Fabrication of a Magnetically Actuated Torsional Beam

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Abstract – **A mesoscopic magnetic beam contained in a silicon frame attached to the bulk of a silicon wafer with pivoting hinges will be used to show the affects of magnetic fields on movable magnetic structures. The pivoting hinges will be etched out of silicon using a Deep Reactive Ion Etcher (DRIE) system and the dimensions of the hinges will determine the force required to deflect the beam. Below each end of the beam will be large copper inductor coils fabricated on a separate wafer. When a current is applied to the coil, the magnetic field generated will attract the beam towards it. The critical component of the pivoting magnetic structure will be the silicon frame that supports the magnetic material.**

Index terms – **Magnetically actuated devices, pivoting silicon, DRIE**

I. INTRODUCTION

In the field of Microsystems Technology components often contain surfaces that are magnetically attracted to devices that generate magnetic fields. The surfaces may be accidentally attracted or the field can be used to activate a device such as a MEMS actuator. One method to demonstrate the strength of magnetic fields to attract a surface is to position large copper inductors near movable parts. Currently at RIT research is ongoing on the affects of inductors and ways to make coils smaller and just as effective. A magnetic beam supported by a pivoting frame of silicon is an effective way to show the affects of a magnetic field produced by an inductor on movable structures.

The objective of this investigation is to design and fabricate a magnetic structure that requires a known amount of force to move or pivot. The structure will then be placed over a set of copper inductors, which will attract the magnetic material when a current is applied creating a magnetic field. The critical component of the pivoting magnetic structure will be the silicon frame that supports the magnetic material. By applying a current to the inductor below the end of the magnetic beam, a magnetic field will be created and interactions of the beam and the magnetic field can be studied.

The copper inductors were fabricated using a Deep Reactive Ion Etching (DRIE) system, copper electroplating, and Chemical Mechanical Planerization (CMP) techniques. Also, the frame of silicon was created using different thicknesses of oxide as masking layers to fabricate a multilevel frame of silicon using one DRIE etch. Following the etch, the frame was filled with a magnetic epoxy and the magnetic beam was placed over the copper inductors. The magnetic beam should be deflected from the resting position with an applied current to the inductors.

II. THEORY

The mechanical force required to tilt the magnetic beam must be less than the generated magnetic force created by the copper inductors for the beam to tilt. First, to simplify calculations the force was assumed to be applied at the end of the beam. The mechanical force required to tilt the beam can be found by calculating the torque. To find torque, constants ?, G, a, b, and K must be calculated.

$$\theta = \tan^{-1}\left(\frac{Beam\_Deflection}{Half\_Length\_of\_Beam}\right)$$

$$G = \left(\frac{Youngs\_Modulus}{2*(1+Poisson's\_Ratio)}\right)$$

$$a = 0.5 * Cross\_Sectional\_Length$$

$$b = 0.5 * Cross\_Sectional\_Width$$

$$K = a\left(b^3 * \frac{16}{3} - 3.36\left[\left(\frac{b}{a}\right)\left(1 - \frac{b^4}{12*a^4}\right)\right]\right)$$

$$Torque = \left(\frac{2*\theta*G*K}{Hinge\_Width}\right)$$

The net mechanical force required to tilt the beam is the Torque * Half Length of the beam. [1]

The magnetic force to tilt the beam is calculated by finding the difference in field strength from the top and bottom of the beam. The magnetic force of the coils can be found by calculating the B field at the top and bottom of the beam. The net magnetic force is the force at the bottom of the beam minus the force at the top of the beam. B must be found for each ring of the coil and then summed for the distance at the bottom and top of the beam. The number of times to find B depends on the number of coils in the inductor. [2]

$$B = \frac{\mu_0 * (coil\_spacing) * (coil\_radius)^2}{2*\left((coil\_radius)^2 + (beam\_distance\_from\_coil)^2\right)^{1.5}}$$

$$Force = Beam\_Width^2 * M_s * B_{Total}$$

Net Force = (Force at Bottom of Beam) – (Force at bottom of beam)

The formulas and amount of book keeping involved to calculate these figures requires the use of a spreadsheet program. Data can then also be plotted to analyze data such as in table 1. See figure 7 for table and hinge dimension key.

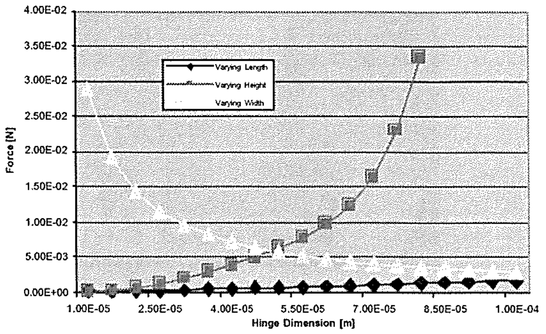

table 1

III. DEVELOPMENT/SIMULATION

Computer rendered images of the silicon frame design can be seen in figures 1-3 to understand the frame structure. Once all formulas were entered into a spreadsheet the mechanical force was found depending on the dimensions of the hinges. Also, the magnetic force generated was found depending on the dimensions of the coils, wire width, depth, and spacing. The mechanical force was then plotted against varying hinge size ranging from 10 - 100μm. Results can be seen in Table 1. An increase in hinge length and width did not have a dramatic impact on force while a change in height drastically increased the force required to tilt the beam. The height measurement is determined by etching, not lithography, meaning careful measurements needed to be made to make the DRIE etch accurate. After hinge and coil dimensions were simulated, sizes were found and can be found in table 2. By using these numbers theoretically the force generated by the coil should be able to tilt the beam.

Dimension	Size (μm)
Beam length	5000
Beam width	1000
Hinge width	40
Hinge height	20
Hinge length	10-60
Coil Width, Spacing, Depth	20
Coil distance from bottom of beam	400
Coil distance from top of beam	500
Coil length	3000
Number of turns	25

table 2

IV. FABRICATION

Fabrication of the beam and copper coils were done simultaneously and concluded about the same time. Once both pieces were fabricated the two structures were brought together for actuation.

The coils and beam frame were fabricated using standard photolithographic processing on Shipley 812 photoresist 1μm thick. The coil pattern was etched 20μm into the silicon using the STS DRIE system and the photoresist was removed. Next a thin oxide of 1000Å was grown and the inductor wafers were ready for metal. Without breaking vacuum a 500Å layer of tantalum was sputtered followed by a 1000Å layer of copper to act as a seed layer. Copper does not adhere well to silicon so a thin layer of tantalum helps with adhesion issues between the silicon wafer and copper. Tantalum adheres very well to silicon and by not breaking vacuum the copper layer can adhere very well to the defect free, non-oxidized surface of tantalum. After the seed layer was blanket coated completely over the surface of the wafer was ready for electroplating. A solution of cupric sulfate and sulfuric acid was prepared and the wafers were electroplated until the 20μm patterns were not visible. The wafers were then polished back using CMP processes until the copper coil was the only conducting objects on the wafer.

The processing for magnetic beam started with patterning oxide and depositing another oxide layer over it. The new layer was also patterned so there were two thicknesses of oxide and bare silicon visible. Last a 1μm layer of TEOS was deposited and patterned, now 3 levels of oxide and bare silicon were visible. Last an 8μm layer of TEOS was deposited on the backside of the wafer for an etch stop. The wafer was placed in the STS DRIE until the sections where bare silicon was visible was completely etched through the wafer. Prior to this etch the etch rates of oxide, TEOS, and silicon in the DRIE system were all found to provide the correct thicknesses for the films to act as hard masks knowing the point when those films will be etched away.[3] When etching was complete the underside of the beam frame is shown in figure 5. The beam is still suspended to the bulk silicon by the layer of TEOS on the backside but it can be easily release by etching the TEOS in buffered oxide etch (BOE). Before the frame was released the middle of the frame was filled with nickel-loaded epoxy. Since the viscosity of the epoxy can be best described as "clumpy," a few drops of deionized water added to the epoxy thinned it out. Using the tip of a needle, a drop of the epoxy was placed into the frame and once the surface tension of the drop contacted the frame, the drop spread out, filling the frame. After the epoxy was cured the beam was soaked in BOE and the beams were released. This concluded the fabrication of the beam.

V. TESTING

Testing took part in three stages. First, the inductors were tested using ferrite powder with a particle sizes less than 5μm. If a current was placed on the coil of wire a magnetic field should be created and the powder will be attracted to the wire. Second the beam will be tested with a permanent magnet. If the silicon frame pivots towards the magnet the beam and hinges work correctly. Last, the beam will be placed over the inductors and a current will be put on the coil to attract the beam.

VI. CONCLUSION

The torsional magnetic beam was successfully fabricated and moved using a permanent magnet. This was captured through a stereomicroscope and also could be seen by the naked eye. Also, the fabricated copper inductors attracted sub 5μm particles of ferrite material moving the particles 5-20μm on average, proving a magnetic field was generated. The inductors however were not powerful enough to have an effect on the magnetic beam when it was placed above as planned. The process to use multiple levels of oxide to hard mask silicon to create a multilevel surface in a single

etch was very successful, and the beam frame was fabricated. After one DRIE 4 levels of silicon were obtained including one level etching completely through the wafer. Last, using a needle tip and a watered down solution of nickel loaded epoxy the beam was filled with the magnetic media via the surface tension of water.

VII. PICTURES/TABLE

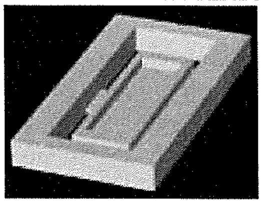

figure 1

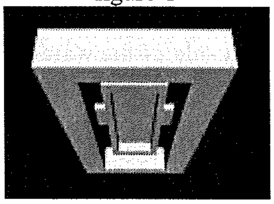

figure 2

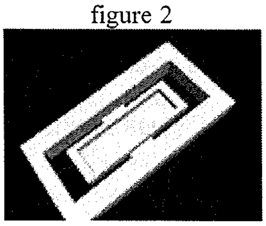

figure 3

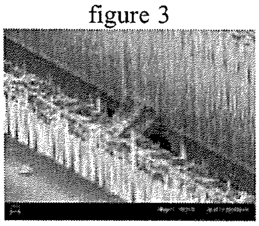

figure 4

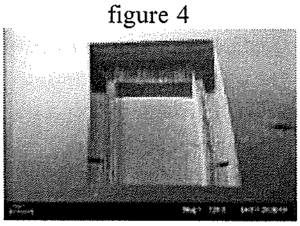

figure 5

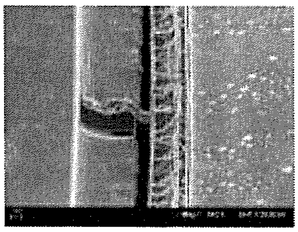

figure 6

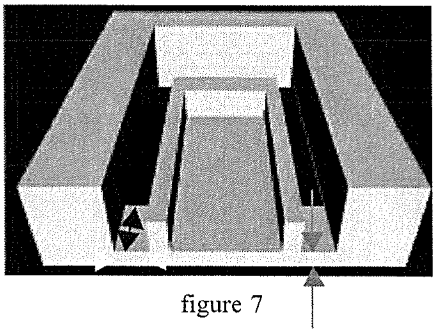

figure 7

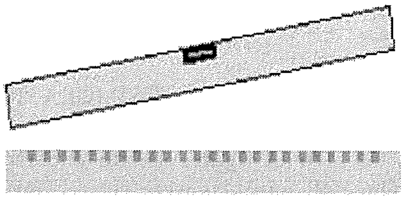

figure 8

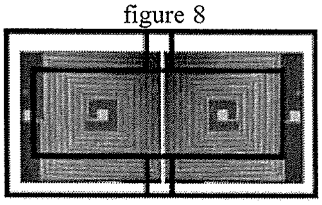

figure 9

Figure 1-3: Computer Rendered Image of beam frame structure
Figure 4,6: SEM image of silicon hinge after DRIE
Figure 5: SEM image of beam frame after DRIE
Figure 7: Computer Rendered image of cross section of beam frame w/hinge dimensions linked to table 1
Figure 8: Side view of beam frame over coils
Figure 9: Top view of beam frame over coils

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[1] Norton, R., *Machine Design,* 2nd Ed., Prentice Hall 2000

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Gary Fino (S'04), originally from Buffalo, NY, received a B.S. in Microelectronic Engineering from the Rochester Institute of Technology in 2004. He obtained co-op work experience at LACOMS in Rochester, NY in the areas of process improvement and power reduction. Also, he has done research on a National Science Foundation grant in Rochester, NY in the field of micromagnetics. He is currently pursuing a career to put his newly earned degree to use.