Electroplated Soft Magnetic Materials for Microsensors and Microactuators

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SUMMARY

A number of micromachined magnetic sensors and actuators require materials with desirable magnetic properties as well as thicknesses in the range of several microns. Materials with appropriate magnetic properties have been reported for magnetic storage applications, but often in thickness ranges insufficient for other sensors and actuators. We report the development of an electroplating bath for the deposition of a high permeability, low coercivity material, a NiFeMo alloy. Using this bath, the NiFeMo alloy may be electrodeposited up to 5 microns in thickness. In addition we report the use of a NiCo soft magnetic alloy, and the use of NiCo and NiFe layered films for improved magnetic performance.

Keywords: Electroplating, Magnetic Material, NiFeMo

INTRODUCTION

The development of micromachined magnetic devices has relied primarily to date on the use of nickel-iron permalloy. Permalloy is used in a number of applications since it has good soft magnetic properties, high permeability, high magnetoresistive effect, low magnetostriction, stable high frequency operation, and excellent mechanical properties [1]. In hard disk magnetic recording heads, permalloy is widely used for magnetoresistive sensors and flux guiding elements. Devices such as microrelays [2], and inductors [3] have also been fabricated using permalloy for their magnetic materials as well as moving members. Permalloy microstructures have been used as flux guides for sensitivity improvement of magnetotransistors [4] and as a ferromagnetic core in mircofluxgate sensors [5]. These structures can be integrated with CMOS circuitry on a single chip.

However, there remains a need to improve the magnetic properties of the materials used in such applications. If the permeability of the films used in magnetic microactuators can be increased, the efficiency of the actuator may also increase. In addition, large permeability may increase the sensitivity of many magnetic sensors. Large saturation flux density allows devices to be made smaller in size, or it may allow for increased actuator force, and allow devices such as transformers to more efficiently store magnetic energy. In many applications for magnetic sensors the coercivity of the material should be as low as possible. Thus the development of high permeability, and large saturation flux density materials may allow for further improvements or new types of magnetic actuators to be developed.

The large body of literature on magnetic materials developed for magnetic storage applications provides many insights for magnetic MEMS. However, in many cases the materials were not electroplated to the thickness required for MEMS applications, in some cases due to large internal stresses in the deposited films. In spite of this, the data can be used as a starting point for the development of new electroplating baths.

Previously permalloy (NiFe 80/20) has been the most widely used electroplated material in magnetic microdevices [see, e.g., 2-6]. The reported relative permeability (without correcting for demagnetization effects) of these films is generally on the order of 500-1000, with coercivity ranging from 1-5 Oe. Some research into alternative materials has begun, e.g., a NiCo alloy of 79/21 has been reported with relative permeability of 19.4 [7].

Another alloy that has been reported in the literature is NiFeMo [8-9]. The original bath was reported in 1965 [8], and only investigated films up to several hundred angstroms in thickness. Previously the NiFeMo alloys presented in the literature had large stresses, and were not demonstrated over 800 Å in thickness [8]. Recent work has reported electroplated films up to 1 μm in thickness [9], however these films are still not thick enough for some micromachining applications. These films in a single layer consisted of Ni-17Fe-4Mo, and had coercivities on the order of 0.06 Oe, with saturation magnetization of 0.72 Tesla, and a relative permeability of 3400 at 10 MHz.

The baths developed in this work are capable of plating films up to and in excess of 5 μm in thickness. In addition, some films were plated in a sandwich structure to show that the magnetic properties of differing materials can be combined to arrive at new magnetic properties for a specific application.

EXPERIMENTAL PROCEDURE

The electroplating baths were developed based on the previous baths in the literature. The bath compositions used in this study are given in Table I. The NiFe bath used was reported in [10]. The NiCo bath reported was described by [11], and is nominally 50% Ni and 50% Co.

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A major difference between the NiFeMo electroplating bath reported in [8] and the NiFeMo electroplating bath reported here was an increase in the saccharin concentration. No pH adjustment was subsequently made after the additional saccharin was used. The motivation behind the addition of saccharin was to reduce the amount of residual stress in the films, and thereby allow thicker films to be plated. This effect has been reported by other authors [12] for permalloy electroplating baths.

TABLE I: Electroplating Bath Compositions

Chemical	NiFe Bath	NiCo Bath	NiFeMo Bath
$NiSO_4 \cdot 7H_2O$	200 g/L	300 g/L	60 g/L
$NiCl_2 \cdot 6H_2O$	5 g/L	50 g/L	-
$FeSO_4 \cdot 6H_2O$	8 g/L	-	4 g/L
$CoSO_4 \cdot 7H_2O$	-	29 g/L	-
$Na_2MoO_4 \cdot 2H_2O$	-	-	2 g/L
H_3BO_3	25 g/L	30 g/L	-
NaCl	-	-	10 g/L
Citric Acid	-	-	66 g/L
Sodium Lauryl Sulfate	-	0.1 g/L	-
Saccharin	3.0 g/L	1.4 g/L	3.0 g/L

Samples were plated on glass substrates with a titanium and gold seed layer. The NiFeMo alloy was also plated on a polished silicon substrate with a titanium and copper seed layer. The NiFeMo alloy was plated at 10 mA/cm^2 and 30 mA/cm^2, using a nickel foil as the anode. No heating was employed during the electroplating processes described, and only gentle stirring was used. The NiFe, NiCo, and NiFe/NiCo/NiFe sandwich structures were all plated at a nominal current density of 10 mA/cm^2. Nickel-iron electroplating was performed by using a nickel foil for the anode, thus allowing the amount of iron to decrease as the plating continued. This method of plating requires a more frequent mixing of new baths. Nickel-cobalt electroplating was performed by using a nickel anode and a cobalt anode and passing an equal amount of current through each anode. The cathode, or sample was connected to the negative terminal of each power supply.

The films were measured on a Lakeshore LS7300 vibrating sample magnetometer to obtain magnetization versus applied field curves. The B-H curves (described below) were then resolved in accordance with standard magnetics analysis techniques [13]. The applied field, H, is measured directly by a built-in field sensor. The magnetic induction, B, may be obtained (for cgs units) by dividing the resultant moment measurements by the sample volume, multiplying by 4 π, and adding the applied field. The effective permeability of the material may then be calculated for cgs units as the ratio of B to H for a given point on the B versus H curve.

The most critical procedure in determining relative permeability and saturation flux density is the measurement of the volume of the thin films. Several approaches to this may be taken. The sample may be measured on a mass balance and the volume determined for a material of known density. However, since plating parameters such as current density greatly influence the composition of the material, this method may not always be accurate. Another method, and the one employed here, is to measure the sample thickness for a known area sample. Since the sample patterns are made using photolithography techniques, the amount of error in the area to be plated is generally small, and does not vary significantly from sample to sample. Determining the actual height of the sample introduces the largest component of error in the volume measurement. Films may have thickness nonuniformities, as well as nodules and grains, both of which reduce the accuracy of the volume measurement. By using a surface profilometer, the height can easily be determined to within 0.5 µm. However, if the films are only 3 µm in thickness, this results in a 15-20 % error. On some samples, an optical profilometer Microfocus UBM was used to measure the thickness. Two-dimensional scans were taken over the complete film area and the film volume was calculated by integration. This technique still has a ±10 % error, but a much more accurate description of the surfaces is obtained. Nodules and grains are included more accurately in this method, and thus the error in the volume measurement is reduced.

It should be noted that the values of saturation flux density and relative permeability reported here contain these volume measurement uncertainties. However, for design purposes, the values of the magnetic induction are reported to allow for comparison between the magnetic materials, which can improve the performance of some micromachined devices.

MAGNETIC PROPERTIES

During initial plating experiments for the NiFeMo system it was determined that by plating in a magnetic field the coercivity of the film could be reduced, and the field required for saturation could also be reduced. A similar improvement in magnetic properties has been reported previously [14] for other materials. Since the properties of this alloy which are of most interest are low coercivity and high permeability, only the NiFeMo films plated in a magnetic field will be discussed.

Two different current densities were used for plating experiments, 10 mA/cm^2 and 30 mA/cm^2. The values at 10 mA/cm^2 showed the best results for sensor applications. Analysis of the atomic composition of the films at 30 mA/cm^2 was performed using EDS analysis and the atomic content of the films plated without the application of a magnetic field was 85 Ni - 14 Fe - 1 Mo. With the application of a magnetic field the films showed increased nickel and molybdenum concentrations, and a decrease of iron content. These changes could explain the decrease of the coercivity when the film is plated in the presence of an applied magnetic field.

For NiFeMo films plated at 10 mA/cm^2 under the influence of a 50 mT applied field, the B_{sat} values range from 0.97 to 1.07 Tesla, with measured effective permeability as large as 7,000 for the easy axis (the in-plane direction of the film parallel to the applied magnetic field during plating) and 2,200 for the hard axis (the in-plane direction of the film perpendicular to the magnetic field during plating). The measured data are corrected for demagnetization according to the actual geometric film parameters using an ellipsoidal approximation [15]. Figure 2 shows the resulting relative permeability versus applied field for the NiFeMo films. After correcting for demagnetization, maximum relative permeability on the order of 20,000 for the easy axis and almost 3,000 for the hard axis are observed. These films showed the lowest coercivity of any of the films, which were in the range of 0.35 Oe and 0.10 Oe for easy and hard axis, respectively.

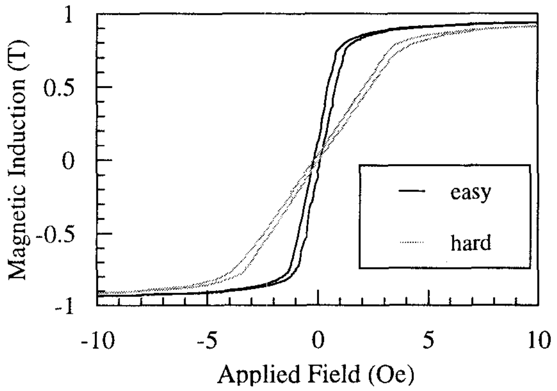

Figure 1: Nickel-iron-molybdenum magnetic induction versus applied magnetic field for easy and hard axis determined by vibrating sample magnetometer.

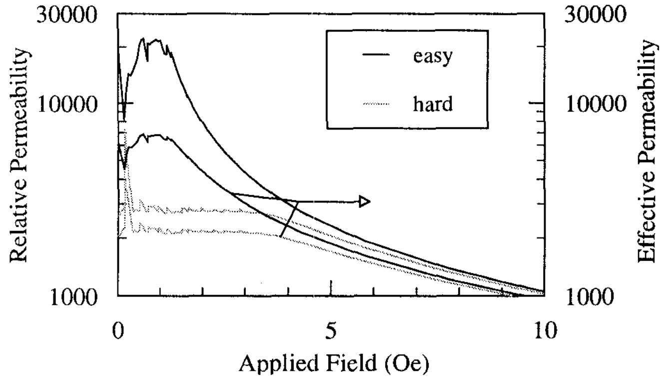

Figure 2: Nickel-iron-molybdenum relative permeability as derived from effective permeability measurement. The relative permeability (left scale) is shown after correction for the film demagnetization effect [15] by ellipsoidal approximation. The effective permeability (right scale) is the as-measured, uncorrected relative permeability.

The AC magnetic properties of the NiFeMo films were also investigated. This was done by measuring the impedance change of a U-shaped ferrite core while closing the core gap with the film. Figure 3 shows the easy and hard axis effective permeability versus frequency. The hard axis effective permeability is constant over the entire frequency range from 30 kHz up to 1 MHz and matches well with the VSM determined low frequency value of 2200. Such results demonstrate the usefulness of this material for high frequency sensors. As expected, the easy axis permeability strongly decreases with frequency.

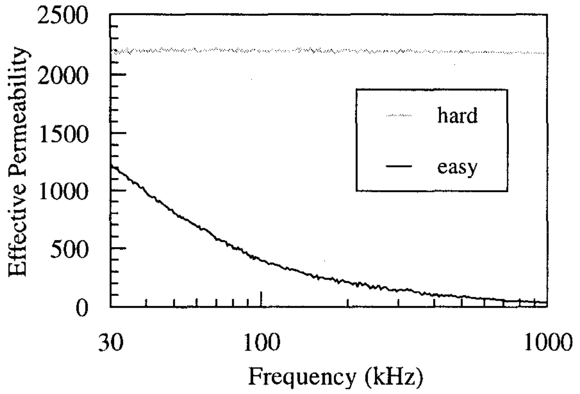

Figure 3: Nickel-iron-molybdenum effective permeability versus frequency of applied magnetic field. The hard axis permeability is constant up to 1 MHz.

The saturation magnetization for NiCo films plated at 10 mA/cm^2 was approximately 0.95-1.05 Tesla. The coercivity of these films was in the range of 15 to 17 Oe. The as-measured (effective) permeability was typically 100 to 150. The atomic composition was measured using EDS and was found to be the nominal composition of 50% Ni and 50% Co within the measurement accuracy of the system. Figure 4 shows the magnetic induction versus applied field for a film of this material.

Conventional NiFe permalloy films were electroplated to compare them with the properties of the new materials. For NiFe films, plated at 10 mA/cm^2, the B_{sat} value was approximately 0.9 - 1.08 Tesla, with as-measured (effective) permeability in the range of 500 to 1,000. The measured coercivities of typical NiFe films ranged from 0.7 to 1.5 Oe. Figure 5 shows the magnetic induction versus the applied field for NiFe films.

Figure 6 shows a typical magnetic induction versus applied field curve for a typical NiFe/NiCo/NiFe sample of approximately 3.5 µm in total thickness. NiFe/NiCo/NiFe multilayer films had a B_{sat} of 1.0 to 1.1 Tesla, with typical as-measured (effective) permeability ranging from 200-500. The coercivity of these films was 1.8 to 2.5 Oe. The multilayer film was deposited by electroplating NiFe at 10 mA/cm^2, then plating NiCo at 10 mA/cm^2, and finally plating NiFe again at 10 mA/cm^2. These films were all plated using direct current conditions. Thus the coercivity is reduced from the value seen for NiCo, but increased over NiFe.

CONCLUSIONS

A variety of magnetic materials have been successfully electrodeposited in thickness ranges useful for many micromachining applications. An electroplating bath capable of plating NiFeMo films up to five microns in thickness has been developed. Films plated from this bath show reduced coercivity and higher effective permeability when compared to other films commonly used for micromachining magnetic applications. Such films have the potential to increase the efficiency of microactuators, and increase the sensitivity of magnetic microsensors, such as fluxgate sensors.

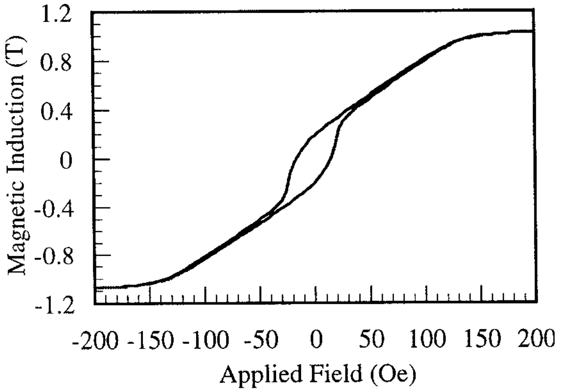

Figure 4: Nickel-cobalt magnetic induction versus applied field.

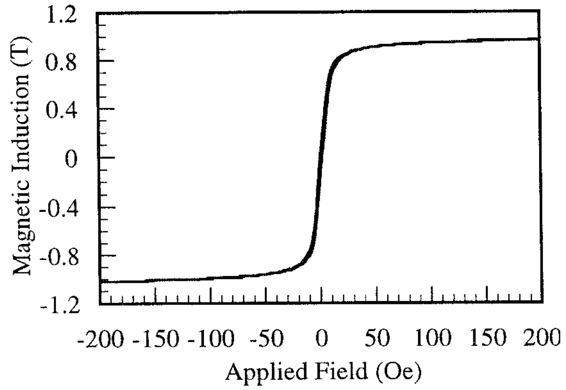

Figure 5: Nickel-iron film magnetic induction versus applied field.

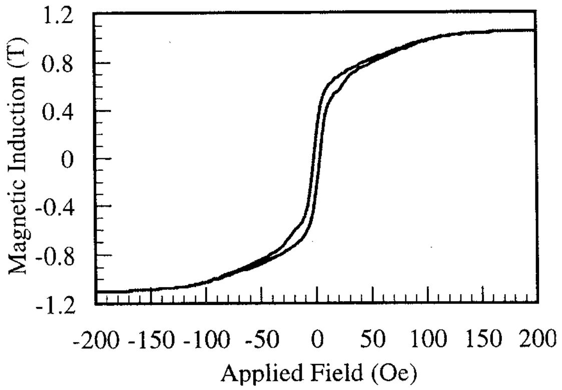

Figure 6: Nickel-iron, nickel-cobalt, nickel-iron multilayer film magnetization induction versus applied field.

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