# Batch-Fabricated Microinductors with Electroplated Magnetically Anisotropic and Laminated Alloy Cores

Jae Yeong Park, Suk H. Han, and Mark G. Allen

***Abstract*—Although many integrated inductors have been made by integrated circuit and electronic packaging batch-fabrication techniques, their magnetic characteristics are inferior to their discrete counterparts, in part because of the relatively poor magnetic properties of integrated magnetic cores. If the permeability of an integrated magnetic core can be increased, the magnetic characteristics of microinductors based on these cores will improve. To address this issue, batch-fabricated, integrated magnetic devices incorporating electroplated magnetically anisotropic cores and electroplated copper coils are investigated. These devices are made by micromachining and electroplating techniques at low temperature. Three different geometries of inductors, each possessing two different core materials [permalloy (NiFe) and supermalloy (NiFeMo)] are presented. The cores have been rendered magnetically anisotropic by application of a magnetic field during electrodeposition, resulting in easy and hard axis orientations. In addition, some cores consist of a two-layer electrodeposit separated by a polyimide thin-film lamination. At low frequencies (less than several hundred kHz), the easy-axis devices have higher inductance than the hard-axis devices. However, the hard-axis devices have better performance at higher frequencies because of a far less steep falloff of material permeability as a function of frequency in the hard axis direction.**

***Index Terms*—Easy axis, electroplating, hard axis, integrated, lamination, low temperature processes, magnetically anisotropic, microinductors, micromachining, permalloy, supermalloy.**

## I. Introduction

MUCH research has been done to integrate passive components with semiconductor circuitry. Planarized versions of discrete-leaded resistors and capacitors, whether in chip component format for surface mount printed circuit board assembly or in integrated planar format in hybrid circuits, have been successful and are available in a wide range of values. However, conductor wire-wound magnetic components such as inductors and transformers have resisted the trend toward integration and planarization, principally due to the difficulty of fabricating these components and achieving appropriate magnetic performance or power handling capability. Even today, surface mount assembly and encapsulated wire wound magnetic components are used to obtain high quality factors and an adequate range of values.

Planar magnetic components are planar versions of conventional wire-wound inductors and transformers. Miniaturization of magnetic components pushes the operating frequency to a few hundred MHz. In discrete or macroscaled devices, the geometries of these devices are often of a solenoid-type in which a conductor coil is wrapped around a magnetic core. Macroscale magnetic devices have high inductance, high quality factor, and low dc resistance because of a large number of turns, thick conductor lines, a thick and large cross-sectional area of magnetic core, and good magnetic properties of the bulk magnetic core. However, assembly requirements and poor packaging opportunities due to size (e.g., in achieving low-profile components) are also disadvantages in applications of macroscaled magnetic devices, especially in electronics applications.

In microscale devices, a large number of coil turns and thick and large cross-sectional area of the magnetic core are difficult to achieve using conventional microfabrication techniques. Also, the geometry constraints because of the difficulty of fabrication as well as poor magnetic properties because of impurity or contamination occurring during the processing are disadvantages in integrated microscaled devices. In integrated microscaled devices, many parasitic effects must be considered in the design stage. For example, when an integrated inductor is fabricated on top of a substrate, the dielectric constant and conductivity of the substrate or the line spacing between adjacent conductors can affect the performance of these magnetic devices; these are effects which can often be neglected in the case of macroscaled inductors.

However, there are several advantages of integrated microscaled magnetic devices such as the potential for high volume production using batch fabrication, ease of manufacturability and cost reduction, and lower leakage inductance. Also, the skin effect which restricts current to within a few skin depths of the surface of conductors at high frequencies makes the use of very thin micromachined windings appropriate. These devices can also yield better thermal management, since their surface-to-volume ratio is high. In integrated microscaled devices, low profile, no assembly requirements, no insertion soldering operations, and minimized winding losses are also strong advantages. But there are some limitations such as limited windings turns and winding correction, high core losses, and poor efficiency. Microscaled magnetic material properties are also often inferior to those of bulk magnetic materials.

Manuscript received May 13, 1998; revised April 15, 1999. This work was supported in part by the National Science Foundation through the Georgia Tech/NSF Engineering Research Center in Electronic Packaging under Contract EEC-9 402 723.

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Publisher Item Identifier S 0018-9464(99)07349-5.

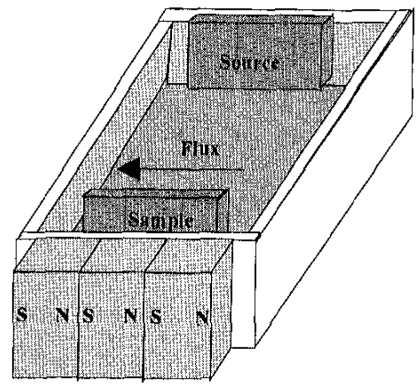
In designing several different types of integrated inductors, performance improvement due to selection of appropriate soft magnetic materials as well as inductor geometries are important issues. Some of the geometrical optimizations undertaken include increasing the number of turns, reducing the gaps between windings, enlarging the cross-sectional area of the magnetic core, etc. However, there remains a need to improve the magnetic properties of the soft magnetic materials used in integrated inductors. For example, microscaled inductors may have low inductance due to the low permeability of integrated magnetic thin films. Improvements in the permeability of an integrated magnetic core material may have significant effects on the inductance of the fabricated microinductors.

## II. Design Issues

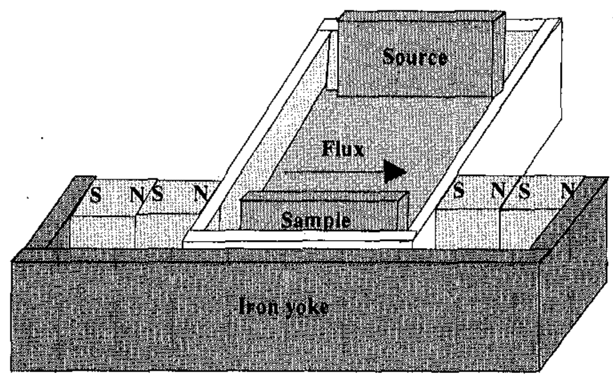
Many magnetic materials suffer from a falloff in permeability as frequency increases. It is important to remember that even if an inductor has good low frequency performance, its high frequency performance may suffer if the material permeability is not sufficiently high at higher frequencies. In such cases, anisotropic magnetic cores may be more useful than isotropic cores in integrated magnetic devices. For example, the easy axis (the in-plane direction of the plated film parallel to the applied magnetic field during plating) of an anisotropic magnetic core has a high permeability and is therefore good for low frequency applications [1], but the hard axis (the in-plane direction of the film perpendicular to the applied magnetic field) is better for high frequency applications. This phenomenon can be explained as follows [2]. The permeability is determined by the magnetization of the film. The magnetization is determined by two processes: domain wall motion and domain rotation. At low frequencies domain wall motion is the dominant mechanism. An applied field causes domain walls to shift, and the motion results in a change in magnetization and hence flux density $B$. Therefore, highly magnetized thin films will have larger low frequency permeability. However, highly magnetized films (easy axis) will have very small restoring forces and therefore are unable to follow rapidly varying fields. At high frequencies, the domain rotation is largely responsible for the permeability. It is hard for the large domains of the easy axis to rotate, while the small domains of the hard axis can rotate much more easily.

As mentioned above, the hard axis properties of anisotropic magnetic films have been used at high frequencies because of their good magnetic properties at these frequencies (MHz range). For example, hard-axis-oriented films have been used to improve the frequency behavior of thin film tape heads [3]–[4]. In order to improve the high frequency properties of an integrated solenoid or "bar type" inductor [5]–[6], appropriate processing techniques for fabrication of fully integrated microinductors with anisotropic magnetic cores are developed.

Fig. 1 shows a schematic drawing of the electroplating apparatus used to form anisotropic cores. Due to its low demagnetizing field, a low applied magnetic field is needed for supermalloy [Ni(85%)Fe(14%)Mo(1%)] films, while for permalloy [Ni(80%)Fe(20%)] films, a higher applied magnetic field will be required. The apparatus shown in Fig. 1 allows the application of various magnetic field strengths.




(a)




(b)

Fig. 1. A schematic drawing of the electroplating apparatus to for magnetically anisotropic cores: (a) for supermalloy with low field and (b) for permalloy with high field.

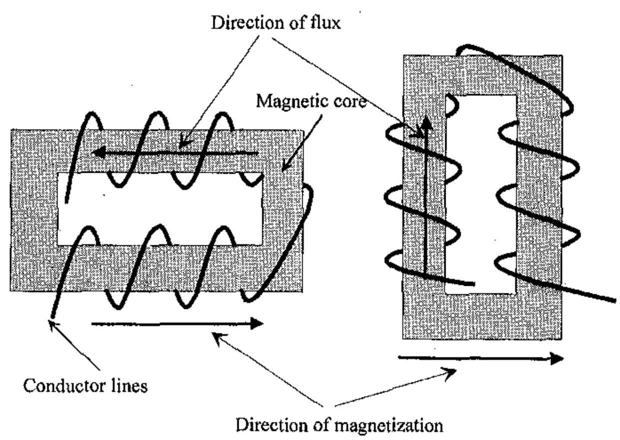



Fig. 2. A schematic drawing of the microinductors with magnetically anisotropic cores: with easy axis core (left) and with hard axis core (right).

Fig. 2 shows a schematic drawing of microinductors with magnetically anisotropic cores, i.e., magnetically easy and hard axes. Solenoid type inductors in which conductor coils are lithographically wrapped around a magnetic core are selected to realize microinductors with magnetically anisotropic cores

A closed magnetic core is implemented in these inductors to increase inductance ($L$) by reducing leakage flux and reluctance ($\Re$) as shown in (1)

$$L = \frac{N^2}{\Re_{\text{total}}} \tag{1}$$

$$\Re_{\text{total}} = \Re_{\text{easy-axis}} + \Re_{\text{hard-axis}} \tag{2}$$

$$\Re_{\text{easy-axis}} = \frac{2\lambda_{c,\text{easy-axis}}}{\mu_0 \mu_{r,\text{easy-axis}} A_c} \tag{3}$$

$$\Re_{\text{hard-axis}} = \frac{2\lambda_{c,\text{hard-axis}}}{\mu_0 \mu_{r,\text{hard-axis}} A_c} \tag{4}$$

where $N$ is the number of windings, $\lambda_c$ is the length of a particular segment of the magnetic core, $\mu_0$ is the vacuum permeability, $\mu_r$ is the relative permeability of a magnetic core, and $A_c$ is the cross-sectional area of a magnetic core. In the solenoid type inductors with a closed magnetic core, the inductance can be calculated by the square of number of turns divided by total reluctance of the closed core at low frequencies as shown in (1). The total reluctance of the closed anisotropic core can be calculated by summing the reluctance of easy and hard axes as shown in (2). The closed anisotropic core is composed of two easy axis cores and two hard axis cores. Thus, the reluctance of easy and hard axis cores can be calculated as shown in (3) and (4). The closed magnetic core cannot avoid having an easy axis and hard axis due to the geometry as shown in Fig. 2. For example, if the left and right side cores are magnetized in a particular direction, the top and bottom cores will be magnetized in the opposite direction. For this work, the easy axis core inductors are defined to be the devices in which the long sections of the core were parallel to the applied field during plating, and the hard axis core inductors are devices in which the long sections of the core were orthogonal to the applied field during plating. Therefore, the total reluctance of the integrated inductor is calculated using (2) since the relative permeability of the easy axis core is not the same as the hard axis core.

To magnetize a thin magnetic film in the plane in the direction of the long geometric axis of the film (geometrically easy axis) is much easier than to magnetize it in the direction in the other in-plane direction (geometrically hard axis). In order to magnetize the magnetic film in the geometrically hard axis, appropriate electroplating molds for the magnetic core are designed. Fig. 3(a) shows a schematic drawing of the films with magnetically anisotropic structures that have easy and hard axes.

Fig. 3(b) shows the principle for the magnetization of magnetic films in the geometrically hard axis direction. As shown in Fig. 3(b), the geometrically hard axis of the thin films can be magnetized by adding pole pieces in the hard axis direction [3]. The added pole pieces aid the total demagnetizing field in the hard axis direction and thereby reduce the external field generation requirements.

In some of the plated magnetic cores, an insulating layer, commonly referred to as a lamination, is formed between one or more magnetic core layers. Such lamination is expected to reduce the eddy current losses as well as to reduce skin effects at high frequency [7]. Skin depth is a function of frequency and

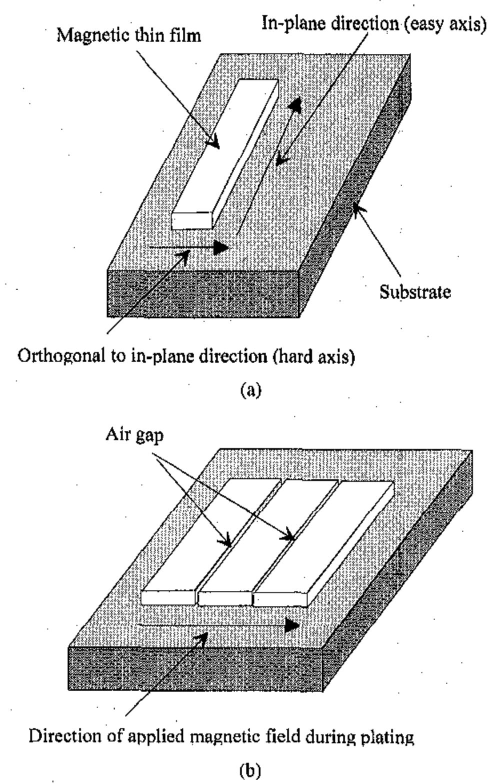



Fig. 3. A schematic drawing of the magnetically anisotropic films: (a) geometrically easy and hard axes and (b) how to magnetize hard axis.

for the electrically conducting metal cores can be represented as follows:

$$\delta = \frac{1}{\sqrt{f \pi \mu_0 \mu_r \sigma}}, \text{ (m)} \tag{5}$$

where $f$ represents frequency, $\mu_0$ and $\mu_r$ vacuum permeability and relative permeability, and $\sigma$ conductivity. Therefore, lamination of the magnetic core may be desirable for integrated inductors and transformers operating at high frequency. Two different soft magnetic alloys (permalloy and supermalloy [8]) as magnetic core materials are electroplated under an applied magnetic field into the designed molds to realize microinductors with anisotropic cores. The skin depth of the supermalloy thin film is smaller than that of the permalloy because of its higher permeability; thus, the supermalloy films are more appropriate candidates for lamination.

## III. Fabrication

A brief fabrication process for this magnetic device is shown in Fig. 4. The process started with a glass substrate. Chromium (200 Å)/copper (2000 Å)/chromium (400 Å) layers were deposited to form a seed layer for electroplating using electron-beam evaporation or dc sputtering. The seed layer was patterned in a mesh-type to form a conductor network to be removed after serving as the seed layer for plating the lower conductor lines and vias. Polyimide (Dupont PI2611) was spun on the top of the mesh-type seed layer to construct electroplating molds for the bottom conductor lines. Two coats

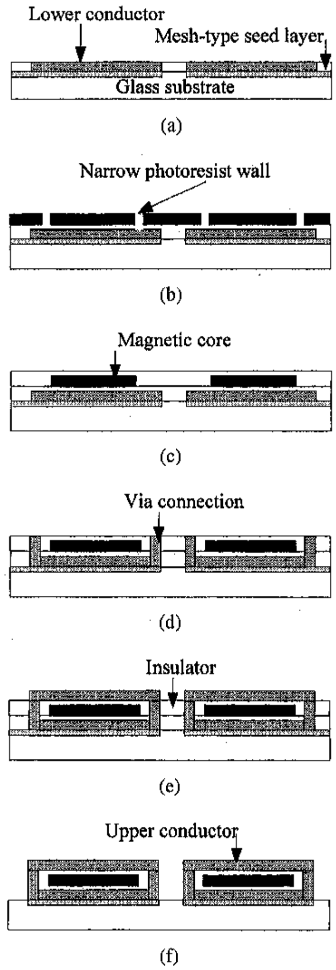



Fig. 4. Fabrication sequences of the integrated microinductors with magnetically anisotropic cores: (a) electroplating of bottom conductor lines, (b) coating of polyimide and electroplating of magnetic core under applied magnetic field, (c) wet etching of magnetic core and coating of polyimide, (d) via conductor plating, (e) upper conductor plating, and (f) removal of polyimide and mesh seed layer.

were made to obtain 20 $\mu$m thick polyimide molds. After coating, the polyimide was cured at 220 °C for 0.5 hour to remove solvents and 350 °C for one hour in nitrogen to fully cure the material. An aluminum layer (0.2 $\mu$m thick) was deposited on top of the cured polyimide as a hard mask for dry etching. Molds for lower conductor lines were patterned and plasma etched until the seed layer was exposed. After etching the aluminum hard mask and the top chromium of the seed layer, the molds were filled with electroplated copper using standard electroplating techniques.

Two coats of polyimide were cast to isolate the lower conductor lines and the magnetic core and to achieve better planarization. The seed layer [chromium (200 Å)/copper (2000 Å)/chromium (400 Å)] was deposited and thick (5 $\mu$m for supermalloy magnetic core and 12 $\mu$m for permalloy magnetic core) photoresist (SJR 5740) was coated. Electroplating molds with narrow photoresist walls (10 $\mu$m wide) were formed using photolithography processes. After etching the top chromium of the seed layer, the molds were filled with plated permalloy and

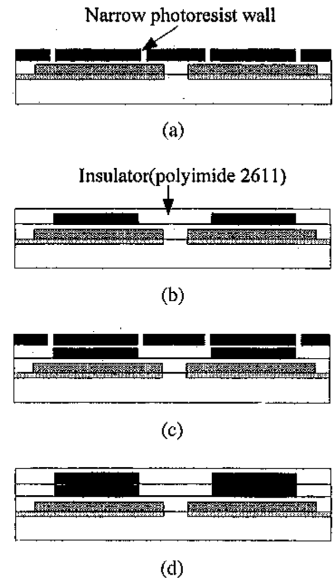



Fig. 5. Fabrication sequences of the laminated magnetic cores using polyimide insulator: (a) electroplating of first layer magnetic core under applied magnetic field, (b) coating of polyimide, (c) repeating of previous (b) steps, and (d) wet etching of magnetic core and coating of polyimide.

supermalloy using electroplating techniques under an applied magnetic field oriented in the appropriate direction. Due to the higher permeability and lower coercivity of the NiFeMo films, they are referred to as supermalloy films. After plating the magnetic alloys, the plating molds were cured in a 120 °C oven for ten minutes to harden the photoresist. A 5 $\mu$m thick photoresist was coated on top of the hard-cured photoresist and patterned to etch the plated magnetic alloys selectively while protecting the magnetic core. Plated thick permalloy and supermalloy magnetic films were etched selectively using wet etching techniques (two parts by volume $H_2SO_4$, one part $H_2O_2$, and ten parts $H_2O$). After selectively etching the magnetic alloys, the copper and chromium seed layers were also wet-etched. After removing the photoresist using acetone, a plasma etch with 95% $O_2$ and 5% $CHF_3$ was used for ten minutes. One coat of polyimide was spin-cast and cured to insulate the core and upper conductor lines.

Fig. 5 shows a brief fabrication sequence for a two-layer magnetic core laminated using a DuPont polyimide 2611 insulating layer. After completion of the first layer of magnetic core, a coat (5 $\mu$m thick) of polyimide 2611 was applied and cured to provide insulation between the lower and upper magnetic core layers. Chromium (200 Å)/copper (2000 Å)/chromium (400 Å) layers were deposited to serve as a seed layer for electroplating the upper magnetic core layer. The same fabrication sequence and wet-etching techniques used to form the lower magnetic core layer were also performed to construct the upper magnetic core.

Via holes were patterned in a sputtered aluminum (0.2 $\mu$m thick) mask layer and etched through the polyimide layer using 100% oxygen plasma. The surface of the opened area of the bottom conductor was oxidized because of the oxygen plasma during dry etching. Since this oxidation could produce high contact resistance, it was removed using a sulfuric acid (5%)

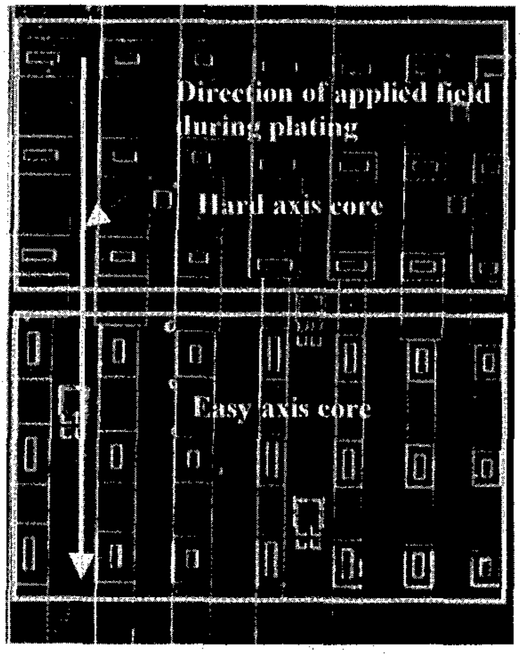



Fig. 6. Photomicrograph of the magnetically anisotropic cores of easy and hard axis in a closed bar shape plated under an applied magnetic field.

solution for 5 s. The metal vias were filled with electroplated copper using the standard electroplating technique described previously.

After completion of the electroplating, a copper/chromium seed layer was deposited, and molds for the upper conductor lines were formed using 20 $\mu$m thick photoresist (SJR 5740). The molds were filled with plated copper and removed. After removing the copper/chromium seed layer, a polyimide passivation layer was coated on the top of the upper conductor lines and cured to protect the top conductor lines. The polyimide was optionally masked using a 0.2 $\mu$m thick aluminum hard mask and dry-etched to the bottom using a plasma etch with 95% $O_2$ and 5% $CHF_3$ gas. The bottom mesh-type seed layer (chromium (200 Å)/copper [2000 Å)/chromium (400 Å)] was then wet-etched. At the completion of fabrication, samples were tested. Fig. 6 is a photomicrograph of magnetically anisotropic cores of easy axis and hard axis in a closed bar shape plated under an applied magnetic field. Fig. 7 shows batch fabricated microinductors with magnetically anisotropic cores on a substrate. Fig. 8 shows integrated microinductors with magnetically anisotropic cores of easy axis and hard axis including signal and ground pads.

## IV. Experimental Results and Discussion

### A. Electroplated Magnetically Anisotropic Films

Fabricated magnetically anisotropic thin films were characterized using a vibrating sample magnetometer (VSM). Fig. 9 shows the magnetic $M$-$H$ (magnetization versus applied field strength) characteristics of electroplated permalloy magnetic films with easy and hard axes. Regarding the magnetically anisotropic permalloy samples shown in Fig. 9, the measured

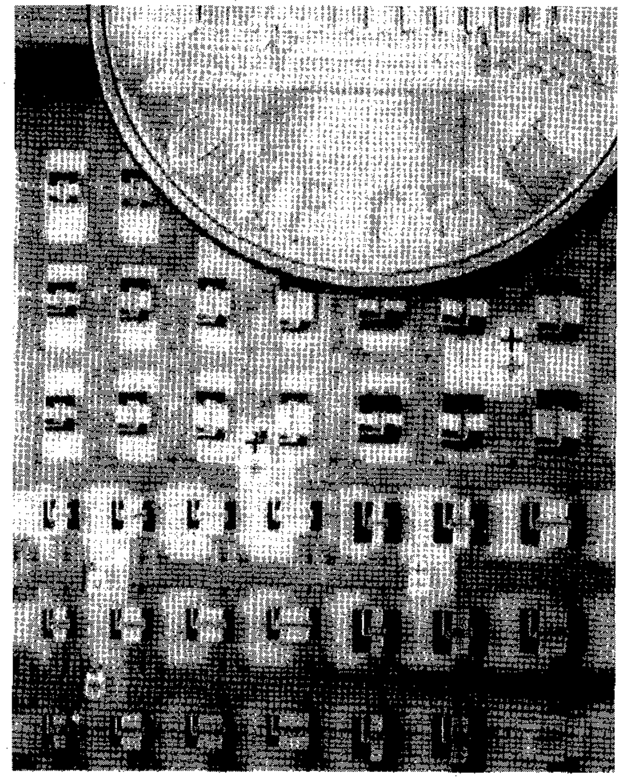


Fig. 7. Photomicrograph of batch fabricated microinductors with magnetically anisotropic cores.

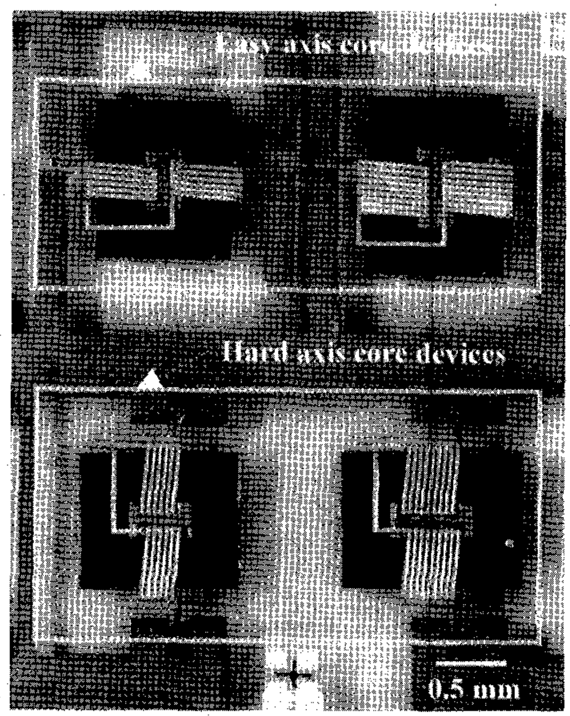



Fig. 8. Photomicrograph of integrated microinductors with magnetically anisotropic cores of easy and hard axes including signal and ground pads.

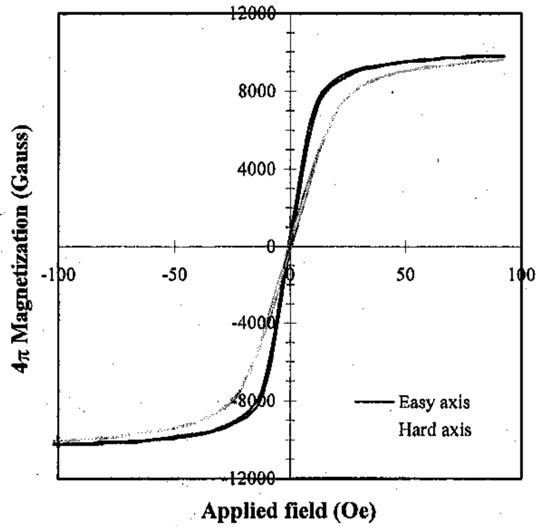



Fig. 9. Magnetization as a function of applied magnetic field of electroplated magnetically anisotropic permalloy film.

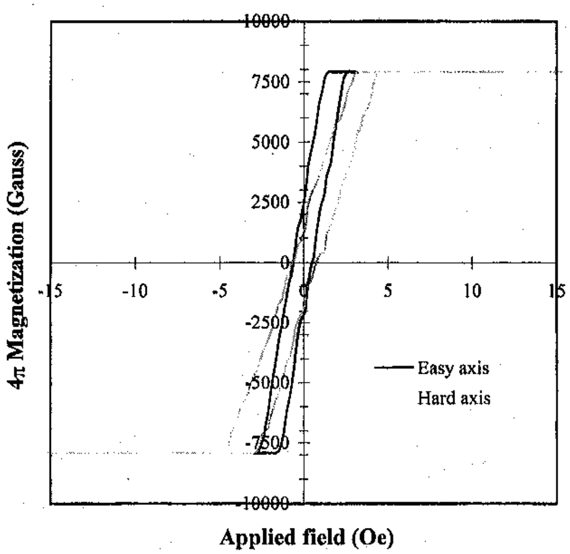



Fig. 10. Magnetization as a function of applied magnetic field for an electroplated magnetically anisotropic supermalloy film. Note the very small values of the horizontal scale.

slope of the magnetization curve in its linear region for the easy axis direction was higher than for the hard axis direction at low frequency. The coercivity of the plated samples was 0.402 Oe and 0.635 Oe along the easy and hard axes, respectively. The saturation magnetization $M_s$ for these permalloy samples ranged from 0.9 to 1.0 Tesla.

Fig. 10 shows the magnetic $M$-$H$ (magnetization versus applied field strength) characteristics of electroplated supermalloy magnetic films with easy and hard axes. The plated magnetically anisotropic supermalloy films also have a relatively high permeability. Regarding the magnetically anisotropic permalloy samples shown in Fig. 10, the measured slope of the magnetization curve in its linear region for the easy axis direction was higher than for the hard axis direction at low frequency. The coercivity of the easy and hard axes of the

TABLE I
DESIGNED PARAMETERS OF THE FABRICATED MICROMACHINED INDUCTORS WITH MAGNETICALLY ANISOTROPIC CORES

| Type | Core materials | Conductor (μm) (width, thickness, and spacing) | Width of magnetic core (μm) | Number of windings | Dimension (mm) |
|---|---|---|---|---|---|
| A | supermalloy | 40, 15, and 20 | 500 | 14 | 1.8 x 1.4 |
| B | supermalloy | 40, 15, and 20 | 500 | 32 | 2.4 x 1.4 |
| C | two-layer supermalloy | 40, 15, and 20 | 500 | 32 | 2.4 x 1.4 |
| D | two-layer supermalloy | 40, 15, and 20 | 300 | 14 | 1.5 x 1.1 |
| E | permalloy | 40, 15, and 20 | 300 | 20 | 1.7 x 1.1 |
| F | permalloy | 40, 15, and 20 | 300 | 26 | 1.9 x 1.1 |
| G | permalloy | 40, 15, and 20 | 300 | 32 | 2.1 x 1.1 |

plated samples was 0.556 Oe and 0.715 Oe, respectively. The saturation magnetization $M_s$ for the electroplated anisotropic supermalloy samples was 0.8 Tesla.

From the above data, supermalloy has higher permeability than permalloy, while permalloy has higher saturation magnetization than supermalloy. Supermalloy films could not be plated thicker than 5 $\mu$m without adhesion loss, while permalloy could be plated much thicker than 50 $\mu$m. The permeability of the easy axis was much higher than that of the hard axis at low frequency. However, ac experiments showed that the permeability of the easy axis fell rapidly at frequencies above 1 MHz, while the permeability of the hard axis remained approximately constant up to 10 MHz and higher. Thus, the hard axis may be most useful for integrated inductors and transformers operating at higher frequencies.

### *B. Fabricated Microinductors with Magnetically Anisotropic Cores*

The fabricated micromachined inductors were distinguished as shown in Table I. Integrated inductors with eight different geometries have been batch fabricated on the same substrate. The inductance of the integrated inductors with magnetically anisotropic cores was measured using a Keithley LCZ meter and a HP-4194A impedence/gain-phase analyzer. The measured inductance and quality factor values of the inductors with supermalloy magnetic cores were plotted as a function of frequency in Fig. 11. The inductors with a hard axis core have higher inductance above 100 kHz than the inductors with an easy axis core. As shown in Fig. 11, the integrated inductors with hard axis core have higher quality factor than the inductors with easy axis core above 100 kHz. This shows the usefulness of the magnetic properties of hard axis for magnetic device applications operating at high frequencies.

Fig. 12 shows the characteristics of resistance of the inductors with supermalloy magnetic cores. The measured dc resistance of the conductor lines in the type A device with supermalloy core was approximately 0.58 ohms. The conductor resistance of the type A device with supermalloy core as calculated from its geometry was approximately 0.57 ohms using a literature value for conductivity of plated copper [9]. The measured dc resistance of the conductor lines in the type B device with supermalloy core was approximately 1.95 ohms. The conductor resistance of the type B device with

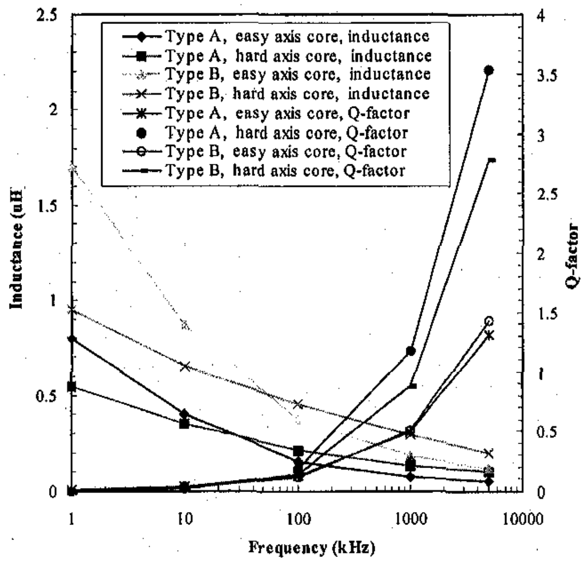



Fig. 11. Comparison of inductance and $Q$ factor as a function of frequency of inductors with type A and type B. These inductors had supermalloy anisotropic cores 4 $\mu$m in thickness.

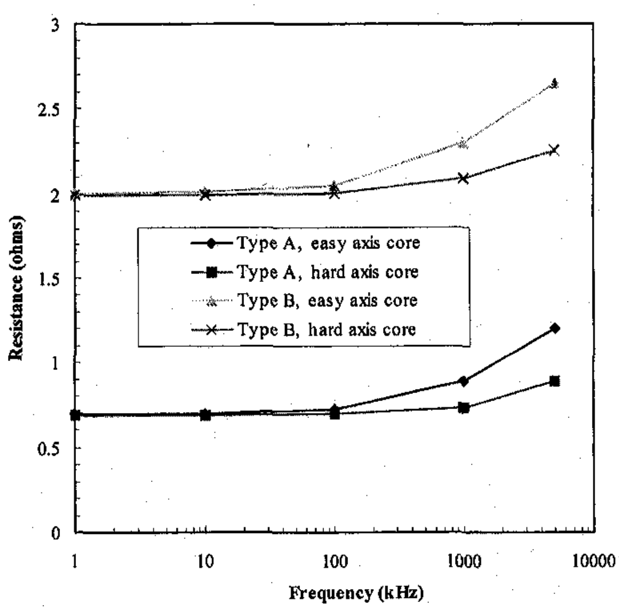



Fig. 12. Comparison of resistance as a function of frequency of inductors with type A and type B. These inductors had supermalloy anisotropic cores 4 $\mu$m in thickness.

supermalloy core from its geometry was approximately 1.2 ohms. In the type A device, the measured and evaluated values were close, while the measured and evaluated values of the type B device were different. The via contact resistance may cause this difference. The type B device has a large of number of vias compared to the type A device. The inductors had a constant resistance up to approximately 100 kHz as shown in Fig. 12. However, the resistance began to increase above 100 kHz and the slope of resistance of the inductors with the easy axis cores was higher than the inductors with hard axis cores.

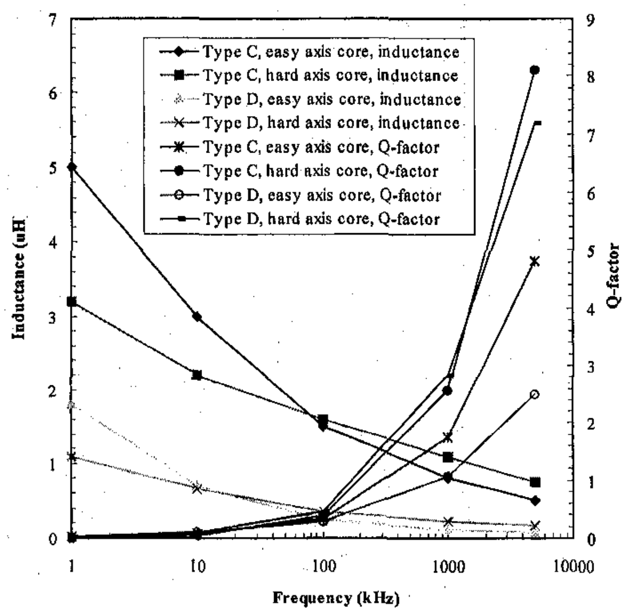



Fig. 13. Comparison of inductance and quality factor as a function of frequency of inductors with type C and type D: Theses inductors had two layer supermalloy anisotropic cores laminated with 5 $\mu$m thick polyimide (12 $\mu$m thick in type C and 14 $\mu$m thick in type D).

The ac resistance is related to the magnetic core geometry and properties, and the hard axis has lower magnetic core losses.

Fig. 13 shows the measured inductance and quality factor of the inductors with two layer supermalloy cores laminated by polyimide. As shown in Fig. 13, the inductors with hard axis core have higher inductance than the inductors with easy axis core at high frequency, while the inductors with easy axis core have higher inductance than the inductors with hard axis core at low frequency. The good high frequency characteristics observed in these devices was due to the increased resistance of the laminated magnetic core. As shown in Fig. 13, the laminated inductors with hard axis core have also higher quality factors than the inductors with easy axis core above 100 kHz. By reducing magnetic core losses in both easy and hard axis devices, the quality factor was increased. This shows the usefulness of the lamination of magnetic cores in integrated inductors and transformers operating at high frequency. Fig. 14 shows the measured resistance of the inductors with the two layer supermalloy cores laminated by polyimide. The measured dc resistance of the conductor lines in the type C device with a laminated supermalloy core was approximately 0.42 ohms, while the conductor resistance evaluated from its geometry and bulk copper properties was approximately 0.38 ohms.

The measured dc resistance of the conductor lines in the type D device with a supermalloy core was approximately 2.5 ohms, while the conductor resistance evaluated from its geometry was approximately 1.35 ohms. The large numbers of via contacts may be the cause of the higher resistance in these devices. Although the thickness of the laminated magnetic core was almost doubled, the inductors with laminated supermalloy magnetic cores have almost the same magnetic loss as the

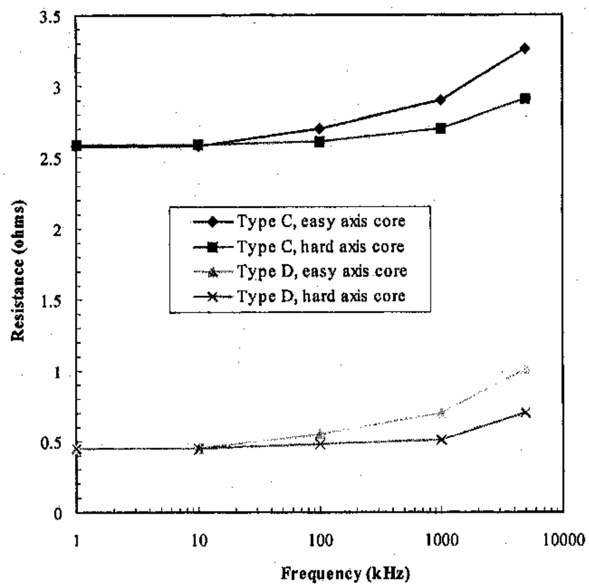



Fig. 14. Comparison of resistance as a function of frequency of inductors with layout 1 and layout 8. These inductors had two layer supermalloy anisotropic cores laminated with 5-$\mu$m thick polyimide (12-$\mu$m thick in type C and 14-$\mu$m thick in type D).

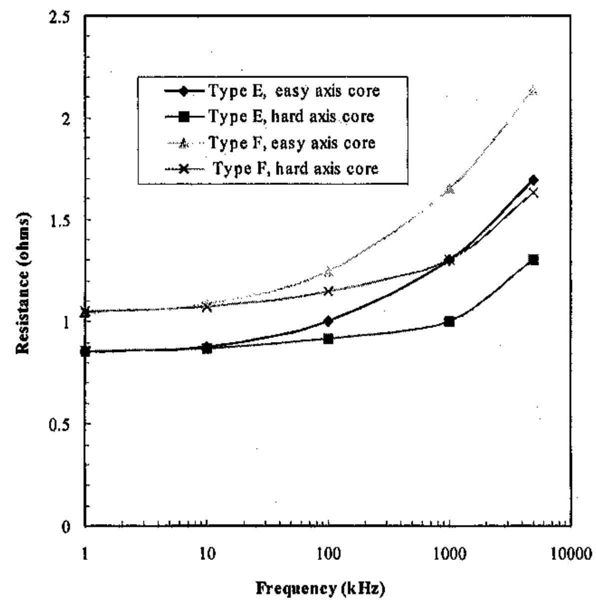



Fig. 16. Comparison of resistance as a function of frequency for inductors with type E and type F. These inductors had permalloy anisotropic cores 12 $\mu$m in thickness.

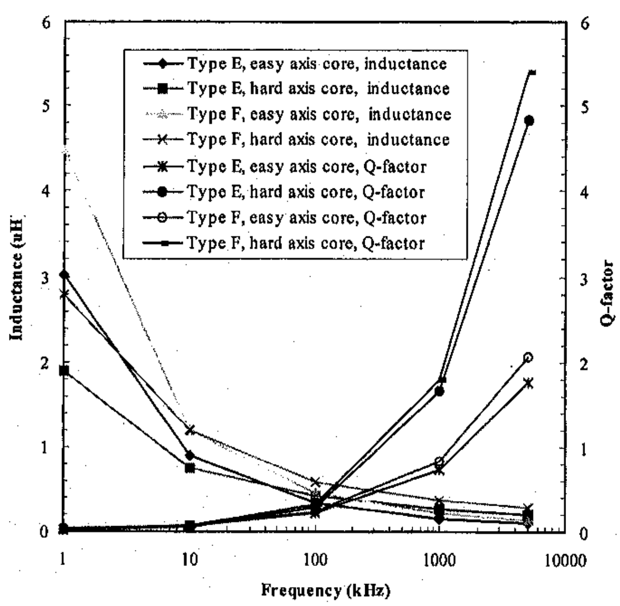



Fig. 15. Comparison of inductance and quality factor as a function of frequency for inductors with type E and type F. These inductors had permalloy anisotropic cores 12 $\mu$m in thickness.

inductors with supermalloy magnetic core, indicating that the laminations are functional.

Fig. 15 shows the measured inductance and quality factor of the inductors with permalloy anisotropic cores. The inductors with hard axis core have higher inductance than the inductors with easy axis core at high frequency, while the inductors with easy axis core have higher inductance than the inductors with hard axis core at low frequency. As shown in Fig. 15, although the devices have high inductance, the quality factor is worse than that of the inductors with laminated cores because of the magnetic core losses. As shown in Fig. 16, when a thick magnetic core was used without lamination, the high frequency characteristics were worse than laminated thick cores because of the skin effect and magnetic core losses. The measured dc resistance of the conductor lines in the type E device with permalloy core was approximately 0.7 ohms, while the conductor resistance evaluated from its geometry was approximately 0.5 ohms. The measured dc resistance of the conductor lines in the layout type F with a permalloy core was approximately 0.95 ohms, while the conductor resistance evaluated from its geometry was approximately 0.6 ohms. The permalloy devices have higher magnetic core losses than the laminated supermalloy devices. As the thickness of the permalloy devices with easy axis core is larger than the skin depth at 100 kHz, the magnetic loss increases at that frequency. Fig. 17 shows the inductance of inductors with permalloy anisotropic magnetic cores with different numbers of turns. As the number of windings was increased, the inductance also increased as predicted. The measured inductance values are much higher than those of inductors with magnetically isotropic cores, despite the fact that the anisotropic core inductors have a much smaller volume. The large increment of inductance in a small volume is a strong advantage of the use of magnetically anisotropic cores.

The inductance of fabricated microinductors was calculated using (1) based on their geometries and the effective relative permeability. The effective relative permeability is derived from the slope of the linear portion of magnetization curve of the plated materials: 2400 and 1300 for permalloy along the easy and hard axis, respectively; and 3900 and 2500 for supermalloy along the easy and hard axis, respectively, at low frequency. Table II shows a comparison of the measured and calculated inductance of the fabricated microinductors. As shown in Table II, there is a discrepancy between the

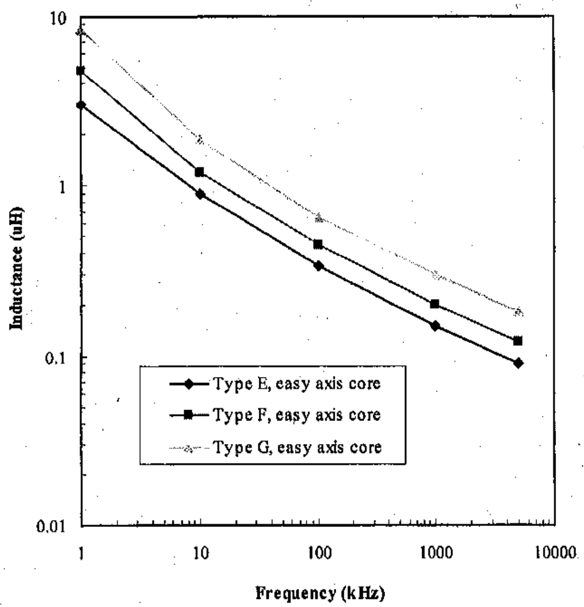



Fig. 17. Comparison of inductance as a function of frequency for inductors with type E, type F, and type G. These inductors had permalloy anisotropic cores.

TABLE II
COMPARISON OF MEASURED AND CALCULATED INDUCTANCES OF THE FABRICATED MICROMACHINED INDUCTORS WITH MAGNETICALLY ANISOTROPIC CORES AT LOW FREQUENCY

| Type | Direction of magnetization | Core materials | Measured inductance (μH) | Calculated inductance (μH) |
|---|---|---|---|---|
| A | easy axis | supermalloy | 0.8 | 0.55 |
| A | hard axis | supermalloy | 0.6 | 0.51 |
| C | easy axis | two-layer supermalloy | 5.4 | 3.84 |
| C | hard axis | two-layer supermalloy | 3.9 | 3.31 |
| F | easy axis | permalloy | 4.8 | 1.97 |
| F | hard axis | permalloy | 2.98 | 1.62 |

measured and calculated inductance, although the functional form of the inductances as a function of frequency (discussed below) are similar. The discrepancy in absolute inductance value may come from variation of the relative permeability of the electroplated magnetic core and geometries due to processing limitations, as well as the assumptions underlying the relatively simple expression given in (1). Alternatively, insufficient saturation in the magnetization/electroplating step could lead to differing permeabilities. Since the permeability of the hard axis magnetic materials has been shown to be reasonably stable over the range of frequencies discussed in this paper, the falloff in inductance value with frequency for the hard axis devices can be attributed at least in part to the increasing reluctance of the short segments (i.e., the easy axis segments) with frequency. These segments are unavoidable if the device is to have a closed rectangular shape; however, their effect can be minimized by increasing the aspect ratio of the devices. Conversely, if large permeability at low frequencies (i.e., the easy axis characteristics) are required, large aspect ratio devices will minimize the lengths of the segments of the cores oriented along the hard axis, which have lower permeability at low frequency.

## V. CONCLUSION

Integrated solenoid-type inductors with electroplated magnetically anisotropic permalloy and supermalloy have been designed, fabricated, and tested. The magnetic characteristics of a hard axis anisotropic core as well as a laminated anisotropic core are favorable for realizing high frequency integrated inductors. Integrated inductors with easy axis cores have better performance than hard axis core devices at operating frequencies less than 100 kHz, while the hard axis core devices have better performance than easy axis core devices at operating frequencies greater than 100 kHz. Integrated inductors with two-layer laminated magnetic cores have better performance than inductors with a single layer magnetic core without lamination because of the reduced skin effect and magnetic core losses. In addition to permalloy, supermalloy is useful in integrated inductive components for signal applications because of its high permeability and high inductance and quality factors at high frequency. However, the achievable thickness of a single layer of supermalloy using electroplating is limited (around 5 $\mu$m), in part due to its high stress. In addition to their high frequency benefits, laminations can also be used to overcome this single layer supermalloy thickness limit, and thus create thicker overall supermalloy films (and thus higher inductance devices). These integrated inductors with magnetically anistotropic cores may have application in integrated magnetic sensors, actuators, signal processing, and low power electronics applications.

## ACKNOWLEDGMENT

Fabrication was carried out at the Microelectronics Research Center of Georgia Tech. The authors also acknowledge the Microsensor and Microactuator (MSMA) Group and Microelectronics Research Center staff for their help with processing questions. Assistance with plating of supermalloy magnetic material from Dr. W. P. Taylor of Georgia Tech is gratefully acknowledged.

## REFERENCES

[1] J. Park, S. Han, W. Taylor, and M. Allen, "Fully integrated micromachined inductors with electroplated anisotropic magnetic cores," presented at the IEEE 13th Applied Power Electron. Conf., Anaheim, CA, 1998.
[2] G. P. Rodrigue, "Dielectric and magnetic properties of solids," Class note book (EE6452), 1995.
[3] L. Romankiw, I. Croll, and M. Hatzakis, "Batch fabricated thin film magnetic recording heads," *IEEE Trans. Magnetics*, vol. 6, pp. 597–599, May 1970.
[4] L. Romankiw and G. Wardly, "Thin film magnetic transducer head," U.S. Patent 3 662 119, 1972.
[5] J. Park and M. Allen, "A comparison of micromachined inductors with different magnetic core materials," presented at the IEEE 46th ECTC Conf., Orlando, FL, 1996, pp. 375–381.
[6] C. Ahn and M. Allen, "A fully integrated micromagnetic actuator with a multilevel magnetic core," presented at the IEEE Solid-State Sensor Actuator Workshop, Hilton Head, SC, June 1992, pp. 14–18.
[7] C. Sullivan and S. Sanders, "Microfabrication of transformers and inductors for high frequency power conversion," *IEEE 24th PESC'93*, pp. 33–41.
[8] W. Taylor, M. Schneider, H. Baltes, and M. Allen, "Electroplated soft magnetic materials for microsensors and microactuators," presented at the IEEE Transducers'97 Conf.
[9] K. Chakravorty, C. Chien, J. Cech, M. Tanielian, and P. Young, "High density interconnection using photosensitive polyimide and electroplated copper conductor lines," *IEEE Trans. Comp. Hybrids, Manuf. Technol.*, vol. CHMT-13, pp. 200–206, 1990.

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