Micromachined Polymer Magnets

Laure K. Lagorce and Mark G. Allen
Microelectronics Research Center
Georgia Institute of Technology
Atlanta, Georgia 30332-0269

ABSTRACT

Micromachinable magnetic polymer composites have been prepared using commercial polyimide (Dupont PI-2555), and ferrite magnetic powders with different concentration levels (85 - 95 wt %). Magnetic, processability, and mechanical properties of these composites were measured. The B-H curve was measured using a vibrating sample magnetometer and showed typical permanent magnet behavior, with coercivity of 4000 Oe and residual induction approaching 3000 Gauss. In order to demonstrate the application of this material to micromachining, a simple permanent magnet microactuator has been fabricated. This actuator consists of a surface micromachined polyimide platform flexibly supported by tether arms. The composite material is deposited on the platform using screen printing. A 20 turn circular coil is integrated under the platform to complete the integrated microactuator. When driving the coil with 300 mA DC current, deflections of the platform in the range of +/- 30 μm have been achieved. By reversing the direction of the current, both attraction and repulsion of the actuator occurred which confirms the permanent magnet character of the material.

INTRODUCTION

Recently there has been much interest in magnetic microactuators. Fully integrated magnetic microactuators are of particular interest. Most of these microactuators have utilized magnetically soft materials. Hard magnetic materials are also desirable due to their favorable scaling [1], and the potential for larger forces applicable to the milli-scale. Permanent magnet actuators have been previously demonstrated by Benecke [2], [3], using hybrid assembled, commercially available permanent magnets. One reason that hybrid techniques have been used is the difficulty in depositing (either by electroplating, evaporation, or sputtering), and in patterning, sufficiently thick layers of permanent magnet materials in an integrated fashion. In this paper, we describe and characterize a magnetic composite material compatible with standard micromachining processes, which can be used to realize integrated permanent magnets. In order to demonstrate the utility of this material, a prototype magnetic microactuator based on this material is also presented.

MATERIALS CONSIDERATIONS

Materials which have suitable hard magnetic properties are usually not compatible with micromachining processes to make a fully integrated magnet. For example, the preparation of samarium-cobalt and neodymium-iron-boron magnets usually requires high temperature, pressing, and sintering. Magnetic polymer composites, in which small particles of magnetic material are suspended in a nonmagnetic (e.g., polymeric) matrix or binder, are a good compromise to combine the favorable properties of the magnetic material with the simple processing sequences of the polymer. In this work, polyimide was used as the binder material due to its common use in micromachining as well as its desirable chemical and thermal properties.

There are a variety of permanent magnet materials commercially available which might be candidates for the powder in a magnetic composite. Such materials can be characterized by their hysteresis loop and their demagnetizing curve. The demagnetizing curve gives two essential points: the residual induction Br of the magnet which can be related to actuation force, and the coercive force Hc which can be related to the resistance of the magnet to demagnetization. Table I (taken from [4]) shows a qualitative comparison of several commerically important magnetic materials.

In terms of large Br and Hc, the materials with the best magnetic properties are the rare earth alloys. However, it is not easy to find these materials in powder form suitable for composites since they are susceptible to oxidation and corrosion and the resultant loss of their desirable magnetic properties. Ceramic ferrites, although possessing lower values of Br and Hc, do not suffer from these problems. In addition, they are by far the most widely used type of permanent magnet material. For example, strontium ferrites are available with typical values of Br = 3600 Gauss and Hc over 4000 Oe. These are fine particle magnets made by powder metallurgical methods. During their production the powder may be milled to particles that are approximately single domain size (about 1 μm diameter). This fabrication process results in the magnetic properties of these ceramic ferrites being based on magnetic anisotropy, which produces a magnet with a high coercivity and an almost square second quadrant B versus H characteristic. Their great popularity is mainly due, though, to the low cost and great abundance of their raw materials.

Due to the above-described manufacturing method, strontium ferrite can be easily found in powder form with low particle size (~1.5 μm), for a reasonable price. In addition, these ferrites are very stable chemically. Due to these reasons, strontium ferrite powder was selected as the filler material in the magnetic composite.

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Table 1. Material comparison chart [4]

Material Class	Mechanical Properties	Density	Br	Hc	(BH) max	Relative cost
Alnico (cast)	Brittle	M	H	L-M	L-H	M
Alnico (sintered)	Brittle	M	H	L-M	L-M	H
Ferrite in organic binder	Soft Binder	L	L	M	H	L
Rare earth	Brittle	H*	H	H*	H*	H*

Key to Table: L = low; M = medium; H = high; H = highest; L-M = low to medium; L-H = low to high*

COMPOSITE FABRICATION

The polymer magnet is composed of 1.5 μm strontium ferrite particles produced by Hoosier Magnetics and Dupont PI-2555 polyimide (a benzophenone tetracarboxylic dianhydride-oxydianiline / metaphenylene diamine formulation). The composite is then formed by introducing various quantities (loading) of the magnetic particles into the polyimide. Various additives are optionally used to improve particle dispersion. The materials are mixed using a ball mill rotating at 4-5 rpm. The mixing period is held for at least 72 hours in order to insure homogeneity of the mixed composite solution. The polymer/ferrite liquid suspension is then deposited on a suitable substrate and patterned, e.g., by screen printing or spin-casting followed by photolithography. After deposition and patterning, the magnetic composite is cured to achieve its final properties. The composition of the magnets described below is based upon the weight percentages of the two constituents in the fully cured film. The weight of the polyimide in the cured film is calculated using the average percent solids of the polyimide solution.

MAGNETIC PROPERTIES

Test specimens were composed of square magnetic polymer sheets of ~ 9 μm thickness, and 2x2 cm area, deposited on square glass slides by using a multicoat procedure. A single coat of the multicoat procedure consists of a 3000 rpm, 40 s spin cycle followed by a 15 min soft bake at 120 °C. Three coats are used to produce the 9 micron thick film. The multicoat is then fully cured at 300 °C for one hour in a conventional oven. Upon final cure, the films are optionally exposed to an external magnetic field. Finally the polymer magnet films are removed from their glass substrates for testing.

Magnetic properties were measured by a vibrating sample magnetometer recording the hysteresis loop of the material, or magnetic flux density B (Gauss) as a function of the applied magnetic field H (Oe). Figure 1 shows a typical B-H curve of this material. From the second quadrant or demagnetizing curve, Hc and Br were deduced. For a 95 wt % sample (loading concentration of ferrite), a coercivity Hc = 4000 Oe and residual induction Br of almost 3000 Gauss were achieved. The overall B-H curve also demonstrates the typical square loop behavior of a permanent magnet.

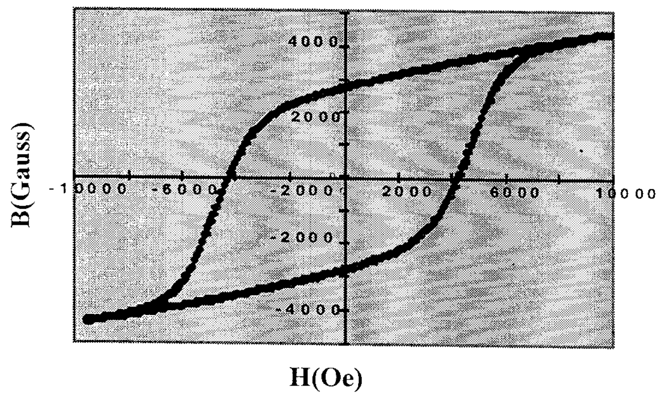

Figure 1. Filled polymer hysteresis loop

MECHANICAL PROPERTIES

The mechanical characteristics are determined by an analysis of the load/deflection behavior of a membrane [5] made from the magnetic polymer material. The load / deflection testing is performed using square membranes of the thin films which are fabricated on a silicon substrate. The suspended membranes are realized using standard micromachining techniques. In the fabrication process, 2 inch <100> wafers are heavily boron doped (> 10^{20} / cm^3) to form a p^+ etch stop layer approximately 3-5 μm thick. Silicon nitride, 5000 Å thick, is deposited using plasma CVD and is used as an etch mask for both sides of the wafer. Square windows are patterned in the Si_3N_4 on the unpolished side of the wafer using a buffered oxide etchant. The wafer is then anisotropically etched from the unpolished side in a 20 wt % potassium hydroxide solution heated to 56 °C to produce a silicon membrane. After the silicon etch is complete, a thin film of magnetic composite material is applied on the Si_3N_4 on the polished side of the wafer using the same single coat procedure as for the preparation of the composite samples for the magnetic measurement. When the composite film has been fully cured at 300 °C for one hour, the p^+ etch stop layer and Si_3N_4 layer are removed from the membrane regions using wet etching: 20 % H_2O, 75 % nitric acid and 5 % HF, resulting in the finished composite membrane. At this point, the mechanical properties (plane strain modulus and residual stress) can be determined from the load/deflection behavior of the membrane.

The mechanical characteristics are determined by an analysis of the load/deflection behavior of a membrane using an energy minimization approach [6], but modified to account for the presence of residual tensile stress and square dimensions [7-8]. For a membrane of side length 2a and thickness t, it can be shown that the relationship between the applied pressure and the deflection at the center of the membrane is given by:

$$\frac{Pa^2}{dt} = 3.04\sigma_0 + 1.33K\left(\frac{d}{a}\right)^2 \qquad (1)$$

with

$$K = \frac{E}{(1-\vartheta)} \qquad (2)$$

where P is the applied pressure, K is the plain strain modulus of the composite film, σ_0 is the residual stress in the film, and E and υ are the Young's modulus and Poisson's ratio of the film, respectively.

The characterization of the thin films is carried out using a material characterization station which allows application and simultaneous measurement of a pressure or vacuum load to the membrane. The apparatus is placed on a microscope stage. The deflection of the membrane at its center is measured by focusing on the membrane center and measuring the amount of microscope head travel necessary to keep the membrane in focus using a a z-axis digimatic indicator mounted on the microscope head. Figure 2 shows typical load-deflection data taken in this manner of an 85 wt% composite membrane.

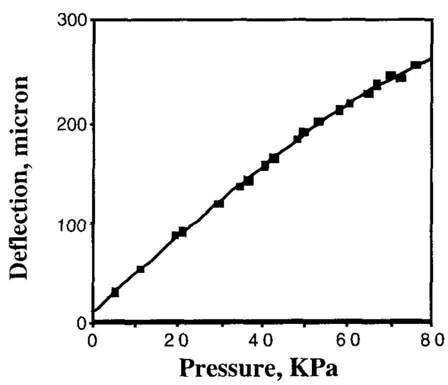

Figure 2. Typical load/deflection characteristics for the magnetic polymer composite (85 wt % loading).

Examination of equation (1) shows that if pressure-deflection data are plotted with $\frac{Pa^2}{dt}$ on the y axis and $\left(\frac{d}{a}\right)^2$ on the x axis, the data should fall on a straight line. The residual stress can then be determined from the y-intercept of the line, and the plane strain modulus from the slope of the line. Figure 3 shows the load-deflection data plotted in accordance with equation (1) for a single membrane. Similar measurements and data analysis on a total of four membranes yields a value of K = 3.99 Gpa and σ_0 = 42.2 GPa. These properties are close to those of unfilled polyimide.

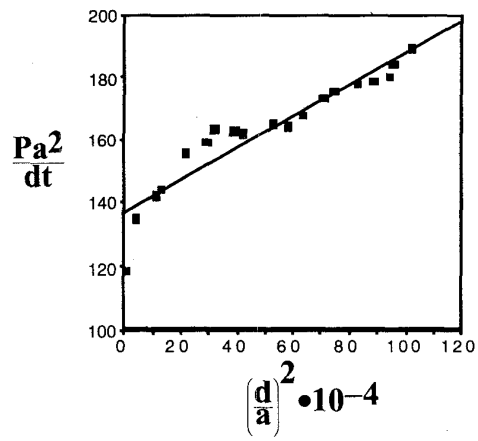

Figure 3. Load/deflection data plotted in accordance with Eq.(1) for the magnetic polymer composite films (85 wt % loading).

PROCESSABILITY OF THE POLYMER MAGNETIC COMPOSITE

The realized polymer magnetic composite can be patterned in different ways. Screen-printing deposition is an attractive technique due to its capacity to produce thick devices (100 µm thick devices have been produced without difficulty). Using this technique, magnets ranging from 250 microns to centimeters in width can be easily achieved. Figure 4 shows a screen-printed film with 250 micron features. Moreover it has also been demonstrated that this material can be patterned by using standard photolitography and wet etching of the polyimide composite. The process consits of depositing by spin-coating the magnetic polymer composite, soft-baking it, then depositing on the top of the composite standard photoresist, and soft-baking the photoresis and exposing using ultraviolet lithography. Upon developing, the photoresist developer also etches exposed regions of the composite. After etching and residual photoresist removal, the composite is fully cured. Devices on the order of 200 microns in width have also been fabricated using this technique.

APPLICATION TO A PROTOTYPE MICROACTUATOR

In order to demonstrate the applicability of this material to micromachining, a simple permanent magnet microactuator has been fabricated. The actuator is similar to that of Benecke [2], but with an integrated composite magnet in place of a hybrid assembled magnet. It consists of a screen-printed circular assembled magnet. It consists of a screen-printed circular polymer magnet prepared from the material described above, supported by a polyimide suspended beam mechanical flexure (see figures 5(a) and 5(b)). The fabrication sequence is described below and in figures 6(a) - 6(d). A 1 mm thick glass slide is used as substrate. On the back side of the substrate, a circular 20-turn planar coil, with inner and outer diameters of 4.2 and 6.6 millimeters respectively, is fabricated using standard photolithography and electroplating techniques. The line and space width of the coil are 40 µm and 20 µm, respectively and the coil thickness is 10 µm.

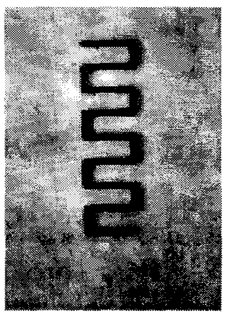

Figure 4. Screen-printed magnetic polymer composite: the width of each meander is 250 µm.

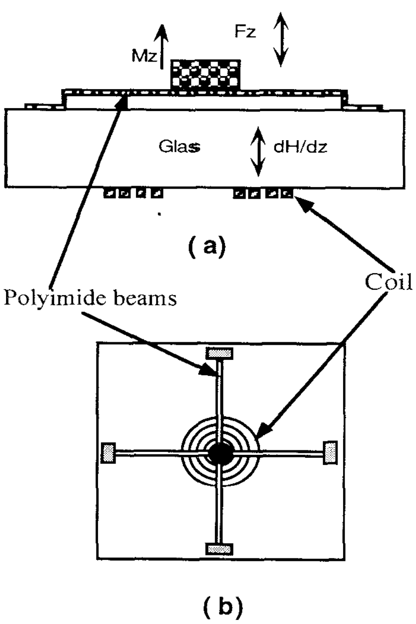

Figure 5. Side view (a), and top view (b) of the microactuator.

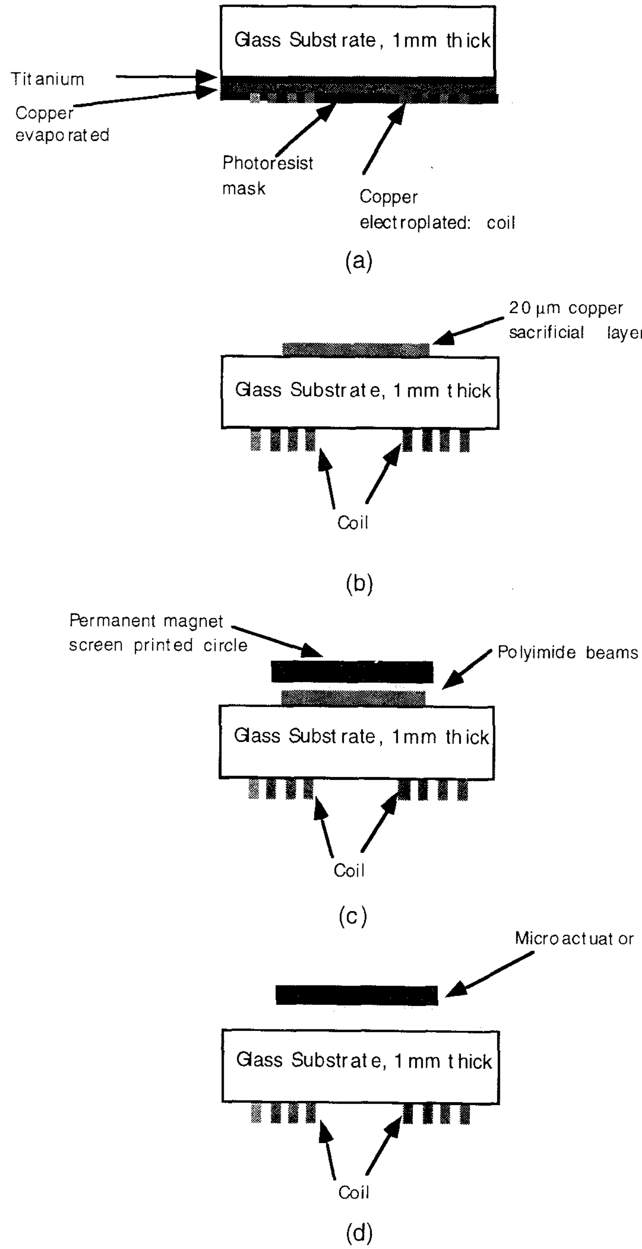

Figure 6. Fabrication process of the prototype microactuator. (a) Coil fabrication; (b) after sacrificial layer deposition; (c) after screen-printing of flexures and magnet; (d) after sacrificial layer etching.

The coil is then protected by an organic layer and fabrication of the actuator proceeds on the front side of the substrate. A titanium/copper layer is deposited and patterned on the front side of the substrate, and used as the seed layer for subsequent electroplating of a copper sacrificial layer. A polyimide mechanical flexure is then aligned and deposited using screen printing so that anchors extend off of the sacrificial layer onto the glass substrate, and the central circular region which will hold the magnet is directly over the coil on the other side of the substrate. The polyimide is then cured. The circular polymer magnet is screen-printed on the circular support of the flexure and cured. The copper sacrificial layer is then removed using a wet etch to release the structure.The magnet diameter is 4 mm and its thickness is 100 μm.The individual flexures are 6 mm long, 1 mm wide, and 20 μm thick. A photomicrograph of the fabricated actuator is shown in Figure 7.

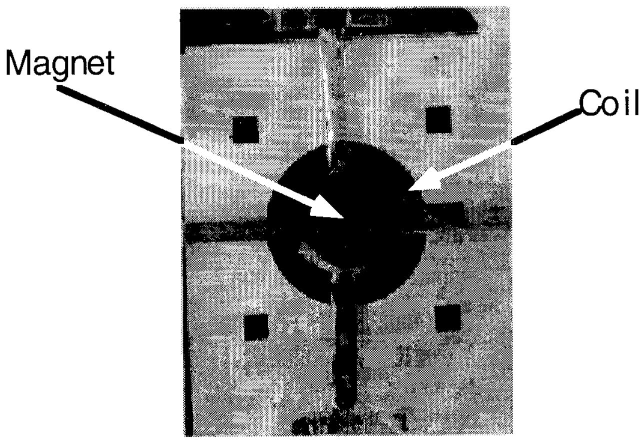

Figure 7. Photomicrograph of fabricated microactuator (type 2 suspensions)

By applying a current to the coil, a magnetic field H is created. The vertical force acting on the magnet with vertical magnetization Mz and volume V is given by [9]:

$$Fz = Mz\int_V d\frac{Hz}{dz}dv. \qquad (3)$$

where Hz is the vertical component of the magnetic field produced by the planar coil. Since the center of the magnet is outside the plane of the coil, a magnetic field gradient is created and thus an electromagnetic force Fz acts vertically on the magnet. Since the magnetic field gradient is proportional to current, and the magnetization Mz of the magnet is constant, this force is expected to be linear as a function of current. In addition, since the mechanical flexure is also linear (over the projected deflection ranges), the actuator deflection is predicted to be a linear function of current.

Tests have been made on two types of actuator. Type 1 consists of one cantilever supporting beam, and type 2 consists of four bridge supporting beams. Figure 8 shows the deflection of the magnet at its center as a function of current applied to the coil for type 1 suspensions. As expected, a linear relationship between deflection and current is achieved. By reversing the direction of the current, both attraction and repulsion of the actuator could be achieved over a range of +/- 30 μm. Type 2 actuators show deflections over a range of +/- 8 μm. The ability to both attract and repel this actuator confirms the permanent magnet character of the material.

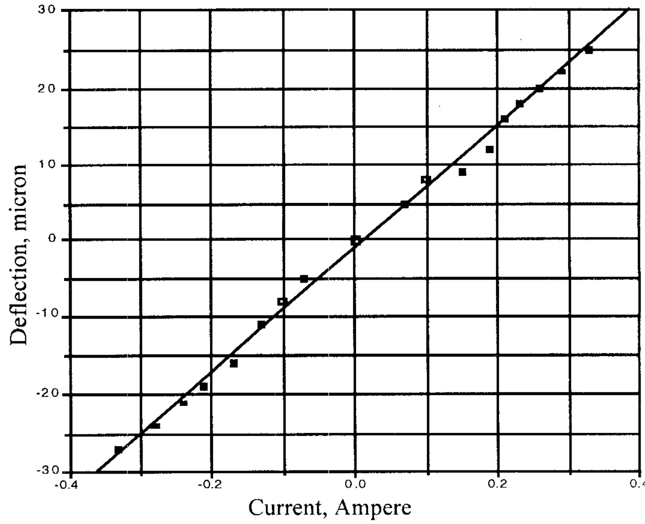

Figure 8. Deflection vs. current of type 1 microactuator

CONCLUSIONS

Integrated permanent magnets can be realized by processing magnetic polymer composites based on Dupont PI-2555 as the matrix, and strontium ferrite powder as an embedded magnetic material. These materials exhibit good hard magnetic properties (square hysteresis loop, with high coercivity Hc= 4000 Oe, and residual induction Br almost 3000 Gauss), and have the potential to produce actuators capable of large forces. The material can be patterned in a variety of ways, including screen-printing or standard photolithography combined with wet etching. Their soft binder material character (plane strain modulus ~ 4 GPa), and their low relative cost, position those magnetic polymer composites as desirable materials for micromachined permanent magnets. The magnetic nature of these materials as well as their potential for fabrication of microactuators has been shown through the realization of a prototype integrated permanent magnet microactuator.

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