2009

**Magnetically Deflectable Mems Actuators For Optical Sensing Applications**

Matthew Montgomery  
*University of Central Florida*

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MAGNETICALLY DEFLECTABLE MEMS ACTUATORS
FOR OPTICAL SENSING APPLICATIONS

by

MATTHEW R. MONTGOMERY
B.S.E.E. University of Central Florida, 2008

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the School of Electrical Engineering and Computer Science in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Summer Term 2009
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ABSTRACT

In this work, new small deflection magnetic actuators have been proposed, designed, and tested for applications in Surface Enhanced Raman Scattering optical sensors.

Despite the fact that SERS sensors have been shown to increase Raman over ten orders of magnitude for molecular detection, several technological challenges have prevented the design of practical sensors, such as making SERS sensors that can efficiently detect a wide variety of molecules. Since the optimum signal-to-noise in SERS occurs at different excitation wavelengths for different molecules, individual metal nanostructures need to be designed and fabricated for each independent chemical species. One possible solution to this problem is to tune the plasmon resonance frequency of the metal nanoparticles to eliminate the need for individually optimized particles.

In order to achieve a tunable local dielectric environment, and thus allow for control over the resonance frequency of metal nanoparticles, a new SERS sensor geometry is proposed and a large deflection magnetic actuator is fabricated and tested as a starting point for the design of a small deflection magnetic actuator. Using the newly developed SERS geometry and the optimized fabrication processing techniques, two small deflection magnetic actuator beam structures were designed, fabricated, and tested. These devices utilizes an off-chip electromagnet source able to produce a magnetic force of approximately 14 μN on the on-chip nickel film generating deflections up to 139 nm for the straight beam device and 164 nm for the curved beam device.
In the process of characterizing the newly developed small deflection magnetic actuator, an integrated magnetic actuator with electrostatic restoration geometry was conceived. This device was designed to meet the specifications of the small deflection magnetic actuator as well as eliminate the need of an off-chip magnetic source and fully integrate the process atop the metal nanoparticle arrays. Using adhesive iron based magnetic strips as the magnetic drive source, circular NiFe beams with 1, 2, 3, and 4 mm diameters were designed and simulated. Calculations predicted maximum achievable actuation of up to 2.5 μm. Processing steps were laid out for a set of integrated devices as a possible predecessor to the newly designed small deflection magnetic actuator.
Dedicated to all of the people who have taught and guided me thus far on my intellectual and academic journey.
ACKNOWLEDGMENTS

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<tbody>
<tr>
<td>$V$</td>
<td>Volts</td>
</tr>
<tr>
<td>$C$</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>$\varepsilon_p$</td>
<td>Permeability of a particle</td>
</tr>
<tr>
<td>$\varepsilon_p$</td>
<td>Permeability of a medium</td>
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<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
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<td>$\varepsilon_{\text{air}}$</td>
<td>Permeability of air</td>
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<tr>
<td>$\varepsilon_{\text{SiO}_2}$</td>
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<td>$\varepsilon_{\text{Si}}$</td>
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<tr>
<td>$N$</td>
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<td>$R_{in}$</td>
<td>Inner coil radius</td>
</tr>
<tr>
<td>$A_m$</td>
<td>Membrane area</td>
</tr>
<tr>
<td>$h_m$</td>
<td>Membrane height</td>
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<tr>
<td>$N$</td>
<td>Newton</td>
</tr>
<tr>
<td>$Pa$</td>
<td>Pascal</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>AFM</td>
<td>Atomic Force Microscopy/Microscope</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium Tin Oxide</td>
</tr>
<tr>
<td>KOH</td>
<td>Potassium Hydroxide</td>
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<tr>
<td>MEMS</td>
<td>Micro-Electro-Mechanical-System</td>
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<tr>
<td>NdFeB</td>
<td>Neodymium Iron Born</td>
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<td>NiFe</td>
<td>Nickel Iron</td>
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<td>PCB</td>
<td>Printed Circuit Board</td>
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<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy/Microscope</td>
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<tr>
<td>SERS</td>
<td>Surface Enhanced Raman Scattering</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>Silicon dioxide/Silica</td>
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<tr>
<td>TMAH</td>
<td>Tetramethylammonium hydroxide</td>
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CHAPTER 1: INTRODUCTION

1.1 Research Motivation

Over the last few decades, micro-actuators have become a staple in field of MEMS (Micro-Electro-Mechanical-Systems) design. Adoption of these actuators expands vastly from traditional sensors and switches in electrical engineering to non-traditional devices such as microvalves, micromirrors and microsurgery tools in mechanical engineering, chemistry, optics, medicine and other areas. Among the range of mechanisms used to drive such devices, magnetically deflectable micro-actuators have surfaced as one of the primary actuation methods due to several inherent advantages. Magnetic actuators’ ability to generate large deflections in the range of 70 to 100 μm and even up to 1.2 mm depending on device geometry, resistance to harsh environments, low power consumption, and low impedance current-driven mechanism (compared to other mechanisms) have been reported as primary benefits of this actuation type [1-5].

When applications require actuator deflection in the range of less than 10 μm, electrostatic or piezoelectric driven micro-actuators are often employed. Electrostatic actuators are perhaps the most studied driving method as they are easily formed by exploiting the attraction that is produced between two parallel conducting plates that are under an applied voltage [6]. These actuators offer precise control at the expense of high drive voltages, up to 150 V, and non-linear force to voltage ratios [6-8]. Similarly, piezoelectric actuators harness the use of the piezoelectric effect, in which applied electric fields to deposited piezoelectric films induce a mechanical strain in the material.
resulting in a precise actuation of approximately 0.2 \mu m/V for cantilever beam type device geometries [9].

Although electrostatic and piezoelectric driven actuators have demonstrated the ability to produce small deflections, these devices are severely limited when exposed to or used in harsh or temperature sensitive environments. Electrostatic actuators are extremely susceptible to static friction, or stiction, as a result of particulates or moisture entering between the charged plates of the device, which can cause a permanent sticking, reduction in actuation ability, or even break-down [10]. In environments were particulates or moisture may be present, great care must be taken to isolate or seal electrostatic components from the environment. Even when device sealing is implemented, such as in the case of electrostatic actuators used as ink jet nozzle liquid dispensers, moisture effects still often result in failure, requiring complex fabrication techniques to be developed [11]. Equally detrimental conditions can result when piezoelectric actuators are used in temperature sensitive environments. Mechanical stress caused in the process of converting electrical energy into mechanical energy within piezoelectric materials causes heat generation at a square rate with respect to applied voltage, which can generate surface temperatures in the range of 25 °C to 350 °C for applied voltages of 20 to 200 V [12]. In situations where or temperature sensitivity is high or stiction due to uncontrolled environment may be a problem, the use of magnetic actuation may be a viable alternative even for small deflection actuation.
Aforementioned operating limitations must be carefully considered before choosing an appropriate actuation mechanism. In this work, MEMS actuators are developed for optical applications which must satisfy several requirements.

For optical signal enhancement of Surface Enhanced Raman Scattering (SERS) metal nanoparticles, dielectric environment can be actively varied employing a MEMS actuator with small deflection range, which suggests electrostatic or piezoelectric actuation. However, stiction problems practically eliminate traditional electrostatic actuation from this device type as stiction between a charged beam and metal resonant nanoparticles would quickly lead to an inoperable device. Additionally, application of optical sensors of this type may be used to detect temperature sensitive liquid or electrically charged gaseous samples that would require direct contact with the nanoparticles and thus the actuator of the device. As such, neither electrostatic nor piezoelectric actuation would be ideal, since injected liquid or particles in an electrostatic device and the possibility of liquid heating due to heat generation inside the piezoelectric material are in opposition with device requirements.

In order to meet the requirements presented by the SERS device described above, magnetic actuation will be used to produce small deflections at low frequency range which is suited for temperature sensitive optical sensor environments. In this research, a magnetic actuator is designed, fabricated, and analyzed as a basis for design of a small deflection magnetic actuator. Two novel device structures are then presented, which utilize magnetic actuation for small deflections. The design, fabrication, and testing of these devices are analyzed in detail. Finally, an integrated device geometry is presented,
which utilizes both magnetic actuation, as well as an isolated electrostatic actuator for restoration. The design and fabrication steps for such a device are outlined and points of interest are suggested for testing in future work.

1.2 A Brief Introduction to Surface Enhanced Raman Scattering

In order to fully understand the requirements and potential challenges associated with designing a small deflection magnetic actuator to alter the dielectric environment close to SERS metal nanoparticles, it is vital to gain a basic foundation regarding the topics of Raman Spectroscopy, surface plasmons, and how the need for a tunable dielectric environment evolved. This discussion will also help clarify why traditional electrostatic and piezoelectric small deflection actuators will not suffice for such applications.

Raman Spectroscopy is an optical sensing technique used to determine the chemical composition of a sample molecule. In this method, visible or near-infrared light is used to illuminate a molecule of interest, resulting in an inelastic, or Raman, scattering of photons. The Raman scattered light is collected and analyzed to determine the changes in energy states between incident and scattered photons. These energy state changes are then equated to a line spectrum that is matched to known spectrums for a given molecule. Though Raman Spectroscopy is well documented and studied, it is inefficient since only a small portion of scattered light is Raman signal (most of the
signal is elastically, or Rayleigh, scattered light) [13, 14]. As a means of increasing this signal, SERS has been employed.

The SERS technique is based off the unique properties exhibited by resonant surface plasmons. A surface plasmon, as it relates to metal nanoparticles, is the collective electron oscillations possibly exhibited by the metal nanoparticle when it is illuminated by an optical field [15]. As opposed to regular Raman Spectroscopy, in a SERS scenario, the molecule under investigation is absorbed on the surface of the metal nanoparticle. When the incident light used to induce surface plasmon resonance on the metal nanoparticle is of the same frequency as the natural resonant frequency of the surface plasmon, the electric field near the nanoparticle is greatly enhanced [15, 16]. The enhanced electric field increases the intensity of the illuminating light, generating an enhanced Raman signal from the light scattered by the molecule [17]. The Raman scattered light is further enhanced by the increased electric field of the particles [17]. The Raman signal has been reported to show an enhancement factor on the order of $10^{14}$ to $10^{15}$ [14]. This process of increasing the Raman signal is referred to as SERS.

Though the physical mechanisms for building highly sensitive optical sensor are laid out through implementation of SERS, a number of challenges must be overcome to produce practical devices. A significant obstacle to face is that currently, different sensors need to be fabricated with optimized metal nanoparticles, as the best signal-to-noise ratio is obtained at different optical frequencies for each molecule [18]. Constructing individual sensors is both costly and inefficient. One possible solution to
this problem is to tune the plasmon resonance frequency of the metal nanoparticles to eliminate the need for individually optimized particles [15].

Several methods can be employed to tune the plasmon resonance frequency, though one of the most readily achievable is to alter the effective dielectric constant experienced by the metal nanoparticle [15, 16]. This can be seen by analyzing the relation:

\[ \varepsilon_{\text{particle}}(\lambda) = -2\varepsilon_m(\lambda) \]  

(1)

where \( \varepsilon_{\text{particle}} \) is the dielectric function of the metal nanoparticle, \( \varepsilon_m \) is the effective dielectric constant of the surrounding medium, and \( \lambda \) is the wavelength of surface plasmon resonance [15]. Since \( \varepsilon_{\text{particle}} \) is considered constant, altering the dielectric medium in this relation will requires a shift in the surface plasmon resonance frequency (or wavelength), thus providing the sought after tuning mechanism for a multi molecule detection device.

One possible realization of a tunable dielectric environment device for metal nanoparticles is to embed the particle in a low dielectric material (such as SiO\(_2\)) and then move a silicon plate close to the particle, as shown in Figure 1.
In this device scheme, the effective dielectric constant of the medium experienced by the metal nanoparticle in state 1 is:

$$\varepsilon_m = \frac{1}{2}(\varepsilon_{\text{air}} + \varepsilon_{\text{SiO}_2})$$  \hspace{1cm} (2)

where $\varepsilon_{\text{air}}$ is the permeability of air and $\varepsilon_{\text{SiO}_2}$ is the permeability of silicon dioxide. Similarly, when the silicon plate is brought close to the metal nanoparticles as in state 2, the effective dielectric constant changes to:

$$\varepsilon_m = \frac{1}{2}(\varepsilon_{\text{Si}} + \varepsilon_{\text{SiO}_2})$$  \hspace{1cm} (3)

where $\varepsilon_{\text{Si}}$ is the permeability of silicon. Using these effective permeability constants and the properties of silver and gold nanoparticles, one can achieve a theoretical shift of 245 nm (375 nm to 620) for silver and 190 nm (from 495 nm to 685 nm) for gold in surface plasmon resonance [19]. As a result, the theoretical realization of a dielectric tunable device is promising. Designing an actual device to vary the dielectric environment of the metal nanoparticles leads to the interest in using a magnetic actuator for closing the air
gap to the point of contact with metallic nanoparticles, as previously discussed, and thus provides the main motivation for this research.

1.3 Review of Previous Work

Since this research aims to combine several concepts and methods that have not been previously used in conjunction with one and other, to the author’s knowledge, a large range of previous work can be analyzed as part of the prior work related to this topic. As such, a fully comprehensive review is not practical; therefore, several key works have been selected that capture the essence of the different aspects pertaining specifically to magnetic actuators, small deflection of such actuators, off-wafer electromagnet driven magnetic actuators, other types of SERS optical sensors, and previously developed tunable dielectric environment based devices for SERS applications.

Classically, magnetic MEMS actuators have been used for large deflection devices. This is due to the ease at which a strong magnetic field can be generated to drive the actuator over the large distance. One of the most well documented magnetic MEMS actuators is the micromirror structure. This device is commonly used to control the path of light (typically laser beams) in optical switches or other optoelectronic devices, where a large deflection is required in order to alter the path of a laser beam and redirect it in the desired direction [20]. Three micromirror actuator structures, comprised of a single beam anchoring, a double beam anchoring, and a torsion beam anchoring, as
shown in Figure 2, are presented by Cui et al. which exhibit different actuation properties [20]. All three structures are modeled, showing that the single beam is the most flexible structure, that the double beam is the most rigid, and that the torsion beam was found to exhibit a smaller rigidity than the double beam structure with the possibility of skewed deflection.

Cui et al. continue by exploring the different design parameters available for adjusting the rigidity of a given beam structure. They divide the criteria into two main categories, magnetic force and beam flexibility. In a fixed magnetic field, altering the magnetic volume on the micromirror structure will result in different rigidities. On the micromirror, this can be accomplished by increasing the mirror plate area (and thus the
area of the magnetic material) or increase the thickness of the magnetic coating [20]. Figure 3 shows simulated results of the magnetic force generated in a given magnetic field for several mirror plate magnetic areas and thicknesses. From the plot one can see that there is a higher sensitivity to magnetic area, thus altering the dimensional area will provide a greater sensitivity in rigidity adjustment than magnetic thickness variations.

![Figure 3: Generated Magnetic Force at Different Magnetic Fields for Different Magnetic Material Dimensions [20]](image)

With respect to adjustments in beam flexibility, Cui et al. assert the intuitive relation that increasing beam length or decreasing beam cross section will increase flexibility [20]. In essence, by altering plate area, magnetic material thickness, beam length, and beam width, one can alter the rigidity of a magnetic actuator structure. All of this information is vital as it provides a foundation of parameters that designers can use to produce magnetic beam actuators of similar style which are customized to their needs.
One of the smallest deflection magnetic actuators reported is the magnetic membrane structure presented by de Bhailis et al, who sought to produce a device with a targeted deflection of 10 μm [4]. To accomplish this aim, a novel design was employed (as shown in Figure 4) that is similar in concept to a standard MEMS pressure sensor.

![Figure 4: Structure of Magnetic Micro-actuator [4]](image)

A double side polished silicon substrate is used as the base of the device and a thin 0.175 μm of silicon nitride is deposited on both surface sides to act as both a masking layer and rigidity enhancement support for the membrane structure. A square 8x8 mm<sup>2</sup> membrane is patterned in the silicon nitride and then defined in the silicon bulk to be 25 μm thick, through the use of wet chemical etching in a KOH solution. A rare earth NdFeB magnet of approximately 5x5x2 mm<sup>2</sup> is placed on the top side of the membrane to serve as the magnetic material that the drive coil can interact with to deflect the membrane. Several different electroplated coils were designed and each fabricated on a separate device to produce a 15 mN force 2.5 mm above the coil at an applied drive current of 1 A. The coils are plated on separate PCBs and attached to the bottom side of a given wafer, thus completing the device fabrication. A summary of the six fabricated device conditions are shown in Table 1, where \( N \) is the number of turns and \( R_{in} \) is the inner radius of the coil and \( A_m \) is the area and \( h_m \) is the height of the membrane.
Each of the fabricated test device conditions were modeled in ANSYS® to determine their simulated deflection under full drive current. Similarly, the actual test devices were tested under the same conditions. The results of the simulated and measured deflections were compared at 1 A drive current as shown in Table 2.

For the simulated model, both a point force at the center of the membrane and a constant pressure distribution were investigated, but the pressure distribution was found to produce deflections much closer to expected values, as it models the real force.
distribution more accurately (Table 2 modeled values represent pressure distributions). Looking at the modeled vs. measured values, a good correlation is found in all samples except for 3 and 4, resulting in a deflection predictability within 20% when these samples are ignored. Samples 3 and 4 were found to have a rough surface etching due to the uniform etching nature of KOH, which could reduce the membrane by 2 μm. Correcting the simulations for samples 3 and 4 to reflect membrane roughness, modeled deflections for samples these samples change to 13.08 μm and 5.41 μm respectively, and thus bringing the samples into the 20% predictability range.

The use of an off-chip electromagnet to drive magnetic actuators has been studied extensively in several previous works [3, 5, 21]. In Cho’s work, a magnetically driven torsion beam optical scanner was designed, fabricated, and tested. The beam and mirror plate of this device are constructed out of a silicon wafer substrate using standard MEMS fabrication techniques. A permanent magnet array is deposited on the back, non-optically polished side of the mirror plate using the bumper filling method developed in this work [3]. These magnets serve as the on device magnetic material needed to interact with the off-chip electromagnet. The electromagnet and mirror structure are packaged together in a way that allows for a constant air gap between the array and the electromagnet at static rest (0 A drive current), as shown in Figure 5 (a).
Figure 5: (a) Magnetically driven optical scanner structure, (b) Deflection vs. electromagnet current in the optical scanner [3]

From device testing, increased deflection can be controlled by increases in supplied electromagnet current. Deflections up to 70 μm at 60 mA were obtained, with a minimum deflection appearing to be in the range of 12 μm, as shown in Figure 5 (b). These results are significant because they demonstrate the ability of precision current controlled magnetic deflection using an on device permanent magnet and an off-chip electromagnet driving source.

Another form of a tunable dielectric environment device for optical SERS sensors applications is a pneumatically actuated Polydimethylsiloxane (PDMS) flexible membrane structure, such as the one proposed by Londe [22]. In this device, as shown in Figure 6 (g), a PDMS membrane with a PDMS slab which holds metal nanoparticles is deflected by removing air from the inner cavity of the device, causing the particles to touch the silicon wafer after a sufficient negative pressure is achieved. To determine the optimized dimensions for the device, an ANSYS® simulation was carried out. Fabrication starts (Figure 6 (a)) with the formation of a 200 μm PDMS membrane on a
hydrophobic glass support slide that is to be removed later in processing. The 75 μm PDMS slab that is holding the particles is formed atop a separate hydrophobic glass slide (Figure 6 (b)), then it is inverted and bonded to the membrane, and after bonding this glass slide is removed (Figure 6 (c)). The metal nanoparticles are subsequently embedded on the PDMS slab (Figure 6 (d)).

Figure 6: Process for Pneumatic Actuated PDMS Membrane [22]
A 100 μm circular PDMS structure is formed on a separate glass slide (Figure 6 (e)), then it is inverted and bonded to a silicon wafer, and after bonding this glass slide is removed (Figure 6 (f)). The device is completed by inverting the PDMS membrane/particle structure, bonding it to the support structure, and removing the support slide (Figure 6 (g)).

Though this proposed device shows great potential, it is plagued by the inherent difficulty of metal nanoparticle imaging. As in any SERS device, a fairly unobstructed optical path must be present to image the metal nanoparticles in order to detect changes in surface plasmon resonance. In this pneumatic PDMS membrane structure, the only possible optical path is through PDMS material, since the particles are completely surrounded by PDMS or silicon and silicon is an almost complete optical reflector. Imaging through PDMS in this device structure is rather challenging as imaging must take place from either the top or side. From the top, imaging is limited by the thick PDMS membrane and nanoparticle slab while focal distance is hard to maintain as the distance changes as the membrane is actuated. Similarly, from the side, inline imaging problems are encountered as focus is attempted to be maintained over the entire distance of actuation through PDMS. The magnetically actuated device presented in this research will aim to eliminate these imaging problems by providing an almost completely unobstructed optical pathway to stationary metal nanoparticles.
CHAPTER 2: LARGE DEFLECTION MAGNETIC ACTUATOR

2.1 Introduction

Large deflection magnetic micro-actuators have been well studied, primarily for their application in micromirror or optical scanner design [1, 3, 5, 20, 23]. Several properties of a large deflection magnetic actuator, particularly specific micromirror designs, allow it to serve as a good base point for a tunable dielectric environment device for applications in SERS optical sensing.

One of the main advantages of this device structure is that inherently, a large deflection actuator is in fact a two state binary actuator. State 1 consists of the mirror at rest under no magnetic deflection and in-line with the wafer plane. Sate 2 consists of the mirror being fully deflected under maximum magnetic force and out of the wafer plane. If a large deflection micromirror design is used and one side of the mirror plate is left as bare silicon, the silicon plate needed in Figure 1 for SERS sensing has been pseudo-created. Combining the mirror structure with a surface plasmon resonant metal nanoparticle so that they are in contact when the mirror is at rest (under no magnetic force) yields the state 2 dielectric environment depicted in Figure 1. Similarly, if the position of the mirror and metal nanoparticles are held in a fixed reference frame and full magnetic deflection is applied to the mirror, the particles will not experience any dielectric contributions from the silicon mirror plate, thus yielding the state 1 dielectric environment depicted in Figure 1.
Another main advantage of first designing a large deflection magnetic actuator is that this device can be used to optimize fabrication and processing conditions, since similar processes are already well documented and have been achieved for similar device types. Selection of wet chemical etchants for bulk micromachining, photoresist and lithography conditions, and specialized fabrication techniques such as Deep Reactive Ion Etching (DRIE) will be analyzed during the design and fabrication of this device. Required amounts of on-chip magnetic material will also be investigated during processing. Additionally, the optical compatibility as it relates to surface smoothness’s of dielectric plates, scattering of imaging light will be determined. Finally, optimal beam dimensions and locations as they relate to stiffness and fabrication ability will be considered during this process for future beam geometries.

2.2 Design and Modeling

Taking into consideration the limitations encountered by previous tunable dielectric environment device for applications in SERS optical sensing, such as the PDMS device proposed by Londe and discussed in Section 1.3 of this work [22], before any magnetic actuator designers were proposed, the actuator geometry with respect to the metal nanoparticles was designed in order to ensure a clear optical imaging pathway. Constraints for new geometry included a complete blocking the optical imaging path from the side of the device which contains the micromirror, since the mirror plate is to be comprised of an optically opaque material, such as a metal or silicon, imaging access
from the side would be completely obstructed when the device is at rest. Taking this into consideration, imaging needs to take place from through the material the metal nanoparticles are embedded on or through some optical window designed into the device. It was decided that the easiest most versatile way to image was to embed the particles on a thin cover slip or glass slide and image through this material as it provides little optical scatter and would not obstruct the imaging of any surface plasmon resonance.

The general geometry decided upon for the magnetic actuator is shown in Figure 7. In this figure, the metal nanoparticles (represented by the yellow half spheres) are embedded in a glass slide and the slide is attached to a silicon wafer.

![Figure 7: Schematic Representation of the Magnetic Actuator Geometry with respect to the Surface Plasmon Resonant Metal Nanoparticles](image)

The wafer has been thinned and released to produce a movable beam structure. The beam structure is coated in a magnetic nickel film, which is originally at rest. When a magnetic force is applied, the beam structure is pulled away from particles. Imaging in this schematic would be conducted from the top, through the glass slide. Unlike the pneumatic PDMS device, in this geometry, the particles will not be moving, only the
beam. Thus, the focal distance will remain constant at all time, easing the optical imaging as a constant focus can be maintained. Another beneficial aspect of this geometry is its reversibility. If for some reason imaging cannot be conducted from the top, the device can be inverted so that silicon structure is on top. In this configuration, imaging can be conducted from the bottom through the glass slide.

To simplify the design, one of the four micromirror structures, particularly the long torsion beam structure, as shown in Figure 8, used to fabricate a rotating out-of-plane micromirror was selected for the basis of this design [23].

![Figure 8: Long Torsion Beam Micromirror Structure](image)

The structure consists of a 400x400 μm² mirror plate, two 800x5 μm beams attached to the bottom of the plate, and two 500x100 μm anchoring posts connected to each beam and the bulk of the device. These dimensions are summarized in Table 3. This device was employed because it was a basic beam design likely to produce a significant amount of out-of-plane deflection [23].
Table 3: Dimensions of Micromirror Structure

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Dimension of mirror plate (μm²)</th>
<th>Dimension of the beam (μm)</th>
<th>Dimension of the post (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long torsion</td>
<td>400x400</td>
<td>800×5</td>
<td>500×100</td>
</tr>
</tbody>
</table>

2.3 Fabrication

The fabrication steps for a large deflection magnetic binary tunable dielectric environment device are shown in Figure 9. Starting from a 3” double-side polished Si wafer (n type, [100] orientation, thickness 381 ± 25 μm), an SiO₂ layer was thermally grown on the Si wafer on both sides by a wet oxidation process (Figure 9 (a)). The thickness of the thus grown SiO₂ was 5200 Å. A positive photoresist (Shipley 1813) was spin-coated and baked on the top side of the wafer. Resist exposure was carried out on an EVG® 620 double-side mask aligner. The beam structure pattern was transferred to the photoresist. The SiO₂ was then patterned using a buffered oxide etchant (Figure 9 (b)). Subsequently the backside alignment was carried out, followed by the second exposure step. The wafer was put into a special wafer holder for SiO₂ patterning, where the top layer was sealed and protected by the holder (Figure 9 (c)). After oxide removal the wafer was cleaned with acetone, methanol and DI water to remove the photoresist, and dried by nitrogen gas.
Figure 9: Fabrication Steps for Large Deflection Magnetic Actuator: (a) thermal oxidation, (b) SiO$_2$ patterning (Mask 1), (c) Backside SiO$_2$ patterning (Mask 2), (d) Backside Si wet-etching, (e) Releasing (DRIE), (f) SiO$_2$ removal, (g) Ni deposition.

For the backside bulk wet Si etching, tetramethylammonium hydroxide (TMAH) was selected (as discussed in Section 2.4.1) to achieve a uniform smooth surface. The etching was conducted at 80 °C with stirring to obtain the desired membrane thickness of 50 μm (Figure 9 (d)). After wet etching is complete, the top side of the wafer was released using DRIE (Figure 9 (e)). All SiO$_2$ was removed following the release of the structure (Figure 9 (f)). Finally a magnetic film (Ni) was deposited on the back side.
2.4 Measurements and Results

Fabrication of the device revealed several processing challenges that needed revisions in order to obtain both a working device and an optimized process for future designs. In this section, magnetic material requirements, working device results, and two process optimization experiments will be covered.

One of the primary difficulties in achieving a working device related to generating enough magnetic interaction between the on chip magnetic material and the off-chip magnetic driving source in order to generate actuation. Fabrication step g from Figure 9 required the deposition of an on chip magnetic film layer to interact with the off-chip magnet. Nickel was selected as the magnetic material to be deposited. To increase adhesion between the silicon substrate and the deposited nickel, a chromium seed layer would first be used. It was decided that thermal evaporation would serve as the deposition method as it would allow for the quick uniform consecutive deposition of each material. Approximately a 10 nm layer of chromium was evaporated on the backside of the device followed approximately by a 100 nm layer of nickel. The devices were then tested to see if deflection was achievable by moving a large permanent magnet in the close vicinity to the actuator. No movement was observed. Several other magnets were then used to test for deflection, including several high flux density rare earth magnets and still no deflection was observed. From this testing it was determined that the volume of the deposited nickel film was not large enough to properly interact and cause deflection with the off-chip magnet.
Given that approximately maximum achievable thickness of thermally evaporated nickel had already been reached and found to be inadequate, another deposition method would be required to generate a thicker metal layer. It was estimated that a 1 μm layer of nickel would be required for proper magnetic interaction. Given the available options for nickel deposition, electroplating was selected as a 1 μm layer could easily be achieved in several minutes, using a simple experimental setup that requires few specialized materials or equipment. A new device with no previous nickel coating was electroplated with approximately a 1 μm thick film. This device, as shown in Figure 10 (a), was then tested to see if deflection was achievable using the new deposition method by moving the same large permanent magnet in the close vicinity to the actuator.

![Figure 10](image)

Figure 10: Large Deflection Magnetic Actuator (a) At Rest Under No Magnetic Deflection, and (b) Deflected in the Presence of a Magnetic Field

In the presence of the permanent magnet driving source and thus a magnetic field, significant out of plane deflection was observed under microscope inspection as seen in
From this experiment, it was shown that a large deflection magnetic actuator can be achieved using the optimized fabrication process and that a 1 μm thick on chip magnetic film is able to produce enough magnetic interaction with an off-chip magnetic source to cause device deflection.

2.4.1 Wet Chemical Etching Experiment Results

In order to yield consistent smooth backside beam structures, much detail was taken in optimizing the bulk micromachining process. Wet-chemical etching was selected to achieve wafer thinning in this process. Two of the most commonly used silicon bulk anisotropic wet chemical etchants are KOH and tetramethylammonium hydroxide (TMAH). Both solutions are commercially available with KOH typically being a less expensive option and thus more economically beneficial for long term heavy use, though, surface finish for KOH has been noted to be poor [24]. In order to determine if surface roughness would be suitable for a consistent beam thickness, as repeatability of device fabrication is highly important, as the small deflection device will be based on these fabrication results, and uniform magnetic material deposition. In this experiment two wafers thinned to approximately the same depth, one in KOH and one in TMAH as shown in Figure 11.
From these microscope images, even at just 10x magnification, surface roughness variations of greater than 2-4 μm can be seen in the KOH etching, while no significant surface roughness can be seen from the TMAH etching. As a result, it was decided that even at higher cost, TMAH is required for membrane thickness consistency, and ease of metal deposition.

Both the etch rate and etching quality of TMAH were found to be highly sensitive to any variations in solution temperature. For this experiment, commercially available 25% w/w aq. soln. Tetramethylammonium hydroxide solution from Alfa Aesar® was used. It was decided that the solution would not be diluted to help insure concentration consistency since more solution would need to be added over the course of many device fabrications. The target temperature selected was 70 °C, as it was reported to yield a moderate etch rate of approximately 20 μm/hr for a 25% concentration [24]. In order to achieve a desired thickness in this and future experiments, time stop methods would be
In order to confirm the etch rate and test for reproducibility, TMAH etching was conducted.

In the original TMAH etching experiment, a hotplate was used as the etch bath heating source. A large aluminum caldron was atop the hotplate and filled with silicon oil to help insulate against temperature variations. A beaker filled with the TMAH solution was placed inside the caldron, nearly completely submerged in the silicon oil, and magnetically stirred. The hotplate was configured to yield a TMAH solution temperature of 70°C. The wafer was placed in the backside isolation holder and submerged in the solution. Etchant temperature was recorded every two to three hours, and large variations of up to 10 or more degrees Celsius were found. Additionally, significant etchant solution evaporation was experienced. Optical microscope depth of focus methods [25] were used to determine the etch depth at several points over the duration of the etching measurement as shown in Figure 12.

Figure 12: TMAH Etch Depth vs. Time for Original Etch Bath
For the 35 hour etching period, an etch depth of 200 μm was observed, yielding an average etch rate of 5.71 μm/hr. This significantly lower etch time from the reported 20 μm/hr can be attributed to the significant temperature variations. Similarly, etching line quality was effected by the large temperature variations as shown in (Figure 13 (a)).

![Figure 13: TMAH Etching in (a) Unstable Temperature Bath, (B) Stable Temperature Bath](image)

To overcome the temperature fluctuation and solution evaporation problems encountered, a new etching setup was designed. For the heating source, a commercially available wet bath was used. This bath was selected due to its integrated thermal feedback controller, which helps maintain a constant solution temperature. The bath was filled with thermally resistive aluminum pellets that would further help to maintain a desired temperature upon heating the pellets to that temperature. The beaker was almost fully submerged in the pellets and fitted with a water-cooled condenser top, to recollect TMAH evaporated solution. Magnetic stirring of the TMAH solution was used. The entire bath was also covered with an acrylic dome to further reduce air flow over the top surface of the bath.
Once a highly stable etch bath environment was created, TMAH etch rate experiments were conducted to confirm reported rates and establish a base line measurement directly on this system. For testing of the new etch bath setup, a wafer was placed in the TMAH solution and the temperature was recorded. Fluctuations in temperature did not exceed ± 2.5 C. Etch depth was also checked using the same methods as before, and in the 16 hour 25 minute etch period, etch depth of 220 μm was observed, yielding an average etch rate of 13.4 μm/hr. Etching quality appeared to be significantly enhanced over the results obtained in the previous setup, as shown in (Figure 13 (b)), producing smooth feature lines and edges.

2.4.2 DRIE and Optical Surface Smoothness Results

In the fabrication process of the large deflection magnetic actuator, DRIE is used as the releasing mechanism in order to produce free moving actuating beam structures. DRIE offers the benefit of extremely anisotropic, high aspect ratio, uniform etching, though the etch rate of this method is highly dependent on both the surface area and material being etched. Therefore, to effectively employ DRIE, the process must be specifically optimized for roughly the amount of surface area and the type of material being etched, including all masking materials. An ADIXEN® AMS100-128 DRIE system was used for the release process. For deep (greater than 100 μm), high aspect ratio trenches in silicon, 10 μm/min has been observed, as well as 0.3 μm/min for bulk
wetly grown SiO₂ and less then 1 μm/min for AZ P4620® photoresist used as a masking materials.

In this device, the DRIE needs to be used on the bulk surface area of the device, thinning the entire topside of the wafer (50 μm) till the protected beam features were freely suspended. For the first DRIE experiment, a worst case scenario was designed. It was determined that for any future experiments, the maximum beam thickness employed would not exceed 100 μm. Based off of the oxide etch rate, an oxide mask of at lest three microns thickness would be needed to mask for this etching depth if the etch times for surface bulk etching were close to that of the silicon trench etch rate. Although growing a 3 μm wet thermal oxide takes a long time, as shown in Figure 14, it was decided to attempt this oxide growth without resorting to the use of photoresist as a masking layer in the initial experiment.
Upon trial of a 100 μm bulk silicon etch, the etch rate of bulk surface area silicon was found to approximately half of the deep trench rate, or about 5 μm/min. As a result, the total etch time exceeded the masking oxide. Since beams for this device and small deflection devices are or will be in the range of 50 to 100 μm, full masking with just oxide will not be possible at this lower etching rate. Before photoresist masking was used, an investigation into the optical quality of DRIE exposed silicon was conducted. If optical quality was sufficient to distinguish surface plasmon resonance from a DRIE exposed silicon surface, complete masking of silicon regions would not be needed and a portion of the wafer/beam thinning could be completed by this dry etching.
For this experiment, a dummy wafer with SiO$_2$ patterned beam structures was used. The device was exposed to DRIE for 5 minutes, which is not long enough to release any of the devices. A bright and dark field image of the etched device is shown in Figure 15 (a) and (b) respectively.

Figure 15: (a) Bright Field, and (b) Dark Field Images of DRIE Exposed Silicon and SiO$_2$
In Figure 15 (a), the bulk yellow region corresponds to bare silicon, while the blue beam region corresponds to SiO₂ covered silicon. In Figure 15 (b), the scattering intensity of light is much more apparent. One can see that a low scattering intensity is seen from the SiO₂ beam region while a much higher scattering intensity is seen from bulk silicon region. This is further observed in Figure 16. In Figure 16 (a) and (c), very little scattering is observed in the SiO₂ region except for several large and small reflections caused by dust particles that have fallen on the device. On the other hand, in Figure 16 (b) and (d), a very granulated surface is observed in the bare silicon region, resulting a very bright high scattering image.

Figure 16: Dark Field Images of DRIE (a) Focused on SiO₂ Region, (b) Focused on Silicon Region, (c) Magnified SiO₂ Region, and (d) Magnified Silicon Region
Quantitative data regarding the surface smoothness of the two regions was obtained through the use of Atomic Force Microscopy (AFM). A 5x5 μm² section of the each region was scanned as shown in Figure 17. For the SiO₂ region (Figure 17 (a)), only very small uniform bumps can be seen from the image and a root-mean-square (RMS) surface roughness of 7.16 nm was recorded. For the bulk silicon region (Figure 17 (b)), more profound variations in the surface are observed and an RMS surface roughness of 13.4 nm was recorded. From this and the dark field information, it can be concluded that the resulting surface roughness and scattering intensity of DRIE exposed silicon is relatively large and would thus make it hard to resolve surface plasmon resonance of metal nanoparticles.

Figure 17: AFM Image of DRIE Exposed (a) SiO₂ Region with surface roughness \(R_{\text{rms}}=7.16\) nm, and (b) Bulk Silicon Region with \(R_{\text{rms}}=13.4\) nm

From the bulk DRIE etch experiment and the optical smoothness experiment, it can be concluded that neither oxide masking alone nor exposure to DRIE are viable methods for processing. This means that thick photoresist masking must be used in...
DRIE processing. A final DRIE experiment was conducted to test both the masking ability of photoresist as well as the etch rate of medium size silicon region, between the size of a narrow trench and the bulk surface area. For masking, 1 μm layer of SiO₂ would be used to define the region to be etched as well as protect the bulk surface area of the silicon. AZ P4620® photoresist was selected as the primary masking material as the etch rate was already known to be low and could be easily coated in a 22 μm thickness, thick enough to mask up to the maximum 100 μm depth. The back side of the wafer was coated along approximately the outer 5 mm and through the center with AI Technology® thermal grease to prevent photoresist melting. DRIE was applied and the etch rate of the medium sized silicon region was found to be 8 μm/min. Thermal grease and photoresist were removed with acetone and mechanical scrubbing. A buffered oxide etch (BOE) was used to remove the protective oxide, leaving an optimized DRIE processed wafer with an optically smooth topside. This process will be used as the basis for release design in the small deflection magnetic actuator.

In these DRIE experiments, it was also found that masking beams of small width (5 μm in this case) was challenging, as the selectivity between the bulk and beams was low, resulting in many beams structures being either completely (Figure 18 (a)) or partially lost (Figure 18 (b)) in the etching process. A two part solution was devised for the future small deflection magnetic actuator design. First, minimum beam widths would be made significantly larger than the 5 μm thick beams in the large deflection device. This alone should resist the DRIE while providing some of the much needed mechanical stiffness for a small deflection device. Additionally, instead of bulk surface DRIE
etching, the medium sized gaps would be used, reducing the etch time needed and facilitating ease of masking.

![Figure 18: (a) Lost Device, and (b) Lost Beams (residual backside oxide holding deflection plate) due to insufficient DRIE Masking](image.png)

2.5 Conclusion

In this design, a large deflection magnetic actuator has been achieved and the fabrication process optimized for future small deflection actuator designs. A new dielectric altering environment for SERS optical detection has been presented for use with both large and small deflection actuator devices. This new geometry overcomes the inherit limitations found in pervious SERS sensor designs. A fabrication process was developed which employs specially optimized wet-chemical etching, DRIE, and electroplating. A new wet-chemical etch bath was designed to provide ±2°C temperature stability as well as condenser recollection of evaporated etchant. TMAH etchant was fully characterized on this new setup and was found to have an etch rate of approximately $13.4 \, \mu m/hr$ at $70^\circ C$ for a 25% concentration. Similarly, DRIE was fully characterized for
bulk silicon thinning and medium silicon surface area trench etching. Etching rates of 5 μm/min and 8 μm/min were found for bulk and medium silicon regions respectively. In these DRIE processes, it was found that thick photoresist masking layers such as a 22 μm thick resist achievable with AZ P4620® are needed in addition to silicon dioxide masking layers, as silicon dioxide layers alone are unable to provide required masking. Initial testing of actuator devices with thermally evaporated on-chip nickel magnetic material were found to be inoperable due to inadequate amounts of magnetic material present in the 100 nm layer of nickel film. As a result electroplating was employed and found to provide enough magnetic interaction when a 1 μm plating layer is formed.
CHAPTER 3: SMALL DEFLECTION MAGNETIC ACTUATOR

3.1 Introduction

Small deflection magnetic micro-actuators have seen limited use in applications, with only a few reported devices employing this actuation method for sub 10 μm deflections [4, 27]. This is likely the result of an abundance of other well documented deflection methods available which are able to accomplish these small deflections for almost all needed cases. For the particular case of a tunable dielectric environment for SERS optical signal enhancement, the two most common small deflection methods, electrostatic or piezoelectric actuation, are inherently incompatible, as electrostatic actuators can become permanently stuck to conductive metal nanoparticles upon contact while piezoelectric actuators can transfer residual heat during contact to molecules being imaged on the metal nanoparticles surface.

Similarly, for a highly tunable dielectric environment, a large deflection magnetic actuator will also be insufficient, as it will only provide the two binary environment states shown in Figure 1 and discussed in Section 2.1. Designing a tunable actuator will allow for the generation of other effective dielectric environments other than the two given in equations (2) and (3). If the silicon plate in Figure 1 is brought to an intermediate distances between the two states shown, the effective dielectric environment of the medium experienced by the metal nanoparticles will take the mathematical form of:

$$
\varepsilon_m = a \varepsilon_{\text{air}} + b \varepsilon_{\text{SiO}_2} + c \varepsilon_{\text{Si}}
$$

(4)
where $a$, $b$, and $c$ represent the fractional contributions of each of the three respective dielectric constants experienced by the metal nanoparticle at a given deflection. This broader tuning range of the dielectric environment should facilitate the large shifts needed in surface plasmon resonance and thus the achievement of a multi-species SERS optical detector.

In the specific case of tunable dielectric environment actuators, no known small deflection magnetic actuators exist. In the following sections, the design, modeling, fabrication, measurement, and analysis are presented for this unique device application.

### 3.2 Design and Modeling

Using the knowledge gained from the fabrication of the large deflection magnetic actuator, design of the small deflection magnetic actuator will employ the newly optimized process as well as newly designed beam structures. Since all fabrication processes were optimized for the geometry developed in Figure 7, and no foreseeable limitations can be determined for this design, the same geometry will be used as the basis for the small deflection actuator.

To determine the design specifications that would need to be met in this device fabrication, the desired requirements were first outlined. The primary requirements concerned the deflection criteria. From an optical standpoint, deflection larger than approximately 1 to 2 μm will result the metal nanoparticles experiencing a complete air gap, like the state 1 depiction in Figure 1, therefore the target maximum deflection should
be at or below this point. Deflection in the rage of 50 nm to 0.5 μm would be most desirable. For the magnetic driving force, any current driven source, either on or off-chip, which would allow for precise current control of the output magnetic field would be acceptable.

The challenge presented by these design requirements is generally in this case, the smaller the deflectable control, the higher the resolvable resolution of surface plasmon resonance shifts. One does not want to design a beam that is so stiff that movement is unachievable in an attempt to produce very precise deflections. On the other hand, one does not want to design a device that is easily movable as too much delectability will render the device useless. In an attempt to avoid either of the two extremes, this device will aim to produce a maximum deflection at the useful maximum requirement of 1 to 2 μm. In this scenario, if a device is produced that is too stiff, possible beam thinning can be attempted through the use of etching techniques to reduce beam thickness or a larger magnetic force can be used. If on the other hand, the device exceeds the maximum deflection, a smaller magnetic force can be used to yield smaller deflections.

As a starting point in the design of unknown parameters, the magnetic drive source would be selected first. From the selection of the magnetic source, the generated magnetic interactive force with the 1 μm thick on-chip magnetic nickel film optimized from the previous large deflection actuator experiment can be determined. From this determined force, the required thickness of the actuator can be selected in a way to achieve a deflection in the desired range.
In the selection of a magnetic drive source, a variable magnetic field is required for tuning the device between intermediate deflection states, thus eliminating the possibility of using a regular permanent magnet. Instead, a current driven electromagnet would fill these requirements. A commercially available electromagnet would be chosen, as it would yield more uniform results over multiple experimental runs than a self fabricated electromagnet source. The APW Company® EM150-12-222 920 turn electromagnet was selected as it could be varied and precisely controlled over a 0 to 500 mA drive current range.

To determine the magnetic force generated on the on-chip nickel film at a fixed reference plane position, an FEM analysis was conducted using the Infolytica MAGNET version 6.26.2 software package. A 3-D solid model was created, including the electromagnet as well as the on-chip nickel film at position 200 μm above and centered over the highest magnetic field intensity/coil region (Figure 19).

Figure 19: 3-D Solid Model of Electromagnetic Source and On-Chip Nickel Film (light blue)
For the magnetic field simulation, a 2-D magnetostatic model (Figure 20) was constructed to determine the location of the radiated magnetic field lines as well as the force exerted on the on-chip nickel by the electromagnet at the maximum drive current (500 mA).

![Figure 20: 2-D FEM Magnetic Simulation for the Small Deflection Magnetic Actuator Device](image)

In Figure 20, the purple lines outline the electromagnet outer casing, while the black lines represent the magnetic field lines and the red line the on-chip nickel film. From the simulation at the maximum drive current of 500 mA, a force of 14.4 mN is generated in the on-chip nickel film.

Using the information gathered in the magnetic modeling simulation, mechanical deflection FEM analysis was conducted with the ANSYS® software package. Known material property values for silicon were used, including a Young’s modulus of 190 GPa and a density of 2.3 g/cm³ [3]. A fixed position was used for the outer rectangle where the beam posts are attached, to simulate the non-deflectable bulk of the wafer. Instead of a point force of 14.4 mN at the center of the beam, a distributed pressure of 3600 kPa was
applied over the square surface of the beam. From Figure 21, the FEM analysis gives a deflection of 1.4 μm for a beam thickness of 70 μm. This simulated deflection is almost exactly between the desired design parameter of a 1 to 2 μm deflection.

3.3 Fabrication

The fabrication steps for a small deflection magnetically tunable dielectric environment device are shown in Figure 22. Starting from a 3” double-side polished Si wafer (n type, [100] orientation, thickness 251 ± 50 μm), an SiO₂ layer was thermally grown on the Si wafer on both sides by a wet oxidation process (Figure 22 (a)). The thickness of the grown SiO₂ was 700 nm. A positive photoresist (Shipley 1813) was
spin-coated and baked on the bottom side of the wafer. Resist exposure was carried out on an EVG® 620 double-side mask aligner. Backside windows were opened in the photoresist and the SiO$_2$ was then patterned using a buffered oxide etchant (Figure 22 (b)). For the backside bulk wet Si etching, TMAH was employed to achieve a uniform smooth surface. The etching was conducted at 70°C with stirring to obtain the desired membrane thickness of 70 μm (Figure 22 (c)). The masking SiO$_2$ was completely removed (Figure 22 (d)) and a new thick 1 micron SiO$_2$ was thermally re-grown (Figure 22 (e)).

Figure 22: Fabrication Steps for Large Deflection Magnetic Actuator: (a) Thermal oxidation, (b) backside SiO$_2$ patterning (Mask 1), (c) Backside Si wet-etching, (d) SiO$_2$ removal, (e) thick reoxidation, (f) Top side SiO$_2$ patterning (Mask 2), (g) DRIE release, (h) SiO$_2$ removal, (i) Ni deposition
In addition to the thick oxide, a thick positive photoresist (AZ 4620) was used to
define the top side beam structures (Figure 22 (f)) and protect the Si membrane surface
during subsequent DRIE release. Both revised beam designs are located on a single 3”
waf. After release (Figure 22 (g)), the masking SiO₂ was once again completely
removed (Figure 22 (g)). A 1 μm thick layer of nickel was electroplated on the backside
of the wafer (Figure 22 (i)), completing the device structure.

To determine the quality of DRIE release, photolithographic patterning, and
sidewall slope of the fabricated devices, scanning electron microscopy (SEM) images
were taken of each device type. Figure 23 shows SEM images of both the straight and
curved beam device designs. Since the lowest SEM magnification was unable to capture
an entire device, three separate images were taken and pieced together to yield individual
complete device pictures. All images in Figure 23 are taken at a 35x magnification with
the complete image scale representing 1 mm. Figure 23 (a) and (c) show the straight and
curved beam devices respectively at a 0° (head on) angle. From these two images, it is
seen that both devices are fully released from the bulk of the wafer, as there is no jointing
and clean edge lines along the center beam plates. Additionally, photolithographic
patterning appears to be successful as all device features are smooth, intact, and almost
completely vertical side walls are observed.
Figure 23: SEM Images (35x magnification) of: Straight Beam Device at (a) 0° and (b) 35°, and Curved Beam Device at (c) 0° and (d) 35°.
In Figure 23 (b) and (d), the straight and curved beam devices respectively are shown at a 35° angle. These two images allow for the thickness of the device to be observed.

In this fabrication process, the targeted device thickness was 70 μm as determined from the previously described simulation results in Section 3.2. To achieve this thickness, the optimized time stop etching method from the large deflection actuator (Section 2.4) was used. Based on this predetermined etch rate of 13.4 μm/hr, the wafer thickness of 290 μm, the desired beam thickness of 70 μm, and thus the desired etch depth of 220 μm, it was determined that the etching time should be approximately 16 hours and 20 minutes. Upon completing of the TMAH wet chemical etching, the optical microscope depth of focus method was once again used to determine if the desired etching depth was achieved [25]. From this method, it was observed that around 220 μm of etching had been achieved. To further confirm the accuracy of the beam thickness, several tilted 35° angle SEM images were taken of selected regions of the devices at higher magnifications, as shown in Figure 24.

![Figure 24: Selected 35° Angle SEM Device Images at (a) 70x and (b) 500x Magnification](image)
Using the image scale, the titled beam image thickness is approximately 41 µm. Correcting this image thickness based on the 35° angle tilt and the SEM geometry, the actual SEM measured beam thickness is 71.48 µm. From this information, it can be concluded that the all three measurement methods (time stop, optical microscope depth of focus, and SEM image) give comparable thickness measurements. Additionally, if the beams are slightly thicker than the simulated 70 µm, deflections should also be slightly lower than the simulated results.

3.4 Measurements and Results

Measuring the precise deflection of a device designed to within the nanometer to micrometer range while ensuring that the observed movement is caused by the intended source can be rather difficult and requires great care. Two experiments were devised in order to observe and measure the deflection of the fabricated devices. In the first experiment, a dark field microscope setup is used to determine if any device deflection is detectable. In the second experiment, a customized wafer holder is built and used with an interferometric microscope setup to obtain precise deflection measurements over a range of drive current values. Both experiments are explained in detail in the following sections.
3.4.1 Experimental Setup 1: Dark Field Microscopy Deflection Testing

The goal of this experiment was to determine if any deflection was observable in the newly fabricated small deflection actuator devices. The principle observation method would once again be based off of the optical microscope depth of focus method, though the experiment would be conducted in a dark field configuration to assist in the observation of any out of focus blurring caused by beam deflection. Additionally, it was expected that estimations on the actual deflection taking place would not be possible in this method since the focus knob on this setup is graduated at 1 μm intervals, which would likely be greater than the maximum deflection observed.

The primary component of this experimental setup is the dark field microscope. To assist in the accurate positioning of the electromagnet drive source with respect to both the microscope and the wafer devices, the dark field microscope was fixed upon a standard optical bench. The stage of the microscope consisted of a flat stage area with an open hole in the center, as well as a mechanical clamp that will allow for a fixed position of the bulk wafer. A second two dimensional stage was mounted to optical bench and affixed with the electromagnet. This stage was used to position the electromagnet in the microscope stage hole in a way that the top surface of the electromagnet was flush with the surface of the microscope stage surface. Figure 25 shows a picture of the microscope stage with both the mechanical clamp and the electromagnet fixed at its final position within the stage hole.
For the experiment, the wafer containing the fabricated devices was placed on the microscope stage and the selected device was aligned over the highest magnetic field area of the electromagnet. The clamp was then used to fix the position of the wafer and thus the position of the selected device (initially a straight beam device). At this point, no current was applied to the electromagnet. The approximant center of the beam plate was then observed through the microscope at 100x magnification. Focus was obtained by centering on a piece of particulate matter found on the surface of the beam plate as shown in Figure 26 (a). The current in the electromagnet was then increased to the maximum drive current of 500 mA and the observation was repeated (Figure 26 (b)). In this image, it is seen that blurring has occurred due to the deflection of the beam plate out of the focal plane of the microscope. The microscope is then refocused while the maximum current is maintained (Figure 26 (c)). This refocusing was less then one interval on the graduated
focusing knob, thus equating to a deflection of less than 1 µm. The current is then reduced back to the initial 0 A drive current and the beam plate is observed to blur of the refocused focal plane as it moves back to the initial undeflected resting position (Figure 26 (d)).

![Figure 26: Dark Field Deflection Measurements at (a) 0 A Drive Current In Focus, (b) Max Drive Current Deflected Out of Focus, (c) Refocused at Max Drive Current, and (d) 0 A Drive Current Moved Back to Resting Position Out of Focus](image)

The experiment was then repeated for one of the curved beam devices and similar results were obtained for each of the device conditions. From this series of observations and the known experimental setup, it is clear that device actuation has been obtained since all variables have been isolated, leaving the change in magnetic field as the only
altering variable. Though these results are what was expected, in order to classify the actual deflection range of the device, as well as what deflection is yielded by intermediate drive current values, more precise instrumentation must be employed in a similar experiment.

3.4.2 Experimental Setup 2: Interferometric Microscopy Deflection Testing

In this experiment, the primary goal was to precisely characterize the deflection results of the small deflection magnetic devices. In the previous experiment, it was found that actuation is obtained when the maximum drive current of the electromagnet is employed, though numerical data regarding an exact value for this deflection was not obtained due to the limited abilities of the experimental setup. These limitations will be eliminated and deflection versus current characteristics will be determined for both maximum and intermediate drive current values in this experiment.

A new experimental setup was developed for current versus deflection testing, which consisted of a Zygo NewView 7000 Series 3D Surface Profilometer and a customized combined electromagnet/wafer holder. The Zygo system was selected mainly due to the fact that it can resolve height variation of less than 1 nm. Other properties such as the large working area and stage leveling abilities were also highly desirable. Unlike the dark field microscope setup, there was no stage hole or bottom access to place the electromagnet, though there is a large working area between the stage and objects. As a result, a customized combined electromagnet/wafer stand was
fabricated. This stand consists of an aluminum cylindrical block with a removed center. The electromagnet was permanently fixed to the aluminum block inside of the hole so that the top active region of the electromagnet was flush with the top surface of the aluminum. Two holes were created in the side of the aluminum to run the electromagnet wiring. Two mechanical spring-driven stage clips were attached to the top surface of the aluminum to fix the position of the wafer with respect to the electromagnet during testing. The completed electromagnet/wafer stand is shown in Figure 27 (a). The wafer was then placed on the stand so that the device of interest was located over the highest magnetic field region of the electromagnet and the stand was placed on the Zygo stage as shown in Figure 27 (b). After Zygo stage leveling, the experimental setup was complete and ready for measurements.

![Figure 27: (a) Electromagnet/Wafer Stand, and (b) Interferometric Experimental Setup Including Zygo Microscope and Electromagnet/Wafer Stand](image)

For the experiment, interferometric surface profiles were first taken. Initially, the electromagnetic drive current was set to 0 A, and 10 individual measurements were taken
of the given device and automatically stitched together by the Zygo software to generate a complete plot of the device. After the measurement process was completed, the electromagnetic drive current was stepped up and the measurement was repeated. Current stepping was iterated until the maximum drive current was reached. The two dimensional and three dimensional surface plots generated for both the straight and curved beam devices at 0 A drive current are shown in Figure 28.

![Figure 28: Two Dimensional and Three Dimensional Surface Profiles for Straight and Curved Beam Devices](image)

Looking at Figure 28, for both devices, there appears to be a slight 1 to 2 μm bowing of the center of the beam plates (please note the scale of the plots as the bowing is exaggerated to assist visual representation). Though the bowing is rather small when compared to 2000x2000 μm² beam plate dimensions, it does provide some added benefit.
Since the bowing is in a way that it helps to protrude the bare silicon side of the plate outward in the direction of where the metal nanoparticles will be located in a fully assembled SERS sensor, the probability of actually generating contact is increased. In these devices, such bowing is likely caused by the strain induced on the silicon beam by the underside coating of nickel. If the bowing of the devices was in the reversed direction, the opposite would be true, and the ability to generate contact with the metal nanoparticles would be reduced if not impossible. As a result, this device attribute can become rather significant and should be properly analyzed and designed for in future device iterations or new device designs in which actuator contact is required.

To generate the desired electromagnet drive current versus measured deflection for a given device, the series of surface profile plots were used. A fixed slice for every measurement through the center of the beam plate (as shown in Figure 28 (a) and (c)) was used. From the position versus height information of these slices, the gap distance between the bulk of the silicon wafer for both the left and right edges of the beam plate were measured. Similar measurements were taken for all of the different drive current surface profile plots. The gap for the 0 A applied drive current was taken to as the base line or zero deflection point and the subsequent deflections were calculated as difference from this point. The resulting electromagnet drive current versus measured deflection is shown in Figure 29.

In Figure 29 (a) the current versus deflection for both the left and right sides of the straight beam device beam plate is shown. For the left side of the beam plate, deflections in the range of 0 to 139 nm are exhibited for 0 to the maximum 500 mA drive
current of the electromagnet. For the right side in the same current range, 0 to 83 nm
deflections are measured. Similar deflections of 0 to 164 nm and 0 to 63 nm for the left
and right sides respectively were measured for the curved beam device as shown in
Figure 29 (b). Explanations for differences in left and right beam plate deflection as well
as the difference in measured versus simulated deflection are given below.

Figure 29: Electromagnet Drive Current versus Measured Deflections for (a) Straight
Beam Device, and (b) Curved Beam Device
Both graphs exhibit a reduced deflection on the designated right side of the beam plate as compared to the left side. This difference in deflection between beam plate sides is due to a lack of one hundred percent compensation of the rotational forces experienced by the beam plate. In the real magnetic interaction between the on-chip nickel film and the off-chip electromagnet, the magnetic pole orientation of the nickel film is perpendicular to the magnetic field generated by the electromagnet. From this orientation and the rounded magnetic field lines of the electromagnet, a rotational torque is generated on the on-chip nickel film. As such, the magnetic force applied to the film has three dimensional x, y, and z components in space. These non-ideal x and y components result in some of the magnetic force acting as a translational or rotational force on the film and thus the beam plate of the device. As such, is rotational force is seen as the slight tilt in the beam plates surface between the two sides of the plate. It is important to note that this tilt of less than 50 nm over the 2000 μm beam plate length is extremely insignificant from the perspective of a single metal nanoparticle or an array of (typically 150 μm by 150 μm) nanoparticles since any rotation or translation movement of such a large plane will not be apparent to such small particles and only vertical deflection should be experienced.

The difference in the simulated and measured deflection values can be attributed to two causes. The primary reason for the reduced deflection measure is due to slight variation in the device alignment over the highest magnetic field region of the electromagnet. In the magnetic simulation, the ideal case was studied in which perfect alignment over the maximum magnetic field density was present. This translates to
higher force values being distributed over the surface of the beam plate in the mechanical deflection simulation. In the experimental case, visual alignment was used to approximate this maximum field location. Any divergence from the ideal point can result in significant reductions in the on-chip experienced magnetic force and thus reduced mechanical deflection.

Another partial cause for a slight reduction in measured deflection is due to non-ideal translational and rotational motion discussed above. Though these components are small, they will still have some influence in the actual measured deflections. Simulations on the other hand were designed to show a more ideal case in which the simulated magnetic force value was translated into a one dimensional downward force applied perpendicular to the surface of the beam plate. Between these two differences in ideal simulated versus non-ideal measured results, reduced deflection measurements can be appropriately accounted for.

3.5 Conclusion

In this design, small deflection tunable dielectric environment actuator devices have been designed, fabricated and tested. Two new suspended beam plates were developed, which incorporate either four straight or four curved beams that act to limit out of plane rotation or translation in order to produce a small vertical deflection. Magnetic and mechanical simulations were used to characterize the generated magnetic field strength of the selected electromagnetic drive source. It was found that theoretically
a deflection range of up to 1.5 μm could be achieved with a 70 μm thick device.

Fabrication was conducted using the optimized processing techniques developed in the large deflection actuator experiment. Several characterization techniques were employed to fully determine the fabrication results and operation abilities of the device. Dark field microscopy showed the device to be magnetically controllable though numerical operating figures could not be obtained. Interferometric profilometer microscopy revealed a 1 to 2 μm bowing of the beam plate in the direction of the metal nanoparticles. From the precise interferometric data, deflection ranges up to 139 nm and 164 nm were shown to be achievable at the maximum 500 mA electromagnetic drive current for the straight and curved beam devices respectively. These new small deflection actuators show great potential for achieving practical SERS optical sensors.
4.1 Introduction

Though the primary focus of this work was the design, fabrication, and testing of the small deflection magnetic actuator device and geometry presented in Chapter 3, an additional small deflection magnetic actuator with an integrated device geometry was conceived during the testing of the original geometry. The motivation for this device laid in the desire to produce a device that required only basic non-specialized fabrication techniques, which is built directly atop the metal nanoparticle arrays to avoid the chance of particulate interference and misalignment in device operation. Building the beam structure directly on top of the nanoparticle arrays eliminates the need to combine separately made actuator and nanoparticle arrays and integrates the complete SERS sensor into one streamlined fabrication process. Additionally, it is desired to eliminate the need for a large off-chip electromagnetic source to further reduce the size and complexity of full SERS sensor. In order to meet these new desired specifications while maintaining those of the original small deflection actuator device, a simple beam structure will be designed. This new device will utilize both the previously described benefits of magnetic actuation (see Section 1.1) to bend the beam into contact with the metal nanoparticles, as well as some of those associated with electrostatic actuation in the form of an isolated electrostatic able to control and restore the beams position. Such a fabrication process will employ a layer by layer fabrication technique, requiring only
photolithography, wet chemical processing, and electroplating processing steps. Post
device processing and external requirements will be limited to a conductive electrostatic
top plate bonded directly to the substrate and an external power supply capable of
producing the need electrostatic field.

4.2 Design and Modeling

In the design of a new geometry, it is primarily important to ensure that all
changes comply with the original design requirements. For this work, these original
requirements consist of a clear, unobstructed optical path with stationary metal
nanoparticles, as well was an actuator able to operate in a harsh environment. Similarly,
it is important to properly incorporate the new requirements of integrated fabrication atop
a nanoparticle array and the elimination of an off-chip electromagnet drive source. To
satisfy both the original and new requirements, a new integrated magnetic actuator with
isolated electrostatic restoration geometry was conceived as shown in Figure 30.
This new device geometry is based on a common circular beam structure and will rely upon both magnetic force to deflect the beam as well as an isolated electrostatic to restore the beam to its original position. The NiFe circular beam is built upon a ITO glass substrate with embedded metal nanoparticles (this substrate is the same as the one holding the metal nanoparticles in the original magnetic actuator geometry shown in Figure 7). Building the actuator upon a particle embedded glass substrate will provide a clear optical path through the transparent substrate for the stationary metal nanoparticles. An electrostatic ITO glass plate is spaced above the beam and two hard magnetic strips run along two sides of the beam. The magnetic strips are used to replace the electromagnetic source, as they are compact and able to be integrated on-chip. Under no applied voltage, the magnetic force deflects the beam into contact with the metal nanoparticles (Figure 30 top schematic). When a voltage is applied, an electrostatic force
is generated between the beam and upper glass plate which pulls the beam back away from the particles and eventually restores the beam to its fully un-deflected position (Figure 30 bottom schematic).

When discussing the advantages and disadvantages of the different actuation mechanisms at the start of this work, electrostatic actuation was cited as inherently incompatible with SERS sensors due to stiction problems that would be encountered with the metal nanoparticles, electrically charged samples, or particulates located between the substrate and beam. Though these facts remain, it is important to note that these facts were based off of the assumption that the electrostatic forces were applied in the typical manner between a conductive substrate and a conductive beam. In this new integrated device geometry, the electrostatic actuator and forces are isolated from any components that would result in stiction problems or device failure. Since the electrostatic force is used to restore the beam, the voltage is applied between the beam and a top plate, not the beam and the substrate as in the normal configuration. This creates an electric field between the beam and top plate pulling the beam away from the particle not towards them (this is the job of the magnetic force). Stiction will not occur between the top plate and the beam if a proper gap is designed between them which is larger than the beams maximum deflection. In this way, a dual magnetic deflection towards the metal nanoparticles and an isolated electrostatic for restoration can be used.

For the magnetic force generation, 1.5x2x20 mm ferrite magnetic strips were selected to run along two sides of the circular beam devices. In order to characterize the amount of magnetic force generated on 1 mm in diameter by 1 μm thick circular plates of
NiFe (the equivalent of the actuator beam), an FEM analysis was once again conducted using the Infolytica MAGNET version 6.26.2 software package.

![2-D FEM Magnetic Simulation for the Integrated Magnetic Actuator with Electrostatic Restoration Device](image)

Figure 31: 2-D FEM Magnetic Simulation for the Integrated Magnetic Actuator with Electrostatic Restoration Device

For the magnetic field simulation, a 2-D magnetostatic model (Figure 31) was constructed to determine the location of the radiated magnetic field lines as well as the force exerted on the NiFe plate. In Figure 31, the purple lines outline the magnetic strips, while the black lines represent the magnetic field lines and the red lines the NiFe beam plate. From the simulation, a force of 1.956 μN is generated in the 1 mm diameter by 1 μm thick NiFe film.

For geometry that are simple or well studied, such as the circular beam geometry of this device, mechanical deflection equations can often be used to accurately approximate deflection results. For the deflection of fixed circular disk under a uniform applied pressure the equation:

\[
\delta = \frac{3}{16} (1-\nu^2) \frac{\Delta p R^4}{Et^3}
\]  

(5)
can be used to approximate the deflection exhibited by the actuator described in this section; where $\delta$ is deflection, $\nu$ is Poisson’s ratio, $p$ is applied pressure, $R$ is radius, $E$ is Young’s Modulus, and $t$ is beam thickness [28]. Converting the simulated magnetic force value to a distributed pressure and using the known material properties of the beam, deflections for several beam diameters were calculated, as shown in Table 1.

Looking at the generated deflections shown in Table 1, for a 1 $\mu$m beam diameter, it is expected that a 120 nm deflection can be achieved. The deflection distance needed to touch the metal nanoparticles will be determined by the difference in the height of photoresist used to mask the metal nanoparticles during fabrication and the top height of the exposed metal nanoparticles, taking the surface of the substrate as the 0 height value. If 50 nm metal nanoparticles are used with half, or 25 nm, of the particle exposed and a typical 1 $\mu$m photoresist is used, beam deflection will need to be approximately 975 nm to establish beam to particle contact. From these calculations, 4 mm diameter beams should easily achieve contact. For the 1 mm diameter beams though, only 120 nm is expected assuming a fully clamped beam. In the actual experiment, clamping will only be in four locations, allowing for more bending and possibly creating contact. For fabrication, beams of 1, 2, 3, and 4 mm diameters will be fabricated and tested. If the beams are unable to establish particle contact, stronger rare earth magnet strips will be used to replace the simulated ferrite strips, solving any contact problems.
Table 4: Generated Deflections for Given Beam Properties

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Beam Thickness</th>
<th>Diameter (mm)</th>
<th>Generated Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>1</td>
<td>1</td>
<td>≈ 150 nm</td>
</tr>
<tr>
<td>Circular</td>
<td>1</td>
<td>4</td>
<td>≈ 2.5 μm</td>
</tr>
</tbody>
</table>

4.3 Fabrication

The fabrication steps for the integrated magnetic actuator with electrostatic restoration are shown in Figure 32. Starting from a 3” glass (Pyrex) wafer (Figure 32 (a)), positive photoresist (Shipley 1813), which is used as a sacrificial layer was spin-coated and baked on the wafer. Exposure was carried out on EVG 620 double-side mask aligner, and the photoresist was developed and hard baked (Figure 32 (b)). A 50 nm Cr layer and 300 nm Au layer were deposited in sequence on the wafer by thermal evaporation as an electroplating seed layer (Figure 32 (c)). Another positive photoresist (AZ P4620) was spin-coated and baked on the wafer to form an 8 μm thick photoresist layer for beam pattern definition.
Exposure was again carried out on EVG 620 double-side mask aligner, and the photoresist was developed and hard baked (Figure 32 (d)). NiFe electroplating was then conducted, forming a 1 μm beam (Figure 32 (e)). The wafer was cleaned to remove the remaining AZ P4620 masking layer. A negative photoresist, (NR9-1500), was spin-coated on the wafer to protect the NiFe layer during the subsequent Au etching step.
Exposure was again carried out on EVG 620 double-side mask aligner, and the photoresist was developed and hard baked (Figure 32 (f)). The Au layer was then etched with a gold etching solution followed by the Cr layer with a commercially available Cr etchant. All the photoresist was removed by Acetone cleaning and the moving structures were released. Cr etching was conducted again to remove the Cr layer underneath the moving plate leaving the Au layer alone (Figure 32 (g)).

After the fabrication processing was completed, final assemble steps were completed. These steps include bonding of the top plate to the beam wafer as well as electrical connections to an external power supply. To bond the top plate, another 3’ glass (Pyrex) wafer was coated around the edge with a thick layer of photoresist and bonded to the device wafer. For electrical connections, standard soldering of wire leads to bonding pads on the wafer were made.

4.4 Conclusion

In this design, a new integrated magnetic actuator with electrostatic restoration has been proposed, designed, and fabricated. In this newly developed geometry, original requirements for a clear optical path of stationary metal nanoparticles have been met in addition to newly sought requirements of direct processing atop these particles and the removal of the need for an off-chip magnetic drive source. Incorporating all of these requirements led to an integrated geometry that utilizes both magnetic and electrostatic actuation techniques in an integrated design that reduces particulate contamination and
requires no off-chip magnetic source. Through simulation it was found that ferrite magnetic strips could produce 1.956 μN of force resulting in up to 2.5 μm of deflection in 4 mm diameter beam structure. A full fabrication process was laid out.
CHAPTER 5: CONCLUSION

5.1 Summary

In this work, both a large and newly designed small deflection magnetic actuator for dielectric environment tuning in SERS optical sensors have been developed and shown to be fully functional. An integrated magnetic actuator with electrostatic restoration for the same application was also conceived and proposed. In the pursuit of achieving these devices, fabrication processes were fully optimized for future experiments. More specifically, both wet and dry etch process conditions were extensively investigated for thinning wafers and generating movable beam structures.

To overcome some of the challenges faced in previously reported tunable dielectric environment SERS optical sensors, a new geometry was designed as a basis for both the large and small deflection magnetic actuators. This new geometry provides a clear optical path through which the metal nanoparticles can be readily imaged. The metal nanoparticles also maintain a stationary position in this geometry in order to provide a constant focal distance over the entire duration of device operation.

The development of the large deflection magnetic actuator was based off of a prior torsion beam micromirror device. Selection of this beam structure severed two main purposes. Primarily, it provided for binary state actuation between the two extreme experienced dielectric environment states. More importantly, it provided a means for optimizing fabrication processing conditions as similar process were previously documented and achieved for analogous device structures.
A new small deflection magnetic actuator was design as the main focus of this work. Two device structures were created, which consist of a beam plate with either four straight or curved beams designed to minimize any rotational or translation motion. An off-chip electromagnetic driven by an input current was selected as the magnetic source for actuation. Through FEA, both magnetic and mechanical simulations were conducted to determine device parameters and operation ranges. Optimized processes were used to fabricate the devices and several optical characterization techniques were employed to determine operation ranges. Precise magnetic deflection up to approximately 160 nm for drive currents up to 500 mA was shown.

Concurrent with characterization of the small deflection magnetic actuator, an integrated magnetic actuator with electrostatic restoration was conceived. A similar geometry was presented, which maintained the clear optical path of the stationary metal nanoparticles with the addition of an integrated process designed to build the actuation structure directly atop the nanoparticles. This new geometry will reduce particulate contamination and eliminate the need for off-chip magnetic drive source. Simulations were conducted to classify theoretical operating conditions and a fabrication process was proposed.

Through the designs presented, it was demonstrated that magnetic actuation can be fully utilized for closing a gap between two plates and creating variable optical environment for SERS device requirements. It was shown that precise active control can be used to accurately tune effective dielectric environments experienced by metal nanoparticles.
5.2 Suggestions for Future Work

Though the initial set goals for this research have been met, several suggestions for future research can be made. Concerning the small deflection magnetic actuator, optical testing to determine if SERS shifts are obtained is of great interest. In order to accomplish this investigation, the fabricated small deflection actuators must be combined with metal nanoparticle arrays (either in a photoresist bonding process or through a mechanical clamping) so that at static rest, the actuators are in contact with the metal nanoparticles. This may be a rather challenging task due to a packaging issue which involves possible particulate interference from dusts in the regular air environment. To prevent this, actuators should be thoroughly cleaned, bonded to prefabricated nanoparticle arrays, and preferably tested in a clean room environment. Once bonded, observations should be made regarding the surface plasmon resonance frequency at different electromagnet drive currents. This will equate to different deflections and thus different experienced dielectric environments and shifts in the plasmon resonance frequency should be observed.

For the integrated magnetic actuator with electrostatic restoration, investigation into proper beam release should be conducted. Residual photoresist may limit deflection of the device due to a lack of full removal. If photoresist removal is a problem beam redesign may be required to provide larger or more holes for photoresist removal. Testing of the achievable magnetic deflection should be fully characterized to determine
if the different device dimensions are able to establish contact with the metal nanoparticles.

Finally, the investigation into a PDMS nano tool for selective placing of metal nanoparticles may be of interest as an economical rapid bonding method. This tool can be used in a dip pen style, so that once the PDMS tool is fabricated to have nanometer scale points in an array configuration, it can be dipped into a gold affinitive chemical solution, and touched onto a clean glass substrate. A gold nanoparticle solution could then be washed over the glass substrate and some particles would bond to the sites where the gold affinitive chemical is present. In this way, localized formation of metal nanoparticles could be easily achieved. Employing this method would help to ensure precise alignment between particles and actuators, increasing the probability of contact and thus successful observation of SERS optical signal enhancement.
APPENDIX A
SHIPLEY 1813 PHOTOLITHOGRAPHY PROCESS
This appendix contains the detailed process used for Shipley 1813 photoresist processing.

1) **Wafer Cleaning:**

   Acetone, Methanol, De-ionized Water rinse and N₂ dry

2) **Spin:**

   Spin Speed: 3000  
   Time: 30 seconds

3) **Soft Bake (On Hot Plate):**

   Temperature: 100 °C  
   Time: 3 minutes

4) **UV Exposure:**

   EVG 620 Aligner Intensity = 13.4 mW/cm²

   Dose ≈ 118 mJ/cm²

   Exposure time = 8.8 seconds

5) **Develop:**

   Pure CD-26  
   Time: Approximately 1 minute

   Agitation used

6) **Hard Bake (On Hot Plate):**

   Temperature: 100°C  
   Time: 10 minutes
This appendix contains the detailed process used for NR9 1500P photoresist processing.

1) **Wafer Cleaning:**
   Acetone, Methanol, De-ionized Water rinse and N₂ dry

2) **Spin:**
   Spin Speed: 3000  Time: 30 seconds

3) **Soft Bake (On Hot Plate):**
   Temperature: 150 °C  Time: 1 minute

4) **UV Exposure:**
   EVG 620 Aligner Intensity = 13.4 mW/cm²
   Dose ≈ 118 mJ/cm²
   Exposure time = 8.8 seconds

5) **Post Exposure Bake (On Hot Plate):**
   Temperature: 100 °C  Time: 1 minute

6) **Develop:**
   3:1 – RD6:De-ionized Water  Time: Approximately 1 minute
   Agitation used

7) **Hard Bake (On Hot Plate):**
   Temperature: 150°C  Time: 3 minutes
APPENDIX C
AZ P4620 PHOTOLITHOGRAPHY PROCESS
This appendix contains the detailed process used for AZ P4620 photoresist processing.

1) **Wafer Cleaning:**
   
   Acetone, Methanol, De-ionized Water rinse and N₂ dry

2) **Spin:**
   
   Spread Speed: 500  Time: 10 seconds
   Spin Speed: 1000  Time: 20 seconds
   
   Gives a PR thickness of approximately 20µm

3) **Soft Bake (On Hot Plate):**
   
   Temperature: 60 °C  Time: 4 minute
   Temperature: 100 °C  Time: 4 minute
   Temperature: 60 °C  Time: 4 minute
   
   In succession, adjusting hotplate to new temperature at the 4 minute marks.

4) **UV Exposure:**
   
   EVG 620 Aligner Intensity = 13.4 mW/cm²
   
   Dose ≈ 2412 mJ/cm²
   
   Exposure time = 3 minutes

5) **Post Exposure Bake (On Hot Plate):**
   
   Temperature: 100 °C  Time: 1 minute

6) **Develop:**
   
   1:4 – AZ 400K:De-ionized Water
   
   Time: Approximately 3.5 to 7 minute (until features are sharp and exposed regions fully removed)
Agitation used

7) **Hard Bake (On Hot Plate):**

   Temperature: 80°C  Time: 10 minutes
APPENDIX D
ELECTROPLATING PROCESS
This appendix contains the detailed process used for electroplating processing.

1) **Plating Solution Preparation:**

   Ni Sulfamate Electroplating Solution:

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni(SO$_3$-NH$_2$)$_2$</td>
<td>200 g</td>
</tr>
<tr>
<td>H$_3$BO$_3$ (Boric Acid)</td>
<td>25 g</td>
</tr>
<tr>
<td>Lauryl Sulfate</td>
<td>3 g</td>
</tr>
<tr>
<td>DI H$_2$O to make 1 liter</td>
<td>1000 ml</td>
</tr>
</tbody>
</table>

   ph between 3.5 – 4 controlled by Sulfuric Acid or NaOH

   Temperature ≈ 52 °C

   Use magnetic stirring

   Current Density: 10 mA/cm$^2$

2) **Plating:**

   Connect Ni Plate as anode

   Connect Wafer as cathode

   Plating time: 6.5 minutes

   Plating thickness ≈ 1 μm
REFERENCES


