A NOVEL BI-DIRECTIONAL MAGNETIC MICROACTUATOR USING ELECTROPLATED PERMANENT MAGNET ARRAYS WITH VERTICAL ANISOTROPY

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ABSTRACT

A novel bi-directional magnetic microactuator using electroplated permanent magnet arrays has been fabricated and tested in this work. To realize the microactuator, a new electroplating technique has been developed to improve vertical magnetic anisotropy in CoNiMnP-based permanent magnet arrays. By applying magnetic field during electroplating, vertical coercivity and remanence have been increased up to 1100 Oe and 1900 G. After electroplating the magnet arrays at the tip of a prototype silicon cantilever beam, bi-directional magnetic actuation has been successfully achieved by exciting an integrated electromagnet under the beam.

INTRODUCTION

There have been many efforts toward realizing hard magnetic component on MEMS devices to achieve bi-directional actuation [1-5]. Specifically for microactuators, a permanent magnet component is highly valued, as bi-directional actuation can be easily achieved by combining a permanent magnet and an electromagnet. By switching the direction of the current in the electromagnet, attracting and repelling motion can be generated depending on the polarity of the permanent magnet. In addition, compared to the actuators using soft magnetic materials, those with the hard magnetic materials are favorable from the viewpoint of scaling factor and power consumption [1].

Until recently, assembling of commercial magnets [1-3] or screen-printing of magnetic particles [4-5] has been suggested as a way of fabricating thick permanent magnet structures on the microactuators. To resolve the discrepancy between fabrication technique of permanent magnet films and standard CMOS circuit fabrication process, we have introduced the electroplating technique of CoNiMnP-based thick permanent magnet arrays[6].

The purpose of this work is to meet another requirement in fabricating the integrated permanent magnet component. The magnetic properties in arrays should be controllable in a given dimension. For this purpose, heat treatment has been commonly used in well-known Nd-Fe-B permanent magnet films [7-8]. Though this method is effective to align the magnetic moment in the hard magnetic films through crystallization, the device must be heated to a temperature of 600°C, which is not suitable for post processing of electronic devices.

In order to meet the requirement of the above, we have successfully developed new method to control the magnetic properties of the magnet arrays by applying external magnetic field during electroplating without any heat treatment. Then, under the optimum plating condition, the permanent magnet arrays were incorporated as a part of prototype actuator to achieve bi-directional actuation. A bi-directional magnetic microactuator, which consists of a silicon cantilever beam with electroplated permanent magnets and an electromagnet, has been fabricated and characterized in this work.

The ability to control vertical anisotropy of the permanent magnet arrays will greatly help to achieve a novel fully integrated bi-directional actuator and will allow numerous other applications that need on-chip permanent magnet component.

PERMANENT MAGNET ARRAYS

Design And Fabrication

The array design was adapted to suppress the residual stress between the CoNiMnP alloy and the substrate. Also demagnetization effects along vertical direction to the substrate were taken into consideration. The typical dimensions of each cell in arrays were 100 μm x 30 μm, 40 μm x 30 μm (rectangular shape), and 50 μm x 50 μm, 40 μm x 40 μm, 30 μm x 30 μm (square shape).

To study the effect of geometry, the thickness was controlled to keep the value between 18 μm and 22μm.

Fig. 1 shows the geometry of an individual cell in each array. Various shapes were devised to understand the geometric effects on the magnetic properties. In designing arrays, the aspect ratio was used as a measure of the geometric effects, which is proportional to demagnetizing factor in those arrays. Aspect ratio is defined by the ratio between the longest dimension and the shortest dimension in an individual cell, where the number is calculated as width divided by thickness in those arrays.

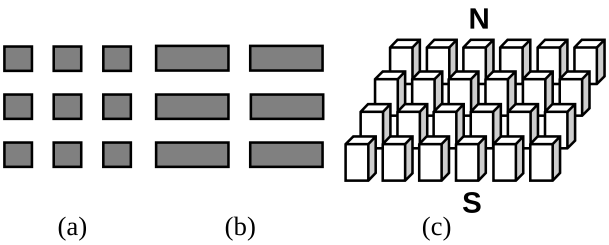


Fig. 1. Array geometry: (a) top view of square cell; (b) top view of rectangular cell and (c) schematic view.

The substrates for electroplating CoNiMnP-alloy films were 2-inch (100) silicon wafers. After the silicon wafer was oxidized to obtain a SiO_2 layer as an insulator, Cr(300Å) / Cu(3000Å) was deposited using an electron-beam evaporator as a plating seed layer. AZ-4620 photoresist was then spun on the wafer and patterned to build the thick electroplating mold arrays. Electroplating was performed at a current density of 5 mA/cm^2 to 10 mA/cm^2. Finally, the remaining photorisist was removed with acetone and the wafers were diced into small square chips for magnetic measurements. Fig. 2 schematically describes the process for fabrication of the magnets.

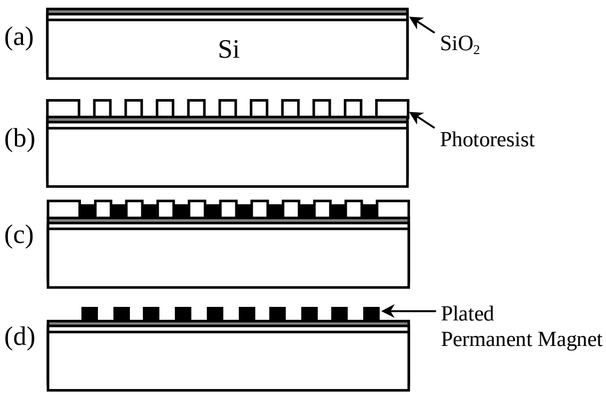


Fig. 2. Fabrication steps of permanent magnet arrays: (a) Cr/Cu seed layer deposition; (b) photoresist patterning; (c) CoNiMnP electroplating and (d) photoresist stripping

The electroplating step plays a major role in constructing array patterns. In order to improve and control the vertical anisotropy in the magnet arrays effectively as well as to reduce surface irregularity of electroplated materials, both ceramic magnets (Ferrimag 8A, Adams Magnetic Products, 3900G) and a paddle agitator [9] were used to build the electroplating system. As shown in Fig. 3, two ceramic magnets were aligned to face each other to produce external magnetic field during electroplating. The sweeping motion of paddle agitator ensured a uniform transportation of metal ions in solution around the substrate and efficiently removed the gas bubbles evolving on the substrate. Co foil was used as an anode to maintain the constant metal ion composition in the bath.

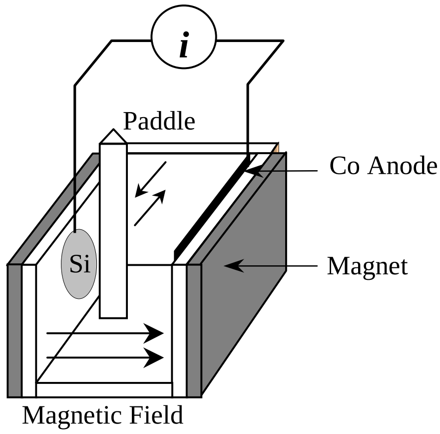


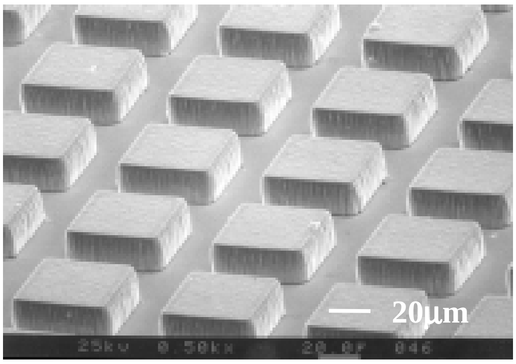
Fig. 3. Schematic illustration of electroplating system.

Electroplating bath composition was adapted from the bath for vertical memory media [10] and modified for our purpose, which is described in Table I.

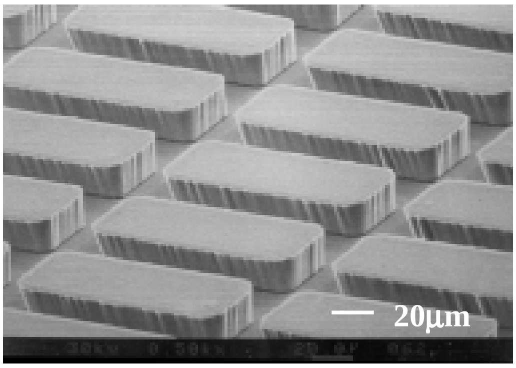
Table I. Chemical composition of electroplating bath.

Compound	*gram/L*
$CoCl_2$ $6H_2O$	24
NiCl $6H_2O$	24
$MnSO_4H_2O$	3.6
NaH_2 PO_2-xH_2 O	4.6
$B(OH)_3$	22
Sodium Lauryl Sulfate	0.2
Saccharin	0.8
NaCl	22

Fabricated permanent magnet arrays showed well-defined features. Typical square and rectangular shapes of arrays are shown in Fig. 4.



(a)



(b)

Fig. 4. SEM photos of electroplated CoNiMnP-based permanent magnet arrays: (a) square cells (40 μm x 40 μm x 20 μm) and (b) rectangular cells (100 μm x 30 μm x 20 μm).

Experimental Results

The magnetic properties of the magnet arrays were characterized with a vibrating sample magnetometer (VSM). The typical $4\pi M$-H hysteresis loops for the samples are shown in Fig. 5. Both the coercivity and the remanence of the magnets increase when the samples are plated under a magnetic field.

As shown in Fig. 6, the magnetic coercivity of the samples fabricated without magnetic field varied from 380 Oe to 500 Oe, depending on the geometry of the array. Whereas, by applying the magnetic field during electroplating, the coercivity (H_c) of the arrays has been improved by up to 220%. The remanence ($4\pi M_r$) of the magnets was also improved from 0.5-0.8 kG without the external magnetic field to 1.7-1.9 kG with the external magnetic field. The measured results are listed in Table II.

Table II. Magnetic propertied of fabricated magnets

Magnetic properties	Fabricated without field	Fabricated with field
H_c	380-500 Oe	710-1100 Oe
$4\pi M_r$	0.5-0.8 kG	1.7-1.9 kG
$(B \cdot H)_{max}$	0.3-0.5 kJ/ m^3	1.9-2.3 kJ/ m^3

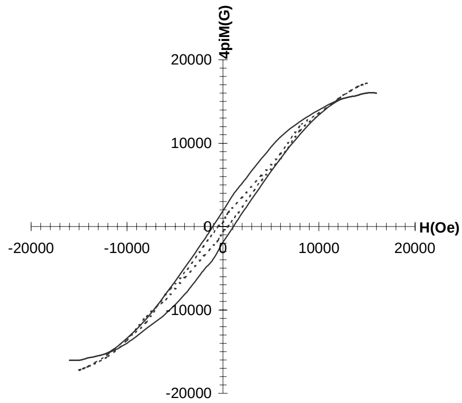
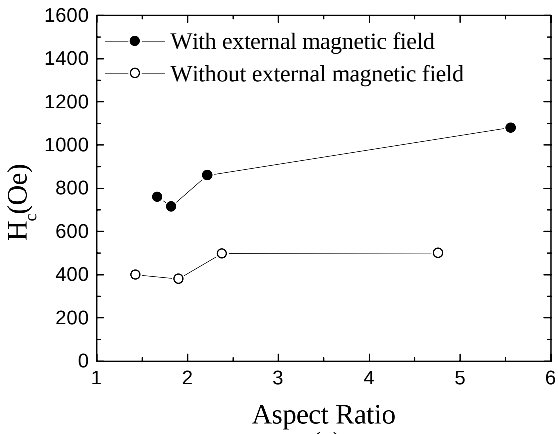
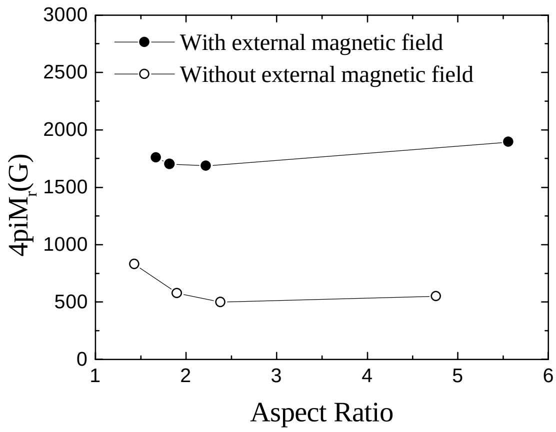


Fig. 5. $4\pi M$-H hysteresis loops of the permanent magnet arrays fabricated: (a) without external magnetic field (dashed line) and (b) with external magnetic field (straight line).



(a)



(b)

Fig. 6. Changes in (a) coercivity and (b) remanence as a function of aspect ratio.

Coercivity of the electroplated magnets is dependent on the film thickness and has been known to decrease with film growth in Co-Ni-P based magnetic films [11]. This trend has imposed limitation on making a thick magnetic film with high coercivity. However, by forming the arrays of small cells and applying the external magnetic field, the coercivity can be enhanced. A high coercivity and remanence of 1100 Oe and 1900G was observed in the arrays composed of rectangular cells e.g., 100µm x 30 µm x 18 µm (Fig. 6).

Since shape anisotropy is related to the energies associated with magnetization in the shortest and longest dimensions of a ferromagnetic body [12] and permanent magnet arrays do not cover all the substrate area, aspect ratio of a magnet was used as variable instead of film thickness to compare the magnetic properties.

As shown in Fig. 6 (a) and (b), for a fixed electroplating condition, the coercivity and the remanence could be varied by modification of the geometry within the limits of 120% to 160%. However, the application of magnetic field applied during electroplating is shown to be a more effective way to improve the coercivity up to 220% and the remanence up to 380% from the same figures.

Although the demagnetizing effect occurs favorably along the direction of long easy axis and thus the vertical magnetization in magnetic films is physically difficult [12], the fabricated magnets indicate the possibility of overcoming the problem. Magnetic properties were successfully improved by using the effects of external magnetic field and geometric factors. This forced alignment of magnetic moments in the arrays can be explained by a magnetocrystalline anisotropy of a Co-alloy film. It has been reported that the c-axis orientation of columnar crystals normal to the surface plane is the origin of high vertical anisotropy in Co-based magnetic films [13].

The magnetic energy density of the fabricated magnets has also been evaluated using the measured magnetic values. The energy density evaluated from the fabricated magnetic arrays also improved from 0.3-0.5 kJ/m^3 without magnetic fields to 1.9-2.3 kJ/m^3 with magnetic fields, which is comparable to the value of the commercially available plastic-bonded ferrite magnets [12].

Since the maximum achievable magnetic energy stored in arrays is dependent on the dimensions and magnetic properties of the magnet arrays, the results clearly show that generated force can be accommodated to meet the functional requirement by adjusting magnetic properties for a given dimension of the fabricated permanent magnet. Furthermore, this electroplating technique does not require heat treatment involved in magnetization of film-type magnetic components, and thus it can be used for post processing of magnetic components without damaging electronic circuitry.

BI-DIRECTIONAL MAGNETIC MICROACTUATOR

Design And Fabrication

With the electroplated permanent magnets, a bi-directional magnetic microactuator has been designed and fabricated, which is composed of a silicon cantilever beam with magnets on its tip and an integrated electromagnet. The basic structure of fabricated cantilever beam is schematically illustrated in Fig. 7. In this structure, the fabricated permanent magnets were embedded as a part of prototype silicon cantilever-beam actuator to confirm the bi-directional actuation.

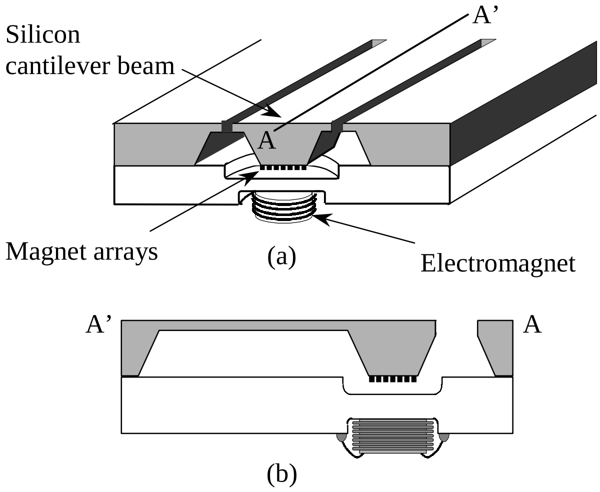


Fig.7. Structure of the cantilever beam microactuator: (a) schematic view and (b) cut view.

The fabrication steps are described in Fig. 8. The permanent magnet patterns were fabricated at a free end of the silicon cantilever beam within an area of 1.5 mm x 1.5 mm. After integrating an electromagnet on the other etched glass substrate, both the cantilever beam and the glass substrate were bonded together, then the deflection of the microactuator was measured as a function of the applied current. A commercially available surface mountable inductor (Coilcraft, DO3316P-105) has been modified and used as an electromagnet in this microactuator, but a microfabricated semi-encapsulated spiral inductor is now being integrated toward a fully integrated microactuator.

The integrated permanent magnet array on the cantilever beam structure is a key element in the realization of this novel microactuator. Fig. 9 shows the actual view of the constructed beam with electroplated permanent magnet arrays at its tip.

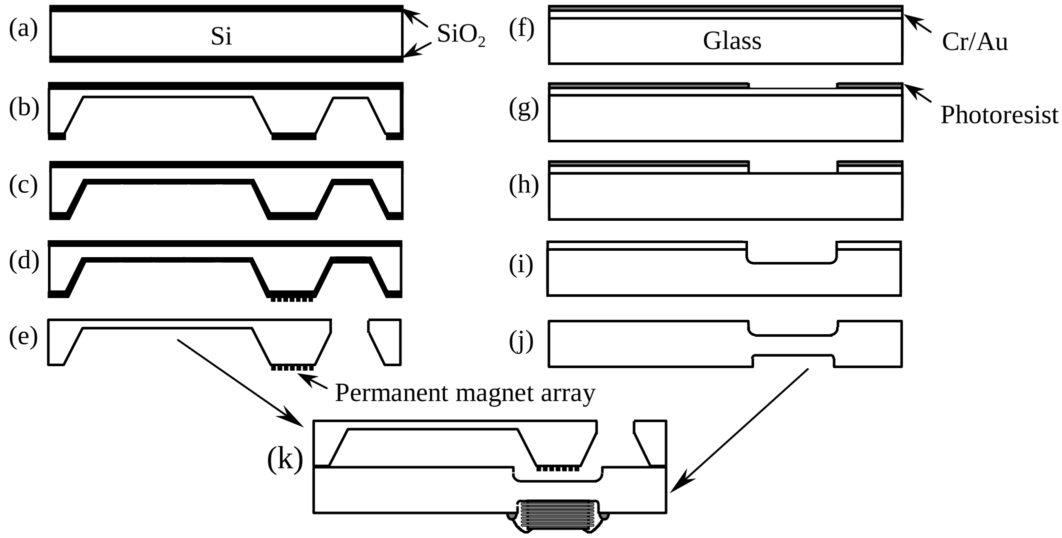
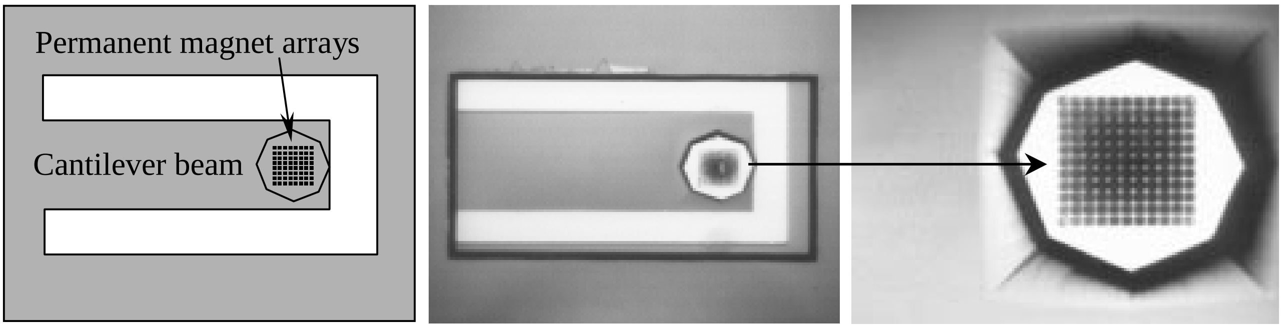


Fig. 8. Fabrication steps of a cantilever beam actuator: (a) oxidation; (b) silicon etching; (c) re-oxidation; (d) electroplating permanent magnet arrays; (e) releasing cantilever beam by RIE and stripping metals and oxide; (f) Cr and Au deposition; (g) patterning and hard baking of photoresist; (h) etching Au and Cr; (i) etching glass in HF (j) back side etching by repeating the steps (f)-(i); (k) assembling a cantilever beam, a glass spacer and an electromagnet.



(a) (b) (c)

Fig. 9. Cantilever beam with electroplated permanent magnets: (a) schematic view; (b) bottom view and (c) enlarged view.

Experimental Results

Fig. 10 shows the variation of deflection in fabricated microactuator using electroplated permanent magnet arrays with vertical anisotropy, in which the bi-directional actuation is successfully achieved.

The electromagnetic force between a permanent magnet and an electromagnet, $\boldsymbol{F}$ is defined as a function of the current density in an air core electromagnet by the equation [14],

$$\boldsymbol{F} = V \boldsymbol{M_z} \cdot \frac{\mu_o \boldsymbol{J}}{2} \, g \quad , \qquad (1)$$

where V is the volume of the magnet, $\boldsymbol{M_z}$ is the magnetization of the magnet, μ_o is the permeability constant , $\boldsymbol{J}$ is the current density in the electromagnet and g is the geometric parameter depending on the configuration of the magnet and the electromagnet.

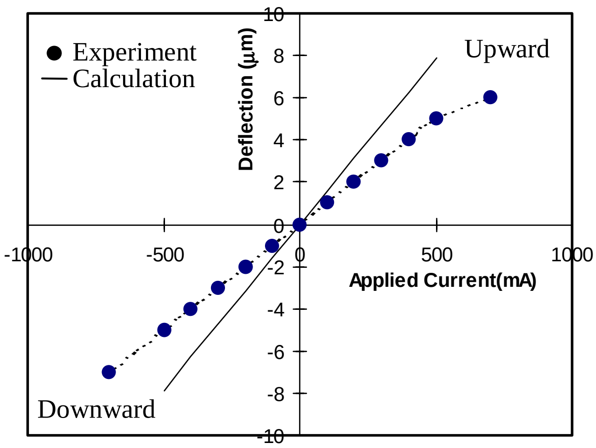


Fig. 10. Bi-directional deflection of magnetic microactuator.

Also, the static deflection of a cantilever beam, δ is given by the following equation [15],

$$\delta = \frac{4 \cdot F \cdot L^3}{E \cdot w \cdot t^3}, \qquad (2)$$

where L, E, w and t are the length, Young's modulus, the width and the thickness of the beam, respectively.

Considering the fact that the actual electromagnet is not an ideal air core electromagnet and that spatial misconfiguration exists, the fabricated microactuator shows strong linear correlation between static deflection and the current in the electromagnet, where L, w and t are 4 mm, 1 mm and 25 μm, respectively.

CONCLUSION

In this work, a novel technique for controlling vertical magnetization in electroplated CoNiMnP-based thick permanent magnet arrays has been demonstrated and the microactuator based on the electroplated permanent magnet arrays has been realized for the first time. The optimized processing conditions with external magnetic fields during electroplating have improved the coercivity and the remanence of the magnets by up to 220 % and 380% respectively, compared to those fabricated without external magnetic fields. Maximum coercivity of 1100 Oe and remanence of 1900 G were observed in the magnet arrays. A silicon cantilever beam microactuator was fabricated to carry the permanent magnet arrays at its free end. Bi-directional actuation according to the direction of electric current in a electromagnet was successfully achieved. The static deflection of the beam was in reasonably good agreement with the theoretical model. The innovative electroplated permanent magnets and prototype bi-directional microactuators are now envisaging numerous CMOS-compatible on-chip magnetic microactuators and sensors.

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