

MEMS 3-DIMENSIONAL SCANNER WITH
SU-8 FLEXURES FOR A HANDHELD
CONFOCAL MICROSCOPE

by

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DEDICATION

To my dad Bin Liu, my mom Dongli Xi and my brother Tianfang Liu.

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ABSTRACT

The conventional method for diagnosing skin cancer is to perform a biopsy followed by pathology. However not only are biopsies invasive and likely to leave permanent scarring, they also sample the body sparsely. Fortunately, a non-invasive method of imaging called confocal laser scanning microscopy has shown great potential to replacing invasive biopsies. Confocal microscopy can use light to achieve high-resolution imaging of cells that lie underneath the surface of the skin. However, the large size of current confocal microscopes limits their application to all but the most accessible sites. In this dissertation, I address the miniaturization of confocal microscopy through the development of a new microelectromechanical systems scan mirror that can scan a focused beam in three dimensions. The scanner has a 4 mm aperture, and has the capability to replace all of the bulky beam scanners and focus mechanisms that contribute to the large size of current confocal microscopes. The fabrication of the scanner explores the use of the polymer SU-8 for its mechanical structures. The gimbal mirror has demonstrated scan angles in excess of $\pm 3^\circ$ mechanical for lateral scanning, and its deformable surface provided controllable deflection up to 10 μm for focus control. This newly developed scanner was integrated into a confocal system to test its imaging capabilities. The device demonstrated high-resolution scanning with simultaneous focus adjustment suitable for the next generation of miniaturized confocal laser scanning microscopes.

CHAPTER ONE

INTRODUCTION

Micro-electro-mechanical systems (MEMS) devices have grown to become a key technology for many of today's applications. In particular, optical MEMS laser scanners are enabling many of the newest advancements in technology including light detection and ranging systems (LIDAR) for self-driving cars [1-4], pico-projector displays in smart phones [5-7], optical switches for high-speed communication [8, 9] and laser scanning microscope imaging systems [10-12]. The focus of this research is the development and fabrication of a MEMS 3-dimensional scan mirror that will serve as the optical engine in a handheld confocal laser-scanning microscope for the in-vivo and non-invasive detection of cancer cells.

The standard method of diagnosing skin cancer is to perform a biopsy and pathology. In fact, more than 18 million biopsies are performed each year in the United States alone. Of these biopsies, approximately 20% or 3.6 million prove positive [13-16]. This means that each year more than 14 million biopsies, approximating 5 billion dollars, turn out to be benign and could possibly have been avoided [17, 18]. Additionally, apart from the tremendous cost, biopsies are an invasive procedure, which can result in permanent scarring.

Fortunately, an alternative non-invasive technology called optical biopsy is an emerging solution to addressing the cost and complexities associated with performing traditional biopsies. Confocal laser scanning microscopy (CLSM) is a promising type of

optical biopsy, which can provide the capability to image cellular structures underneath the skin in its living environment. This is a non-invasive procedure allowing highly accurate levels of diagnosis. It can provide imaging of cellular detail and tissue architecture with levels of sensitivity of 92% [19-21] and specificities as high as 97% for non-melanocytic lesions [19, 22]. The imaging depth of CLSM is capable of reaching the dermo-epidermal junction lying between the epidermis and underlying dermis, which is a crucial location of interest for diagnosis [23, 24]. Even with all the benefits of confocal microscopy, the current size of the microscopes renders it impractical in all but the most accessible locations. The large size can be attributed in part to the bulky mechanisms required for scanning and focusing the imaging beam. A miniaturized handheld confocal microscope enabling the imaging of sites that were previously not possible is proposed. Micro-electromechanical systems (MEMS) provides the key to achieving this desired miniaturization. The bulky individual beam scan and focus elements can be replaced by a single MEMS device only millimeters in dimension.

Apart from miniaturization, in order to fully address the requirements of clinical applications, the confocal system must also be able to maintain high-resolution results throughout its entire depth of imaging. This, along with the large NA required to achieve good optical sectioning, will lead to the need for mitigation of spherical aberration as the imaging depth is changed. This dissertation describes a new MEMS device that combines both dual axis scanning with large stroke focus control, with a focusing range three times greater than that of prior devices and the capability to control spherical aberration [25, 26].

MEMS Scanners and Microscopy

MEMS scanners generally refer to small mechanical mirrors with dimensions ranging from hundreds of micrometers to millimeters. They are often used for the scanning or steering of light in imaging and display systems. Silicon wafers are commonly used as the foundation for the fabrication of these devices. Since the development of the first MEMS scanners in 1980 [27], the area of study has contributed to a broad range of applications. MEMS scanners, due to their small size, superior speed at resonant operation and low power consumption are often more desirable to traditional galvanometer laser scanners.

The first application of micromachined torsional MEMS mirrors in a confocal laser scanning microscope (CLSM) was demonstrated in 1996 when two MEMS single axis scan mirrors were coupled orthogonally to achieve x and y scan of a laser beam [28]. Since then, numerous types of MEMS scanners have been developed and applied. Olympus Corporation integrated a single axis magnetic scanner capable of $\pm 8^\circ$ of optical scan angle into a commercial confocal microscope [11]. Handheld confocal microscopes utilizing MEMS scanners have been demonstrated by Arrasmith et al. [29] and Kumar et al. [30], where dual axis scanners were applied. Further optimization of the mirror technology and the optical system have led to microscopes with dimensions small enough for endoscopy. Liu et al. and Murakami et al. have demonstrated the imaging of rat brain tissue and dyed pig tissue with confocal endoscopes [31, 32]. Another confocal microscope that images vertical “slices” inside the tissue has been built by Qiu et al. [33] The system uses a 3-kHz single axis scanner for lateral scanning in one dimension, which is mounted onto a

piezoelectric actuator that can provide 400 μm of axial movement. The system achieved lateral and axial resolutions of respectively 4 μm and 5 μm .

The application of MEMS scanners has also quickly expanded to other forms of microscopy that rely on laser scanning. Aguire et al. demonstrated the use of a dual axis gimbaled scan mirror in a catheter for in-vivo optical coherence tomography (OCT), achieving axial and lateral resolutions of 4 μm and 12 μm [34]. The imaging of animal tissue using OCT systems enabled by various MEMS scanners have also been shown by research groups [35-41] from around the world. Apart from confocal and OCT systems, two photon microscopy has also benefited from MEMS scanners [10, 12].

Common methods of actuation for MEMS scanners include electrostatic [25], magnetic [11], thermal bimorph [42], and piezoelectric actuation [40]. Electrostatic actuation can be sub-divided into parallel plate and comb drive actuation [43]. Parallel plate actuation relies on the electric field that is formed between the mirror and a set of underlying electrodes to induce tip-tilt motion. Comb drive actuation uses two sets of interdigitated fingers that appear visually to be like combs. One set is normally fixed in place while the other set that is connected to the mirror can translate with respect to the fixed set of combs. Torsional hinges that support the mirror constrain this movement to a rotational degree of freedom about the axis defined by the hinges. This method of actuation was originally described by Tang et al. [44]. Magnetic actuation involves a microfabricated coil and either an integrated magnet or an external magnet. It utilizes the Lorentz force that acts on the coil when a current is applied. Thermal bimorph is based on the difference of stress between two bonded materials when temperature is changed (usually through

resistive heating) which causes the bimorph structure to bend. Thin film piezoelectric actuation relies on the stress deformation that occurs when a voltage is applied to a piezoelectric material to achieve actuation. When comparing the benefits and tradeoffs of these actuation methods, parallel plate actuation is compact and relatively easy to fabricate when compared to the other types of operation, but generally requires large actuation voltages. Comb drives generally allow for larger scan angles compared to parallel plate actuation, but require exacting fabrication tolerances to ensure the alignment and position of the combs. Comb drives also tend to have a bigger footprint compared to parallel plate actuation. Thermal bimorph actuation is capable of achieving the largest amount of movement but is limited by a slow response time and a large footprint due to the length of its bimorph beams. Thin film piezoelectric action (unimorph and bimorph) generally requires lower voltages than electrostatic actuation and can deliver high forces, but suffers from short stroke length [45][46].

Deformable Mirrors

MEMS deformable mirrors have the capability of changing their curvature to achieve a range of optical powers. A common method to achieve a varifocal surface is to suspend a thin membrane over a cavity. The shape of the membrane is controlled using an electric field formed between the membrane and the bottom of the cavity. Moghimi et al. [47, 48] and Lukes et al. [49, 50] described mirrors based on such principles. There are also varifocal mirrors that rely on arrays of single actuators or mirrors that can be individually adjusted to achieve various overall surface shapes [51]. The actuators in some

of these devices only support piston while others can achieve piston along with tip and tilt [52, 53]. These pixel array mirrors can generally be divided into segmented mirrors where each actuator is a standalone mirror [54, 55] and continuous facesheet mirrors where the motion of neighboring elements are coupled using a continuous mirror facesheet [56-58]. Deformable mirrors are often used for focus control and zoom in micro-imaging applications. Wick et al. [59] demonstrated optical zoom using two segmented-array deformable mirrors while Kaylor et al. [60] used two suspended membrane mirrors. Mirrors capable of high-speed focus adjustment have demonstrated the capability of rapidly cycling between multiple planes of focus. This can be applied to increase the axial depth of field of microscope systems that suffer from shallow depth of focus [47].

Apart from adjusting the plane of focus, deformable mirrors have also been applied towards aberration correction of optical wavefronts. Zernike polynomials (Z_n^m) are used for the description of aberrations in this dissertation and will be discussed in detail in Chapter 2. Primary (Z_4^0) and secondary (Z_6^0) spherical aberration correction has been demonstrated using suspended deformable mirrors by applying concentric actuation electrodes that can be independently adjusted to tune the curvature of the active optical surface [48, 61]. This is often used to counteract the introduction of spherical aberration as the mirror is deformed which will be discussed in subsequent sections. It can also be applied to pre-shape the membrane to offset the anticipated amounts of subsequent spherical aberration introduced by the sample. Higher-order aberrations have also been addressed through the use of pixel array deformable mirrors described above by independently actuating each actuator/mirror to control the topography of the optical

surface. In general, the suspended membrane type mirrors can usually achieve more stroke than the actuator array mirrors while the array mirrors can handle more types of aberration. The contrasting but complementary abilities of these mirrors have naturally led to systems that employ both simultaneously. A large-stroke suspended membrane mirror (woofer) takes charge of the bulk of the focusing and spherical aberration control while a segmented mirror (tweeter) tackles the higher-order aberrations. Zhang et al. demonstrates such a combination in a scanning laser microscope to obtain rapid focus adjustment and compensate for the wavefront errors caused by the propagation of light through optically inhomogeneous tissue [62]. It has also been used in astronomy for the correction of aberrations induced by the atmosphere [63-65].

3-Dimensional MEMS Scanner

The initial application of MEMS scanners to confocal microscopy was demonstrated by relaying two single-axis scan mirrors to perform beam scanning [28]. Since then, single axis scanners have merged into dual-axis scanners and have been applied to the miniaturization of various optical systems as described in previous sections. However, in most of these systems, focus adjustment is performed using separate actuators (motors, piezoelectric stages) and often requires additional optical elements such as relay lenses. This tends to result in a bulkier and slower system. In order to eliminate the need for alignment of the active optical elements and achieve higher levels of system miniaturization, it is often advantageous to integrate the ability to perform scanning and focusing onto a single device. Attempts at such levels of integration have been made in the

past. Hokari et al. show the side by side integration of a separate single axis scanner with a varifocal mirror onto the same chip [66]. Nakazawa et al. [67] and Sasaki et al. [68] fabricated a varifocal mirror that is attached to a single axis scanning platform. Although these devices have merged scanning with focusing, the scanning is limited to one axis, whereas biaxial scanning is required in most imaging and display systems. Schematic of these devices are found in Figure 1. The figures have been included here with permission from their respective publishers.

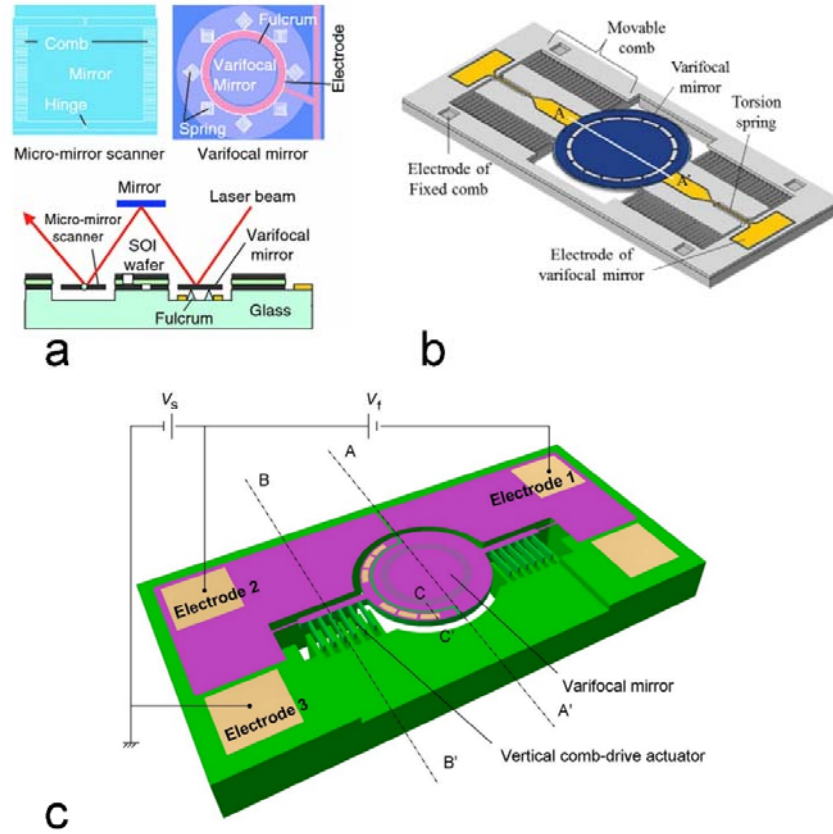


Figure 1. (a). MEMS device by Hokari et al. that features side by side integration of single axis scanner and varifocal mirror [66]. (b). Single axis scanner with varifocal mirror by Nakazawa et al. © 2017 IEEE [67]. (c). Single axis scanner with varifocal mirror by Sasaki et al. © 2012 IEEE [68].

A dual-axis gimbal based scanner capable of two-dimensional scanning and focus control has been shown by Shao et al [25, 69]. The device was based on using silicon nitride as the material for the deformable membrane and the torsional hinges. Strathman et al. reports a similar device to that of Shao et al. [26]. Gimbal-less mirrors that are capable of scanning in two axis and achieving piston motion in the third have also been built [70, 71]. A gimbal-less mirror based on electro-thermal bimorph actuation that is able to achieve four degrees of freedom (tip, tilt, focus and piston) has been shown by Morrison et al. but the device is slow and does not demonstrate the scan speed necessary for microscopy of living tissue [72].

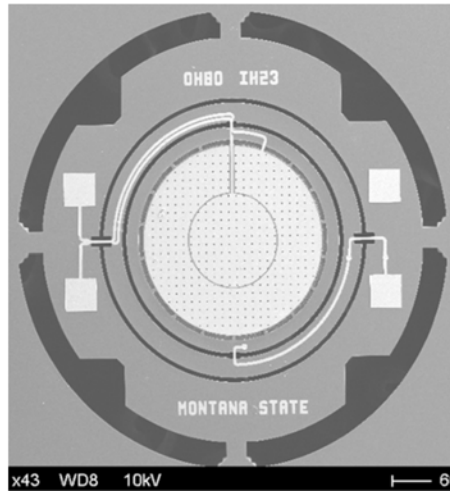


Figure 2. Dual axis scan mirror with deformable mirror built by Shao et al. © 2004 IEEE [25].

In this research, a single MEMS device that is capable of two-dimensional scanning and simultaneous focus control in the third dimension was built. To allow such degrees of motion, the 3-D MEMS scanner is based on a dual-axis gimbal platform, which enables

biaxial scanning. At the center of this gimbal platform, a deformable module is integrated to allow for focus control during scanning. Evenly spaced on the surface of the mirror are four concentric electrodes to provide focus actuation, and at the same time, allow for mitigation of primary (Z_{40}) and secondary (Z_{60}) spherical aberration. The gimbal platform is then bonded to a separate wafer carrying quadrant electrodes to achieve parallel plate electrostatic actuation of tip-tilt scanning. A photosensitive polymer called SU-8 was used to construct both pairs of torsional hinges on the gimbal and to construct the deformable membrane.

The MEMS was designed with the requirements of a newly proposed miniature confocal microscope in mind. Although the design and construction of this microscope exceeds the scope of this dissertation, it is briefly introduced here to shed light on certain aspects of the design of the 3-dimensional MEMS scanner. This new optical system integrates the MEMS device directly within the objective lens in a coaxial manner. For this reason, the MEMS device features a unique aperture that crafts a coaxial light path for both the incident and reflected light. Aside from the confocal aspects, the optical system incorporates a widefield camera (not shown) to provide a widefield dermoscopy image that overlays the confocal image, which guides and clarifies the location of imaging. This new optical system is called the integrated laser-scanning microscope or iLSM. The 3-dimensional scanner allows the iLSM to be sufficiently compact for incorporation into a handheld pencil-sized probe while maintaining excellent confocal image quality and optical sectioning. A schematic of the iLSM is provided in Figure 3 to illustrate the purpose of the annular aperture.

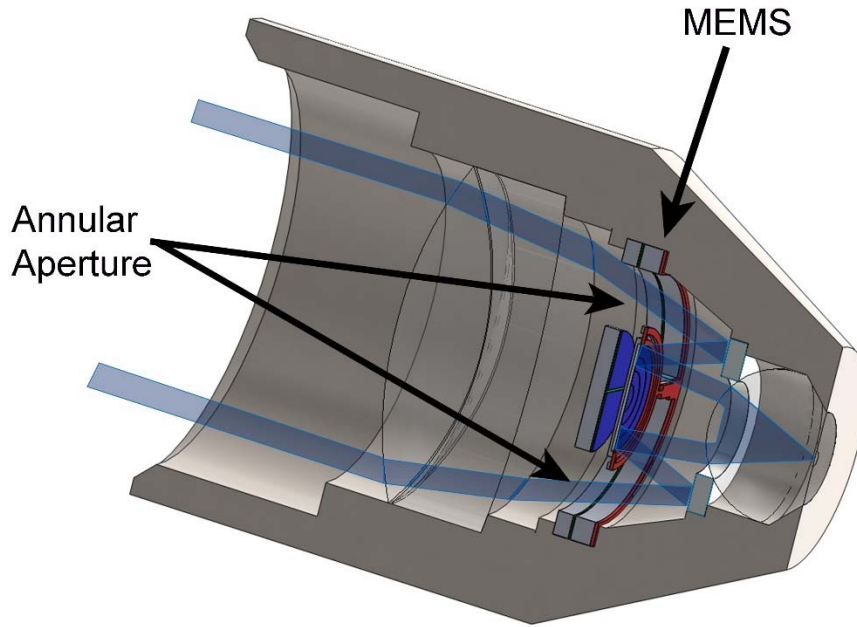


Figure 3. Cross-sectional Solidworks view of iLSM with 3-dimensional scanner.

The 3-dimensional scanner was integrated into a benchtop version of the iLSM to demonstrate the capabilities of the device, which is included in Chapter 5. Before we get there, the design of the 3-dimensional scanner is presented in Chapter 2. It covers the details of the mechanical aspects of tip-tilt scanning and focus control. Chapter 3 provides an introduction to micromachining techniques, the mask design, a detailed fabrication process of the 3-dimensional scanner as well as challenges and solutions encountered along the way. Chapter 4 documents the opto-electro-mechanical characterization of the MEMS scanner. This covers aspects such as initial mirror flatness, membrane deflection, scanning, dynamic distortions and sensitivity to changes in temperature and humidity. Chapter 5 describes the benchtop confocal microscope and its performance. Mirror actuation, image acquisition and processing are also documented in detail. Confocal images of onion cells

and human cheek cells that were acquired with the MEMS enabled bench top microscopes are included. Chapter 6 concludes the work and provides thoughts regarding the direction of future efforts.

Advancements to the State of the Art

The large aperture of this device, when paired with its wide scan angles, provides a large θD product (discussed in Chapter 2) that exceeds most of the single axis and dual axis scanners mentioned earlier in this chapter. What truly sets this mirror apart from the majority of existing devices is its ability to achieve a large range of focus adjustment and mitigate spherical aberration in addition to two-dimensional scanning. Although devices with similar degrees of freedom have been previously developed, they either lack the speed for real time imaging [70, 72], or provide less lateral resolution [71]. In terms of functionality and application, perhaps the most comparable device to the one in this dissertation is that developed by Shao et al [25, 69], which also supports bi-axial scanning with focus control. Though similar, the device in this dissertation is capable of at least 2.5 times the focus stroke. Additionally, the $\theta_{mech} D$ product of 3.5 demonstrated by Shao et al. has been increased to 12, which equates to 3.4 times the number of resolvable spots. Numerous innovations in the design of this mirror are also evident. For example, the horizontal and vertical etch stops installed on the device ensure precise rendering of critical dimensions, which was not guaranteed in Shao's process. Furthermore, as mentioned previously, this new device also has an annular aperture, which allows for the coaxial integration into the optical path of an imaging system. Perhaps the most significant

difference lies in the choice of material for the deformable membrane and torsional hinges. Shao et al. used a single layer of LPCVD silicon nitride for both the membrane and the hinges. For this new device, SU-8, which is a photosensitive polymer, is used to construct such structures. Compared to silicon nitride, it has much lower stress, which helps to reduce the voltage required for the actuation of the deformable membrane. SU-8 also provides a larger range of thicknesses and greater flexibility in independently selecting the thickness of the deformable membrane and hinges.

This is the first 3-dimensional scan mirror to feature polymer mechanical structures [73, 74]. The mirror has demonstrated a large range of focus and high resolution scanning which exceeds the performance of all existing 3-dimensional scanners. A novel method for creating etch and location tolerant through silicon vias has been developed [75]. Additionally, a new concept of using nanostructured black silicon to coat the non-active regions of optical MEMS devices has been described and implemented [76, 77] (Appendix C). Last, the new 3-dimensional scanner has been integrated into a confocal microscope and provides imaging of human cells and volumetric samples.

CHAPTER TWO

DESIGN OF THE 3-DIMENSIONAL MEMS SCANNER

This chapter presents the design of the 3-dimensional (3D) MEMS scanner. The device is designed specifically for a handheld confocal microscope, but can easily be adapted to suit a wide range of micro-imaging applications. The architecture of the 3D scanner is introduced along with the performance requirements for both scanning and focusing. The opto-mechanical design parameters are then carefully optimized to adhere to the requirements. The chapter concludes with a discussion of the merits and tradeoffs of certain aspects of the design. This section includes excerpts from a previous publication in the IEEE Journal of Microelectromechanical Systems [73].

General Architecture

The 3-dimensional MEMS scanner is based on a dual-axis gimbal platform with two degrees of torsional freedom. An additional third degree of freedom is supplied by the deformable mirror positioned at the center of the gimbal platform. The dual-axis platform allows axial rotation of the deformable mirror about both the x and y axes. This torsional motion is controlled by a set of quadrant electrodes located underneath the gimbal platform. The surface curvature of the deformable mirror is controlled by four concentric electrodes that are actuated independently of the quadrant electrodes. The deformable mirror is capable of achieving a large stroke while managing the spherical aberration. The scanning was designed according to the correct balance between maximum scan angle (dynamic and

static), mirror aperture, and scan frequency. These design concerns and more will be addressed in the following sections.

Torsional Gimbal Plate Architecture

A Solidworks model of the device is shown in Figure 4. The overall device dimension is 13 mm. The center plate and the active optical surface are, respectively, 4.4 mm and 4 mm in diameter. A dual-axis gimbal platform that allows two rotational degrees of freedom is made by suspending a center plate via a pair of torsional hinges to an outer ring. The outer ring is then suspended via another pair of torsional hinges to the frame. The axes of rotation defined by these two pairs of hinges are orthogonal to each other. The framework of the gimbal platform includes the center plate, outer gimbal ring and frame. An annular aperture is situated between the outer gimbal ring and the frame of the device to allow coaxial integration into the light path of an optical system. A photosensitive polymer material called SU-8 is patterned to form the hinges and hinge anchors, which are shown in red. A deformable mirror that is also constructed from SU-8 is integrated onto the center of the gimbal platform, which is discussed in section 2.4.2.

Before delving into the performance of this new architecture. I would like to explain the reason for choosing SU-8 as the deformable membrane and hinge material. As described in Chapter 1, the 3-dimensional scanner is most similar in terms of structure and application to the mirror developed by Shao et al [69]. The biggest set back for the mirror built by Shao et al. was its low stroke for focus control. This was due to their use of silicon nitride, which had high intrinsic stress as the membrane material. Since then, SU-8, which

has much lower intrinsic stress has been explored as the membrane material for deformable mirrors and has demonstrated much larger stroke [47, 49]. For this reason, SU-8 is employed to achieve the desired 15 μm of deflection. At the same time, it is convenient to use SU-8 as the torsional hinge material as well due to its low stress and Young's modulus and fabrication compatibility. (Shao et al. used silicon nitride for both membrane and torsional hinge). Additionally, to the best of my knowledge, there have been no scanners with three degrees of freedom that have explored the use of SU-8 as torsional hinges. For these reasons, SU-8 was chosen as the material for the deformable membrane and torsional hinges.

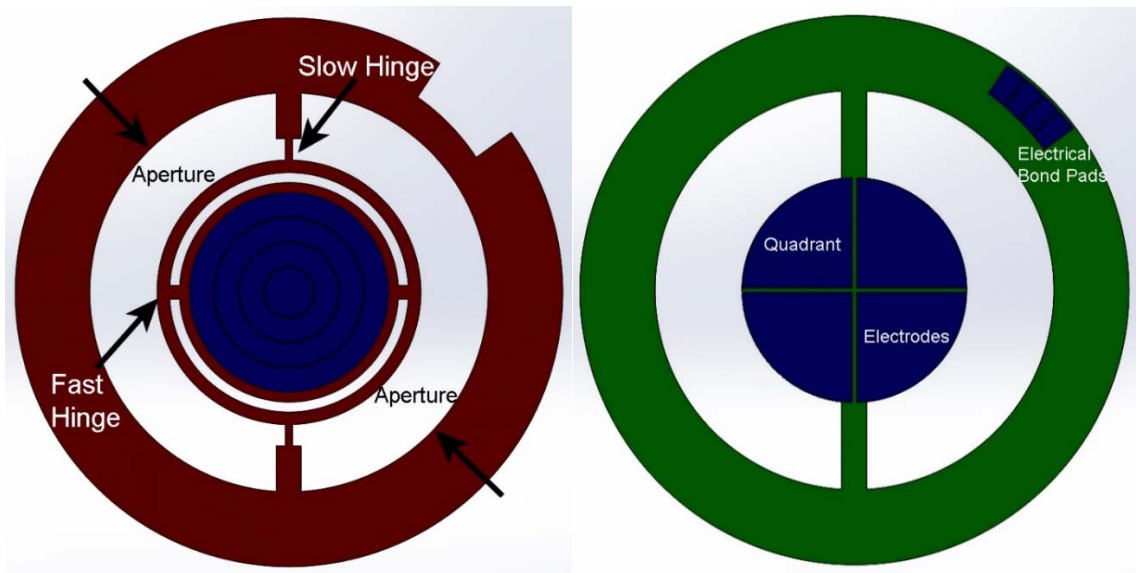
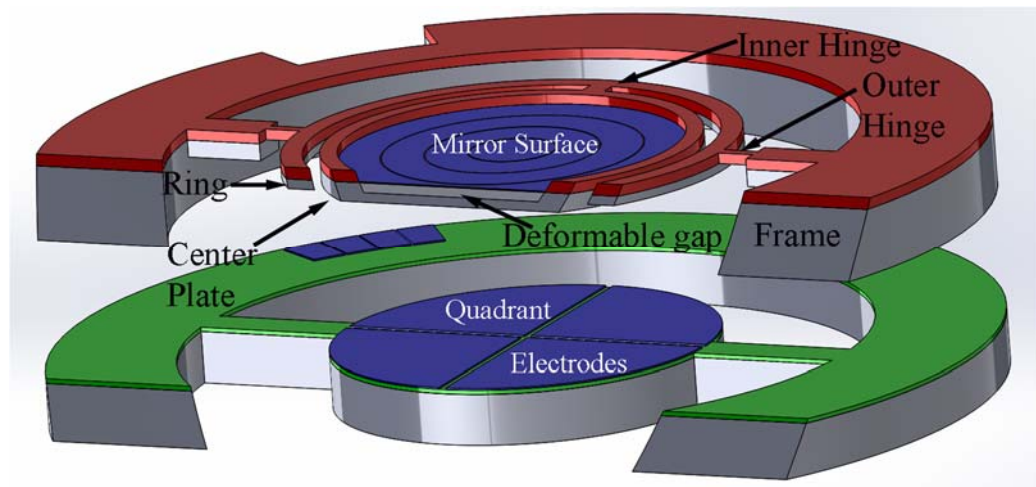


Figure 4. Schematic of 3-dimensional MEMS scanner. The relative proportions of features is similar to that of actual device. Gray represents silicon, red represents SU-8, blue represents metal aluminum (optical surface and electrodes) and green represents oxide.

Figure 4 Continued



Torsional scanning is achieved by a set of quadrant electrodes (Figure 4) underneath the device that is biased relative to the (grounded) center plate. The principle of operation is parallel plate electrostatic actuation, which has desirable characteristics such as fast response, ease of fabrication and small footprint, as it can be “hidden” underneath the active portions of the device. Depending on the electrodes that are active, the mirror can scan about either or both of the axes. The resultant scan angle is governed by a balance of the electrostatic torque provided by the electrodes and the mechanical restoring torque from the SU-8 hinges. These hinges are essentially rectangular bars that twist against the rotation of the mirror. This is discussed in more detail in the next section. To achieve the desired $\pm 2^\circ$ (static) scan angle, the separation gap for scanning is set to $230\text{ }\mu\text{m}$, as previous results indicate that instability (snap down) occurs when the edge displacement is approximately one third of the separation [78].

[Begin Excerpt] The mechanical requirements of the 3D scan mirror were set by the optical specifications for the target application, which is confocal microscopy of skin

with a lateral field of view of $300\ \mu\text{m}$. To achieve axial resolution sufficient for cross sectioning that clearly resolves cellular details, reflectance confocal microscopy of highly scattering tissue like skin performs best with a numerical aperture (NA) of at least 0.7. Using the Rayleigh criterion, the lateral resolution can be defined as $r_R = 0.61\lambda_o/NA$. With $\lambda_o = 0.633\ \mu\text{m}$ and $NA = 0.7$, it can be seen that $r_R = 0.55\ \mu\text{m}$. The desired lateral field of view of $300\ \mu\text{m}$ therefore represents approximately $N_r = 545$ resolvable spots in the radial direction. Diffraction analysis of a circular aperture tip/tilt mirror shows that the number of resolvable spots (based on the Rayleigh criterion) is $N_r = 4\theta_m D/1.22\lambda_o$, where θ_m is the 0-peak mechanical scan angle and D is the mirror diameter. With $N_r = 545$, the required $\theta_m D$ product is 0.105 radian-mm, or 6 deg-mm. With an aperture diameter of 4 mm, a lateral scanning of approximately $\pm 1.5^\circ$ about both the x and y axes is required. This is readily achieved by the mirror described below [63]. [End excerpt] A comprehensive guide regarding performance requirements with regards to application can be found in the paper published by Urey et al. [79].

In addition to the number of resolvable spots, the line density (the number of lines per frame) is determined by the ratio of the frequency of fast-axis to the refresh rate (slow-axis frequency). This means that at a given refresh rate (frame rate) a mirror with a higher scan frequency will produce a higher line density than a mirror with a lower scan frequency. However, there are tradeoffs to having a high scan frequency. The resonant frequency of the fast axis is generally designed to match the required operating frequency. This is to allow the fast axis to operate at resonance, which reduces the actuation voltage and power consumption during scanning. In order to increase the line density without decreasing the

refresh rate, the resonant frequency of the fast axis must increase. For the resonant frequency to increase, the torsional stiffness of the hinges must increase and/or the angular moment of inertia of the mirror must decrease. This would result in either higher actuation voltages or a smaller θD product (fewer resolvable spots). But the primary reason that limits the torsional resonant frequency of the mirror is the inertial deformation on the surface of the mirror at high scan speeds. This is analyzed in Chapter 4. With the merits and tradeoffs of scan frequency in mind, as well as the needs of the application (*in vivo* confocal microscopy), a target resonant frequency of 1000 Hz was assigned to the fast axis. This provides a line density of 500 lines per frame (bi-directional) at a refresh rate of 4 frames per second. Based on Fourier optics analysis of a periodic structure, a pixel pitch no larger than $\frac{0.5\lambda}{NA}$ is required to sample the object. With 500 lines/frame, this provides approximately 410 resolvable spots in the vertical direction. This along with the number of resolvable spots at a fast axis scan angle of $\pm 1.5^\circ$ mechanical will provide an image aspect ratio of approximately 4:3.

Deformable Mirror Architecture

The deformable mirror is positioned on the center plate of the dual-axis gimbal platform. It is constructed by suspending a thin film of SU-8 across a circular boundary made from silicon. The SU-8 membrane is parallel to the ground electrode lying 40 μm beneath it. The thin SU-8 layer largely determines the mechanical characteristics of the deformable membrane. On top of the SU-8 is a layer of highly reflective thin film aluminum created using physical vapor deposition (PVD). This thin metallic layer serves

as both the active optical surface and the bias electrode for actuation. However, instead of being a single electrode, the metal surface is divided into four concentric electrodes. This is for the correction of spherical aberration, which increases with the deformation of the mirror. An enlarged Solidworks cross sectional view of the deformable mirror is provided in Figure 5. The outer gimbal ring as well as inner hinge are also included for reference.

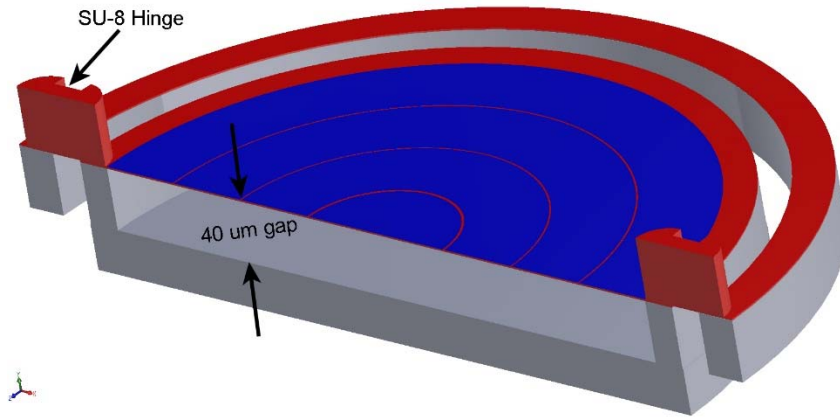


Figure 5. Solidworks cross sectional model of deformable mirror. The reduced hinge anchor arrangement is displayed.

The diameter of the active optical surface D (the reflective metallic membrane) is 4000 μm . The desired amount of mirror deflection is dictated by the skin imaging application. [Begin excerpt] Depth of imaging in skin is typically limited to about 200 μm for reflectance confocal microscopy. It is possible to define a Rayleigh resolution axially as the distance from the peak of the light intensity distribution to the location of the first zero, leading to $z_R = 2n\lambda_o/NA^2$, which is 3.69 μm for $NA = 0.7$, $\lambda_o = .633 \mu\text{m}$ and $n = 1.43$ [80, 81]. Diffraction analysis from a circular pupil shows that the incremental parabolic wavefront phase delay required to shift the focus along the axis a distance z_R is

$2\pi\rho^2$ for normalized radial variable ρ . This corresponds to an increase of the mirror sag by $\lambda_o/2$. The number of resolvable axial zones using this criterion is $N_z = 2\delta/\lambda_o$, where δ is the maximum mirror sag. For a mirror that can focus throughout the accessible 200 μm depth with $\text{NA} = 0.7$, $N_z = 200/3.69 = 54$ resolvable depths of focus are required. This corresponds to a peak mirror sag of 17.1 μm . The first-generation mirror described below were designed for a maximum sag of approximately 15 μm , limited by snap down, which is described below. This corresponds to approximately 175 μm of focus range in skin at a $\text{NA} = 0.7$. Future mirrors can employ a larger air gap or active feedback control, in order to achieve the full 200 μm focus control range at $\text{NA} = 0.7$. [End excerpt] [73].

At small deflections (compared to the mirror diameter), the focal length is calculated using the following equation [82]:

$$f = \frac{D^2}{16\delta}, \quad (1)$$

where D is the diameter of the mirror and δ is the center deflection. A center deflection of 15 μm equates to a focal length of approximately 67 mm. The amount of center deflection at a given actuation voltage is a balance between the electrostatic forces and the mechanical restoration forces. However, similar to the snap down of the gimbal platform, once the deflections exceed a certain value, the mechanical restoring forces become overwhelmed by the electrostatic pull in force. When this occurs, the membrane is forced into contact with the electrodes on the bottom of the gap. This is an undesirable effect that can result in irreversible damage. Previous measurement (and numerical simulation) suggests that the amount of center deflection achievable before snap down is reached is about 40% of the

total gap depth. The mirror in this dissertation features a gap depth of $40\text{ }\mu\text{m}$ to allow the maximum design deflection.

With the requirements of both scanning and focus control as well as practical limitations in mind, a set of performance specifications were proposed for the device. These are summarized in Table 1.

Table 1. Target Performance Specifications.

Device Dimensions • Total size: 13 mm diameter including frame. • Active optical aperture diameter: $4000\text{ }\mu\text{m}$ • Gimbal center plate diameter: $4400\text{ }\mu\text{m}$ • Gimbal outer ring Inner diameter: $4620\text{ }\mu\text{m}$, Outer diameter: $4920\text{ }\mu\text{m}$. • Frame Inner diameter: $8000\text{ }\mu\text{m}$, Outer diameter: $13000\text{ }\mu\text{m}$
Gimbal Scanning Specifications • Resonant frequency of fast axis: 1000 Hz. • Resonant frequency of slow axis: 200 Hz (for resistance to external vibrations). The outer axis is operated quasi-static at 4 Hz. This equates to a line density of 500 lines/frame at 4 frames/second. • The fast axis at resonant actuation is capable of scan angles of $\pm 3^\circ$ mechanical. This equates to approximately 1024 resolvable spots at 633nm wavelength.

Table 1 Continued

Deformable Mirror Specifications • Maximum center deflection: 15 μm. This equates to a focal length of 67 mm. The focal range of the mirror is from 67 mm to ∞. • Surface shape will be controlled using four evenly spaced concentric electrodes. This provides the capability to mitigate primary and secondary spherical aberration.

Calculations and Simulations

In this section, we mathematically investigate the effects of design parameters in order to meet the proposed performance specifications. These include intrinsic material properties such as Young's modulus and Poisson's ratio, as well as the geometrical aspects such as hinge dimensions and membrane thickness. The effects of various actuation parameters are also analyzed. Ansys ADPL is used to verify the analytic calculations of the torsional resonant frequency.

Torsional Scanning

The geometrical arrangement of the scanning plate and the quadrant electrodes is akin to that of a parallel plate capacitor. Electrostatic force is used for the actuation of the scanning motion for both the fast and slow axes. This is based on the electrostatic field generated between two parallel plates when a voltage differential is present. The bottom plate (quadrant electrode) is fixed, while the top plate is suspended via two pairs of

torsional hinges to provide rotational degrees of freedom about the suspension axes. Rotation of the top plate (mirror) begins when the electrostatic torque generated by the electrodes on either side of the suspension axis is not equal. This rotation is counteracted by the restoring torque generated in the hinges. The angle of rotation depends on the net electrostatic torque and the amount of mechanical restoration torque generated by the suspension axis. With a quadrant electrode array, depending on the bias voltages, the mirror can be scanned independently and simultaneously about both axes. Figure 6 illustrates the rotation about one axis. A schematic of the quadrant electrodes is also provided for reference.

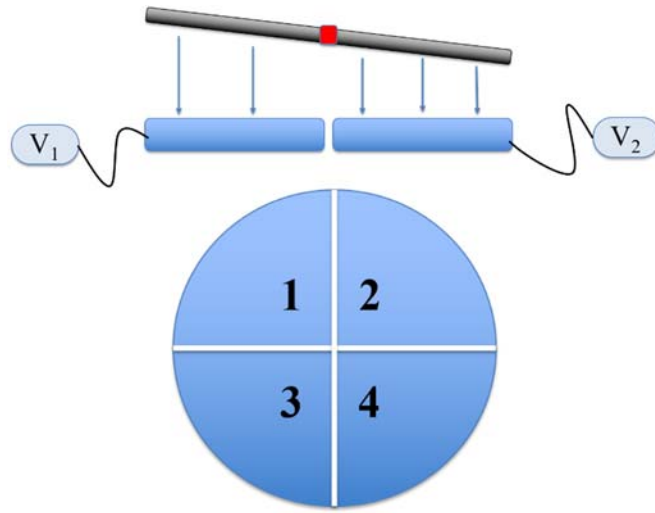


Figure 6. Schematic of scanning plate and quadrant electrodes.

Equation of Motion. The rotation of a plate about a fixed axis can be described using the following second-order differential equation.

$$I\ddot{\theta} = T_e - T_m, \quad (2)$$

where

$$I = \frac{\pi \rho t R^4}{4}. \quad (3)$$

In the above equations, (I) is the angular moment of inertia, $\ddot{\theta}$ is the second derivative of the scan angle, T_e is the electrostatic torque and T_m is the mechanical torque generated by the hinges. First we will look at the mechanical torque T_m . The restoring torque of a single hinge is a function of the torsional spring constant (k_θ) and the scan angle given by $T_{ms} = k_\theta \theta$. The torsional spring constant is a function of the material properties and physical dimensions of the hinges, and is described by the following equation [83]:

$$k_\theta = G \frac{ab^3}{l} \left[\frac{1}{3} - 0.21 \frac{b}{a} \left(1 - \frac{b^4}{12a^4} \right) \right], b \leq a, \quad (4)$$

where

$$G = \frac{E}{2(1 + \nu)}. \quad (5)$$

The height, width and length of the hinges are indicated by a , b and c , respectively, under the condition that $b \leq a$. G is the shear modulus and is a function of the Young's modulus (E) and the Poisson's ratio (ν). For this MEMS device, there are two hinges suspending the mirror for each axis of rotation. Thus, the total mechanical restoring torque (T_m) is $2k_\theta \theta$.

The calculation for the electrostatic torque (T_e) is more involved. To simplify the initial calculations, we assume single sided-actuation where only the right half electrodes (2 and 3) are biased relative to the top scanning plate while the other electrodes are

grounded. The electrostatic force per unit area between the two parallel plates can be expressed as

$$F = \frac{\varepsilon_0 V^2}{2s^2}, \quad (6)$$

where ε_0 is the relative permittivity, A is the overlap area and s is the separation. The electrostatic torque provided by the electrodes is a function of the drive voltage (V) and the angle of scanning (θ) and can be expressed using the following equation:

$$T_e = \int F(x) x dA \quad (7)$$

under the approximation that the direction of the electrostatic forces are normal to the electrodes. At small scan angles, the electrostatic force (F) per unit area can be expressed as

$$F(x) = \frac{\varepsilon_0 V_2^2}{2(s_0 - x\theta)^2}. \quad (8)$$

The differential area (dA) is a function of the distance (x) from the center of the electrode and can be expressed as $dA = 2\sqrt{R^2 - x^2} dx$. The torque generated by the two electrodes on the same side of the axis of rotation can now be written as

$$T_e(V, \theta) = \varepsilon_0 V^2 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 - x\theta)^2} dx. \quad (9)$$

During actual operation of the mirror, it is more common for the electrodes on both sides of the rotating axis to be used in conjunction. For this double-sided actuation, the electrodes on either side of the axis are biased using a differential voltage. Assuming the right half of the electrodes are biased using V_1 while the left side is biased using V_2 , the net

electrostatic torque simply comes the difference of the torque generated on either side and can be written as

$$T_e(V_1, V_2, \theta) = \varepsilon_0 \left[V_1^2 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 - x\theta)^2} dx - V_2^2 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 + x\theta)^2} dx \right]. \quad (10)$$

We can see that the torque is proportional to the square of the actuation voltage. This leads to an effect where the frequency of the torque and therefore the scan frequency becomes twice that of the actuation voltage. In order for the scan frequency to be the same as the frequency of the actuation voltage rather than twice that frequency, a DC bias is often used to maintain uni-polar actuation voltages. However, a DC bias will have an effect on the resonant frequency of the plate [84]. To quantify its effects, V_1 and V_2 are set to V_{DC} in the above equation, and by expanding the resulting equation into a power series of θ , we have

$$T_e(V_{DC}, \theta) = \frac{\pi \varepsilon_0 R^4 V_{DC}^2}{4s_0^3} \theta + O(2), \quad (11)$$

where $O(2)$ represents second or higher order terms of θ . By neglecting these terms, the equation of motion becomes

$$I\ddot{\theta} = \frac{\pi \varepsilon_0 R^4 V_{DC}^2}{4s_0^3} \theta - 2k_\theta \theta. \quad (12)$$

Solving for this second order differential equation, the resonant frequency can be obtained:

$$f_0 = \frac{1}{2\pi} \left(\frac{2k_\theta}{I} - \frac{\pi \varepsilon_0 R^4}{4s_0^3 I} V_{DC}^2 \right)^{\frac{1}{2}} \quad (13)$$

We can see that the resonant frequency is determined by the mechanical properties of the torsional hinges and plates and is also influenced by the DC voltage on the electrodes [84].

Performance Specifications. The mathematical theory provided above is used to yield device dimensions that satisfy the proposed performance specifications. However, fabrication variations and limitations need to be considered in order to arrive at a practical set of dimensions. For example:

- The hinges, apart from mechanical purposes, also serve as a bridge to route the electrical traces from the center gimbal plate to the outer gimbal ring and then to the frame of the device. The separation between the electrical traces that are routed across a given hinge must be sufficient as to avoid electrical breakdown between adjacent traces. This sets a lower limit on the width of the hinges.
- The inner and outer hinges must each have the required torsional stiffness to ensure the corresponding resonant frequency is achieved. To meet this requirement, the lengths and width of the inner hinge can be adjusted independently of the outer hinge. However, the thickness of the two pairs of hinges must be the same due to the nature of the fabrication process.
- Theoretically, the various types of SU-8 can cover a large range of thicknesses, however, each type of SU-8 has a very limited thickness range for consistent and even coating. This sets a constraint for the thickness of the hinges.
- The thickness of the center gimbal plate plays a big part in the mass of the gimbal platform. To maintain a given resonant frequency, a thinner center plate would

mean less inertial mass, which would require less torsional hinge stiffness. This could lead to less actuation voltage. However, the initial flatness of the deformable mirror also relies on the bending stiffness of the center plate. Therefore these competing design concerns set limits for the thickness of the center gimbal plate. A similar situation is true for the thickness of the outer gimbal ring.

- The gap between the center gimbal plate and the outer gimbal ring should ideally be as small as possible to achieve a smaller overall device footprint and mass. However, photolithography and subsequent etch processing set a lower limit for the gap width.
- The center plate ideally should be no bigger than the active optical area. This however is not possible during actual construction as there needs to be a region surrounding the perimeter of the active optical membrane to secure the boundary of the membrane.

After thoroughly considering the various fabrication restrictions and tolerances, a set of device dimensions were chosen. Since, it is crucial that the fast hinges can achieve the proposed resonant frequency so that the frame resolution (lines/frame) can be met, three different hinge designs that are centered at approximately 800 Hz, 1000 Hz and 1150 Hz were made for the fast axis. This is to mitigate the variations during actual fabrication and alleviate the consequences due to inaccuracies in the estimation of certain mechanical parameters such as the Young's modulus and Poisson's ratio of the SU-8 material. Although it is also desirable for the slow axis to have a resonant frequency in excess of 200 Hz for increased shock resistance, it does not affect the

performance since the slow axis is operated at a few hertz, well below the resonant frequency. The properties of the material that are used for the design and the calculated device dimensions are shown in the Tables 2 and 3 below.

Table 2. Material properties of silicon and SU-8.

Density of silicon	$\rho_{si} = 2320 \text{ kg/m}^3$
Density of SU-8	$\rho_{SU} = 1160 \text{ kg/m}^3$ Note: This is the density of fully cured, hard baked SU-8 and is only a best estimate [85].
Density of aluminum	$\rho_{AL} = 2700 \text{ kg/m}^3$
Young's modulus of SU-8	$E = 4.5 \text{ GPa}$ Note: The Young's modulus varies depending on the processing temperature [86].
Poisson's ratio of SU-8	$\nu = 0.22$

Table 3. Geometrical dimensions of gimbal architecture and torsional hinges.

Radius of active optical surface	$R_{opt} = 2000 \text{ }\mu\text{m}$
Radius of center gimbal plate	$R_{cp} = 2200 \text{ }\mu\text{m}$
Thickness of SU-8 membrane	$t_{mem} = 4 \text{ }\mu\text{m}$
Thickness of optical surface	$t_{os} = 100 \text{ nm}$

Table 3 Continued.

Thickness of center gimbal plate	$t_{cp} = 30 \mu m$
Height of deformable gap	$g = 40 \mu m$
Inner radius of outer gimbal ring	$R_{ir} = 2250 \mu m$
Outer radius of outer gimbal ring	$R_{or} = 2460 \mu m$
Thickness of outer gimbal ring	$t_{gr} = 40 \mu m$
Length of inner hinge	For the slow, reference and fast resonant frequency designs, the hinge length is respectively: $L_{ih} = 110 \mu m, 110 \mu m \text{ and } 90 \mu m.$
Width of inner hinge	For the slow, reference and fast resonant frequency designs, the hinge width is respectively: $w_{ih} = 76 \mu m, 100 \mu m \text{ and } 110 \mu m$
Thickness of inner hinge	$t_{ih} = 50 \mu m$
Length of outer hinge	$L_{oh} = 300 \mu m$
Width of outer hinge	$w_{oh} = 40 \mu m$
Thickness of outer hinge	$t_{oh} = 50 \mu m$
Separation between center gimbal plate and quadrant electrodes	$s_0 = 230 \mu m$

Table 3 Continued.

Thickness of SU-8 hinge anchor	$t_{ach} = 50 \mu m$
Note: The footprint of the hinge anchor varies considerably, from continuously around the perimeter of the center plate and the outer gimbal ring to just in areas immediately surrounding the hinges.	

It is necessary to clarify that the quadrant electrodes only cover the extent of the center plate. The quadrant electrodes do not interact with the outer gimbal ring in terms of generating torque. This means that the force generated by the center plate and the quadrant electrodes will be the sole torque responsible for driving both the inner and outer axis. If we assume that the maximum scan angle of the mirror is limited by snap down, then extending the electrodes to include the outer gimbal ring would necessitate a proportional increase in the quiescent separation to preserve the maximum scan angle. Since the electrostatic torque that can be generated (Eq. 11) is proportional to the radius of the outermost perimeter, it seems that more torque could be achieved with the participation of the outer ring using the same actuation voltage. This is indeed the case. Calculations show that using the same actuation voltage, approximately 10% more total torque is available when the electrodes extend to include the outer gimbal ring. Even when we subtract the torque lost in the gap between the center plate and the outer gimbal ring, there is still a 5%

increase in total torque. It seems advantageous to extend the quadrant electrodes and gain this extra torque. The problem is, the increase in quiescent separation to maintain snap down limited maximum scan angles would cause the torque for the inner (fast) axis (governed by area of center plate) to drop by almost 30% under a given actuation voltage. This would reduce the number of spots resolvable per line by 30%. Of course, the quadrant electrodes could be extended without increasing the quiescent separation but this would decrease the maximum scan angle of the outer axis. For these and other fabrication and practical reasons, the quadrant electrodes only extend to overlap the center gimbal plate. The characterization results of the scanning performance shown later in this dissertation sheds light on this design aspect. The results indicate that it would take a smaller increase in voltage to compensate for the 5% torque lost in the outer axis when using the current electrodes than it would to compensate for the 30% torque lost in the inner axis if the electrodes were to be extended.

Resonant Frequency vs Hinge Dimensions. The influence of hinge dimensions on resonant frequency for both the inner and outer axis is analyzed. It should be noted here that the equations for modeling angular moment of inertia does not take into account the influence of the thickness of the plate. Thickness is merely used for calculation of mass. For future reference, the more accurate equation for angular moment of inertia that accounts for the thickness of a plate with finite thickness is provided in the following equation.

$$I = \frac{mR^2}{4} + \frac{mt^2}{12} \quad (14)$$

In the above equation, m is the mass of the plate assuming uniform distribution. For the rotational bodies in this mirror, the thickness is almost negligible compared to the diameter. The calculation results from Eq. 3 and Eq. 14 are almost identical (0.013% difference). Thus, for simplicity, Eq. 3 will be used for all angular moment of inertia calculations in this paper. The angular moment of inertia for both the inner and outer axes are given in the two equations below [84].

$$I_{cp} = \frac{\pi}{4} [\rho_{si}(t_{cp}R_{cp}^4 + gR_{cp}^4 - gR_{opt}^4) + \rho_{SU}t_{anh}(R_{cp}^4 - R_{opt}^4) + \rho_{SU}t_{mem}R_{opt}^4 + \rho_{AL}t_{os}R_{opt}^4] \quad (15)$$

$$I_{tot} = I_{cp} + \frac{\pi}{4}(R_{or}^4 - R_{ir}^4)(\rho_{si}g + \rho_{SU}t_{anh}) \quad (16)$$

A definition of the variables can be found in Table 3. If we set aside the influence of the DC bias, the resonant frequencies for the inner and outer axis can be expressed as

$$f_i = \frac{1}{2\pi} \left(\frac{2k_{ih}}{I_{cp}} \right)^{\frac{1}{2}} \quad (17)$$

$$f_o = \frac{1}{2\pi} \left(\frac{2k_{oh}}{I_{tot}} \right)^{\frac{1}{2}} \quad (18)$$

where k_{ih} and k_{oh} are the torsional spring constants for the inner and outer hinges (Eq. 4). The spring constants are a function of the length, width and thickness of the hinges. The plots in Figure 7 indicate the effects of each of these dimensions on the resonant frequencies. In each plot, apart from the dimension of interest, all other values will adhere to that listed in Table 3.

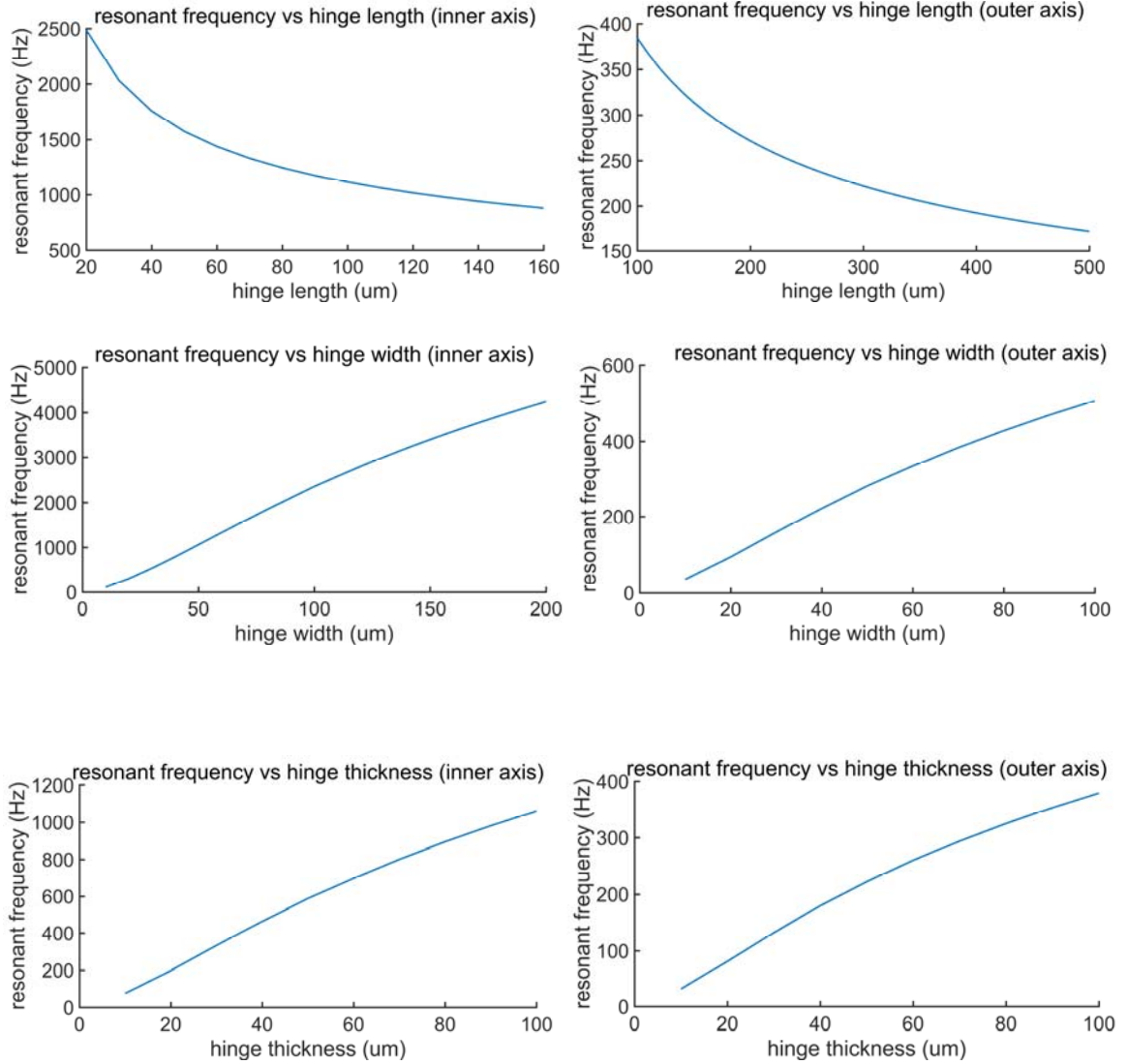


Figure 7. The influence of hinge dimensions on resonant frequency for the both the inner (left) and outer (right) axis. Top: Resonant frequency as a function of hinge length, $w_{ih} = 100\mu m$, $t_{ih} = 50\mu m$, $w_{oh} = 40\mu m$, $t_{oh} = 50\mu m$. Middle: Resonant frequency as a function of hinge width, $L_{ih} = 110\mu m$, $t_{ih} = 50\mu m$, $L_{oh} = 300\mu m$, $t_{oh} = 50\mu m$. Bottom: Resonant frequency as a function of hinge thickness, $L_{ih} = 110\mu m$, $w_{ih} = 100\mu m$, $L_{oh} = 300\mu m$, $w_{oh} = 40\mu m$.

During actual operation, the drive voltage includes a DC component. Therefore, it is important to consider the amount of influence that the DC bias has on resonant frequency.

The resonant frequency is plotted as a function of the DC bias. The dimensions of the

hinges are the standard values listed in Table 3. From Figure 8, it can be seen that the influence of the DC bias is not very significant.

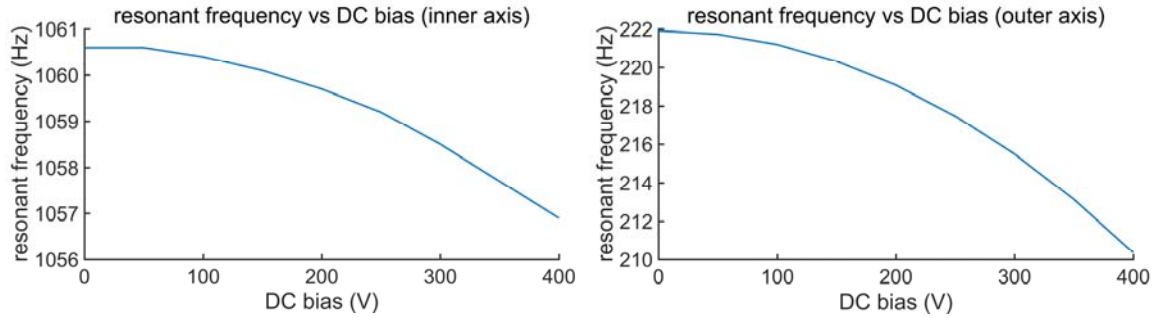


Figure 8. Influence of DC bias on resonant frequency.

Modal Analysis with Ansys ADPL. The accuracy of the equations used for the calculation of the torsional resonant frequency was verified using Ansys ADPL finite element modeling. The resonant frequency of the fast axis is modeled as a function of the inner hinge dimensions. It should be noted that at the time of this simulation, the dimensions of the inner hinges differ slightly from that indicated in Table 3. The hinge dimensions used during the Ansys simulation are listed below.

Table 4. Dimensions used for Ansys simulation.

Length	Width	Thickness	Young's Modulus	Poisson Ratio
100 μm	80 μm	40 μm	4.8 GPa	0.22

The model is based on a circular plate and takes into consideration features such as the spacer layer, hinges and deformable membrane. Simulation results indicate a resonant frequency of 1167 Hz, which is shown in Figure 9. Eq. 17 was used to calculate the resonant frequency based on the hinge dimensions in Table 4 that were used for the Ansys

simulation. The spacer layer and membrane are also considered in the calculation. The calculation yields a resonant frequency of 1153 Hz. This calculated value closely matches the simulated Ansys value. There is only a 1.2% difference between the two values.

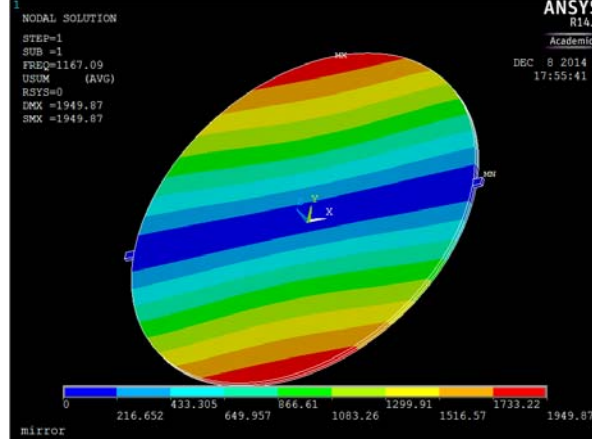


Figure 9. Ansys simulation of the first torsional mode of the inner gimbal.

Static Actuation. The static response of the mirror is investigated. First, we will start with the situation of single sided drive where only half of the quadrant (same side of axis, not diagonal) electrodes are actuated. Because the mirror is static, the equation of motion becomes $T_e - T_m = 0$, substituting in for the expressions of torque, we have:

$$2k_\theta\theta = \varepsilon_0 V^2 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 - x\theta)^2} dx. \quad (19)$$

The relationship between the applied voltage and the scan angle is plotted in Figure 10 for both the inner and outer axis. The turnaround point in the plot for the outer axis indicates the snap down angle, which is about 2.75 degrees (0 to peak mechanical). The point of snap down is when the restoring mechanical forces provided by the hinges will no longer be able to counteract the electrostatic pull in force. This causes the edge of the

scanning plate to clash with the electrodes. The effect is generally undesirable because it can result in irreversible mechanical damage from the forceful contact and possible electrical failures due to shorting of the two electrodes. Results from the simulation results, as well as previous literature, indicate that snap down occurs when the edge displacement is approximately one third of the quiescent separation [78]. Additional precautions, such as encasing the quadrant electrodes in a dielectric material have also been taken to minimize damage in the event of snap down. It should also be noted that snap down is generally only a concern during static actuation of the mirror (the outer axis). The resonant scan is less prone to snap down due to the nature of the phase lag between the actuation voltage and the position of the mirror where the applied voltage is greatest when the mirror is parallel to the actuating electrodes [87].

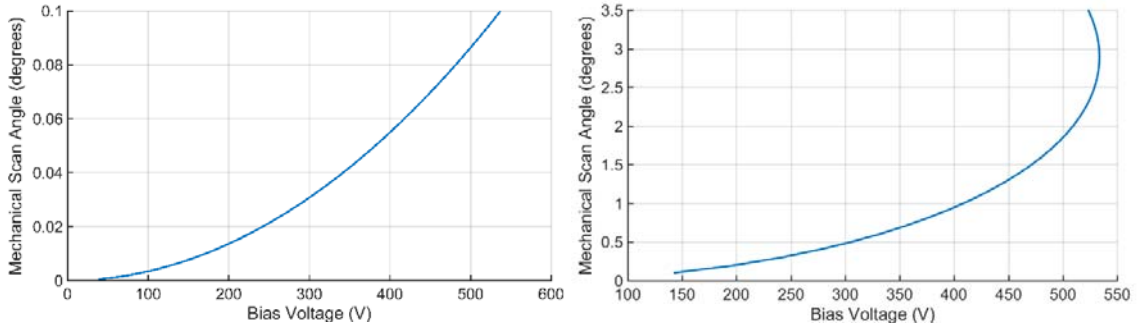


Figure 10. Scan angle as function of bias voltage.

Although the mirror can be actuated using just half of the electrodes, like the resonant actuation, it is normally driven with all four electrodes using a DC bias and an imposed differential voltage. The electrodes on one side of the scanning axis are driven with $V_1 = V_{DC} + V_{diff}$, while the opposing electrodes are driven using $V_2 = V_{DC} - V_{diff}$.

Borrowing from Eq. 10, the electrostatic torque that is generated can be expressed as

$$T_e(V_{DC}, V_{diff}, \theta) = \epsilon_0 \left[(V_{DC} + V_{diff})^2 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 - x\theta)^2} dx - (V_{DC} - V_{diff})^2 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 + x\theta)^2} dx \right]. \quad (20)$$

The mechanical restoring torque generated by the hinges (T_m) are still the same as before. From the equation of motion $T_e - T_m = 0$, we arrive at the following relationship between the differential drive voltage, the DC bias voltage and the scan angle:

$$V_{diff} = \frac{-AV_{DC} - BV_{DC} - \sqrt{AT_m - BT_m + 4ABV_{DC}^2}}{A - B}, \quad (21)$$

where

$$A = \epsilon_0 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 - x\theta)^2} dx \quad (22)$$

and

$$B = \epsilon_0 \int_0^R \frac{x\sqrt{R^2 - x^2}}{(s_0 + x\theta)^2} dx. \quad (23)$$

The relationship between the differential drive voltage and scan angle for a range of DC bias is plotted in Figure 11. Similar to the single sided drive, the turn-around point indicates the snap down point of the mirror. At smaller differential voltages, it can be seen from the plots that the scan angle is almost linear to the differential drive voltage. This near linear relationship is due to the value of $(A - B)V_{diff}^2$ being small compared to $2(A + B)V_{DC}V_{diff}$ at smaller values of V_{diff} . The near linear relationship creates a desirable operating regime. This means the non-resonant axis of the mirror (frame scan) can be driven with a saw tooth signal without too much non-linear image distortion.

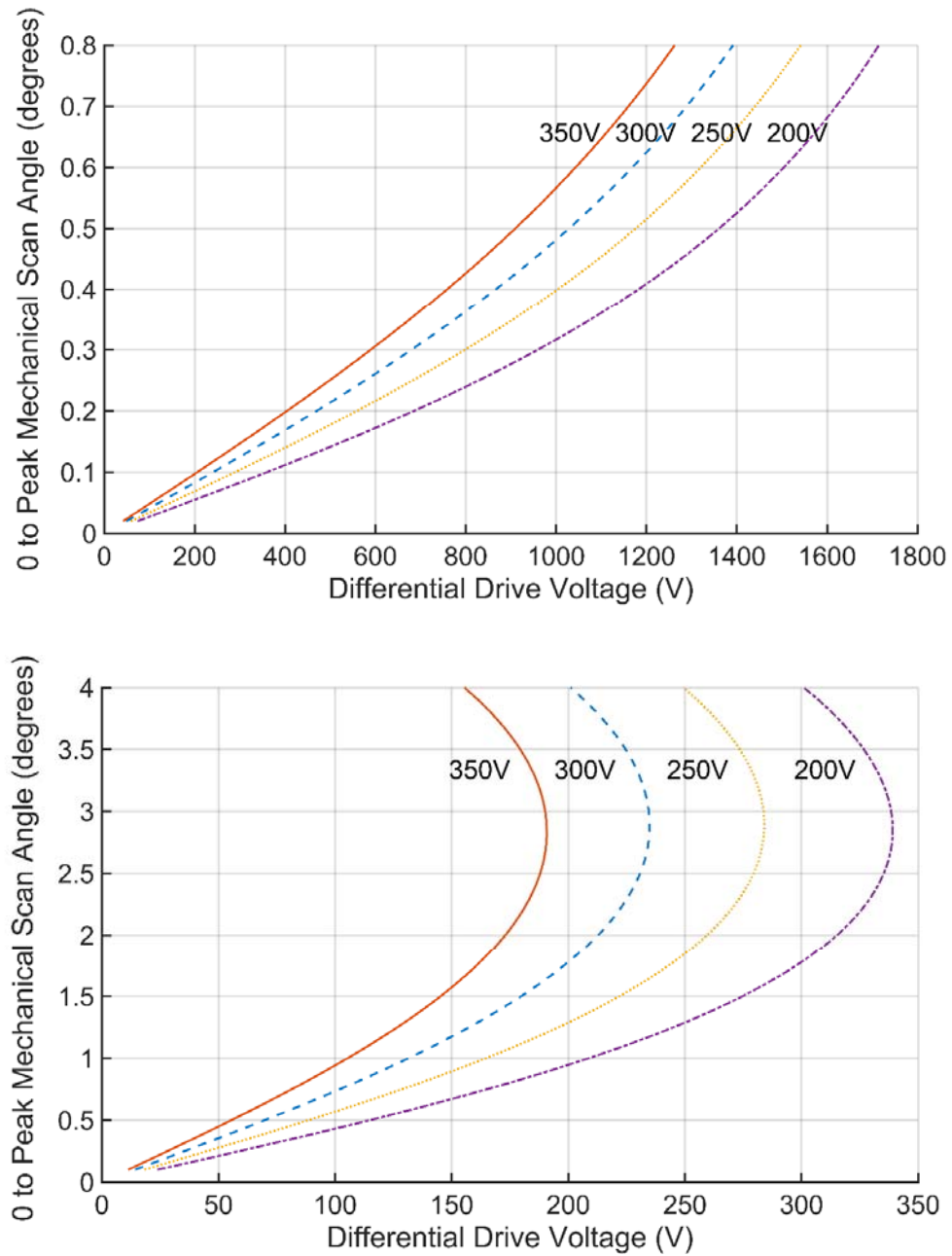


Figure 11. Scan angle as a function of differential drive voltage.

Bending of Hinges. Additionally, operating with a DC bias will inevitably cause the suspended gimbal platform to be pulled towards the quadrant electrodes (piston motion). This effect should be minimized in order to maintain a constant quiescent separation

distance as the DC bias is changed. Therefore, it is crucial to ensure that the bending stiffness (different from torsional stiffness) of the hinges are sufficient to ensuring minimal displacement of the gimbal and that the piston resonance is well separated from the torsional resonance. The electrostatic force as a result of the DC bias is calculated using the equation below.

$$F_{DC} = \frac{\pi \epsilon_0 R_{cp}^2 V_{DC}^2}{2s_0^2} \quad (24)$$

Ansys simulation was used to find the amount of vertical displacement as a function of DC bias. The force from the DC bias was applied to the mirror surface in the form of uniform pressure $P_{DC} = \frac{\pi \epsilon_0 V_{DC}^2}{2s_0^2}$. Figure 12 provides simulation results of the displacement of the mirror due to a DC bias of 300V. The maximum amount of vertical displacement at DC bias of 50V, 100V, 200V, 250V, 300V, 350V and 400V is respectively 25 nm, 120 nm, 240 nm, 430 nm, 650 nm, 960 nm 1300 nm and 1700 nm. The bending of the outer gimbal ring makes up a large proportion of the overall displacement. At a DC bias of 300V (which is used for the imaging results in this dissertation), the displacement amount is small compared to the overall separation. This means that we can accurately use the value of the quiescent separation without considering the pull in distance in the above equation.

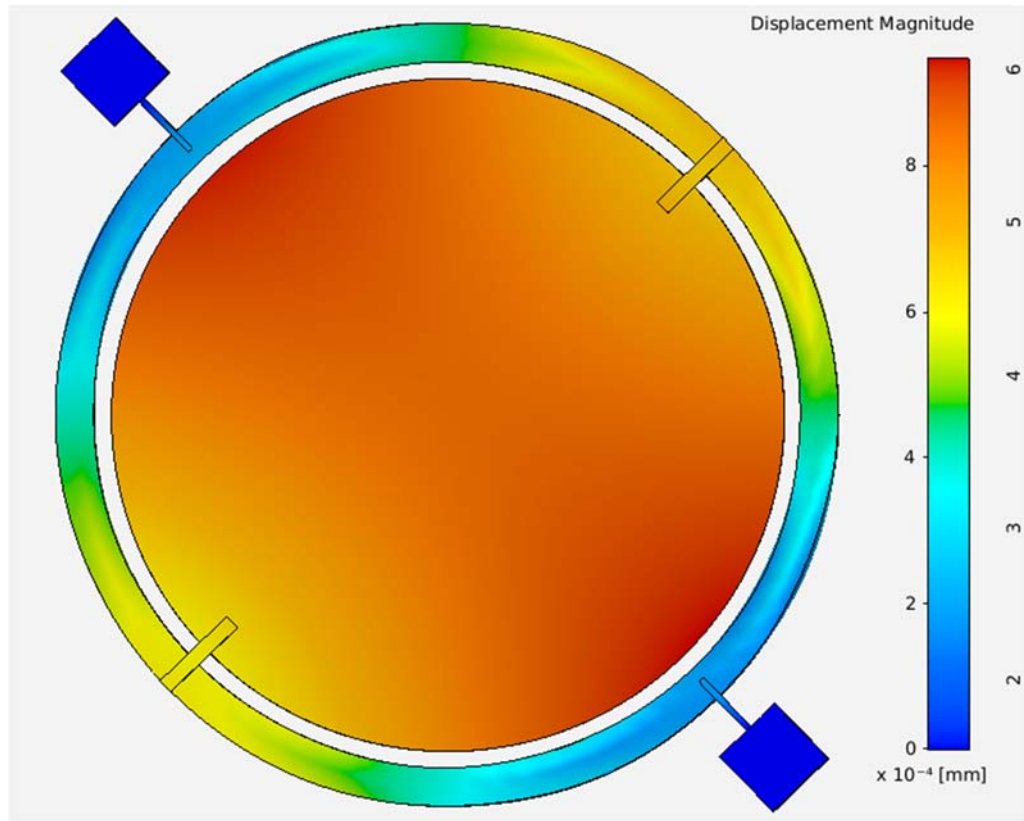


Figure 12. Displacement caused by 300V of DC bias. Scale bar displays from 0 - 8×10^{-4} mm.

As with most engineering endeavors, the actual results almost always deviate from the theoretical predictions. This should be kept in mind when following the methods presented in this section for calculating the various scanning performance characteristics. Even when the design adheres strictly to the terms of simulation, variations during fabrication can cause the results to vary. For example, the dimensions of the torsional hinges rely on the precision and consistency of the spin coat and photolithography process. One of the most influential dimensions is the thickness of the SU-8 hinges. It is not uncommon for there to be a $\pm 5\%$ variation in thickness, which would result in approximately $\pm 15\%$ in torsional stiffness and therefore $\pm 15\%$ in the resonant frequency.

The consistency of the Young's Modulus and Poisson ratio of the hinges are at the mercy of the manufacturing process of the resists and the fabrication process. Any unpredicted variations could result in deviations from theoretical values. For this reason, three sets of hinge dimensions centered about the target frequency of 1000Hz were designed for the inner hinges. The three sets of hinges provide a theoretical resonant frequency tolerance of $\pm 20\%$.

Deformable Mirror

The concept and design of the deformable mirror at the center of the scanning gimbal platform is discussed in this section. The deformable mirror in this research is based on suspending a thin membrane carrying actuation electrodes with a fixed boundary over a circular counter electrode. The membrane is clamped between a circular silicon cavity and a thick (46 μm) polymer ring. This structure is mechanically similar to a drum.

Electrostatic Actuation. When an electric voltage is placed between the aluminum concentric electrodes on top of the deformable membrane and the ground electrode (center plate), an electric field is formed within the cavity sandwiched between the structures. This electric field generates a force that pulls the two structures towards each other. Because the center plate is far more rigid than the thin aluminum electrode and membrane, the initially flat membrane becomes a curved surface. The curvature of this surface can be tuned by adjusting the amount of actuation voltage. At small deflections, the focal length of the mirror can be expressed as $f = \frac{r_0^2}{4v_0}$, where v_0 is the center deflection of the membrane [82].

When the concentric electrodes are biased using the same voltage, the membrane is fairly

parabolic for deflections less than approximately 10% of the initial separation of the two surfaces, and the center deflection is given by Eq. 25 [60]:

$$v_0 = \frac{\varepsilon_0 V^2 r_0^2}{8g^2 \sigma t}, \quad (25)$$

where ε_0 is the permittivity of air, r_0 is the radius of the mirror, g is the initial air gap separation, σ is the stress, t is the thickness of the membrane and V is the actuation voltage. Substituting the center deflection into the focal length, we can see that:

$$f = \frac{2g^2 \sigma t}{\varepsilon_0 V^2}. \quad (26)$$

The optical power of the mirror is equal to the reciprocal of the focal length. The amount of optical power that can be achieved for a given voltage is inversely proportional to the intrinsic stress of the membrane. In other words, if the intrinsic stress of the membrane is decreased, less voltage will be required to achieve the same amount of optical power. This has been the governing factor for selecting SU-8 polymer as the membrane material instead of the conventional silicon nitride or polysilicon.

Spherical Aberration Correction. In an ideal optical system, light is focused to a single point whose spatial distribution is governed only by diffraction. However, it is not uncommon for optical systems to produce a focal point that is larger than the diffraction limited focal point. This is mainly due to optical aberrations in the system. Optical aberrations describe the deviations of the wavefront from a spherical shape. Aberrations are not only caused by fabrication tolerances and imperfections but also are related to lens shape, the position of the lens and the propagation of light through different mediums.

Zernike polynomials are used to describe the aberrations in this dissertation. A summary of the Zernike polynomials can be found in Appendix A.

Common types of aberrations include tip, tilt, defocus, astigmatism, coma and spherical aberration. Under optimal fabrication conditions, it would theoretically be possible to create a mirror free of aberrations. However, spherical aberration is unique in that its presence, aside from fabrication capabilities, is also a function of the amount of deflection of the mirror. This is due to the nature of the electrostatic actuation method used by the mirror. When an equal potential pressure is applied to the deformable membrane, the membrane assumes a parabolic shape, which maintains a reflected wavefront that is free of aberration (granted an aberration free incident plane wave). However, electrostatic actuation using a conformal bias voltage does not exert a spatially equal force on the membrane. This is because of the geometry of the deformable surface and the dependence of electrostatic force on the gap distance. As the mirror deforms, the gap between the center of the mirror and the counter electrodes becomes relatively smaller compared to that at the edge of the mirror. This means the center of the deformable membrane experiences a relatively larger force compared to the edge of the mirror. This causes the mirror to deviate from the desirable parabolic shape. At small deflections (approximately 10% of the quiescent separation), the difference in the gap between the center and edge of the mirror is very small compared to the overall separation [88]. Therefore the mirror is still capable of maintaining a relatively parabolic shape. This is explored in more detail by Himmer et al. [89]. However, as the deflections increase, the deviation from a parabolic shape is accentuated and spherical aberration becomes more pronounced. If this growing amount of

spherical aberration is not addressed then diffraction limited performance cannot be maintained, which leads to a degradation in the resolution of the system. Thus, to maintain a diffraction limited performance throughout the entire focal range of the mirror, spherical aberration must be kept under control. Annular electrode zones are used to tune the force across the membrane.

To visualize the influence of spherical aberration on the shape of the surface of the mirror. Primary (Z_4^0) and secondary (Z_6^0) spherical aberration is plotted along with defocus (Z_2^0) in Figure 13. The influence of positive and negative primary spherical aberration on defocus is plotted in Figure 14.

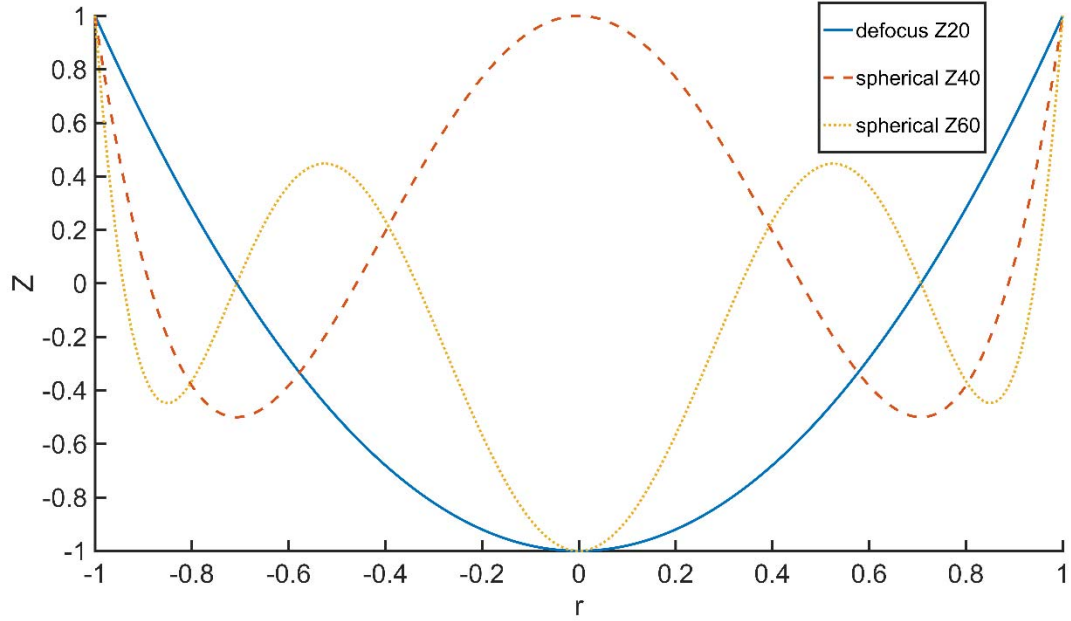


Figure 13. Plots illustrating the Zernike terms for defocus (Z_2^0), primary (Z_4^0) and secondary (Z_6^0) spherical aberration.

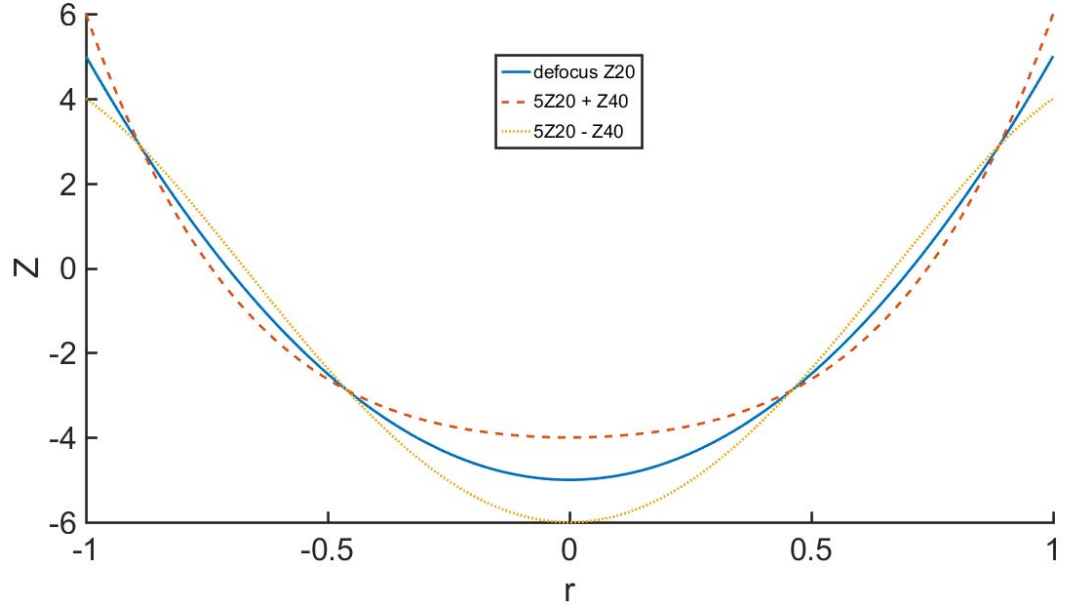


Figure 14. Defocus with the influence of positive and negative primary spherical aberration.

From the two figures above, it can be seen that having the ability to control electrostatic force as a function of radial distance from the center of the mirror would be advantageous in tuning the amplitudes of Z_4^0 and Z_6^0 therefore keeping spherical aberrations under control. To do this, instead of one continuous electrode, four independent concentric electrodes are designed to actuate the mirror. This provides the ability to mitigate both Z_4^0 and Z_6^0 by independently tuning the electrostatic force applied to each segment of the mirror. For example, as the amount of defocus is increased, the bias voltage on the center two electrodes can be correspondingly reduced to maintain a balanced electrostatic force across the membrane. With this, the mirror is capable of keeping spherical aberration under control throughout its focus range. Apart from being able to compensate for the spherical aberration due to actuation of the mirror, the concentric

electrodes can also be used to compensate spherical aberration introduced from light propagating into tissue.

Table 5 provides the material properties and selected design dimensions for the deformable mirror. These selected values are based on theoretical analysis, characterization of similar devices and fabrication limitations.

Table 5. Material properties and design dimensions for deformable mirror.

Material	Cured SU-8 polymer
Density of SU-8	$\rho_{SU} = 1160 \text{ kg/m}^3$ Note: This is the density of fully cured, hard baked SU-8 and is only a best estimate [85].
Young's modulus of SU-8	$E = 4.5 \text{ GPa}$ Note: The Young's modulus varies depending on the processing temperature [86].
Poisson's ratio of SU-8	$\nu = 0.22$ (from Microchem website)
Radius of deformable mirror	$R_{cp} = 2200 \text{ }\mu\text{m}$
Radius of active membrane/optical surface	$R_{opt} = 2000 \text{ }\mu\text{m}$
Thickness of optical aluminum	$t_{os} = 100 \text{ nm}$
Thickness of SU-8 membrane	$t_{mem} = 4 \text{ }\mu\text{m}$
Thickness of electrodes	$t_{os} = 100 \text{ nm}$
Quiescent separation	$g = 40 \text{ }\mu\text{m}$
Radius of center (1 st) concentric electrode	$r_{c1} = 500 \text{ }\mu\text{m}$

Table 5 Continued

Inner radius of 2 nd concentric electrode	$r_{c2i} = 510 \mu m$
Outer radius of 2 nd concentric electrode	$r_{c2o} = 1000 \mu m$
Inner radius of 3 rd concentric electrode	$r_{c3i} = 1010 \mu m$
Outer radius of 3 rd concentric electrode	$r_{c3o} = 1500 \mu m$
Inner radius of 4 th concentric electrode	$r_{c4i} = 1510 \mu m$
Release via dimensions on optical surface	$5 \mu m \times 5 \mu m$
Release via dimensions on membrane	$7 \mu m \times 7 \mu m$
Arrangement of release vias	Square grid, 30 μm separation
Outer radius of 4 th concentric electrode	$r_{c4o} = 2000 \mu m$
Material of ground electrode (center plate)	<100> Silicon
Shorting prevention (snap down)	4 μm of SU-8 and 300 nm of buried SiO ₂

CHAPTER THREE

FABRICATION OF THE 3-DIMENSIONAL MEMS SCANNER

In this section, fabrication techniques and the materials that are used are introduced. The detailed fabrication process for the 3-dimensional MEMS device is presented. The fabrication process is reproduced verbatim from previous publication (IEEE, Journal of Microelectromechanical Systems [73]) along with newly added figures. A few passages of supplementary text are added to the fabrication process as additional information and is italicized to provide distinction. Problems encountered during the process and their solutions are included at the end of this section. The majority of the fabrication of the MEMS scanner is performed at the Montana Microfabrication Facility and the release is performed at Cornell NanoScale Science and Technology Facility.

Introduction to Micromachining Techniques

Micromachining techniques such as photolithography, thin film deposition, oxidation, wet chemical etching, dry etching and solvent processing are used for the fabrication of the MEMS device. Materials used for the construction of the device include silicon, silicon dioxide, thin film aluminum, copper and SU-8. These materials as well as various other photoresists and chemicals that were employed during the process are introduced along with the associated fabrication technique.

First, we will start with photolithography, which is one of the most commonly used processes in micromachining. Photolithography is the use of light to transfer patterns onto

the substrate surface by selectively exposing a photosensitive polymer that is commonly known as photoresist. The pattern to be transferred is normally displayed on a photomask, which is like a stencil. There are two main types of lithography systems to perform the transfer of the photomask pattern onto the photoresist. The first is called a contact aligner where the photomask is placed in close proximity of the wafer and is used as a shadow mask. The entire mask is exposed with light. The portions of the mask that are opaque will prevent the underlying (shadowed) photoresist from being exposed, whereas the portions of the mask that are transparent will allow the light to expose the photoresist. This process is similar to spray painting using stencils. The second type of lithography system is called a stepper. A stepper uses optics to form a miniature image of the mask pattern onto the wafer. Instead of exposing at the wafer scale like in contact lithography, a stepper normally exposes one die at a time and “steps” around the wafer. This process is similar to the projection enlargement (miniaturize in this case) of photographic negatives in a darkroom. After exposure, the photoresist is then developed using chemicals to reveal the pattern.

There are two types of photoresists, positive resist and negative resist. A positive resist is where the portions that are exposed by light will be “washed away” during the development process. A negative resist does just the opposite. The type of resist that is used will depend largely on the application and mask design considerations. In terms of application, photolithography can be divided into a subtractive process or a lift-off process. During the subtractive process, photolithography is often used to pattern a thin film of photoresist onto the surface of a wafer to form an etch mask for the underlying target layer. Then, the etchant for the target thin film is applied to remove the regions not covered by

the photoresist. In the liftoff process, the photoresist is patterned onto the substrate first and then the film of interest is deposited on top of the photoresist. The photoresist is then removed (acetone is commonly used for this process) which “lifts off” the portion of material that resides on top of the resist. Only the deposited thin film that adhered to the substrate surface remains.

One of the most important performance aspects of photoresist is its resolution, which apart from optical constraints, is related to the thickness of the resist. Because of this, the resolution for a certain type of photoresist is normally stated using a ratio of its thickness to smallest resolvable lateral dimensional. For example, a photoresist with a 10:1 resolution means a 20 μm thick layer of this photoresist can resolve features as small as 2 μm . The resolution limitation should be kept in mind both during the mask design and when choosing photoresists.

Physical vapor deposition (PVD) of thin metal films is another technique that is used in the fabrication of the 3-dimensional scanner. Three types of PVD are used, thermal, electron beam evaporation and sputtering. Thermal evaporation is the most straightforward and simply uses resistive heating to melt and evaporate the target metal. It is used in this fabrication process for the deposition of the backside aluminum etch mask. Electron beam evaporation works by directing a beam of electrons onto the target in a vacuum chamber to heat it to the point of evaporation. Compared to thermal evaporation where resistive heating is applied to the target, electron beam is more directional and less heat is transferred to the substrate of the wafer. This makes it useful for liftoff coating of metals where there is a demand for high directionality and minimal increase in substrate temperature due to

resist burning concerns. Electron beam is used in this fabrication process for the deposition of thin film aluminum for the optical surface, electrodes and surface electrical traces. Sputter deposition is based on using heavy ions (Argon) that are accelerated to high energies with an electric field to bombard the surface of the target, which will “sputter” target material onto the surface of the substrate. Sputtering is used in this process to coat the inner walls of though silicon vias that are 40 μ m deep.

Another process is thermal oxidation, which is used to create silicon dioxide onto the surface of the silicon substrate. There are two main types of thermal oxidation, which are dry oxidation and wet oxidation. Dry oxidation is when only oxygen (and sometimes nitrogen) is introduced to the silicon at an elevated temperature and the reaction is described by the following equation:



When water vapor, often in the form of steam is introduced into the process, the previous reaction changes to the following:



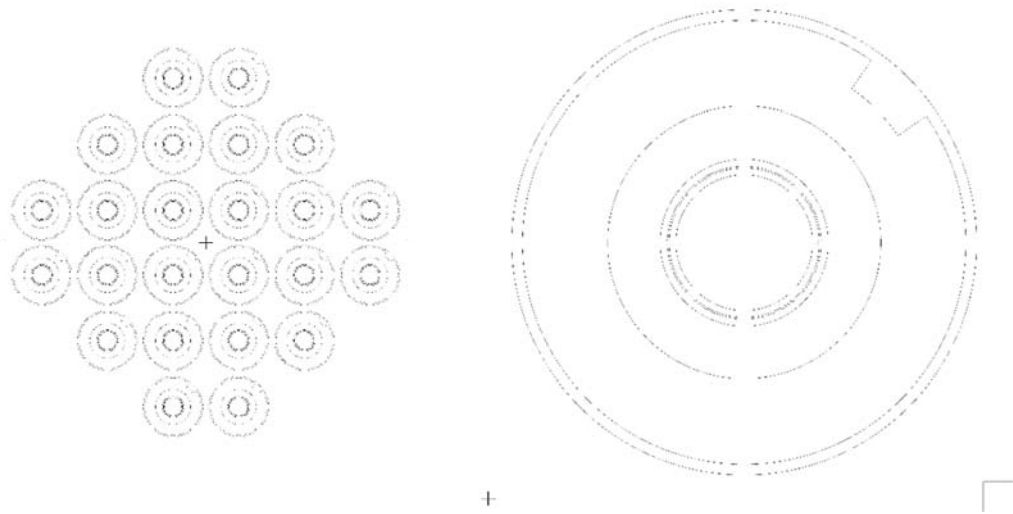
With the introduction of water vapor, the process becomes a wet oxidation. The oxide formation rate is much higher in a wet oxidation process compared to the dry process. However, in general the dry oxidation process though slower usually results in higher quality films [90, 91]. For the fabrication of the device in this dissertation, a wet oxidation is used to create approximately 300 nm of oxide on the inner walls and adjacent lateral linings of the vertical etch stops.

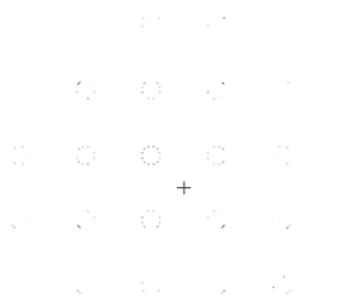
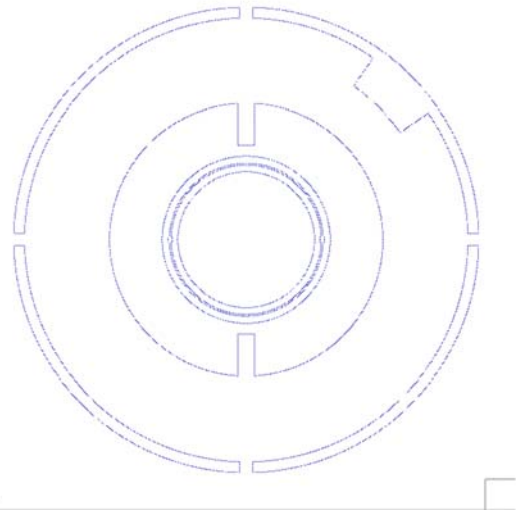
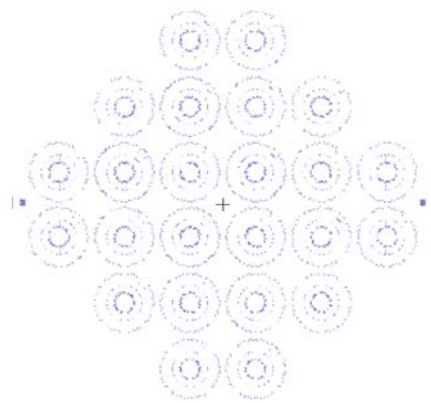
Wet chemical etching is another process commonly used in micromachining. This includes a wide variety of chemicals. The types of chemicals that are relevant to the fabrication of the 3-dimensional scanner are discussed. The first one is piranha etch which is a mixture of H_2SO_4 and H_2O_2 , is used to strip organic films and clean the wafer. The ratio of H_2SO_4 to H_2O_2 can vary from 9:1 to 3:1. A ratio of 3:1 is used for this fabrication process. Piranha etch is very effective at removing fully cured and hard baked SU-8 as well as a wide range of other organic matter. Organic matter such as photoresist eventually gets turned into CO_2 and H_2O when allowed sufficient time in piranha etch [92]. The second one is aluminum etch which consists of phosphoric acid, acetic acid and nitric acid and is used in this process for the patterning of aluminum features and removing copper from certain areas on the surface of the wafer. The third is BOE, which stands for buffered oxide etch and is composed of a solution of hydrofluoric acid (HF) and water. BOE that is used to pattern oxide generally has a ratio of H_2O to HF of 6:1. A more diluted form of BOE (50:1) is used to remove native oxide from silicon surfaces as part of the RCA clean process. The 3-dimensional MEMS fabrication process will use both the 6:1 and 50:1 BOE etchant. Another chemical etchant that is commonly used in silicon micromachining is Tetramethylammonium hydroxide (TMAH). TMAH is used to etch silicon in an anisotropic manner. The etch front is guided by the crystal orientation of the silicon. In an $\langle 100 \rangle$ crystal orientation, inverse pyramids are formed in the silicon when TMAH is applied. The etching of silicon is required for the fabrication process, but instead of using TMAH, dry etching is employed instead and is introduced next.

An alternative to etching with liquid chemicals is to use plasma and gas phase etchants. This is known as dry etching and is commonly used for the removal of silicon, silicon oxide and various types of metals. Compared to wet etching, such as the use of TMAH for the removal of silicon, plasma etching is more precise, increased capability of achieving different profiles and does not require drying afterwards which is an advantage for building micro-structures due to the effects of stiction [93]. In this fabrication process, SF_6 , O_2 , C_4F_8 and CF_4 , are used for the etching of silicon and oxide in the Oxford 100 ICP and the Oxford 81 RIE plasma etcher. A plasma etcher works by using powerful electromagnetic fields to ionize the gas atoms. The ions are then accelerated towards the substrate using the sheath potential formed between the ionized gas and the substrate and/or a separate bias potential [94]. The chemical reaction process between the SF_6 and O_2 ions and Si is rather complex and was described by d'Agostino [95]. Using the Oxford 100 ICP etcher, the gas flow rate, chamber pressure, substrate temperature, ICP power, and bias power can all be adjusted to achieve different etch rates and profiles. Apart from prescribed etching of material using plasma, it can also be used to clean residue. For example, O_2 plasma is commonly employed in a plasma asher for the cleaning of residual photoresist on the surface of the wafer following photography. In addition to the plasma based dry etching, gas phase etchants such as XeF_2 gas is commonly used to remove bulk silicon in an isotropic manner. The fabrication of the scanner employs XeF_2 gas as part of the release process.

Mask Design

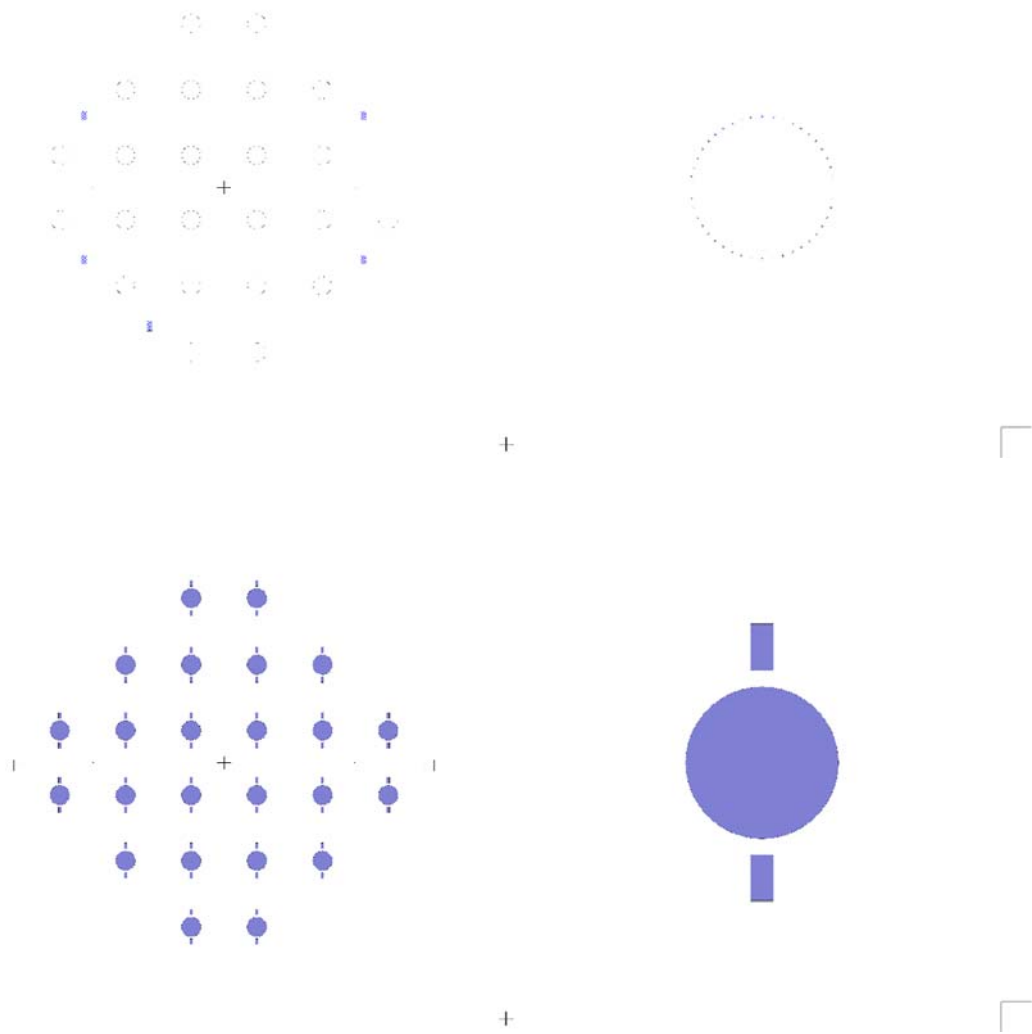
The MEMS device consists of a gimbal with an integrated deformable mirror that is aligned and bonded to a set of quadrant electrodes for tip-tilt actuation. The fabrication is divided into two parts. The first part is the gimbal with deformable mirror, which is fabricated using an SOI wafer with a device layer, oxide and handle layer thickness of respectively 40um, 300nm and 270um. This is referred to as the gimbal wafer. The second part uses a double-side polished wafer to fabricate the quadrant electrodes. The lithography masks for the gimbal wafer and the quadrant electrode wafer were designed in L-edit and are shown respectively in Figure 15 and Figure 16. For each mask, a schematic of the full size mask is shown along with a zoomed in view corresponding to an individual device. An additional magnified image of specific regions on the device to show fine details is also included when necessary. A total of 10 masks are used for the gimbal wafer and up to 4 masks for the electrode wafer.

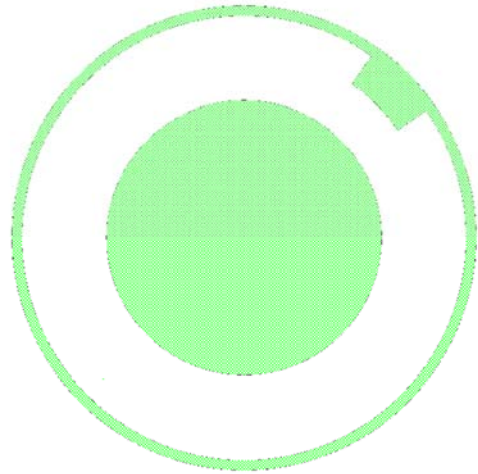
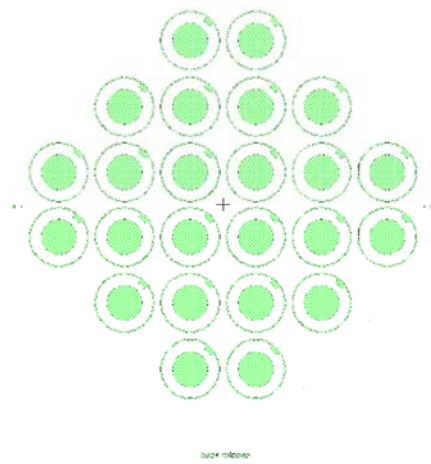




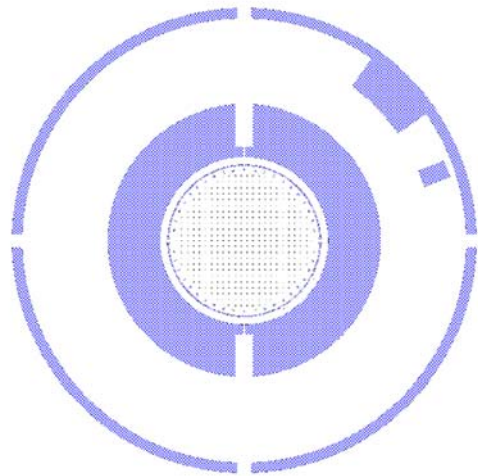
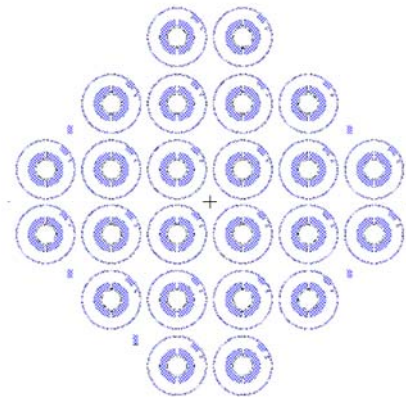
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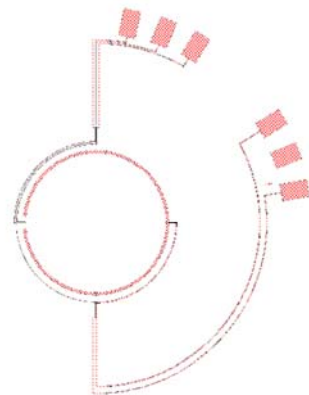
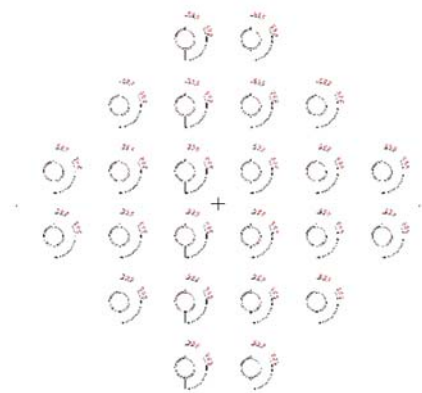
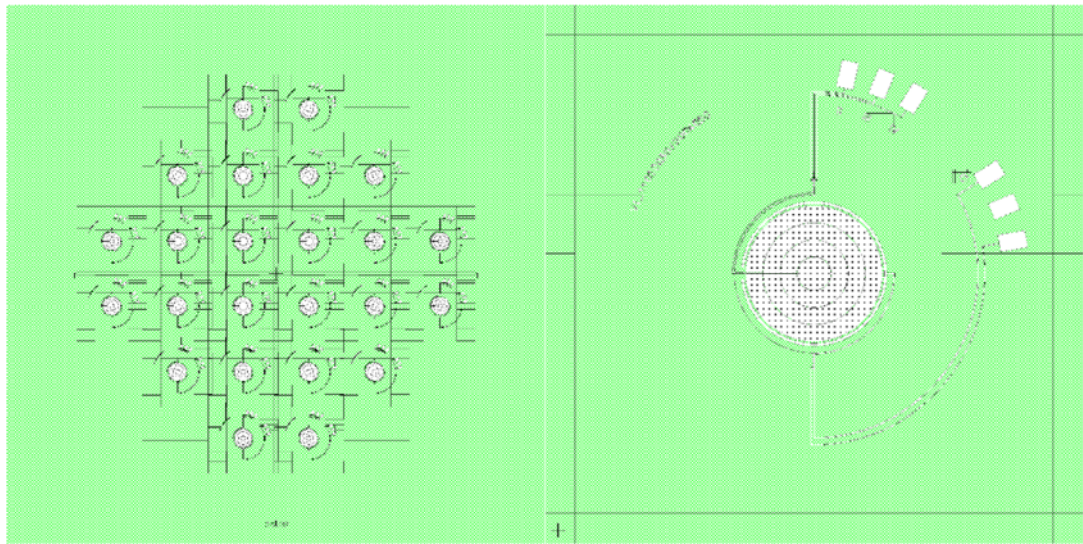


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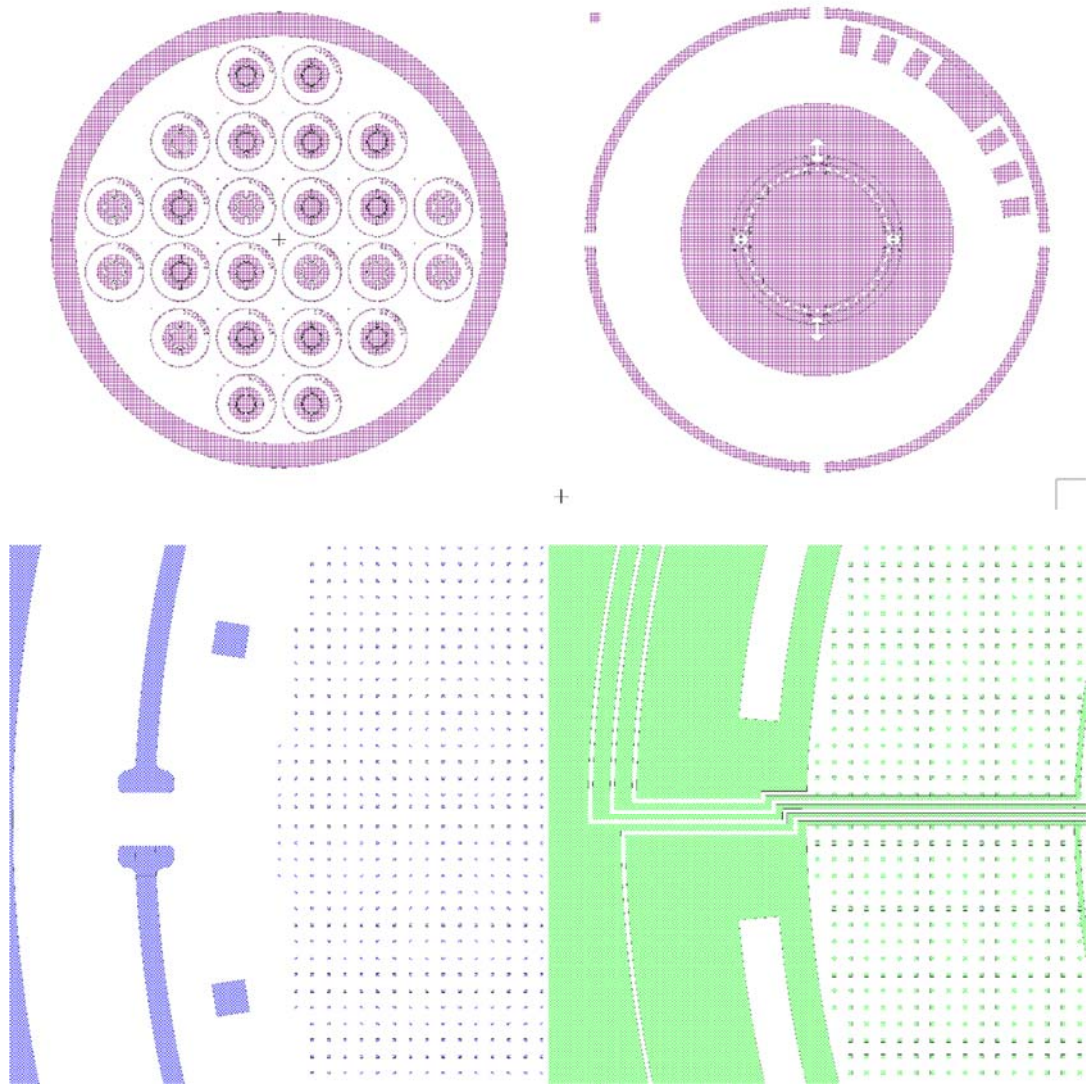
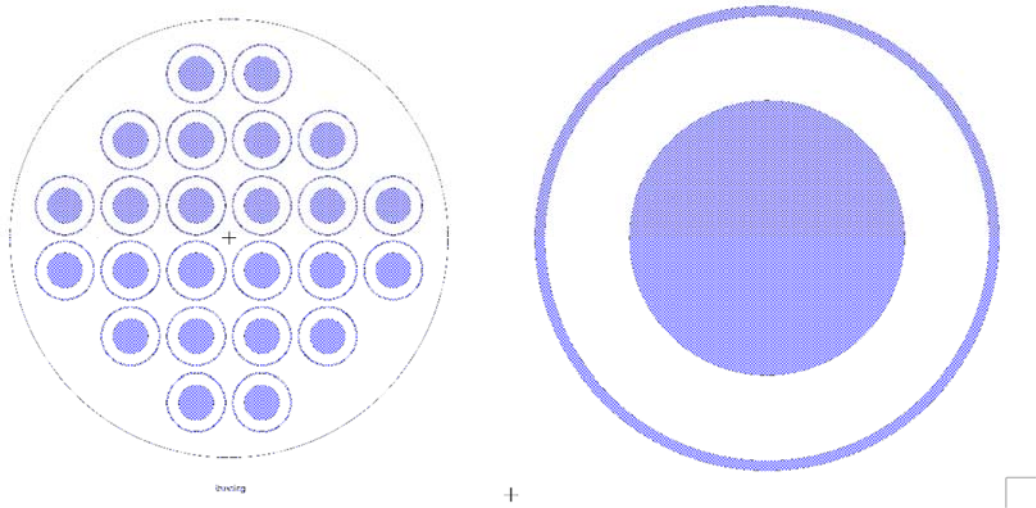
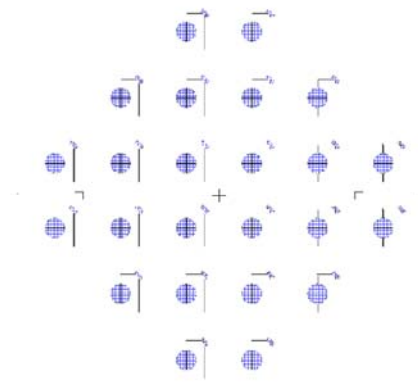


Figure 15. (a). The location of vertical etch stops are defined using this mask. (b). The mask patterns the oxide in and around the vertical etch stops. (c). The mask is used to define the location of through-silicon vias. (Details in full size mask image is only visible under high screen resolution setting when viewed on computer.) (d). The deposited copper for coating the through silicon vias are patterned using this mask. The relative large rectangular structures visible on the full size mask are staggered arrays of vias for cleaving to measure etch depth during the optimization of the etch process. (e). This mask patterns the oxide on the backside of the wafer. Oxide remains according to the location of the center gimbal plate. This mask is the first part of the bi-layer differential etch mask. Oxide also remains on the silicon extension arms to the slow axis. (f). This mask is the second part of the bi-layer differential etch mask. The deposited aluminum on the backside of the wafer is patterned according to the outer frame of the device and the location of the annular pupil. (g). The deformable membrane that is spin cast from SU-8 is patterned using this

mask. Bridges for routing electrical traces across the vertical etch stops are also formed. (h). This mask is used in a lift-off process for the formation of the optical surface, electrical traces and electrodes. (i) The mask is used to define locations where a second thicker layer of metal is required. This includes, the openings in the SU-8 corresponding to the through silicon vias, the electrical traces and bondpads. (j). The hinges and hinge anchors are created using this mask. Notice that a ring has been created around the perimeter of the wafer to lithographically define edge bead removal. (k). Left: A magnified image of mask (g) showing the hinge locations where the trenches are bridged using SU-8 and the release vias on the surface of the deformable membrane. Right: A magnified image of a region of mask (h) showing the electrical traces routed from the center gimbal plate across the bridged trenches to the outer gimbal ring. The optical surface also has apertures that correspond to the location and size of the release vias.

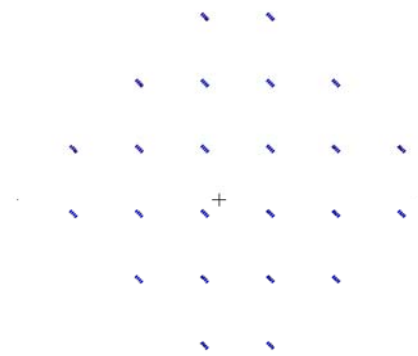
The 4 masks that are used for the fabrication of the quadrant electrode wafer are shown in Figure 16. As will be described later in this process, only a subset of these masks were utilized for the fabrication of the quadrant electrodes.





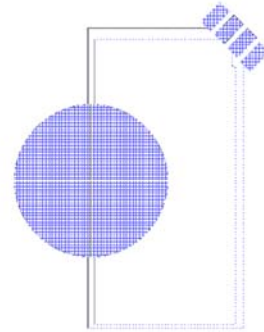
bottom metal

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bottom metal

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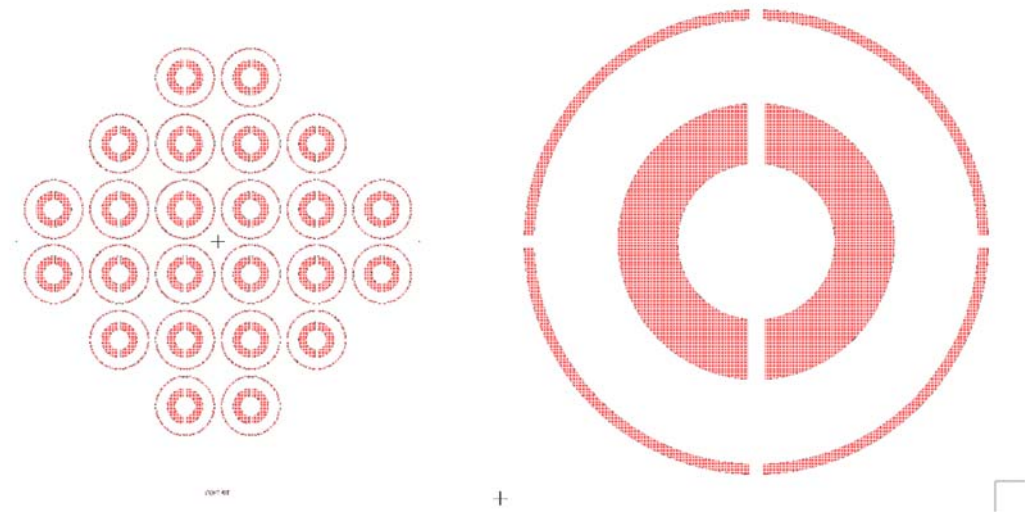


Figure 16. Photo-masks for fabrication of the quadrant electrode wafer. (a) Backside thinning mask. The outer perimeter of the annular aperture and the perimeter of the frame is defined. (b) The quadrant electrode and traces are patterned using a lift-off process with this mask. (c) When necessary the thickness of the electrical bondpads can be augmented. (d) Front side etch mask to create annular pupil and break tabs for separating the individual devices from the wafer.

Fabrication Process

[Begin Excerpt]

The gimbal with deformable mirror was fabricated using an SOI wafer with 40 μm device layer, 300 nm oxide and 270 μm handle layer thicknesses. This is referred to as the gimbal wafer. Figure 17 shows the fabrication process of the gimbal wafer.

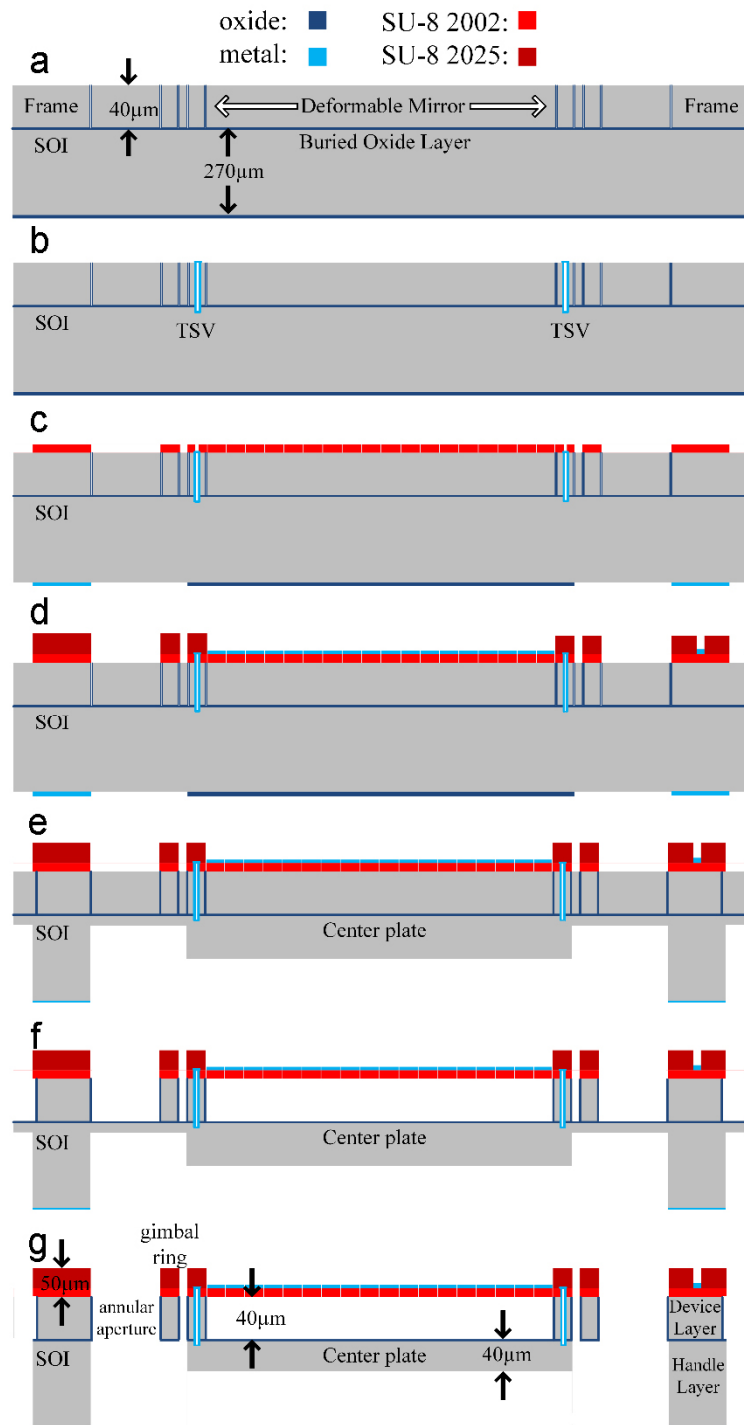


Figure 17. Fabrication schematic of gimbal wafer.

The fabrication of the gimbal wafer begins with creating vertical, oxidized trenches that function as lateral etch stops during the final XeF_2 release etch. These 3 μm wide trenches are etched through the 40 μm thick device layer to the buried oxide and subsequently oxidized, to define the boundaries of the deformable mirror air gap, center plate, gimbal outer ring and annular aperture. A 2 μm thick SU-8 etch mask was used for this process. The Oxford Plasmalab System 100 ICP was used to perform an anisotropic dry etch employing a mixture of SF_6 and O_2 , given in Table 6. The amount of SF_6 and O_2 in the mixture can be varied to tune the etch profile from negative to positive taper [77, 96]. The etch rate is approximately 2 $\mu\text{m}/\text{min}$ with silicon to SU-8 selectivity of 40:1.

Table 6. Etch recipes.

		ICP Power (W)	Bias Power (W)	SF ₆ (sccm)	O ₂ (sccm)	Temp. (°C)	Pressure (mtorr)
Oxford Plasmalab System 100 ICP Plasma Etcher	Trench Etch	600	3	38	21	0	12
	Via Etch	600	3	30	23	0	12
	Oxide Etch	2000	32	25	25	25	10
Xactix X4 Xenon Difluoride Etcher	XeF ₂ Etch	XeF ₂ Pressure (torr)	N ₂ Pressure (torr)		Time/Cycle (seconds)		Time/Cycle (seconds)
		2	0		30		30
Oxford 81 Etcher	SiO ₂ Etch	RIE Power (W)	CF ₄ (sccm)		Temp. (°C)		Pressure (mtorr)
		100W	0		10		40

After completion of trench etching, the SU-8 was stripped from the wafer using a heated piranha etch. A wet oxidation at 1050 $^{\circ}\text{C}$ for 3 hours created an oxide barrier of approximately 700 nm on the sidewalls of the trenches. The newly grown oxide was patterned so that it only remained on the inner walls, top surface regions immediately

adjacent to the trenches, and on the backside of the wafer. NR9-6000PY photoresist was used for this patterning step. The high viscosity of this resist allowed for the trenches to be bridged during the spin coat process so that the oxide within the trenches could be sufficiently isolated from the buffered oxide etch used in the subsequent step to pattern the oxide. A static dispense and slight delay (20 seconds) before spinning was critical to the conformal bridging, as it allowed the resist to flow into the trenches. The thickness of the photoresist after developing was approximately $8\mu\text{m}$ on the surface of the wafer.

Next, TSVs were created for electrical connection to the center plate under the buried oxide layer. This was a two-step process, which includes etching the TSVs and then coating with metal. An etch mask of SU-8 2002 was spin coated and patterned to define the location of the TSVs. The etch recipe was tuned to achieve etch profiles exhibiting a positive taper by decreasing the SF_6 flow to 30sccm while increasing the O_2 flow to 23sccm. A positive taper is desirable to promote the conformal coating of inner sidewalls during subsequent metal deposition. The vias were etched to the buried oxide layer, and then an oxide dry etch with a silicon to oxide selectivity of approximately 1:1 was immediately performed to etch through the buried oxide layer and 1-2 μm into the handle layer silicon. The oxide etch recipe is given in Table 6.

After completion of the via etch, a heated piranha etch was used again to strip the SU-8. The wafer was placed into BOE dip (50:1) for 1 minute, to remove any oxide films that might have formed on the bottom of the vias due to the strong oxidation characteristics of the piranha etch. After the BOE dip, the surface of the wafer was sputtered with 2.5 μm of copper to coat the vias to provide electrical connection from the device layer to the center

plate underneath the buried oxide. Then, the vias were protected with patterned photoresist (PR1-4000a) and the copper was etched from the rest of the wafer. The photoresist was stripped, and then re-coated as a continuous film to protect the front side of the wafer during backside processing.

To form a bi-layer differential etch mask, oxide on the backside of the wafer was patterned using AZ1512 (positive resist) and the “oxide etch” recipe from Table 6 to define the location and dimensions of the center plate. Next, 200 nm of aluminum was evaporated onto the backside of the wafer and patterned to define the outer frame of full-thickness silicon that will support the structure. The wafer was cleaned using a 3-solvent clean after the aluminum etch process to remove both front and back side photoresist.

At this point, a 2:1 mixture of SU-8 2002 and SU-8 2007 was spun onto the front side of the wafer and patterned to form a 4 μm thick deformable membrane, and to permanently seal the vertical etch trenches. An array of 5 μm wide etch vias spaced on a 30 μm grid was patterned in the deformable membrane, permitting access of XeF_2 to the underlying silicon during the release etch. *Figure 18 shows a scanning electron microscope image of the mirror surface. The release vias as well as the separation gap between the concentric electrodes are visible.*

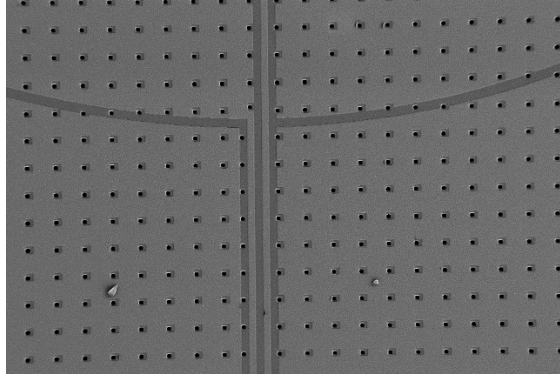


Figure 18. SEM of the surface of the deformable mirror. The $5\text{ }\mu\text{m}$ release vias are visible. The separation between vias is $30\text{ }\mu\text{m}$.

Ports are also created in the SU-8 at the location of the TSVs to allow electrical access. A double exposure is used for this step so that a proper UV dose can be delivered to the thin film of SU-8 on the surface as well as the SU-8 deep in the trenches. The first exposure was performed after the soft bake and was optimized for the $4\text{ }\mu\text{m}$ thick surface resist. The wafer was then post exposure baked and developed. After development, a second, mask-less exposure was performed to provide additional cross-linking of the SU-8 inside the trenches. Since the surface resist has already been developed, this second exposure does not affect the resolution. The wafer was then post exposure baked again and finally hard baked at 180°C . Previous experimental results show that the underexposed SU-8 in the trenches can be expelled onto the surface during hard bake, resulting in unwanted formations without the additional exposure. The cured SU-8 was left permanently to bridge the trenches and planarize the wafer. The SU-8, when coupled with the oxidized trenches and the buried oxide layer completes the sealing against XeF_2 during release. Table 7 summarizes the bake temperature profiles used for processing the permanent SU-8

deformable membrane. These temperatures are selected for stress control and to reduce cracking at feature boundaries. All bakes are performed on a hot plate.

Table 7. Bake recipes.

Structures	Deformable Membrane SU-8
Soft Bake	Start at 45°C, bake for 1 minute. Ramp at 6°C/minute to 65°C. Bake at 65°C for 1 minute. Ramp at 6°C/minute to 80°C. Bake at 80°C for 2 minutes. Remove from hotplate onto a stack of cleanroom wipes. Do not remove onto a metal surface as this will thermally shock the SU-8.
Post Exposure Bake & Post Exposure Bake for Trenched SU-8	Start at 45°C. Ramp at 6°C/minute to 85°C. Hold at 85°C for 3 minutes. Turn off hotplate. Allow to cool to 50°C (cooling process takes about 10 minutes). Remove from hotplate to stack of cleanroom wipes.
Hard Bake	Start at 45°C. Ramp at 6°C/minute to 180°C. Hold at 180°C for 30 minutes. Turn off hotplate. Allow to cool to 50°C. Remove from hotplate to stack of cleanroom wipes.

Figure 19 shows an SEM image of the side profile of a cleaved wafer displaying a trench filled with fully cured SU-8.

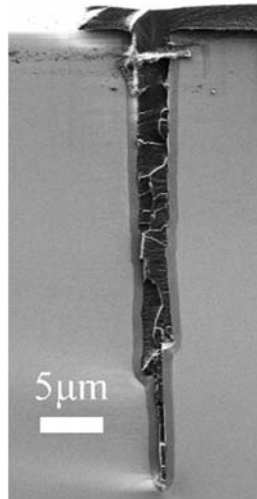


Figure 19. SEM of trench filled with SU-8.

The reflective optical mirror is made from 100 nm of aluminum deposited using an electron beam evaporator. Prior to evaporation, a negative lift-off resist (Futurex NR9-1500PY) was spin coated to achieve a 1.5 μm film, and patterned to define the four concentric electrodes and connecting electrical traces, and to protect the etch vias from metallization. After evaporation, the resist was dissolved to complete the lift-off process. Next, a second liftoff process with 2.4 μm of NR9-1500PY was used to pattern a thicker layer of aluminum (500 nm) to coat the openings in the SU-8 around the TSVs to ensure the continuous transition of metal from the TSVs to the electrical traces on top of the SU-8. This thick aluminum was also used to form the metal bond pads for electrical connection to external circuits.

The final lithography step was the patterning of thick SU-8 2025 that will combine with the previous thin SU-8 to form the hinges. A dehydration bake was performed at approximately 100°C for 1 hour immediately before spin coating of the SU-8. The photoresist was spun to achieve a target thickness of 46 μm which, when layered with the 4 μm -thick thin SU-8, meets the hinge design thickness of 50 μm . The electrical traces across the hinges become encapsulated between two layers of SU-8 at this point. Thick SU-8 “plugs” are also left to provide added protection of the TSVs during the subsequent release etch. Figure 20 shows the SEM image of an inner hinge connecting the center gimbal plate to the outer gimbal ring. The thick hinge, TSV plugs, release vias on the thin SU-8 deformable membrane and electrical traces are all visible.

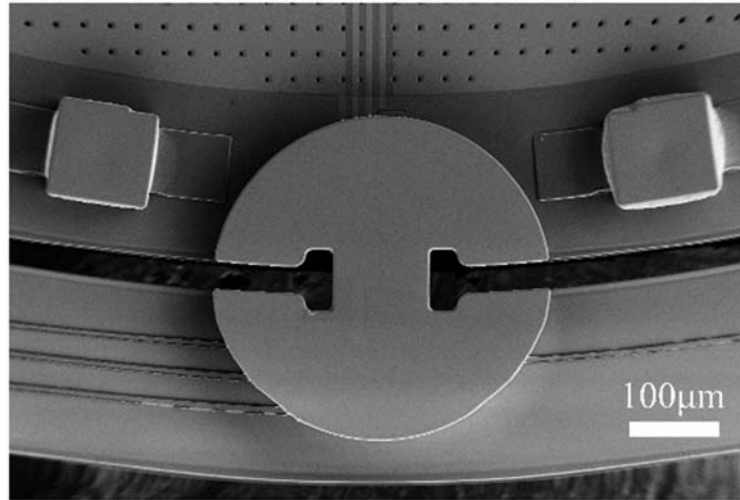


Figure 20. SEM of inner (fast) hinge after XeF_2 release etch.

Device release begins from the backside of the wafer. First, the bilayer (oxide, aluminum) differential etch mask was utilized to complete the handle layer etch and define the thickness of the center gimbal plate. The “trench etch” recipe in Table 6 was used to etch approximately $50\ \mu\text{m}$ into the wafer. It was essential that the etch depth was made to be slightly deeper than the target thickness of the center gimbal plate ($40\ \mu\text{m}$). This allows room for compensation of subsequent etch variations. The “oxide etch” in Table 6 was used to remove the oxide portion of the bilayer mask. The silicon “trench etch” recipe in Table 6 was used once more to etch the handle layer silicon to within $10\text{-}20\ \mu\text{m}$ of the buried oxide. This remaining thin layer of silicon is essential in maintaining the structural integrity of the buried oxide during front-side XeF_2 etching.

Next, a Xactic xenon difluoride etcher was used to isotropically etch the exposed device layer silicon from the front side of the wafer. The recipe is given in Table 6. Due to feature-size dependent etching, the silicon in the larger exposed regions is removed much faster than through the $4\ \mu\text{m}$ release vias. It takes about 180 cycles of etching for

larger regions, compared to 440 cycles for the silicon underneath the deformable membrane. The vertical etch stops ensure precise etch boundaries in both large open areas and underneath the deformable membrane. *Figure 21 shows an image illustrating the effectiveness of the etch stops.*

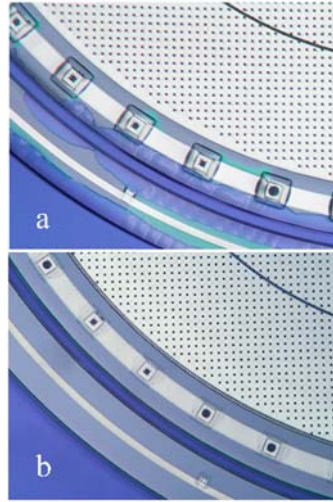


Figure 21. *Comparison of features after XeF₂ release etch. (a) Without vertical etch stops. (b) With vertical etch stops.*

The final stage of the release process was the removal of the remaining thin layer of handle layer silicon and the buried oxide layer. To remove the silicon, the wafer was etched from the backside using the previous xenon difluoride recipe. The height of the gimbal center plate can also be thinned by overetching during this step if required. Achieving the target center plate thickness required careful monitoring and tuning of the etch process. Once the silicon was completely removed and the thickness of the center gimbal plate satisfactory, a low power oxide etch was performed using an Oxford 81 plasma etcher (Table 6) to consume the buried oxide. This completes the fabrication of the gimbal wafer with deformable mirror.

The quadrant electrodes used for tip-tilt actuation of the gimbal platform were fabricated on a separate double-sided polished silicon wafer. The design of the electrodes allows for the fabrication of an annular aperture, which when paired to that of the gimbal platform provides a coaxial passage for the optical beam. The presence of this aperture does not affect the optical or mechanical characterization of the 3D mirror, and the silicon etch was omitted here for simplicity of fabrication. The process schematic is shown in Figure 22.

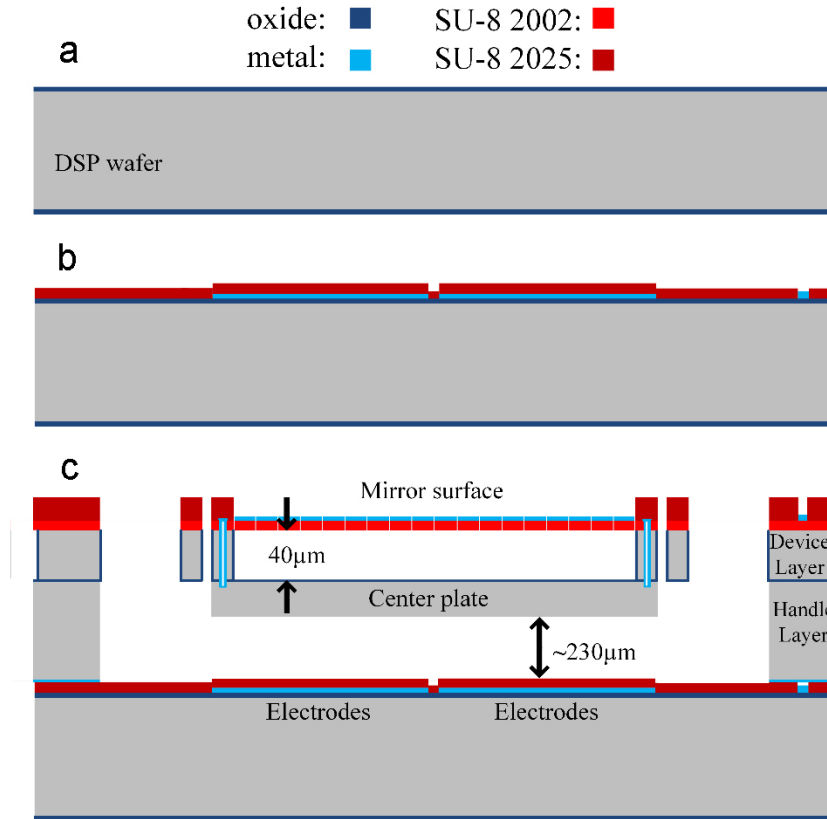


Figure 22. Fabrication schematic of electrode wafer and finished device after bonding to the gimbal wafer.

The fabrication begins with a wet oxidation to form a thick oxide layer (700nm) for electrical isolation of the individual electrodes from the silicon substrate. Next, NR9-

1500PY lift-off resist was patterned to define the electrodes, traces and bond pads. A thick 500 nm layer of aluminum was then evaporated onto the wafer. An oxygen glow discharge immediately prior to the evaporation of aluminum improved its adhesion to the substrate. The lift-off took place in acetone and was immediately transferred to an isopropyl bath afterwards and then rinsed and dried. SU-8 2005 was spin coated over the electrodes and patterned with openings over the bond pads. This dielectric encapsulation was mainly to prevent shorting from the electrodes to the gimbal plate in the event of a “snap down”. The singulated gimbal platform and actuation electrodes were aligned visually using a microscope and bonded using epoxy to complete the device. The device was then attached and wire bonded to a supporting printed circuit board. [End Excerpt]

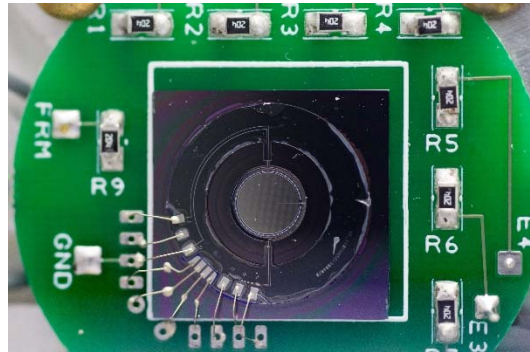


Figure 23. Device wire bonded to supporting printed circuit board.

Challenges, Solutions and Failure Analysis

In this section, the challenges encountered during the fabrication, solutions to these challenges, failure analysis of the fabricated devices, mistakes that should be avoided and some “tricks” learned during the process are described. This, in hope, will benefit future researchers who wish to construct similar devices or borrow some of the techniques

presented in this paper for their own devices. The content presented in this section does not necessarily follow the chronological order of the fabrication process, nor are all of the steps in the fabrication analyzed, as many are standard procedures and do not require special techniques or treatment.

Vertical Etch Stops

The vertical etch stops refer to the oxidized trenches used to limit the lateral etch front of the XeF_2 gas during the release process. In order to create the vertical etch stops, trenches that are 3 μm wide were etched through the device layer silicon (40 μm) to the buried etch layer. It was found that a photoresist mask (SU-8) was able to achieve a better anisotropic profile than an aluminum mask. The original etch mask that was used for this process was made using 100 nm of thin film aluminum. Aluminum was chosen due to its selectivity during plasma etching, which exceeds 1000:1. However, it was difficult to maintain an anisotropic etch profile to the buried oxide layer. Although most of the profile was anisotropic, the region closest to the surface of the wafer generally ended up with 1 μm to 2 μm of undesirable undercut, which enlarged the opening of the trenches. The problem was mitigated by tuning the etch parameter, but it was not completely resolved. Turning to published literature, the influence of masking material on etch profile was studied [97]. With this knowledge, SU-8 was investigated as an alternative to the aluminum mask. This solved the undercut problem that was occurring in regions near the surface of the wafer.

Notch-Free TSVs

As described in the fabrication process, TSVs were employed to obtain electrical connection from the surface of the device to the gimbal center plate underneath the buried oxide. One of the challenges associated with creating TSVs on SOI wafers is the notching that forms at the silicon/buried oxide interface during the etching of the vias. The notching is a product of charge accumulation and delayed etch termination once the etch front has propagated to the buried oxide, which breaks down the sidewalls surrounding the buried oxide [98, 99]. This becomes problematic, as it results in a shadowed recess that is difficult to coat during metal deposition, which results in faulty electrical connections. We used a simple method that utilizes aspect ratio dependent etching to mitigate notching without the need for sophisticated endpoint detection systems or varying process parameters to reduce charging [100-103]. An array of via apertures with incrementally varying sizes were created on each device. The vias were then etched according to the time predicted for the median size vias to terminate on the buried oxide layer. If the etching proceeds as predicted then the median size vias will indeed terminate accurately on the buried layer, and the subsequent oxide etch will expose the handle layer silicon without notching. If however, the administered etch time proves to be slightly excessive or insufficient for the median sized vias, then neighboring smaller or bigger vias will accurately terminate onto the oxide without notching. Provided a subset of the vias terminate close to the buried oxide without notching, successful electrical connection to the handle layer silicon will be achieved. This method can also mitigate the effects of location dependent etching (etch rate variability across the wafer). A smaller via will be correctly etched at a location on the wafer where

the etch rate is relatively higher whereas a larger via will be correctly etched at a location where the etch rate is relatively slower. Ranging from $18\mu\text{m}$ to $30\mu\text{m}$ in $3\mu\text{m}$ increments with 8 of each size, the TSVs on our devices were designed to accommodate a $\pm 10\%$ variation in etch time.

Figure 24 shows SEM images of a subset of the via array. It can be seen that the undercut, which is quite significant in the largest via, gradually recedes with decreasing via size, and becomes negligible in the smallest via.

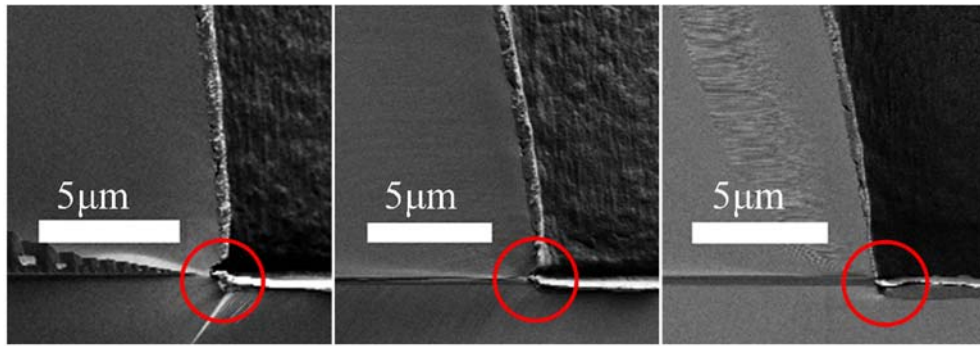


Figure 24. Notching reduction due to aspect dependent etching. The amount of notching is reduced with decreasing via aperture size from left to right. The etch profile has a slight positive taper for conformal metal coating.

Using SU-8 to Bridge Silicon Trenches

A parametric study of spin coating SU-8 over high aspect ratio trenches and vias was conducted to determine optimized parameters for spin coating during MEMS mirror fabrication. The parameters investigated included feature width ($3 - 12\mu\text{m}$), depth ($20 - 40\mu\text{m}$), radial location on the wafer ($10 - 40\text{ mm}$), angular orientation ($0 - \sim 90^\circ$), resist viscosity (SU-8 2002, 2007, and a 5:3 mixture of 2002 and 2007), and spin velocity ($3000 - 4000\text{ rpm}$). The term high aspect ratio is used to denote the proportion of vertical dimension or depth to feature width. For this study aspect ratios were as high as 13.3:1. Features were

evaluated on successful bridging (continuity of resist across the trench or via) and planarity (smoothness of the resist profile over the features). Successful bridging was defined as the continuity of resist over a coated feature as shown in Figure 25.

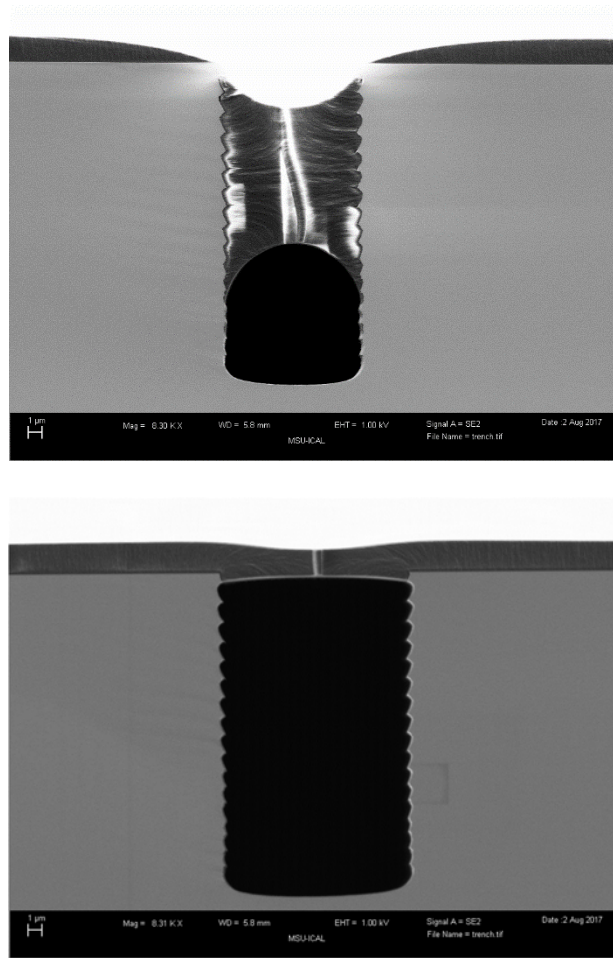


Figure 25. Unsuccessful (left) bridging compared to successful bridging (right).

All wafers were fabricated using a standard ICP etch (Trench Etch, Table 6) and photolithography to create substrate topography. The process for spinning the experimental coat of SU-8 consisted of the following in the order stated: dehydration bake, spin coating with static dispensation, ramped soft bake, photolithographic exposure, immersion in SU-

8 developer, ramped hard bake. All bakes utilized hotplates and all ramps were at 360°C/hour.

In order to bridge the high aspect trenches on the surface of the wafer, SU-8 was used to permanently fill and planarize the trenches. The spin coating of a variety of viscosities of SU-8 using different spin speeds onto wafers carrying a spectrum of trench dimensions (width: 3 - 12 μm , depth: 20 - 40 μm) was investigated. Our results indicate that more successful bridging was correlated with higher viscosities, higher spin speeds and shallower etch depths. Correlations between trench width and bridging were inconclusive within the tested parameters. No obvious trends were observed between bridging and location on wafer. Results signified that bridging was influenced by both spin speed and resist viscosity. A higher spin speed or viscosity resulted in better bridging, but successful bridging did not correlate directly with resultant film thicknesses. This means that a more viscous resist at higher spin speed is more desirable than a less viscous resist at lower spin speed even if the final film thickness is the same. Related to fabrication, the findings of the study suggests using ramped hard bakes during the fabrication process to minimize and even eliminate the presence of air bubbles. Similar experiments involving spin coating over substrate topography have been conducted and have reported decreasing planarity with increasing feature width [104, 105]. However, these past studies have focused on topography with a far lower aspect ratio than was investigated in the in this work (13:1) which is often required for MEMS applications.

Fracturing of SU-8 and Electrical Traces

Perhaps the biggest problem that occurred during the fabrication process is the fracturing and delamination of the SU-8 photoresist during the xenon difluoride release process. It appears that the SU-8, both thick and thin would fracture and lift from the silicon substrate. This would occur at numerous locations around the wafer. A portion of the fractures were located in blank areas between devices, which did not affect the functionality of the devices. However, when the fracturing did occur at the device, especially at the locations of the electrical traces, it would sever the traces, rendering the device inoperable. It was noticed that the amount of fracturing would also increase as more silicon was removed. Figure 26 displays microscope images of these fractures taken after xenon difluoride release. Close inspection of the device suggested that the fracturing was most severe on the devices with the smallest hinge anchors, whereas less was found on the devices with the continuous hinge anchors.

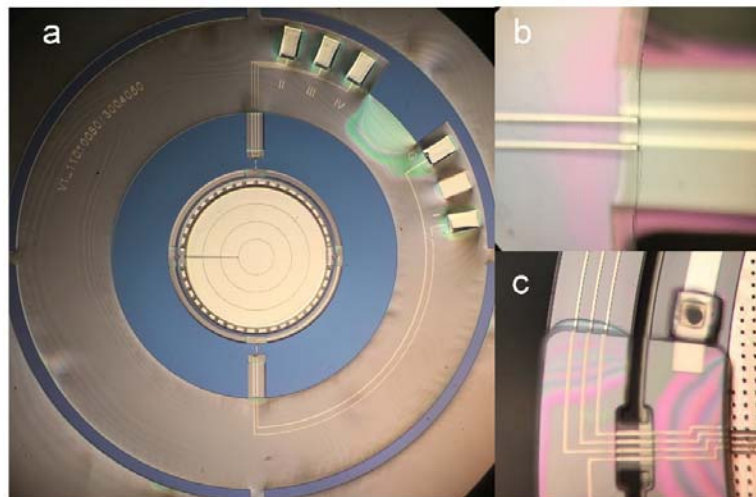


Figure 26. (a). Microscope image of a single MEMS device on the wafer. (b). A magnified image of the fracturing close to the slow hinges. It can be seen that the electrical traces have been severed due to the fracturing. (c). A magnified image of the fractured traces near the fast hinges.

One hypothesis for the fracturing was insufficient dehydration of the wafer prior to the xenon difluoride etch. Although the wafer was hardbaked for an extended duration of time after the thick SU-8 hinge material was patterned. However, between the completion of patterning and the xenon difluoride release etch, the wafer was stored in an atmospheric environment. Since SU-8 is known to absorb water, this provided the opportunity for rehydrating the wafer again [106]. This theoretically could be a problem, as the presence of water during a xenon difluoride etch enables the following side reaction:



The hydrofluoric acid (HF) formed by the above reaction is known to reduce the adhesion of resist to the substrate and eventually result in delaminated resist [107]. To test this hypothesis, the dehydration bake performed immediately prior to release process was increased from 10 minutes at 95°C on a hotplate to an extended ramped oven bake. The extended oven bake started at room temperature and ramped gradually to 200°C in approximately 50 minutes. The wafer was then held at 200°C for approximately 50 minutes before naturally cooling back down to room temperature. The entire process took 500 minutes. This unfortunately did not improve the fracturing and delamination issue. The number of fractures that occurred on this wafer was no less than that of those without the extended dehydration bake treatment.

Additionally, to further improve the adhesion of the SU-8, the substrate material was redesigned from silicon dioxide to silicon [108]. This did not seem to help with the fracturing either.

The second hypothesis was as more silicon was removed, the amount of area anchoring the SU-8 decreased and eventually, the tensile stress in the SU-8 layer was great enough to delaminate itself from the substrate. The residual stress in the SU-8 is a function of the temperature of the bakes that the resist has been through [109]. A slow ramped bake along with a gradual cooling process generally resulted in less stress than a baking process that was more abrupt. This was taken into consideration during subsequent fabrication attempts, but no significant improvement was observed during the release process. The final yield was approximately 14%. This was based on the number of devices that could both scan and perform some degree of focusing. Perhaps in the future, a more dedicated analysis of thin film stress could shed light on how to mitigate this problem.

CHAPTER FOUR

DEVICE CHARACTERIZATION

In this chapter, the optical, electrical and mechanical characterization of the fabricated devices are described. This includes the deflection of the membrane, the intrinsic stress of the SU-8, both the static and resonant scan of the gimbal platform and a demonstration of 3-dimensional scanning. This chapter contains excerpts from a previous journal publication [73].

Deformable Mirror Electrostatic Actuation

We begin with the characterization of the deformable mirror. Details regarding the initial flatness of the mirror is provided. The measurements of the center deflection as a function of the applied voltage is also included. Last, the experimental results of the spherical correction capabilities of the mirror is assessed using differential voltages applied to the concentric electrodes.

Initial Flatness

[Begin excerpt] The structural SU-8 layers develop an intrinsic stress, largely due to the difference in coefficient of thermal expansion compared to the underlying silicon (SU-8: 52ppm/°C, Si: 2.6ppm/°C) [110]. The SU-8-on-silicon structure of the gimbal ring and the central gimbal plate forms a bimorph with a bending moment. This induces a curvature of both the central plate and the gimbal ring, potentially compromising the flatness of the mirror membrane. To investigate this issue, torsional hinges with anchors of

various sizes were fabricated. The first type of hinge anchor is the full hinge anchor, where the thick SU-8 forms a continuous ring around the perimeter of the center gimbal plate and the gimbal ring (Figure 27a). The second type is the reduced hinge anchor where the thick SU-8 is localized to the tether points on the central plate and the gimbal ring (Figure 27b). The surface shape of the released mirror was measured using a Michelson phase shift interferometer. Representative interferograms (measured with $\lambda=650$ nm) are shown in Figure 27. The mirrors with full and reduced hinge anchors are located at similar locations on the same wafer, to minimize the influence of other fabrication variables. With a continuous ring of SU-8 at the perimeter of the mirror and on the gimbal ring, we observed strong astigmatism with a peak-to-valley amplitude of ~ 2.5 waves (at 650 nm), corresponding to $2.5 \times \lambda / 2 = 810$ nm of surface height variation. With the reduced footprint hinge anchor, the observed astigmatism is less than 0.5λ , corresponding to less than 160 nm peak-valley surface deviation. The measurements indicate that the reduced hinge anchors result in better initial optical flatness of the mirror surface, which we attribute to minimizing the bimorph effect of the stressed SU-8 layer over the silicon.

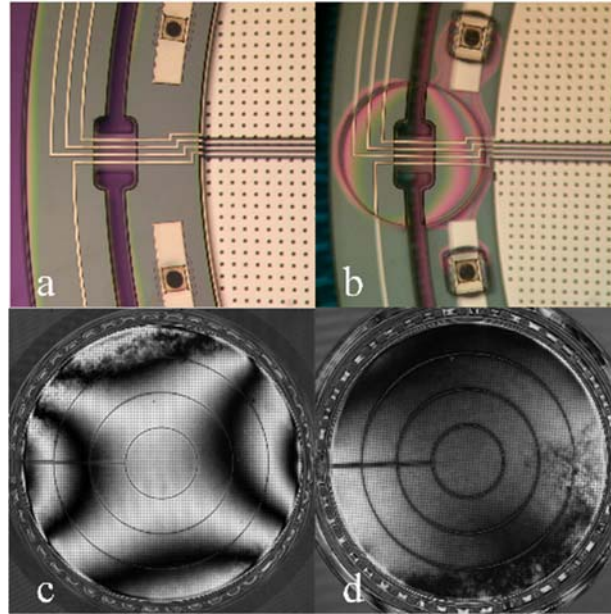


Figure 27. (a) Photograph of full hinge anchor (thick structural SU-8 continuous over the perimeter of the center plate and the gimbal ring). (b). Photograph of reduced-size hinge anchor. (c). Interferogram of mirror surface with full hinge anchor. (d) Interferogram of mirror surface with reduced hinge anchor. Interferogram data is taken after release of the device.

Focus Control

For electrostatic deflection of the deformable membrane, the metal mirror layer was biased relative to the underlying silicon of the gimbal center plate. Figure 28 shows a plot of the center deflection of the membrane as a function of applied voltage. At 160V, the mirror deflection is $9.1\text{ }\mu\text{m}$, which corresponds to a focal length of approximately 110 mm.

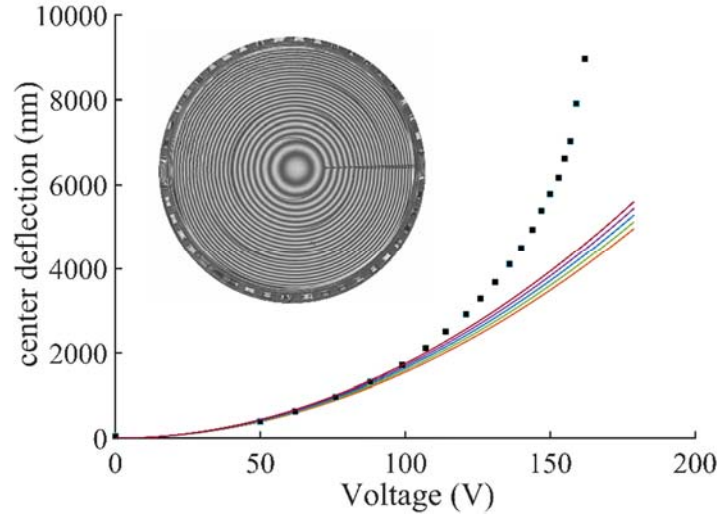


Figure 28. Center deflection as a function of voltage for the deformable mirror. The solid lines are quadratic curve fits representing intrinsic stress from 3.75MPa to 4.25MPa. The inset is an interferogram image of the surface of the mirror at 9 μ m of center deflection.

From this data, we calculated the intrinsic stress of the membrane. The intrinsic film stress directly relates the actuation voltage to membrane deflection. At small deflections, the membrane deflection depends quadratically on the applied voltage according to $s_0 = \frac{\epsilon_0 V^2 r_0^2}{8g^2 \sigma t}$ [88], where ϵ_0 is the permittivity of air, V is the applied voltage, r_0 is the radius of the membrane (2000 μ m), g is the depth of the air gap (40 μ m), σ is the intrinsic stress and t is the thickness of the deformable membrane (4.2 μ m). By performing a quadratic curve fit to the portion of deflections under 2 μ m, the intrinsic stress is calculated to be approximately 4.0MPa (tensile) [74]. This is quite low compared to that of similar SU-8 suspended membranes with intrinsic stress ranging from 13.8MPa to 32MPa [88, 109]. The reason for this lower intrinsic stress is uncertain, but several parameters of the current process are different from those reported previously, including the specific thermal processing steps, the use of a mixture of SU-8 2007 and SU-8 2002 for the

membrane, and the double exposure process used to pattern the vias in the membrane. [End Excerpt]

With the center deflection data, we can assess the axial imaging depth in skin. As mentioned before, the axial Rayleigh resolution defined as the distance from the peak of the light distribution to the first null can be expressed as $z_R = 2n\lambda_o/NA^2$, where n is the index of refraction of the media being imaged (human skin: $n = 1.43$) [80, 81] and NA is the image-space numerical aperture. For a proposed $NA = 0.70$ and $\lambda_o = 633nm$, $z_R = 3.69\mu m$. The number of axial zones that are resolvable is $N_z = 2\delta/\lambda_o$, where δ is the maximum achievable deflection. The mirrors have demonstrated deflections as high as $10\mu m$, which when integrated into our optical system, corresponds to $N_z = 2 \times 10/0.633 = 31.6$ zones. This provides $116.6\mu m$ of focus range. In order to maintain a parabolic profile throughout this range, the concentric electrodes need to be utilized to offset the induced spherical aberration. The correction of spherical aberration is provided below.

Spherical Aberration Correction

The ability of the mirror to control spherical aberration is experimentally tested. To do this, the quadrant electrodes are biased using independent voltages. The amount of spherical aberration correction that can be achieved at a given defocus is limited by the differential voltage that can be maintained between the electrodes. Electrical breakdown, or arcing, limits the amount of voltage differential that can be maintained between the concentric electrodes. The location on the 3-dimensional scanner that is most prone to electrical breakdown is at the hinges where the separation between neighboring electrode

traces become as small as 8 μm . In order to avoid arcing, it is necessary to evaluate the maximum voltage differential that can be tolerated. To do this, each of the concentric electrodes, in turn, were biased relative to the remaining three electrodes. Experimental results have shown that the electrodes are capable of handling differential voltages in excess of 200V, and up to 250V between the outermost electrode and the innermost electrode. The increased tolerance between the outermost and innermost electrode is due to the layout of the electrodes and the traces on the device. Adhering to the voltage limitations described above, the range of adjustment for first order (Z_{40}) and second order (Z_{60}) spherical aberration was tested centered on a baseline defocus (Z_{20}) value of approximately 1850nm (3.7 μm nominal deflection). The maximum observed values for Z_{40} and Z_{60} (non-normalized) were 255 nm and 175 nm, respectively, while the minimum values were -149nm and -236nm. This does not represent the full range of values that can be achieved. A more in depth analysis of the spherical aberration adjustment capabilities using a deformable mirror very similar to the one shown in this dissertation is documented by Lukes, et al. [111].

Torsional Scanning

In this section, the torsional scanning is characterized. This includes the resonant frequency, the static scan angle as a function of bias voltage, dynamic scan angle, inertial deformations on the surface of the mirror and a demonstration of simultaneous bi-axial scanning with focus adjustment. The influence of temperature and humidity on the SU-8 flexures is also investigated by monitoring the resonant frequency of the device.

Torsional Resonant Frequency

[Begin Excerpt] To characterize torsional scanning, the resonant frequencies for both the inner fast axis (y) and slow outer axis (x) were measured. To do this, the fast and slow axes were actuated individually using the quadrant electrodes to scan a reflected laser beam onto a position sensitive detector. For actuation of the slow axis, electrodes 2 and 3 (Figure 7) are tied together and biased relative to the grounded gimbal center plate using a $50V_{pp}$ (peak-to-peak) sinusoidal voltage with a $100V_{DC}$ offset. The remaining two electrodes are grounded. The scan angle amplitude (peak-to-peak mirror mechanical scan angle) was monitored as the frequency of the sinusoidal input was gradually increased. Figure 29 (solid line) shows the measured slow axis (x) frequency response from a selection of devices. The variation in resonant frequency is mainly due to slightly different inertial masses as a result of a selection of hinge anchor sizes. The mechanical Q factor for these measured devices is approximately 22. The frequency response of the inner fast axis (y) was measured similarly, except that electrodes 1 and 2 were actuated instead of 2 and 3, and the actuation voltages were increased to $120V_{pp}$ sinusoidal voltage and $240V_{DC}$. As mentioned before, flexures with three different values of torsional stiffness were designed to compensate for variances in the fabrication process. The results are shown in Figure 29. The mechanical Q factor for the measured resonant slow, standard and fast flexures are respectively 32, 35 and 39.

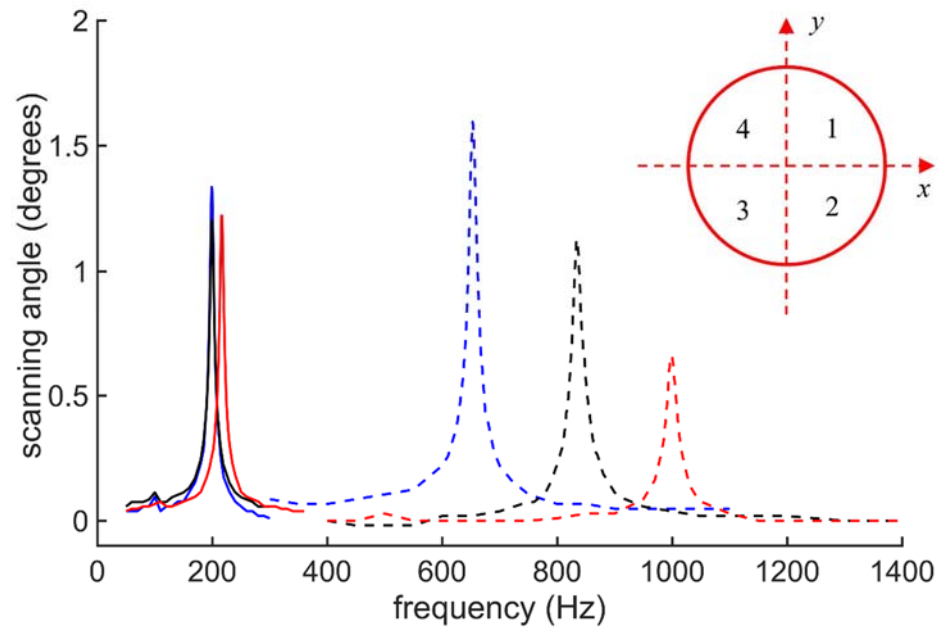


Figure 29. Frequency response of the fast and slow axes (peak-to-peak mechanical).

Static Scan Angle

The static scan angle of the outer axis (x) as a function of actuation voltage was also measured and displayed in Figure 30. As was done for the frequency response measurements, electrodes 2 and 3 were tied together and biased relative to the grounded center plate using a DC voltage. The DC voltage was increased gradually and the position of the scanned beam on the image plane was recorded.

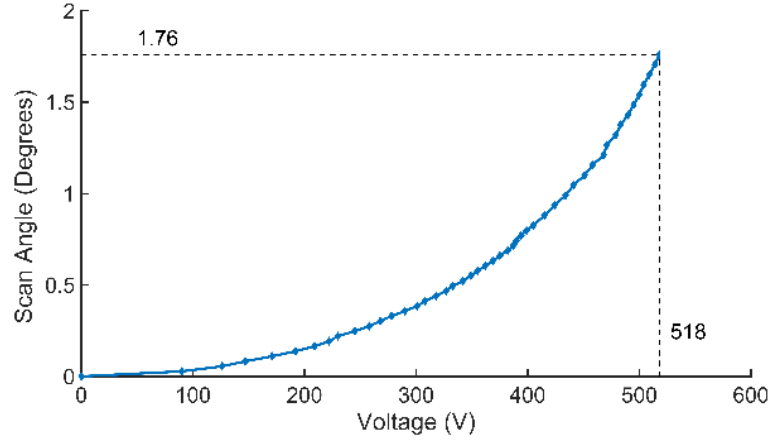


Figure 30. Outer axis 0-to-peak mechanical static scan angle.

As described in Chapter 2, at any given point along the plot in Figure 30, the restoring mechanical torque generated by the torsional hinges is equal to the electrostatic torque provided by the electrodes. The electrostatic torque generated from actuating half of the mirror is $T_E = \int F(x) x dA$, where $F(x)$ is the electrostatic force. For small scan angles, $(x) = \frac{1}{2} \frac{\epsilon_0 V^2}{(s_0 - x\theta)^2}$, where V is the applied voltage, s_0 is the quiescent separation between the quadrant electrodes and the center plate, and θ is the mirror mechanical scan angle. For a circular plate, the differential area of applied force can be expressed as $dA = 2\sqrt{R^2 - x^2} dx$, where R is the radius of the center plate ($2200\mu\text{m}$). The restoring torque of the hinges is a function of the mechanical scan angle and the torsional stiffness of the hinges. The torsional stiffness is governed by material properties that include the Young's modulus and Poisson's ratio. We assign a Poisson's ratio of 0.22 to the SU-8 hinges, based on values reported in the literature and from the SU-8 datasheets, taking into account our process parameters. By equating the electrostatic torque to the mechanical torque generated by the hinges along the curve in Figure 30, we calculated the Young's modulus to be 4.8 GPa for

the combined SU-8 layers. To ascertain consistency of results, the calculated Young's modulus value was used to compute the slow axis resonant frequency for the same device, a different device on the same wafer, and a device on a different wafer. The results are shown in Table 8. For this calculation, measured device dimensions were used. The small variations suggest a relatively consistent result for Young's modulus.

Table 8. Verification of Young's Modulus using Resonant Frequency

Location	Measured	Calculated	Variation
Same device	223 Hz	229 Hz	2.6%
Different device same wafer	199 Hz	203 Hz	2.0%
Different device different wafer	219 Hz	234 Hz	6.4%

Dynamic Scan Angle

During bidirectional scanning, all four electrodes were activated, with superimposed DC and AC voltages. To test this mode of actuation, the dynamic scan angle as a function of the peak-to-peak amplitude (V_{pp}) of the drive voltage was measured for both the x and y axes under resonant operation, with $V_x = \frac{V_{ppx}}{2} \sin(\omega_x t)$ and $V_y = \frac{V_{ppy}}{2} \sin(\omega_y t)$. For off-resonance 1Hz scanning for the x axis, V_x was a 1 Hz triangle wave with amplitude V_{pp} . The drive voltages for the four quadrants of the electrode are, respectively, $V_1 = V_{DC} + V_x + V_y$, $V_2 = V_{DC} - V_x + V_y$, $V_3 = V_{DC} - V_x - V_y$ and $V_4 = V_{DC} + V_x - V_y$.

The results, shown in Figure 31, indicate that the fast axis (y) is capable of achieving a mechanical scan angle times mirror diameter product (θD product) of 12

deg·mm with applied $V_{pp} = 530V$ and $V_{DC} = 300V$. This is sufficient for XGA resolution of 1024 resolvable spots, assuming a diffraction-limited reflected beam [79].

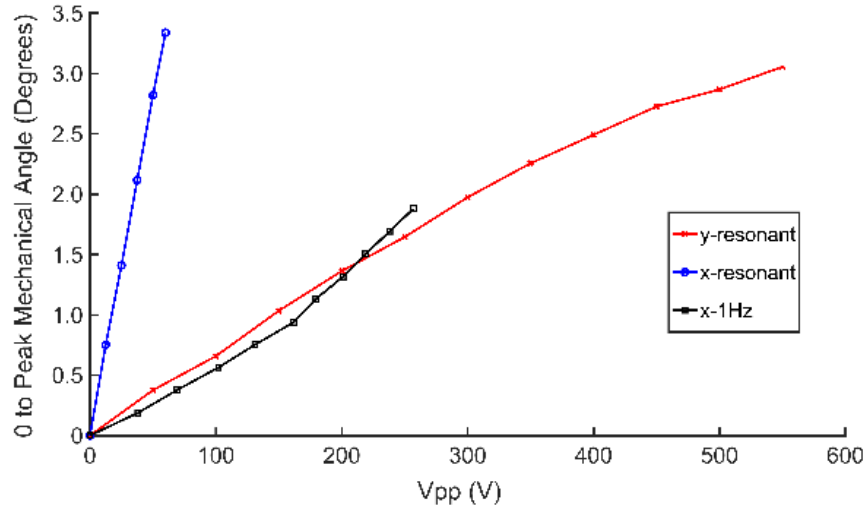


Figure 31. Dynamic scan angle as a function of actuation voltage.

Inertial Deformations on Mirror Surface

We measured as much as $\pm 3^\circ$ deg mechanical scan angle for the resonant fast scan. However, large scan angles coupled with high-frequency scanning can lead to degradation of the optical flatness of the mirror surface. This is due to the inertial forces associated with the angular accelerations. It is a dynamic effect, maximum at the peak excursion and absent in the center of the scan. Figure 32 shows a finite element simulation of the maximum deflection of the surface of the membrane due to inertial forces when the fast axis is operated at 1kHz with a $\pm 3^\circ$ mechanical scan angle. The membrane thickness, density, and intrinsic stress used for this simulation were, respectively, $4\mu\text{m}$, 1100kg/m^3 and 4MPa . By performing a Zernike polynomial fit to this surface, we find that the main optical aberration is coma $Z_{3,1}$ [112]. Approximately 66nm (rms surface deviation) of coma was present at

$\pm 3^\circ$ peak scan angles, which is double the target deflection. For operation at our target range of $\pm 1.5^\circ$ peak scan angle (with a θD product of 6 deg·mm, equivalent to approximately 500 resolvable spots) the inertial coma aberration was simulated to be approximately 32nm rms. Modifying the design of the membrane could also be effective at reducing dynamic distortion. For example, reducing the membrane thickness while increasing residual stress to maintain overall tension (and hence maintaining the mechanical restoring force) would reduce the area mass density, proportionally reducing dynamic distortion.

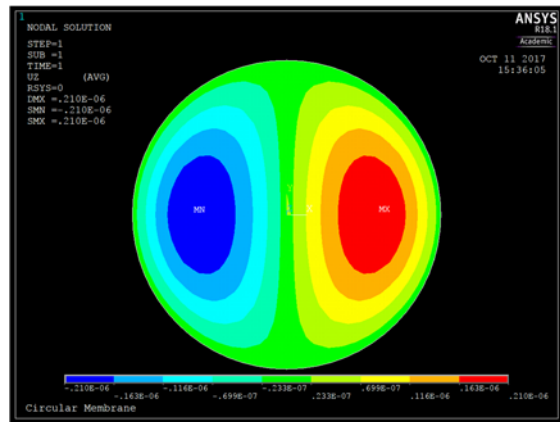


Figure 32. Simulation of deformations on the membrane surface due to inertial forces. Scale bar range is from $-0.210\text{E}-6$ to $0.210\text{E}-6$.

Demonstration of 3-Dimensional Scanning

Biaxial scanning with focus control was demonstrated using the MEMS device. While the target application for this mirror is a scanning laser microscope as illustrated in Figure 3, we used a simplified test setup for this demonstration, as shown in Figure 33. A 633nm laser is expanded using a 200mm lens to fill the aperture of the mirror. The MEMS mirror was then used to scan and focus the laser onto an image plane.

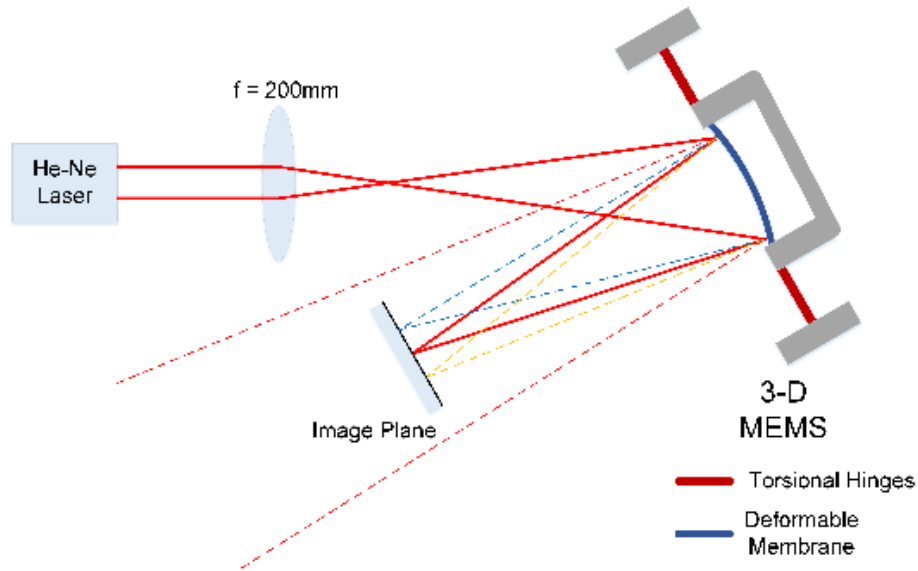


Figure 33. Schematic of setup for biaxial scanning with focus control.

Figure 34 is a Lissajous pattern scanned onto the image plane by the MEMS device, with the fast frequency 808 Hz and the slow frequency 207 Hz. With no voltage on the deformable mirror, the device acts like a flat mirror and the reflected beam from the mirror maintains its expanding path, forming a defocused scan-pattern on the image plane (Figure 34a). Biasing the deformable mirror with 129V produces a surface with positive optical power to focus the expanding beam accurately onto the image plane (Figure 34b). The distance from the lens to the mirror and from the mirror to the image plane is, respectively, 584mm and 1016mm, corresponding to a focal length of the mirror of 278 mm with 129 V applied.

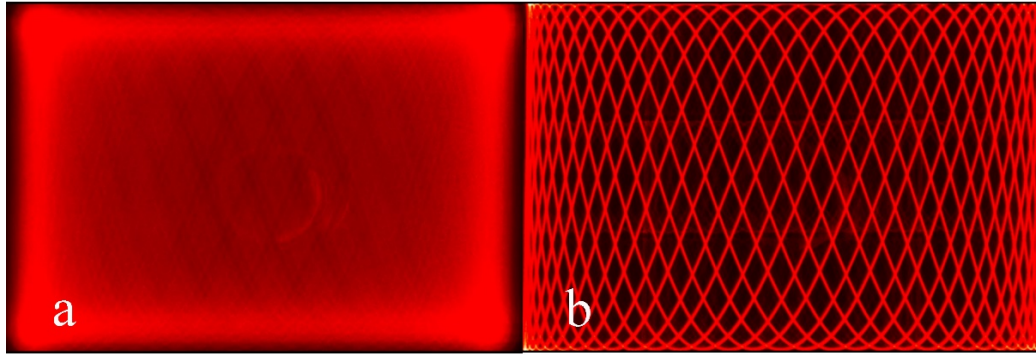


Figure 34. Biaxial scan pattern. (a) Not focused. (b) Focus is achieved through actuation of deformable membrane. $V_{DC} = 200V$, $V_{ppx} = 32V$, $V_{ppy} = 152V$ and $V_{focus} = 129V$ (when applied).

[End excerpt]

For the confocal imaging described in Chapter 5, the mirror is used to raster the imaging beam onto the sample. To create the raster pattern, the slow axis is driven non-resonant using a saw tooth waveform while the fast axis is driven at its resonant frequency using a sinusoidal waveform. Figure 35 provides a picture of a raster scan pattern with the slow axis at 5 Hz and the fast axis at the resonant frequency of 808 Hz.

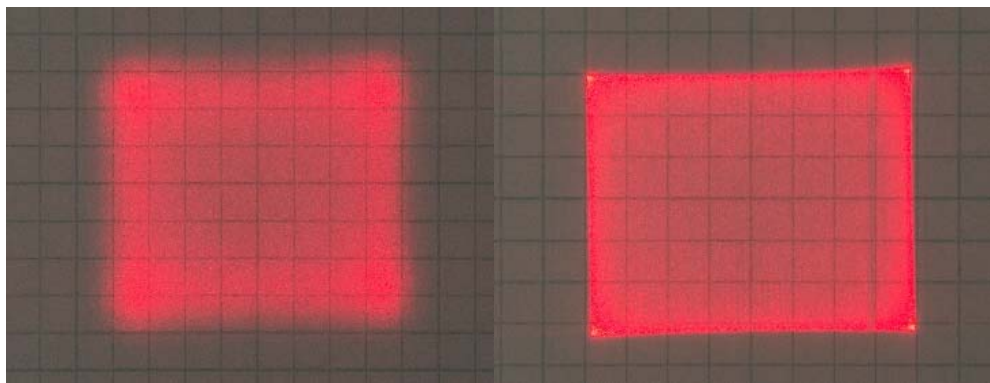


Figure 35. Raster scan patterning illustrating the concept of scanning laser imaging. The beam is focused using the MEMS device. $V_{DC} = 200V$, $V_{ppx} = 32V$, $V_{ppy} = 280V$ and $V_{focus} = 118V$ (when applied).

Influence of Temperature and Humidity on Measured Behavior

The mechanical properties of SU-8 is susceptible to change under varying ambient temperature and/or humidity [113]. To quantify the influence of these environmental factors, the resonant frequency and scan length were monitored when the devices were subject to varying temperatures and relative humidity (RH). A four-quadrant photo detector is used to detect the scanned beam position, which is used to extract the resonant frequency and scan length. A temperature humidity chamber allowing independent control of temperature and humidity was constructed for this experiment. An illustration of the chamber is shown in Figure 36. The humid air is generated using a commercial humidifier capable of providing 100% RH, whereas the dry air source has approximately 5% RH. This allows for a range of 5% to 100% RH. The setup is divided into a mixing chamber where humid air is mixed with dry air to acquire the desired humidity before it is directed to the experimental chamber where the MEMS device resides. The MEMS is heated/cooled using a thermal electric cooler (TEC). The TEC is sandwiched between an aluminum stage holding the MEMS device and heat sink. This provides a maximum temperature range of approximately 5°C to 60°C. The thermistor fixed onto the aluminum stage is calibrated to an external thermal couple (not displayed) that is positioned onto the frame of the MEMS device. The thermistor reading is used to indicate the temperature of the MEMS device during measurements. The temperature and RH in both chambers are monitored and recorded for each measurement.

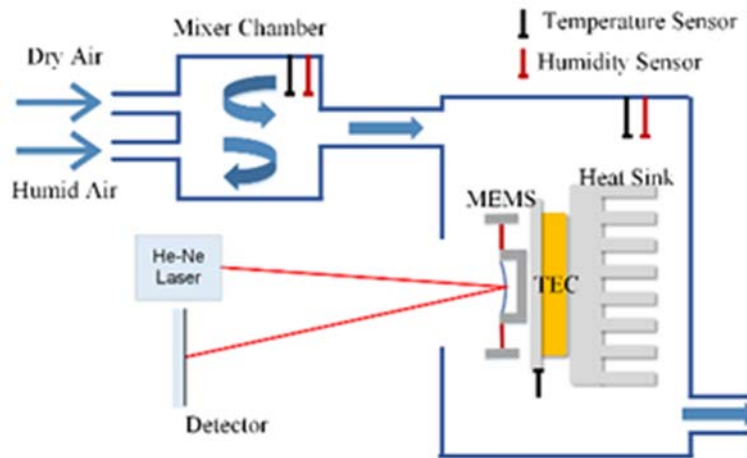


Figure 36. Schematic of temperature/humidity chamber.

[Begin Excerpt] The MEMS scanner was placed inside the chamber and exposed to either a humidity or temperature variation while the other parameter was maintained at a constant value. For each experiment, the resonant frequency was monitored until steady state operation was achieved before measurements were recorded. The settling time after a change to temperature was on the order of seconds and humidity, minutes. For the temperature testing, the humidity was kept constant at 5% relative humidity to reduce the likelihood of condensation on the MEMS device. Figure 37a shows the resonant frequency shift as a function of temperature. Over the range of temperatures tested, a decrease of approximately 20Hz (2%) was observed. [End Excerpt] Figure 37b shows scan length as a function of temperature. A longer scan length is observed with an increase in temperature. It is speculated that the increase in temperature reduces the Young's modulus of the SU-8 (becomes softer). This reduction in Young's modulus results in less torsional stiffness and therefore a longer scan length.

[Begin Excerpt] Humidity also has a measurable effect on the resonant frequency at high relative humidity (Figure 37c). The overall change in frequency over the humidity range tested was small, approximately 6 Hz (0.6%) shift. A possible explanation of the resonant frequency effect is absorption of water into the SU-8 flexures and anchors. This will cause mass loading, as well as a possible change in the Young's modulus. The frequency shift results were similar to that reported by Schmid et al. [113]. [End Excerpt]

Though slight variations in the scan length were detected in Figure 37d, no general trend was obvious.

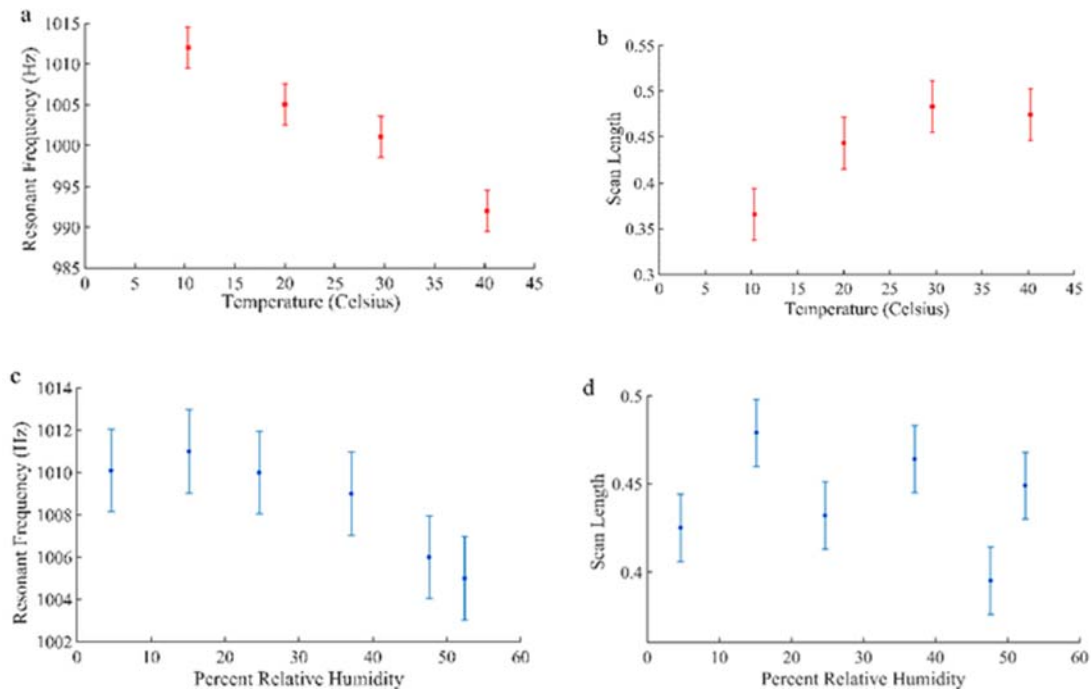


Figure 37. The effects of temperature (top) and humidity (bottom) on the resonant frequency (left) and scan length (right) of the MEMS device.

The response of the mirror to temperature and humidity could pose a problem to applications outside of a controlled laboratory environment. The shift in resonant frequency due to humidity and especially temperature is on the order of the mechanical

bandwidth of the mirror. This must be addressed to ensure consistent imaging using the MEMS device. This could be done by minimizing the change in these environmental factors and/or by adjusting the actuation to compensate for these changes. In terms of minimizing the impact, the MEMS device could be housed in a sealed enclosure to eliminate the effects of change in external humidity. The MEMS can also be mounted to a thermal electric heating stage (like in Figure 36), this along with feedback temperature sensors can be used to offset the fluctuation in external temperature. In terms of compensation through actuation, position sensing closed loop control can be used to adjust the drive voltages according to the change in scan length/angle.

CHAPTER FIVE

CONFOCAL MICROSCOPY WITH THE MEMS 3-D SCANNER

Confocal microscopy demonstrates great potential to becoming an alternative to physical biopsies for the detection of malignant skin cells. Compared to physical biopsies, in-vivo confocal microscopy is non-invasive, dense sampling and can provide real time results. However, the current size of confocal microscopes renders it impractical in all but the most accessible locations. For example, skin cancers such as lentigo maligna melanomas, basal and squamous cell carcinomas often occur in the regions around the neck, nose, ears and eyes that are hard if not impossible to access with a large objective lens [23]. The large size is mainly attributed to the bulky mechanisms required for scanning and focusing the imaging beam. Microelectromechanical systems (MEMS) have proved instrumental to addressing this weakness. Prior work have shown the use of MEMS scanners and deformable mirrors to replace large galvanometric metal scanners and mechanical focus components to result in handheld microscopes [28, 30, 34, 49, 114-116].

In this chapter, the integration of the MEMS 3-dimensional scanner into a benchtop confocal microscope to demonstrate the imaging capabilities of the scanner is described. This is a proof of principle demonstration for a future pencil-sized confocal microscope based on this scanner. The construction of the microscope, optical performance of the system, image acquisition process, sample preparation and actual images acquired with the system are presented in detail in this chapter.

System Setup

A confocal microscope based on the MEMS 3-dimensional scanner was constructed to assess the imaging capability of the integrated laser scanning microscope. The schematic of the optical setup is shown in Figure 38. The illumination is from a 633 nm helium neon laser. The optical fiber is a single mode fiber with NA between 0.10 to 0.14 and a mode field diameter of 3.6 μm to 5.6 μm . The compound lens system (including hyperhemisphere) has an effective focal length of 14.78 mm (in air), image space NA of 0.57 and an object-space NA of 0.010 to match that of the single mode fiber. The compound lens data as well as its Zemax rendition is provided in Figure 39. The 2 mm diameter hyperhemisphere objective lens is made from a half-ball lens centered on and cemented to a 500 μm thick, 50.8 mm diameter glass wafer, which also serves as the sample stage. The sample is attached to the side of the glass wafer opposite to the hyperhemisphere lens. The MEMS scanner is mounted onto a stage (not shown) with three degrees of translational freedom and two degrees of rotational freedom facilitating focus adjustment and alignment. A 50/50 beam splitter is positioned between the optical fiber and the compound lens element to direct the incident and reflected light. A 10 μm pinhole is positioned conjugate to the optical fiber to spatially filter the reflected light. An avalanche photo detector is used to collect the light. The laser from the optical fiber travels to the beam splitter where it is directed to the compound lens. The lens converts the diverging beam to a converging beam, which, after passing through the transparent sample stage, becomes an annular shaped beam due to the obstruction of the hyperhemisphere. This annular beam is incident onto the MEMS device and scanned back onto the hyperhemisphere. The hyperhemisphere

completes the focusing of the beam onto the sample. The return beam from the sample travels back through the hyperhemisphere onto the MEMS device where it is de-scanned and sent to the compound lens. The light from the compound lens is then directed by the beam splitter to the pinhole. Upon passing the pinhole, the light is collected by the avalanche photodetector where the intensity information is sent to the computer.

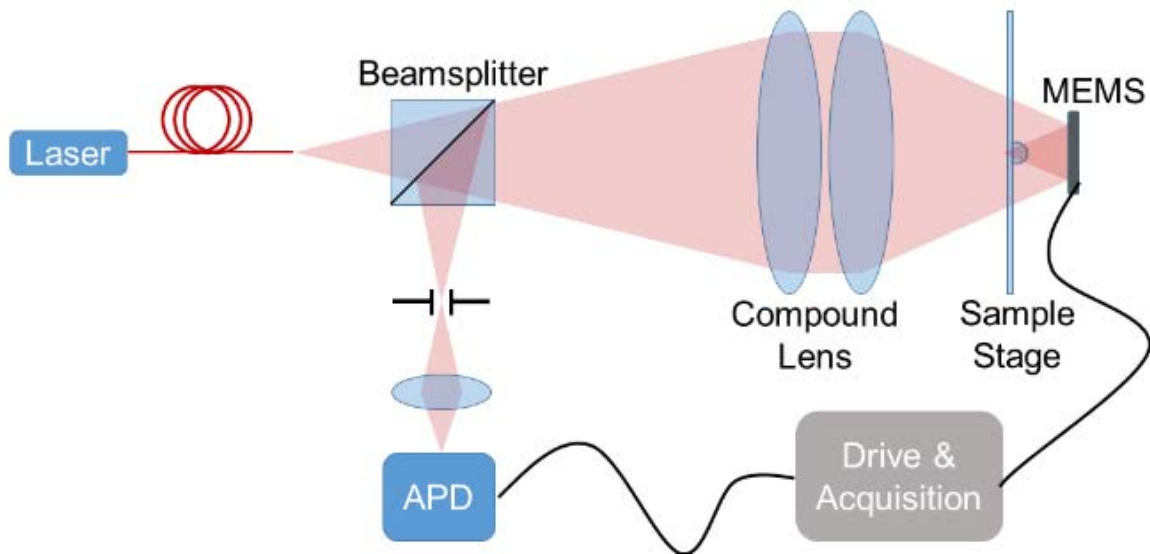


Figure 38. Schematic of confocal imaging setup.

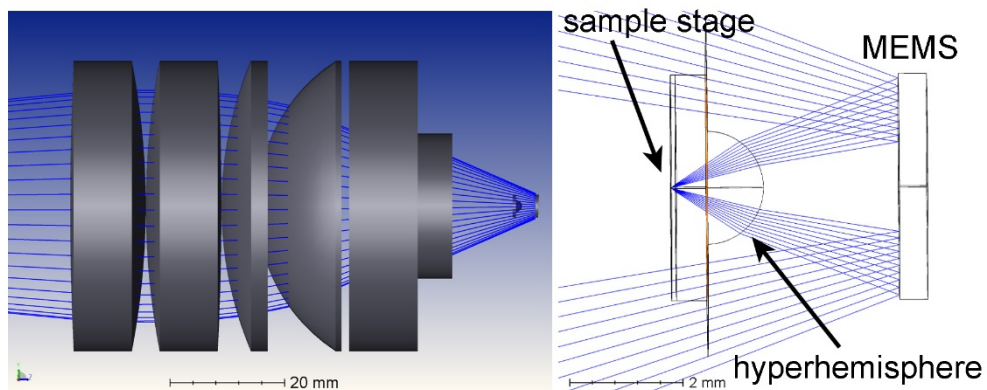
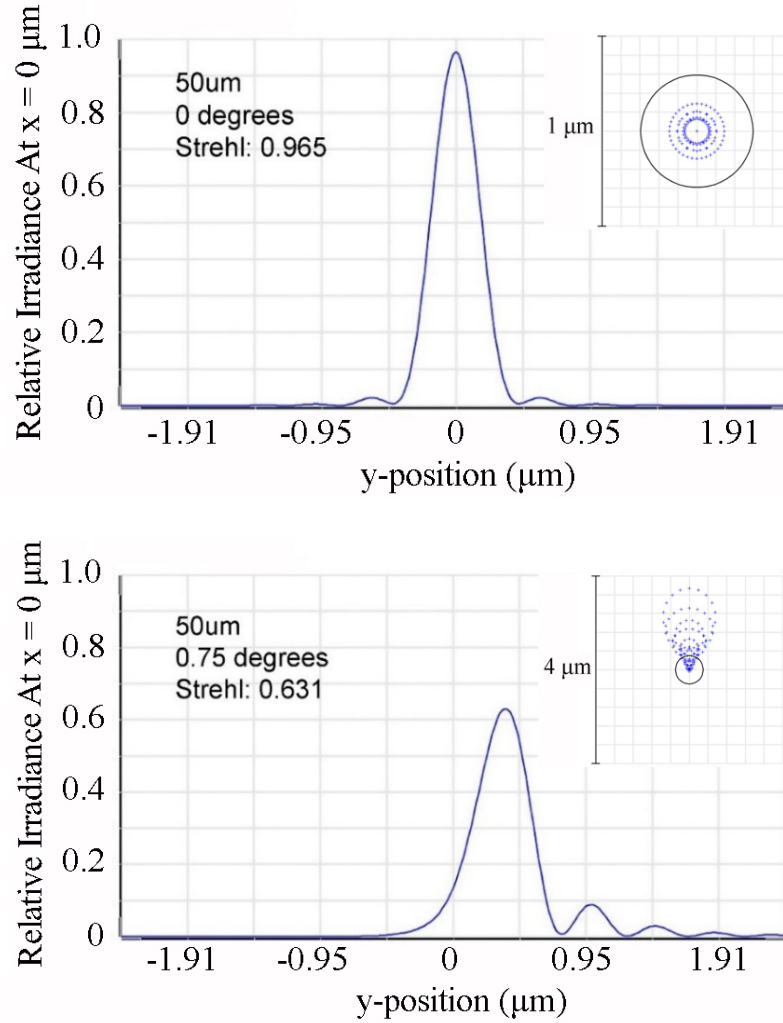
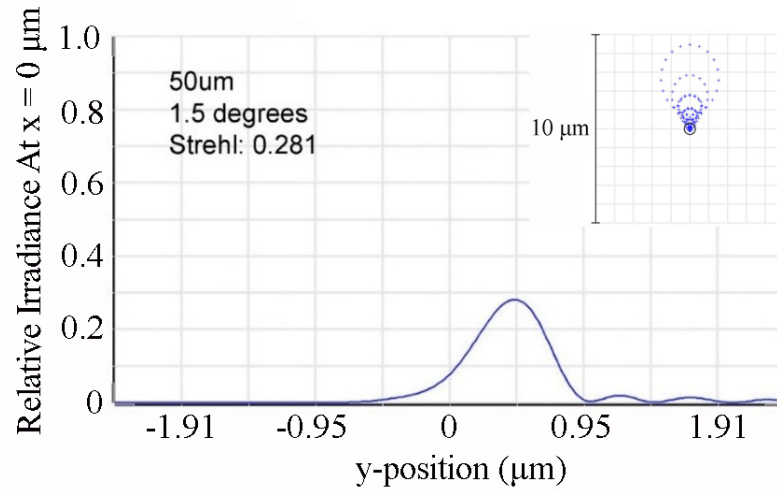
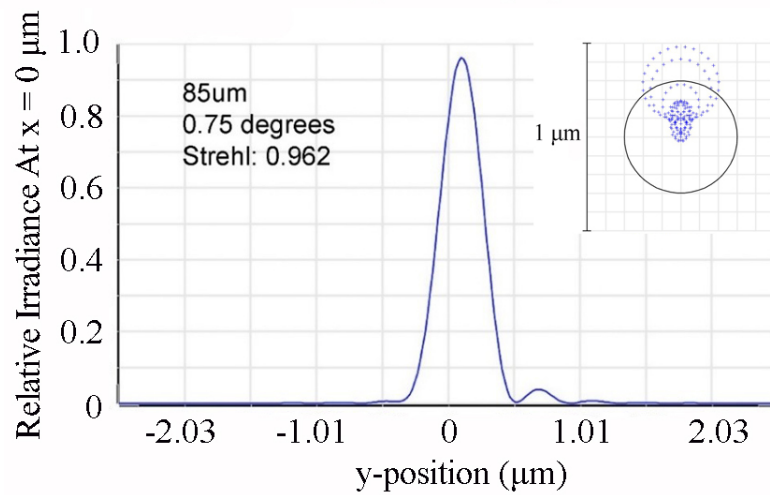
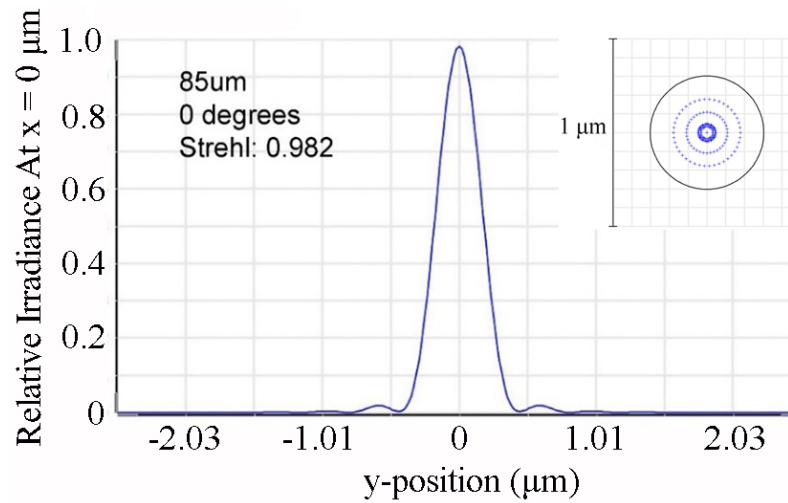
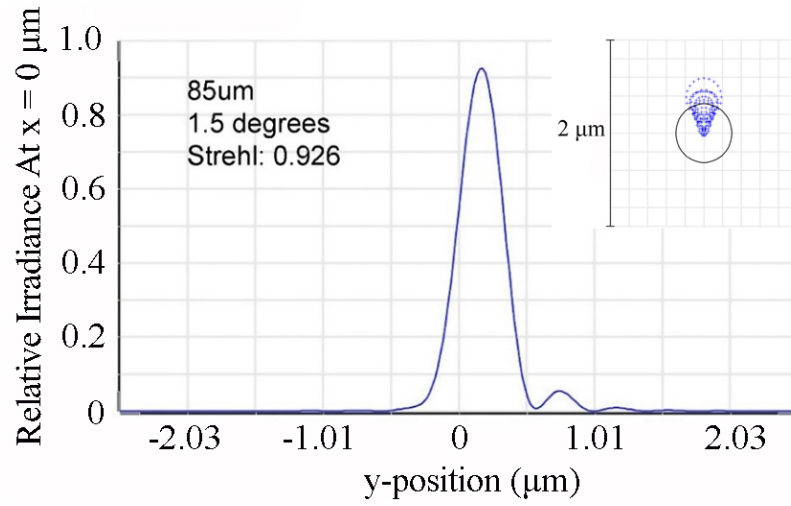
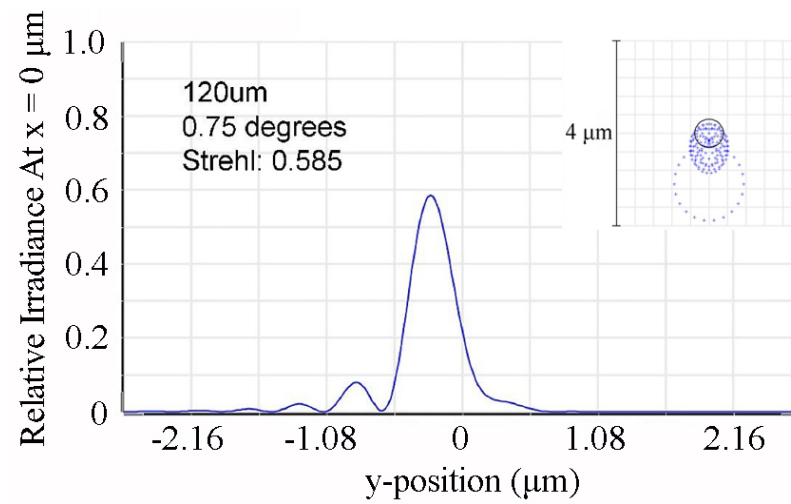
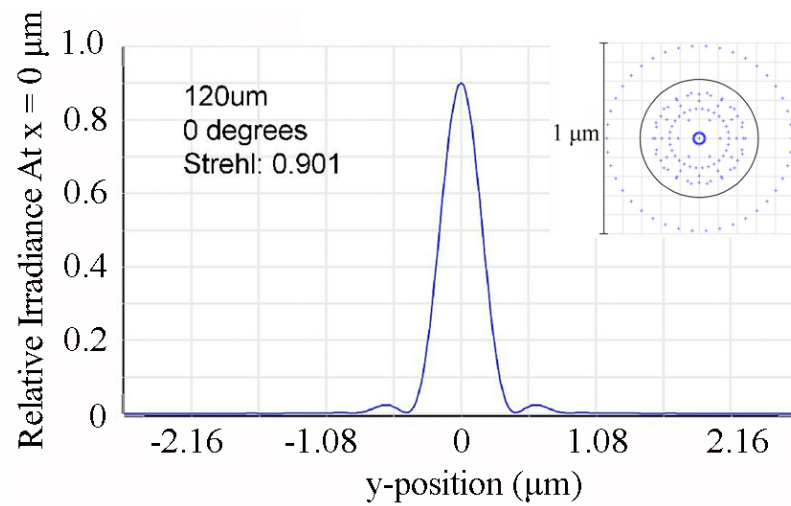


Figure 39. Zemax illustration of lens system. Left: Overview of lens system. Right: Zoomed in view of MEMS scanner, hyperhemisphere and sample stage.

The point spread function (PSF) of the optical system is simulated in Zemax for scan angles from 0° to 1.5° and for depth of imaging of $50\text{ }\mu\text{m}$, $85\text{ }\mu\text{m}$ and $120\text{ }\mu\text{m}$ into the sample. The hyperhemisphere provides aplanatic imaging at an axial depth of $85\text{ }\mu\text{m}$ into the sample. Figure 40 to Figure 42 show the PSF and Strehl ratios of these configurations. The figure inlay displays the corresponding spot diagram.



Figure 40. System PSF at 50 μm into sample.

Figure 41. System PSF at 85 μm into sample.

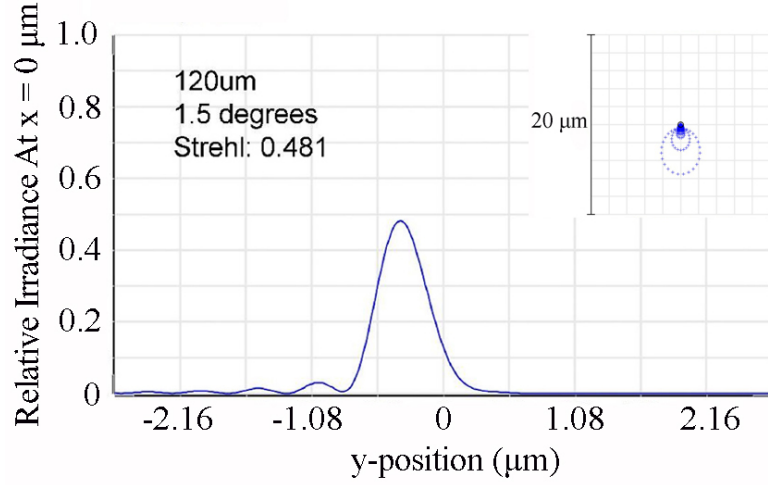


Figure 42. System PSF at 120 μm into sample.

Drive Circuitry and Signal Synthesis

Each of the electrodes for scanning were connected to a high voltage amplifier. The slow axis (x) was driven using a 2 Hz sawtooth waveform with an amplitude V_x . The resonant fast axis was driven using a sinusoidal waveform: $V_y = \frac{V_{ppy}}{2} \sin(\omega_y t)$. A four-channel op-amp mixer circuit was used to sum the signals according to the layout of the electrodes. The drive signals for each channel were sent to the high voltage amplifiers which generated $V_1 = V_{DC} + V_x + V_y$, $V_2 = V_{DC} - V_x + V_y$, $V_3 = V_{DC} - V_x - V_y$ and $V_4 = V_{DC} + V_x - V_y$ for each of the quadrant electrodes. Unless otherwise expressed, $V_{DC} = 300$ V, $V_{ppx} = 300$ V and $V_{ppy} = 200$ V were used to drive the mirrors for the experiments in this section. The frequency of the slow axis was 2 Hz. The fast axis frequency was at the resonant frequency and varied from approximately 800 Hz to 1000 Hz depending on the mirror that was used. The concentric electrodes for focus control were tied together and connected to a separate high voltage amplifier.

Image Acquisition

An avalanche photo detector (APD) was used to measure the intensity of the laser after passing through the pinhole. The APD has a bandwidth from DC to 10 MHz. The data from the avalanche photodetector is sampled with a digitizer at the computer. For ease of data processing and image formation, the data acquisition is set up for single directional scanning. This means that only the data collected during the forward motion of the beam (eg. left to right) will be used to form the image. The sample rate required to record this resolution is dictated by the fastest portion of the sinusoidal scan. The speed of the fast scan can be found by taking the differential of the sinusoid and is shown in the equation below:

$$\frac{d(Y\sin(2\pi ft))}{dt} = Y2\pi f \cos(2\pi ft), \quad (30)$$

where Y is the amplitude of the scan (not the drive signal amplitude). The fastest portion of the scan happens when the scan angle is at 0° . At this location, the relationship the incremental shift of the beam be written as: $\Delta y = Y2\pi f \Delta t$, where Δt is the increment in time. We can therefore write

$$\Delta t = \frac{\Delta y}{Y2\pi f} \quad (31)$$

and

$$f_{sample} = \frac{1}{\Delta t} = \frac{Y2\pi f}{\Delta y}. \quad (32)$$

To find the sample frequency, Δy is set to a pixel pitch of $\frac{0.5\lambda}{NA}$ (Nyquist). Additionally, assuming 545 resolvable spots per line ($\pm 1.5^\circ$ scan angle), the width of the scan is $2Y =$

$\frac{545 \times 0.61\lambda}{NA}$. Substituting Δy and $2Y$ into Eq. 32, we can see that $f_{sample} = 664.9\pi f$.

Therefore, at a scan frequency of 1000 Hz, a minimum sample rate of 2.1 MS/sec is required. Due to this and other considerations regarding data processing speed and digitizer capabilities, a sample rate of 25 MS/sec was chosen.

In order to ensure that data acquisition starts at the beginning of the image (top left corner), triggers for both the start of the frame (slow scan) and the line (fast scan) were used to initiate digitizer acquisition. The acquired data from the digitizer is then reconstructed to form the image. Additionally, linear interpolation has been used for all of the data in this section to correct for the sinusoidal distortion of the fast scan. The slow scan (x), is approximately linear and therefore did not require additional processing. However, the fast scan (y) is sinusoidal and requires linearization. The coordinates for each of the sample points in the direction of the fast scan can be calculated using the following:

$$y_n = A \cos\left(\frac{2\pi}{S_c} s_n\right), \quad (33)$$

where S_c is the total number of samples per cycle of fast scan and s_n is the sample of interest. Assuming operation at 1000 Hz with a sample rate of 25 MS/sec, the total number of samples per cycle becomes 25000 samples (12500 samples per line), and equation becomes:

$$y_n = \cos\left(\frac{2\pi}{25000} s_n\right). \quad (34)$$

The processing and linear interpolation to form the image is performed in Matlab. The Matlab code will be included in Appendix B.

System Characterization

In this section, the edge response and axial response of the system is characterized. The translation of the focus in the sample as a function of the mirror translation is investigated both experimentally and by using the ray trace equations.

Edge Response of the Optical System

To characterize the edge response of the system. The MEMS scanner was used to image the edge of a cleaved wafer piece that was mounted on the sample stage. 65 μm thick microscope coverslip is inserted between the wafer piece and the sample stage. This is to place the wafer edge at the imaging depth where spherical aberration is compensated by the fixed optics. This optimal axial focus location is dictated by the design of the optical system. Figure 43 shows a plot of the intensity data as the beam is scanned across the edge. The distance is calibrated by imaging an electrical trace with a known width of 15 μm . The MEMS mirror used for this test has an initial surface flatness variation of 42nm across a diameter of 4mm with no focus voltage applied. The plot indicates that the distance associated with a change from 20% to 80% intensity is 0.55 μm .

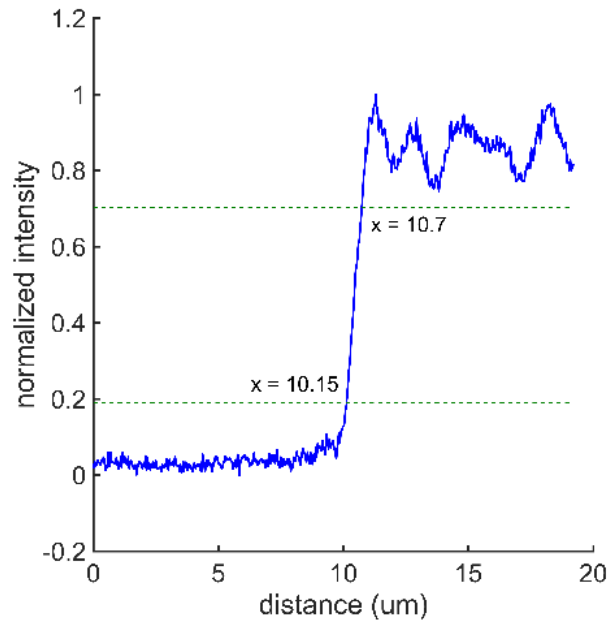


Figure 43. Edge response of confocal system using MEMS scanner.

The theoretical diffraction-limited edge response for a full aperture was also calculated and is plotted in Figure 44. The 20% to 80% response is approximately 0.285 μm . From comparison, we can see that the optical system is not quite diffraction limited.

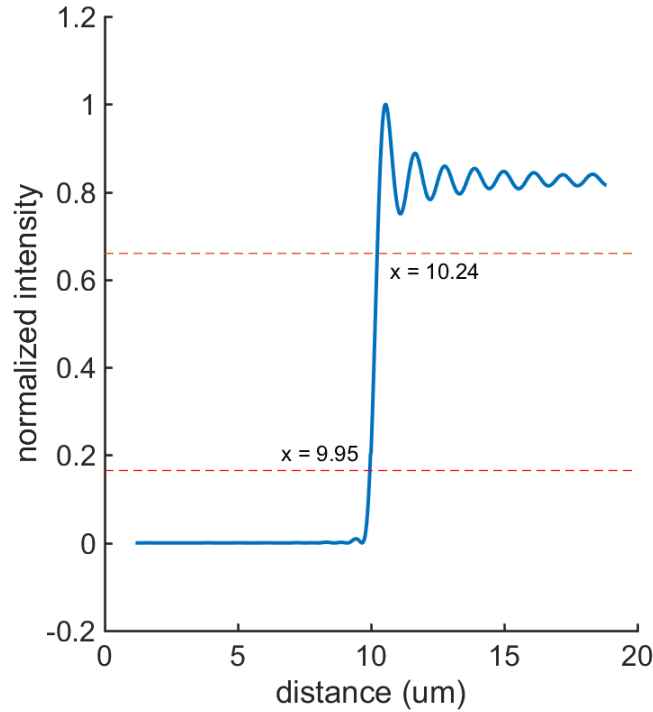


Figure 44. Diffraction-limited edge response.

System Axial Response

The axial response of the system was characterized. To do this, a clean piece of silicon was mounted onto the sample stage. Since the axial position of the sample stage was fixed, the axial focus position was adjusted by translating the MEMS mirror towards or away from the sample. The MEMS was acting purely as a mirror and was not actuated. The reflected light after passing through the pinhole was collected by the photodetector and the intensity was measured using an oscilloscope. However, this only shows the intensity as a function of the axial translation of the mirror in air, not the focus position in the sample. The translation of the mirror was converted to actual distance of focus shift using the following paraxial ray trace matrix:

$$\begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \frac{n_{hh}}{n_{sam}} \end{bmatrix} \begin{bmatrix} 1 & t_{hh} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} -\frac{1}{n_{hh}R_{hh}} & \frac{n_{air}}{n_{hh}} \\ \frac{n_{hh}-n_{air}}{n_{hh}R_{hh}} & \frac{n_{air}}{n_{hh}} \end{bmatrix} \begin{bmatrix} 1 & L-a \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_{mems}} & 1 \end{bmatrix} \begin{bmatrix} h_1 \\ \theta_1 \end{bmatrix} = \begin{bmatrix} h_2 \\ \theta_2 \end{bmatrix},$$

where z is the actual translation of the focus, n_{hh} is the index of refraction of the hyperhemisphere (1.517), n_{sam} is the index of refraction of the sample (the media through which the focus is translated), t_{hh} is the thickness of the hyperhemisphere (1.5mm), R_{hh} is the radius of curvature of the hyperhemisphere (1.0 mm), L is the distance between the MEMS mirror and the hyperhemisphere, a is the translation of the MEMS mirror and f_{mems} is the focal length of the MEMS mirror, which is infinity for this characterization since the mirror is not actuated. The initial ray height at the MEMS mirror is $h_1 = 1 + a(\frac{1}{D})$ and the incident angle is $\theta_1 = \frac{-1}{D}$, where D is the distance from the MEMS to the initial focus location as defined without the hyperhemisphere. Starting from the equal sign and moving left, the matrices respectively describe the initial ray height and angle of incidence onto the mirror, the refraction of the light with the mirror, the refraction of light from the mirror to the first surface of the hyperhemisphere, the interaction of light at the surface of the hyperhemisphere, propagation of light through the hyperhemisphere to the second surface, the transition of light from glass to sample media and finally the axial distance propagated before arriving at a focus in the sample. By setting h_2 to zero (focusing the beam), the relationship between the mirror translation distance and the actual focus translation can be established. Figure 45 provides a schematic of the MEMS and hyperhemisphere to illustrate the paraxial ray trace.

The accuracy of the ray trace matrix was verified experimentally as well. To do this, a 65 μm thick microscope coverslip was mounted onto the sample stage and used as the calibration thickness target through which the focus will be translated. Red ink was used to create a marker on either side of the coverslip for confirming that the surface is in focus. The coverslip was imaged with the MEMS performing only biaxial scanning, while the focus was moved from the top marker to the bottom marker by mechanically translating the mirror. This required 115 μm of mirror translation. Using the above ray trace matrix and setting $a = 115 \mu\text{m}$ and $n_{sam} = 1.517$ for coverslip, the calculated focus translation (z) equals 63 μm which closely matches the actual thickness of 65 μm . Figure 46 shows a plot of the amount of axial translation in the sample as the mirror is shifted.

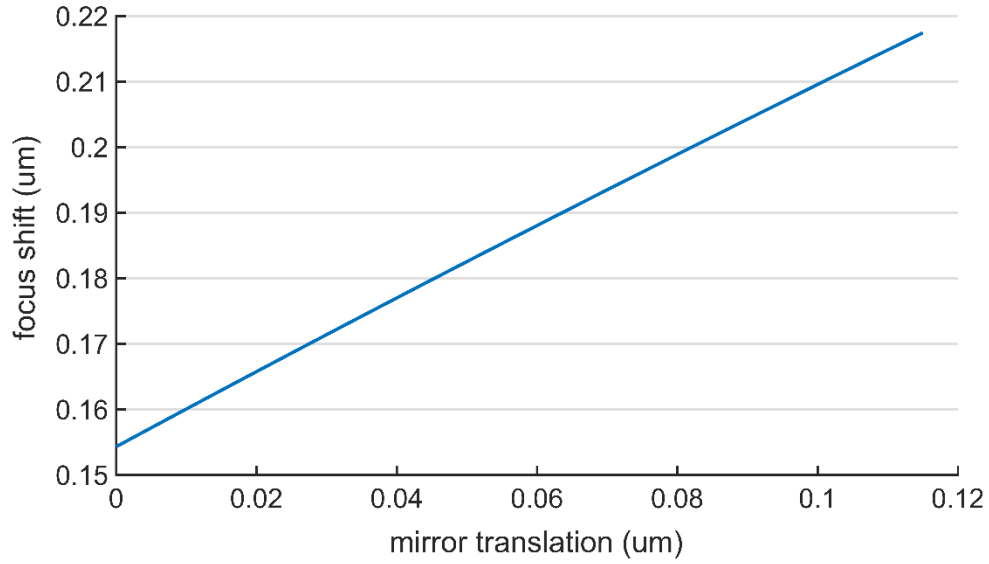


Figure 46. Axial focus shift as a function of mirror translation.

After verifying the accuracy of the ray trace equation, it was then applied towards calculating the focus shift for the system axial response. The mirror translation was 310 μm in air, the index of refraction of the sample was set to $n_{sam} = 1.5$. The axial response of the system is shown in Figure 47. The plot indicates a full width at half maximum value of 6.1 μm .

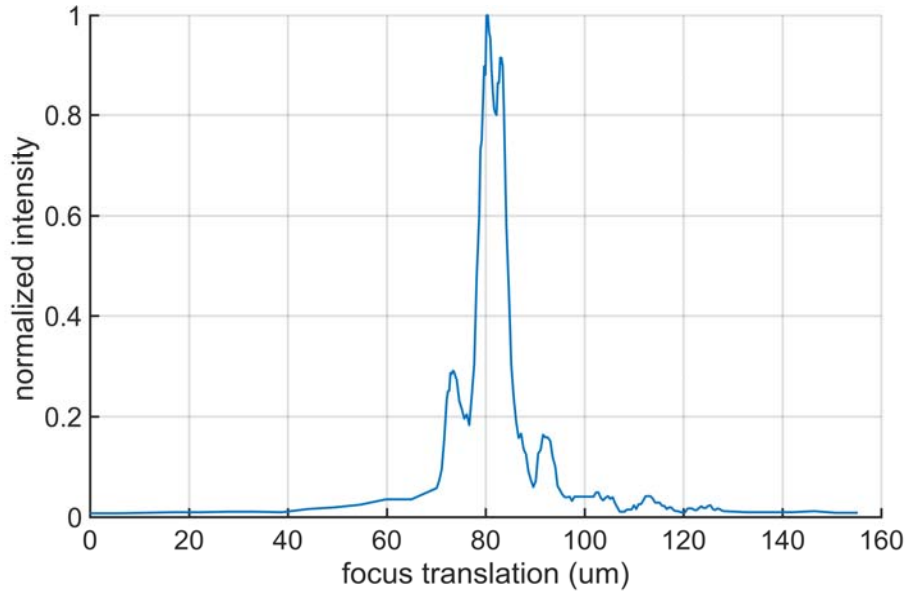


Figure 47. Axial response of optical system using MEMS scanner.

Imaging With the 3-Dimensional Scanner

Imaging of features on a micromachined sample is demonstrated using the 3-dimensional scanner. The sample was the surface of a prototype non-released scan mirror that was mounted to the sample stage using a thin layer of ultrasonic gel. This was so that the micrometer-sized features on the surface of the mirror can be used as targets to test the resolution of the imaging system. Figure 48 displays a confocal image of the aluminum surface of the mirror. The spacing of the vias is 30 μm . From the image, we can see that the field of view of the system is approximately 390 μm by 180 μm . This corresponds to an angular scan of the mirror of $\pm 1.625^\circ$ mechanical in the fast axis (y) and $\pm 0.750^\circ$ in the slow axis (x). The right side of the image is a cropped sub region of the release vias. The dimensions of the ports on the aluminum is 7 μm by 7 μm . The dimensions of the release vias, which are patterned into the SU-8 membrane are 5 μm by 5 μm (visible in the

magnified image). The scattered specks are imperfections on the mirror surface possibly as a result of contaminations during deposition of the aluminum thin film. These specs are also visible under a light-field microscope. The spatial arrangement of the vias follows a square grid pattern. However, as can be seen from the images, the linear grid appears to be curved (in the horizontal direction). This could be due to a misalignment of the electrodes to the gimbal, which pulls the mirror to one side at higher voltages. This is more noticeable at the bottom of the frame where the slow axis voltage is highest. Additionally, under close inspection, it can be seen that the vertical separation between vias at the bottom of the frame appear slightly larger than that of the vias at the top of the frame. This is due to the scan angle being approximately linear to the differential scan voltage, but the deviation from linear increases with larger voltages as was shown in Eq. 20.

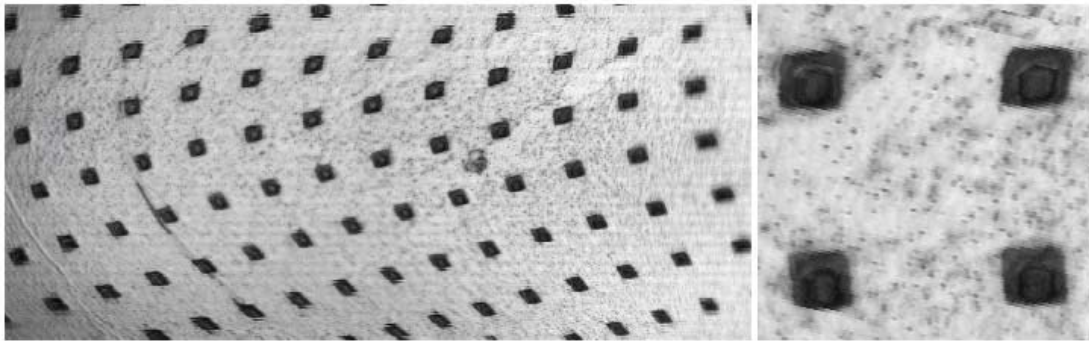


Figure 48. Confocal image of the surface of a prototype 3-dimensional scanner.

Human cheek cells were also imaged using the microscope. The cheek cells were introduced to the sample stage using a cotton swab. A few drops of acetic acid (approx. 6% concentration) in the form of balsamic vinegar was applied to the cells. This was done to induce coagulation in the cells to enhance its reflectance. It has been suggested that acetic

acid induces alterations in protein structure [117, 118]. Figure 49 shows an image of the cheek cells. The size of the cheek cells is approximately 80 μm .

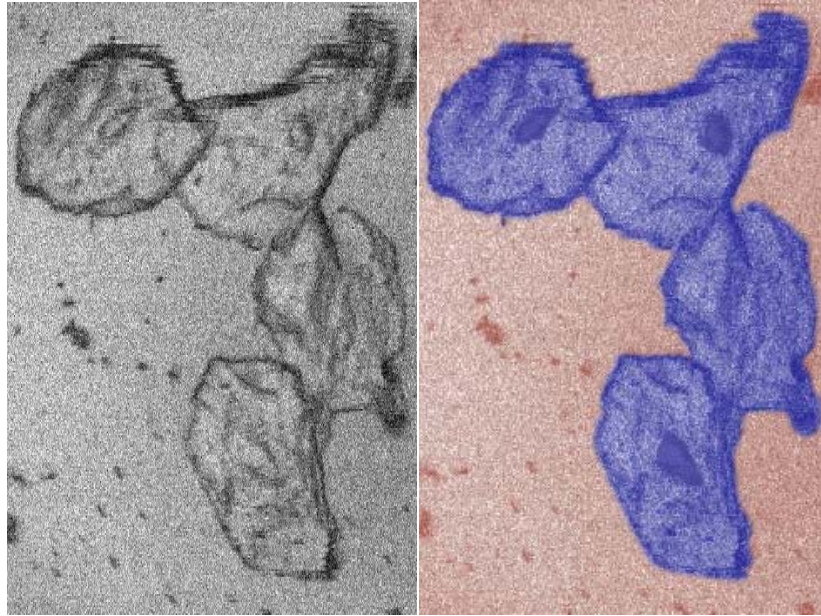


Figure 49. Confocal image of human cheek cells. The nucleus is also visible. The image on the right has been colored with post image processing techniques

As a side note, for imaging of cheek cells using a light field microscope, it is a common practice to use methylene blue as a staining agent to accentuate the nucleus of the cells. This is because of its affinity for DNA and RNA. A higher concentration of the stain will accumulate in areas where those components are present. A Nikon lightfield microscope is used to capture an image of cheek cells stained using a methylene blue solution and is provided in Figure 50.

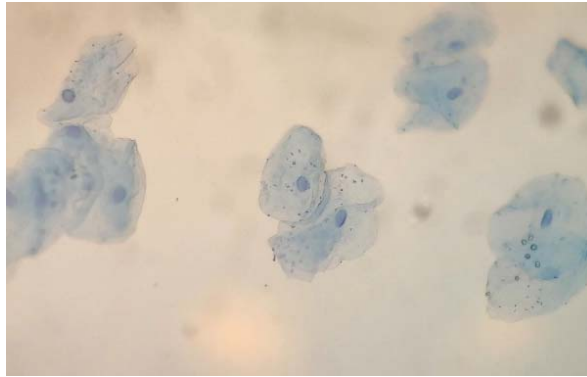


Figure 50. Light field microscope image of human cheek cell stained with a methylene blue solution.

To demonstrate the focus capabilities of the 3-dimensional scanner. A piece of the unreleased mirror surface was used again as the sample. The MEMS was actuated (scanning) to image the surface and the axial location of the MEMS was adjusted until the surface was properly focused. At this point, a focus voltage of 120V was used to actuate the deformable mirror, which defocused the image. Using the deflection information in Figure 28 and the ray trace equation above, this corresponds to a focal shift of $28\text{ }\mu\text{m}$ in air. With this voltage still applied, the MEMS was translated to the second location to restore the location of focus to the mirror. Last, the bias on the deformable mirror was removed to defocus the image again. This set of results is shown in Figure 51.

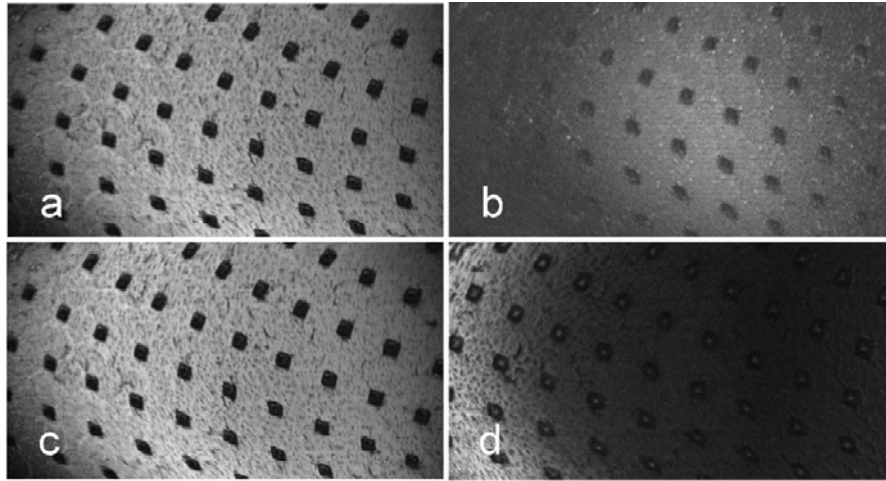


Figure 51. (a).Position 1 no voltage. (b). Position 1 voltage applied. (c). Position 2 no voltage. (d) Position 2 voltage applied.

The axial sectioning capability of confocal microscopy allows for imaging beneath the surface of the sample. The 3-dimensional scanner is used to demonstrate this. For this experiment, a sample composed of 6 μm polystyrene microbeads suspended in ultrasonic transmission gel was used as the imaging target. The initial focus of the system was positioned inside the sample (approximately 200 μm) so that the plane of imaging will not exit the sample as the beam focus is pulled axially towards the MEMS during actuation of the deformable mirror. The applied focus voltage is from 0V to 150V. The corresponding focus shift displays a relationship that is roughly linear to the squared value of the applied voltage. Therefore, to maintain a relatively consistent distance separation between each voltage increment, the voltage is increased according to a quadratic step of 400V^2 . The actual total focus shift was measured experimentally by the amount of mirror translation required to shift between the two focal positions. Measurements indicate a mirror translation of approximately 250 μm . This equates to approximately 127 μm of focus shift

in the sample when calculated using the ray trace equation with $n_{sam} = 1.3$. Figure 52 displays the image of the beads at four different focus locations. A 20 μm pinhole was used for this experiment. Images a-d are each separated axially by 26 μm . Under close inspection, the defocused blur of the in-focus bead in the pictures can be spotted in subsequent pictures.

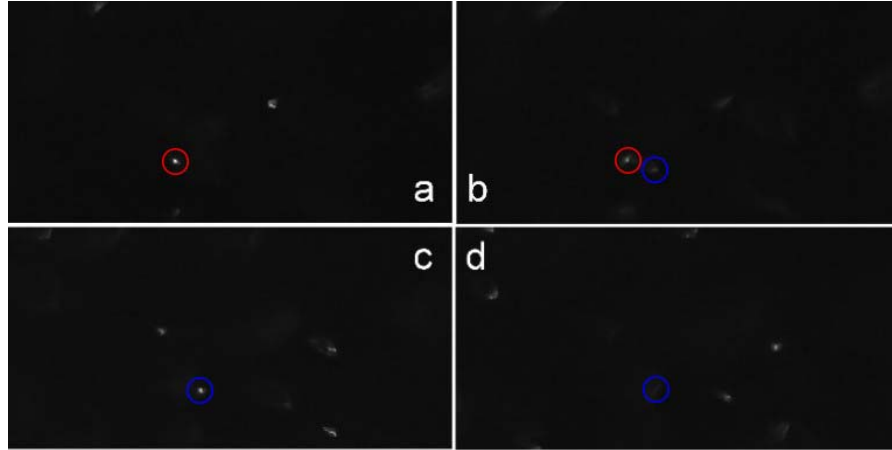


Figure 52. Confocal sectioning of microbeads suspended in ultrasonic gel. Two beads have been circled using different colors to show their focus change in the frames.

The axial response of the system was characterized by tracking the intensity of the brightest spot of a bead for each frame. Figure 53 indicates a half width at half maximum of approximately 12 μm . The mirror that was used for this experiment is a different mirror to the one that was used for the axial response shown in Figure 47.

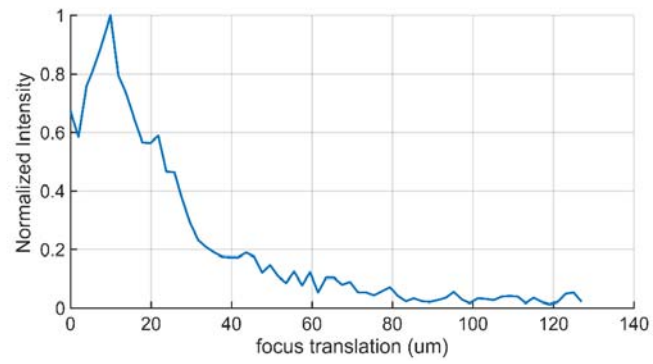


Figure 53. Measured axial response of optical system.

CHAPTER SIX

CONCLUSION AND FUTURE WORK

Summary of Research

This dissertation has described a MEMS 3-dimensional scanner that is capable of bi-axial scanning with integrated focus control. The device is designed to serve as the optical scan engine of a handheld confocal microscope.

This new MEMS device has demonstrated performance exceeding that of any existing MEMS scanners that offer similar degrees of freedom. The optical characterization results indicated dynamic mechanical scan angles in excess of $\pm 3^\circ$. This along with its large mirror diameter, provides a scan angle diameter product of $(\theta_{mech}D)$ of 12 deg·mm, which allows the scanner to resolve more than 1000 spots at an imaging wavelength of 633 nm. This resolution is more than 3 times that of previous 3-dimensional scanners and even outperforms most biaxial scanners. With a fast axis resonant frequency of 1000 Hz, a refresh rate of 4 frame/second featuring 500 lines per frame is possible. To complement scanning, the deformable mirror integrated onto the center of the scanner has demonstrated stroke in excess of 10 μm . This provides a maximum focal length of approximately 100 mm. The mirror is also capable of correcting for spherical aberration during imaging by employing a set of concentric focus electrodes. Experimental results indicate a correction range for primary spherical aberration (Z_{40}) from -149 nm to 255 nm, and secondary spherical aberration (Z_{60}) from -236 nm to 175 nm. In addition to combining multiple degrees of freedom onto one device, the architecture of the scanner also promotes

miniaturization by featuring an annular aperture to allow for coaxial integration into the optical system.

The MEMS was integrated into a benchtop confocal microscope to test its performance. The system was capable of resolving features that were 5 μm in size and demonstrates the imaging of human cheek cells. The volumetric imaging of polystyrene microbeads suspended in ultrasonic gel was also demonstrated by the confocal microscope. The MEMS was able to achieve a focus translation of more than 120 μm ($\text{NA} = 0.57$, 633 nm wavelength) through the ultrasonic gel ($n = 1.3$). Further optimization of the deformable mirror could increase the focus range to match the needs of in-vivo confocal microscopy.

Apart from the advancements in opto-mechanical performance, the construction of the device explored the use of a polymer material called SU-8 for the torsional hinges and deformable membrane. This is the first demonstration of polymer mechanical structures on MEMS devices featuring similar degrees of freedom. Compared to conventional materials such as silicon nitride, the Young's modules of SU-8 is much lower. Because of this, large torsional scan angles and membrane stroke are achieved using relatively lower actuation voltages.

Future Efforts

Susceptibility to Environmental Variations

The use of SU-8 polymer for the construction of mechanical structures is desirable because its flexibility allows for large deflections. However, the mechanical properties of SU-8 is highly susceptible to changes in temperature and humidity. For instance,

experimental results in this dissertation have indicated that a temperature variation of 40°C can cause a noticeable shift in the resonant frequency of the mirror. Such issues must be addressed to ensure consistent and reliable performance when integrated into optical systems.

One approach would be to employ sensors and feedback control to minimize the variations in temperature and humidity. A second approach could be to monitor the mechanical behavior of the MEMS in real time and adjust the actuation accordingly using feedback control. The mechanical behavior of the deformable mirror can be tracked by employing capacitive sensing. Another approach to addressing this problem is to look for new materials that have the desirable mechanical properties of SU-8 while at the same time, not as susceptible to changes in temperature and humidity.

Dynamic Distortions

Currently, the inertial distortions that appear on the surface of the mirror during dynamic scanning sets an upper limit to the torsional resonant frequency and the dynamic scan angle of the device. This is to keep the distortions under control in order to maintain diffraction limited performance of the mirror. To permit acutation at higher scan frequencies and angles, the inertial deformation has to be mitigated. As mentioned in Chapter 4, the inertial deformation is related to the mass and intrinsic stress of the membrane. A thinner membrane (less mass) with a proportional increase in intrinsic stress (to maintain the tension of the membrane) could result in less dynamic distortion. At the same time, the thickness and intrinsic stress needs to be balanced to not negatively impact the deflection characteristics of the deformable membrane.

Stress Fracturing

Perhaps the most important issue that needs to be addressed in future work is the fracturing of SU-8 that occurs during the XeF₂ release process of the mirror. As described in the dissertation, as the silicon is removed by the XeF₂, it is hypothesized that the stress in the bi-layer SU-8 causes it to lift from the substrate and eventually fracture. The fracturing severs electrical traces and renders the device inoperable. To address this issue, the stress between the two layers of SU-8 and the substrate must be better understood. In addition, an improvement in the adhesion between the SU-8 and the oxide substrate could also help prevent delamination and fracturing.

Integrated Laser Scanning Microscope

The future goal is to use the MEMS 3-dimensional scanner to enable a miniaturized handheld confocal laser scanning microscope for the in-vivo imaging of malignant cells beneath the surface of the skin. To promote clinical usage, the handheld confocal microscope will also feature an integrated wide field camera to guide the location of confocal imaging. The handheld microscope is to provide an alternative to the conventional method of detection using biopsies that are not only invasive but also can be costly. Because confocal microscopy is not invasive, it can be used to sample each and every location that appears suspicious, which was not possible using conventional biopsies.

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APPENDICES

APPENDIX A

ZERNIKE ABERRATIONS

Optical aberrations describe the deviations of the wavefront from a spherical shape. Currently, there are various standards used to characterize and quantify the types of optical aberrations to describe the amount of deviation from an ideal model. One method that is commonly used to describe optical aberrations is called the Zernike polynomials. The Zernike polynomials are a set of polynomials with two variables that are continuous and orthogonal over a unit disk [1]. The condition of orthogonality means that the polynomials used to describe the aberrations are independent of each other. This is important because additional polynomials can be added to a previously calculated set of values without affecting the existing values. The characterization of aberrations in this dissertation are based on the normalized Zernike polynomials.

A circular wavefront can be described in polar coordinates using a set of polynomials that are orthogonal with the following expression [2]:

$$W(r, \theta) = \sum_{n,m} C_n^m Z_n^m(r, \theta),$$

where Z is the Zernike polynomial and C is the coefficient of the polynomial. The Zernike polynomials in polar coordinates can be expressed as:

$$Z_n^m(r, \theta) = R_n^m(r) \cos(m\theta) \quad m \geq 0$$

$$Z_n^{-m}(r, \theta) = R_n^m(r) \sin(m\theta) \quad m < 0,$$

where r is limited by the unit circle and θ is calculated in a clockwise direction from the positive x axis. $R_n^m(r)$ is the radial function and is expressed using the following equation [2]:

$$R_n^m(r) = \sum_{l=0}^{(n-m)/2} \frac{(-1)^l (n-l)!}{l! \left(\frac{1}{2}(n+m)-l\right)! \left(\frac{1}{2}(n-m)-l\right)!} r^{n-2l}.$$

Figure 1 shows the first 10 orders of the Zernike polynomials. Table 1 lists the algebraic expansion of the Zernike polynomial sequence.

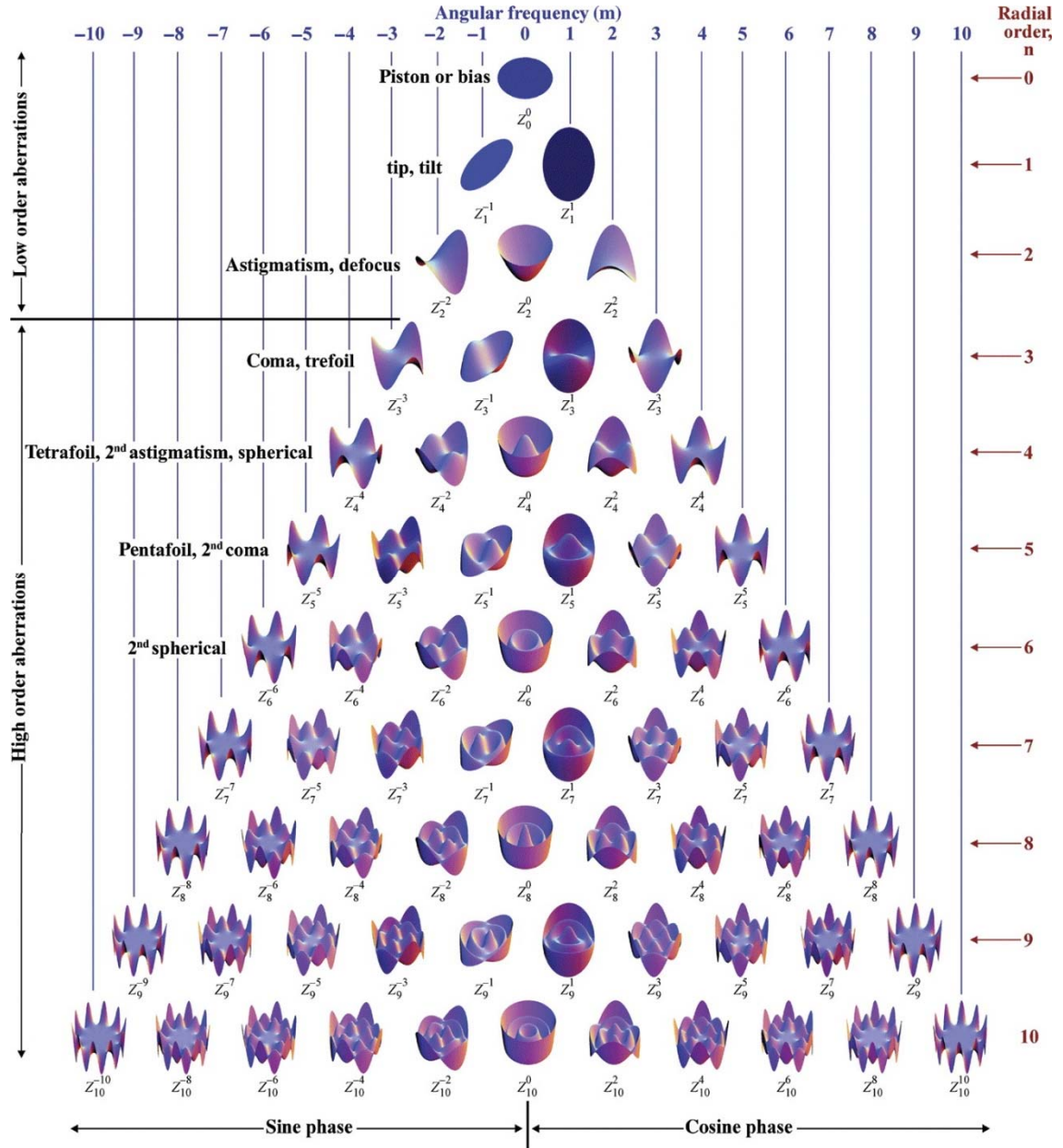


Figure 1. Surface plots of the Zernike polynomials. Used with permission © 2011 Journal of Modern Optics [2].

Table 1. Algebraic expansion of the Zernike polynomials. Used with permission ©1994 OSA [3].

n	m	Z_n^m	RMS	Polar form $(dx^2 \rightarrow r d\theta dr)$	Cartesian form $(dx^2 \rightarrow dxdy)$
0	0	Z_0^0	$\sqrt{2}$	1	1
1	-1	Z_1^{-1}	2	$r \sin \theta$	x
1	1	Z_1^1	2	$r \cos \theta$	y
2	-2	Z_2^{-2}	$\sqrt{6}$	$r^2 \sin 2\theta$	$2xy$
2	0	Z_2^0	$\sqrt{3}$	$2r^2 - 1$	$-1 + 2x^2 + 2y^2$
2	2	Z_2^2	$\sqrt{6}$	$r^2 \cos 2\theta$	$-x^2 + y^2$
3	-3	Z_3^{-3}	$2\sqrt{2}$	$r^3 \sin 3\theta$	$-x^3 + 3xy^2$
3	-1	Z_3^{-1}	$2\sqrt{2}$	$(3r^3 - 2r) \sin \theta$	$-2x + 3x^3 + 3xy^2$
3	1	Z_3^1	$2\sqrt{2}$	$(3r^3 - 2r) \cos \theta$	$-2y + 3y^3 + 3x^2y$
3	3	Z_3^3	$2\sqrt{2}$	$r^3 \cos 3\theta$	$y^3 - 3x^2y$
4	-4	Z_4^{-4}	$\sqrt{10}$	$r^4 \sin 4\theta$	$-4x^3y + 4xy^3$
4	-2	Z_4^{-2}	$\sqrt{10}$	$(4r^4 - 3r^2) \sin 2\theta$	$-6xy + 8x^3y + 8xy^3$
4	0	Z_4^0	$\sqrt{5}$	$6r^4 - 6r^2 + 1$	$1 - 6x^2 - 6y^2 + 6x^4 + 12x^2y^2 + 6y^4$
4	2	Z_4^2	$\sqrt{10}$	$(4r^4 - 3r^2) \cos 2\theta$	$3x^2 - 3y^2 - 4x^4 + 4y^4$
4	4	Z_4^4	$\sqrt{10}$	$r^4 \cos 4\theta$	$x^4 - 6x^2y^2 + y^4$
5	-5	Z_5^{-5}	$2\sqrt{3}$	$r^5 \sin 5\theta$	$x^5 - 10x^3y^2 + 5xy^4$
5	-3	Z_5^{-3}	$2\sqrt{3}$	$(5r^5 - 4r^3) \sin 3\theta$	$4x^3 - 12xy^2 - 5x^5 + 10x^3y^2 + 15xy^4$
5	-1	Z_5^{-1}	$2\sqrt{3}$	$(10r^5 - 12r^3 + 3r) \sin \theta$	$3x - 12x^3 - 12xy^2 + 10x^5 + 20x^3y^2 + 10xy^4$
5	1	Z_5^1	$2\sqrt{3}$	$(10r^5 - 12r^3 + 3r) \cos \theta$	$3y - 12y^3 - 12x^2y + 10y^5 + 20x^2y^3 + 10x^4y$
5	3	Z_5^3	$2\sqrt{3}$	$(5r^5 - 4r^3) \cos 3\theta$	$-4y^3 + 12x^2y + 5y^5 - 10x^2y^3 - 15x^4y$
5	5	Z_5^5	$2\sqrt{3}$	$r^5 \cos 5\theta$	$y^5 - 10x^2y^3 + 5x^4y$
6	-6	Z_6^{-6}	$\sqrt{14}$	$r^6 \sin 6\theta$	$6x^5y - 20x^3y^3 + 6xy^5$
6	-4	Z_6^{-4}	$\sqrt{14}$	$(6r^6 - 5r^4) \sin 4\theta$	$20x^5y - 20xy^3 - 24x^3y^3 + 24xy^5$
6	-2	Z_6^{-2}	$\sqrt{14}$	$(15r^6 - 20r^4 + 6r^2) \sin 2\theta$	$12xy - 40x^3y - 40xy^3 + 30x^5y + 60x^3y^3 - 30xy^5$
6	0	Z_6^0	$\sqrt{7}$	$20r^6 - 30r^4 + 12r^2 - 1$	$-1 + 12x^2 + 12y^2 - 30x^4 - 60x^2y^2 - 30y^4 + 20x^6 + 60x^4y^2 + 60x^2y^4 + 20y^6$
6	2	Z_6^2	$\sqrt{14}$	$(15r^6 - 20r^4 + 6r^2) \cos 2\theta$	$-6x^2 + 6y^2 + 20x^4 - 20y^4 - 15x^6 - 15x^4y^2 + 15x^2y^4 + 15y^6$
6	4	Z_6^4	$\sqrt{14}$	$(6r^6 - 5r^4) \cos 4\theta$	$-5x^4 + 30x^2y^2 - 5y^4 + 6x^6 - 30x^4y^2 - 30x^2y^4 + 6y^6$
6	6	Z_6^6	$\sqrt{14}$	$r^6 \cos 6\theta$	$-x^6 + 15x^4y^2 - 15x^2y^4 + y^6$
7	-7	Z_7^{-7}	4	$r^7 \sin 7\theta$	$-x^7 + 21x^5y^2 - 35x^3y^4 + 7xy^6$
7	-5	Z_7^{-5}	4	$(7r^7 - 6r^5) \sin 5\theta$	$-6x^5 + 60x^3y^2 - 30xy^4 + 7x^7 - 63x^5y^2 - 35x^3y^4 + 35xy^6$
7	-3	Z_7^{-3}	4	$(2r^7 - 30r^5 + 10r^3) \sin 3\theta$	$-10x^3 + 30xy^2 + 30x^5 - 60x^3y^2 - 90xy^4 - 21x^7 + 21x^5y^2 + 105x^3y^4 + 63xy^6$
7	-1	Z_7^{-1}	4	$(35r^7 - 60r^5 + 30r^3 - 4r) \sin \theta$	$-4x + 30x^3 + 30xy^2 - 60x^5 - 120x^3y^2 - 60xy^4 + 35x^7 + 105x^5y^2 + 105x^3y^4 + 35xy^6$
7	1	Z_7^1	4	$(35r^7 - 60r^5 + 30r^3 - 4r) \cos \theta$	$-4y + 30y^3 + 30x^2y - 60y^5 - 120x^2y^3 - 60x^4y + 35y^7 + 105x^2y^5 + 105x^4y^3 + 35x^6y$
7	3	Z_7^3	4	$(2r^7 - 30r^5 + 10r^3) \cos 3\theta$	$10y^3 - 30x^2y - 30y^5 + 60x^2y^3 + 90x^4y + 21y^7 - 21x^2y^5 - 105x^4y^3 + 63x^6y$
7	5	Z_7^5	4	$(7r^7 - 6r^5) \cos 5\theta$	$-6y^5 + 60x^2y^3 - 30x^4y + 7y^7 - 63x^2y^5 - 35x^4y^3 + 35x^6y$
7	7	Z_7^7	4	$r^7 \cos 7\theta$	$y^7 - 21x^2y^5 + 35x^4y^3 - 7x^6y$

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APPENDIX B

IMAGING PROCESS USING LINEAR INTERPOLATION IN MATLAB

The Matlab code used for correcting the sinusoidal distortion of the fast axis is given below. The math behind this has been included in Chapter 5.

```
%batch sinusoidal distortion correction for a set of images

%import .fig files into Matlab.
files =
'C:\Users\W97D925\Desktop\sine_correction\batch_corrections\test_files'
;

images = dir(fullfile(files, '*.fig'));

%writing figure data into .m file.
for n = 1:size(images);
open(fullfile(files, images(n).name));
D = get(gca, 'Children');
data = get(D, 'CData');
close Figure 1
%process data (make x,y,I pairs for each pixel); The first number
is
%samples per line and second number is lines per frame. This will
vary
%according to the resonant frequency of the fast axis.
[Xlin,Ylin] = meshgrid( 1:12500 , 1:480 ); %x then y

%get Y locations
Y = Ylin;

%get x locations
radfreq = (2*pi)/25000; %spatial frequency of scan
cosreference = cos(radfreq*Xlin); %possible shift (need xlin-1 to be
correct
X = ((-cosreference + 1)/2)*12500; %rescale so we still go from 1-12500
ish
%interpolate
Z = interp2(X,Y,data,Xlin,Ylin);
%plot

s = figure;colormap gray;

% clims = [0.046 0.068];
clims = [0.0 0.10];
imagesc(Z,clims);
daspect([14 1 1])
% saveas(gcf, 'Barchart.png')
saveas(s,sprintf('Focus_position_b%d.png',n));
close all
end
```

APPENDIX C

BLACK SILICON AND ETCH TUNING

This appendix describes a nano-structured light absorbing material called black silicon. The material is developed to be fabricated onto the non-active surfaces of optical MEMS devices to eliminate unwanted reflections. The contents of this appendix has been published in the Journal of Micro/Nanolithography, MEMS, and MOEMS. (T. Liu and D. L. Dickensheets, "Black silicon integrated aperture," Journal of Micro/Nanolithography, MEMS, and MOEMS, vol. 16, no. 4, p. 045501, 2017) [76]. For the purpose of coherence, the journal article in its original and complete form, although a few passages include content similar to previous sections of this dissertation. This was a multi-author manuscript.

This paper is included as part of the dissertation because the formation of black silicon provides insight to the tuning of etch profiles during plasma etching. It covers the effects of etch parameters such as gas flow rate, temperature, and plasma power when performing an anisotropic silicon etch using a SF_6 and O_2 plasma. The silicon plasma etch processes presented in Chapter 3 are based on the etch tuning described in this chapter. Additionally, the concept of using nanostructured black silicon to darken the non-active areas of optical MEMS devices could be useful for future improvements to the 3-dimensional scanner. For example, black silicon could be integrated onto the perimeter of the center gimbal plate and the gimbal ring to eliminate unwanted reflections. The experimental results in this chapter have demonstrated a large improvement in imaging contrast with the use of black silicon on a MEMS deformable mirror.

[Begin Excerpt]

BLACK SILICON INTEGRATED APERTURE

Abstract. This paper describes the incorporation of nanotextured black silicon as an optical absorbing material into silicon-based micro-opto-electromechanical systems devices to reduce stray light and increase optical contrast during imaging. Black silicon is created through a maskless dry etch process and characterized for two different etch conditions, a cold etch performed at 0°C and a cryogenic etch performed at -110°C. We measure specular reflection at visible wavelengths to be less than .001% at near normal incidence for both processes, while the total diffuse scatter is less than 3% and 1% for the cold and cryogenic processes, respectively. These surfaces exhibit less reflectivity and lower scatter than black velvet paint used to coat optical baffles, and compare favorably with other methods to produce black surfaces from nanotextured silicon or using carbon nanotubes. We illustrate the use of this material by integrating a black silicon aperture around the perimeter of a deformable focus-control mirror. Imaging results show a significant improvement in contrast and image fidelity due to the effective reduction in stray light achieved with the self-aligned black aperture.

Introduction

Silicon-based micro-opto-electromechanical systems (MOEMS) devices have wide spread applications for optical imaging and display [1] that include beam scanning devices [2] for imaging [3], information display [4], printing [5], and laser marking [6], and focus control devices for cameras with agile electronic focus [7-13] and zoom capability [14-16].

In most systems, and critically important for imaging and display systems, it is necessary to limit the light illumination solely to the active optical regions. Stray reflections and scattering from surrounding regions should be suppressed to avoid double images or other artifacts including background haze. These unwanted reflections have traditionally been avoided by implementing an external diaphragm with an aperture to limit the optical path to only the desired portion of the optical surface. This, however, relies on accurate alignment of this external aperture to the original device, which may be challenging if not impossible for ultra-miniature optical systems. We propose a new approach to this problem that incorporates a self-aligned integrated aperture made from a light absorbing material called black silicon to prevent unwanted reflections from regions that are not part of the active optical surface. Black silicon is created by etching the exposed silicon surface into densely packed micro/nano silicon pillars. Light incident onto this surface layer is efficiently absorbed, therefore giving it a black appearance [17-19]. While black silicon has received considerable attention for use as an antireflection layer [20, 21] as well as for its interesting photoelectric applications [17, 22-24], it has so far not been incorporated for use as a flocking material within a MOEMS imaging system. However, we find that it has excellent optical absorption properties and is inherently compatible with silicon MOEMS processing, making this a highly useful new application for the material.

Current methods for creating black silicon include dry etching [20, 25-27], wet etching [22, 28] laser treatment [29] and chemical vapor deposition (CVD) [18]. Because dry etching can produce strongly absorbing layers and is particularly compatible with MOEMS fabrication, we developed two, simple, single step, self-masked dry etch black

silicon recipes. Both etches are performed at reduced temperature using a mixture of SF_6 and O_2 , as has been reported by several others [27, 30-32]. The “cold etch” keeps the sample at 0°C , while the “cryogenic etch” keeps the sample at -110°C . We have measured the reflectivity and backscatter from surfaces created with these two recipes, finding both to be extremely low and thus a good material for an optical baffle. The paper also shows that the reflectivity and scattering of the developed black silicon surfaces compares favorably to other nano-structured absorbers and conventional optical paint coatings. Finally, we demonstrate the integration of the black silicon layer into a MOEMS fabrication process, creating a self-aligned aperture around an electrostatic deformable mirror, and show the consequent improvement in the quality of images made using this properly masked variable focus device. To the best of our knowledge, this is the first experimental demonstration of imaging enhancement through the utilization of a black silicon integrated aperture [33].

Materials and Methods

The formation of black silicon through dry etching is a relatively well-known process. In general, the formation of the dense array of pillars that form black silicon begins when micro masking, either from lithography or spontaneous deposition during plasma etching, is present on the silicon surface and anisotropic etching conditions exist [31, 34, 35]. A common way to achieve anisotropic etching of silicon is to utilize the cryogenic etch properties of SF_6 [30, 31, 36, 37]. In this section, we describe a recipe for creating self-masked single step black silicon at cryogenic temperature, and an adjusted recipe operating closer to room temperature for compatible integration onto a MOEMS

electrostatic deformable mirror. The Oxford Plasmalab System 100 ICP etcher was used for all dry etching processes described in this paper.

Initial black silicon formation experiments were based on etch results reported by Sainiemi et al. [25]. New, single side polished 525 μm p-type <100> silicon wafers were employed. No dedicated cleaning was performed other than using pressurized nitrogen to remove any stray debris. The newly developed maskless recipe, which is shown in Table 1, was optimized for the Oxford Plasmalab System 100 ICP etcher. With this process, the surface of a polished silicon wafer would become velvet black after 7 minutes of cryogenic etching, shown in Fig. 1.

Table 1. Cryogenic Black Silicon Recipe

ICP Power (W)	Bias Power (W)	SF ₆ (sccm)	O ₂ (sccm)	Temp. (°C)	Pressure	Duration
700	3	38	22	-110	9mtorr	7minutes

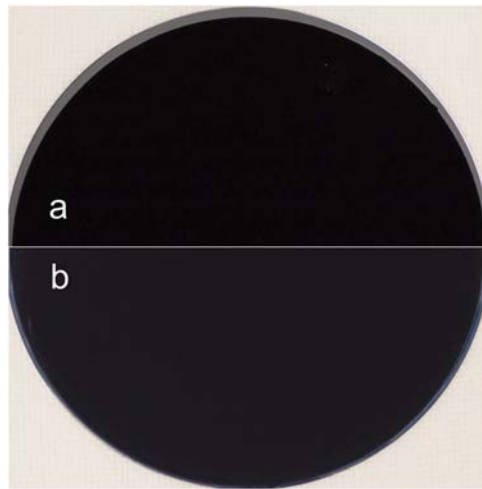


Fig. 1. Comparison of black silicon wafers made using the cryogenic etch and the 0°C etch. Both photos were captured under identical conditions (lighting, location, camera settings). (a) Cryogenic black silicon. (b) 0°C black silicon. The surface texture of the 0°C black silicon wafer appears visually to be rougher.

The specular reflectivity of this surface was characterized at two wavelengths, using a 633nm and a 477nm laser. The specular reflection could be visually isolated from the diffuse scatter from near-normal to grazing incidence. A silicon photodiode based power meter with a 6mm diameter aperture was used to capture the power in the reflected specular beam when the angle of incidence of the incident beam was scanned from 2 to 82 degrees. The power meter sensor was located approximately 40cm from the wafer surface. The specular reflectivity measurements were collected at both wavelengths. The power in the specular reflected beam was normalized by the total incident power to calculate the reflectivity.

The diffuse laser scatter of this surface was also characterized. Like the previous specular reflection measurements, a 633nm laser and a 477nm laser were used. The laser illuminated the surface at normal incidence while the small aperture power meter was used to collect the power in the diffused laser scatter as a function of viewing angle. The distance between the power meter and the point of incidence on the wafer remained constant. The approximate solid angle (Ω) of the light collected by the power meter could be calculated with the diameter of power meter entrance aperture (D) and the distance from the scatter source (R) using the relationship $\Omega = \pi D^2 / 4R^2$. The bidirectional reflectance distribution function ($BRDF$) of the scattered light is determined using the power detected by the power meter (P_D), the solid angle of the power meter (Ω), the cosine of the scatter angle and the incident power (P_I) using Eq. (1) [38].

$$BRDF = \frac{P_d}{\Omega P_i \cos \theta} \quad (1)$$

The cosine corrected BRDF shown in Eq. (2), which is normalized to the measurement solid angle, rather than the projected solid angle, is used in this paper.

$$\cos \theta BRDF = \frac{P_d}{\Omega P_i} \quad (2)$$

Finally, a discrete integration was performed across the diffuse scatter hemisphere to calculate the total diffuse reflectivity.

The use of cryogenic etch conditions (-110°C) to achieve an anisotropic etch profile poses a strict limit on the types of materials that can be present on the micro-fabricated devices. For example, the MOEMS electrostatic deformable mirror used for our demonstration relies on permanent SU-8 structures for mechanical movement, but SU-8, which is a photoset epoxy, is prone to fracturing under such low temperatures [39]. This necessitated a simple compatible black silicon recipe that could operate at near room temperatures. In order to do this, we employed the Black Silicon Method reported by Jansen, et al. [34] to tune the etching parameters from the cryogenic black silicon recipe to near room temperature operation. The ICP power was first lowered, and then the O₂ flow rate was increased gradually until the wafer would turn black. This recipe is provided in Table 2 with results shown in Fig. 1. Experiments showed that the surface of a silicon wafer could be darkened with the O₂ flow ranging from 22sccm to 33sccm. However, at lower O₂ flow rates, the darkened surface would appear smooth and dark while at higher flow rates it would appear rough and gray/brown in color. This observation is relatively

consistent with the results reported by Jansen et al. [34]. Temperature also has a big impact on the silicon grass formation. The original intent was for this process to operate at room temperature (25°C); however, a temperature gradient existed on the wafer due to the nature of the cooling stage. At 25°C, only the perimeter of the wafer, which was clamped to the cooling stage and, we posit, had the best thermal conduction, could be darkened. Perhaps with improved thermal conduction, uniform black silicon formation can be achieved across the wafer at room temperature. Furthermore, using the Oxford etcher, the chuck temperature needed to be decreased by 10°C when a carrier wafer (500 μm thick silicon) is used in order to compensate for reduced thermal conduction and maintain black silicon formation. Finally, the process is also very sensitive to pressure; an increase from 12mtorr to 15mtorr was enough to cause a significant reduction in darkness. Depending on plasma etcher capabilities, an extra plasma ignition step might be necessary for Table 2 recipe to be initiated due to low ICP power.

ICP Power (W)	Bias Power (W)	SF ₆ (sccm)	O ₂ (sccm)	Temp. (°C)	Pressure	Duration
550	3	38	27	0	12mtorr	20- 25minutes

We characterized specular reflectivity and diffuse scatter of this black silicon surface using the same procedures as described above for the cryogenic black silicon. Both a 633nm laser and a 477nm laser were used for this experiment. Unlike the cryogenic black silicon, the specular reflection could only be visually isolated from the diffuse laser speckles at high angles of incidence. At smaller angles where the specular reflected beam was too faint to be visually isolated from the diffuse speckle, the power meter was

positioned according to the law of reflection to capture the reflected specular beam. The data in this region is likely strongly dominated by diffuse scatter rather than specular reflection. The diffuse laser scatter for the black silicon surface etched at 0°C was measured using methods identical to that of the cryogenic black silicon.

The 0°C black silicon process was selected for the integrated, self-aligned aperture around our deformable mirror, due to temperature compatibility with the SU-8 material. Fig. 2 shows the fabrication process for the electrostatic MOEMS deformable mirror with black silicon integrated aperture [33]. The process consists of bonding a membrane wafer which carries the active optical mirror to a perforated wafer that holds the actuation electrodes and includes air channels to control mechanical damping during dynamic deflection of the membrane. Both wafers are n-type double sided polished (DSP) <100> silicon wafers. The membrane wafer thickness is 480µm while the perforated wafer thickness is 300µm.

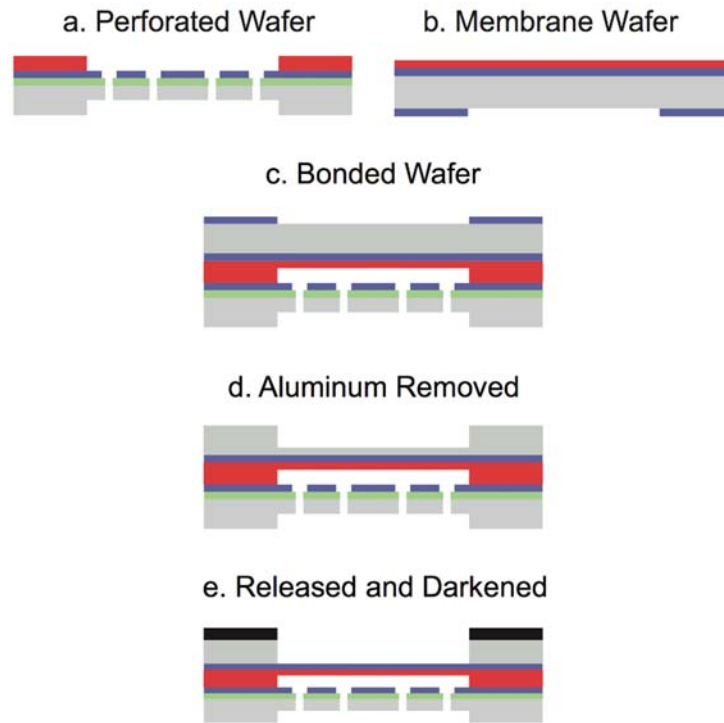


Fig. 2. MOEMS deformable mirror with integrated black silicon aperture fabrication process. Legend: gray represents the substrate silicon wafer, green represents silicon oxide, blue represents aluminum thin film, red represents SU-8 negative photoresist and black represents black silicon. (a) Schematic of the perforated wafer. The thick SU-8 2025 layer serves as the spacer layer to form the deformable cavity. (b) Schematic of the membrane wafer. (c) The perforated and membrane wafers are bonded at the interface between the thin and thick SU-8. (d) A SF₆ dry etch is employed for the partial release process. The aluminum etch mask is then removed. (e) The integration of the black silicon aperture is performed, this simultaneously completes the release of the deformable membrane.

The fabrication of the membrane wafer starts with creating the backside etch mask for defining the aperture of the mirror. This etch mask is made by thermally evaporating

and patterning 200nm of aluminum. Next, approximately 100nm of aluminum is thermally evaporated onto the front side of the wafer, creating the reflective optical surface. SU-8 2002 is spun onto the optical aluminum and cured to form an elastic deformable membrane.

For the perforated wafer, a wet oxidation is performed to create a thick layer (500 nm) of SiO₂ that will eventually be used to isolate the actuation electrodes from the silicon substrate. Air channels are created through the perforated wafer using an anisotropic dry etch process. These channels are for air damping control to reduce response time during dynamic actuation of the deformable mirror. Due to the relatively large thickness of the perforated wafer and the decreased etch rate at large etch depths, the perforated wafer is pre-thinned from the backside using an SF₆ isotropic etch process; ICP power: 1500 W, RIE power: 5 W, SF₆ flow: 82 sccm at 25°C under 15 mtorr pressure. Backside IR alignment and deep reactive ion etching is then employed to define the location of and etch the air channels. Then, a thick aluminum layer (400 nm) is thermally evaporated and patterned to form the actuation electrodes. SU-8 2025, purchased from Microchem, (Westborough, MA, USA), is spin coated and patterned to create a 40 µm spacer layer defining the cavity between the optical membrane and the bottom electrodes. The two wafers are then bonded at 150°C under 300 KPa of pressure for 2 hours.

After bonding, an SF₆ dry etch process is employed to release the mirror according to the backside etch mask on the membrane wafer. This release process is completed in two steps. First, the silicon in regions above the mirror is removed to within a few microns of the optical surface. Then a CL₂ dry etch is performed to strip the aluminum mask, exposing the underlying silicon to prepare the surface for the formation of black silicon.

The thin layer of silicon covering the optical surface serves as a barrier to protect the optical aluminum from being removed by the CL_2 dry etch. At this point, the wafer is diced into individual devices using a wafer saw. Finally, black silicon is created by employing the recipe in Table 2. The thin layer of silicon over the mirror aluminum is simultaneously etched away during this process, terminating on the underlying aluminum, resulting in a free-standing mirror membrane. All other exposed silicon becomes black, creating the desired optical flocking surrounding the active membrane surface. Fig. 3 shows the final device after wire bonding to a supporting printed circuit board. For comparison, a mirror without black silicon is also shown.

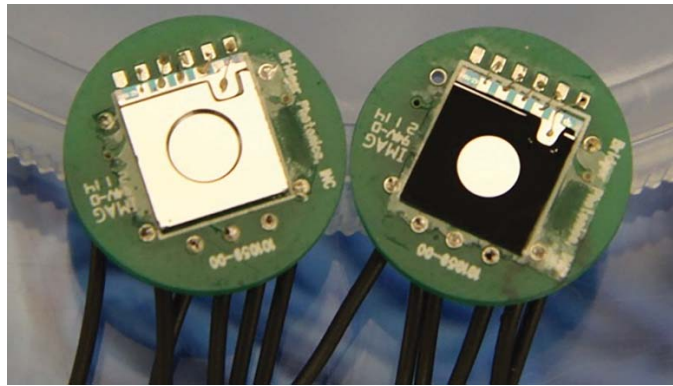


Fig. 3. Comparison of fully wire bonded and functional deformable mirrors. Left: without black silicon integrated aperture. Right: with black silicon integrated aperture.

As mentioned in the fabrication description, the need to perform the black silicon process after dicing is mainly due to concerns regarding the mechanical integrity of the fragile black silicon nanostructures, which do not tolerate the protective tape used during the dicing process. Of course, alternate methods of cutting that are less destructive to the black silicon surface could prove effective as well, such as laser dicing [40]. In addition to using the near room temperature process to create black silicon, we also attempted the

cryogenic recipe, which resulted in fractured devices. Moghimi et al. [12], provides additional details regarding the fabrication of the MOEMS variable focus mirrors without black silicon.

Results and Discussion

The specular reflectivity plotted against incidence angle for the cryogenic black silicon is shown in Fig. 4. When the angle of incidence was less than 10 degrees, less than 0.001% of the total incident power remains in the specular reflected beam at both wavelengths. This surface exhibits lower specular reflection compared to similar silicon structures reported by Tsakalakos, et al. (1% at 8 degrees from 300 - 850nm) and Lee et al. (0.09% at 30 degrees at 1 μ m wavelength) [18, 41].

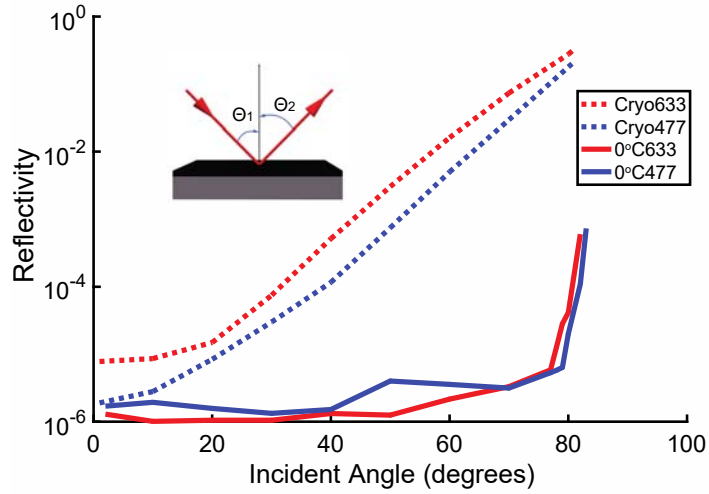


Fig. 4. Specular reflectivity as a function of angle of incidence for both types of black silicon. Legend: dotted red line represents the reflectivity of the cryogenic black silicon tested using 633nm, dotted blue represents cryogenic black silicon tested at 477nm, solid red represents 0°C black silicon tested at 633nm and solid blue represents 0°C black silicon tested at 477nm.

However, the reflectivity starts to increase rapidly once the angle of incidence exceeds approximately 20 degrees. Mizuno et al. and Wang et al. report similar findings regarding the dependence of specular reflectivity on incidence angle. Those reported measurements were conducted on densely packed $2\mu\text{m}$ tall carbon nanotubes exhibiting physical structures similar to the cryogenic silicon grass. Both papers reported specular reflectivity values of approximately 0.02% from 10 to 20 degrees which increases rapidly to approximately 7% at 68 degrees [42, 43].

Figure 5 shows the cosine corrected BRDF plotted against viewing angle. Calculations show the full hemisphere integrated diffuse scatter for this surface was approximately 0.6%-0.7% of the total incident power at both wavelengths. Due to extremely low specular reflectivity (0.001%) at normal incidence, the total reflectivity of this surface is approximately the diffuse reflectivity.

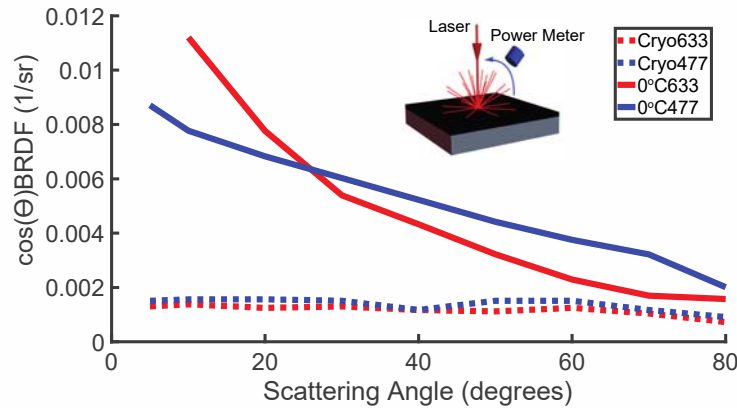


Fig. 5. The cosine corrected BRDF of the two black silicon surfaces is provided at both 633nm and 477nm wavelengths. Legend: dotted red line for the cryogenic black silicon tested using 633nm, dotted blue for the cryogenic black silicon tested at 477nm, solid red for the 0°C black silicon tested at 633nm and solid blue for the 0°C black silicon tested at 477nm.

This surface compares favorably to the total reflectivity measurements of similar silicon structures reported by Tsakalakos et al., Koynov et al., Nguyen et al., Steglich et al., Lee et al., and Kanamori et al., that reported total reflectivity ranging from approximately 1% to 8% at wavelengths ranging from 300nm to 1 μ m [18, 22, 31, 32, 41, 44]. The results also show lower total reflectivity compared to conventional black coatings used in optical systems such as Aeroglaze Z-306 which is about 4.5% and 3M Nextel Black Velvet paint which is about 3.5% in the visible spectrum [45]. This surface also potentially outperforms commercially available wafer level patternable light absorbing material such as Litho-Black produced by Acktar (Kiryat Gat, Israel), which displays a total reflectivity of 2% - 3% [46]. Shown below in Fig. 6 are the SEM images of the darkened surface. Measurements indicate that the silicon nanostructures are approximately 1 μ m in height while the widths range from 100nm to 200nm.

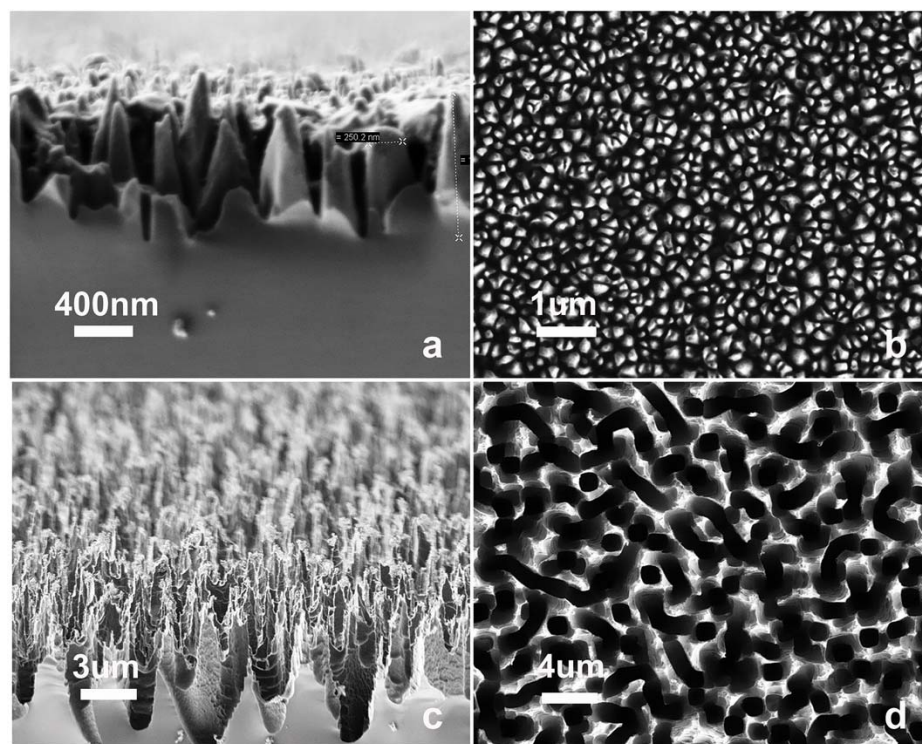


Fig. 6. Scanning electron microscope images of the side and surface profile of the black silicon micro/nano structures. (a) Side profile of cryogenic black silicon. (b) Surface image of cryogenic black silicon. (c) Side profile of 0°C black silicon (tilted at 8.9°). (d) Surface image of 0°C black silicon.

The measured specular reflectivity as a function of angle of incidence for the black silicon created at near room temperature is also shown in Fig. 4. The specular reflectivity of the surface is lower than 0.001% below 75 degrees angle of incidence. Fig. 5 shows a plot of the cosine corrected BRDF against viewing angle. A discrete integration of the diffuse reflection indicates that approximately 2.1% of the total incident power is in the diffuse laser scatter at 633nm and 2.8% at 477nm. This is approximately the total reflectivity due to the extremely low specular reflectivity at normal incidence. The height of the silicon pillars are approximately 10 μ m and display a tapered profile. SEM images are provided in Fig. 6. For comparison, Pezoldt et al. has demonstrated black silicon fabrication through plasma etching under non-cryogenic temperatures with a total reflectivity of 4% in the visible spectrum [47].

Scattered light provides a background intensity that sets a lower limit to our ability to measure specular reflections, using our simple apparatus. We can estimate the diffuse scatter baseline from our BRDF data (measured for a normally incident beam) by multiplying the cosine corrected BRDF by the solid angle of the detector during specular reflection measurements. Results suggest that specular reflections less than 2.3×10^{-7} and 2.7×10^{-7} for the cryogenic black silicon, measured respectively at 633nm and 477nm, will be dominated by the diffuse scatter. It can be seen from Fig. 4 that specular reflectivity is several times larger than this for all angles of incidence. For the 0°C black silicon, specular reflectivity less than 2×10^{-6} for 633nm and 1.5×10^{-6} for 477nm will be dominated by the

diffuse scatter. For this material we infer that the specular reflectivity data of Fig. 4 for angles of incidence less than about 40 degrees is therefore likely attributable to scatter, with the actual specular reflectivity less than 2×10^{-6} for 633nm and 1.5×10^{-6} for 477nm. The specular reflected beam emerges from the diffuse scatter baseline only for incidence angles greater than about 40 degrees.

As a further observation, it seems that the formation of dry etched black silicon is tolerant of variation of the plasma etching equipment as well as etch parameters. Along with the Oxford System 100 ICP that was used in this paper, Nguyen et al., Steglich et al. and Pezoldt et al. have fabricated black silicon using O_2/SF_6 by employing respectively an Alcatel 601E, SI-500°C plasma reactor and STS 320 RIE [31, 32, 47]. These authors, along with Dussart et al., [27] have achieved black silicon fabrication with reactor power ranging from 100W to 3000W, flow ratio of O_2/SF_6 ranging from 0.05 to 1.33, pressures ranging from 7mtorr to 50mtorr and temperatures from -130°C to 30°C. This makes the integration of black silicon onto MOEMS devices highly accessible.

Imaging was performed using the MOEMS deformable focus control mirror with integrated black silicon aperture to demonstrate its haze reduction property. An otherwise identical MOEMS deformable mirror that does not have the black silicon was used as the control. Fig. 7 displays the imaging setup. The experiment took place in an environment where an incandescent lamp that provides illumination for the objects was the sole source of light. Three pinecones were used as imaging objects for this demonstration. The distance between the first, second, and third pinecones from the beam splitter was respectively 480mm, 340mm and 200mm. The pinecones were staggered so that none of the pinecones

were obscured when viewed from the beam splitter. The MOEMS device was placed flush against the beam splitter. Optical baffles (not shown) were positioned to prevent reflected light directly from the pinecones from being collected on the CMOS sensor. Light reflecting off the pinecones would travel through the beam splitter, be focused by the MOEMS device and redirected through the 40mm focal length achromatic doublet onto the sensor. The MOEMS mirror diameter is 4mm, yielding an f-number of $f/10$ for the system. The CMOS sensor is an APS-C sensor on a Canon EOS 60D (no lens). The sensor was positioned so that the optical system was focused at infinity when the MOEMS mirror was flat. The MOEMS device with integrated black silicon aperture was first mounted and deflected to scan and acquire focus onto each of the three pinecones. It required respectively 78V, 112.2V and 148V for pinecones 1, 2 and 3 to be individually in focus which corresponds to focal lengths of approximately 870mm, 366mm and 186mm.

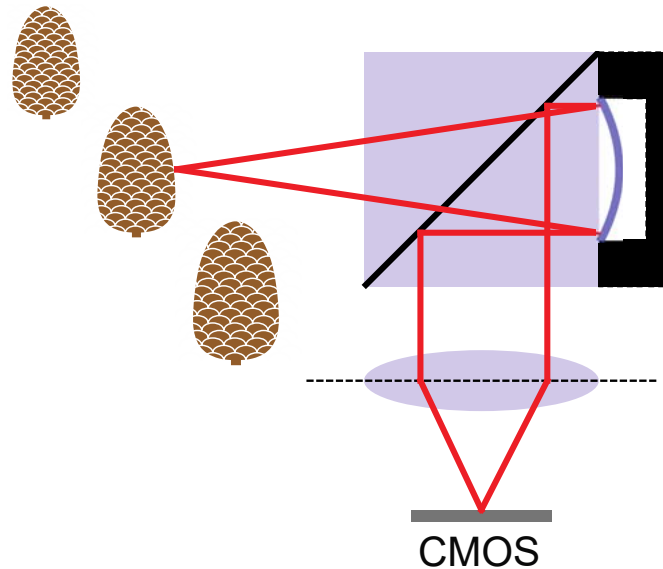


Fig. 7. Imaging setup for experimental evaluation of contrast improvement due to the black silicon integrated aperture.

The device with black silicon was then replaced with its counterpart lacking an integrated aperture. The same imaging procedure was performed with the voltage adjusted to achieve the same focal lengths as the black silicon mirror. This was to ensure that differences in the images produced by the two mirrors were not due to inaccurate focusing. Fig. 8 compares the imaging results when using the two mirrors. The images produced by the MOEMS mirror with the integrated black silicon aperture exhibit significantly better contrast and less haze from improperly focused light.

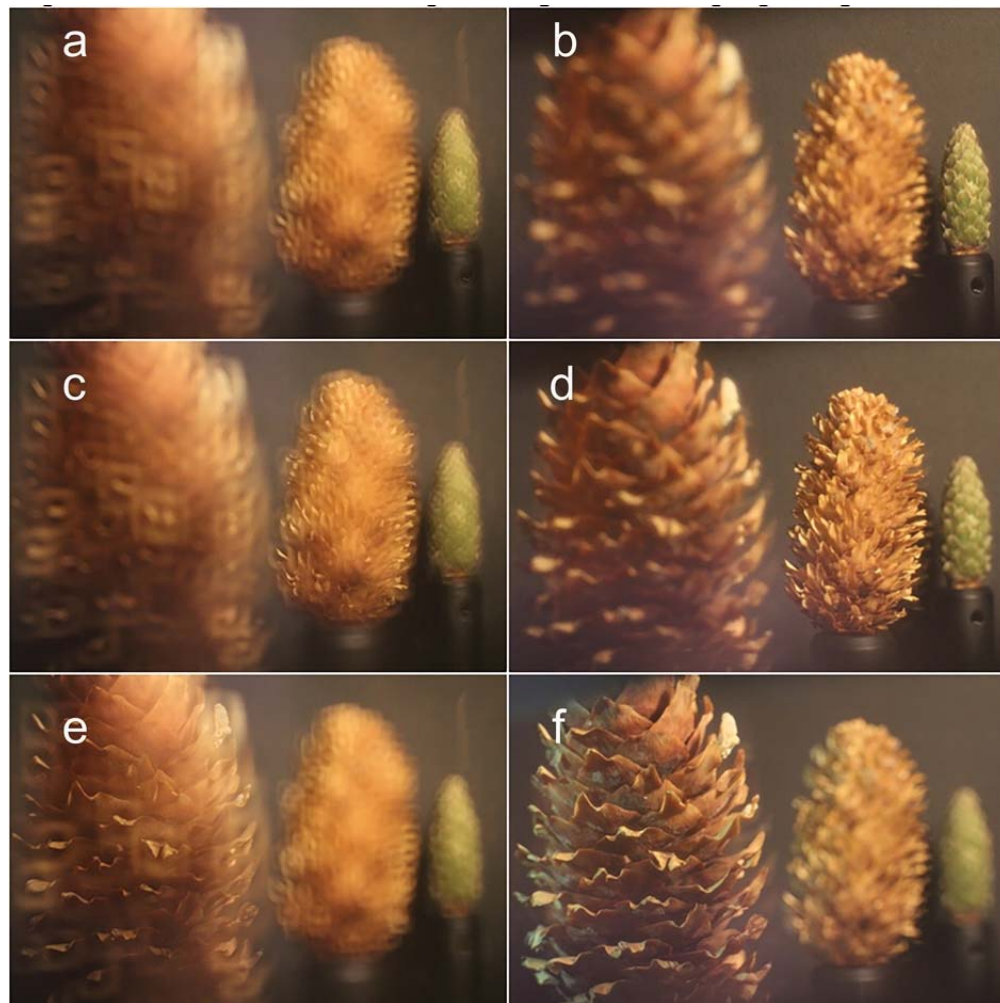


Fig. 8. Imaging results from the deformable mirror without (left) and with (right) black silicon integrated aperture. (a), (b) The mirror is focused on the furthest pinecone. (c), (d) The mirror is focused on the middle pinecone. (e), (f) The mirror is focused on the closest pinecone.

4 Conclusion

In this paper, a new concept for the use of black silicon as a flocking material for MOEMS devices is proposed and experimentally demonstrated. Two recipes for a single step, self-masked black silicon process were described, one performed at cryogenic temperature and one performed at closer to room temperature in order to be compatible with MOEMS devices with polymer structures. Both types of surfaces are found to exhibit excellent suppression of reflected and scattered light, comparing favorably with other published nanotextured optical absorbers. When referenced to each other, the cryogenic black silicon reflects less light in total but has a higher specular reflectivity, while the 0°C black silicon has lower specular reflectivity but higher total reflectivity. The near room temperature black silicon was incorporated into a self-aligned aperture around a MOEMS deformable mirror. Due to its effective reduction in stray light, imaging results with the black silicon aperture delivered a significant improvement in contrast and image fidelity. Because of its simplicity, process compatibility, and the excellent optical absorption properties of the resulting material, the method here described is attractive as an adjunct to benefit a wide variety of MOEMS devices.

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