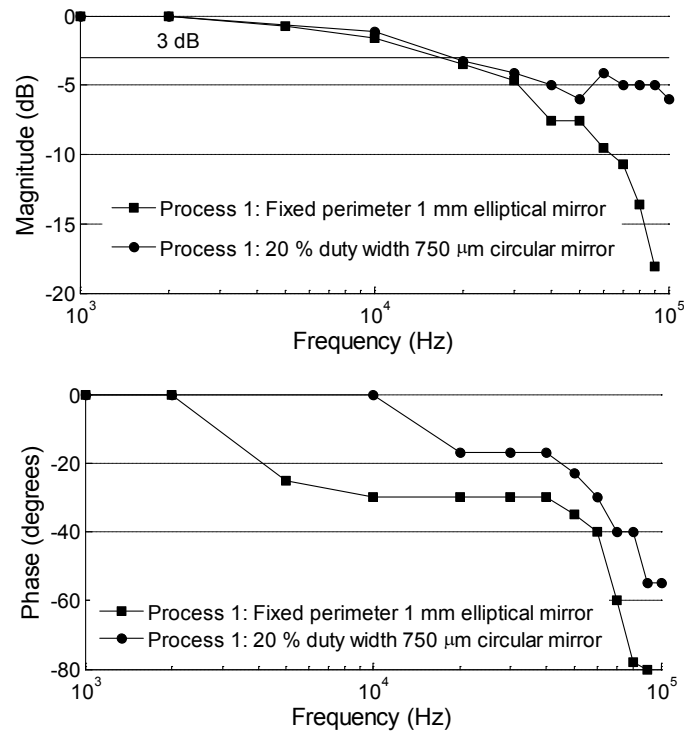


Figure 57: Frequency response of Process 1 mirrors. The 3 dB magnitude cutoff frequency was around 20 kHz for both the fixed perimeter 1 mm elliptical boundary mirror and 20 % duty width 750 μ m circular boundary mirror.

The frequency responses of Process 4: 3 mm x 4.24 mm and Process 4: 1 mm x 1.41 mm 20 % duty width elliptical boundary mirrors are shown in Figure 58. It should be noted that the mechanical extent of the membrane is much larger than the perimeter of the mirrors due to undercutting. The small signal displacement magnitude falls below 3 dB around 500 Hz and 5 kHz for the 3 mm and 1 mm ellipses, respectively. However, the response does not decline by more than 20 dB out to 50 kHz for both mirrors.

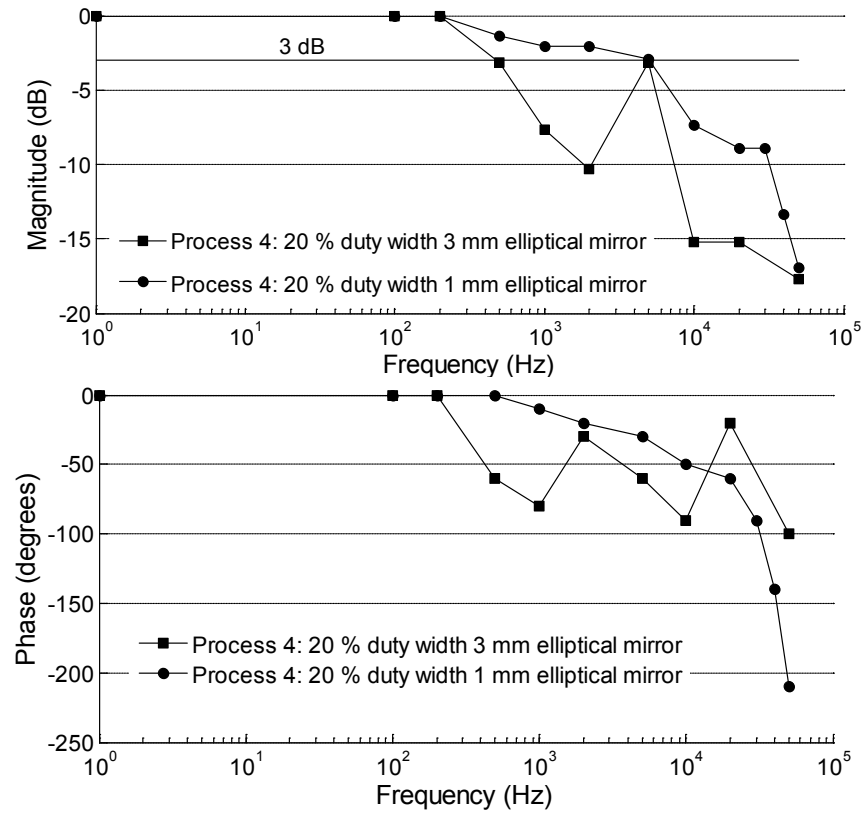


Figure 58: Frequency response of Process 4 mirrors. Both the 3 mm and 1 mm 20% duty width elliptical boundary mirrors had less than 20 dB loss in magnitude out to 50 kHz.

Microscopy Demonstration

A 3 mm x 4.24 mm elliptical boundary mirror was used at 45° incidence for focus control in a microscope to demonstrate its feasibility for endoscopic imaging. A diffuser is used with incoherent illumination on a transparent object (Figure 59). The diffuser provides more homogeneous illumination of the object. An Olympus 50x 0.40 NA objective lens images the object and a 1:1 relay with L1 and L2, both $f=100$ mm lenses, makes the MEMs mirror a conjugate aperture plane to the exit pupil of the objective lens, as described previously in Figure 8. An achromatic lens L3 (150 mm focal length) forms an image on the CCD camera with magnification

$$M = \frac{L3 * L1}{L2 * f_o}. \quad (18)$$

This provides a system magnification of 40x.

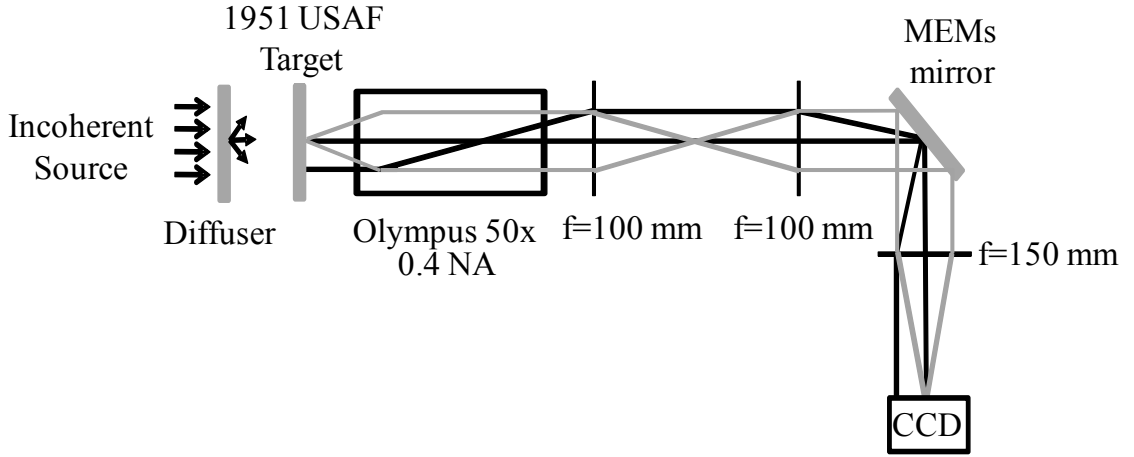


Figure 59: Microscopy set-up with the varifocus MEMs mirror positioned at 45° . The system magnification is 40x with a 0.4 NA objective lens.

The MEMs mirror provided focus adjustment of $159\text{ }\mu\text{m}$ to track the axial translation of the USAF Target (Figure 60). Group 7 elements 3-6 are shown in Figure 61 as the target is translated. A reference image was taken with a flat optical mirror in place of the MEMs varifocus mirror. The target imaged with the flat MEMs varifocus mirror ($\Delta f = 0$) had less contrast than the target imaged with the reference mirror. This may be attributed to scattering and diffraction from the MEMs mirror. The decrease in image quality for further focal ranges may be due to induced spherical aberrations from the MEMs mirror. Furthermore, as the MEMs mirror deflects, the rays entering the objective lens deviate more from the infinite conjugate case. This lens was designed to minimize aberrations for the infinite conjugate case; so the further the rays deviate from this, the

more aberrations this lens will induce. This experiment was done with all electrodes in parallel and no attempt to adjust voltages to better maintain parabolic shape of the displaced membrane or to correct for any spherical aberrations arising from other optics in the microscope.

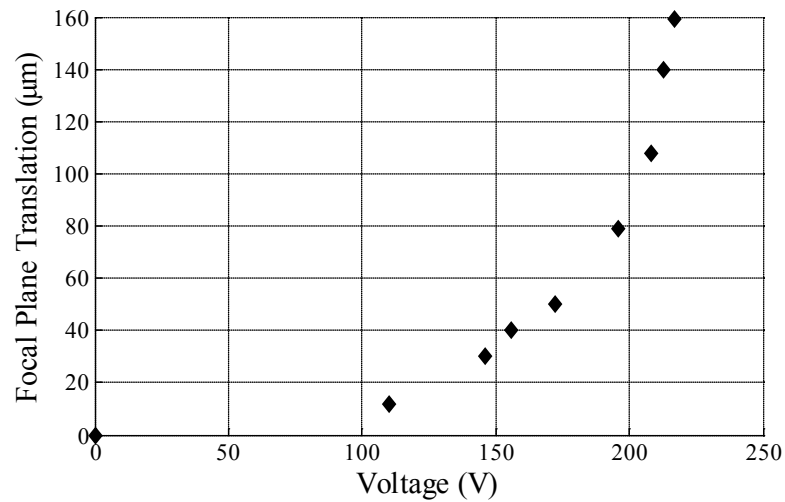


Figure 60: Translation of focal plane as voltage is applied to the MEMS mirror.

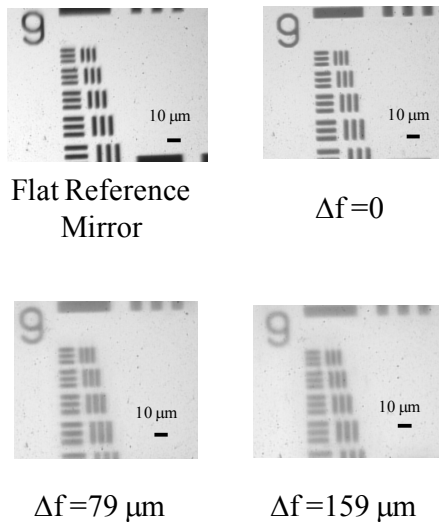


Figure 61: Group 7 elements 3-6 USAF target images. The change in focus corresponding to the translation distance of the target is also shown.

CONCLUSION

A surface micro-machining process has been developed for fabricating SU-8 2002 deformable mirrors with a three-fold improvement in deflection compared with previously described silicon nitride membrane mirrors. 6.8 μm of stable deflection with a 1 mm x 1.4 mm ellipse was demonstrated with a wet-etch release process. Dry release with XeF_2 significantly improved deflection of the surface micro-machined SU-8 membrane mirrors by allowing the realization of larger mirrors. 16.7 μm center membrane deflection of a 3 mm x 4.24 mm ellipse was demonstrated with the dry-etch release process (reflective mirror surface sag was less than this value, since the reflective portion does not extend to the edge of the membrane).

The processing of a good quality 2.25 μm thick SU-8 2002 membrane layer proved to be challenging. The recipes needed to produce well defined features, good adhesion of the film to the substrate (psg or silicon), minimal cracking or stress in the film, and a film that could withstand the release process. Cracking and delamination were minimized by a maximum of 7 $^{\circ}\text{C}/\text{min}$ ramp rates and intermittent temperature soaks for the baking steps. Slow ramping of the softbake allowed sufficient time for the solvent to fully evaporate out of the resist and prevented the mask from sticking to the wafer during exposure. A lower PEB temperature may have prevented photoacid diffusion into unexposed resist, thus producing better patterning and features. Leaving the membrane in the developer for more than an additional 10 s than prescribed or not immersing the wafer in IPA prior to the H_2O rinse led to unviable membranes. Whereas just rinsing with IPA without an H_2O rinse left a film on the membrane. The process was dependent on the

substrate beneath the SU-8. The membrane on Si needed less time in the developer than the membrane on 8 % psg and thermal oxide. The hardbake healed cracks in the film and increased its durability for the release processes.

As previously stated, the intrinsic stress needs to be minimized for increased displacement of these mirrors. The intrinsic stress is approximately 22 MPa and 8-10 MPa for Process 1 and Process 2, respectively. Both the hardbake temperatures and PEB temperatures were lower for Process 2 than Process 1. Process 1 and Process 2 had hardbake temperatures of 250 °C and 190 °C, respectively. The PEB temperatures of Process 1 and Process 2 were 80 °C and 60 °C, respectively. 8-10 MPa of intrinsic stress is nearly as low as the lowest published values, which are approximately 2.5 MPa [30]. With additional investigation of the PEB and hardbake temperatures, this stress value could potentially be further reduced while still producing a decent quality film. Both processes stress values were much lower than the more common LPCVD silicon nitride membrane mirrors, where Himmer reported a stress of 100 MPa for similar surface-micromachined silicon nitride mirrors [27]. The XeF₂ released mirrors did not need to withstand high temperatures and wet chemicals for release, which meant that Process 4 could be made with the lowest hardbake temperature, but its intrinsic stress value was not determined due to difficulty in identifying the effective air gap depth. Development of the SU-8 2002 membrane recipe for the Si substrate was severely time limited and not explored in great detail. Experience with the process and the material guided the decision to reduce the development time, but other process parameters should be investigated before many conclusions are drawn from this.

A trade-off between intrinsic stress, size and the mechanical frequency response exists. The reduction of intrinsic stress leads to reduction in the total mechanical bandwidth of the device. The small (1 mm), higher 250 °C hardbake temperature mirrors had large bandwidths with 3 dB frequencies larger than 10 kHz, so these mirrors have the potential for fast focus control applications. By comparison, the larger, lower stress (190°C hardbake temperature) mirrors had smaller bandwidths, but could deflect further with less applied voltage. The process parameters and device may be chosen to achieve the best stress and frequency response for a given application.

The surface roughness was below 5 nm and the surface flatness of an un-deflected 3 mm x 4.24 mm elliptical boundary membrane was below 100 nm. The importance of the flatness depends on the application and the wavelength of light. For wavelengths longer than 800 μm , the surface flatness would be better than $\lambda/8$ peak-to-valley and would provide better than 80 % Strehl ratio, as is desired for most microscopy applications [58]. Furthermore, the mirrors show nearly parabolic surface shapes (measured along the short axis of the ellipse), with 3.9 μm and 8.6 μm of total mirror sag exhibiting peak-to-peak spherical aberrations of only 65 nm and 255 nm, respectively. This was done without effort to alter voltages on the three electrodes to determine the best shape. With some effort to reduce voltage at the center of the devices, better than 80 % Strehl ratios for spherical aberration at further membrane displacements should be possible.

The bottom topography of the XeF_2 released mirrors could cause some problems with surface shape, but this has not been observed up to the current displacements

achieved under open-loop conditions. Ensuring the via patterns are truly periodic would mitigate this problem. The via pattern also creates diffraction at angles greater than 1° , so applications that spatially filter out this angle should not be affected. This does reduce the irradiance by approximately 3 %.

The voltage that can be applied to the devices is ultimately limited by the breakdown voltage of the material. Melai et. al. examined the dielectric behavior of SU-8 and their results would suggest a breakdown voltage for 2.25 μm thick SU-8 2002 of approximately 1 kV. In practice greater than 420 V often led to enough current flow to ruin narrow portions of the electrode traces. Some devices had traces less than a few microns wide due to via encroachment. We do not know whether current flow was due to SU-8 conductivity, capacitor charging, or air breakdown. Lower voltages are generally more desirable for most applications. When examining the use of these mirrors under closed loop control or for scanning applications, high voltage often comes at a price of decreased bandwidth or both are attained for a higher monetary price. When looking at the feasibility of these mirrors in cell-phone cameras or medical instrumentation, then lower voltages are also desired.

If definitive etch stops were created for the XeF_2 release process that resulted in a relatively flat silicon counter electrode, then our target deflection of 30 μm for high NA microscopy focus control could theoretically be achieved with the 10 MPa stress membrane recipe and 4 mm diameter circular boundary fixed perimeter mirrors. This is based on Equation 16 with $\epsilon_2 = \epsilon_o$ for air, $\epsilon_{r1} = 4.1$ for SU-8, 400 V applied, and an air gap of $s_o = 60 \mu\text{m}$ to allow for 50 % deflection of the membrane prior to snapdown.

Based on previous feedback and closed loop control experiments, it would be expected that these mirrors could be deflected to 70 % of their air gap [60-62]. Making the same assumptions as made in the previous calculation except an air gap of $s_o = 43 \mu m$, a 3 mm diameter circular boundary fixed perimeter mirror could attain our target displacement if the control loop allowed for 70 % deflection.

The overall objective of this research is to add depth information to imaging systems that are currently limited to one finite focal distance and/or to decrease size and complexity of current focus control elements in other imaging systems. We demonstrated the utility of these mirrors for focus control at 45° beam incidence in a microscopy demonstration, thus illustrating their feasibility for focus control. They provided resolvable images of group 7 element 6 USAF target (228 lp/mm) over a focal range of $159 \mu m$ at 0.4 NA and 40x magnification. They only require connections at the electrodes and varying the three concentric electrode voltages can alter their surface profiles to reduce both aberrations these mirrors induce and/or aberrations arising from other optical elements in the system. Not only can these mirrors act as varifocus elements; but the fabrication process is simple and low cost, and leads to mirrors capable of large electrostatic deflection.

FUTURE WORK

Future work consists of improving the current design of the mirrors, aberrations investigation, implementation in other imaging systems, and actuation under closed-loop control for further deflection. To address the long range non-uniformity of the silicon counter electrode, the vias could be made truly periodic.

According to Xactix, Inc, XeF_2 does not readily attack the passivation layer used in the Bosch process for deep anisotropic silicon etching, most metals, photoresists, polymers, silicon dioxide, most dielectrics, or silicon nitride [63]. It has fast etch rates for silicon, molybdenum, germanium, and silicon-germanium [63]. A potential solution to the extensive lateral undercutting of the 20 % duty width supported perimeter mirrors and to the diffraction from top surface etch vias would be etch vias on the bottom of the mirror through the silicon. After patterning of the membrane layer and top metallization, the top-side could be protected with photoresist. Deep anisotropic silicon etching through backside etch vias could be done with the Bosch process. Finally, the mirrors could be released in XeF_2 . Alternatively, lateral etch stops could be used to better define perimeters of the mirrors. These etch stops would essentially be trenches around the perimeters of the mirrors that are either oxidized or filled with SU-8 resist or silicon nitride prior to spinning of the SU-8 2002 membrane layer. Another strategy would be the use of silicon-on-insulator wafers to create buried etch stops. Lateral etch stops could also be used with the buried etch stop to fully define the air gaps.

The surface roughness measurements suggested the SU-8 2002 membrane layer was not completely immune to XeF_2 . If this is the case, then the membrane could be of

varying thicknesses for the released mirrors. This would be more likely to cause problems for future designs that have long etching times. Exactly how much the membrane and the metal are etched could be further explored in the future.

The utility of the three electrodes for surface shaping was not evaluated in this thesis. It could be investigated in the future to improve surface profiles at greater displacements and to obtain higher quality imaging in the microscope set-up presented here by reducing spherical aberration. These mirrors can also be demonstrated in other imaging systems, such as confocal microscopy, cameras, and time-domain optical coherence tomography imaging. Finally, position feedback and closed loop control have been previously demonstrated and could be used in the future to increase the total stroke of these devices [60-62].

The low intrinsic stress value achieved shows promise for reaching our goal of greater than 30 μm stroke. If this can be attained in the future, then this would provide sufficient focus control to greatly benefit small form factor imaging systems.

REFERENCES CITED

- [1] Werber, A. and Zappe, H. "Tunable Pneumatic Microoptics," *JMEMS* 17(5), 1218-1227 (2008).
- [2] Weisong, W., Ji, F. and Varahramyan, K. "Compact variable-focusing microlens with integrated thermal actuator and sensor," *IEEE Photonics Technology Letters* 17(12), 2643-2645 (2005).
- [3] Yang, H., Yang, C.-Y. and Yeh, M.-S. "Miniaturized variable-focus lens fabrication using liquid filling technique," *Microsystem Technologies* 14(7), 1067-1072 (2008).
- [4] Kuwano, R., Tokunaga, T., Otani, Y. and Umeda, N. "Liquid Pressure Varifocus Lens," *Optical Review* 12(5), 405-408 (2005).
- [5] Shaw, D. and Lin, C. W. "Design of O-ring Driven Liquid-Filled Lens," *Proceedings of the 35th International MATADOR Conference*, pp. 63-66 (2007).
- [6] Lee, S. W. and Lee, S. S. "Focal tunable liquid lens integrated with an electromagnetic actuator," *Applied Physics Letters* 90(12), 121129 (2007).
- [7] Kuiper, S. and Hendriks, B. H. W. "Variable-focus liquid lens for miniature cameras," *Applied Physics Letters* 85(7), 1128-1130 (2004).
- [8] Berge, B. "Liquid lens technology: principle of electrowetting based lenses and applications to imaging," *18th IEEE International Conference on MEMS*, 227-230 (2005).
- [9] Commander, L. G., Day, S. E. and Selviah, D. R. "Variable focal length microlenses," *Optics Communications* 177(1-6), 157-170 (2000).
- [10] Martinez, T., Wick, D. V., Payne, D. M., Baker, J. T. and Restaino, S. R. "Non-mechanical zoom system," *SPIE Sensors, Systems, and Next-Generation Satellites VII*, 5234, 375-378 (2004).
- [11] Wick, D. V., Bagwell, B. E., Sweatt, W. C., Peterson, G. L., Martinez, T., Restaino, S. R., Andrews, J. R., Wilcox, C. C., Payne, D. M. and Romeo, R. "Active optical zoom for space-based imaging," *SPIE Unconventional Imaging II*, 63070A (2006).

- [12] Kinoshita, H., Hoshino, K., Matsumoto, K. and Shimoyama, I. "A thin camera with a zoom function using reflective optics," *Sensors and Actuators a-Physical* 128(1), 191-196 (2006).
- [13] Himmer, P. A., Dickensheets, D. L. and Friholm, R. A. "Micromachined silicon nitride deformable mirrors for focus control," *Opt. Letters* 26(16), 1280-1282 (2001).
- [14] Himmer, P. A. and Dickensheets, D. L. "Spherical aberration correction using a silicon nitride deformable membrane mirror," *IEEE/LEOS Intl. Conf. on Optical MEMS and Their Applications*, 185-186 (2005).
- [15] Lutzenburger, B. J., Moghimi, M. J., Lukes, S. J., Kaylor, B. and Dickensheets, D. L. "MEMS deformable mirrors for focus control in vital microscopy," *SPIE MOEMS and Miniaturized Systems IX*, 759406-8 (2010).
- [16] Mescheder, U. M., Estañ, C., Somogyi, G. and Freudenreich, M. "Distortion optimized focusing mirror device with large aperture," *Sensors and Actuators A: Physical* 130-131, 20-27 (2006).
- [17] Bagwell, B. E., Wick, D. V., Cowan, W. D., Spahn, O. B., Sweatt, W. C., Martinez, T., Restaino, S. R., Andrews, J. R., Wilcox, C. C., Payne, D. M. and Romeo, R. "Active zoom imaging for operationally responsive space," *SPIE MEMS Adaptive Optics*, 64670D (2007).
- [18] Korde, U. A. "Large-displacement Closed-loop Control of Variable Area Electrostatic Actuation for Membrane Reflectors," *Journal of Intelligent Material Systems and Structures* 20(6), 697-721 (2009).
- [19] Lin, M.-J. and Wu, K.-W. "Design and fabrication of an electrostatically actuated microdeformable focusing mirror," *Journal of Micro/Nanolithography, MEMS and MOEMS* 10(1), 011504-7 (2011).
- [20] Yang, V. X. D., Youxin, M., Standish, B. A., Munce, N. R., Chiu, S., Burnes, D., Wilson, B. C., Vitkin, I. A., Himmer, P. A. and Dickensheets, D. L. "Doppler optical coherence tomography with a micro-electro-mechanical membrane mirror for high-speed dynamic focus tracking," *Opt. Letters* 31(9), 1262-4 (2006).
- [21] Sherman, L., Ye, J. Y., Albert, O. and Norris, T. B. "Adaptive correction of depth-induced aberrations in multiphoton scanning microscopy using a deformable mirror," *Journal of Microscopy* 206(1), 65-71 (2002).
- [22] Potsaid, B., Bellouard, Y. and Wen, J. "Adaptive Scanning Optical Microscope (ASOM): A multidisciplinary optical microscope design for large field of view and high resolution imaging," *Opt. Express* 13(17), 6504-6518 (2005).

- [23] Wright, A. J., Poland, S. P., Girkin, J. M., Freudiger, C. W., Evans, C. L. and Xie, X. S. "Adaptive optics for enhanced signal in CARS microscopy," *Opt. Express* 15(26), 18209-18219 (2007).
- [24] Peters, R. D., Lay, O. P. and Jeganathan, M. "Broadband phase and intensity compensation with a deformable mirror for an interferometric nuller," *Appl. Opt.* 47(21), 3920-3926 (2008).
- [25] Zhou, P., Wang, X., Ma, Y., Ma, H., Xu, X. and Liu, Z. "Simultaneous phase-distortion correction and beam steering only employing a deformable mirror," *Electronics Letters* 45(20), 1049-1050 (2009).
- [26] Zhao, X., Xie, Y. and Zhao, W. "Broadband and wide field of view foveated imaging system in space," *Optical Engineering* 47(10), 103202 (2008).
- [27] Himmer, P. A. "Silicon nitride deformable mirrors for focus and spherical aberration correction in micro-optical systems," in electrical engineering, PhD, Bozeman, MT: Montana State University (2002).
- [28] Voldman, J. Massachusetts Institute of Technology. "Material Properties," Massachusetts Institute of Technology, <http://www.mit.edu/~6.777/matprops/> (2011).
- [29] Anhoj, T. A., Jorgensen, A. M., Zauner, D. A. and Hubner, J. "The effect of soft bake temperature on the polymerization of SU-8 photoresist," *J. Micromech. Microeng.* 16(9), 1819-1824 (2006).
- [30] Keller, S., Blagoi, G., Lillemose, M., Haeffliger, D. and Boisen, A. "Processing of thin SU-8 films," *J. Micromech. Microeng.* 18(12), 125020 (10 pp.) (2008).
- [31] Sameoto, D., Tsang, S.-H. and Parameswaran, M. "Polymer MEMS processing for multi-user applications," *Sensors and Actuators A: Physical* 134(2), 457-464 (2007).
- [32] Seidemann, V., Rabe, J., Feldmann, M. and Büttgenbach, S. "SU8-micromechanical structures with in situ fabricated movable parts," *Microsystem Technologies* 8(4), 348-350 (2002).
- [33] Foulds, I. G., Johnstone, R. W. and Parameswaran, M. "SU-8 surface-micromachining process utilizing PMGI as a sacrificial material," *IEEE 20th Intl. Conf. on Micro Electro Mechanical Systems*, 291-294 (2007).
- [34] Seidemann, V., Bütetfisch, S. and Büttgenbach, S. "Fabrication and investigation of in-plane compliant SU8 structures for MEMS and their application to micro valves and micro grippers," *Sensors and Actuators A: Physical* 97-98, 457-461 (2002).

- [35] Chronis, N. and Lee, L. P. "Electrothermally Activated SU-8 Microgripper for Single Cell Manipulation in Solution," J. of Microelectromechanical Systems 14(4), 857-863 (2005).
- [36] Friese, C. and Zappe, H. "Deformable Polymer Adaptive Optical Mirrors," JMEMS 17(1), 11-19 (2008).
- [37] Dunbar, E., Leone, M., Lukes, S. and Dickensheets, D. L. "Polymer deformable membrane mirrors for focus control using SU-8 2002," IEEE/LEOS Intl. Conf. on Optical MEMs and Nanophotonics, 138-139 (2008).
- [38] Friese, C., Wissmann, M. and Zappe, H. "Polymer-based membrane mirrors for micro-optical sensors," Proceedings of IEEE Sensors 1, 667-672 (2003).
- [39] Dickensheets, D. L. "Requirements of MEMS membrane mirrors for focus adjustment and aberration correction in endoscopic confocal and optical coherence tomography imaging instruments," Journal of Microlithography, Microfabrication, and Microsystems 7(2), 021008 (9 pp.) (2008).
- [40] Himmer, P. A., Dickensheets, David L. "Off-axis variable focus and aberration control mirrors and method," U.S. Patent 7,494,233 B2; United States: Montana State University (Bozeman, MT, US),(2009).
- [41] Himmer, P. A. and Dickensheets, D. L. "Off-axis variable focus and aberration control mirrors," MOEMS and Miniaturized Systems III, 4983, 296-303 (2003).
- [42] Ulaby, F. T. "Fundamentals of Applied Electromagnetics," 5th Edition ed Upper Saddle River: Pearson Prentice Hall (2007).
- [43] Graff, K. F. "Wave Motion in Elastic Solids," Mineola, NY: Dover Publications (1991).
- [44] MicroChem Corp, www.microchem.com (2009).
- [45] ECEn IMMERSE Web Team. "Coefficient of Thermal Expansion (CTE)," Brigham Young University, http://cleanroom.byu.edu/CTE_materials.phtml (2011).
- [46] Park, J.-G., Lee, S.-H., Ryu, J.-S., Hong, Y.-K., Kim, T.-G. and Busnaina, A. A. "Interfacial and Electrokinetic Characterization of IPA Solutions Related to Semiconductor Wafer Drying and Cleaning," Journal of The Electrochemical Society 153(9), G811-G814 (2006).
- [47] Kanto Corp., "PGMEA MSDS," Portland: Kanto Corporation (2004).

- [48] Li, B., Liu, M. and Chen, Q. "Low-stress ultra-thick SU-8 UV photolithography process for MEMS," Journal of Microlithography, Microfabrication, and Microsystems 4(4), 043008-6 (2005).
- [49] General Chemical Corp., "TECHNICAL DATA:BOE[®] BUFFERED OXIDE ETCHANTS," General Chemical Corporation, pp. 1-8 (2000).
- [50] Sato, K., Shikida, M., Yamashiro, T., Asaumi, K., Iriye, Y. and Yamamoto, M. "Anisotropic etching rates of single-crystal silicon for TMAH water solution as a function of crystallographic orientation," Sensors and Actuators A: Physical 73(1-2), 131-137 (1999).
- [51] ECEn IMMERSE Web Team. "Tables and Graphs of the Complex Index of Refraction for Common Microfabrication Materials," Brigham Young University, <http://photonics.byu.edu/tabulatedopticalconstants.phtml> (2011).
- [52] Siklitsky, V. "Semiconductors on NSM," <http://www.ioffe.rssi.ru/SVA/NSM/Semicond/> (2011).
- [53] Voldman, J., "Material Properties," Massachusetts Institute of Technology, <http://www.mit.edu/~6.777/matprops/> (2011).
- [54] Williams, J. D. and Wang, W. "Study on the postbaking process and the effects on UV lithography of high aspect ratio SU-8 microstructures," Journal of Microlithography, Microfabrication, and Microsystems 3(4), 563-568 (2004).
- [55] Chu, P. B., Chen, J. T., Yeh, R., Lin, G., Huang, J. C. P., Warneke, B. A. and Pister, S. J. "Controlled pulse-etching with xenon difluoride," Solid State Sensors and Actuators, 1997. TRANSDUCERS '97 Chicago., 1997 International Conference on, 1, 665-668 vol.1 (1997).
- [56] Su, K. and Tabata, O. "Effects of aperture size and pressure on XeF₂ etching of silicon," Microsystem Technologies 9(1), 11-16 (2002).
- [57] Sameoto, D. and et al. "Electrical interconnection through optimized wirebonding onto SU-8 structures and actuators," J. Micromech. Microeng. 18(7), 075023 (2008).
- [58] Mahajan, V. N. "Aberration theory made simple / Virenda N. Mahajan," Tutorial texts in optical engineering ; v. TT 6 Bellingham, Wash., USA :: SPIE Optical Engineering Press (1991).
- [59] Veeco Instruments, Inc., "NanoScope Software 6.13 User Guide," (2004).

- [60] Lukes, S. J., Himmer, P. A., Moog, E. J., Shaw, S. R. and Dickensheets, D. L. "Feedback-stabilized deformable membrane mirrors for focus control," J. of Micro/Nanolithography, MEMS, and MOEMS 8(4), 043040 (7 pp.) (2009).
- [61] Lukes, S. J., Lutzenberger, B. J., Dunbar, E., Shaw, S. R. and Dickensheets, D. L. "Variable-focus SU-8 membrane mirror with enhanced stroke using feedback control " IEEE/LEOS Intl. Conf. on Optical MEMs and Nanophotonics(2009).
- [62] Lukes, S. J., Himmer, P. A., Moog, E. J., Shaw, S. R. and Dickensheets, D. L. "Feedback stabilized deformable membrane mirrors for focus control," SPIE MOEMS and Miniaturized Systems VIII, 7208, 72080Q-8 (2009).
- [63] Xactix, Inc., "Unique Capabilities of Xenon Difluoride for Releasing MEMS," www.xactix.com (2011).