Hard Magnetic Material for Perpendicular Magnetic Anisotropic Field in Electromagnetic Actuator Fabrication

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Abstract

This paper describes a high power electromagnetic microactuator fabrication method that combines the hard magnetic Fe/Pt process, Ni/Fe permalloy magnetic circuit design, bulk micromachining, and excimer laser ablation. The hard magnetic material Fe/Pt is deposited under low temperature less than 300\textdegree C by sputter onto a suspension diaphragm to produce a perpendicular magnetic anisotropic field. The magnetic circuit with closed loop design is applied to concentrate the magnetic flux and increase the magnetic force. The magnetic field induced by the planar coil and Ni/Fe permalloy enhances the interaction with Fe/Pt to induce attractive and repulsive displacement, provide a large output force, and operate at high frequency. This high power electromagnetic microactuator is demonstrated with minimum dimensions with a magnetic force two times greater than conventional magnetic micro-actuators.

1. Introduction

The magnetic and structural properties of Fe/Pt equiatomic alloy thin films elicit great scientific and application interest. These films have potential for high-density recording media and high-energy permanent magnets because of their exceptional magnetic properties. The film of NiFe-Au-NiFe layers and helical microcoil structure were deposited by means of radio-frequency (RF) sputtering [1]. It was fabricated to measure the off-diagonal impedances in the high frequency range up to 100 MHz. Magnetic microactuators have seen significant growth in the microelectromechanical system (MEMS) field [2]. The MEMS process offers many advantages; including integrated elements and miniaturized dimensions for microactuators fabricated using IC (integrated circuit) compatible processes [3-6]. The huge power consumption required to actuate a component is an existing problem in these integrated systems. This study presents a high efficiency electromagnetic microactuator consisting of a planar coil with high aspect ratio, a closed loop micromagnetic circuit design, Ni/Fe(80/20) permalloy using micro-electroplating, and sputtered hard anisotropic magnetic material Fe/Pt [7].

The produced magnetic field can be used to enhance the driving force of the electromagnetic microactuator, induce large displacement, generate large output force, and provide high frequency operation. The implementation of electromagnetic actuators heavily depends on the micro-fabrication technologies. Actuators have a movable structure constructed onto a sacrificial layer in the fabrication process. When the sacrificial layer is removed, the structure has an extremely flat surface resulting in stiction [8], which increases the process difficulties and decreases the yield rate. Hence, excimer laser ablation technology is used to construct the desired shape and avoid stiction. Laser ablation is useful in various microstructure manufacturing processes, laser-LIGA, and rapid prototyping [9]. In the following sections, the design procedure, the fabrication and the results will be presented in detail.

2. Design

With the growing interest in the MEMS field, we present the perpendicular hard magnetic field concept and apply it to microactuators traditionally used in recorder hard drives. Soft magnetic material is usually used in microactuators to facilitate diaphragm actuation. Force through magnetic actuation is known to be a strong and long force range compared with other actuator driving methods [10-11]. Magnetic actuation is the method of choice for driving microsystems. Electromagnetic microactuators are designed using the following processes.
The hard magnet Fe/Pt is sputtered onto the suspension diaphragm to apply perpendicular magnetic anisotropy. This is coupled with the magnetic field using an efficient planar coil and resulting in larger displacement output. The Ni/Fe permalloy on the planar coil is centered using micro-electroplating. The closed loop magnetic circuit can concentrate the magnetic flux and increase the magnetic force. An electromagnetic actuation for microactuators is designed as shown in Figure 1. Because the polyimide microstructure has higher Young's modulus after full curing, polyimide shows excellent electrical, mechanical, chemical and thermal properties [8]. Under the same actuation force, the polyimide microstructure produces larger deflection. It was selected as the vibrating suspension diaphragm for this reason.

![Figure 1: Illustration of magnetic actuation for the designed microactuator.](image)

Passing a current onto the planar coil generating a magnetic field actuates the device. The closed loop magnetic flux goes through the air gap and repulses and attracts the Fe/Pt thin film. The magnetic field thus induces a force to switch the microactuator toward the direction of the magnetic flux. When the current is dispelled, the mechanical suspension arms pull the diaphragm back. The magnetic and structural properties of Fe/Pt equiatomic alloy thin films elicit great scientific and application interest. These films have potential for high-density recording media and high-energy permanent magnets because of their exceptional magnetic properties [12]. With the growing interest in the MEMS field, we present the perpendicular hard magnetic field concept and apply it to microactuators traditionally used in recorder hard drives. Soft magnetic material is usually used in microactuators to facilitate diaphragm actuation. In this study, a perpendicular hard magnet is applied to microactuator to enhance the vibration angle and displacement. A planar coil is placed at the bottom to provide electrical induction to the magnet. This is an innovative approach that enhances the membrane displacement.

The essential feature is that the Fe/Pt thin film can undergo a phase transition from a disordered face centered cubic structure into an ordered face centered tetragonal structure after post-deposition annealing, or when deposited at an elevated substrate temperature. The long range ordering has critical effects on the magnetic properties of the films. It is well known that the ordered Fe/Pt alloy has a very high anisotropy constant $K_1$ of $7 \times 10^7$ erg/cc. Fe/Pt thin film deposited using magnetron sputtering tends to grow with a (111) texture. In this research, the Fe/Pt thin film was deposited onto a NiO buffer layer of nanometer size. Fe/Pt can grow onto the NiO layer within the normal film direction and produce perpendicular magnetic anisotropy. The Fe/Pt multilayers were deposited onto NiO buffer substrates by sputtering. The Fe/Pt layer thickness was about 1500 nm. The base pressure of the sputtering chamber was $2 \times 10^{-6}$ Torr at high purity. Ar ions were used for deposition at a pressure of 1 mTorr. Two targets were used, Fe target (99.95% in purity) and Pt target (99.995% in purity). The Fe/Pt composition was adjusted using the sputter-gun power. The film structure was investigated using transmission electron microscopy (TEM) and x-ray diffraction with Cu/K radiation.

### 3. Fabrication

#### 1. Device fabrication

The fabrication process for the magnetic microactuators consists of thick photoresist lithography, electroplating, bulk micromachining and excimer laser ablation. In this study, a perpendicular hard magnet is applied to microactuator to enhance the vibration angle and displacement as described in the following section. A planar coil is placed at the bottom to provide electrical induction to the magnet as depicted in Figure 2. The component parameters involved in this design are as follows: coil inner diameter 400 mm, track width 10 mm,
track spacing 10 mm and thick single layer 25 mm. The number of turns is 13 and the driving current is 0.5A. From the coil simulation, a magnetic field is generated at a working distance 25 mm between the coil planes. According to the calculations, the force reaches optimal when the hard magnetic material is placed at the center along the Z-axis.

Sixteen hundred nanometers of SiO$_2$ were wet oxidized at 1100°C onto a two-side polished (100) wafer. This was used as the etching mask and bulk-etching area on the backside of a patterned silicon wafer. Polyimide film was then spin-coated onto the top side of the silicon wafer. After fully curing the polyimide at 350°C, the PI thickness was 10 µm. One hundred nanometers of Ag was deposited as the seed layer by sputtering on the top side of the silicon wafer. Five µm thick photoresist was then patterned using UV-lithography. Two µm thick Fe/Pt alloy thin film was then sputtered onto the photoresist pattern. The photoresist and seed layers were then stripped away. Using a Teflon chuck to protect the top side, the wafer backside was immersed into 30 wt % KOH solution at 70°C until the SiO$_2$ etching stop film reached the top side of the silicon wafer. The final process involved removing the top side SiO$_2$ etching stop layer and fabricating microbeams using excimer laser ablation on the backside. The finished electromagnetic microactuator is shown in Figure 3. The top figure shows the hard magnetic film on the suspension diaphragm. The right figure has two types of coils: planar coil and toroidal coil. Both

![Figure 2: Cross-sectional view of coil and magnetic film composition.](image)

![Figure 3: Schematic of the electromagnetic microactuator; top figure is the hard magnetic film on the suspension diaphragm and bottom figures are a planar coil and a toroidal coil.](image)

### 2. Magnetic Film Processing

<table>
<thead>
<tr>
<th>Layer</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>Cr (capping layer): avoid oxidation</td>
</tr>
<tr>
<td>FePt</td>
<td>FePt: magnetic film</td>
</tr>
<tr>
<td>NiO</td>
<td>NiO: underlayer with (200) texture</td>
</tr>
<tr>
<td>Si substrate</td>
<td>Si(100): clean with HF solution and remove SiO$_2$</td>
</tr>
</tbody>
</table>

![Figure 4: The composition of Fe/Pt alloy film.](image)

The Fe/Pt alloy thin film was sputtered onto the vibrating suspension diaphragm. A 10 mm thick Ni/Fe permalloy array was arranged as shown in Figure 4. To induce a magnetic dipole along each axis, a strong
magnetic field was applied during electroplating. Passing a small current to induce a magnetic field was used to actuate the microactuator. The film arrangement is based on the following consideration.

1. The co-sputtering thin film technique was used by adjusting various powers to control their composition. The thin film with multiple layers also affects its crystalline and magnetic properties.

2. Using the annealing temperature and the sputtering power can change the film orientation and microstructure and investigate its relation to magnetic properties.

3. The substrate and buffer layer selection can directly affect the film crystalline orientation and microstructure, the proper buffer layer is helpful in the film composition control and magnetic properties.

4. The annealing and heat treatment can change the film structure and phase transformation. The post-annealing was performed in a vacuum chamber to avoid Fe oxidation. Figure 6 shows the x-ray diffraction diagram for Pt/Fe crystalline orientation.

![Figure 5: X-ray diffraction diagram for FePt film.](image1)

Figure 6: Simulation results of the magnetic field using ANSYS software, the magnetic field generated by the planar coil.

![Figure 6: Simulation results of the magnetic field using ANSYS software, the magnetic field generated by the planar coil.](image2)

### 4. Results and Discussion

The magnetic field generated by the planar coil was simulated using ANSYS software, as shown in Figure 6. The soft magnet Ni/Fe on a planar coil had the same dimensions, 200 × 200 × 20µm³ in volume. With the Biot-Savart law the magnetic force was simulated at 35 mN at a driving current of 0.5 A. To induce a magnetic dipole along each axis, a strong magnetic field was applied during electroplating. Passing a small current to induce a magnetic field was used to actuate the microactuator. The higher the coil thickness, the larger the force output generated. When a current is applied to the planar coil, a magnetic field and perpendicular magnetic anisotropic force is generated that acts on the vibrating suspension diaphragm resulting in suspension diaphragm deflection. This magnetic field intensity induces an attractive force on the diaphragm plate.
5. Conclusion

The research provides a new method for integrating the Ni/Fe permalloy, high aspect ratio (more than 5) microelectroplating, closed loop magnetic circuit, hard magnetic material Fe/Pt anisotropy, bulk micromachining and excimer laser ablation processes. The fabrication process reduces the procedure complexity, etching selectivity and residual stress problems. This design method concentrates the magnetic flux and increases the magnetic force. This microactuator can provide 2 times greater output force larger than the conventional method.

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REFERENCES