UNIVERSITY OF CALIFORNIA
Santa Barbara

Bulk Titanium Microelectromechanical Systems

A Dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Materials by

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April 2005
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Acknowledgments

This dissertation, and the work it contains, is dedicated to Maya Sutton. Without her inspiration, understanding, support and sacrifice none of this could have been possible.

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MARCH 2005

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M. F. Aimi, M. P. Rao and N.C. MacDonald, “Fatigue and yield of micron-scale titanium under torsion” Materials Science and Technology, September 2004

Abstract

Bulk Titanium Microelectromechanical Systems

Marco Francesco Aimi

Bulk micromachining is a subtractive process in which structures are etched down into a substrate to fabricate devices out of the substrate material. Typically, this requires a highly directional or cycled plasma etch to achieve high-aspect-ratio structures. Several of these processes exist for the deep etching of semiconductor materials, with the Bosch process being the most common for the deep etching of silicon. Until now, limited ability has existed for the deep etching of metals, thus restricting the range of materials available for bulk micromachining. The current work details efforts to address this limitation through the development of high-aspect-ratio bulk titanium microelectromechanical systems (MEMS).

In order to address this need, a suite of processing techniques have been developed including a high-aspect-ratio titanium deep etch called the Metal Anisotropic Reactive Ion Etching with Oxidation (MARIO) process, that enables the fabrication of bulk titanium MEMS. Several devices are fabricated to showcase these developed processing techniques and to validate titanium as a bulk MEMS material.
One of the devices fabricated is a bulk micromachined hybrid torsional micro-mirror composed of titanium mirror structures bonded to an underlying silicon sloping electrode array. The performance of this mirror array is characterized and revisions are made to improve the device’s transient response. An array of torsion structures similar to the micro-mirror is also fabricated to measure the elastic and plastic behavior of bulk titanium on the micron scale. Two models are explored to explain the observed trends of yield stress and resonant frequency with torsion beam width. The predominant model, which accounts for the effect of titanium oxide surrounding the titanium torsion beams, is further used to measure the oxidation rate of titanium resonators.
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Chapter 1: Introduction

1.1 Historical Perspective

Microelectromechanical Systems (MEMS) represent a broad class of devices whose defining characteristics are their micrometer-scale feature sizes and electromechanical functionality. Their utility arises largely due to their small dimensions that enable exceptional sensitivity for sensing and high precision movement for actuation. Some examples of MEMS currently in large-scale commercial production include accelerometers for automotive air bags, ink-jet printer heads and micro mirrors for digital projection systems [1]. The methods used for the fabrication of MEMS are almost as varied as their applications, but generally fall within three categories: LIGA, surface micromachining and bulk micromachining. LIGA (German acronym for Lithographie Galvanomoformung and Abformung) is a method of backfilling metal into a sacrificial polymer mold to produce components with high aspect ratios – the ratio of height to width of the structural element. The mold is created by masking sections of a polymer with an x-ray absorbent material, typically gold, and exposing it to an x-ray synchrotron beam. The exposed areas are then developed away leaving the polymer mold with straight sidewalls. Metal is deposited in the mold by electroplating, or other backfilling methods that conform to the shape of the mold such that when the polymer is dissolved away, the metal component is a precise impression of the mold. This process requires special processing equipment not normally used in
silicon fabrication [2]. Electrical isolation on the micron/nanometer scale is a challenge for most LIGA based MEMS.

Surface micromachining is another approach for the fabrication of MEMS. It is an additive process originating from the integrated circuit industry, whereby structures are built on top of a substrate by sequential deposition of materials and subsequent selective removal of sacrificial layers via wet chemical or dry plasma etching [3]. This bottom-up approach offers significant flexibility with regards to the device geometries that can be realized and offers the further benefit of providing a wide variety of materials from which to choose including silicon, silicon dioxide, silicon nitride and various metals. However, the deposited layers frequently suffer from residual stresses and limited thickness, reducing the aspect ratio of fabricated devices. For many applications, high aspect ratio structures (HARS) are desired to enhance mechanical integrity, stiffness, and flatness. This is especially crucial in larger devices with structures on the order of hundreds of microns, such as micromirrors for optical switching applications [4]. Furthermore, given that many MEMS rely on electrostatic actuation methods, HARS provide larger surface areas for in plane capacitive actuators, which increase the amount of force that can be generated.

Bulk micromachining is a subtractive process in which structures are etched down into a substrate via wet chemical or dry plasma methods to fabricate devices out of the substrate material [5]. This process has no inherent limitation to
the aspect ratios that can be achieved, nor does it generally have issues with residual stresses. Hence, bulk micromachining is preferred when large, rigid, flat, and/or high force actuators are desired. However, to date there has been a limited ability to select materials based upon specific application in bulk micromachining. Single crystal silicon is the most common material of choice because of the vast infrastructure currently in place for silicon processing. Silicon Deep Reactive Ion Etching (DRIE) is a common method for creating MEMS from bulk silicon, and has been the process of choice for most MEMS applications [6].

1.2 Materials Selection

Semiconductor materials, in particular silicon, are commonly used as the material of choice for HARS. There are several reasons why silicon is used for these HARS applications and they mainly involve the availability of the processing tools, availability of high quality material, and the desire to fabricate integrated circuits (IC) monolithically with MEMS devices [7]. Under the assumption that these three reasons are currently valid, silicon and other semiconductor devices are the only materials that can be used to create MEMS via bulk micromachining. With the desire to move onto other material systems, the validity of these assumptions needs to be investigated.

Processing tools used in semiconductor manufacturing are highly specialized systems with a focus on process uniformity and throughput. Typically these tools are expensive, but these upfront costs are acceptable due to the large
volume of devices that can be processed at a high rate. Batch fabrication, in which many devices are created simultaneously with a high throughput, allow the cost per device to be small even given the large cost to tool a production line [8]. Using this same model for the production of MEMS devices, batch fabrication is a necessity to drive down the cost per device. Being able to develop a way to use currently existing toolsets for batch fabrication avoids the need of developing new tools which can be extremely costly. Given this need for batch fabrication and throughput for MEMS devices, the tools used in semiconductor manufacturing must be used even in the development of bulk MEMS created from non-semiconductor materials.

Having verified that batch fabrication is an expected requirement for a new MEMS material, the other initial assumptions need to be investigated. The integration of an IC on chip with MEMS is becoming less of a necessity in the production of fully packaged MEMS devices. The added processing complexity of integrating the structural elements with electronic elements has reduced the desire and cost effectiveness of creating fully monolithic devices. The necessity to drive down cost of integration has lead to a System In a Package (SIP) technology, which was used in 60% of cell phones in 2003 [9] as a way of cost effectively integrating various components that can not be processed on the same chip at low cost. An example of a SIP device is shown in Figure 1.1.
This trend opens the door for non-semiconductor materials, which first can have HARS fabricated off chip then integrated back onto a semiconductor chip containing all the electronics through external bonds. In this instance, the issue of on chip integration is eliminated since the processing of the IC and the MEMS device can occur separate to one another. Eliminating the need for on chip integration, new materials for MEMS can be investigated that were previously unusable because they could not support IC fabrication. In order to fully take advantage of the trend away from on chip integration, a material system with a
drastically different set of material properties should be investigated to bring bulk MEMS into previously untapped markets.

This new material will have some constraints; first it will have to look similar to a wafer for the processing tools used in batch fabrication, secondly, it must be polished to ensure good feature resolution during the traditional semiconductor processing steps. It may be noticed that having a single crystal is not one of the qualifications for this new bulk MEMS material. It is expected that using polycrystalline material produced from sheet rolling will be an acceptable material for fabricating MEMS. Without the limitation of a single crystal material, larger wafers can be created without larger cost. Metals in sheet form can come in almost any desired size, both in thickness and in area.

A few materials become interesting when looking at alternatives to silicon for micromachining. Metals are the most interesting because they have the most drastically different set of material properties compared to silicon and other semiconductors. Most metals are ductile, conductive and have high fracture toughness. Aluminum, steel, titanium and copper are a few materials of interest due to their desirable material properties. Picking from this list is difficult, but if one assumes that the material of interest should have an endurance limit and not contaminate other processing equipment, the list can be thinned down.

Titanium has these qualities and a number of other properties that make it attractive relative to single crystal silicon [11]. First, and perhaps foremost, as a
metal it has inherently higher fracture toughness than silicon [12] [13], which is a brittle semiconductor. This has obvious implications for enhanced durability and mechanical shock-resistance relative to silicon. Titanium also has greater biocompatibility [14] and is suitable for many in vivo applications, being the material of choice for hip replacements, surgical tools, dental implants and pacemakers. The native oxide that grows on exposed titanium protects it from most harsh environments [14], such as seawater, steam and hydrogen chloride gas. The surface of titanium can also be modified through plasma nitridization [15] or carburization [16], which may widen the envelope of material properties even further.
Table 1.1: Material properties for various titanium compounds [11] [17] [18] [19].

<table>
<thead>
<tr>
<th>Titanium at titanium compounds</th>
<th>Ti</th>
<th>TiO2</th>
<th>TiB2</th>
<th>TiC</th>
<th>TiN</th>
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<tbody>
<tr>
<td>Elastic Modulus (Gpa)</td>
<td>108</td>
<td>282</td>
<td>400</td>
<td>100-500</td>
<td>600</td>
</tr>
<tr>
<td>Resistivity (ohm m)</td>
<td>3.90E-07</td>
<td>0.1</td>
<td>9.00E+04</td>
<td>0.005</td>
<td>2.05E-07</td>
</tr>
<tr>
<td>Specific modulus (E/p)</td>
<td>2.40E+07</td>
<td>6.67E+07</td>
<td>9.13E+07</td>
<td>6.12E+07</td>
<td>1.15E+08</td>
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<tr>
<td>Thermal Expansion (K-1)</td>
<td>8.60E-06</td>
<td>7.50E-06</td>
<td>5.60E-06</td>
<td>6.40E-06</td>
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<td>Thermal Cond. (W/m K)</td>
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<td>1830</td>
<td>3225</td>
<td>3140</td>
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<tr>
<td>Hardness Mohs (knoop)</td>
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<td>6.2</td>
<td>(2850)</td>
<td>(2470)</td>
<td>9 (1770)</td>
</tr>
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<td>5</td>
<td>4</td>
<td>3</td>
<td>5</td>
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<tr>
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<td>Rutile</td>
<td>Hexagonal</td>
<td>Cubic</td>
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<th>SiC</th>
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<td>134</td>
<td>90</td>
<td>300</td>
<td>410</td>
</tr>
<tr>
<td>Resistivity (ohm m)</td>
<td>1.00E+16</td>
<td>1.00E+16</td>
<td>4.09E+07</td>
<td>8.72E+07</td>
<td>1.30E+02</td>
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<tr>
<td>Specific modulus (E/p)</td>
<td>7.30E+07</td>
<td>5.75E+07</td>
<td>4.09E+07</td>
<td>8.72E+07</td>
<td>1.30E+02</td>
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<td>Thermal Expansion (K-1)</td>
<td>2.60E-06</td>
<td>5.00E-07</td>
<td>8.00E-07</td>
<td>3.30E-06</td>
<td></td>
</tr>
<tr>
<td>Thermal Cond. (W/m K)</td>
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<td>29</td>
<td>120</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>11.9</td>
<td>11.8</td>
<td>3.9</td>
<td>8</td>
<td>9.7</td>
</tr>
<tr>
<td>Melting Temperature (C)</td>
<td>1414</td>
<td>1414</td>
<td>1722</td>
<td>1900</td>
<td>2830</td>
</tr>
<tr>
<td>Hardness Mohs (knoop)</td>
<td>7</td>
<td>6.5</td>
<td>6.5</td>
<td>9.3 (2500)</td>
<td></td>
</tr>
<tr>
<td>Fracture Toughness (MPa m1/2)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.95</td>
<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>Structure</td>
<td>Diamond</td>
<td>Amorphous</td>
<td>Quartz</td>
<td>Amorphous</td>
<td>Wurtzite</td>
</tr>
</tbody>
</table>

The various mechanical and electrical properties listed in Table 1.1 shows how creating MEMS from a bulk titanium substrate can offer a different set of material properties. It is important to note that these material properties are based on bulk properties and do not include the effect of small size scale.
1.3 Scaling of Material Properties

Many material properties remain valid well below the micron length scale, however it has been shown that a few of these properties can be altered by a geometry dependent term. Several researches have shown that the yield stress of certain materials increase when the gradient of strain becomes a significant factor, typical for small components in bending or torsion. Observed results from Fleck et. al. [20] show for annealed copper wire in torsion, the stress to achieve a fixed permanent surface strain increases with a decrease in wire diameter. Results from his paper are shown in Figure 1.2, where the normalized torque is plotted against the normalized surface strain.
Figure 1.2: Normalized torque versus normalized surface strain for copper with various wire diameters [20].

This data was also compared with tensile tests that showed only a small increase in tensile stress with decreased diameter attributed to a decrease in the grain size of the annealed copper wire.

Similar observations are made by Stolken et al. for thin nickel foils bent around a small cylinder [21]. By measuring the permanent surface strain and the maximum applied load, a normalized plot of bending moment versus surface strain is obtained and shown in Figure 1.3.
Both of these results show that the stress required to achieve the same plastic strain increases with decreased wire diameter or foil thickness. Several different theories have been developed to help explain these observations and will be investigated further in this dissertation.

1.4 Application Driven Choice of Titanium Over Silicon

Other research groups have also addressed the material limitations of silicon and have chosen titanium as an alternative substrate or deposited film. Surface micromachining of sputter-deposited titanium thin films has been shown to be capable of producing freestanding titanium structures [22]. However, as with
many other surface micromachined structures, undesirable residual stress-induced bowing of the structures was observed and the structures were limited to low aspect ratios. Wet etching [23] and electrochemical etching [24] of bulk titanium has also been reported in the literature, including the development of a wet etch to create titanium based micro aerial vehicle wings [25]. These etches are compatible with semiconductor processing but are isotropic, which limits the minimum feature size and aspect ratio of the etch, and thus places significant constraints on device design and functionality. Despite the difficulty with both of these processing methods, they have successfully shown that departing from semiconductor materials can improve the functionality of devices and open the door to new applications that were previously not attainable.

1.5 Titanium as a Structural Material

Titanium has been used as a structural material for the last 50 years. It has found a niche in high-end applications such as the SR-71 Blackbird and gas turbine engines [13]. Outside defense applications, titanium sees use in offshore drilling from the drilling tips to the enormous anchoring brackets used in deep-sea oil pipelines [26]. Titanium also is used in many high-end sporting goods from golf clubs to bicycles, making the visibility of titanium high for consumer products. The many current uses of titanium in various industries and applications create a significant processing infrastructure to fabricate these macro sized products.
The fabrication of titanium plays an important part in the designing of titanium alloys and the tailoring of mechanical properties. The amount of work hardening and strengthening due to oxygen impurities can change the properties of the final product [27]. Commercially pure (CP) titanium is chosen as a starting material for MEMS processing to eliminate potential complications from using precipitation hardened alloys or multiple phase alloys. Due to the limitations of the 4 inch semiconductor process tools available at UCSB, only foils of titanium ranging from 10 micron to 1 millimeter in thickness are used with a maximum diameter of 100 millimeters. The foils used in this process are commercially pure titanium rolled from titanium ingots. This rolling process can change the material properties of the final sheet when compared to the initial ingot, making it important to understand how the foils are made.

The titanium, after being refined, is flattened and elongated by rolling. This rolling process causes the titanium to work harden which makes subsequent rolling more difficult. To generate very thin titanium sheets and foils, the work hardened material must be softened by annealing. The annealing process, preformed at high temperatures, softens the material but can also form a thick oxide layer on the surface due to titanium’s high affinity for oxygen. This oxide layer can change the mechanical properties of the sheet or foil and can also affect the quality of finish on the final rolled product. Typically, the sheet is pickled in an acid solution to remove this surface oxide layer [14]. If properly done, this process can produce
high quality titanium sheets and foils. However, if the oxide is not removed properly it can be imbedded into the outer surface of the titanium leading to titanium oxide inclusions in the material. If nothing is done to remove these inclusions, they can cause havoc in future processing steps, which will be discussed later. The annealing steps can also allow diffusion of oxygen into the bulk of the titanium. The amount of oxygen in the titanium can greatly change the mechanical properties of the rolled foil. Table 1.2 shows how the yield stress and ultimate tensile strength of commercially pure titanium is altered with the concentration of oxygen into the bulk material.

Table 1.2 Tensile and ultimate strengths of different grades of titanium with various oxygen concentration [14].

<table>
<thead>
<tr>
<th>Titanium Grade</th>
<th>Oxygen Concentration (%)</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP1</td>
<td>0.18</td>
<td>170-310</td>
<td>240</td>
</tr>
<tr>
<td>CP2</td>
<td>0.25</td>
<td>275-410</td>
<td>343</td>
</tr>
<tr>
<td>CP3</td>
<td>0.35</td>
<td>377-520</td>
<td>440</td>
</tr>
<tr>
<td>CP4</td>
<td>0.4</td>
<td>480</td>
<td>550</td>
</tr>
</tbody>
</table>

Titanium is one of a few in a class of materials showing an endurance limit, which means that below a threshold stress level, the material will not fail given a near infinite number of cycles. This critical aspect was the main reason why titanium was chosen as an alternative to silicon in the fabrication of MEMS. The fatigue strength of macro materials is typically shown on a plot of stress versus number of cycles curve. Fatigue can be classified into two regions, low and high
cycle fatigue. With low cycle fatigue, < $10^3$ cycles, the yield stress doesn’t vary much with the number of cycles, and typical yield strength can be used with the appropriate safety factor. High cycle fatigue is typically $10^3$-$10^7$ cycles where the maximum allowable stress decreases with an increased number of cycles until the endurance limit is reached. Materials with no endurance limit fail even at a small fraction of the tensile strength [28]. The large number of actuation cycles typically common in MEMS devices made finding a material that shows an endurance limit on the macro scale a key component in the materials selection, assuming the effect of endurance limit will not change with the decreasing length scale.

1.6 Titanium Oxide

The oxide that forms on titanium, which increases the difficulty of rolling thin sheets, plays a major part in many of the industrial applications of titanium. The high affinity of titanium for oxygen allows titanium to self passivate with a native oxide typically ~5 nanometers thick [14], allowing titanium to be used in many harsh environments from salt water to the human body. This native oxide consists of TiO$_2$ at the surface with an oxide-titanium interface consisting of a few monolayers of Ti$_2$O$_3$ [29]. Titanium oxide invokes an inert tissue response, which is in contrast to other metallic oxides that can be either toxic or can cause the tissue to capsize the oxide due to a foreign body response, known as sequestration. A summary of various metallic oxides, solubility and typical tissue response are shown in Table 1.3.
Table 1.3: Tissue response, water solubility, and dielectric constant for metal oxides [14].

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Dielectric Constant</th>
<th>Solubility at pH 7 (mol/L)</th>
<th>Typical tissue response</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO$_2$</td>
<td>86-170</td>
<td>$3 \times 10^{-6}$</td>
<td>Inertness</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>9.3-11.5</td>
<td>$10^{-6}$</td>
<td>Sequestration</td>
</tr>
<tr>
<td>V$_2$O$_5$</td>
<td>13.8</td>
<td>&gt;1</td>
<td>Toxicity</td>
</tr>
<tr>
<td>V$_2$O$_4$</td>
<td>13.8</td>
<td>~$10^{-4}$</td>
<td>Toxicity</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>12.5</td>
<td>&lt;$10^{-6}$</td>
<td>Inertness</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td>24-65</td>
<td>~$10^{-5}$</td>
<td>Inertness</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>14.2</td>
<td>&lt;$10^{-10}$</td>
<td>Sequestration</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
<td>11.9</td>
<td>~$10^{-11}$</td>
<td>Toxicity</td>
</tr>
<tr>
<td>Co$_2$O$_3$</td>
<td>12.9</td>
<td>~$10^{-12}$</td>
<td>Toxicity</td>
</tr>
</tbody>
</table>

Titanium oxide can exist in three different crystal polymorphs: rutile, anatase and brookite, with rutile being the most common phase. Native oxide films are amorphous, but thermally grown oxides above 200 °C are typically microcrystalline rutile [14]. Titanium oxide has interesting electrical properties including a very large dielectric constant. Typically, thermal oxides tend to suffer from non-stoichiometry being oxygen deficient [30] causing this material to be a poor insulator due to ion mobility. This oxide, that is always present on a titanium surface exposed to air, is a key aspect of titanium processing and will be shown to be a key aspect throughout this dissertation.

1.7 Dissertation Preview

This dissertation will focus on the development of bulk titanium MEMS devices through the process development, device development, device testing and development of design guidelines for future bulk titanium MEMS. The details of a
high-aspect-ratio titanium deep etched called the Metal Anisotropic Reactive Ion Etch with Oxidation (MARIO) process will be explained in Chapter 2 including the effect of altering etch conditions. This etch, along with other newly developed etching techniques, is then used in the fabrication of a macro and micro scale mirror array detailed in Chapter 3. Refinement of the micro-mirror array used to improve the performance characteristics. Finally, a device similar to the micro-mirror array is fabricated to measure the yield stress and resonant properties of titanium at the micrometer length scale explained in Chapter 4. An analytical model is then developed in Chapter 5 to explain the observed trends that can be used to predict the behavior of bulk titanium MEMS devices in torsion. Chapter 6 then expands on this theory and applies it to other observed trends in the behavior of bulk titanium MEMS.
Reference


[18] www.accuratus.com


Chapter 2: Titanium Etch Process Development

Prior to the development of the bulk titanium etch discussed here, the ability to etch bulk metal substrates with high aspect ratios was limited. Traditionally bulk etching was limited to semiconductor materials, in particular silicon, because of the availability of the Bosch process [1], which is a specialized plasma process used to deep etch high aspect ratio silicon structures. This etch has allowed for the development of many silicon MEMS and is now considered common practice for bulk micromachining. Due to the wide appeal of this process, many of the processing conditions and characteristics for the BOSCH process are known in the MEMS community. This provides a set of processing standards that will be used as a driving goal for any titanium deep etching process. Two key aspects of the Bosch process, which cannot be compromised in a metal etch, are high selectivity and the ability to etch high aspect ratio structures. A typical silicon deep etch has an aspect ratio of up to 30:1 and a selectivity to SiO₂ of 120 to 200:1 with an overall etch rate of 1.5 to 3.0 microns per minute [2].

2.1 Etching Bulk Titanium

With these criteria in mind, the process of developing a deep etch for titanium started with the erroneous assumption that bulk titanium would etch under the same plasma conditions as sputtered titanium. After optimizing a fluorine based etch from the literature for the etching of sputtered titanium [3], an attempt
was made to etch CP titanium substrates using the same chemistry. The results from this etch are shown in Figure 2.1

![Figure 2.1 SEM of titanium surface with photoresist mask after etching with a SF$_6$ plasma.](image)

With no etching of the bulk titanium observed from this fluorine etch, a chlorine based etch was attempted. The masking layer for this etch was PECVD silicon oxide, patterned using standard lithography and a standard fluorine based silicon oxide etch, which has shown from the previous fluorine etch not to etch the underlying titanium. This mask pattern was defined on a 1 inch square, 500 micron thick titanium foil that had been polished by Valley Design Corporation (Santa Cruz, CA) to a surface roughness adequate enough to perform contact lithography. These dimensions were chosen to form the titanium foil into a similar shape as a
small wafer to be easily processed in the semiconductor processing tools already available. Running a twenty minute plasma etch, using chlorine gas in a parallel plate capacitive etcher (SLR 770 Plasmatherm, Unaxis Semiconductors, St. Petersburg, FL.) resulted in the following titanium etch shown in Figure 2.2.

![Etched titanium substrate using Cl₂ gas with a PECVD silicon oxide etch mask](image)

**Figure 2.2: Etched titanium substrate using Cl₂ gas with a PECVD silicon oxide etch mask**

This etch showed that chlorine could be used to etch bulk titanium, however there are many issues that are very apparent from Figure 2.2. First, there is a significant amount of undercutting where the masking layer overhangs the underlying titanium forming a lip. This undercut limits the minimum feature size of the etch because line widths less than twice the undercut length will be
completely removed. Another issue with this etch is the etch damage, which can be seen by the pockmarks on all of the etched sidewalls. Such etch damages decrease the mechanical integrity of the beams, particularly if they eventually become free standing. In addition, the effect of the high residual stress due to the PECVD silicon oxide, not shown in Figure 2.2, can cause undesired deformation of these beams upon release. This stress is caused by both the growth stress of the high temperature PECVD silicon oxide deposition, as well as the large mismatch in the coefficient of thermal expansion between silicon oxide and titanium.

In order to better understand how these issues change with etch time, in particular the rate of undercutting, an experiment was run to track these changes over time. A bulk titanium substrate with a silicon oxide mask was etched using a chlorine plasma, then placed in an Scanning Electron Microscope (SEM) to observe the amount of undercut. The substrate was then placed back in the etch chamber and etched again using the same chlorine etch. By analyzing the etch results after each step, the lateral etch rate should have been obtainable, however this was not possible. The lateral etching stopped after each removal of the titanium from the etch chamber resulting in Figure 2.3. The halting of the lateral etch rate is of great interest because it is one of the key components in the development of an etch to match the properties of the silicon deep etch. Several experiments were run to better understand the cause of this effect, which pointed to oxygen exposure being the root cause of this sidewall passivation.
To verify this effect, an attempt was made to duplicate this sidewall passivation, this time keeping the titanium in the etch chamber. The same effect from successive removals of the titanium foil from the chamber was achieved by cycling between the etch plasma and an oxygen plasma. Decreasing the etch time from the conditions used to produce the etch shown in Figure 2.3 and running for a higher number of cycles, the etch shown in Figure 2.4 and Figure 2.5 was achieved.
Figure 2.4: Comb fingers of the first titanium deep etched structure

Figure 2.5: First cycling titanium deep etch: note the tall grass like features on the surface.
From Figure 2.4 and Figure 2.5 it is possible to see the beginnings of a titanium deep etch process that is capable of forming high aspect ratio structures. It is also possible to see from the above figures that there are many tall thin structures in the etched floor. This effect is commonly known as “grassing” or “micromasking” and can be caused by many different processing issues and impurities from both semiconductor processing [4] and titanium foil processing. Most of the grassing from this etch was eliminated by increasing the quality of the polish, increasing the amount of argon in the plasma and also over etching the oxide mask to ensure no residual masking material remained on the surface.

The selectivity of the silicon oxide mask to the titanium, measured to be 5:1, was adequate for this etch, but is a not near the selectivity of the Bosch etch, which is upwards of 200:1. After several attempts to improve the selectivity by altering the etch conditions, it was decided to develop a new masking material for the titanium deep etch. Since titanium oxide was resilient enough to prevent lateral etching, it was expected that this material would also act as a good mask. The method chosen to deposit the titanium oxide was reactive sputtering, where a titanium target is sputtered in an argon and oxygen environment, causing the titanium to oxidize in transit and be deposited on the substrate. During the development of this process, many samples were run by varying pressure, argon and oxygen flow rates, power and time. The final deposition conditions were
chosen to maximize the deposition rate while maintaining material with high enough quality to act as an adequate mask.

Along with a method of depositing titanium oxide, the titanium oxide needed to be plasma etched. Wet etching would not be an option for this case, due to the risk of undercutting. As a first attempt the same etch condition used to etch silicon oxide was used to etch the sputtered titanium oxide. This worked the first time with the only change being a decrease by a factor of 5 in the overall etch rate of the film. Aside from this drawback, the etch proved to be adequate and even allowed for the patterning of sub-micron features into the oxide.

With these improvements, the titanium deep etch process was approaching the performance criteria from the silicon equivalent Bosch process, so it too also deserved a name. The term Metal Anisotropic Reactive Ion etch with Oxidation (MARIO) Process [5] was coined to describe this cyclic process, conveniently named after the author’s grandfather, Mario. A deep etch using the MARIO process is shown in Figure 2.6.
2.2 The MARIO Process

The MARIO process begins with an initial etch step in which a small amount of oxide is preferentially removed from all exposed horizontal surfaces via highly directional physical sputtering by energetic ions. In areas covered by the etch mask, this bombardment only results in a small reduction of the mask thickness. In contrast, this sputtering process completely removes the thin oxide in unmasked areas, therefore exposing the underlying titanium to chemical etching by the highly reactive chlorine ions in the plasma. The oxide on the sidewalls is not
physically sputtered due to the low energy interaction of the ions with the sidewall keeping the underlying titanium protected from exposure to the chlorine ions.

The duration of the etch step is intentionally limited to only allow a small amount of etching to take place and is immediately followed by a short exposure to the oxidation plasma, which grows a new thin protective oxide on all exposed titanium surfaces. Subsequent cyclic repetition of the etch and oxidation steps yields highly anisotropic etching of all unmasked areas, therefore allowing for the definition of HARS. A schematic of the MARIO process is shown in Figure 2.7.
Figure 2.7 Process diagram of the MARIO titanium deep etch.

Mask undercutting is reduced significantly in the MARIO process because of the short duration of the etch step and sidewall protection afforded by the oxide, allowing for definition of vertical, but corrugated, sidewalls. This corrugation, also known as “scalloping”, is common to cyclic etch/passivation processes and results from the slight isotropic nature of the etch step. Altering the oxidation plasma conditions can change the quality and thickness of the grown oxide, which in turn changes the amount of protection offered during successive etching steps. The angle of the sidewall and degree of scalloping can be altered by changing the time
of the oxidation and etch step. Increasing the etch time increases the amount of scalloping, but can also be used to create reentrant sidewalls, i.e. sidewalls that slope inwards, thus slightly undercutting the etch mask. Decreasing the etch time can create vertical sidewalls and also decrease the amount of scalloping.

Currently, the process is operated in a Plasmatherm, SLR770 (Unaxis Semiconductors, St. Petersburg, FL) capacitively coupled plasma etcher. The etch step is run with a mixture of chlorine (45 sccm) and argon (15 sccm) operated at a pressure of 23 mTorr with a power of 220 watts. The most commonly used etching time is 2 min 30 s, which achieves vertical sidewalls with an acceptable overall cycle etch rate. The oxidation plasma is run directly after the etch plasma with oxygen (50 sccm) at a pressure of 23 mTorr with a power of 10 watts for 10 s. Increasing the oxidation time above 10 seconds does not affect the etch greatly, but reduction below 10 seconds causes breakdown of the protective sidewall oxide resulting in pitting of the surface. These two plasma conditions are cycled one after another until the desired depth of the etch is achieved. Depending on the condition of the etch chamber, a pump down may be necessary between both the etch and oxidation cycle. This reduces the reflected power in the matching network and allows for removal of the previous etch chemistry before the following plasma is struck. The MARIO process also allows for the creation of notches in the sidewall by changing the etch time during a single loop. Increasing the amount of
etching in a single loop, more isotropic etching can occur notching the surface, as shown in Figure 2.8.
Figure 2.8 MARIO deep etch with an extended chlorine etch during the last step used to partially undercut the beam.

Figure 2.9 4 micron wide titanium beam deep etched using the MARIO process.
2.3 Baseline Titanium Deep Etch Process

Titanium deep etching begins with commercially pure titanium substrates with thickness ranging from 10 to 500 microns. Owing to the greater toughness of titanium relative to silicon, free-standing substrates thicker than 25 microns can be processed without the need for backing or carrier wafers. Titanium substrates thinner than 25 micron are generally too compliant to support their own weight, and thus require extra support to prevent kinking from handling. This support is normally provided by temporary adhesion to a handling wafer.

The titanium substrates used thus far are rolled annealed sheet-stock with as-received surface roughness in excess of 150 nanometers RMS. Therefore, they
generally require polishing to enable subsequent optical lithographic patterning. Process development to optimize the polish has shown that a single step chemical-mechanical polishing process using colloidal silica is often sufficient to reduce the fine-scale roughness that otherwise interferes with high-resolution lithography. Typically, polished substrates have a surface roughness less than 50 nanometers RMS.

Following the polish, a titania etch mask is deposited on the titanium substrate by reactively sputtering titanium from a DC target in an oxygen/argon environment using the Endevor 3000 (Sputtered Films, Santa Barbara, CA) cluster sputter tool. The optimal flow rates for oxygen and argon are 10 sccm and 20 sccm, respectively, which achieve a process pressure of 3.7 mTorr. A power of 2.2 kilowatts for 1 hr 15 min. achieves a 1.2 micron titania film.

The titania-coated titanium substrates are then patterned using standard photolithography techniques with a reproducible minimum feature size of 1.25 microns. The patterned and developed photoresist is used as an etch mask for the underlying titania layer that is etched using a standard silicon oxide plasma etch using the Panasonic E640 (Osaka, Japan). The titania etch has a high selectivity to bulk titanium because it is a fluorine based plasma. The etch process consists of CHF₃ (40 sccm) as the etch gas with an ICP and bias power of 500 W and 400 W for 9 min 30 s at a pressure of 1 Pa.
Once the titania etch mask has been defined, the titanium substrate is deep etched using the MARIO process, which is shown earlier to be a cycling plasma etch that alternates between short exposures to an etching plasma and an oxidation plasma to yield HARS in bulk titanium. The etch plasma is fed by a combination of chlorine and argon gases operated at high power, while the oxidation plasma is pure oxygen and operated at low power. The process outlined here is just a baseline titanium deep etch and are the minimum required steps to deep etch bulk titanium.

2.4 Undercutting Titanium Structures

Undercutting structures is a common technique used in the fabrication of many silicon based MEMS devices. It was initially assumed that any titanium MEMS device would have to use an undercutting process to create movable structures. Undercutting is a process in which material below a previously deep etched beam is removed using an isotropic etch, where the amount of lateral etching is approximately equal to the amount of vertical etching. An example of such a process that utilized undercutting is the Single-Crystal Reactive Etching And Metallization (SCREAM) process shown below in Figure 2.11 [6].
Figure 2.11 Single Crystal Silicon Reactive Ion Etch And Metalization (SCREAM) process in silicon. 1) Deposit or grow silicon oxide. 2) Pattern photoresist 3) Transfer pattern to oxide mask 4) Remove photoresist 5) Deep etch silicon 6) Deposit CVD oxide 7) Anisotropically etch oxide 8) Deep etch silicon to extend the floor 9) Undercut silicon using an isotropic etch 10) Sputter deposit metal [6].

This process is misleadingly simple. Assuming a non-directional bombardment of ions on the titanium surface, the resulting etch will be non-directional. This is true of the Bosch process where the silicon etch plasma is inherently non-directional and a polymerization step is necessary to achieve an overall anisotropic etch. This is not the case for the MARIO etch, which was developed in a parallel plate plasma etcher where in order to sustain a plasma, a directional bias must be generated between the surrounding electrodes and substrate. This limits the etch to be mostly anisotropic and can cause great difficulty in undercut structures.
Several attempts were made to try to generate an isotropic etch, raising the pressure, decreasing the RF power and decreasing the concentration of argon in the plasma. There were a few etches that were re-entrant which, when run for a long enough period of time, were successful in undercutting narrow structures. However, such an etch is not very useful when trying to create high quality MEMS devices. An example of such an etch is shown in Figure 2.12.

Figure 2.12 Partly released titanium beam with a poor undercut.

From Figure 2.12 it can be seen that this undercutting process is not practical because it forms very sharp release points and sidewalls with a lot of damage. There was no success undercutting using this technique, therefore other
methods of releasing titanium had to be explored to enable the fabrication of movable MEMS.

2.5 Thin Foil Processing

With the difficulty in releasing titanium MEMS, another approach for creating moving structures was taken. Due to the mechanical properties of titanium it is possible to process very thin foils (10 micron foils are used in the micro-mirror device explained later in this dissertation). With the titanium deep etch process, thin foils are able to be through etched and processed just like their thicker counterparts. These thin foils can be also be bonded onto other structures to create released devices with the added benefit of being able to fabricate MEMS with more design flexibility. This simple idea has allowed for the fabrication of all of the devices presented in this dissertation and is a solution to avoid inadequate process techniques to achieve an undercut. Details of this process will be explained in Chapter 3.

2.6 Micromasking

Micromasking, or grassing, is a significant issue in bulk MEMS and is a critical issue in bulk titanium MEMS. Grassing occurs due to the introduction of an impurity with a slower etch rate than the base substrate, causing a small area to etch slower than of that the surrounding field. Sometimes this grassing is so great, it will slow the etch rate to zero. SEM images of these samples show very fine
spikes or hairs coming off the surface, very similar to a well cultivated lawn, hence the term “grass”.

![Figure 2.13 SEM image of micromasking during the deep etch of a comb drive.](image)

It is not the intent of this research to determine the full reasoning for grassing or develop solutions to this problem, but it is an important component to the deep etching of titanium. Several different conjectures exist that explain the presence of grass in some titanium samples. It has been noticed in thick samples with large grains, that grassing occurs at grain boundaries. For thinner samples with smaller grains, the grass occurs everywhere. The explanation proposed is the migration of impurities, such as iron or oxygen, to the grain boundaries which micromask during the deep etch. Another possibility is the existence of retained beta phase at
the grain boundaries from heat treatment. Either explanation needs to be investigated with the aid of the titanium producer to achieve a solution.

2.7 Summary

Using the silicon deep etch as a baseline process, a titanium deep etch has been developed that also uses two different plasma chemistries, but instead of an etch/passivation cycle the titanium etch is an etch/oxidation cycle. Along with the titanium deep etch, other process developments were made to enable lithography and oxide etching on titanium substrates. All of the newly developed processes allow for the etching of titanium using standard semiconductor equipment.
References

Chapter 3: Titanium Device Development

With the development of the titanium deep etch and other bulk titanium processing techniques, it is possible to consider fabricating the first bulk titanium MEMS device. Many different titanium devices are exciting when considering the very different set of newly available material properties. Biological, high shock and large array type of devices are of interest because of the unique properties of titanium. It is also possible to evaluate traditional MEMS devices using the new processing techniques such as thin foil stacking. This is the approach taken when choosing to fabricate an array of micro-mirrors.

For an initial attempt, a simpler version of a micro-mirror is created to better understand the processing specifics for the fabrication of a mirror device. This first attempt of a bulk titanium MEMS device is called the macro-mirror device because the mirrors created are over one square millimeter with 10 micron wide torsion bars used as restoring springs.

3.1 Macromirror Array

A 2 x 2 mirror array is fabricated by taking advantage of thin titanium foil processing. Three layers are used in this device, the first being a 25 micron thick foil that is deep etched to create the released mirror and torsion springs, the second, a 30 micron thick foil is wet etched to create a square through hole that will be placed under the mirror and finally, the silicon substrate is oxidized and metalized creating isolated electrodes. By bonding these three layers together
using gold to gold thermal compression bonding, the metal stack can operate as a macro-mirror device. This device is operated through electrostatics and is actuated by applying a voltage across the air gap from the underlying electrode and the underside of the mirror surface. A schematic of the layers and final device are shown in Figure 3.1 and Figure 3.2.

![Figure 3.1 Schematic of the separate layers for an element of the macro-mirror device. Top layer is the through etched mirror pattern, second layer is the spacer foil and the final layer is the electrode layer.](image-url)
3.1.1 Fabrication of the Macro-Mirror

The fabrication process for the macro-mirror is relatively simple due to the design and large feature sizes, making it a good choice for the first bulk titanium MEMS device. The process shown here shows some of the strengths and flexibility of processing titanium. To better explain the process, it is broken into three sections, one for each layer. All of the processing is done using an Endevor 3000 sputter cluster tool, a SRL770 Plasma Etcher, a MJB 3 UV400 contact aligner (Suss Microtec, Waterbury, VT), a MRC 51 Plasma etcher (Praxair, Danbury, CT), SEC600 E-Beam Evaporator (CHA Industries, Fremont, CA) and a M-8A flip chip aligner bonder (Research Devices, Piscataway, NJ).
3.1.1.1 Mirror Layer

In order to create the released mirror and torsion bars, the titanium foil needs to be through etched. Along with the deep etching, a gold layer for gold thermal compression bonding needs to be deposited on the backside of the foil. This gold layer is patterned only on the supporting structure of the mirror to prevent this gold from coming into contact with the metalized electrode during full tilt of the macro-mirror. This is done to prevent stiction between two gold surfaces that is traditionally problematic for MEMS.

A rolled and annealed 25 micron thick titanium foil is obtained from Goodfellow corporation (Lancaster, PA) to fabricate the top layer. For this process, no polishing is required because the minimum feature size is 10 microns, which can be defined using the contact aligner even on the as-received surface roughness of the foil. Using a similar process flow to the titanium deep etch explained in Section 2.3, a sputtered titanium oxide film is deposited onto the titanium foil. This etch mask is patterned using a photoresist mask and an oxide etch. After stripping the photoresist from the front side, the backside of the foil is patterned using photoresist designed for lift off.

Due to the limitations of the contact aligner, direct alignment from the backside of the foil to the front side is not possible. In order to circumvent this issue, a secondary alignment is performed using the edges of the titanium foil as alignment marks. This alignment is preformed using two lines on the outskirts of
the mask field that is transferred into the oxide mask. Scissors are then used to cut the foil along these two lines, making the new edge of the foil a known distance from the front side pattern. These two new edges are then used as alignment marks for aligning the backside liftoff pattern to the front side deep etch pattern. This method is successful for this large device because the features are very large and the tolerances for alignment are +/- 300 microns which can easily be achieved using a good pair of scissors and steady hands.

After the backside liftoff mask has been defined, a layer of titanium and gold are deposited using an E-beam evaporator. The titanium layer is 100 nanometers thick and is used for an adhesion layer, while the much thicker gold, 500 nanometers, is used for thermal compression bonding. The thick gold layer allows for flow to occur at the bonding pressures and temperatures. With the gold deposited, lift off is performed by soaking the foil in acetone. For best results, no ultrasonication is used due to the tendency for the removed gold film to cold weld to the other gold and titanium surfaces.

After an additional clean in acetone and isopropanal, the foil is placed with the oxide mask facing up into the chlorine dry etch system for the MARIO process. The etch conditions used are the same conditions presented perviously for a total time of 2 hrs. This through etches the foil, releasing the mirrors with only the torsion bars holding the mirror in pluptateace.
Figure 3.3 Dark field mask layout of the macro-mirror for the upper titanium foil

Figure 3.3 shows a dark field mask of the macro-mirror where the shaded sections will be through etched. The mask layout shows the center clear section that defines the macro-mirror, while the enlarged section shows the anchor between the mirror and the torsion spring.

3.1.1.2 Spacer Foil

The spacer foil is fabricated from a 30 micron thick titanium foil. This foil is wet etched with a square pattern to allow for a raised bond surface for the mirror supports. A wet etch is chosen because it is faster than dry etching and the lateral
etching, consistent with most wet etches, is allowable. To make the spacer, the foils are patterned with photoresist making an exposed square and covered surroundings. The backside of the foil is then also covered in photoresist to prevent the backside of the foil from being etched. This foil is then etched in a 10:1 DI water: HF solution for 5 min or until all of the titanium is removed from the exposed hole. After removing the photoresist, 100 nanometers of titanium and 500 nanometers of gold are deposited on both sides of the spacer using an E-beam evaporator.

3.1.1.3 Electrodes

The electrodes for this device are created from a silicon wafer due to the ease of electrically isolating each of the electrodes with thermal oxide. Using a liftoff process, thin films of 100 nm of titanium and 500 nm of gold are patterned on to a silicon wafer with 1 micron of thermal oxide. The pattern consists of two electrodes and a thermal compression bond region. The light regions of the dark field mask shown in Figure 3.4 define the locations of the deposited titanium and gold.
Figure 3.4 Dark field mask layout of the macro-mirror for the silicon substrate.

3.1.1.4 Bonding

Using the maximum settings on the flip chip bonder of 10 Kg and 350 °C for a bond time of 3 minutes, the electrode die and spacer foil are bonded together. After cooling, the top foil containing the mirrors is bonded onto the electrodes and spacer foil using the same bonding conditions. SEM micrographs of the macro-mirror device are shown in Figure 3.5 and Figure 3.6.
Figure 3.5 SEM of the final bonded macro-mirror with the mirror suspended above the electrodes by a gap height dictated by the spacer foil thickness of 30 microns.

Figure 3.6 Enlarged image of the torsion spring of the macro-mirror.
3.1.2 Testing of the Macro-Mirror

Some of the basic mechanical properties of bulk titanium MEMS can be investigated using this simple torsional mirror device. By fabricating this device, concerns over releasing structures from a titanium foil were suppressed. The released mirror remained in plane with the surrounding frame, even with it only being supported by thin torsion bars. The mirror surface also is not detectably warped during the release and bonding of the foil. Other questions about the mechanical integrity of the device can be answered through actuation of the device, mainly observing if the endurance limit assumption remains valid on this length scale. To test this assumption, the device is cycled using electrostatic actuation.

Grounding the mirror foil and applying a voltage to one of the underlying electrodes actuates the mirror. The degree of mirror rotation can be controlled with the applied voltage up to the point where the upper mirror reaches its instability and snaps down to the electrode. The velocity response of the system under conditions with and without snap down at a 25 microsecond pulse width and 50% duty cycle can be seen in Figure 3.7. The measurement shown in this figure is made with a Polytec Laser Doppler Vibrometer (Polytec PI, Auburn, MA) that uses the Doppler shift between the incident light and reflected light to measure the velocity of the measured surface. The laser for the vibrometer is passed through an optical microscope to allow the measurement of MEMS devices. This device is
measured at the farthest point on the mirror surface from the torsion bar, giving the maximum velocity of the device. From the measurements, it can be seen that the device behaves like an over damped system with a very slow response time due to the huge torsional mass and compliant springs.

![Velocity of mirror through one cycle](image)

**Figure 3.7 Time response of the macro-mirror to two different amplitude step inputs.**

Despite the poor dynamic performance of this device, it does show a few aspects of bulk titanium MEMS and can be used to answer some of the basic mechanics and materials questions. It is of interest to note that the mirror does not
show problems with stiction even at one million snap down cycles and also does not short when the mirror is in direct contact with the electrodes. The large lifetime of the torsion springs is consistent with the macro properties of titanium, having a modeled stress amplitude of only 16 MPa, which is below the endurance limit for titanium. The lack of shorting is anticipated to be due to the poor quality of the through etch on this device. During the fabrication process, the etch is timed to stop only when the large features are fully etched. This caused sections near the walls to still have thin strands of titanium that are expected to have oxidized through. These strands can be seen in the SEM micrograph of Figure 3.6 by the white hair on the bottom side of the mirror and spring. It is proposed that these hairs are what touch the gold electrodes during the snap down cycle and prevent the mirror from sticking to the surface.

The macro-mirror array shows how the developed titanium fabrication processing techniques are used to make the very first bulk titanium MEMS. It also shows the potential of making torsion based titanium MEMS with the ability to achieve large number of cycles without failure.

3.2 Micro-mirror Array

The results of the macro-mirror array lead way to proposed research for a micro-mirror array for an optical delay path system being developed at another university. The specifications for this array are listed in Table 3.1.
Table 3.1 Design specification for the micro-mirror device.

<table>
<thead>
<tr>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 x 10 mirror array</td>
</tr>
<tr>
<td>100 x 100 µm mirror size</td>
</tr>
<tr>
<td>250 µm distance between mirrors</td>
</tr>
<tr>
<td>Turn on voltage less than 100 volts</td>
</tr>
<tr>
<td>Response time &lt; 500 µs</td>
</tr>
<tr>
<td>Three position mirror with -10, 0, and +10 degree tilt</td>
</tr>
<tr>
<td>Half the mirrors tilt north-south, other half east-west</td>
</tr>
</tbody>
</table>

In order to reach these design parameters, several new processing techniques needed to be developed. The state of the art after development of the macro-mirror device limited feature sizes to 10 micron, which would be too large to meet the desired requirements of mirror pitch. Along with the need for better process control, new mirror designs needed to be investigated to keep a fast response time, but also maintain a low drive voltage. With the fixed requirements of each micro-mirror being able to swing to both +10 and -10 degrees and a fixed mirror size, not much can be done to reduce the drive voltage with a design similar to the macro-mirror device. The torsion springs can be redesigned to be more compliant, but this will cause an increase in the response time because of the lowered resonant frequency. To decrease the drive voltage but maintain adequate response time, another electrode design was developed.

3.2.1 Electrode Development

In order to improve the drive voltage without altering the response time, a new electrode design is necessary to increase the electrostatic force but still
maintain the +/- 10 degree maximum angle. The proposed solution is to make three-dimensional electrodes that slope downward from the mirror centerline to the edge, decreasing the air gap between the electrode and mirror, but still allowing the maximum tilt angle, resulting in a decreased drive voltage. A schematic of both the flat electrode design and the sloping electrode design are shown below in Figure 3.8.

![Figure 3.8 Schematic of the sloping and flat possible electrodes for the micro-mirror array.](image)

### 3.2.1.1 Analytical Reasoning for Sloping Electrodes

An estimate of the reduction in drive voltage can be calculated by analyzing the electrostatic force and restoring mechanical force for both a flat and sloping electrode. Assuming the mechanical stiffness of the beam is linear within the deflection during normal operation, the restoring mechanical torque can be determined.

\[ T_m = K_0 \beta \]  \hspace{1cm} (3.1)

Where,
\[ K_0 = \frac{2Gab^3}{3L} \left[ 1 - \frac{192b}{\pi^5 a} \tanh \left( \frac{\pi a}{2b} \right) \right] \]  

Valid for \( b < a \)

Where \( a \) is the beam height, \( b \) is the beam width, \( L \) is the beam length and \( G \) is the shear modulus of the beam material.

The electrostatic torque generated from the backside of the mirror to the electrodes can be determined by integrating the differential area across the whole mirror, tracking the gap between the mirror and electrode.

![Figure 3.9 Schematic of the mirror device showing pertinent geometry.](image)

The gap initial length, \( d \), can be determined by the following.
Knowing capacitance and thus the force along each delta x, the total applied torque can be determined by integrating the differential torque from the inner edge of the electrode to the outer edge of the electrode.

\[
T_e = \int_{x_o}^{x_e} x \left( \frac{\varepsilon_0 w V^2}{2(d + x \tan(\alpha - \beta)))^2} \right) dx \\
\]

Where \( \varepsilon \) is the permittivity of air, \( w \) is the width of the electrode, \( V \) is the applied voltage and \( \alpha \) and \( \beta \) are the angle of the electrode and mirror respectively.

Plotting both the torque applied by the electric field and the restoring torque, the instability voltage to cause the mirror to snap to the electrode can be determined. Two examples of the torque versus mirror angle are shown in Figure 3.10 and Figure 3.11, where 70 volts gives a stable mirror tilt angle of 1.7 degrees, but at 87 volts the maximum stable solution is obtained of 4.5 degrees. Any voltage above this will cause snap down. Both of these solutions use the geometry in Table 3.2.

\[
d = g_o \cos(\beta) \]

3.3
Figure 3.10 Electrostatic applied torque and mechanical restoring torque at 70 volts for various mirror tilt angles. Results show a stable and unstable solution for the mirror angle.
Figure 3.11 Electrostatic applied torque and mechanical restoring torque at 87 volts for various mirror tilt angles. Results show a single stable solution being the maximum mirror tilt before snap down.

Table 3.2 Geometry used in the above calculations of the minimum voltage for snap down.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$g_0$</th>
<th>$x_0$</th>
<th>$x_e$</th>
<th>$w_m$</th>
<th>$\alpha$</th>
<th>a</th>
<th>B</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (microns)</td>
<td>0.9</td>
<td>5</td>
<td>44.25</td>
<td>100</td>
<td>10 deg</td>
<td>10</td>
<td>1.0</td>
<td>60</td>
</tr>
</tbody>
</table>
Using the same formulation, but for a flat electrode with $\alpha=0$ and $g_0=8.68$ microns to give a 10 degree final slope, the snap down voltage is 152 volts. By using the geometry of a sloping electrode verses a flat electrode for the mirror design, the driving voltage is reduced by 43 percent. This decrease in voltage is done without sacrifice of the device response time, increasing the possibility of reaching the design criteria.

3.2.2 Electrode Fabrication

The processing of three-dimensional electrodes is not as easy as first anticipated. After considering resist reflow and using the Focus Ion Beam (FIB) as a fabrication tool, the proposed solution to make three-dimensional electrodes is to use Reactive Ion Etching (RIE) lag to produce different height structures. RIE lag is an effect characterized by a decreased etch rate with the increased aspect ratio of etch holes [3]. This etching effect is normally considered a corollary due to the decreased gas transport into and out of a deep trench, but it is possible to utilize this effect by patterning small vias causing significant lag.

A good example of RIE lag in a silicon deep etch is shown below in Figure 3.12, where a series of trenches are etched with continuously decreasing gap spacing from right to left.
Figure 3.12: Example of RIE lag in silicon from the Bosch Process (cross sectional view shown).

From the cross section above it is possible to see that the floor of the etch in the narrow trenches is etched less than in the wide, open area. This lag effect can be accentuated even more by defining square vias, not just trenches, allowing variation in etch depth up to 10 micron for a 22 minute etch. With this process, almost any height variation can be fabricated just by changing the size of the etch via. Thus, by making a gradual transition from large to small vias, a sloped structure can be fabricated. A mask layout for this process is shown in Figure 3.13, where two sloping electrodes are fabricated along with the interconnect wires and bond frame.
Since the floor of the etch is the only interest from the deep etch, the via frame needs to be removed. In silicon, it was realized the best method for this process is to oxidize all the way through the frame, then use hydrofluoric acid to wet etch off all of the formed oxide. The oxidation process for silicon is quite slow when compared to the deep etch, allowing full gas transport into and out of the etched vias resulting in a consistent thin film of oxide grown over the whole via frame and etch floor. Subsequent wet etching in HF removes this oxide, but is highly selective to the underlying silicon, which allows for over etching with out risk of removing any non-oxidized silicon.
It was quickly learned that there is a significant problem with this process if all of the oxidation is preformed in one step. The volume expansion of the oxidized silicon in the via frame causes enough stress to plastically flow the silicon under the frame at the oxidation temperature, causing the silicon to warp out of plane. An example of this processing induced stress can be seen in Figure 3.14, where the stress due to oxidation causes the bond frame to bow out of plane. This effect is best seen on the bond frame sidewall, which is no longer vertical.
In order to eliminate this problem, the oxidation and wet etching processes are cycled. After the deep etch, the wafer is oxidized to grow 300 nanometers of oxide then wet etched in HF to remove the grown oxide, followed by another 300 nanometers of oxide and wet etch. Running through this process for approximately 8 cycles, all of the deep etch frame is removed leaving only the etch floor with no out of plane bowing, verified using the Wyko 1100 white light interferometer (Veeco, Woodbury, NY).
Along with the formation of the sloping electrodes, other three dimensional structures necessary for the micro-mirror device are formed using the same process. These elements consist of a bonding frame, to allow the mirror foil to be bonded onto the electrode die without the use of a spacer foil, and electrical interconnects that run under the mirror foil from the electrodes to bond pads. The nature of the process makes it possible to create all three elements; electrodes, bond frame and interconnect lines all at the same time using the same process, even though all three elements require different heights [4]. A schematic of the deep etch and oxidation process is shown in Figure 3.15.
With the silicon wafer in the desired topology, electrical isolation between each of the electrodes and bond frame needs to be created. This is done by oxidizing the wafer for the final time, growing a 500 nanometer oxide on all of the surfaces. Then by taking advantage of the deep etched structure, gold is deposited anisotropically by E-beam deposition, which allows for the majority of the gold to be deposited on horizontal surfaces, but not on vertical surfaces because of the directionality of the deposition. This is then followed by a brief gold wet etch used
to remove any electrical shorts that may exist due to gold deposition on the sidewall, which is possible since the gold wet etch is isotropic. Different sections of the electrode device are shown in the following figures. A SEM image of the array is shown in Figure 3.16, while a close up of one of the elements is shown in Figure 3.17. It can be seen from this figure that there is no retained gold on the sidewall of the structure exposing the silicon oxide. Finally, the last figure, Figure 3.18, shows the termination of the interconnect lines out to wire bond pads. From all of these SEM micrographs it is possible to see texture on the gold surface, this is due to the oxidation of the via frame that results in bumps wherever there is a crossing point in the frame. This texture does not hinder the future bonding steps, but may have negative implications when dealing with issues of stiction.
Figure 3.16 Array of sloping electrodes also showing the bond frame and interconnect lines.

Figure 3.17 Single sloping electrode covered in gold. Notice the lack of gold on the sidewalls.
After all of the fabrication is performed, the wafer is divided into each die by dicing a cleave line into the wafer along the perimeter of each of the die. A thick layer of photoresist covers the entire wafer to protect it from damage and shield the surfaces from debris during dicing. After dicing, the resist is removed and each die is singulated.

### 3.2.3 Mirror Development

Focusing on the mirror, new handling and processing techniques are required to further the development process of the 10 micron thick foils with 1.5 micron wide springs, a necessity to meet the given design requirements. Processing foils less than 25 micron thick proves to be difficult because of their tendency to kink or fold. The higher stiffness of the 25 micron thick foils allows
the spinning of the whole 1 inch square foil on a resist spinner without any kinking. In contrast, 10 micron thick foils required attachment to a carrier wafer during most of the processing steps. Typically, the carrier wafer is silicon and the attaching adhesive is a thin layer of diffusion pump oil that allowed adequate adhesion and thermal conduction while also allowing for the necessary removal of the foil after the processing.

The reduction of the minimum feature size also required further process development. Differing from the macro-mirror device, lithography with the stepper is required to expose 1.5 micron features in photoresist, thus a polished titanium substrate is necessary to accept these micron features. Initial lithography tests without polishing caused the photoresist to peel or fail during the development of small features. An example of this is shown below in Figure 3.19, where the photoresist peeled in such a way to create an arch where the torsion spring pattern is exposed. This effect is most likely due to a rough surface that can scatter the exposed light, causing thinning and undercutting of the resist profile.
In order to achieve smaller feature sizes during photolithography, a polishing technique was developed and the final optimized process presented here. This process begins with the mounting of the 10 micron foil onto a polishing puck for the Allied High Tech MultiPrep System (Allied High Tech, Ranncho Domingues, CA). After an adequate bond, the thin foils are polished in a 0.2 µm colloidal silica slurry on a “red final C” CMP cloth from Allied High Tech. After 20 min of polishing under the highest load at a speed of 120 RPM, the foil is removed and placed in micro organic soap from Allied High Tech. The soap
allows the silica particles to be removed from the surface with best results achieved using ultrasonication. As a point of caution, ultrasonication under high powers caused the foil to curl, destroying the sample.

After polishing, a lift off structure, shown in Figure 3.20 by the striped layer, is patterned onto the foil using stepper lithography. Along with the lift off structure, alignment marks are also deposited onto the foil (different from the macro-mirror array, the micro-mirror array process is all done on one side of the wafer to eliminate the need for backside alignment). With this lift off pattern, titanium and gold are deposited onto the foil in the same manner as the macro-mirror device. After liftoff in acetone and isopropanal, titanium oxide is sputtered onto the entire surface covering the bare titanium and gold film. Next, the mirror pattern is exposed onto the foil using the alignment marks from the previous gold lift off, which are visible through the sputter oxide film. Using this pattern, the oxide is etched with the standard titanium oxide etch then cleaned in an ultrasonic bath of acetone then isopropanal, removing residual photoresist.
With the masking oxide defined, the foil is deep etched using an optimized MARIO process reducing the degree of scalloping to improve the minimum feature size at the sacrifice of the overall etch rate. The titanium is over etched by 50% to ensure a clean sidewall and lower edge, which was not implemented in the macro-mirror. The deep etch not only releases all of the mirrors, but also releases each of the mirror die from the foil. Typically, each foil contains 9 to 16 mirror die
per square inch and singulating each die with the deep etch avoids the need of mechanical separation, such a cutting that can cause warping.

After the deep etch, the masking oxide needs to be removed to expose the gold used in bonding. The fastest way to remove this oxide is to use the ICP Panasonic E640 etcher, but due to the high power of the etch a good thermal conductivity from the sample to the carrier wafer is required. This proved difficult with released devices. In order to avoid over heating, a different tool with a capacitively coupled plasma is used to remove the titanium oxide etch mask. The MRC 51 parallel plate etch tool is used to remove the oxide on the surface with CF₄, which has adequate selectivity to the underlying gold. This tool is lower power and the sample does not require good thermal conductivity to the platen, so resting the foil on a silicon wafer is sufficient. The trade off for low power plasma is a very long etch time, which can be upwards of 6 hours to remove the 1 micron of masking oxide. Mirrors processed up through the deep etch step are shown below in Figure 3.21 and Figure 3.22. The spring widths shown here are 1.5 microns with 100% yield over the entire single die.
Figure 3.21: SEM image of the free standing micro-mirror etched from a 10 micron thick titanium foil.

Figure 3.22: Spring support of the micro-mirror showing the scallops due to the cyclic nature of the MARIO etch.
After the long oxide etch, all of the gold on the bond area is exposed. Due to the lift off pattern, gold is only exposed on the bonding frame and not the backside of the mirror or torsion bars. Alignment and bonding the mirror die to the electrode die is performed in the flip chip bonder. With the upper platen modified to accept a single mirror die, both the mirror foil and electrodes are placed in the upper and lower platen respectively. After alignment and ensuring parallelism using the optics of the flip chip, bonding is preformed using the maximum load and temperature of 10 Kg and 350 °C for 3 minutes. This aligned bonding allows the mirrors to be placed directly over the sloping electrodes, where the gap between the mirror and top of the electrode is dictated by the gold thickness and the etch height of the bonding frame. Due to the limitation of the flip chip bonder, accuracies down to only 2 microns are possible, which is a significant drawback to this process but can be overcome with better calibration and a better bonder. A schematic of the final device is shown below in Figure 3.23 and a SEM image of the final device with one of the mirrors snapped down is shown in Figure 3.24. Another SEM image showing the wiring of the interconnects entering under the mirror foil is shown in Figure 3.25.
Figure 3.23 Schematic cross section of the micro-mirror with the titanium foil bonded onto the silicon substrate using thermal compression gold, which is on top of oxidized silicon.

Figure 3.24: Bonded micro-mirror array with one of the titanium mirrors actuated.
3.2.4 Package Assembly

With the mirror chip fabricated, it needs to be assembled into a package for testing under vacuum conditions and other applications where probing is not convenient. The 208 pin package chosen is a Kyocera Pin Grid Array (PGA) with a die cavity of 14 millimeters which just fits the total electrode size of 13.5 millimeters. The die is soldered into the package and wire bonds are made with gold wire from the package to each of the wire bond pads using gold wire. Figure 3.26 shows the attachment of the ball bonds onto the wire bond pads, onto the gold-coated electrode die.
3.3 Testing the Micro-mirror Device

The micro-mirror is driven in the same manner as the macro-mirror device. A voltage is applied to the underlying electrode while keeping the mirror containing titanium foil grounded. Each mirror element contains two electrodes, one to drive it to +10 degrees and another to drive it to -10 degrees, which correlates to 200 separate signals for the whole device plus one common ground signal. Applying a bias to an interconnect line will make the correlating mirror device actuate. Basic testing is done in air by probing the bond pads, but tests
under vacuum are completed with the device fully packaged and electrical feeds running out of the vacuum systems.

Several different aspects of the mirror device can be tested by measuring both the transient and steady state responses of the device to a variety of input voltages at different pressures. The main focus of testing for the mirror device is to determine the settling time, drive voltage and stiction. Other tests are also performed to determine the resonant frequency and quality factor that are more of an interest for future titanium MEMS devices, not necessarily this mirror device.

Initial tests showed that stiction is a major problem for these devices. After several snap down cycles, the mirror would stick for some period of time, limiting how these devices can be tested. Several different designs are attempted to avoid this problem, but it is still a large unresolved issue. In order to work around this problem, the mirrors are run in analogue/scanning mode limiting the applied voltage and maximum mirror angle to below the snap down instability. Running under this mode, the settling time and angle of twist for a given voltage can be determined.

The settling time, damping coefficient and resonant frequency can be determined by applying a step input signal. Mirrors with springs 1.25 microns wide and 60 microns long have a resonant frequency of about 75 kHz, with a snap down voltage of approximately 75 volts with well aligned sloped electrodes. One
of the step responses of a micro-mirror with a 60-volt input signal is shown below in Figure 3.27.

![Graph of the step response of the mirror device to a 1 degree tilt](image)

Figure 3.27 Step response of the mirror device with a comparison to a second order underdamped system.

The damping for this device is not large and by fitting the response of the mirror to a second order underdamped resonant system, the damping coefficient of 0.019 is obtained with a total settling time of 2.7 milliseconds, defined by the time to reach 2% of the steady state value. This settling time is well above the design specs and alternative device designs need to be investigated for improvement. One obvious
solution is to increase the damping in the system either by altering the mirror or electrode geometry.

Both alterations to the mirror and electrode geometry are made in the next generation of devices. The open areas in the electrodes are filled in with tall structures to impede air being pushed by the mirror. Similarly, the gap between the mirror and surrounding frame is decreased with the similar intent of impeding the movement of displaced air. Figures of both the electrode and mirror are shown in Figure 3.28 and Figure 3.29.
Figure 3.28 New electrode design with open areas closed in to reduce the settling time of the mirror device.

Figure 3.29 New mirror design with enclosed area around the springs and mirror platform to reduce the settling time of the mirror device.
Both of these design alterations greatly improve the settling time of the system. Settling times to a displacement an angle and back to the zero state are shown in Figure 3.30 and Figure 3.31. The settling time for the mirror to reach 2.5 degrees is 0.60 milliseconds while the time to settle for the mirror to return to the zero state is 0.46 milliseconds. Again, fitting these two responses to a second order underdamped system, the damping coefficient is 0.312 for the swing to a displacement angle, while 0.3 for the swing to zero.

![Step Response of Mirror Device to a 2.5 Degree Tilt](image)

Figure 3.30 Step response of the new mirror device to the positive slope of the input signal compared with a second order underdamped system.
The mirror surface roughness poses an issue with the current micro-mirror device. The small scale surface roughness and the larger scale surface roughness decrease the ability to reflect the laser light. Measurements have been taken over an array of 100 mirror devices, analyzing the small scale surface roughness using a Fourier transform to filter out roughness above 10 microns and large scale roughness using the same transform but filtering out roughness below 10 microns. This filtering allows for the analysis of the surface roughness due to polishing and overall warping of the mirror surface. These measurements are made with the

Figure 3.31 Step response of the new mirror device to the negative slope of the input signal compared with a second order underdamped system.
Wyko 1100 NT. A summary of this analysis is shown in the histograms below in Figure 3.32 and Figure 3.33.

Figure 3.32 Histogram of the small scale surface roughness filtered below 10 microns for a set of the mirror surfaces.
Figure 3.33 Histogram of the large scale surface roughness filtered above 10 micron for a set of the mirror surfaces.

Both the large scale and small scale surface roughness reduce the efficiency of light reflection and is a major issue. An estimation of the effect of surface roughness on the reflective properties of a surface can be determined from Equation 3.5.

\[
\frac{R_s}{R_o} = e^{-\left(\frac{4\pi\delta}{\lambda}\right)^2}
\]  

[5] 3.5

Where \(R_s\) is the intensity of the reflected signal including the surface roughness, \(R_o\) in the intensity of the input signal, \(\delta\) is the RMS surface roughness and \(\lambda\) is the signal wavelength.
Not only scatter will affect the reflected signal, but also the material itself will have a different reflectance. Reflectance data measured with a center frequency of 1550 nanometers is shown below on a mirror polished titanium sample from Tokyo Stainless Grind and also a silicon wafer coated with 0.5 microns of E-beam evaporated gold.

![Reflectivity of gold and titanium referenced to gold](image)

**Figure 3.34** Reflectivity of gold and titanium referenced to the gold signal over a range of wavelengths centered around 1550 nm.

This experimental reflectivity is compared to the reflectivity from literature values. Using the index of refraction ($n$) and damping constant ($k$) of 0.559 and 9.81 for
gold and 4.04 and 3.52 for titanium both at a wave length of 1550 nanometers [6],
the reflectivity of each material can be calculated using the following equation.

\[ R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \]  

Using this method, the reflectivity of gold and titanium are 0.97 and 0.57 respectively. This compares with the experimental values of -2dBm of loss between the gold and titanium output signals. Assuming the gold has a reflectivity of 0.97, the measured reflectivity for titanium would be 0.61. Knowing that this poor reflectivity is an inherent loss mechanism in the titanium, it is proposed that any future device used to reflect light of this wavelength, be coated in gold to improve the reflectivity. Along with this coating, a diffusion barrier would also be necessary to prevent titanium from diffusing through the gold and oxidizing on the exposed surface.

3.4 Summary

In this chapter the titanium deep etch process is used to fabricate two torsion devices. Using the deep etch and thin foil stacking, it is possible to create the first bulk titanium MEMS device called the macro-mirror device. This device has a poor transient response, but gives indications that bulk titanium is able to withstand high cycle fatigue, giving confidence to the future of bulk titanium MEMS. To improve the macro-mirror, a micro-mirror array is fabricated. Using the process development of RIE Lag, 10 micron foil processing and micron scale
lithography on titanium, the micro-mirror is fabricated. After testing, the initial
design is altered to achieve a better response time allowing a 10 x 10 mirror array
with a switch time of approximately 500 microseconds and a turn on voltage of
less than 100 volts. Unresolved issues involving stiction, reflectivity and bond
alignment need to be further investigated.
References


Chapter 4: Mechanical Properties of Micron-Scale

Titanium

As previously mentioned, one of the main advantages of using titanium as a basis for MEMS is the differing material properties when compared to those of semiconductor based materials. The known properties that are available are those based on the bulk material properties and little is known on how these properties change for titanium when trying to predict the behavior of small scale structures.

The elastic modulus and residual stress for a sputtered film of titanium has been investigated [1] however this film will behave very differently than bulk etched titanium because of the difference in grain structure, residual stress and stress gradient. In general it is true that a sputtered film will have a drastically different set of material properties than their bulk counter parts due to these altered factors [2]. Titanium beams fabricated from deep etching a foil are expected to have mechanical properties not dictated by grain size, but by geometry and size.

The development of the macro and micro scale mirror devices assumed the material properties didn’t change relative to scale. These assumptions are necessary to build an initial device, but with the ability to fabricate these structures it is now possible to measure the mechanical properties of the material at the length scales and loading conditions of MEMS devices. Understanding these
properties will allow for better design and fabrication of titanium MEMS devices, in particular, titanium MEMS devices that operate in torsion.

Some of the important mechanical properties necessary for the appropriate design of MEMS devices include an understanding of the yield stress, fatigue resistance, elastic modulus and information about how the titanium devices will resonate. This chapter will focus on the yield stress and resonance of thin titanium beams.

4.1 Starting Material

The titanium sheet used for the subsequent processing is a 10 micron thick titanium foil obtained from the Goodfellow Corporation. These foils are rolled and annealed then cut from big strips to 1 inch squares. They have been measured to have a grain size of 3 microns and show a strong rolling texture with c-axis alignment normal to the sheet surface. A pole figure plot of the 002 plane for the titanium foil is shown below in Figure 4.1. This material is used for both the resonance tests and testing of the yield strength.
4.2 Resonance

Two important factors can be determined from the resonance of titanium devices. First, the shear modulus and in turn elastic modulus can be determined if the density, geometry and resonant frequency of the device is known. The second is the quality factor, which is a measure of the amount of energy dissipation. To determine the resonant frequency and quality factor for a range of geometries, an array of torsional devices is created that are very similar to the micro-mirror with the exception that the length and the width of the beams are varied across the die of 100 devices. Widths varying from 0.5 to 10 microns and lengths from 9 to 50
microns long are investigated to determine if the generalized equations are consistent with the experimental data of the expected design space for future titanium torsional devices.

Figure 4.2 Thermal compression gold mask and torsion structures used in the resonance and yield stress experiments.

4.2.1 Quality Factor

All of the resonance tests are performed in a vacuum of $3 \times 10^{-6}$ Torr to eliminate the effect of air damping on the resonance. Using a laser vibrometer to measure the velocity at the edge of the torsion device, a frequency sweep is
applied using the square root of an AC signal with an amplitude of 50 volts. The square root voltage is used to avoid driving higher order resonances that can occur when using just a sine function because the driving force is based on the square of the applied voltage. From this frequency sweep, the quality factor, measured by the resonant frequency divided by the width of the resonance peak 3dB lower than the peak maximum, can be calculated. An example of such a frequency sweep can be seen in Figure 4.3, which has a resonant frequency of 96 kHz and a quality factor of 389.
This type of response is similar for all of the devices tested in the array. The average quality factor is 315, which is much lower when compared with silicon that can have a quality factor upwards of 3,000 [3]. It is also interesting to note that there is no observed trend in this quality factor with beam width, length and overall resonant frequency. This lower quality factor can be explained by the decrease in purity of a crystal structure for the torsion springs. Grain boundaries, native oxide, etch oxide and the existence of dislocations can all decrease the quality factor in metals [4]. The effect of the existence of the etch oxide on the

Figure 4.3 Resonance response of a torsion device to a frequency sweep preformed in vacuum.
quality factor is measured by using the Focus Ion Beam (FIB) to sputter partway into the side of the beams to remove this oxide. Since the test and FIB equipment are located in different chambers, it is not possible to avoid the development of a native oxide, approximately 3-5 nanometers thick, when the devices are exposed to air using this technique. These beams are retested under vacuum conditions and the measured quality factor is relatively unchanged, leading to the belief that the etch oxide is not the main contributor to energy dissipation in the device. It is expected that the mobile dislocations in the titanium dissipate much of this energy.

4.3 Experimental Determination of the Yield Stress

The yield stress of the thin titanium beams is of interest when attempting to design future bulk titanium MEMS. Of further interest is the effect of small size on the yield stress of titanium, which has been shown in some material systems to change depending on the length scale of the tested structure. Interesting effects from the gradient of strain can affect the overall yield stress of the material in torsion and bending, complicating the ability to predict the yield stress of titanium on reduced length scales. A series of torsional tests are preformed on thin titanium beams with the thickness and length of the beam altered to measure the effect of size on titanium torsion beams. The micro-mirror array with several alterations is used for this test where the mirror platform is used as a lever arm to allow an applied load to be converted to a torque.
The Hysitron TriboIndenter (Hysitron, Minneapolis, MN) is used to apply this load and measure the displacement of the indenter tip. This data, along with the known distance from the indenter tip to the torsion bar, can then be used to calculate the angle of twist from a given torque. The conversion from the measured torque to a maximum stress requires the geometry of the torsion beam and stress distribution to be known. A FIB is used to cross section and measure one of each different width beams from each die. The measurements of the whole torsion structure with the torsion plate and both torsion bars can be imported into a finite element package, ANSYS 5.7 (ANSYS Inc., Canonsburg, PA), to determine the stress distribution with the known beam width, length, height and taper. Using the raw data from the nanoindenter, the measured load can be converted into a maximum stress and the tip displacement can be converted into a maximum strain in the structure. By converting to stress and strain it is possible to look for trends in the plastic behavior for a variety of geometries. In order to observe these trends in the yield stress for different beam geometries, the maximum stress for 0.2% maximum plastic strain is calculated. Each of these steps is explained in more detail.

4.3.1 Alterations to the Micro-mirror Device

The same torsion array used for the resonance testing is used for the yield testing with the only change being the elimination of the electrodes from under each of the released structures. This is done to reduce the possibility of the silicon
surface interfering with the mirror during testing. In this version of the device there is a 40 – 50 micron pit etched into the silicon under each of the torsion devices, allowing for plenty of room for the full torsion of the mirror device without interference.

The torsion bars are over exposed during the lithography of the device to thin down each of the torsion bars in hopes that a few would be less than one micron wide. The alteration of this step did cause the thinnest of the torsion bars to be removed due to the over exposure. However, the sacrifice of these few devices allows for easier fabrication of sub-micron features. The other drawback to over exposing the torsion bars is the unknown final width of the beams, which further emphasizes the use of the FIB to obtain accurate geometry.

4.3.2 Nanoindentation

The Hysitron nanoindenter is originally designed to measure the hardness of a material where an indenter tip of known geometry is imbedded into a surface with a known load. The hardness and sometimes the elastic modulus of the material under the indenter tip can be determined from measuring the depth of the indent at an applied load and unloading characteristics. In this test, the hardness of the titanium is not where the interest lies, but rather the tool is adjusted to record the measured displacement for a given load.
The maximum force that can be applied is 10 micronewtons with a resolution as low as 10 nanonewtons. Along with the maximum force there is a 5 micron maximum displacement of the indenter head with a resolution of 0.2 nanometers. The calibration for this tool consists of an alignment of the indenter head to the optics and adjustment for the mass of the indenter tip. Several system parameters are used to remove some systematic errors in the tool, such as an adjustment of the compliance of the indenter, which can be important when trying to accurately measure the indenter tip displacement, and the elastic modulus of a material. The tool also allows automation of multiple loading and sample
positioning sequences that allows for the testing of a larger number of structures in a short amount of time.

After the fabrication and bonding, the nanoindenter is used to apply a load on the mirror surface that is now being used as a torsion bar. The indenter is fit with a 5 micron conical tip to prevent plastic deformation under the tip at the applied loads used for the tests. The displacement limitation of 5 microns requires the indenter head to be placed much closer to the torsion bar than initially intended, reducing the torsion arm distance from 50 microns down to 15-20 microns. This increases the error during the test because of the lateral error from the nanoindenter, which is measured to be approximately 1 micron.

After aligning the indenter optics to the indentation tip, the indenter is used to place a pair of thin beams into torsion. The indenter is programmed to run through several loading and unloading cycles with an increasing load until either the maximum indentation load or displacement is reached. All of these loading and unloading cycles are preformed at the same loading rate of 200 µN/Sec. The elastic response, onset of yielding and work hardening for the material is determined by cycling each indentation with an increasing load. Raw data from the nanoindenter is shown in Figure 4.5 and the input load function is shown in Figure 4.6.
Figure 4.5 Raw data of the indentation load and depth from the testing of a torsion device using the nanoindenter. The plastic behavior can be seen from the deviation from the initial elastic response. Slight hysteresis is seen during the loading and unloading curves in the elastic region which is expected to be caused by the measurement technique.
Figure 4.6 Input load function used for testing all of the torsion devices. Note: This load function achieves the maximum load the device can withstand of 3000 micronewtons.

### 4.3.3 Focused Ion Beam (FIB)

The FIB uses a beam of gallium ions to sputter away material that is in the beam’s path. Rastering the ion beam across the surface of the torsion bar slowly cuts the torsion beam until it is fully cross-sectioned. Using the SEM also contained in the FIB, images and dimensions from each of the cross-sections can be gathered. A typical cross-section is shown below in Figure 4.7. Compensating for the tilt of the
SEM micrograph, the width, height and taper of each of the beams can be determined.

Figure 4.7 Cross-section of a 7 micron wide beam using the FIB.

4.3.4 ANSYS

Knowing the geometry of the beam, the location and intensity of the applied load, ANSYS is used to determine the maximum stress in the beam. This is just an estimate since it assumes an elastic responding material, however it should provide fairly accurate results when analyzing the onset of yielding. The
stress distribution for one of the beams under the applied load of the nanoindenter is shown in Figure 4.8. It can be seen that the maximum stress is indeed in the center of the beam.

Figure 4.8 Stress distribution from the loading of the torsion bar with the nanoindenter.

From this stress distribution, the maximum Von Mises stress can be determined. It is important to note that this stress is only based on the applied load and not on the displacement, so it is independent of the elastic modulus used in the model and the resulting displacement. The Von Mises stress from ANSYS can be confirmed using an analytical model where the maximum stress in a rectangular beam is shown in Equation 4.1.
\[
\tau_{\text{max}} = \frac{T}{c_1 ab^2} \quad [5]
\]

4.1

Where \( c_1 \) is 0.312, for a beam with an aspect ratio of 10:1.

This simplified equation only accounts for the applied torque and not the transmitted normal load. In using this equation the error between ANSYS and Equation 4.1 is only 2\%, which gives confidence that the ANSYS model is producing reasonable results.

The ANSYS model can also be used to relate the given displacement from the indentation test to a maximum Von Mises strain. This strain is located on the outer surface of the beam along with the maximum Von Misses stress. Assuming the total amount of plastic strain is small, this predicted strain will be a good estimate of the real strain in the beam. Using the ANSYS model, it is possible to convert the data from the raw nanoindentation test to terms of maximum stress and maximum strain. This conversion allows the comparison between beams of different widths and lengths. An example of a stress versus strain plot for an indentation run is shown in Figure 4.9.
Figure 4.9 Maximum stress in the torsion beam versus maximum strain, converted from the raw data from the nanoindenter.

4.3.5 Analysis

The concept of yielding can be thought of in a few different ways. In the extreme, the first onset of yielding is the stress where there is any plastic deformation. This can be a very difficult task to detect because this will be the stress where a dislocation propagates, giving an almost infinitesimal plastic displacement. Measuring these displacements is very difficult and as a result, in most engineering applications, the stress at first yield is unimportant. To create a
standard, the 0.2% offset yield stress is typically used as the yield stress. This yield stress is determined by the stress to cause 0.2% plastic strain. This standard is used to avoid inconsistency between different experimental techniques and offers a stress to be used in most engineering applications.

Since metals are not typically used for bulk MEMS devices, it is hard to assume a standard for measuring the yield stress. Here it has been chosen to report two different sets of yield stress. The first being the 0.2% offset yield stress and the second being the stress at the first detectable yield. The stress at first detectable yield is very sensitive to the previous history of the material and the accuracy in being able to measure plastic deformation, which causes this method to be poor and inconsistent. However in some MEMS applications it is an important stress to report, particularly when deviation from non-linear behavior is detrimental. The 0.2% offset yield stress is determined by finding the 0.2% strain, then following the 0.2% plastic strain up the elastic line until it crosses the stress strain curve. An example is shown for structure 52 in Figure 4.10.
Using this method it is possible to measure the 0.2% offset yield stress for all of the devices measured and observe trends in the yield stress across several design parameters.

### 4.3.6 Yield Stress in Tension

The tensile yield stress of the titanium foil from the same batch is measured to compare to the yield stress measured in the torsion experiment. Dog bone style
samples are fabricated from 10 micron thick foils using the same oxide masking and deep etch process used in the fabrication of the mirror arrays. The samples range in size from 100 microns to 1.5 millimeters in width and are all 6.35 millimeters long. The light field mask in Figure 4.11 shows the design of the dog bone samples. Along with the region being tested, supporting structures with identification tabs are also fabricated. These tabs are cut after the foil has been placed in the tensile tester to ensure minimal damage to the region being tested.

![Light field mask layout for the dog bone samples.](image)

These samples are placed in a Micropull tensile test machine (MicroPull Science, Thousand Oaks, CA) by gluing each of the samples into disposable
holders which are inserted into the tester. Using a constant strain rate, the maximum load at failure for each of the dog bones is measured. Knowing the cross sectional area of the sample, an average failure stress of 500 MPa is measured. Due to the thickness of the foil it is difficult to measure any strain hardening since the system is not sensitive enough to measure the necking. The full yield stress cannot be determined from this test, therefore the overall failure stress from this test will be used as an estimate of the yield stress. It is also of interest to note that no trends are observed between the width of the beam and the yield stress.
Figure 4.12 Stress versus cross head displacement from the tension test of a thin foil dog bone sample.

The measured samples all failed in the center of the dog bone 45 degrees to the loading direction. SEM images of the failure surfaces show a ductile failure indicated by spherical dimples.
Both the 0.2% offset yield stress and the stress at the first detectable plastic deformation in the torsion experiment follow an interesting trend. They show that with the decrease of the beam width there is an increase in the stress to cause the same amount of plastic deformation. If one assumes that there would be no change in the yield stress and that the beams are purely titanium, the yield stress should not change with a change in the beam width, however apparently, this is not the case. As can be seen in Figure 4.14 and Figure 4.15 for both the measured yield stress for the 0.2% plastic strain and first detectable plastic deformation, the yield stress increases dramatically with decreased beam width.
Figure 4.14 Summary of the yield stress for various beam width gathered from the torsion testing.
Figure 4.15 Summary of the first detectable yield stress versus beam width for the torsion bars.

It is also of interest to note that the yield stress does not change when plotted against the length of the torsion bars, shown in Figure 4.16.
Several possible hypotheses may explain the observed behavior and the two most probable explanations will be discussed later in this dissertation.

### 4.3.8 Design of the Experiment

Several different aspects of the test are engineered to reduce measurement error and to ensure the test is measuring the yielding of the torsion beam and not other effects. The anchor is designed to avoid stress concentrations due to the supports that may overshadow the desired yielding of the torsion bar. All of the torsion bars are connected to the supports using 5 micron radii. Using ANSYS, the predicted stress increase due to these anchors is less than 5% higher than the

![Von Mises Stress at 0.2% Plastic Strain vs. Beam Length](image-url)

Figure 4.16 Summary of yield stress versus beam length.
maximum stress located in the torsion beam. This can also be confirmed by observing the deformed shape in a SEM image after testing.

Figure 4.17 SEM image of a torsion device after destructive testing with the nanoindenter.

Figure 4.17 is a good example of how the mirror looks after testing. It can be seen that the mirror is still in place, however the torsion bars have undergone significant plastic deformation. Part of this is due to the final loading step during the torsion test, where upon reaching the maximum displacement, the tip becomes uncontrolled and drops much lower than the final displacement of 5 microns. A
torsion beam is cross-sectioned to observe the shape along the length of the beam to determine if there indeed is plastic deformation consistent with an applied torque. Figure 4.18 shows the final plastic deformed shape of one beam showing deformation along the entire length of the beam.

![Torsion Beam Image](image)

**Figure 4.18 Torsion beam after testing. Cross-sectioned using the FIB.**

It is interesting to note the contrast of this type of failure compared to that of a brittle material. All the energy absorbed in a brittle material will be located at the stress concentration in the formation of a fracture surface. This is very different from what is observed here where yielding will begin at the stress concentration
from the anchors, but due to work hardening, the area of plastic deformation grows until the whole beam plastically deforms.

Beyond just the tailoring of the design of the structures, several different tests are performed using the nanoindenter to achieve the best combination of load head and indenter tip. Originally, a cube corner tip was used, but it was soon noticed that because of the sharp tip, the tip was indenting into the titanium foil and also yielding the torsion structure. The indentation depth was masking the actual yielding of the structure causing inconsistent data. The 5 micron conical tip is chosen to prevent indentation into the titanium surface. Several indents are preformed on a titanium foil, both suspended over the substrate and also bonded to the substrate. Up to the maximum load used during the indentation test, the depth of the indent depth is limited to several nanometers. Also during each test, the alignment of the tip to the optics of the nanoindenter is done after every 4-5 indents to insure accurate placement of the indenter tip during each indentation.

4.4 Summary

In this chapter, two of the mechanical properties of bulk titanium are investigated. The quality factor for these devices is measured running frequency sweeps with the applied electrostatic force and measuring the amplitude of the displacement all under vacuum conditions to avoid damping effects from atmospheric testing. The measured quality factor for these devices is low and the losses are hypothesized to be originating from the titanium beam and not external
factors. In addition, the yield stress of thin titanium beams is measured in torsion using a nanoindenter and FIB. Results from this analysis show an increase in yield stress for a decreased beam width. Several different probable causes are developed in the following chapter.
References


Chapter 5: Theoretical Analysis of Yield Stress

A better understanding of how titanium behaves at small length scales is a key factor in the development of MEMS devices. It is important to develop an analytical model that fits the observed experimental data, allowing for accurate predictions of how designed titanium MEMS will behave. Two separate models are used in this analysis. One model uses the gradient of strain as a factor to increase the observed yield stress, the other takes a composite model approach of thermal oxide and titanium which can also have the effect of increasing the yield stress.

5.1 Strain Gradient Plasticity (SGP)

Strain gradient plasticity is a theory that is used to describe the effect of geometrically necessary dislocations on the observed yield stress. In several different experiments it has been noticed that in bending and torsion, there is an observed increase in yield stress with a decrease in the overall dimensions of the tested structure. Traditionally, using continuum mechanics this is not an expected observation since strain hardening does not account of the gradient of strain.

5.1.1 Strain Gradient Plasticity Theory

In order to relate the effect of a strain gradient to the yield stress, a different relationship is used. Under the assumption that the density of geometrically necessary dislocations ($\rho_g$) have the same effect as the density of
statistically stored dislocations ($\rho_s$) on the shear stress, the following Taylor relationship can be used [1].

$$\tau = \alpha \mu b \sqrt{\rho_s + \rho_G}$$  \hspace{1cm} 5.1

Where $\alpha$ is a fitting parameter, $\mu$ is the shear modulus, $b$ is the magnitude of the Burger’s vector.

It is assumed in this relationship that the density of statistically stored dislocations does not have an affect on the density of geometrically necessary dislocations giving only an additive effect to the density of dislocations.

From the theory of dislocations, it is implied that the density of stored dislocations is a function of the plastic strain, and from strain gradient theory the density of geometrically necessary dislocations is a function of the gradient of strain. Under these two assumptions it is possible to obtain the deformation theory of $J_2$, which is not explained here but can be found in the literature [1]-[4]. The result of this analysis is a new effective strain that includes both the gradient of strain and the plastic strain

$$\varepsilon = \left( \frac{2}{3} \varepsilon_p + \ell_s^2 \eta_p + \frac{2}{3} \ell_r^2 \chi_p \right)^{\frac{1}{2}}$$  \hspace{1cm} 5.2

Where
\[ \varepsilon_e = \varepsilon_{ij} \varepsilon_{ij} \]
\[ \eta_e = \eta_{ijk} \eta_{ijk} \]
\[ \chi_e = \chi_{ij} \chi_{ij} \]

Where \( \mu_l \) is the displacement vector,
\[ \varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad \eta_{ijk} = \frac{\partial u_i}{\partial x_j} \frac{\partial u_k}{\partial x_i} \quad \text{and} \quad \chi_{ij} = \frac{1}{2} e_{iqr} \eta_{jqr} \]

Where \( e \) is the permutation symbol.

The two lengths in the effective strain equation are the stretch and rotation length scales. These fitting parameters normally both range between \( \frac{1}{4} \) and 5 microns [1].

5.1.2 Determination of the Strain Gradient Plasticity Fitting Parameters

The three unknown parameters from the SGP theory are the work hardening exponent, the rotational and stretch length scale. From the experimental torsion data, the work hardening coefficient can be estimated in the same technique used by Fleck et al [4]. From this data the work hardening exponent is approximately 0.7. The other two length scale parameters can be determined from fitting the experimental torsion data with the SGP theory.

This analysis requires a direct displacement solution for a beam in torsion to include the effect of the strain gradient. Due to the difficulty of a direct solution for the displacement field of a rectangular cross section, an ellipse is used as an approximation.
Figure 5.1 Schematic of an ellipse in torsion with the appropriate dimensions labeled.

The displacement field for a fixed-fixed ellipse in torsion is

\[ u_1 = -\phi x_2 x_3 \]
\[ u_2 = \phi x_1 x_3 \]
\[ u_3 = 0 \]  

Where \( \phi \) is the angle of twist per unit length.

From the displacement field it is possible to calculate the strain, rotational strain gradient and stretch strain gradient from Equation 5.2 and 5.3.

The calculated torque predicted from the SGP theory uses a work energy argument. For simplicity, the stress strain relationship is assumed to be a power law formulation.
\[ \sigma = \sigma_0 \varepsilon^n \] 5.5

Where n is the strain hardening exponent and \( \sigma_0 = \sigma_y \left( \frac{E}{\sigma_y} \right)^n \), which ensures that at the yield strain, the stress is equal to the yield stress.

From this stress formulation, the work for a given strain is shown below.

\[ \partial W = \frac{\sigma_0 \varepsilon^{n+1}}{n+1} \partial A \] 5.6

Where A is the area of the cross-section

The total work in the beams is calculated by integrating the differential work over the cross sectional area of the beam.

This method is used to compare the work required to achieve the same angle of twist with and without the effect of strain gradient. The ratio of the work from both analyses is also equal to the ratio of applied torque. This is possible because each comparison is made at the same geometry, thus the geometry terms in the torque calculation will cancel. This ratio will be a scaling factor that can be used to adjust the expected torque to achieve yielding without the effect of the gradient of strain, to a torque that does include the effect of the gradient of strain. This scaling can be compared to the measured data by multiplying the scaling factor by the yield stress of titanium. Results of this analysis and fits from the two
strain gradient length scales are shown in Figure 5.2. The two fit lines are shown one with the yield stress of 500 MPa and the other with a yield stress of 1000 MPa.

![Von Mises Stress at 0.2% Plastic Strain](image.png)

Figure 5.2 Yield stress predicted from the strain gradient plasticity model with the experimentally measured yield stress.

Another method to measure the length scale parameters is through a nanoindentation test. The effect of these length scales for indentation can be seen as an increase in measured hardness with decreasing indentation depth. An example of such an observation is shown by McElhaney et al. who indented copper and observed the following [5].
Figure 5.3 Indentation test in copper showing the effect of the gradient of strain on the hardness of the material.

This increase in hardness with decreased indentation depth is attributed to SGP. Several methods exist to determine the length scale parameters from the amount of hardness increase. The larger the increase in hardness with decreased indentation depth, the larger the length scale parameters, making the effect of SGP more dominant.

\[
\frac{H}{H_0} = \sqrt{1 + \frac{h^*}{h}} \tag{5.7}
\]

Where \( H \) is the indentation hardness that is depth dependent, \( H_0 \) is the hardness for a deep indent, \( h \) is the indentation depth and \( h^* \) is the indentation length scale parameter.
The length scale parameters for titanium are measured using a nanoindentation test on 500 micron thick polished titanium samples provided by Tokyo Stainless Grind (Tokyo, Japan). This material is chosen because it proved to be very difficult to perform nanoindentation on the very thin 10 micron thick foil. Results from these indentation tests are shown in Figure 5.4.

![Nanoindentation of Titanium](image)

Figure 5.4 Nanoindentation on a polished CP titanium foil for various indentation depths.

The lack of an increase in hardness implies that the combination of stretch and rotation length scale parameters are very small, making the effect of strain gradient plasticity not measurable. This implies that strain gradient plasticity may
not be the root cause of the increase in observed yield stress. Even further, it is possible to estimate the length scales using Equation 5.8.

\[ h^* = \frac{81}{2} b \alpha^2 \tan^2 \theta \left( \frac{\mu}{H_0} \right)^2 \]  

Where \( \alpha \) is the constant taken to be 0.5 and \( \theta \) is the angle of the indenter tip.

This estimation predicts a length scale for the hardness measurements well below the length scale of the titanium torsion beam. This deems the SGP theory to be less relevant to our observation.

### 5.2 Composite Oxide Model

As mentioned in the introduction, titanium has a tendency to oxidize and provides titanium with many of its interesting properties. As dimensions decrease, the effect of this oxidation can play a more important role since the oxide thickness remains the same, independent of beam width. Having this stiff oxide layer on the outer region of the beam will cause a change in the applied torque necessary to achieve the same deformation, which will scale inversely with beam width. This effect is observed in the experimental data, so using a composite oxide model may be a better prediction for the observed trend in yield stress.

#### 5.2.1 Yield Stress Prediction

Another possibility for the measured increase in the yield stress of the titanium beams is the unaccounted effect of the oxide which exists on the outside
of the torsion beams. This oxide will be much stiffer than the titanium and the location on the outermost section of the beam will cause the most effect. A simple model is used to determine if the effect of the oxide is significant and if it can be used to predict the observed increase in yield stress. The hypothesis assumes that the oxide is only on the other most region of the beam and covers it completely. It also assumes a sharp transition between the oxide and titanium. A cross section of the proposed model is shown in Figure 5.5.

![Figure 5.5 Schematic of the geometry used in the composite oxide model.](image)

Using the material properties of titanium and titanium oxide from the literature, the basic relationship between the beam’s angle of twist and surface stress for a thin rectangular beam in torsion can be used.
Using Equation 5.9 it is possible to determine the angle of twist that will cause the surface of the beam to yield. This model does not include the effect of the oxide, but it is used to develop a baseline prediction for what the angle of twist required to get the outer surface of the beam to yield.

The torque required to get this angle of twist can be calculated knowing the spring constant of the torsion beam. According to Timoshenko [7], the solution of the spring constant for a rectangular cross section in torsion is given by:

$$K_o = \frac{2G_t ab^3}{3L} \left( 1 - \frac{192b}{\pi^5} * \text{Tanh} \left( \frac{\pi a}{2b} \right) \right)$$

5.10

Using this spring constant, the torque needed to achieve the desired angle of twist is simply

$$T = K_o \theta$$

5.11

If there is no oxide on the outside of the beam, the torque would scale with beam width in order to maintain a constant surface strain, but this is not the case.

The effect of the oxide on the outside of the beam can be accounted for by using a composite beam approach. The new spring constant for the composite oxide beam is show below.
\[
K_{\text{oxide}} = \frac{2G_{\text{oxide}}ab}{3L} \left( 1 - \frac{192b}{\pi^2a} \tanh \left( \frac{\pi a}{2b} \right) \right) + \\
\frac{2(G_{\text{titanium}} - G_{\text{oxide}})(a - 2t)(b - 2t)}{3L} \left( 1 - \frac{192(b - 2t)}{\pi^2(a - 2t)} \tanh \left( \frac{\pi(a - 2t)}{2(b - 2t)} \right) \right) 
\]

5.12

This effectively treats the composite beam as a solid oxide beam, with the core replaced with titanium. Another method to analyze the composite beam is to treat the thin oxide layer as a thin walled tube and the titanium core as a solid shaft. Assuming again no interaction between the oxide and titanium, the spring constant can be calculated from the linear combination of the titanium core and thin walled oxide. Such a relationship is shown below in Equation 5.13.

\[
K_{\text{oxide}} = \frac{4(a - t)^2(b - t)^3 t}{(a - t)(b - t)} + \\
\frac{2(G_{\text{titanium}})(a - 2t)(b - 2t)}{3L} \left( 1 - \frac{192(b - 2t)}{\pi^2(a - 2t)} \tanh \left( \frac{\pi(a - 2t)}{2(b - 2t)} \right) \right) 
\]

This formulation is within 2% of the spring constant in Equation 5.12. For simplicity, the former equation will be used throughout this dissertation.

Assuming the oxide does not disturb the strain across the titanium beam, the angle of twist required to place the interface of the titanium and oxide into yielding can be determined from Equation 5.11.

\[
\theta = \frac{\tau_{\text{max}} l}{G_{\text{titanium}}(b - t)} 
\]

5.11

The angle of twist and spring constant for the oxide model can be multiplied together to determine the required torque to place the interface at the yield stress. Similarly, the angle of twist and spring constant for the pure titanium beam model
can be multiplied together to determine the required torque to place the surface of the titanium beam at the yield stress.

The data from the torsion experiments are normalized to provide the stress on the outside of a pure titanium beam. The increase in stress for decreased beam width is simply an indication that the torque required to achieve a 0.2% plastic strain is higher than what is expected to achieve a constant yield stress. This same normalization can be applied to the composite oxide model. The torque required to yield the titanium-oxide interface divided by the torque required to yield the titanium alone will scale from unity for very large beams, to much higher factors for smaller beams. This scale is equivalent to what is reported from the experimental data. In order to convert this scaling factor to a stress, the normalized torque is multiplied by the titanium yield stress of 1100 MPa. This allows the experimental and theoretical data to be plotted on the same figure. Using the following material properties and with an oxide thickness of 100 nanometers, the predicted yield stress matches quite well with the experimental data, shown in Figure 5.6.

\[
\sigma_e = 1100 \text{ MPa} \\
G_{Ti} = 41 \text{ GPa} \\
G_{oxide} = 81 \text{ GPa}
\]
Composite Oxide Model Prediction of the Measured Yield Strength

![Graph showing experimental data and composite oxide model prediction.]

Figure 5.6 Experimental yield stress data with the prediction of the measured data using the composite oxide model.

This model shows it may be the effect of the oxide that is being misinterpreted as a measured increase in yield stress. In order to validate this model, the material parameters chosen need to be verified. First, both the shear moduli are literature values with a range from 81 GPa to 112 GPa for titanium oxide and 41 GPa for titanium [9]-[10]. The yield stress used in this model is higher than the tensile strength of 500 MPa measured by tensile testing. Several different explanations can account for this increase. First is the effect that diffused
oxygen has on the mechanical properties of titanium. It may be due to the processing at elevated temperatures that cause the formation of the oxide, but also increase the yield stress of the material just under the surface. A second explanation for this increased yield stress may be from the effect the oxide has on the material. If there is good adhesion between the oxide and titanium, the oxide may be preventing the titanium from yielding because it is constraining the outer surface. This will also have the effect of increasing the yield stress. Finally, it is interesting to notice that the hardness from the nanoindentation averages 3.3 GPa using the Bercovich tip. In general, it is observed that the yield stress using this geometry is 1/3 the hardness [12]. This gives a yield stress of 1100 MPa for the titanium samples, which matches the yield stress used in this model. All of these concerns cast doubt on using the bulk yield stress for titanium in this situation, making the use of 1100 MPa as the yield stress a practical assumption.

5.3 Summary

In this chapter, two models are investigated to explain the increase in yield stress with decreased beam width. The effects of strain gradient plasticity in this particular material system and size are analyzed, coming to the conclusion that this is probably not the root cause of the strength increase. A different model, which includes the effect of the oxide on the exterior of the beam, is used to better understand this strength increase. Assuming the interface between the oxide and titanium yields at a constant stress, the measured behavior fits with the predicted
behavior. This composite oxide model explains the observed trend in yield stress and can also be used to predict other mechanical behavior in titanium torsion beams.
Reference

Chapter 6: Implications of the Composite Oxide Model

The previous chapter showed the increase in measured yield stress could be attributed to titanium oxide on the exterior of the torsion beams. The effect of this oxide is the increase in applied load over what is considered the yield stress for just a titanium beam. The composite oxide model used to predict this behavior best explains the trend of increasing yield stress with decreased beam width, with the existence of 100 nanometers of titanium oxide on the beam’s exterior. The presence of this oxide and the composite oxide model can also be used to predict other measurable changes in the thin titanium torsion beams. The resonant frequency will change with the beams altered spring constant due to the oxide. This resonant frequency can be used to determine the thickness of the oxide after device processing, but also to measure the growth of titanium oxide due to thermal oxidation.

6.1 Resonant Frequency Analysis

The elastic modulus is not expected to change with length scale because it is one of the most structurally insensitive of the mechanical properties [1]. The elastic modulus is based on the interaction of atoms and should remain valid for devices that are much larger than the atomic scale. Under this assumption, the following development of the resonant frequency for any size beam can be used.
As previously stated, the spring constant for a pure titanium rectangular cross section in torsion is given below.

\[
K_\theta = \frac{2Gab^3}{3L} \left( 1 - \frac{192b}{\pi^2a} \cdot \text{Tanh} \left( \frac{\pi a}{2b} \right) \right)
\]  

6.1

To complete the calculation of the resonant frequency, the polar moment of inertia must also be calculated.

\[
I_\theta = \int \int \int \rho(y^2 + z^2) \, dx \, dy \, dz
\]

6.2

From both of these solutions, the resonant frequency can be determined by,

\[
f = \frac{1}{2\pi} \sqrt{\frac{K_\theta}{I_\theta}}
\]

6.3

This simple analysis ignores the complication due to the chamfered anchor supports and assumes a known density of titanium. Even with these assumptions, this analysis can be used to get a better understanding of how the device is operating.

The geometry of each beam is measured using the FIB. The width of each beam from the top down is measured along with the cross-section of a sample of beams to determine the thickness of the titanium under the etch oxide. The internal width of the titanium beam is 1 micron smaller than the width of the beam measured from the top down, due to the inclusion of the etch oxide. This oxide is very cracked and is not expected to carry any mechanical load.
The ability to predict the resonant frequency of each device along with the measured resonant frequency makes it possible to normalize the raw data by the predicted data to determine if there is systematic error associated with the prediction. Taking each measured resonant frequency, dividing it by the calculated resonant frequency and then plotting it against the beam width, interesting trends can be seen.

![Normalized Resonant Frequency vs. Beam Width](image)

**Figure 6.1** Experimental resonant frequency data normalized by the predicted resonant frequency using Equation 5.12.

It can be noted from Figure 6.1 that with a decrease in beam width the normalized resonant frequency increases, which implies that there is another effect
that is not being accounted for in the current predicted model. An alteration to the model is necessary to better predict how these devices resonate. In contrast, no trend is observed with the normalized resonant frequency and beam length.

6.1.1 Composite Oxide Model

The total stiffness of the beam, with the addition of the oxide, can be modeled as the stiffness of the rectangular titanium section added to the stiffness of a hollow rectangle with the thickness and mechanical properties of the oxide. Since both structures will rotate the same amount, adding both the stiffness of the oxide and the stiffness of the titanium will give the total stiffness. The altered spring constant, Equation 5.9 previously used in Section 5.2.1, can now be used to predict the resonant frequency of the beams.

Using this updated spring constant, the data can be renormalized and replotted as shown in Figure 6.2.
Figure 6.2 Experimental resonant frequency data normalized to Equation 5.9 using the composite oxide model.

This normalization uses a shear modulus of 41GPa for titanium and 81GPa for the oxide with a total oxide thickness of 100 nanometers. These values are identical to those used in the determination of the yield stress adding further evidence to the hypothesis that the increase in measured yield stress is due to the presence of titanium oxide on the exterior of the beam.

6.2 Oxidation of Titanium

Thus far, the oxide thickness has been a constant for both resonance and yield tests. This oxide thickness is a result of the device processing from the deep
etching, oxide etching, and flip chip bonding which was not varied between the resonance and yield test chip fabrication. All of these processing steps formed 100 nanometers of titanium oxide, determined from the composite oxide model. Varying the thickness of the oxide on the torsion beams can further test the validity of the composite oxide model.

One method to change the thickness of oxide of the exterior of the beam is to thermally grow an oxide. This oxide will grow from the initial thickness of 100 nanometers to the final thickness based upon the time, temperature and oxidation gas. The quality of the oxide can vary with oxidation temperature and oxidation gasses. Oxidation under high humidity can cause hydrogen embitterment, and oxidation above 600 °C can cause the oxide to crack or spall [2]. The oxidation performed for the following experiment is at 350 °C in air for up to 2 days. These conditions should prevent spalling, assuming the 100 nanometer initial oxide layer is similar to a thermally oxidized film, which would significantly alter the testing of the resonant frequency since a non-continuous film will alter the mechanical properties of the oxide.

6.2.1 Resonance of Oxidized Titanium Beams

The torsion array is used again in this experiment where the resonant frequency of several titanium devices are measured for several different oxidation times. The oxidation is performed at 350 °C on a hotplate in air. The testing of the resonant frequency of the devices is performed in air after the device has cooled to
room temperature. The test is performed in air, because the damped quality factor of 160 is not much worse than the quality factor in vacuum conditions. The measurement error is calculated from the resonant frequency range from 5 resonance sweeps. Figure 6.3 and Figure 6.4 show the resonant frequency for two devices undergoing thermal oxidation.

![Device 45 Resonant Frequency](image)

**Figure 6.3** Resonant frequency for device 45 for a series of oxidation times at 350 C in air.
6.2.2 Resonance Analysis of Oxidized Titanium Beams

Both devices tested show an increase in resonant frequency with oxidation time. The composite oxide model can be used to calculate the amount of additional oxide from the change in resonant frequency. Assuming the initial oxide thickness is 100 nanometers, Equation 5.9 is used to calculate the oxide thickness based on the measured resonant frequency. The calculated oxide thickness for various oxidation times is shown below in Figure 6.5 for two devices.
Figure 6.5 Calculated oxide thickness from the composite oxide model for various oxidation times.

The thickness of the measured oxide shows reasonable agreement between both devices. They both also show a logarithmic increase in oxide thickness with time which is consistent with the low temperature oxidation of titanium [3].

This method of testing is very sensitive to small changes in the spring constant and mass of the device. The effect of the mass gain due to the growth of titanium oxide can be calculated based on the measured titanium growth rate. The change in polar moment of inertia can be calculated by accounting for the additional mass due to the oxidation. For this analysis, a 25 nanometer thick oxide
film will be assumed to be grown on the surface of the titanium. The additional mass of the oxide will be based on the molecular weights of oxygen and titanium. From Table 1.1 the density of titanium oxide is 4230 Kg/m³. This along with the molecular weight of O₂ (32.0) and titanium (79.9) [2], the change in polar moment from the growth of the oxide can be estimated. Using Equation 6.2, the polar moment of inertia can be calculated for the titanium torsion plate, and for the torsion plate with 25 nanometers of oxide on the top and bottom. The result of this oxidation is a 0.27% change in polar moment, which correlates to a 0.13% change in resonant frequency. This error is approximately the same as the error bars in the resonance test.

This oxidation test also shows the stability of titanium devices at 350 °C in air. The slow increase in resonant frequency may prove to be an advantage or disadvantage in the final performance of titanium devices. One potential advantage is the ability to tailor the transition between ductile and brittle failure on micron length scales. This may allow for the development of devices that can withstand high constant loading, but also withstand high shock loading. Such an ability to change material properties after the fabrication of a device may prove to be a powerful aid in the fabrication process.

6.3 Summary

The composite oxide model has been used to explain the observed higher than expected resonant frequency for newly fabricated devices along with the
growth of titanium oxide due to thermal oxidation. Both of these tests further support the importance of titanium oxide to the fabrication of titanium devices. Not only does the oxide allow for the deep etching of titanium using the MARIO process, but also affects the mechanical properties of fabricated devices. It has become apparent that this oxide will always exist on titanium structures, increasing the importance of understanding the effects, advantages and disadvantages of this oxide on device performance.
Reference:


Chapter 7: Summary

This dissertation has covered the development of titanium MEMS from an initial concept through the fabrication of a micro-mirror device to the measurement of the mechanical properties of fabricated titanium torsion beams. Several new processes were developed to achieve the milestones along the way.

- Development of the MARIO process for the deep etching of titanium
- Further etch development to deep etch sub-micron features
- Titanium oxide deposition and oxide etch to produce an etch mask
- Use of RIE Lag to fabricate sloping electrodes, interconnect lines and bonding frame in silicon
- Ability to stack thin foils of titanium to fabricate released MEMS devices
- Titanium polish to attain sub-micron photolithographic features
- Deep etching completely through titanium foils
- Techniques to bring titanium thin foils through the necessary processing steps without damage

With these techniques it is possible to fabricate both a macro-mirror and micro-mirror device. The dynamic behavior of both of these devices is tested showing that further refinement to the micro-mirror design is required to improve the response time. Decreasing the size of the air gaps between moving and fixed structures increased the amount of air damping. This refinement improved the
settling time without the need of increasing the drive voltage or the use of shaping the input signal.

The resonant response of the micro-mirror device is measured under vacuum conditions to determine the quality factor of titanium torsion beams, which averaged 380. This is a low quality factor when compared to silicon devices, so several attempts were made to improve this quality factor by removing the etch oxide on the outside of the beam using the FIB. Results from this test showed no significant change between quality factors before and after removal of the exterior oxide, implying that the loss is inherent to the titanium beams.

Using a similar process as used in the fabrication of the micro-mirror device, an array of torsion structures is fabricated to measure the effect of beam width and length on yield stress. This test showed no trend with altered beam length, but did show a significant change with beam width. The yield stress significantly increased as the torsion beam width decreased. A strain gradient plasticity model and composite oxide model were used to explain this behavior. After analysis and further testing, including nanoindentation, the composite oxide model proved to be the more suitable model. In order to validate this model, the resonant frequencies of devices with different beam widths were measured under vacuum conditions. The results from this test showed a higher than expected measured resonant frequency than predicted using a pure titanium beam model. Using the same composite oxide model used to explain the increase in measured
yield stress, the resonant frequency of the torsion devices is accurately predicted. This same composite oxide model is used to measure the growth rate of titanium on the exterior of titanium torsion beams. The resonant frequency of several devices measured through several different oxidation times. The change in resonant frequency is then correlated to an oxide thickness using the composite oxide model.

The experimental data and theory used to predict the plastic and elastic properties of titanium torsion beams can be used in the design of future titanium devices. This information is independent on the etch process used as long as it is possible to establish a baseline for the amount of oxide that is present on the exterior of the fabricated sidewalls. The models, experimental data, and processing advancements developed in this dissertation will hopefully help the fabrication of future bulk titanium MEMS.
7.1 Concurrent and Future Work

Titanium has proven to be a very interesting materials system for bulk micromachining. Other members of the MacDonald research group are currently working in different aspects of bulk titanium MEMS. A summarized list is included below.

- Altering of titanium into other compounds such as TiN and TiC through ion implantation or other routes
- 3D titanium electrodes
- Development of a titanium based dielectrophoresis device to separate bioparticles
- Using titanium channels to align biomolecules for x-ray diffraction studies
- Development of bulk titanium based RF devices
- Integration of piezoelectric and of titanium MEMS

Along with the current research into titanium MEMS devices, it is important to continue the research into the basic mechanical properties. The effect of fatigue, creep and further testing on the effect of the mechanical properties due to the effect of an oxide layer need to be known before titanium can fully be used without hesitation as a bulk MEMS material.
In the author’s opinion, the true strength of bulk titanium MEMS is not going to be the replacement of some silicon MEMS device which currently exists, but in allowing new devices to be fabricated which previously were not feasible. It is very difficult to imagine such a device because the design will need to be driven by an unfulfilled need and will most likely not look or have the functionality of MEMS in production today. This device will, perhaps, take advantage of one or many of the differing mechanical, thermal and electrical properties that titanium has to offer. Whatever the future of titanium MEMS, its past has been exciting.
Chapter 8: Appendix

8.1 Macromirror Process Flow

8.1.1 Starting Materials
25 µm thick titanium foil
50 µm thick titanium foil
Standard silicon wafer (level doping not critical)

8.1.2 Processing Tools
Zuis contact aligner
E-beam evaporator
PlasmaTherm SRL 770 chlorine based plasma etcher
MRC flourine based plasma etcher
Endevor sputter cluster
Flip chip bonder
Oxidation furnace

8.1.3 Process Steps

Mirror foil
• Liftoff on the backside of the foil
  o Clean foil in acetone and isopropanal for 5 min each
  o Coat foil with HMDS for 30 sec then spin off
  o Coat with AZ 5214 negative resist 6000 rpm 30 seconds
  o Bake 95 C for 60 seconds
  o Expose 5 seconds
  o Post exposure bake 110 C for 60 seconds
  o Develop AZ400K:DI 1:4 for 60 seconds
• E-beam evaporation
  o Deposit 20 nm titanium
  o Deposit 500 nm gold at 4-5 angstroms per second
• Lift off gold
  o Soak foil in acetone and isopropanal to liftoff deposited metal
• Cut with scissors along deposited alignment marks
• Sputter oxide
- Sputter titanium oxide for 9000 seconds at 2.2 kilowatts, 10 sccm oxygen and 20 sccm of argon

- Pattern oxide
  - Coat with AZ 4330 resist 4000 rpm 30 seconds
  - Bake 95 C for 60 seconds
  - Expose 20 seconds
  - Post exposure bake 105 C for 60 seconds
  - Develop AZ400K:DI 1:4 for 4.5 minutes

- Oxide etch
  - 20 sccm CHF₃, 0.7 sccm O₂ 10 mTorr, 450 volts, 7 hour etch

- Titanium deep etch (with He cooling), 1.5 hour etch or approximately 18 loops.
  - Stabilize A
    - 20 mTorr, 45 sccm Cl₂, 25 sccm Ar, 5 seconds
  - Etch
    - 20 mTorr, 45 sccm Cl₂, 25 sccm Ar, 250 watts, 3 minutes
  - Pump A
    - 1 mTorr, 3 sccm Ar, 6 seconds
  - Stabilize B
    - 20 mTorr, 50 sccm O₂, 5 seconds
  - Oxidation
    - 20 mTorr, 50 sccm, 10 watts, 5 seconds
  - Pump B
    - 1 mTorr, 3 sccm Ar, 6 seconds
  - Restart Loop

- Spacer Foil
  - Pattern etch hole
    - Coat with AZ 4330 resist 4000 rpm 30 seconds
    - Bake 95 C for 60 seconds
    - Expose 20 seconds
    - Post exposure bake 105 C for 60 seconds
    - Develop AZ400K:DI 1:4 for 4.5 minutes

  - Coat backside
    - Coat with AZ 4330 resist 4000 rpm 30 seconds
    - Bake 95 C for 60 seconds

  - Wet etch
    - 1:5 HF:DI water, until titanium is fully etched

  - E-beam evaporation
    - Deposit 20 nm titanium
    - Deposit 500 nm gold at 4-5 angstroms per second
    - Repeat on other side of spacer foil

- Electrodes
• Oxide wafer
  o Grow 1 micron of thermal oxide
• Pattern electrodes for liftoff
  o Clean wafer in acetone and isopropanal for 5 min each
  o Coat wafer with HMDS for 30 sec then spin off
  o Coat with AZ 5214 negative resist 6000 rpm 30 seconds
  o Bake 95 C for 60 seconds
  o Expose 5 seconds
  o Post exposure bake 110 C for 60 seconds
  o Develop AZ400K:DI 1:4 for 60 seconds
• E-beam evaporation
  o Deposit 20 nm titanium
  o Deposit 500 nm gold at 4-5 angstroms per second
• Lift off gold
  o Soak foil in acetone and isopropanal to liftoff deposited metal
Bonding
• Align and bond the spacer foil to the electrodes at 350 C, 10 Kg for 2 minutes
• Align and bond the stack to the mirror foil at 350 C, 10 Kg for 2 minutes
8.2 Micro-mirror Process Flow

8.2.1 Starting Materials
10 μm thick titanium foil  
Standard silicon wafer (level doping not critical)

8.2.2 Processing Tools
CGA Stepper  
Allied High Tech MultiPrep System  
E-Beam evaporator  
PlasmaTherm SRL 770 chlorine based plasma etcher  
Panasonic E640  
Endevor sputter cluster  
Flip chip bonder  
PlasmaTherm SiRIE Bosch etcher  
Oxidation furnace  
MRC flourine based plasma etcher

8.2.3 Process Steps

Mirror foil
- Polish titanium foil  
  - Adhere foil to polishing puck.  
  - Polish on a “red final C” CMP cloth for 20 minutes at 120 RPM  
    using 0.2 μm colloidal silica  
  - Ultrasonicate in micro-organic soap for 20 minutes
- Pattern for liftoff  
  - Clean foil in acetone and isopropanal for 5 min each  
  - Attach foil onto silicon backing wafer with diffusion pump oil  
  - Coat foil with HMDS for 30 sec then spin off  
  - Coat with AZ 5214 negative resist 6000 rpm 30 seconds  
  - Bake 95 C for 60 seconds  
  - Expose 1 second  
  - Post exposure bake 110 C for 60 seconds  
  - Develop AZ400K:DI 1:4 for 60 seconds
- E-beam evaporation  
  - Deposit 20 nm titanium
- Deposit 500 nm gold at 4-5 angstroms per second
- Lift off gold
  - Soak foil in acetone and isopropanol to liftoff deposited metal
- Sputter oxide
  - Sputter titanium oxide for 4500 seconds at 2.2 kilowatts, 10 sccm oxygen and 20 sccm of argon
- Pattern etch mask
  - Attach foil onto silicon backing wafer with diffusion pump oil
  - Coat foil with HMDS for 30 sec then spin off
  - Coat with SPR 220-3, 2500 rpm 30 seconds
  - Bake 115 C for 90 seconds
  - Align to buried gold alignment marks
  - Expose 2.4 seconds
  - Post exposure bake 115 C for 90 seconds
  - Develop MF701 for 60 seconds
- Oxide etch
  - 1 Pa, 40 sccm CHF$_3$, ICP power 500 Wattts, Bias power 400 W for 9 minuts and 30 seconds
- Foil clean
  - Clean foil in acetone, isopropanol, and DI for 10 min each
- Titanium deep etch (with He cooling), 45 minute etch.
  - Stabilize A
    - 20 mTorr, 45 sccm Cl$_2$, 25 sccm Ar, 5 seconds
  - Etch
    - 20 mTorr, 45 sccm Cl$_2$, 25 sccm Ar, 250 watts, 2 minutes 30 seconds
  - Pump A
    - 1 mTorr, 3 sccm Ar, 6 seconds
  - Stabilize B
    - 20 mTorr, 50 sccm O$_2$, 5 seconds
  - Oxidation
    - 20 mTorr, 50 sccm, 10 watts, 5 seconds
  - Pump B
    - 1 mTorr, 3 sccm Ar, 6 seconds
  - Restart Loop
- Oxide etch (MRC)
  - Keeping the same carrier wafer from the SLR tool perform oxide etch
  - 10 mTorr, 10 sccm SF$_6$, 200 Volts, 1.5 hours

Electrodes
- Clean
• 3000 RPM, 5 second acetone, 5 second isopropanal
  • Dehydration bake 150 C for 3 minutes
• Pattern for deep etch
  • 45 second HMDS then spin off
  • Spin on SPR510A at 3000 RPM for 45 seconds
  • Bake at 90 C for 90 seconds
  • Let cool for 1 minute
  • Expose for 1.25 seconds
  • Post exposure bake at 105 C for 60 seconds
  • Develop in MF 701 for 1 minute
• Deep Etch
  • 30 second O2 ash (300 mTorr, 100 Watts)
  • Run Bosch etch morthed from 9-12 watts for 80 loops
• PR Strip
  • Acetone for 2-3 minutes with no sonication
  • Strip in PRX-127 at 80 C for 30 minutes
  • Isopropanal, DI rinse
  • Oxide strip BHF 30 seconds
• Cyclic oxidation (4-5 cycles)
  • 55 minutes 46 seconds wet oxidation at 1050 C (0.5 micron)
  • 1 minute HF
  • 10 minute DI rinse
• Dicing
  • Cover in SPR 220-3 at 3000 RPM for 30 seconds
  • Hard bake at 115 C for 2 minutes
  • Dice
• PR Strip
  • Acetone for 2-3 minutes with no sonication
  • Strip in PRX-127 at 80 C for 30 minutes
  • Isopropanal, DI rinse
  • Oxide strip BHF 30 seconds
• E-beam evaporation
  • 20 nm of titanium
  • 500 nm of gold
• Cleave into single die

Bonding
• Flip chip
  • Place mirror foil on modified upper platen
  • Place electrode die on lower platen
  • Align and bond at 350 C for 2 minutes
Packaging
- Attach die to package
  - Heat package enough to melt solder
  - Place die into package cavity
  - Cool

Wire bonding
- Heat package to 120 C
- Use gold wire to bond the package to the die
- Yes there are 200 wire bonds, have fun!

8.3 ANSYS Input File

/FILNAME,Torsion Mirror ! DEFINE JOBNAME
/PREP7
smrt,off
ET,1,SOLID92
*AFUN,DEG
LEN = 13
UWIDTH = 2
BWIDTH = 2
H = 15
DIST=15
Force = 200
T=-(60+LEN)
MP,EX,1,108E3
MP,PRXY,1,0.30
MP,ALPX,1,8.6E-6

! DEFINE ANCHOR1
K,1,0+T,5+UWIDTH/2
K,2,5+T,UWIDTH/2
K,3,5+T,-UWIDTH/2
K,4,0+T,-(5+UWIDTH/2)
K,5,0+T,5+BWIDTH/2,-H
K,6,5+T,BWIDTH/2,-H
K,7,5+T,-BWIDTH/2,-H
K,8,0+T,-(5+BWIDTH/2),-H

! REFERENCE POINTS FOR CURVATURE
K,9,10+T,50
K,10,10+T,-50
K,11,10+T,50,-H
K,12,10+T,-50,-H

! DEFINE ANCHOR2
K,13,5+LEN+T,UWIDTH/2
K,14,10+LEN+T,5+UWIDTH/2
K,15,10+LEN+T,-(5+UWIDTH/2)
K,16,5+LEN+T,-UWIDTH/2
K,17,5+LEN+T,BWIDTH/2,-H
K,18,10+LEN+T,5+BWIDTH/2,-H
K,19,10+LEN+T,-(5+BWIDTH/2),-H
K,20,5+LEN+T,-BWIDTH/2,-H

!DEFINE LOADING PLATE
K,21,10+LEN+T,DIST
K,22,60+LEN+T,DIST
K,23,60+LEN+T,-DIST
K,24,10+LEN+T,-DIST

!DEFINE UPPER AREA FOR ANCHOR1
LARC,1,2,9,5
L,2,3
LARC,3,4,10,5
L,4,1
AL,1,2,3,4

!DEFINE LOWER AREA FOR ANCHOR1
LARC,5,6,11,5
L,6,7
LARC,7,8,12,5
L,8,5
AL,5,6,7,8

! DEFINE SIDE SECTOINS FOR ANCHOR1
L,1,5
L,2,6
L,3,7
L,4,8

! DEFINE UPPER AREA FOR ANCHOR2
LARC,13,14,9,5
L,14,15
LARC,15,16,10,5
L,16,13

! DEFINE LOWER AREA FOR ANCHOR2
LARC,17,18,11,5
L,18,19
LARC,19,20,12,5
L,20,17

!DEFINE SIDE SECTIONS
L,13,17
L,14,18
L,15,19
L,16,20

!DEFINE LOADING PLATE LINES
L,21,22
L,22,23
L,23,24
L,24,21

!DEFINE AREAS FOR ANCHOR1
AL,1,9,5,10
AL,2,10,6
AL,3,11,7,12
AL,4,9,8,12

!DEFINE AREAS FOR ANCHOR2
AL,13,22,17,21
AL,14,22,18,23
AL,15,23,19,24
AL,16,21,20,24
AL,13,14,15,16
AL,17,18,19,20

!DEFINE AREAS FOR LOADING PLATE
AL,25,26,27,28

!DEFINE VOLUME ANCHOR1
VA,1,2,3,4,5,6
!DEFINE BEAM1
V,2,3,7,6,13,16,20,17

!DEFINE VOLUME ANCHOR 2
VA,7,8,9,10,11,12

VEXT,13,,,-H
VSYM,M,X,ALL,,0,0
VADD,1,2,3,4,5,6,7,8
VSEL,ALL
ESIZE,,10
VMESH,ALL
NSEL,S,LOC,X,T
D,ALL,ALL
NSEL,S,LOC,X,-T
D,ALL,ALL
ANTYPE,0
NSEL,S,LOC,X,0
NSEL,R,LOC,Y,DIST
NSEL,R,LOC,Z,0
F,ALL,FZ,Force
NSEL,ALL
FINISH
/SOLU
OUTPR,BASIC,1
POUTRES,S
SOLVE
FINISH
/POST1