Multilayered ferromagnetic-polymer composite structures for high-density power inductors

Dibyajat Mishra, P.Markondeya Raj, Joel Tishler, Teng Sun, Erik Shipton and Rao Tummala

3D Systems Packaging Research Center
Georgia Institute of Technology
Atlanta, GA 30332-0560

Abstract **-This paper presents the modeling, design, processing and characterization of a new class of multilayered ferromagnetic-polymer composite structures for high-density power inductor applications. The multilayered composite structures comprise of high-permeability, high saturation magnetization (M_s>0.5T), low-coercivity magnetic layers stacked with ultrathin polymer adhesives. The adhesive acts as an insulating layer to reduce eddy current losses while also enabling high permeabilities at higher operating frequencies. Fundamental material models were used to design the composite structures to achieve permeability of above 500 in the frequency range of 1-10 MHz. A new adhesive coating and layering process was developed to achieve thicker composite structures in a single lamination step for increasing the inductance density and power handling. The frequency-dependent effective permeability of the composite structure was estimated from the measurement and analysis of S11 parameters from a shorted-strip transmission line using vector network analyzer. The fabricated composite structures showed a permeability of ~500, saturation magnetization of 0.6T and coercivity of 4.4 Oe at 10 MHz. Such composite structures with excellent magnetic properties can be used to design power inductors in 1-10 MHz frequency range.**

Index Terms—**Multilayered composite structures, high frequency permeability, eddy-current losses, high-density power inductors.**

I. Introduction

The evolution of smart and wearable electronic systems is driving a strong need for miniaturization and integration of passive components with other functional modules. The design and fabrication of miniaturized, ultra-thin magnetic passive components such as inductors and antennas for power and RF applications is limited by the choice and availability of magnetic materials that can be cost-effectively processed into films with suitable properties and geometries. Inductors for power supply applications require magnetic cores with high permeability and high saturation magnetization along with low loss in the MHz frequency regime (<10 MHz) for achieving high power-handling capability. Power inductors have, to date, been limited to ferrites because of their relatively high resistivity and hence low losses due to eddy currents. They have, however, reached fundamental volumetric density limitations because of their low saturation flux density (M_S), limiting their use in high power-density applications. In addition, ferrites show unstable frequency response due to strong relaxation behavior in 1-100 MHz and have processing constraints due to high sintering temperatures[1, 2].

Metal-based magnetic materials have been traditionally considered unsuitable for microwave applications due to their frequency instabilities from eddy current losses. However, recent advances in high frequency magnetic materials have established the suitability of metal nanocomposites and laminated metallic cores for microwave applications by demonstrating high permeability with frequency stability and suppression of losses. Nanoscale composite thin films have been successfully demonstrated via co-sputtering techniques. These nanocomposites are typically composed of (<10 nm) magnetic nanoparticles surrounded by an amorphous insulating matrix. The Fe and Co-based nanocomposite thin films can have high permeabilities (>100) with essentially flat frequency response up to 1 GHz due to exchange coupling, significantly better than those of conventional ferrite and metal powder cores[3-5]. These advanced films from sputtering processes, however, cannot be made into the required film thickness for magnetic components economically and hence impose processing constraints for high power-handling. Magnetic nanocomposites consisting of chemically processed metallic nanoparticles are more attractive for high-frequency applications because they enable thicker films at lower cost. However, the permeability and frequency-stability of chemically synthesized metal nanoparticle-insulator nanocomposites are much inferior to those of the sputtered films and do not meet the property requirements for power inductor applications[6-8].

Another approach for low-loss magnetic cores is based on layering or microscale magnetic films. This is achieved by stacking alternate layers of magnetic metal and an insulating material that blocks eddy current flow. Layering techniques are particularly effective when the thickness of an individual lamination layer is smaller than the magnetic skin depth of the given material at the desired frequency of operation, while simultaneously maintaining total core thicknesses of 10-100 microns for high power handling. Previous approaches to layered magnetic cores include electroplating of vertical high-aspect-ratio structures[9], sequential electroplating followed by sacrificial etching [10] and multiple sputtering of thin magnetic and dielectric layers[11]. Although these approaches have demonstrated improvement in device performance, processability and scaling remain as unaddressed issues. For example, in case of electroplated vertically-layered structures, the mold fabrication becomes more complex as the aspect ratio of the layers increases. Horizontal layering using repeated deposition of magnetic thin films and insulators, e.g.,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2016.2589925, IEEE Transactions on Magnetics

by sequential sputtering, overcomes this difficulty and has been successfully demonstrated for lower power applications. Electroplating of sequential magnetic and sacrificial metal layers offers the possibility of fabricating structures of sufficient overall thickness for higher power-handling. The sacrificial layers need to be subsequently etched away to create isolation between the magnetic layers.

The focus of this paper is to explore an unique and innovative ferromagnetic-polymer composite structure, which is scalable to thicker composite structures, while using thinner individual metal layers. The composite structure, therefore, addresses the fundamental challenge of eddy current losses at high frequencies thereby achieving high permeability (μ) and high saturation magnetization M_s with adequate thickness for power supply inductors. Such a composite structure consists of multiple layers of ferromagnetic freestanding films, stacked alternately with ultra-thin laminated insulating polymer dielectric layers. The polymer-dielectric layer acts as both an insulating layer as well as an adhesive to stack the magnetic layers. NiFeMo (Moly-permalloy) is chosen as the candidate for magnetic material because of its high-permeability, high-Ms and low-coercivity. This paper starts with modeling of the composite structure resulting in the design of required film thickness for low losses. This is followed by process demonstration and characterization of such structures

II. Modeling And Design

The main objective of modeling is to identify the metal thickness to achieve high permeability without high losses. To accomplish this objective, the thickness of each magnetic layer has to be maintained such that it is thinner than the skin depth computed using the following equation in the desired frequency regime. The main objective of modeling is to identify the metal thickness to achieve high permeability without high losses. To accomplish this objective, the thickness of each magnetic layer has to be maintained such that it is thinner than the skin depth computed using the following equation in the desired frequency regime:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \qquad (1)$$

where δ is the skin depth, f is the frequency, ρ is the resistivity and μ is the intrinsic permeability of the magnetic material. This reduces the eddy current loss and ensures frequency stability of permeability. The computed skin depth of NiFeMo is 4.83 microns at 10MHz assuming an intrinsic permeability of 800 and resistivity of 60μohm-cm. The effective permeability due to eddy current screening for an infinitely wide film can be obtained using Maxwell's equations as[12]

$$\mu = \mu_i \, \frac{2\delta}{(1+j)d} tanh \frac{(1+j)d}{2\delta} \qquad (2)$$

where μ_i is the intrinsic relative permeability, d is the film thickness and δ is the skin depth. Fig.1 plots the variation of permeability with frequency for different thicknesses of NiFeMo films, using Equations 1 and 2. Based on this analysis, the thickness of the NiFeMo layer was selected to be 2 μm, which is much lesser than the skin depth at 10MHz.

The thickness of the polymer layers affects the M_s and permeability of the composite structure. The effective M_s of the structure can be computed as:

$$Ms_{eff} = qMs_i \qquad (3)$$

where Ms_{eff} is the effective composite saturation magnetization, q is the volume fraction of ferromagnetic layers and Ms_i is the saturation magnetization of individual magnetic layers. Thus, it can be seen that higher effective composite M_s can be achieved with thinner polymer layers.

The effective DC permeability μ_{eff} of the composite can be easily calculated using Wiener's law as

$$\mu_{eff} = q(\mu_i\text{-}1) + 1 \qquad (4)$$

where q is the volume fraction of the magnetic material and □$_I$ is the intrinsic permeability of the ferromagnetic layer. To ensure a high volume fraction q of magnetic layers for high Ms and high permeability, the thickness of the ultra-thin polymer layers was chosen to be 0.5 μms, based on modeling using Equation 2 and 3. Fig. 2 shows a schematic of the designed multilayered composite structure

III. Materials And Processing

Magnetic foils of ~2 microns thickness are laminated together using ultra-thin polymer adhesives of ~0.5 microns thickness to form the multilayered composite structure. Commercial magnetic foils of molypermalloy (NiFeMo) that are two-microns thick are obtained for this purpose. To form the multilayered structures, spin-on BCB polymer (Cyclotene 3022-46) was chosen as the ultra-thin polymer adhesive layer as it can be very easily diluted to coat submicron level thicknesses, but still have enough adhesion strength to bond the magnetic layers.

The magnetic foils are temporarily held against Si carrier wafers for ease of spin coating. Multiple foils are individually spin-coated with a coupling agent AP3000 to promote adhesion. Diluted BCB is then individually spin-coated on these foils. The dilution of the polymer and spin-coating speed are maintained such that the final thickness of BCB is 0.5 microns. The BCB-coated foils are then stacked together in a vacuum laminator and initial low-temperature bonding is performed at 100c for 60s to ensure wrinkle-free lamination. Finally, the multilayered foil stack is cured in a hot press at 300C for 1 hour. Fig. 3 shows the image of a freestanding 16-layered foil of thickness ~50 microns. These films are robust and no cracks or wrinkles are seen as depicted in the figure. Fig. 4 shows the FIB-SEM cross-section of a multilayered composite formed by foil-lamination showing ultra-thin BCB layers.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2016.2589925, IEEE Transactions on Magnetics

Fig. 5 shows the B-H loop of a 4-layered foil laminate composite of thickness ~10 microns compared with a single foil layer (original film) of 2 microns. The B-H loop represents the DC magnetic properties and is measured using vibration sample magnetometry (Lakeshore 736 model). It should be noted that there is no hard and easy axis of magnetization as no magnetic field is applied during fabrication of the structure to induce magnetic anisotropy. The multilayered composite structure formed by foil lamination has high Ms, high μ and low coercivity (~4.4 Oe). The single foil layer sample has a Ms of 0.8T while the 4-layered foil laminate has a Ms of 0.6 T. This is due to the dilution effect of the polymer layers, which is proportional to their volume fraction as shown in Equation 2. The coercivity of both the samples is 4.4 Oe, which shows that the presence of intermediate polymer layers has an insignificant effect on the coercivity of the magnetic layers.

IV. High Frequency Magnetic Characterization

The frequency-dependent effective permeability of the composite structure is estimated from the measured S11 parameters with a shorted-strip transmission line, as described by Bekker et.al[13]. The measured S11 parameters represent the reflection coefficient of the strip line (R=ln (S11)). The expression for the reflection coefficient of a transmission line section is given by the equation[14]:

$$R = R_o e^{-2\gamma l} \qquad (5)$$

where γ is the propagation constant, l is the length of a section and R_O is the reflection coefficient of the strip line at the termination. The propagation constant, valid for a transverse electromagnetic (TEM) mode, is defined by the general solution of the Maxwell's equations. According to a quasi-TEM wave approximation, the propagation constant of an inhomogeneous medium (air + material) can be modeled by an effective homogenous expression[15]:

$$\gamma = \frac{i\omega\sqrt{\varepsilon_{eff}\mu_{eff}}}{c_0} \qquad (6)$$

where ε_{eff} is the effective permittivity, μ_{eff} is the effective permeability of the material and c_0 is the velocity of light in vacuum. Thus, it can be seen that that the effective permeability of a material directly influences the reflection coefficient of a shorted strip transmission line.

The permeability measurement was made in three steps, the first one with an empty strip line, and the second one with the strip line loaded with kapton tape as substrate only. The third step was made with the strip line loaded with the multilayered composite film laminated on the substrate kapton tape. This procedure eliminates frequency dependent errors associated with conducting losses and dielectric losses as well as strip line fabrication and connection mismatches. The effect of permittivity of substrate and sample on reflection losses is also taken into account. Fig.6 shows the shorted strip transmission line setup with the multilayered composite foil laminate. The shorted strip line is connected to a network analyzer to measure the S11 parameters. The shorted strip line structure with magnetic film underneath it is shown in Fig.7. Fig.7 shows the plot of effective permeability vs frequency of a 4-layered composite structure. It can be seen that the composite structure has stable high permeability (~500) till 10 MHz.

V. Discussion

The frequency dependent permeability of magnetic thin-films are governed by two major mechanisms: eddy current damping and Landau-Lifshitz-(L-L) phenomenological damping because of ferromagnetic resonance (FMR). For the multilayered composite structure, each magnetic layer can be considered as an independent magnetic thin-film which is not magnetostatically coupled to the adjacent magnetic layers because they are separated by an intermediate polymer-dielectric. Thus, eddy current damping and FMR behavior of the individual layers represent that of the net composite.

L-L damping is determined by the intrinsic magnetic properties of the material. The precessional motion of magnetization can be described by the Landau-Lifshitz-Gilbert (LLG) phenomenological equation. The FMR frequency for a magnetic thin-film derived from the LLG equation can be written as[16]:

$$F_{fmr} = \frac{\gamma}{2\pi}\sqrt{(M_s + H_k)H_k} \qquad (7)$$

where H_k is the anisotropy field, M_s is the saturation magnetization and γ is the gyromagnetic ratio.

For thicker films, eddy current effects dominate at frequencies lower than those at which L-L damping effects are observed. From Equation 1 and 2, it can be seen that the thickness and resistivity of magnetic thin-films are major factors in determining the frequency dependent permeability especially due to eddy current damping.

Jayasekara et.al[17] measured the permeability of NiFe single layer films of thickness ranging from 54nm to 2.2 μms. Thin NiFe samples (54nm-120nm) showed a behavior that could be fit with the L-L model. The permeability of thicker NiFe samples (2.2μms) was in agreement with eddy current theory. Similarly, for the multilayered composite structure consisting of NiFeMo films of 2 microns thickness, it can be shown that the permeability roll-off with frequency occurs due to eddy current damping as it occurs at much lower frequencies compared to the FMR frequency for NiFeMo. The FMR frequency for anisotropic NiFeMo thin-film is computed as 1.2GHz from Equation 6, while that of the isotropic film is ~30 MHz. The multilayered composite structure is shown to have a permeability roll-off with frequency occurring at 10 MHz.

The frequency stability of permeability for the multilayered composite structure can be enhanced by decreasing the thickness of each magnetic layer or by increasing its resistivity, as dictated by the eddy current theory. The thickness of the magnetic layers can be decreased by controlled wet-etching of NiFeMo foils before lamination. Doping the NiFeMo alloy precursor with Si before casting and cold rolling can increase the resisitivity of the foils and thus enhance the frequency stability of permeability. It should be noted that addition of Mo increases the resistivity of Moly-permalloy compared to permalloy (NiFe) and thus it has better frequency stability of permeability.

VI. SUMMARY

A new class of multilayered ferromagnetic-polymer composite structures was studied through modeling, design, fabrication and characterization, to demonstrate magnetic cores for high-density power inductor applications. The composite structures were modeled and designed to achieve high permeability, high and frequency stability till 10MHz. A novel adhesive coating and layering process was demonstrated to fabricate the composite structure using ultra-thin polymer adhesives and molypermalloy foils. B-H loop measurements of the composite film showed high M_s of 0.6 T and low coercivity of 4.4 Oe. The frequency-dependent effective permeability of the composite structure is estimated from the measurement and analysis of S11 parameters for a shorted-strip transmission line using vector network analyzer. The fabricated composite structures showed a permeability of ~500 at 10 MHz. The frequency roll off of permeability was shown to be due to eddy current damping. Such composite structures are shown to suppress eddy current losses and maintain frequency stability of permeability till 10 MHz. Therefore they can be used as thick magnetic cores (50-100 microns) for power inductors designed to function in the frequency range of 1-10 MHz.

FIGURES

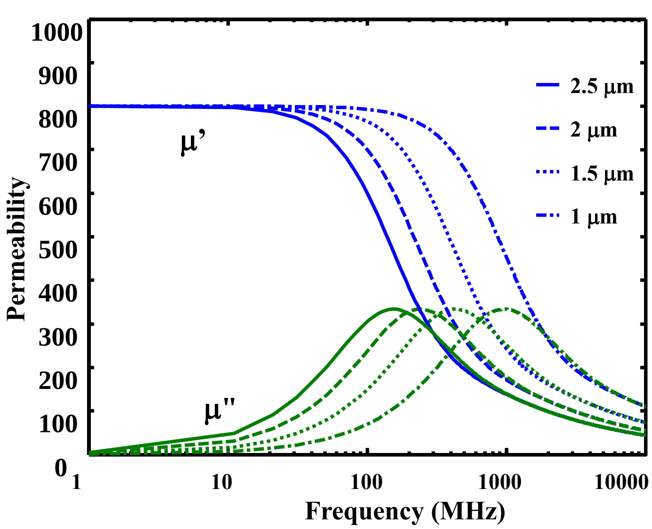

Fig.1. Variation of permeability with frequency for different NiFeMo film thicknesses

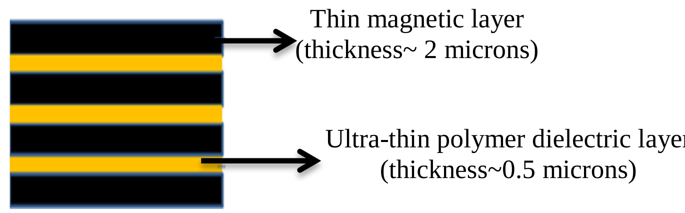

Fig.2. Schematic cross-section of multilayered composite structure

Fig.3. 16-layered freestanding foil laminate

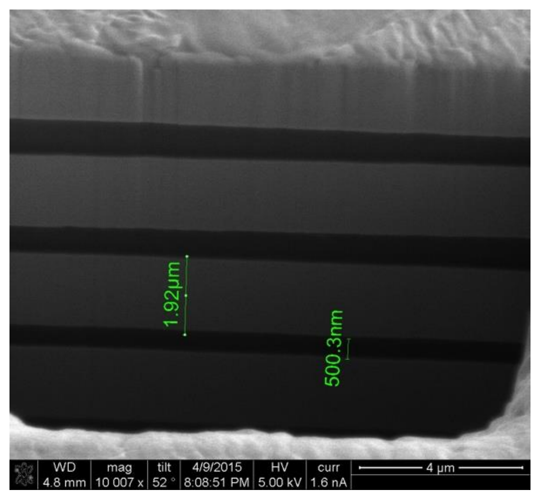

Fig.4. SEM cross-section of multilayered composite structure

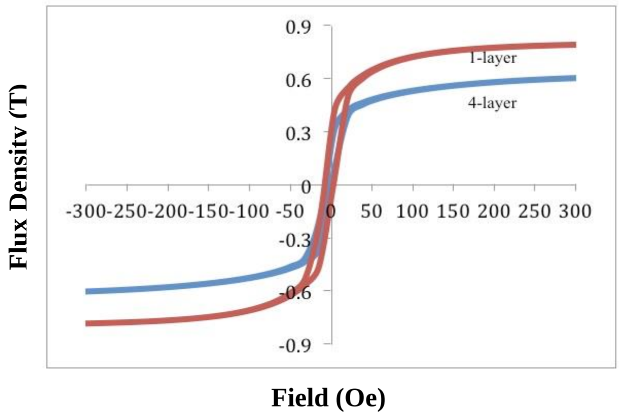

Fig. 5. B-H loop of multilayered composite structure

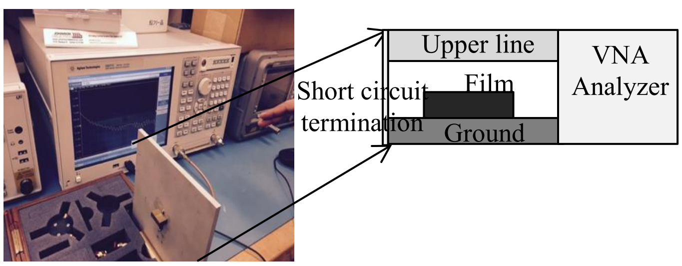

Fig.6. Setup for measuring high-frequency magnetic properties.

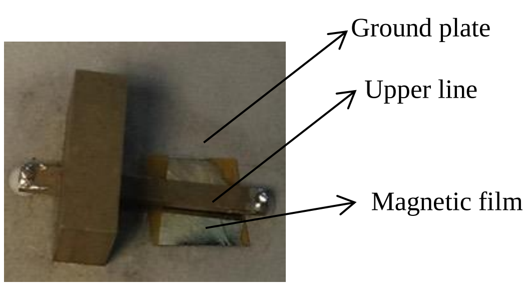

Fig.7. Shorted strip-line structure with magnetic film.

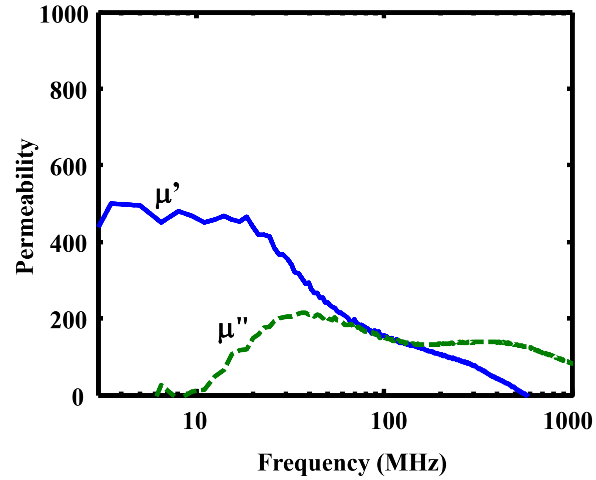

Fig.8. Variation of permeability with frequency for multilayered composite structure (measured)

REFERENCES

[1] J. S. a. H. P. J. Wijn, *Ferrites*. Holland: Philips, 1959.
[2] T. Nakamura, "Snoek's limit in high-frequency permeability of polycrystalline Ni–Zn, Mg–Zn, and Ni–Zn–Cu spinel ferrites," *Journal of applied physics,* vol. 88, pp. 348-353, 2000.
[3] D. S. Gardner, G. Schrom, F. Paillet, B. Jamieson, T. Karnik, and S. Borkar, "Review of on-chip inductor structures with magnetic films," *Magnetics, IEEE Transactions on,* vol. 45, pp. 4760-4766, 2009.
[4] Y. Hayakawa, A. Makino, H. Fujimori, and A. Inoue, "High resistive nanocrystalline Fe-MO (M= Hf, Zr, rare-earth metals) soft magnetic films for high-frequency applications," *Journal of applied physics,* vol. 81, pp. 3747-3752, 1997.
[5] S. Mathuna, T. O'Donnell, N. Wang, and K. Rinne, "Magnetics on silicon: an enabling technology for power supply on chip," *Power Electronics, IEEE Transactions on,* vol. 20, pp. 585-592, 2005.
[6] D. Kim, M. Ohnishi, N. Matsushita, and M. Abe, "Magnetic cores usable in gigahertz range: permalloy/Ni-Zn ferrite microcomposite made by low-temperature wet process," *Magnetics, IEEE Transactions on,* vol. 39, pp. 3181-3183, 2003.
[7] Y. Zhan, S. Wang, D. Xiao, J. Budnick, and W. Hines, "Nanocomposite Co/SiO2 soft magnetic materials," *Magnetics, IEEE Transactions on,* vol. 37, pp. 2275-2277, 2001.
[8] N. Tang, W. Zhong, W. Liu, H. Jiang, X. Wu, and Y. Du, "Synthesis and complex permeability of Ni/SiO2 nanocomposite," *Nanotechnology,* vol. 15, p. 1756, 2004.
[9] M. Xu, T. M. Liakopoulos, C. H. Ahn, S. H. Han, and H. J. Kim, "A microfabricated transformer for high-frequency power or signal conversion," *Magnetics, IEEE Transactions on,* vol. 34, pp. 1369-1371, 1998.
[10] J.-W. Park, F. Cros, and M. G. Allen, "A sacrificial layer approach to highly laminated magnetic cores," in *Micro Electro Mechanical Systems, 2002. The*

Fifteenth IEEE International Conference on, 2002, pp. 380-383.

[11] C. R. Sullivan and S. R. Sanders, "Microfabrication process for high-frequency power-conversion transformers," 1995, pp. 658-664 vol. 2.

[12] E. Valstyn and H. Huang, "An extended, dynamictransmission-line'model for thin-film heads," *Magnetics, IEEE Transactions on,* vol. 29, pp. 3870-3872, 1993.

[13] V. Bekker, K. Seemann, and H. Leiste, "A new strip line broad-band measurement evaluation for determining the complex permeability of thin ferromagnetic films," *Journal of Magnetism and Magnetic Materials,* vol. 270, pp. 327-332, 2004.

[14] C. Nelson, *High-frequency and microwave circuit design*: CRC Press, 2007.

[15] R. F. Soohoo, "Microwave magnetics," *New York, Harper and Row Publishers, 1985, 270 p.,* vol. 1, 1985.

[16] C. Kittel, "On the theory of ferromagnetic resonance absorption," *Physical Review,* vol. 73, p. 155, 1948.

[17] W. Jayasekara, J. Bain, and M. Kryder, "High frequency initial permeability of NiFe and FeAlN," *Magnetics, IEEE Transactions on,* vol. 34, pp. 1438-1440, 1998.