# Magnetic Materials for MEMS

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***Abstract***— **The use of magnetic materials in MEMS are considered with particular emphasis on ferromagnetic materials. Soft ferromagnetic materials have thus far found the most utility in microsensors, microactuators, and microsystems, but hard magnetic materials have unique advantages that are driving their integration with MEMS. Batch-fabrication processes for micromachining thick films of high-performance hard magnetic materials are improving. The design of ferromagnetic MEMS and the methods of integrating both soft and hard magnetic materials with MEMS are described.**

## I. Introduction

Commercially successful devices and systems that use microfabrication and MEMS technologies include many microsensors (e.g., inertial sensors, pressure sensors, magnetometers, chemical sensors, etc.), microactuators (e.g., micromirrors, microrelays, microvalves, micropumps, etc.), and microsystems (e.g., chemical analysis systems, sensor-feedback-controlled actuators, etc.) [1]. In microsensors, physical quantities are converted into easily measured electrical signals by different transduction mechanisms (e.g., piezoresistance, magnetostriction, photoconductivity, etc.). In microactuators, typically an electrical signal is converted into a mechanical output through other transduction mechanisms or forces (e.g., electrostatic, magnetostatic, thermal expansion, piezoelectric, etc.). In microsystems, the components consist of variety of microsensors, microactuators, and passive microstructures.

The most successful MEMS products exploit one or more of the following characteristics: (1) advantageous scaling properties for improved device or system performance; (2) batch fabrication to reduce size and hopefully cost; and (3) circuit integration to improve performance, increase capabilities, or to reduce barriers to incorporation into larger systems. Since MEMS were largely developed with integrated-circuit (IC) technology and infrastructure, early MEMS were made out of conventional IC materials. In addition, early microsensors and microactuators used conveniently available transduction mechanisms (e.g., piezoresistance and variable capacitance) and driving forces (e.g., electrostatic and thermal forces) respectively.

As the field of MEMS evolves, it has taken advantage of the materials, microfabrication technologies, transduction mechanisms, and driving forces developed by other industries. Among these industries a large contribution to the field of MEMS has been provided by the magnetic information-storage industry, and specifically from the recording-head and disk-drive industries. These industries developed many microfabrication technologies (e.g., thick-film photolithography, electroplating, chemical mechanical polishing, etc.), microsensor transduction mechanisms (e.g., magnetoresistance and variable inductance), driving forces (e.g., magnetostatic, magnetostriction, and lorentz force), and novel magnetic materials.

## II. Magnetic Materials

Before a description of the magnetic materials used in MEMS can be presented, the units and fundamental equations of magnetism must first be discussed. The relationship between magnetic field $H$ and magnetic flux density $B$ in free space is $B = \mu_0 \cdot H$, with permeability of free space $\mu_0 = 4\,\pi \cdot 10^{-7}$ V·s/A·m. The mks units of magnetic field are A/m and an older unit still commonly used is oersteds (79.577 A/m = 1 Oe). The mks units of magnetic flux density are V·s/m$^2$ or Tesla and an older unit still commonly used is gauss (1 Tesla = 1 V·s/m$^2$ = 10,000 gauss). When the magnetic fields and flux densities of interest are inside magnetic materials, the equation for free space must be adjusted to account for the magnetization $M$ of the material. There are many forms of this equation, but the one used here is $B = \mu_0 \cdot H + M, = \mu_r\, \mu_0 \cdot H$, with relative permeability $\mu_r$, and thus the units of $M$ are the same as $B$ [2].

Magnetic materials can be classified according to their magnetic susceptibility $\chi = M / H$ and relative permeability $\mu_r = (\chi / \mu_0 + 1)$ into several categories: ferromagnetic, ferrimagnetic, antiferromagnetic, paramagnetic, diamagnetic, and superconducting materials. Listed in Table I are the typical ranges of $\chi / \mu_0$ for each category of magnetic material and examples of each are identified. Of these, ferromagnetic materials have found the most use in magnetic microsensors, microactuators, and microsystems. Their high relative permeability amplifies small magnetic fields into large flux densities for microsensors and their high saturation magnetization can generate strong fields for microactuation.

TABLE I
MAGNETIC MATERIAL CLASSIFICATION

| Category | $\chi/\mu_0$ | Examples |
|---|---|---|
| Ferromagnetic | $10^7$ to $10^2$ | Ni, Fe, Co, NiFe, NdFeB |
| Ferrimagnetic | $10^4$ to $10^1$ | $Fe_3O_4$, ferrites, garnets |
| Antiferromagnetic | small | MnO, NiO, $FeCO_3$ |
| Paramagnetic | $10^{-3}$ to $10^{-6}$ | Al, Cr, Mn, Pt, Ta, Ti, W |
| Diamagnetic | $-10^{-6}$ to $-10^{-3}$ | Ag, Au, C, H, Cu, Si, Zn |
| Superconducting | -1 | $YbBa_2Cu_3O_x$ |

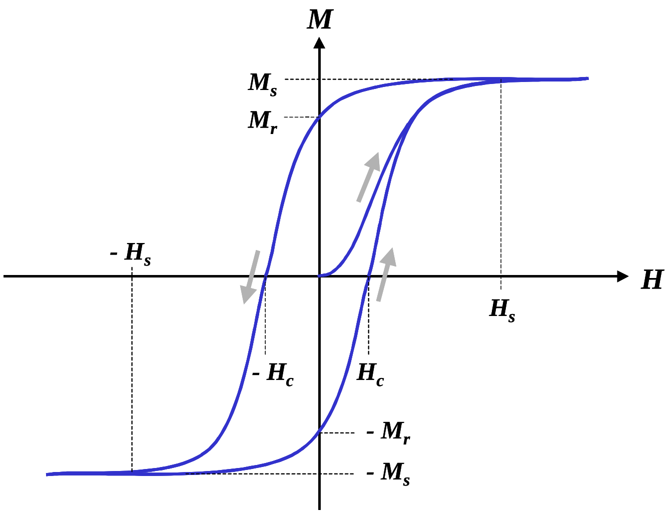


**Fig. 1. Generic hysteretic plot of magnetization as a function of magnetic field for a ferromagnetic material.**

When ferromagnetic materials are magnetized, demagnetized, and re-magnetized, they exhibit a hysteretic behavior illustrated as shown in Figure 1. Important and often quoted features of these graphs are the saturation magnetization $M_s$, remanent magnetization $M_r$, coercivity $H_c$, and saturating field $H_s$. With these parameters, ferromagnetic materials can be divided into so-called soft magnetic materials (i.e., with a small coercivity and low saturation field) and hard magnetic materials (i.e., with a large coercivity and high saturation field).

## III. Soft Magnetic Materials in MEMS

The most commonly used magnetic materials in MEMS are soft ferromagnetic materials, such as NiFe alloys (e.g., permalloy, which is typically 81% Fe and 19% Ni). The combination of relatively high saturation flux density, low hysteretic losses, and near zero magnetostriction (i.e., stresses in the device will not impact its magnetic performance) has driven their use in macroscopic and microscopic sensors, actuators, and systems. Perhaps the most significant reason for their common use in magnetic MEMS is that these materials are used in magnetic recording heads and the technologies necessary for depositing and micromachining them have been well developed by that large industry.

The design and construction of magnetic microactuators has generally mimicked that of their macroscopic counterparts. Specifically, most involve ferromagnetic cores (NiFe) wrapped with current-carrying windings (Cu) that generate the fields and flux densities used to actuate the devices. The methods used to integrate ferromagnetic cores and conductive windings have largely followed the procedure developed for magnetic recording heads. The process consists of three primarily steps: (1) deposition and patterning of the lower part of the ferromagnetic core, (2) deposition and patterning of the conductive windings, and (3) deposition and patterning of the upper part of the ferromagnetic core [3]. A creative though-little used alternative is to swap the magnetic and conducting materials so that the coil is deposited and patterned in one step, instead of two, and then the ferromagnetic core requires a two-step process, instead of one [4]. The potential advantage of this unique process is that it may provide a lower coil resistance, but at the cost of a higher core reluctance.

Prominent examples of ferromagnetic microactuators constructed with on-chip coils include the early micromotors developed by Christenson [5] that used assembled windings (Fig. 2a) and the micromotors with integrated windings used by Ahn and further developed by his lab (Fig. 2b) [6]. The same coil-integration process has also been used to produce flux-gate magnetometers [7] non-destructive crack detection systems [8], and even a complete microfluidic system (i.e., microvalves, micropumps, and molecular detectors that sense the presence of magnetic beads attached to target molecules) [9].

The most sensitive and commercially successful microfabricated ferromagnetic magnetometers use magnetoresistive or MR elements (e.g., thin films of low-noise NiFe) that can be used to detect magnetic fields as small as 2.16 mA/m (27 μOe) [10]. Multi-layer films that exhibit larger magnetoresistive sensitivity are the so-called giant magnetoresistive (GMR) or colossal magnetoresistive (CMR) films. Higher film noise limits their use in low-field detection systems [11].

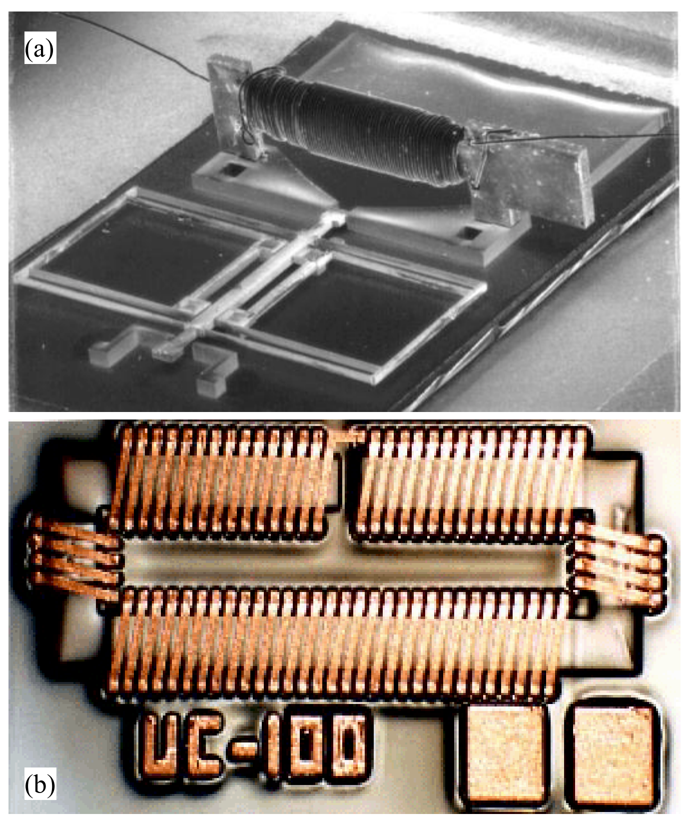


**Fig. 2. Micromotors constructed with (a) assembled (from [5]) and (b) integrated windings (from [6]).**

In addition to coil-based magnetic sensor and actuator designs, less conventional designs have also been developed that have some particular advantages. One example uses a simple ferromagnetic bar integrated onto a non-magnetic micromechanical flexure [12]-[14]. Such devices are readily able to achieve extremely large relative motion both in the plane of the substrate and perhaps more importantly out of the plan of the wafer (Fig. 3). The use of an external source for the magnetic field that drives the actuator greatly simplifies the fabrication process at the expense of a more complex and demanding package. The same basic design (i.e., a ferromagnetic bar attached to a non-magnetic microflexure system) is also used to realize a new low-power micromechanical magnetometer [15].

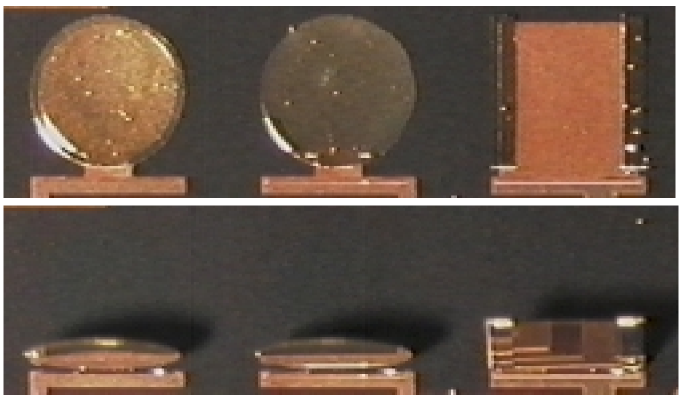

**Fig. 3. Ferromagnetic microactuator that uses off-chip coils top achieve large deflections (from [14]).**

Yet another class of magnetic microactuators are driven by soft magnetic materials that have been optimized for maximum magnetostriction [16]. Primary examples include TbFe alloys, TbCo alloys, and TbFe/FeCo multilayers. The typical microactuator configuration is a cantilever or membrane coated on one side with the magnetostrictive material. The application of a field induces a large strain mismatch that deflects the bimorph microstructure.

## IV. Hard Magnetic Materials in MEMS

Although soft magnetic materials can be used to realize high-force actuators and sensitive magnetometers, hard magnetic or permanent magnetic materials would be more appropriate in some cases. For example, hard magnetic materials with a high remanent magnetization $M_r$ can be conveniently used in bi-directional (push-pull) microactuators [17]. In addition, microactuators driven by off-chip coils could be activated with lower fields and hence lower power levels if a hard magnetic material is used instead of a soft magnetic material. However, except for a few instances hard magnetic materials have not been used extensively in MEMS [18]. The primary reason for this has been the lack of readily available and reliable deposition and micromachining processes. Various hard magnetic materials can be prepared by metallurgical processes (e.g., sintering, pressure bonding, injection molding, casting, extruding, and calendering), vacuum processes (e.g., evaporation, sputtering, MBE, CVD), and electrochemical processes (e.g., electroless deposition and electrodeposition).

Originally, most hard magnetic materials have been based on cobalt alloys because its hcp structure has a high crystal anisotropy. Thus far Co-based alloys with P, As, Sb, Bi, W, Cr, Mo, Pd, Pt, Ni, Fe, Cu, Mn, O and H have been deposited. Elements alloyed into Co tend to become concentrated at the grain boundaries. The result is isolated magnetic Co particles surrounded by non-magnetic or weakly magnetic boundaries [19]. Such formations create microscopic energy barriers that increase the coercivity $H_c$ of the film, thereby making it magnetically harder. The exceptions are that Pt and Pd are readily alloyed with Co or CoNi and have the effect of increasing the magnetocrystalline anisotropy [20]. Luborsky electrodeposited Co and CoNi with P, As, Sb, Bi, W, Mo and Cr, and the amount of the alloying element required for maximum deposit coercivity in decreasing order is P > As > Sb > Bi and W > Mo > Cr [19]. As expected, the saturation magnetization $M_s$ decreased with the increasing content of the non-magnetic alloying element. Low deposit contents of phosphorus or tungsten, however, have resulted in high coercivity with still a relatively high $M_s$.

Promising hard magnetic thin film materials include CoPt and FePt due to their high magnetocrystalline anisotropy and magnetic saturation [20]. Specifically, tetragonal L1O ordered phase materials (Co50Pt50 and Fe50Pt50) show very high coercivities (>10,000 Oe) [21]. Most investigations of CoPt and FePt deposits were conducted using vacuum processes (e.g., MBE [22] and sputtering [21]-[24]), where CoPt and FePt were deposited in multilayered structures and then annealed to produce ordered phases. A major disadvantage of these deposition methods for some magnetic MEMS applications is the requirement for high-temperature post-processing annealing (e.g., 500 to 700°C), as ICs and some materials commonly used in MEMS (e.g., Al, polymers, etc.) will not survive at these temperatures. Although Farrow and Marks report that electrolytically charging the transition metal alloy with hydrogen can mitigate the annealing process [25], it is nevertheless still a problem.

CoPt and Co/Pt multilayers can be electrodeposited from various plating solutions at or near room temperature [26]-[29]. Cavalloti obtained hard magnetic Co-Pt electrodeposits with a coercivity that reduced from 4000 to 2000 Oe as the film thickness was increased from 50 nm to 10 μm [30].

In 1983 the production of NdFeB magnets using sintering or melt spinning processes led to their use in many commercial products. These bulk NdFeB alloys represented an exciting new type of hard magnetic material because it did not contain expensive and rare elements, such as cobalt, and was able to produce a maximum energy product of up to 50 MGOe (0.4 MJ/$m^3$). A nanocomposite structure of NdFeB alloys enhances the remanent magnetization $M_r$ while maintaining high coercivity $H_c$. Long and Grandjean reviewed the properties and structure of bulk rare-earth iron-group (RE- IG) alloys in detail [30].

Processes have been developed for micromachining NdFeB permanent magnets using injection molding and pressure bonding [31], but it is not a fully integrated or batch-fabricated process (i.e., some assembly required). A batch-fabricated process that enables photolithographically definable composites of strontium ferrite powder and polyimide has also been developed that only requires a 300ºC-curing step [32]. Although thin films of CoSm and NdFeB (<1 µm) can be vacuum deposited [20]-[21], in most cases the as-deposited RE-IG films were amorphous and had soft magnetic properties (e.g., $H_c < 100$ Oe) [33]-[34]. In order to enhance the coercivity, high temperature annealing (>400°C) [20] or a high substrate temperature (>600°C) during deposition was needed. Lastly, although RE-IG alloys have great potential for use in MEMS, a high corrosion rate means that they will need to be coated with a protective layer before being exposed to the strong chemistries often used in micromachining (e.g., concentrated HF, KOH, etc.).

## V. Conclusions

Magnetic materials, particularly ferromagnetic materials, have many uses in MEMS. Although soft magnetic materials have found the greatest utility in MEMS, improved processes for integrating hard magnetic materials with MEMS are increasing the frequency of their use in high-force microactuators and low-power microsensors.

## References


[1] G. T. A. Kovacs, *Micromachined Transducers Sourcebook*. WCB/ McGaw-Hill, ISBN 0-07-290722-3 (1998).

[2] S. Chikazumi and Z. H. Charap, *Physics of Magnetism*. Robert E. Krieger, ISBN 0-88275-662-1 (1986).

[3] A. Chiu, I. Croll, D. E. Heim, R. E. Jones, Jr., P. Kasiraj, K. B. Klaassen, C. D. Mee, and R. G. Simmons, "Thin-film inductive heads", *IBM Journal of Research and Development*, vol. 40, no. 3, pp. 283-300 (1996).

[4] C. H. Ahn and M. G. Allen, "A New Toroidal-Meander Type Integrated Inductor with Multilevel Meander Magnetic Core", *IEEE Transactions on Magnetics*, vol. 30, no. 1, pp. 73-79 (1994).

[5] H. Guckel, T.R. Christenson, J. Klein, T. Earles, S. Massoud-Ansari, "Micro Electromagnetic Actuators Based on Deep X-Ray Lithography", International Symposium on Microsystems, *Intelligent Materials and Robots*, Sendai, Japan, (September 27-29, 1995).

[6] D. J. Sadler, T. M. Liakopoulos, and C. H. Ahn, "A Universal Electromagnetic Microactuator Using Magnetic Interconnection Concepts", *IEEE Journal of Microelectromechanical Systems*, vol. 9, no. 4, pp. 460-468 (2000).

[7] T. M. Liakopoulos and C. H. Ahn, "A micro-fluxgate magnetic sensor using micromachined planar solenoid coils", *Sensors and Actuators A (Physical)*, vol. A77, no. 1, pp. 66-72 (1999).

[8] D. J. Sadler and C. H. Ahn, "On-chip eddy current sensor for crack detection in metals", *Solid-State Sensor and Actuator Workshop Technical Digest*, Hilton Head Island, SC, pp. 142-145 (4-8 June 2000).

[9] J.-W. Choi, K. W. Oh, J. H. Thomas, W. R. Heineman, H. B. Halsall, J. H. Nevin, A. J. Helmicki, T. H. Henderson, and C. H. Ahn, "An integrated microfluidic biochemical detection system with magnetic bead-based sampling and analysis capabilities", *14th IEEE International Conference on Micro Electro Mechanical Systems, Technical Digest* Interlaken, Switzerland, pp. 447-450 (Jan. 2001).

[10] HMC1001/1002 Data Sheet, Honeywell Inc., Morristown, NJ 07962.

[11] E. W. Hill, A. F. Nor, J. K. Birtwistle, and M. R. Parker, "A giant magnetoresistive magnetometer", *Sensors and Actuators A (Physical)*, vol. A59, no. 1-3, pp. 30-37 (1997).

[12] J. W. Judy, H. H. Zappe, and R. S. Muller and, "Magnetic microactuation of polysilicon flexure structures", *IEEE Journal of Microelectromechanical Systems*, vol. 4, no. 4, pp. 162-169 (1995).

[13] J. W. Judy and R. S. Muller, "Magnetic microactuation of torsional polysilicon structures", *Sensors and Actuators A (Physical)*, vol. A53, no. 1-4, pp. 392-396 (1996).

[14] J. W. Judy and R. S. Muller, "Magnetically Actuated, Addressable Microstructures", *IEEE Journal of Microelectromechanical Systems*, vol. 6, no. 3, pp. 249-256 (1997).

[15] H. Yang, N. Myung, J. Yee, M. Schwartz, K. Nobe, and J. W. Judy, "Ferromagnetic Micromechanical Magnetometers", *International Conference on Solid-State Sensor and Actuators (Transducers 2001)*, Munich, Germany, (June 10-14, 2001).

[16] A. Ludwig, and E. Quandt, "Giant magnetostrictive thin films for applications in microelectromechanical systems", *Journal of Applied Physics*, vol. 87, no. 9, pt.1-3, pp. 4691-4695 (1 May 2000).

[17] H. J. Cho, S. Bhansali, and C. H. Ahn, "Electroplated thick permanent magnet arrays with controlled direction of magnetization for MEMS application", *Journal of Applied Physics*, vol. 87, no. 9, pt. 1-3, pp. 6340-6342 (2000).

[18] T.-S. Chin, "Permanent magnet films for applications in microelectromechanical systems", *Journal of Magnetism and Magnetic Materials*, vol. 209, no. 1-3, pp. 75-79 (2000).

[19] F. E. Luborsky, "High coercive force films of cobalt-nickel with additions of group VA and VIB elements", *IEEE Transactions on Magnetics*, vol. 6, no. 3, pp. 502-505 (1970).

[20] R. M. Bozorth, *Ferromagnetism*, D. Van Nostrand (1963).

[21] K. R. Coffey, M. A. Parker and J. K. Howard, "High anisotropy L1/sub 0/ thin films for longitudinal recording", *IEEE Transaction Magnetics*, vol. 31, no. 6. pp. 2737-2739 (1995).

[22] C. H. Lee, R. F. C. Farrow, C. J. Lin and E. E. Marinero, "Molecular-beam-epitaxial growth and magnetic properties of Co-Pt superlattices oriented along the (001), (110), and (111) axes of Pt", *Physical Review B*, vol. 42, no. 7, pp. 11384-11386 (1990).

[23] P. F. Garcia, Z. G. Li, and W. B. Zeper, *Journal of Magnetism and Magnetic Materials*, vol. 121, pp. 452-60 (1993).

[24] R. F. Farrow and R. F. Marks, U.S. Patent #5,792,510.

[25] Y. Jyoko, S. Kashiwabara, Y. Hayashi and W. Schwarzacher, "Characterization of electrodeposited magnetic nanostructures", *Journal of Magnetism and Magnetic Materials*, v. 198-199, pp. 239-242 (1999).

[26] J. Horkans, D. J. Seagle, and I. Chia Hsu Chang, "Electroplated magnetic media with vertical anisotropy", *Journal of the Electrochemical Society*, vol. 137, no. 7, pp. 2056-2061 (1990).

[27] M. Monew, I. Krastev, and A. Zielonka, "In situ stress measurements during electrodeposition of Ag-Sb and Pt-Co alloy multilayers", *Journal of Physics: Condensed Matter*, vol. 49, no. 11, pp. 10033-10040 (1999).

[28] V. Tutovan and V. Georgescu, "The magnetic behavior of thin electrolytically deposited Co-Pt films", *Thin Solid Films*, vol. 61, no. 2, pp. 133-140 (1979).

[29] P. L. Cavallotti, N. Lecis, H. Fauser, A. Zielonka, J. P. Celis, G. Wouters, J. Machado de Silva, J. M. Brochado Oliveria and M. A. Sa, "Electrodeposition of magnetic multilayers", *Surface and Coatings Technology*, vol. 105, pp. 232-39 (1998).

[30] G. J. Long and F. Grandjean, "Supermagnets, Hard Magnetic Materials", *NATO ASI Series*, vol. 331, Kluwer Academic Publishers, Dordrecht (1990).

[31] T. J. Garino, T. Christenson, and E. Venturini, "Fabrication of MEMS devices by powder-filling into DXRL-formed molds", *Materials Science of Microelectromechanical Systems (MEMS) Devices*, Boston, MA, USA, pp. 195-200 (1-2 Dec. 1998.).

[32] L. K. Lagorce and M. G. Allen, "Magnetic and mechanical properties of micromachined strontium ferrite/polyimide composites", *Journal of Microelectromechanical Systems*, vol. 6, no. 4, pp. 307-312 (1997).

[33] C. Prados and G. C. Hadjipanayis, "Magnetic and structural properties of high coercivity Sm(Co, Ni, Cu) sputtered thin films", *Journal of Applied Physics*, vol. 83, no. 11, pp. 6253-6255 (1998).

[34] S. N. Pirmanayagam, M. Matsumoto, A. Morisako, "Thickness dependence of magnetic properties of NdFeB thin films with perpendicular magnetic anisotropy", *Journal of Magnetism and Magnetic Materials*, vol. 212, pp. L12-L16 (2000).