DESIGN, FABRICATION, AND CHARACTERIZATION OF ELECTROSTATICALLY-
ACTUATED SILICON MICRO-MIRRORS

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ABSTRACT

Design, Fabrication, and Characterization of Electrostatically-actuated Silicon Micro Mirrors

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Micrometer-scale mirrors are used in many electronic devices today such as digital light projection. One common type of mirror is a thin plate structure supported by torsional hinges which rotates when actuated. These devices are popular because the design allows for high stability and reliability. Parallel plate electrostatic actuation is commonly used to create the force which rotates the plate structure. The device consists of one deformable parallel plate electrode and one immovable electrode. In order for these devices to rotate to a specific angle when actuated, both the mechanical and electrostatic forces must be characterized. This project analyzes both of these forces through modeling equations, and compares theoretical performance to experimentally measured values. The rotational measurements involve reflecting a laser spot off the surface of the actuator face and recording any displacement of the laser spot with a position sensitive device. The electrostatic device created consists of a rotating hinged structure, a fixed aluminum electrode, and a polymer spacer to create an air gap between the electrodes. These components are created using standard semiconductor fabrication techniques. The hinged structures are created from a 500 μm thick, double-sided polished, single crystal (100) silicon wafer. The wafers are etched using both wet etching, and reactive ion etching techniques, which produce approximately 8 μm thick plate structures. Physical vapor deposition is used to deposit a thin aluminum film onto the silicon in order to form a conductive layer. Rigid aluminum counter-electrodes and SU-8 polymer spacers are fabricated on a glass slide. The silicon actuator chip is aligned and mounted onto the glass slide. Once fabricated, the micro-mirror actuator was

tested for angular rotation as a function of applied voltage. The applied voltage ranged from 0 to 100V and produced an angular rotation up to 0.3 degrees. During testing it was observed that the stability of the angular tilt was poor enough to merit further examination. Angular stability over time can be a serious issue for micro mirrors, and can cause complete failure of the device. Short and long term angular drift as well as a rotational settling phenomenon were investigated.

Angular drift was found to be most likely caused by electrical or environmental factors. The rotational settling had an electrical root cause, which caused charge to migrate on the glass substrate beneath the actuator. The charge formed by the migration created a counteracting force on the actuator causing the rotation angle to reduce over time. The migrating charge was eliminated by creating a second neutrally charged counter-electrode which prevented charge from building on the glass surface.

Key Words: MEMS, torsional mirror, electrostatic actuation, angular drift, charge migration.

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SECTION 1: INTRODUCTION

1.1 Background

The field of Microelectromechanical systems (MEMS) has seen rapid growth over the past decade with the ability to heavily influence society and the economy [1,2,3]. The fabrication processes used to create MEMS was translated from the integrated circuit manufacturing industry. Translating these processes allowed for high volume production with low unit cost which resulted in the integration of both mechanical and electrical components onto a single chip. In addition to the economic advantages, exclusive applications could be achieved such as micromotors [4], digital-micromirror-devices (DMD) [5], and chemical reactors [6]. It is the scale of these devices that allows for high sensitivity and reliability while keeping cost to a minimum. These small scale structures which are typically tens of microns in size become much more sensitive as size decreases [1]. Forces in the range of millinewtons are used to actuate these structures, which would be nearly impossible with macro-scale structures. When the increased mechanical sensitivity is combined with an electrostatic actuation system less power is required to operate [2].

Most actuating MEMS can be divided two main components: structure and actuation force. Common types of structure include membranes, cantilevers, fixed-fixed beams, and torsional hinges. Micro-mirrors which incorporate the torsional hinge structure are widely employed because of their good dynamic response and small possibility of adhesion when the electrodes come in close contact [2]. Specific examples of this type of design include spatial light

modulators [7] and optical switches [8]. The actuator created in this study is a thin plate supported by two torsional hinges which allow for a single axis of rotation (Figure 1). The second component involves the type of force which creates rotation of the thin plate about the axis of rotation. Common actuation forces include: piezoelectric, thermomechanical, and electrostatic [9]. Electrostatic actuation is common in MEMS because there is little restriction on materials used, actuation is quick, and little power is consumed [10]. All that is required for electrostatic actuation is two conducting or semiconducting electrodes and a power source (Figure 1).

Figure 1 – Isometric view (left) of the silicon torsional mirror and side view (right) of the electrostatically actuated device.

1.2 Motivation

MEMS are inherently complicated structures involving a system of components which are both electrical and mechanical. The design and analysis of these devices must take the entire system into consideration in order to be successful. For this study, the design and analysis focused on electrostatically actuated silicon micro-mirrors. Characterizing these structures allows for a better understanding the actuators complicated nature. A greater understanding of these actuators also allows for improvements in the fabrication process as well as the measurement of

small angle deflection. This research will support the fabrication of more complex hinges that allow for larger angles of deflection.

The objective of this thesis was to design an actuator using modeling, realize the design using the fabrication capabilities available, and characterize the actuators performance. The main focus of this research was to characterize the rotation, stability over minutes to days, and actuated angular repeatability of an electrostatic actuator.

SECTION 2: OPERATION AND DESIGN

2.1 Desired Response

An electrostatically actuated device which routes light to precise locations must switch in the microsecond range in order to route information with as little delay as possible [11]. The actuator must also hold the position and return to that exact position after a large number of cycles without drifting out of the allowed range for that specific application. Accuracy is not as important because the position of the incoming and outgoing light source can be adjusted to suit the device [12]. The torsional micro-mirror fabricated in this study has been used in this exact situation (Figure 2) [12].

Figure 2 - Model of the torsional hinge silicon plate structure fabricated during this study.

The actuator should deform elastically, rotating to some specified angle and holding that position until force is relieved (Figure 3a). Figure 3a represents an ideal situation where an applied actuating force causes a rotation of 0.3 degrees. The actuator goes from a stable position at zero degrees to 0.3 degrees almost instantly when a rotational force is applied. No drift over time is present at the rotated angle, and when the force is removed the actuator instantly rotates back to zero degrees. Figure 3b is the experimentally observed response which indicates a large deviation from the ideal response.

Figure 3 - The ideal (a) and observed (b) rotational response from an actuator over time.

Characterization completed in this study revealed a non-ideal response that resulted in significant rotational settling of the actuator. The rotation of the actuator differs from the idea situation in that it experiences a period of time dependant settling. The actuator deflects to a maximum rotation and then loses rotation as a function of time until after a certain time the rotation stabilizes (Figure 4).

Figure 4 - Side view of a micro-mirror actuator displaying the rotation settling phenomenon.

The loss of rotation observed can render a device ineffective if used in an applied situation. The settling may cause the light reflected off the actuator surface to end up in the wrong location. This phenomenon has an electrical cause which is explained later on. Investigating the root cause and magnitude of the non-ideal settling is one of the motivations behind this study.

2.2 Electrostatic Actuation

In order to characterize the actuator and determine the cause of the non-ideal settling, the actuator is separated and analyzed as two different systems: the electrostatic and the mechanical. The electrostatic system creates a force which causes the actuator to rotate. This force is counteracted and balanced by the spring constant of the torsional hinge which is considered the mechanical system.

2.2.1 Electrostatic and Mechanical Forces

Electrostatic force arises from the separation of two opposite charges attracting. In this case two parallel plates, one fixed and the other moveable, are charged oppositely. When voltage is applied, the plates charge and an electrostatic force is created (Figure 5). The mechanical system is comprised of the silicon torsional hinge which is covered by a thin aluminum film. The

purpose of the aluminum film is to provide an electrically conductive path to the rotating silicon actuator. The second plate which is referred to as the counter-electrode is made from aluminum as well, and provides a conductive path to carry an opposite charge.

Figure 5 - Electrostatic actuator which encompasses both mechanical and electrostatic properties.

The rotational hinge resists movement when a force is applied to the face of the plate. This relation can be solved using Hooke's Law (Eq. 1) [9].

$$F_m = k\Delta d \quad (1)$$

Where F_m is the mechanical restoring force (N), k is the torsional spring constant of the hinge (N/m), and Δd is the change in distance (m). When a voltage is applied between the electrodes a force is created (Eq. 2) [9]. This force overcomes the intentionally weak spring constant of the hinge and rotation occurs. The mechanical and electrostatic forces will eventually balance and a stable rotation can be held.

$$F_{electro} = E_{field} \times \rho \quad (2)$$

Where $F_{electro}$ is the electrostatic force (N), E_{field} is the electric field created (V/m), and ρ is the charge density between the two electrodes (F·V).

$$E_{field} = \frac{V}{d} \quad (3)$$

Where V is the applied voltage (V), and d is the distance between the electrodes (m). Charge density is dependent on both the capacitance of the electrodes, and the voltage applied between them. To determine charge density Eq. 4 and 5 are used [9].

$$\rho = CV \quad (4)$$

$$C = \frac{\epsilon_r \epsilon_0 A}{d} \quad (5)$$

Where C is the capacitance (F), ϵ_r is the relative permittivity of air, ϵ_0 is the permittivity of free space (F/m), A is the area of the electrode (m^2), and d is the electrode spacing. The resulting electrostatic force can be created using equation 3, 4, and 5.

$$F = \frac{\epsilon_r \epsilon_0 A V^2}{d^2} \quad (6)$$

2.2.2 Capacitive Charging and Mechanical Response

Another important aspect in characterizing the actuator is the time it takes for both the capacitor to charge and the actuator structure to respond. The total time taken is referred to as the response time of the actuator. Determining the response time will also support whether or not the actuator response causes the rotational settling phenomenon presented in section 2.1.

The time required to achieve a 95% charge (RC_{tc}) is calculated by multiplying the resistance of the aluminum electrodes by the capacitance in equation 7 [9]. Using a gross overestimate for the resistance of the aluminum of 100k Ω the resultant time becomes 85 nanoseconds.

$$RC_{tc} = 5(R \times C)$$
$$C = \frac{\epsilon_0 A}{d} \quad (7)$$

In order to determine the mechanical response of the actuator the mechanical system must be decoupled from the electrostatic system. The electro-mechanical coupling restricts the ability to study the mechanical system independently. To achieve this decoupling, the actuator is rotated using the direct mechanical force of a profilometer. An Ambios XP-2 profilometer was used to replicate a 0.112 degree rotation caused by an electrostatic potential of 100V (Figure 6). Using equations 9 and 10 a 40 μ N force applied by the profilometer would result in a theoretical rotation of 0.120 degrees. It was not possible to measure the exact rotation due to the applied mechanical force. The response of the actuator was recorded once the load was applied and a total of three measurements were taken (Figure 7).

Figure 6 - Direct mechanical force from profilometer tip causing actuator rotation.

Figure 7 - Actuator response to an applied mechanical force showing an average drift of 25nm.

Under an applied load of $40\mu\text{N}$, the actuator drifts an average of 25nm and begins to stabilize around 30 seconds. A drift of 25nm translates to a rotation of 0.002 degrees which is far below the 0.150 degree rotation loss seen during 100V tests. The actuator also rotates in the opposite direction of the non-ideal behavior shown in Figure 3b. The 0.002 degree rotation is most likely due to a viscoelastic effect in the aluminum film which has been studied previously [13]. This eliminates the silicon structure and aluminum film as a possible source of the rotation settling phenomenon.

The total response time of the actuator is well under 30 seconds, making any response that occurs past this period is unlikely due to capacitive charging or mechanical response. Therefore, the non-idea behavior is most likely due to an electrical occurrence such as charge migration on the surfaces underneath the silicon actuator. The large electric field created by the oppositely charged electrodes causes charge to migrate in and on the glass substrate surrounding the aluminum counter-electrode. These charges have the ability to dramatically change the electric field and forces on the actuator, which explains the observed actuator response in section 2.1.

SECTION 3: TESTING EQUIPMENT

3.1 Measurement Test Stand

Modeling actuator rotation with FEA software and other equations allows for at best a rough idea of the true reaction. These theoretical models provided a good starting point in designing the actuators, but are only numerical models of a physical situation. In order to fully understand the rotation of the device a testing setup was required. This setup is commonly known as the test stand and has the ability to measure rotation to a high degree of precision. The test stand has an actuator rotation range of approximately 10.6 degrees and a maximum angular precision of 0.002 degrees [14].

The test stand is a system consisting of two main components: measurement and actuation (Figure 8, 9 & 10). The components are monitored and controlled using software created in Visual Basic (Appendix E). The software allows for automated control and data collection over

any period of time. Examples of the test stand capabilities include position repeatability, actuation response, and long term actuator stability testing [13].

Figure 8 - Overview of the test stand and the system components.

Figure 9 – System block diagram including showing the direction of information.

The test stand measurement component uses a method which involves reflecting a focused laser beam off the surface of the mirror face onto a position sensitive detector (PSD). The laser beam begins at a HeNe cylindrical laser which emits a beam at a wavelength of 632nm. The beam is precisely angled to produce an angle of incidence (AOI) of 67.5° to the actuator face. The diameter of the emitted laser beam is larger than the width of the actuator face (550 μ m). To

reduce measurement error the beam diameter was reduced to approximately 300 μ m using a focusing lens (Figure 10).

Figure 10 - Test stand components which allow for high resolution rotational measurements.

The laser spot reflects off the actuator which is secured to the test stand by moveable stage. The reflected beam strikes the PSD and creates electron-hole pairs which are swept away by an applied potential bias. The separation of electron and hole creates a potential which can then be measured. The PSD detector face has potential applied in both the vertical and horizontal

directions allowing for detection of movement in both the x and y directions up to 30mm in either direction. The locations of the detected electron-hole pairs from the laser spot are averaged and output as a voltage. If the laser spot moves in the vertical or horizontal direction the vertical or horizontal potential will change. This voltage ranges from -10V to 10V and changes linearly with movement in the horizontal or vertical directions [14].

Data is collected from the PSD through a signal amplifier using an Agilent 34970A data acquisition unit (DAQ). The DAQ reads incoming signals in the form of voltage, current, or resistance, and can store the information or export it. In this case, data collected from sensors is exported from the DAQ to a file on the computer. The most important data comes from the horizontal voltage (V_x) output by the PSD. This voltage relates to the movement of the laser spot on the PSD surface due to a rotation of the actuator. The voltage is transformed into a rotational measurement using Equation 8 [14].

$$Rotation \ (degrees) = \frac{90}{\pi} \left(AOI - \left(\arctan \left(\frac{1}{\frac{V_x}{d_p} + \cot(AOI)} \right) \right) \right) \quad (8)$$

Where AOI is the angle of incidence at 1.178 radians (67.5°), V_x is the voltage output from the PSD, and d_p is the perpendicular distance from the actuator face to the PSD (55mm).

Determining the noise of the system before applying an electrostatic force is necessary for obtaining relevant data. The background noise sets the angular resolution limit for the

measurement system. The angular resolution of the test stand was measured using a zero degree reference mirror securely fastened to the test stand. Stability measurements in a previous study have shown the test stand to have a noise of approximately 0.0001 degrees over 15 minutes and 0.002 degrees over a period of 24 hours [14]. Noise was measured during the current testing period and was determined to have a similar value of 0.0002 degrees over 15 minutes and 0.0018 degrees over a period of 24 hours (Figure 11).

Figure 11 - Long term drift of used to set a baseline for the test stand measurements.

The second component of the test stand is the actuating system. The actuator electrodes become oppositely charged using an AdvancedMEMS high-voltage MEMS driver which supplies the potential [15]. The driver is controlled by a computer running a custom LabView interface. Connections to the device are made with 22-gauge wire and alligator clips. The driver has a voltage output range of 0-300V as well as signal generation capabilities. For this study, only static DC voltages were employed.

SECTION 4: DESIGN

4.1 Summary

The objective of the design was to create a simple torsional hinge structure that would rotate due to an electrostatic force. In order to characterize the actuator, a minimum rotation of 0.002 degrees was required due to the resolution limit of the test stand. An equation for the rotation was developed (Eq. 10) and used alongside finite element analysis (FEA) called COSMOSWorks in order to determine the correct dimensions for the structure. These modeling methods were used in conjunction with other design constraints. These constraints included fabrication limits, material choice, dielectric breakdown strength of air, and the occurrence of actuator “snap-down” when the actuators come in physical contact with one another. Also, in order to focus on an electrostatic cause of the non ideal behavior the mechanical factor had to be decoupled and disproven.

4.2 Initial Design Equation and Modeling

The shape of the silicon structure was first chosen, and then modeled with both a rotation equation and FEA. The shape was chosen from a simplified torsional hinge design previously characterized (Figure 12). This shape was chosen due to the simplicity and the success of a previous study in accurately modeling the actuator [13]. The modeling equation took the electrostatic force in Eq. 9 and modeled the force as a torque [9].

Figure 12 - SolidWorks model of the torsional hinge silicon plate structure.

$$T = F \left(\frac{l}{4} \right) \quad (9)$$

The applied moment (T) on the hinge is dependent on the electrostatic force, and the length of the actuator. In the actual actuator, the electrostatic force is applied over the electrode area, but the equation assumes a single force half way between the edge and hinge of the actuator.

Rotation is then calculated using equation 10.

$$\theta = \frac{TL}{JG} \quad (10)$$

Where θ is the rotation in radians, T is the applied moment (N·m), L is the length of the actuator hinge (m), J is the polar moment of inertia of the cross-section of the hinge (m⁴), and G is the shear modulus of the material (Pa). This equation, along with the system constraints were then used to determine the dimensions of the actuator face and hinges.

In order to assure that the modeling equation was using valid concepts FEA software was used to check the numbers. A model of the actuator was built in SolidWorks and rotation was modeled using COSMOSWorks (Figure 13). Instead of using a point force like the equation model, the FEA model replicated a more real situation by applying a uniform force over the surface of the actuator face.

Figure 13 - FEA model used to predict the rotation angle of the plate structure.

The model shown in Figure 13 can be used to calculate rotation through the use of deflection data. It can be seen in Figure 14 the neutral axis of rotation is not located along the axis of the actuator. In order to determine the rotation a geometric model (Figure 14) and equation (Eq. 11) were created.

Figure 14 - Total deflection and length of rotated actuator

$$\theta = \arcsin\left(\frac{\text{Total Deflection}}{\text{Actuator Length}}\right) \quad (11)$$

The two modeling methods were compared and the results in table I show that the methods correspond to a maximum percent difference of 10.3%. The difference in predicted rotation between the two methods arises due to the way the rotation is calculated. The initial design equation uses a simplified torque and lever arm scenario while COSMOSWorks uses an FEA approach. The modeling methods are compared to the actual data in section 7.3.

Table I - Comparison of Rotation Data

Actuation voltage (V)	Initial Design Equation Rotation (millidegrees)	COSMOSWorks Rotation (millidegrees)	Percent Difference
25	7.0	7.8	10.3%
100	112.4	112.7	0.27%

4.3 Constraints

The design constraints were broken up into structural and electrical limitations. The structural constraints included the material choice for the structure and spacer. Silicon was chosen as the structural material due to first, the knowledge and equipment gained from previous silicon processing. Previous studies have worked extensively with silicon micromachining, which has simplified the fabrication process [16]. Secondly, the shear modulus of silicon allows for both a stiff plate structure and low stiffness hinges [17].

The electrostatic constraints included applied voltage, snap-down of the actuator, and electrical breakdown of the air gap. First, the actuation voltage was limited to 200V, which was the limit of the available power supplies. Second, as the actuator rotates, the distance between the two electrodes decreases. The decreased spacing increases the capacitance and results in a greater force on the electrode. At a certain applied voltage the mechanical restoring force is overcome by the electrostatic force and the top electrode will “snapdown” onto the counter-electrode. In most cases if the electrode spacing decreases by more than one-third the original gap, snapdown will occur [18]. Therefore, the deflection of the structure at the edge was limited to one-third of the gap. Third, breakdown voltage of the air gap (V_{max}) can be predicted using Paschen’s law (Eq. 12) [9].

$$V_{max} = \frac{a(pd)}{\ln(pd) + b} \quad (12)$$

Where a and b are the dielectric constants, p is the pressure (atm), and d is the electrode spacing (m). When air is at atmospheric pressure $a=43.6 \times 10^6$ and $b=12.8$. The chosen air gap distance of $16\mu\text{m}$ relates to a breakdown potential of 400V which is well above the available supply of 200V . With all three constraints incorporated, all the dimensions of the silicon structure could be determined, and fabrication could move forward (Figure 15).

Figure 15 - Top view of the final silicon actuator design which has a thickness of $8\mu\text{m}$.

SECTION 5 FABRICATION

5.1 Summary

To create the actuators, a thermal oxide was grown on double sided polished wafers. Certain areas of the oxide layer were removed using lithography and an etching process which exposed the underlying silicon. These exposed rectangular areas of silicon were anisotropically wet etched at a rate of $22.9\mu\text{m/hr}$ which created pits approximately $490\mu\text{m}$ deep. What remained

were thin rectangular membranes approximately $8\mu\text{m}$ thick. The oxide layer on the opposite side of the wafer was patterned to create the actuator outline. Reactive ion etching (RIE) using SF_6 and O_2 was employed to etch through the membrane creating the silicon plate structure. RIE was used instead of wet etching because the RIE gases will not break the silicon structures during processing. During removal of the devices after a wet etch process the fluid pressure can easily break these structure. A film of conductive aluminum was sputtered onto the surface of the structures as well as a glass slide. The aluminum film on the glass was patterned to create the counter electrodes. The slide was then coated in SU-8 in order to form a uniform spacer layer. A set of actuators were released from the original silicon wafer using dicing and were aligned with their corresponding counter-electrodes. Finally, the silicon die was bonded to the glass slide using a hot melt adhesive. The cross sectional view for each step can be seen in Appendix B.

5.2 Thermal Oxidation

The purpose of growing an oxide layer on the silicon surface is to create an etch mask. This etch mask allows certain areas to be exposed to the etchant while protecting others. Silicon dioxide is used because has relatively low etch rate compared to silicon. This low etch rate is necessary when etching through a majority of the wafer.

The fabrication process began with cleaning the wafers by using piranha and buffered oxide etch (BOE) to remove surface contaminants and oxide growth respectively. Piranha is a 4:1 solution of sulfuric acid (H_2SO_4 , 40%) and hydrogen peroxide (H_2O_2 , 30%). When heated, the solution

oxidizes organic matter, but also oxidizes the silicon surface creating a thin oxide layer. BOE which contains hydrofluoric acid is used to remove this layer to expose the bare silicon surface.

The wafers were first soaked in 70°C piranha for 10 minutes, rinsed in deionized water, and then soaked in room temperature BOE for 2 minutes. The wafers were rinsed again to remove any remaining BOE, and blown dry using low purity (LP) nitrogen. The wafers were placed in a quartz boat with an extra wafer at either end. These extra wafers are known as dummy wafers and are placed on the end to stabilize the airflow around the device wafers. Stable air flow around the device wafers improves the uniformity of the oxide growth.

In order to ensure that the oxide etch mask would stay intact throughout the wet etch process a thick enough film had to be grown. It has been shown in previous research that a 500nm “wet” oxide film is sufficient for long term silicon etching [16]. The etch rate of silicon compared to silicon dioxide is referred to as selectivity. The silicon to oxide selectivity for 25 wt% TMAH at 80°C is more than 6000:1 [16]. The oxide growth rate is given by the Deal-Grove model [19]:

$$t + \tau = \left(\frac{X_o^2}{B} \right) + \left(\frac{X_o}{(B/A)} \right) \quad (13)$$

where, t is the oxidation time in hours, τ is a factor which takes initial oxide thickness into consideration, X_{ox} is the oxide film thickness, B and B/A at 1050°C are 0.35 $\mu\text{m}^2/\text{hr}$ and 1.20 μm , respectively for (100) silicon and wet oxidation. It was determined by Eq. 13 that a time of 68 minutes at 1050°C would result in a 500nm thick oxide film.

The oxide growth process began with preheating the furnace to 700°C. High purity nitrogen gas (99.999%) was then flown into the furnace tube. The boat and wafers were inserted into the furnace and the temperature was brought up to 1050°C. High purity oxygen gas (99.999%) was pumped through deionized boiling water in order bring both oxygen and water vapor into the chamber. When the oxidation process was completed, the furnace was cooled. The final oxide thicknesses ranged from 470-500µm.

Table II - Process Sequence for Wet Thermal Oxide Growth

Process Step	Temperature	Gases
1. Preheat furnace	23°C - 700°C	None
2. Insert wafer boat	700°C	High purity N ₂
3. Ramp up temperature	700°C - 1050°C	High purity N ₂
4. Soak for 68 min	1050°C	High purity O ₂ + H ₂ O
5. Cool down	1050°C	High purity N ₂
6. Cool down	700°C	None

5.3 Positive Resist Photolithography and Bottom-side Patterning

In order to expose certain areas of the silicon to etchant, the oxide layer had to first be patterned. A photosensitive polymer layer was spin coated onto the surface of the oxide, and was patterned

using standard lithography techniques. BOE could then be used to pattern and expose each etch window.

Following the thermal oxide growth, the wafers were placed on a 150°C hotplate for 60 seconds in order to remove any moisture present on the surface. The wafers were cooled and individually secured in a Laurell Technologies WS-400B-6NPP spin-coater. MicroChem's MCC Primer 80/20 (3mL) was dispensed onto the surface of the wafer and was spun until the primer evaporated. The MCC primer was used to remove adsorbed water and promote adhesion between a substrate and the photoresist. Rohm-Haas Microposit S1813 positive photoresist (4mL) was dispensed onto the surface and the wafer was spun using a four step process (Table III).

Table III - Positive Photoresist Spin-Coating Program

Process Step	Spin Speed (RPM)	Time (seconds)
1	200	5
2	500	10
3	2500	35
4	300	5

The first two steps are used to spread the resist over the surface evenly, the third planarizes the film to a desired thickness, and the fourth step slowly brings the speed down to where the wafer can be stopped. Each wafer was placed on a 90°C hotplate for 60 seconds in order to drive off a majority of the solvent in the resist film. The resulting thickness of the resist was 2.4µm.

The resist film was exposed to ultraviolet light using a Canon. The exposure time was set to a light integral of 4.5 which corresponds to an exposure time and dose of 16.7seconds and $108\text{mJ}/\text{cm}^2$ respectively. The first mask in Appendix A was used to expose the etch squares to the UV light. The wafers were submerged in a Shipley 1165 developer for two minutes to dissolve the exposed resist regions. The regions unexposed acted as a mask protecting the underlying oxide. Once rinsed in DI water, each wafer was placed on a 150°C hotplate for 60 seconds to remove any remaining solvent in the photoresist. The wafers were placed back in the spin coater to coat the top side of the wafer. The wafers were placed on a 150°C hotplate for 60 seconds to drive off the solvent in the film. Coating the top side of the wafers was necessary to keep the oxide layer on the top side intact. The wafers were submerged in BOE for 6.5 minutes to remove the exposed oxide and 2 minutes in Shipley's photoresist stripper to leave only the patterned oxide film.

5.4 Wet Anisotropic Etching

In order to create an $8\mu\text{m}$ thick actuator from a $500\mu\text{m}$ thick silicon wafer, square membranes had to be fabricated. Wet chemical etching was used to anisotropically etch the exposed squares until only an $8\mu\text{m}$ silicon membrane remained. This anisotropic etching was possible due to different crystal planes in the monocrystalline silicon. The crystal planes have specific activation energies which cause certain crystal planes to etch faster [20]. The etch rate for the crystal planes is ranked as follows: $(100) > (110) > (111)$ [20]. The (100) silicon wafers used, form pits which follow the angles of the crystal planes (Figure 16).

Figure 16 - Cross section of a (100) silicon wafer pit demonstrating variable etch rates.

The etchant used was a 25wt% Tetra methyl ammonium hydroxide (TMAH) and water mixture. Isopropyl alcohol (IPA) was added to the etchant at a 1:9 volume ratio. The purpose of adding IPA was to increase the uniformity of the etched surface. It is said to decrease the formation of hillocks [21]. The solution was placed in a heated vessel with a reflux condenser to maintain the solution concentrations (Figure 17). The etchant was heated to 80°C because previous etching at 85°C encountered an increase in etch rate when the membrane reached 10μm [16]. Heating the solution to 80°C was accomplished by setting the hotplate to 125°C, and using the Omega resistance heater to raise and control the temperature of the fluid to 80°C. The Omega heater is equipped with a thermocouple which is immersed in the heated solution and allows for a feedback loop. The temperature of the solution can be held at 80°C ± 0.2°C.

Figure 17 - Wet silicon etching setup used to create silicon membranes.

The oxide wafers with the exposed silicon etch windows were placed face up into a Teflon wafer cassette and submerged in the heated solution. A magnetic stir bar was used and set to a speed of “1” on the knob which relates to approximately 100RPM.

To obtain an etch rate, an Ambios XP-1 profilometer was used to measure the pit depth up to 400 μ m. The profilometer stylus was dragged from the top surface of the wafer down into the pit (Figure 18). The recorded depths were taken from eight pits on each of the three wafers. These depths translated to an average etch rate of $22.9 \pm 5.7\mu\text{m/hr}$.

Figure 18 - Depth measurement of an etch pit using the profilometer.

When the pit depth reached the maximum profilometer range of $400\mu\text{m}$ a second method of determining membrane thickness was used. This method took advantage of the formation of through-holes in the membranes that occur during the silicon etching process. Through-holes are formed when pinholes in the oxide layer allow silicon etchant to etch from the top side and through the membrane. These small through-holes like the larger membrane pits becomes angled and an optical microscope can be used to determine the membrane thickness. The microscope is used by focusing on the top and bottom of the membrane individually and recording the working distance of each. The working distance of the optical microscope is recorded from the focus dial tick marks, and the difference is calculated. Using the 20x objective lens, every tick mark corresponds to $1.09 \pm 0.11\mu\text{m}$. This conversion factor was calculated by comparing the working distance measurement to a calibrated profilometer standard.

5.5 Top-side Patterning and Dry Etching

To create the silicon torsional mirrors, the deep etched square membranes were patterned. This process began with patterning the top side oxide layer using similar lithography techniques as

described in Section 5.3. The spin programs and exposure time remained the same. The photoresist and oxide layer mask was used to transfer the pattern to the silicon membrane below using RIE. The RIE etched fully through the membrane creating the mirror structure.

The first main deviation in the lithography process was the need for a different photoresist dispensing routine. The top side of the wafer was covered with a large number of pits caused by the wet etching process. These pits impede the flow of photoresist over the surface during spin coating. To alleviate this problem the entire wafer's surface was covered in resist prior to spinning. The second deviation in the lithography process was the need for alignment of mask two to the membranes below. The membranes were not visible from the top side of the wafer which made alignment difficult. Three silicon membranes were intentionally broken out which revealed the edges of the bulk silicon pits from the top side. Mask 2 was then aligned by hand using the holes as a reference. It is suggested that intentional alignment holes be included in future mask designs to eliminate physically breaking membranes.

The wafers were exposed, developed, hard baked, and carefully submerged in BOE to pattern the top oxide layer. Steps involving a "wet" process had to be carefully performed because the membranes as well as the entire wafer became fragile after etching a large number of silicon pits. A beaker of DI water and an 80°C hotplate were used to rinse and dry the wafers respectively. The wafers were then placed top side up into the RIE chamber (Figure 19).

Figure 19 – Cross section of the RIE and actuator showing directionality of etchant.

The reactive ion etcher was used to anisotropically etch through the exposed silicon resulting in near vertical sidewalls shown in Appendix B. The anisotropic etching is in part due to ion bombardment and possibly the chemical nature of the plasma [20]. The RIE works by creating a plasma of sulfur hexafluoride (SF_6) and oxygen (O_2). Fluorine ions and radicals are formed in the plasma and react with the exposed silicon surface. The process described in Table IV removes the silicon at an etch rate of approximately $4\mu\text{m}$ per minute. The resultant structure is a large rectangular sheet supported by two hinges (Figure 20)

Table IV - Process Specifications for Etching Silicon Using RIE

Gases	High Purity SF_6 and O_2
Mixture ratio	80:20
Pressure	300mTorr
Power	300W
Time	5 minutes

Figure 20 - Optical micrograph of the released one axis rotational actuator.

5.6 Physical Vapor Deposition

In order to create both the conductive electrodes on the silicon mirrors and the counter electrodes below them, a 150nm thick conductive layer of aluminum was coated onto the surfaces.

Physical vapor deposition (PVD) was used to sputter aluminum from a target material onto a surface. This process involves evacuating a chamber, creating an argon plasma, and accelerating the argon ions into the aluminum target. The aluminum atoms are physically removed from the surface and deposited on the silicon structure surface.

The device wafers were placed individually in the Torr CrC-150 chamber bottom side upwards and coated according to the specifications in Table V. The counter electrodes were fabricated by first cleaning standard microscope slides in Piranha for 10 minutes. The slides were then sputtered using table V specifications. Each time the chamber was pumped down for 30 minutes prior to sputtering.

Table V - Process Specifications for Sputtering Al in the Torr

Target material	99.999% Aluminum
Power	50 W
Gas	High Purity Argon
Pressure	8 mTorr
Sputtering time	20 minutes
Resultant thickness	130 nm

5.7 Counter-electrode Patterning

Each aluminum coated slide was coated in photoresist using the same spin-coating procedure as used in the oxide patterning process. The photoresist and aluminum were patterned by placing the counter electrode mask in Appendix A on the surface of the photoresist. The mask was then exposed for 13 seconds resulting in a dose of $84.4\text{mJ}/\text{cm}^2$. The developer used to pattern the photoresist can also be used to remove the exposed aluminum, eliminating the need for an aluminum etchant. The resultant aluminum features become only a few microns smaller than the mask features. The photoresist was stripped away using methods discussed in section 5.3, leaving aluminum counter-electrodes (Figure 21).

Figure 21 - Nine patterned aluminum counter-electrodes which are connected to by the bond pad.

5.8 Negative Resist Processing

The electrode gap between the two electrodes was created with the use of a permanent spin-coated negative photoresist called SU-8. SU-8 is epoxy based and forms a rigid film when fully cured. SU-8 reacts oppositely to UV light than positive resist. The UV exposed areas of SU-8 are thermally cross-linked during subsequent baking step and remain.

The slides were rinsed in acetone and DI water, and were dehydrated on a 90°C hotplate for 5 minutes. One slide at a time was placed into the spin-coater and primed with the Microchem 80/20 primer. A quarter sized dollop of room temperature SU-8 2007 was poured onto the slide and spun according to table VI.

Table VI - SU-8 Spin Speed Program

Step	Speed (RPM)	Time (seconds)
1	400	20
2	1700	25

The slides were soft baked at 95°C for 90 seconds. The slides were then coated once more in SU-8 using the exact same process, and a second soft bake at 95°C was carried out for 3.5 minutes. A second SU-8 film was applied in order to obtain the correct thickness of 16µm. The viscosity of the SU-8 limits the thickness range and must be coated twice.

The SU-8 mask (Appendix A) was placed in direct contact with the SU-8 layer and exposed for 100 seconds. A post exposure bake was carried at 95°C for 4.5 minutes in order to cross-link the exposed SU-8. Unexposed SU-8 was dissolved using Microchem SU-8 Developer with periodic agitation for 5 minutes. The slides were rinsed in IPA and blown dry using low purity nitrogen.

The height and uniformity of the resultant SU-8 spacers were determined using the profilometer. The profilometer stylus was scanned over the SU-8 spacer and onto the glass substrate to obtain a height measurement. Two scans with two repetitions were taken at each spacer resulting in an average spacer height of $16.3 \pm 0.3\mu\text{m}$.

5.9 Final Assembly

Both electrode components were fabricated and needed to be bonded to one another. The silicon chip containing the rotational mirrors was gently placed onto the supporting SU-8 spacers. With

the use of an optical microscope and a steady hand the top and bottom electrodes were aligned to one another. Each chip contained multiple mirrors which allowed for a precise alignment. Once aligned, pressure was applied to the silicon chip with the use of a hobby knife. With pressure applied, the silicon was bonded to the glass slide using a hot-melt thermoplastic adhesive (Figure 22). Copper tape was placed in close contact with the aluminum bond pads and film covering the silicon chip. Colloidal silver was then used to ensure a connection with low electrical resistivity. This process allowed for a simple connection to the top and bottom electrodes.

Figure 22 - Assembled actuator chip with six mirrors and external connections.

5.10 Fabrication Issues

A number of issues arose while fabricating the actuators which affected both the yield and performance of the actuators. The first set of problems came about from fabricating the silicon structure. First, due to a variation in thickness of the silicon wafer of approximately $30\mu\text{m}$ the

final silicon membrane thickness varies. Only about a third of the membranes created were used because the thicknesses were either too thick or thin. To alleviate the variation a wafer with a more tightly controlled thickness should be used. Second, the large difference in the thermal expansion coefficients between silicon and SiO_2 create stress which causes plastic deformation of the silicon [22]. The silicon actuators are created from this deformed silicon layer which causes the actuators to warp slightly. To prevent or alleviate the warping the thermal oxide should be replaced with a chemical vapor deposited oxide or nitride. These films work well as etch masks during wet etching with TMAH because of the high etch selectivity to silicon [23].

The second set of issues came about when mounting the actuator chip to the glass slide. Both the electrode gap and alignment could not be precisely controlled. The electrode gap distance was difficult to measure and varied as much as $5\mu\text{m}$ across a set of actuators. One method to eliminate the problem could involve creating smaller and more numerous SU-8 spacers to distribute the load more evenly. If the problem lies with the bonding method then a more secure method should be used such as soldering. Alignment of the top and bottom electrodes was also a problem because alignment was carried out by hand with the aid of a microscope (Figure 23). Misalignment of the electrodes can cause error in predicting rotation as well as twisting of the actuator. Using a more steady method such as incorporating mechanical arms that push the silicon actuator into place would improve alignment.

Figure 23 - Misalignment of the top and bottom electrodes causes performance issues.

SECTION 6: Positional Drift of the Actuator

6.1 Introduction

All testing was completed on a single torsional actuator due to the varying dimensions throughout the actuator, and the unpredictable rotations. Both the actuator thickness ($\pm 15\mu\text{m}$) and the electrode spacing ($\pm 5\mu\text{m}$) varied which would make comparing the actuators difficult. The unpredictable nature of the actuator rotation makes it so testing of multiple actuators would provide little statistical support.

The glass slide was mounted to the aluminum block using the same hot-melt adhesive used to bond the chip to the glass slide. Electrical connections between the actuator and the voltage supply were made with the use of alligator clips. The laser spot was positioned on the edge of the actuator face opposite to the electrode edge.

6.1.1 Stability of the Actuator

Instability of the system can be broken up into three parts: the test stand, the device holder, and the actuator. The resolution of the test stand was stated previously as 0.0002° over 15 minutes and 0.0018° over a period of 24 hours. The rotational stability of the device holder was measured on the bulk silicon surface outside of the etched pits. Monitoring this surface allowed for the measurement of drift of the entire system up to the actuator itself. The actuator face was then monitored in the same fashion. The rotational stability of the bulk and actuator had a noise of approximately 0.0018° and 0.003° respectively over a period of 20 hours (Figure 24). These measurements indicate that the mounting method and actuator contribute little to the instability while no electrostatic force is present.

Figure 24 - Rotational drift of (a) the entire chip and (b) the actuator surface.

6.2 Procedure

Testing for drift of the actuator during actuation can be separated into three types of tests in order to understand actuator drift. The first test type is long term drift which records angular drift of

the actuator at an applied voltage of 100V over a period of 24 hours. Long term data can reveal slow changing drift which would not be visible in shorter tests. The second type records short term angular drift at five different applied voltages over a period of 16 minutes. The third test type uses the short term test data and focuses on the initial rotational settling that occurs. This data can then be used to draw conclusion about angular drift and the settling phenomenon.

6.2.1 Long Term Drift

Long term drift testing focused on the instability of the actuator at the rotation of 0.16° (100V). Long term drift is the stability range of the actuator over a period of 24 hours. The drift data is taken once the mirror has reached a stable rotation with no noticeable rotational settling. Stabilization occurs at approximately five minutes after actuation so data was analyzed six minutes into the test. Data points were taken at 30 second intervals for the entire length of the test. Three separate tests were conducted with a one hour break in-between.

6.2.2 Short Term Drift and Rotation Settling

Each test conducted collected both short term drift and rotational settling data. The short term drift data is similar to the long term data in that it presents the drift once the mirror rotation has settled. Instead of 24 hours, the short term drift and rotational settling test took measurements over a period of 16 minutes. The actuator was at rest for 30 minutes prior to each test. Data points were taken every five seconds, and drift was monitored at five different actuation voltages. Three tests were taken for each actuation voltage.

6.3 Results

6.3.1 Long Term Drift

Long term drift measurements were taken from each of the three tests and an average range of 19.7 ± 13.0 millidegrees was determined. The range is much larger than the test stand resolution of 3 millidegrees, but also has a relatively large error. This error is due to the high variability in the amount of drift between tests. Figures 25 and 26 show single long term tests with relatively little drift and large drift respectively. A t-test was also completed on the three runs, which were found to be statistically different. Possible causes of this variable drift include discharging of the capacitor, current leakage, changes in temperature and humidity, or a combination of these.

Figure 25 – Single long term drift data with a relatively little drift value of seven millidegrees.

Figure 26 – Single long term drift data with a relatively large drift value of 28 millidegrees.

6.3.2 Short Term Drift

Short term drift is much smaller in magnitude compared to long term drift. The largest short term drift value is 0.7 millidegrees compared to the smallest long term drift value of 7 millidegrees. Figures 27 and 28 present drift data from two individual tests at the minimum and maximum actuation voltage. The drift at each of the five actuation voltages were also determined and presented in Figure 29.

Figure 27 - Short term drift for a period of 10 minutes at an actuation voltage of 25V.

Figure 28 - Short term drift for a period of 10 minutes at an actuation voltage of 100V.

Figure 29 - Comparison of short term drift at six different applied potentials.

The natural drift of the actuator is shown in Figure 29 as zero applied potential. The only actuation voltage to cause significant drift is 100V because it has the only value that is outside the 95% confidence interval of the natural drift. The other applied potential drift values are not statistically different than the natural drift of the actuator. It should be noted that a possible trend is present where the rotational drift increases as the applied potential increases. With more testing the trend could become significant.

6.3.3 Short Term Rotation Settling

While testing, it was observed that the actuator rotated to a maximum amount when potential between the electrodes was first applied. The time required to rotate the mirror to its maximum

rotation is less than one second, which is the minimum time between data collection periods for the DAQ. The actuator then loses approximately half of the initial rotation over the next five minutes and stabilizes (Figure 30).

Figure 30 - Initial maximum rotation and subsequent loss over time for an actuation potential of 45V.

The initial 50% loss in rotation is consistent through all applied potentials. The rotation vs. time graph for each applied potential can be found in Appendix D. The time required to stabilize is also consistent though all applied potentials (Figure 31). It takes approximately five minutes for the actuator to stabilize.

Figure 31 - A compiled graph of five different applied potentials and their similar stabilization times.

6.4 Discussion

6.4.1 Long and Short Term Drift

The factors that cause drift most likely affects both short and long term drift. The reason the magnitude of short term drift is smaller than long term is because drift occurs slowly. Relative to the rotation angles, the maximum drift rate is small enough that over a 10 minute period drift is nearly below the resolution of the test stand. Unlike short term drift, long term drift is quite substantial and deserves discussion into the possible causes. These causes can be broken up into two categories: electrical, and environmental. A mechanical cause is not included because of the work presented in section 2.2.2.

The electric field which causes actuation is created using a number of electrical components. If any of the components causes a change in the electric field, the actuator will rotate and drift will occur. Charging and discharging of the capacitor could possibly cause a change in rotation of the actuator, but it is unlikely. It was shown in section 2.2.2 that the response time for charging the electrodes is under 30 seconds. The capacitive and mechanical fluctuations would cause a much faster rate of drift than seen in Figures 27 and 28. Current leakage and changes in the relative permittivity of the air are more likely the cause of angular drifting. Current leakage can be caused by any type of short between the electrodes which can occur easily due to the small gap spacing. The relative permittivity can be changed by altering the gas composition or humidity. Changes in humidity are much more likely than gas composition.

Environmental factors include both temperature and humidity fluctuations. Temperature and humidity fluctuations have the potential to cause a change in the electrostatic system.

Temperature has the ability to affect the mechanical properties of the actuator hinges if the temperature change is large enough. Temperature and humidity of the air were measured approximately 3cm from the actuator. Each run during the testing period took temperature measurements, but did not measure humidity. It was not until testing of the actuator had completed that humidity was questioned as a possible cause of drift. Temperature was initially measured to investigate the influence of temperature on rotation (Figure 32).

Figure 32 – Long term temperature stability of the air showing little fluctuation.

The magnitude of temperature change is less than one degree making temperature an unlikely cause of drift. More localized heating of the actuator could be occurring, but was not measured. Heating of the actuator would have to be caused by the actuation process, which is unlikely.

Humidity fluctuations have the ability to affect the electrical properties responsible for electrostatic actuation. As mentioned above, humidity was not measured during testing so an extra test was completed with an actuation voltage of 100V over a period of 20 hours (Figure 33).

Figure 33 - Long term rotational drift (left) and the corresponding humidity measurements (right).

The data presented in Figure 30 presents a possible inverse relation exists between humidity and rotation angle. Changes in humidity can affect the amount of adsorbed water on the electrode surfaces. The humidity-drift relation was not investigated further because the evidence for the relation is weak. Further testing and research is recommended.

6.4.2 Short Term Rotation Settling

The short term rotation settling at the beginning of each test is more concerning than the long term drift. There are two important characteristic of the rotation settling. First, at every applied voltage a rotation loss of approximately 50% of the initial rotation occurs, and the actuator takes approximately five minutes to stabilize. Second, the rotation settling is repeatable to a high degree of precision as seen in Appendix D. The cause of rotation settling can be narrowed down to a time dependant electrical root cause.

A few of the theories used to explain rotational drift can also be applied to rotation settling.

First, capacitive charging and mechanical response may be responsible, but occur much faster

than the consistent five minute stabilization which makes it an unlikely cause. Second, rotation settling due humidity fluctuations, however possible, is unlikely due to the inconsistent humidity. Rotation settling is consistent and time dependant, and would require the humidity to change or an adsorbed layer of water to form every time the actuator is powered up.

The glass substrate charging theory is both consistent and time dependant. Substrate charging is described as the buildup of charge on the surface of the glass substrate around the counter-electrode and beneath the actuator. Charge buildup occurs on the surface and in the bulk of the glass dielectric due to the potential gradient formed by the counter-electrode. When the counter-electrode is charged, a potential gradient is formed, and charge carriers such as electrons and ions (Na^+) begin to migrate (Figure 34).

Figure 34 - Charge migration on the surface of the glass substrate

The migration of charge can be thought of as a diffusion process which is time dependant. The time it takes for the diffusion of charge to reach the edge of the actuator does not depend on the applied potential [24]. This is supported by the fact that testing shows that the settling time of the actuator is consistent throughout all applied potentials. The charge migration theory also supports the idea that a larger actuation voltage will cause a greater charge on the surface of the

glass [24]. Every applied voltage experienced a 50% rotation “settling” loss which would only occur if the charge magnitude increased with an increasing applied voltage.

In order to eliminate the surface charge, a second conductive electrode was placed beside the counter-electrode, which acted as a sink for the migrating charge (Figure 35). The second electrode allowed for the quick removal of surface charge which would otherwise build up and cause rotation settling. The second electrode was connected to a floating ground which is neutral and has no charge. The floating ground is conductive and causes any high density negative charge that reaches the electrode to disperse. This dispersion is due the attraction that occurs between charges of different electrical potential. In this case the negative charge buildup is attracted to neutrally charged aluminum. The charge that reaches the second electrode is small enough that when it disperses, the electrode remains dominantly neutral. It is possible that the second electrode could begin build a negative charge over time, but was not seen during testing.

Figure 35 - Modified design using a second electrode to eliminate surface charge.

The result of adding the second electrode was a complete elimination of the rotation settling phenomenon (Figure 36). The modified actuator which contains the second counter-electrode rotates to a set angle with no apparent settling, and displays a typical angular drift.

Figure 36 – Elimination of rotation settling when a second electrode is used.

Section 7: Voltage versus Rotation

7.1 Introduction

Once the actuator rotation stabilized, a rotation and actuation voltage value was recorded. The recorded data point was taken from the short term tests data, which was presented in section 6. The rotation and voltage values were plotted to allow for accurate prediction of rotation at a certain actuation voltage. The test data was then compared to three prediction models, two of which were used to model the actuator initially.

7.3 Results

Each applied voltage resulted in a specific stabilized rotation angle. The numbers were plotted and fitted to a trend line which made it possible to predict the rotation at any actuation voltage between 25 and 100 volts (Figure 37). The trendline fits well with an R^2 value of 0.9952. Both the stabilized rotation of the actuator face and actuation voltage are repeatable to a high degree of accuracy as seen by the insignificant error bars.

Figure 37 - Actuator rotation at specific actuating voltages.

Once the actuator performance was determined, the data was compared to three different models. The first two models are the original design equation (Eq. 10), and the COSMOSWorks FEA analysis, both of which were initially used to model the actuator. The third equation (Zhang) was found during the data analysis period of this study and included due to the previous success

in predicting torsional micro-mirror rotation [25]. Each model was used to determine a rotation value at the five actuation voltages (Figure 38).

Figure 38 - Compiled graph of actuator rotation comparing the actual rotation to various models.

The actuator rotation recorded by the test stand is larger than all three models and begins to deviate from the models at approximately 45 volts. It should be mentioned that even though the models do not accurately predict the actuator rotation the model curves do follow the same general shape as the actuator. The initial design equation and COSMOSWorks models resulted in approximately equal rotation at each voltage which resulted in a minimum deviation of 12% from the actuator at 25V, and a maximum deviation of 39% at 100V. The Zhang model had the largest difference from the tested actuator with a minimum deviation of 48% at 25V, and a maximum deviation of 63% at 100V. For both models, the deviation increases with increasing actuation voltage. This is most likely due to bending of the actuator face.

7.4 Discussion

The tested actuator rotation is consistently larger than the prediction models. This divergence can be possibly attributed to the bending of the actuator face during actuation as well as misalignment of the electrodes, and residual stress present in the silicon and aluminum. Bending of the actuator face that overlaps the counter-electrode is the most likely cause of the increasing deviation seen previously (Figure 39). As the actuation voltage increases, the electrostatic force and rotation increase as well causing the leading tip of the actuator to bend downwards. When bending occurs, the force on the actuator increases even more causing a higher than predicted rotation as seen in Figure 38.

Figure 39 – Bending of the actuator face causes a larger than predicted force and rotation.

It was mentioned previously that each model follows generally the same curve, which makes it possible adjust each model to fit the actuator curve. The adjustment is known as a fitting factor and can be used to predict the rotation of that specific actuator. Once these issues are resolved or accounted for a model can be chosen which accurately predicts rotation of any similar actuator.

SECTION 8: Position Repeatability

8.1 Introduction

Devices such as these go through a large number of on/off cycles during the lifetime of the product. Maintaining a precise rotation throughout the lifetime is extremely important when designing the device. Therefore, testing the position repeatability was determined to be essential in characterizing the performance of the actuator.

8.2 Procedure

Testing was comprised of 2025 on/off cycles over a period of approximately 270 hours. Each cycle involved rotating the actuator, recording the stabilized rotation, removing the potential, and allowing the actuator to stabilize, which took approximately 8 minutes to complete. The stabilized rotation data point was taken six minutes after each initial 100V actuation. When the actuating voltage was shut off, the actuator was given two minutes before repeating the process.

8.3 Results

In order to characterize the overall repeatability of the actuator the stabilized position was plotted (Figure 39). Both a cyclic trend and overall drift of the stable position was observed. Each cycle takes approximately 24 hours to complete, but the data deviates at certain points. Not every low or high peak has a separation of 24 hours, and some days no cyclic response took place.

Figure 40 - Angular repeatability over a period of eight days showing significant drift.

8.4 Discussion

Drift in the stable position of the actuator is likely due to the causes of drift discussed in section 6.4.1. A change in environmental or electrostatic properties has been shown to achieve a drift seen in the previous sections. Temperature and humidity of the lab change throughout the day and have been seen to follow a cyclic trend (Figure 32 and 33). The overall drift of 20 millidegrees also matches the typical long term drift values seen previously. Actuators similar to these experience fatigue which can cause drifting and failure of the silicon structure [26]. The failed structures seen in literature went through anywhere between 10^5 and 10^{10} cycles with is much larger than the 2025 cycles actuated. Therefore, cyclic fatigue can be eliminated as a source of position repeatability drift.

SECTION 9: CONCLUSIONS AND FUTURE WORK

The work completed has established that electrostatically actuated torsional micro-mirrors can be successfully modeled, designed, fabricated and characterized at Cal Poly University. The performance of the actuator was characterized by first analyzing the short and long term rotational drift of the actuator. Actuator drift was found to occur slowly but had a significant impact on the rotation angle over longer periods of time. Drift is most likely caused by a number of factors including current leakage and changes in the dielectric between the electrodes. The actuator rotation settling was a consistent, time dependant phenomenon which was found to be caused by charge migration on the glass slide surface. When a second electrode was placed, the migrating charge was dissipated and the rotational settling was eliminated. The third characterization technique involved analyzing actuator rotation as a function of applied voltage. The function was found to accurately predict the rotation of the actuator at any applied voltage. The actuator rotation was compared to three models and the original design equation was found to be the most accurate hand calculation modeling technique. The design equation does deviate from the actuator rotation which is due to measurement inaccuracies and material properties. The fourth and final characterization was an analysis of the actuator position repeatability. The cyclic drift has a period of approximately 24 hours is most likely caused by temperature or humidity.

The accuracy of the characterization and predication models is limited by the control of the fabrication processes. Many improvements can be made to create a better understood actuator. For example, the range in thickness of the silicon wafer should be reduced in order to minimize

actuator thickness variations. Thermal oxide should be replaced with a chemical vapor deposited oxide or silicon nitride wet etch masking film in order to alleviate the internal stress of the actuators. The alignment of the top and bottom electrodes of the actuator would be improved if the process was performed using mechanical adjustments or if the actuator self aligned using a pin and groove method. The problem of a varying electrode gap sizes could be alleviated by first using a single SU-8 layer instead of spinning on two thinner layers, and second by bonding the actuator chip to the glass slide surface using a more secure method such as soldering. In addition to fabrication improvements, work investigating the rotation settling phenomenon will improve the understanding of these actuators.

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Appendix A – Lithography Masks

Figure – First mask which exposes silicon “windows” to the TMAH etchant.

Figure - Second mask which is responsible for patterning the actuator structure.

Figure - Aluminum electrode mask.

Figure - Original SU-8 spacer mask (left) and the modified mask (right).

Appendix B – Process Diagrams

Appendix C – SEM Pictures

Appendix D – Graphs

Voltage	Rot (rad)	Rot (deg)
24.4	0.00012	0.00701
43.9	0.00040	0.02269
63.5	0.00083	0.04748
83	0.00142	0.08112
97.7	0.00196	0.11240

Voltage	Rot(Rad)	Rot(deg)
24.4	0.00007	0.00401
43.9	0.00023	0.01313
63.5	0.00049	0.02780
83	0.00084	0.04832
97.7	0.00119	0.06822

Voltage	Rot (deg)
24.4	0.0078
43.9	0.0237
63.5	0.0481
83	0.0815
97.7	0.1127

Appendix E – Source Code

MODFUNCTIONS

Option Explicit

'Initialize the com port on the computer
'for the motion controller

Function ConfigCOM1() 'Motion Controller
 'initialize the motion controller
 frmDataTrans.CWSerial1.BaudRate = 19200

```

frmDataTrans.CWSerial1.ComPort = 1
frmDataTrans.CWSerial1.DataBits = 8
frmDataTrans.CWSerial1.StopBits = cwStopBitsOne
frmDataTrans.CWSerial1.Parity = cwParityNone
frmDataTrans.CWSerial1.Configure
frmDataTrans.CWSerial1.Write ("1VA0.5\13") 'set axis 1 high speed to 0.5mm/s
frmDataTrans.CWSerial1.Write ("2VA0.5\13") 'set axis 2 high speed to 0.5mm/s
End Function

```

'Initialize the com port on the computer for the temperature controller

```

Function ConfigCOM7() 'Temperature Controller
    frmDataTrans.CWSerial7.BaudRate = 9600
    frmDataTrans.CWSerial7.ComPort = 7
    frmDataTrans.CWSerial7.DataBits = 8
    frmDataTrans.CWSerial7.StopBits = cwStopBitsOne
    frmDataTrans.CWSerial7.Parity = cwParityNone
    frmDataTrans.CWSerial7.Configure
End Function

```

Function InitDataAcq()

'Initialize the channels on the DAQ and
'set up the GPIB to usb connection

On Error GoTo INRETY

INRETY:

```

'Configure GPIB
frmDataTrans.CWGPIB1.BoardNumber = 0
gpiib_address = 9
frmDataTrans.CWGPIB1.PrimaryAddress = gpiib_address

frmDataTrans.CWGPIB1.SecondaryAddress = 0
frmDataTrans.CWGPIB1.TimeoutValue = cwGPIBTimeoutT10s
frmDataTrans.CWGPIB1.Configure

frmDataTrans.CWGPIB1.Write "*RST" 'Reset meter
frmDataTrans.CWGPIB1.Write "*CLS" 'Clear Status

'set integration time for each reading higher: reduce measurement noise
frmDataTrans.CWGPIB1.Write "CONF:RES AUTO,MIN,(@101)"
frmDataTrans.CWGPIB1.Write "CONF:VOLT:DC 10,(@102)"
frmDataTrans.CWGPIB1.Write "CONF:TEMP TC,K,(@103)"
frmDataTrans.CWGPIB1.Write "CONF:VOLT:DC 10,(@104)"
frmDataTrans.CWGPIB1.Write "CONF:VOLT:DC 10,(@105)"

```

```
'Save this code as examples on how to configure the Agilent
'34970A DAQ.....Read the manuel for additional examples and instructions
'*-*-* frmdataTrans.CWGPIB1.Write "CONF:VOLT:DC 10,(@101)"
'*-*-* frmdataTrans.CWGPIB1.Write "CONF:RES AUTO,MIN,(@105)"
'*-*-* frmdataTrans.CWGPIB1.Write "CONF:TEMP TC,K,(@106)"
'''
```

End Function

Function Motor2()

```
'turn on motors
frmdataTrans.CWSerial1.Write ("1MO\13") 'axis one MO = for turning on power
frmdataTrans.CWSerial1.Write ("2MO\13") 'axis two MO = for turning on power

'Moves to reference on WSA1 from 3rd party
strMotorCmd = "1PA" & Trim(Str(-1.0832)) & "\13" 'x coord
frmdataTrans.CWSerial1.Write (strMotorCmd)
Call Wait_CWSerial1(1)
strMotorCmd = "2PA" & Trim(Str(-15.7684)) & "\13" 'y coord
frmdataTrans.CWSerial1.Write (strMotorCmd)
Call Wait_CWSerial1(2)
```

End Function

Function Motor1()

```
'turn on motors
frmdataTrans.CWSerial1.Write ("1MO\13") 'axis one MO = for turning on power
frmdataTrans.CWSerial1.Write ("2MO\13") 'axis two MO = for turning on power

'Moves to 3rd Party Mirror from ref mirror
strMotorCmd = "1PA" & Trim(Str(-31.686)) & "\13" 'x coord
frmdataTrans.CWSerial1.Write (strMotorCmd)
Call Wait_CWSerial1(1)
strMotorCmd = "2PA" & Trim(Str(-7.033)) & "\13" 'y coord
frmdataTrans.CWSerial1.Write (strMotorCmd)
Call Wait_CWSerial1(2)
```

End Function

Public Function delay(count)

```
For i = 0 To count
DoEvents
Next i
i = 0
```

End Function

Function Wait_CWSerial1(Coord)

'This code is for the Newport motion controller. Without it the daq will
'take data while the motors is moving to where you told it to go

'wait for axis one to finish moving

End Function

Public Function ReadDataAq(Channel As String)

'This code actually reads the Agilent 34970A channel and stores the
'reading as a variable, that variable is written to a file in another
'part of the code.

Dim intNumRead As Integer

If Channel = "101" Or Channel = "All" Then

On Local Error GoTo Retry1

Retry1:

'select the channel and measurement type

frmDataTrans.CWGPIB1.Write "MEAS:RES? AUTO,(@101)"

intNumRead = 3 'Number of times a data point is taken per measurement

For dblRead1 = 1 To intNumRead Step 1

dblRead2 = frmDataTrans.CWGPIB1.Read

dblRead3 = dblRead3 + dblRead2

If CInt(dblRead1) <= (intNumRead - 1) Then

frmDataTrans.CWGPIB1.Write "READ?"

End If

Next dblRead1

dblRead3 = dblRead3 / intNumRead

dblHTMTemp = ((-24.714761 * Log(dblRead3)) + 253.101103)

dblRead1 = 0

dblRead2 = 0

dblRead3 = 0

Call delay(1000)

End If

If Channel = "102" Or Channel = "All" Then

On Local Error GoTo Retry2 'if one of read lines comes back as zero, then recycle measurements

Retry2:

```

'select the channel and measurement type
frmDataTrans.CWGPIB1.Write "MEAS:VOLT:DC? 10,0.0001,(@102)"
intNumRead = 3   'Number of times a data point is taken per measurement
For dblRead1 = 1 To intNumRead Step 1
    dblRead2 = frmDataTrans.CWGPIB1.Read
    dblRead3 = dblRead3 + dblRead2
    If CInt(dblRead1) <= (intNumRead - 1) Then
        frmDataTrans.CWGPIB1.Write "READ?"
    End If
Next dblRead1
dblRead3 = dblRead3 / intNumRead
dblRelHum = ((0.0375 * (dblRead3 * 1000)) - 37.7)
dblRead1 = 0
dblRead2 = 0
dblRead3 = 0
Call delay(1000)

End If

If Channel = "103" Or Channel = "All" Then

On Local Error GoTo Retry3
Retry3:

    frmDataTrans.CWGPIB1.Write "MEAS:TEMP? TC,K,1,DEF,(@103)"
    intNumRead = 1   'Number of times a data point is taken per measurement
    For dblRead1 = 1 To intNumRead Step 1
        dblRead2 = frmDataTrans.CWGPIB1.Read
        dblRead3 = dblRead3 + dblRead2
        If CInt(dblRead1) <= (intNumRead - 1) Then
            frmDataTrans.CWGPIB1.Write "READ?"
        End If
    Next dblRead1
    dblTempPSD = dblRead3 / intNumRead
    dblRead1 = 0
    dblRead2 = 0
    dblRead3 = 0
    Call delay(1000)
End If

If Channel = "104" Or Channel = "All" Then

On Local Error GoTo Retry4 'if one of read lines comes back as zero, then recycle measurements
Retry4:

```



```

'select the channel and measurement type
frmDataTrans.CWGPIB1.Write "MEAS:VOLT:DC? 10, 0.0001,(@104)"
intNumRead = 3   'Number of times a data point is taken per measurement
For dblRead1 = 1 To intNumRead Step 1
    dblRead2 = frmDataTrans.CWGPIB1.Read
    dblRead3 = dblRead3 + dblRead2
    If CInt(dblRead1) <= (intNumRead - 1) Then
        frmDataTrans.CWGPIB1.Write "READ?"
    End If
Next dblRead1
dblRead3 = dblRead3 / intNumRead
dblVoltX = dblRead3
dblRead1 = 0
dblRead2 = 0
dblRead3 = 0
Call delay(1000)
End If

If Channel = "105" Or Channel = "All" Then

On Local Error GoTo Retry5 'if one of read lines comes back as zero, then recycle measurements
Retry5:

'select the channel and measurement type
frmDataTrans.CWGPIB1.Write "MEAS:VOLT:DC? 10, 0.0001,(@105)"
intNumRead = 3   'Number of times a data point is taken per measurement
For dblRead1 = 1 To intNumRead Step 1
    dblRead2 = frmDataTrans.CWGPIB1.Read
    dblRead3 = dblRead3 + dblRead2
    If CInt(dblRead1) <= (intNumRead - 1) Then
        frmDataTrans.CWGPIB1.Write "READ?"
    End If
Next dblRead1
dblRead3 = dblRead3 / intNumRead
dblVoltY = dblRead3

dblRead1 = 0
dblRead2 = 0
dblRead3 = 0
Call delay(1000)
End If

End Function
Public Function SaveFile()

```

'This code opens a dialog box so that you can save your test data to a file, make sure
'you add the .csv extension to the file name

```
outfile = "Enter test name and date and whatever.csv"
```

```
frmDataTrans.cmdlgFile.DialogTitle = "Select File to Append To"  
frmDataTrans.cmdlgFile.Flags = &H2 + &H800 'require valid path, warn before overwriting  
existing file  
frmDataTrans.cmdlgFile.InitDir = App.Path  
frmDataTrans.cmdlgFile.FileName = App.Path + "\" + outfile  
frmDataTrans.cmdlgFile.ShowSave  
ofilename = frmDataTrans.cmdlgFile.FileName  
ofitle = frmDataTrans.cmdlgFile.FileTitle  
tlen = Len(ofitle)  
flen = Len(ofilename)  
ofilepath = Left(ofilename, (flen - tlen))  
ofilename = FreeFile  
Open ofilename For Append As 255  
  
'create file headings  
Write #255, "HTM Temp", "HTM %RH", "TempPSD", "Volt X", "Volt Y", "DataPoint",  
"Month&Day", "HrMinSec"  
End Function
```

```
Public Function WriteData()
```

'This is the code that takes the variable that was stored from the DAQ and writes
'it to your file

```
'increase datapoint number each time a reading is collected  
lngCnt = lngCnt + 1
```

```
'Write the info to the file  
Write #255, dblHTMTemp, dblRelHum, dblTempPSD, dblVoltX, dblVoltY, lngCnt,  
Format(Now, "mmdd"), Format(Now, "hh:mm:ss")
```

```
End Function
```

```
Public Function PurgeNumericInput(ByVal strPurgeNum As String) As Variant
```

```
Dim blnHasDecimal As Boolean, i As Integer  
Dim s As String
```

```

strPurgeNum = Trim$(strPurgeNum)

If Len(strPurgeNum) = 0 Then
End If

For i = 1 To Len(strPurgeNum)
    Select Case Mid$(strPurgeNum, i, 1)

        'Is this character a number?
        Case "0" To "9"
            'Add it to the string being built.
            s = s & Mid$(strPurgeNum, i, 1)

        'The char is a decimal.
        Case ".", ",", " "

            If Not blnHasDecimal Then
                blnHasDecimal = True
                s = s & "."
            End If

    End Select
Next i

strPurgeRet = Val(s)

End Function

Public Function ZeroMotors()

    'read the start position from motion control after WSA1 A1 is found
    'start positions equate to the (0,0)
    frmDataTrans.CWSerial1.Write ("1TP\13") 'axis one TP = for reading meter
    Start_position_X = frmDataTrans.CWSerial1.ReadLine
    frmDataTrans.CWSerial1.Write ("2TP\13") 'axis two TP = for reading meter
    Start_position_Y = frmDataTrans.CWSerial1.ReadLine
End Function

Public Function ActivateMotors()
    'turn on motors
    frmDataTrans.CWSerial1.Write ("1MO\13") 'axis one MO = for turning on power
    frmDataTrans.CWSerial1.Write ("2MO\13") 'axis two MO = for turning on power
End Function

```

```
Function MoveToMirror(intPart As Integer, intRow As Integer, intDevice As Integer)
```

```
    'turn on motors
```

```
    frmDataTrans.CWSerial1.Write ("1MO\13") 'axis one MO = for turning on power
```

```
    frmDataTrans.CWSerial1.Write ("2MO\13") 'axis two MO = for turning on power
```

```
    If ((intPart = 0) And (intRow = 0)) Then
```

```
        strMotorCmd = "1PA" & Trim(CStr(AccMirr(intDevice, 1))) & vbCr
```

```
        frmDataTrans.CWSerial1.Write (strMotorCmd)
```

```
        Call Wait_CWSerial1(1)
```

```
        strMotorCmd = "2PA" & Trim(CStr(AccMirr(intDevice, 2))) & vbCr
```

```
        frmDataTrans.CWSerial1.Write (strMotorCmd)
```

```
        Call Wait_CWSerial1(2)
```

```
    End If
```

```
End Function
```

MODLOCATIONDATA

```
Sub arrAccuracyMirror() 'accuracy mirror code
```

```
    'AccMirr (intDevice, Direction X) accuracy mirror positions    AccMirr(0, 1) = -16.422
```

```
    AccMirr(0, 1) = 0#
```

```
End Sub
```

MODVARIABLEDEFINITION

```
Option Explicit
```

```
'File variable for SaveFile function
```

```
Global outfile As Variant
```

```
Global ofilename As Variant
```

```
Global oftitle As Variant
```

```
Global tlen As Variant
```

```
Global flen As Variant
```

```
Global ofilepath As Variant
```

```
Global ofilenum As Variant
```

```
Global gpib_address As Integer
```

```
Global i As Long
```

```
Global K As Integer
```

```
Global strMoveMirror As String
```

```
Global Start_position_X As Double
```

Global strMotorCmd As String
Global Coord As Integer
Global Start_position_Y As Double
Global Pos
Global strPurgeNum As String
Global strPurgeRet As String
Global intDevice As Integer

Global intX As Integer
Global lngCnt As Long
Global intPart As Integer
Global intCnt As Integer
Global intRow As Integer
Global intNumDataPoint As Integer
Global intCount As Integer
Public AccMirr(5, 2) As Double

Global dblTempPSD As Double
Global dblVoltX As Double
Global dblVoltY As Double
Global dblHTMTemp As Double
Global dblRelHum As Double

Global dblRead1 As Double
Global dblRead2 As Double
Global dblRead3 As Double
Global dblRead4 As Double
Global dblRead5 As Double

FRMDATATRANS

Option Explicit
Private Sub Form_Load()
Call arrAccuracyMirror
Call ConfigCOM1
End Sub

FRMFIXED

Option Explicit
Private ErrCheck As Integer

```
Private lngTime As Long
Private intCycles As Integer
```

```
Private Sub Form_Load()
TimerFixed.Enabled = False
```

```
End Sub
```

```
Private Sub txtCycles_KeyPress(KeyAscii As Integer)
'only allow numbers and backspace to entered
If (KeyAscii >= vbKey0 And KeyAscii <= vbKey9) Or KeyAscii = vbKeyBack Then
Exit Sub
Else
KeyAscii = 0
Beep
End If
```

```
End Sub
```

```
Private Sub txtTime_KeyPress(KeyAscii As Integer)
'only allow numbers and backspace to be entered
If (KeyAscii >= vbKey0 And KeyAscii <= vbKey9) Or KeyAscii = vbKeyBack Then
Exit Sub
Else
KeyAscii = 0
Beep
End If
```

```
End Sub
```

```
Private Sub cmdStartTest_Click()
Frame2.Enabled = False
Frame3.Enabled = False
cmdStartTest.Enabled = False
```

```
'Assign Value to Cycles Value
intCycles = Int(txtCycles.Text)
If ((intCycles > 35000) Or (intCycles < 1)) Then
MsgBox ("Invalid number of cycles")
ErrCheck = 1
Frame2.Enabled = True
Frame3.Enabled = True
cmdStartTest.Enabled = True
End If
```

```

'Assign Value to Time Value
lngTime = CLng(txtTime.Text)
If ((lngTime > 72000) Or (lngTime < 1)) Then
    MsgBox ("Invalid time between cycles")
    ErrCheck = 1
    Frame2.Enabled = True
    Frame3.Enabled = True
    cmdStartTest.Enabled = True
End If

If ErrCheck = 0 Then
    'Save file to .CSV
    Call SaveFile

    'Initiate timer program
    TimerFixed.Enabled = True
    TimerFixed.Interval = 1000
    Call TimerFixed_Timer

ElseIf ErrCheck = 1 Then
    ErrCheck = 0
End If

End Sub

Private Sub TimerFixed_Timer()

If (lngTime = 0) And (intCycles > 0) Then
    Call ReadDataAq("All") 'Datapoint on the reference mirror
    Call WriteData

    'reset values every cycle
    intDevice = 0
    intRow = 0
    intPart = 0
    lngTime = CLng(txtTime.Text)
    intCycles = intCycles - 1
    lblCounter.Caption = intCycles
    lngTime = CLng(txtTime.Text)

ElseIf (intCycles = 0) Then
    TimerFixed.Enabled = False
    'close the .CSV file number; otherwise the file can't be "reopened"
    Close #255

```

```

        lblCounter.Caption = intCycles

        MsgBox ("Test is Complete WOOT!")

ElseIf ((lngTime > 0) And (intCycles > 0)) Then
    lngTime = lngTime - 1
    lblCounter.Caption = intCycles

End If

End Sub

```

FRMMANUALMOVE

```

Private Sub cmdMoveToMirror_Click()

'Assign Value to intDevice/Check Value
intDevice = CInt(txtMirNum.Text)

If ((intDevice > 40) Or (intDevice < 0)) Then
    MsgBox ("Invalid Mirror Number")
End If

Call MoveToMirror(intPart, intRow, intDevice)

End Sub

Private Sub cmdZeroMotors_Click()
    Call ZeroMotors
End Sub

```

FRMSELECTTEST

```

Option Explicit

Private Sub Form_Load()
    frmDataTrans.Enabled = True
    'Initialize da DAQ
    Call InitDataAcq

End Sub

Private Sub cmdfixed_Click()

```



```
frmDataTrans.Enabled = True  
frmFixed.Show  
End Sub
```

```
Private Sub cmdManualMove_Click(Index As Integer)  
frmDataTrans.Enabled = True  
frmManualMove.Show  
End Sub
```