J. Micromech. Microeng. 23 (2013) 095011 (9pp)

A MEMS lamination technology based on sequential multilayer electrodeposition

Minsoo Kim, Jooncheol Kim, Florian Herrault, Richard Schafer and Mark G Allen

School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA

E-mail: mallen@gatech.edu

Received 28 February 2013, in final form 5 July 2013 Published 6 August 2013 Online at stacks.iop.org/JMM/23/095011

Abstract

A MEMS lamination technology based on sequential multilayer electrodeposition is presented. The process comprises three main steps: (1) automated sequential electrodeposition of permalloy (Ni₈₀Fe₂₀) structural and copper sacrificial layers to form multilayer structures of significant total thickness; (2) fabrication of polymeric anchor structures through the thickness of the multilayer structures and (3) selective removal of copper. The resulting structure is a set of air-insulated permalloy laminations, the separation of which is sustained by insulating polymeric anchor structures. Individual laminations have precisely controllable thicknesses ranging from 500 nm to 5 μ m, and each lamination layer is electrically isolated from adjacent layers by narrow air gaps of similar scale. In addition to air, interlamination insulators based on polymers are investigated. Interlamination air gaps with very high aspect ratio (>1:100) can be filled with polyvinylalcohol and polydimethylsiloxane. The laminated structures are characterized using scanning electron microscopy and atomic force microscopy to directly examine properties such as the roughness and the thickness uniformity of the layers. In addition, the quality of the electrical insulation between the laminations is evaluated by quantifying the eddy current within the sample as a function of frequency. Fabricated laminations are comprised of uniform, smooth (surface roughness <100 nm) layers with effective electrical insulation for all layer thicknesses and insulator approaches studied. Such highly laminated structures have potential uses ranging from energy conversion to applications where composite materials with highly anisotropic mechanical or thermal properties are required.

(Some figures may appear in colour only in the online journal)

1. Introduction

Sequential electrodeposition, in which repeated, alternating electrodeposition of two materials is performed, is an effective way to produce metallic multilayer structures with intriguing properties. Examples include materials with increased hardness compared to original solid materials [1], or giant magnetoresistance [2] resulting from magnetic coupling between the layers. In forming these multilayers, the advantages of an electrodeposition-based approach over vacuum deposition techniques (e.g., evaporation and sputtering) include higher deposition rates, higher total achievable thicknesses, lower built-in stress and lower capital cost of fabrication equipment [3].

An extension of this technique involves one of the sequentially deposited materials being a structural layer, and one being a sacrificial layer. Selective removal of the sacrificial layers, e.g., using chemical or electrochemical etching, results in formation of high aspect ratio lateral trenches between the structural layers. Leith *et al* studied this method by investigating the selective etching of Ferich layers from multilayer structures comprised of Ferich layers sandwiched by nickel-rich layers [4]. Similar structures were fabricated using nickel (Ni)/copper (Cu) multilayers by selectively removing either nickel [5] or copper [6]. Lim *et al* has fabricated a metallic nanomold [7] by creating relief structures on the sidewall of Ni/Cu multilayers structures by a timed, preferential etching of copper. Ni/Cu multilayers



Figure 1. Overall sequence of MEMS lamination process. (*a*) Fabrication of multilayer structures, (*b*) fabrication of polymeric anchors, (*c*) removal of sacrificial layers and (*d*) polymer infiltration.

for the realization of a variety of energy storage devices have also been investigated. For example, batteries and capacitors exploiting the high surface-to-volume ratio of these multilayer structures have been fabricated and characterized [8, 9].

This fabrication methodology can be further expanded for the realization of MEMS-scale laminations, in which the trenches extend through the entire lateral area of the multilayer material. Lamination of electrically conducting, soft magnetic materials is a general way to mitigate eddy current loss within these materials without compromising their power handling capacity. This is enabled by forming layers of magnetic material with thicknesses less than the skin depth of the material at operating frequency, and stacking the layers so as to achieve large total magnetic fluxes within the material volume. For this approach to be effective, it is necessary that the electrical conductivity between the layers be minimized. The skin depth of typical metallic magnetic alloys (e.g., NiFe and CoNiFe) at frequencies of several MHz are in the micron to submicron regime. It has been demonstrated that by scaling the individual lamination thicknesses to these levels, it is feasible to suppress eddy current losses in these materials to negligible values even at high-flux density (0.5 T) and high frequency (10 MHz). These structures enable miniaturized power converters with power handling capacity exceeding 5 W [10].

This paper focuses on the fabrication process for MEMS-scale laminations based on automated sequential electrodeposition. The fabrication process starts with batch-scale electrodeposition of permalloy/copper metallic multilayers through photoresist molds. At the end of the process, the multilayers are released by selective removal of copper, forming air-insulated laminations comprised of thin magnetic layers anchored by polymeric insulating structures. Polymer infiltration techniques are demonstrated in order to fill the air gaps between magnetic layers, thereby reinforcing interlayer insulation as well as providing mechanical robustness. Such polymer infiltration into air gaps with very high aspect ratio (>1:100) has been performed with polyvinylalcohol (PVA) and polydimethylsiloxane (PDMS).

2. Fabrication

The MEMS-based lamination fabrication approach can be divided into four main steps. First, multilayer structures are formed in a lithographically defined photoresist mold by automatic sequential electrodeposition of structural and sacrificial layers (figure 1(a)). Second, polymeric anchors are defined within the multilayer structure using either SU-8 or PDMS (figure 1(b)). Third, selective removal of the sacrificial layers to release the multilayer structures is performed. Ideally, after completion of this step, each permalloy layer is isolated by narrow air gaps, and the resulting structure is mechanically supported by the polymeric anchors (figure 1(c)). This structure is referred to as 'air-insulated laminations'. Fourth, an additional process is performed on the air-insulated laminations to refill the air gaps with insulating polymeric materials (figure 1(d)). We present two distinct ways to infiltrate polymers into the air gaps. The first relies on drying of aqueous solutions of PVA in water into which the air-insulated laminations have been immersed. The second relies on vacuum infiltration of PDMS into the air gaps.

2.1. Multilayer structure fabrication

The metallic multilayer structure is comprised of alternating layers of a structural material and a sacrificial material. In this work, electrodeposited permalloy is chosen as the structural material. Permalloy is a well-known soft magnetic metallic alloy exhibiting relatively high permeability ($\mu_r \sim 1000$) and high saturation flux density (~ 1.2 T) [10]. Copper is chosen as the sacrificial material, since (1) it is selectively etched away in an ammoniacal solution

[8, 9] without damaging various nickel alloys including permalloy; and (2) it is able to be electroplated on the permalloy without any unwanted displacement reactions. Both dual-bath electroplating and single-bath electroplating have been reported for the fabrication of permalloy/copper multilayer composites [11, 12]. The former approach uses two independent electroplating baths where a sample is transferred from one bath to the other in order to electroplate alternating layers of permalloy and copper. The latter approach utilizes a single bath containing parent metals for both deposits, and relies on changes in current density to deposit the respective metals. Although it results in additional equipment complexity, a dual-bath electrodeposition technique is employed for our application as it offers a higher degree-of-freedom in selecting electroplating solutions for the deposition of a specific metal pair, yields higher compositional contrast between the alternating layers and possesses a larger process window resulting from the complete independence of the two cathodic deposition reactions. However, it should be noted that dualbath plating may suffer from cross-contamination between baths and/or unwanted oxidation of samples during interbath transfer unless the process is carefully controlled [3].

Dual-bath plating is accomplished using an automated sequential electroplating system [8, 9, 13]. The system is comprised of two plating baths dedicated to permalloy and copper electrodeposition, respectively; two rinse baths filled with deionized (DI) water; and a robot arm capable of transferring a sample wafer from bath to bath. The sequential electrodeposition begins with electrodeposition of a first metallic layer in a first electrodeposition bath, followed by a sample transfer into two sequential rinse baths to avoid any cross-contamination between plating baths. Then, the sample is transferred into a second electrodeposition bath to deposit a second metal layer on top of the first layer. Note that the sample transfer process is sufficiently rapid (<2 s) that the metal surface does not oxidize. This process is automatically repeated until the desired number multilayers are formed. The thickness of each layer is controlled by adjusting the electroplating time and current. The plating system allows the fabrication of hundreds of pairs of metallic layers with precisely controlled individual layer thicknesses, which is a significant improvement over previous work done by manual multilayer electrodeposition [14].

The sequential electrodeposition of multilayer structures is performed on a sputtered titanium/copper/titanium seed layer, through a mold defined by photolithography [9]. A Watts type bath [15] is selected for the permalloy deposition. The pH of the bath is set rather low $(1.8 \sim 2)$ to enable long operation (>24 h) with minimal iron ion oxidation. The composition of plated metal is close to an ideal permalloy alloy composition (Ni₈₀Fe₂₀) when the bath is operated with a current density of 10 mA cm⁻². Two types of copper baths are tested for the deposition of sacrificial layers. The first is a copper bath based solely on copper sulfate and sulfuric acid, whereas the second is a commercially available bright copper bath containing organic brighteners and levelers to reduce surface roughness (Clean EarthTM Mirror Copper solution, Grobet USA). Figures 2(*a*) and (*b*) are side

views of multilayer composites with copper layers deposited from different solutions. To obtain clear contrast between permalloy and copper layers, a short period of selective copper etch is performed prior to imaging. Dark layers correspond to the etched copper layers, while bright layers represent permalloy layers. It is observed that the roughness of the layers continually increases with layer count for the sample deposited using the first copper bath, while the layers from the sample plated with the second, bright copper bath are smooth and uniform throughout the deposit. Atomic force microscope (AFM) measurements of the roughness of the topmost permalloy layer (40th layer) of multilayer structures formed from the first and the second copper bath are shown as insets of figures 1(a) and (b), corresponding to roughnesses of 171 and 7 nm, respectively. From these observations, the bright copper bath is selected for this work, as smooth copper deposits are essential to build thick multilayers of large total thickness (>100 μ m) with smooth and uniform permalloy layers throughout the volume. A 180 μ m thick multilayer structure with 300 pairs of 300 nm thick permalloy layers and 300 nm thick copper layers is shown in figures 2(c) and (d). It has been observed that hundreds of submicron-thick metal layers can be multilayered uniformly, while simultaneously achieving a total multilayer composite thickness in excess of 100 μm.

2.2. Polymeric anchor fabrication and sacrificial copper removal

Polymeric anchors are fabricated within the multilayer structures prior to the removal of sacrificial layers. The main role of the anchors is to provide mechanical support for the free-standing laminations that are created after the copper removal. Note that the anchors need to be good electrical insulators so as to not add any conductive route for eddy currents between individual magnetic layers. Figure 3 depicts anchoring procedures employing two different kinds of insulating polymers: SU-8 and PDMS. Beginning with the fabricated multilayer structures, the process involves a short selective etching of copper to create microscale lateral trenches on the sidewall of the multilayer structures (figures 3(a) and (b)). The width of the trenches is identical to the individual copper layer thickness within the multilayer structures (500 nm \sim 5 μ m), while the depth is defined by the etching time. Typically, the multilayer structures are etched for 20 min to create trenches as deep as 10 μ m. Then, a subset of the etch holes are filled with polymer and the polymer is crosslinked. Note that the polymer filled in the etch holes should also fully penetrate into the lateral trenches in order to provide stable mechanical support for the laminations after the complete sacrificial copper removal. The definition of the subset of etch holes is done in a material-specific manner. For SU-8, either a blanket manual dispense which fills all of the etch holes is performed (SU-8 2005, Microchem), or spin-casting followed by photolithography is performed (SU-8 2005 and 2025, Microchem) to selectively open some etch holes (figure 3(d)) [10, 16–17]. In the latter case, a low-viscosity photoresist SU-8 2005 is first spun-cast on



Figure 2. Comparison between deposits fabricated employing (*a*) a copper bath based solely on copper sulfate and sulfuric acid and (*b*) a bright copper bath. Both deposits are comprised of 40 pairs of 1 μ m thick copper (bright) and permalloy (dark). Insets are 10 μ m × 10 μ m AFM images for the topmost layer of the respective samples. (*c*) A 180 μ m thick multilayer composite with 300 pairs of 300 nm copper (bright) and permalloy layers (dark). (*d*) A magnified view of the same sample shown in (*c*).

the partially etched multilayer structures to facilitate the penetration of SU-8 into the trenches on the sidewall, before spin coating relatively viscous SU-8 2025 to fabricate the anchors with desired thickness. Patterning of PDMS anchors is performed by spin-cast micromolding [18]. In this process, photoresist post structures (NR21-20000P, Futurrex) thicker than the multilayer structures are formed in some of the etch holes using traditional photolithography. Then, degassed PDMS (Sylgard 184 A and B, Dow Corning) is dispensed to fill the non-resist-containing holes as well as to cover the post structures. The penetration of PDMS into the exposed microscale trenches in the non-resist-containing holes is achieved by a short vacuum infiltration step immediately after dispensing PDMS. Although PDMS is relatively viscous, its highly air-permeable nature allows excellent infiltration of the polymer into the trenches in a vacuum environment. Then, the sample is spun at a high speed of 4000 rpm to leave only a thin layer of PDMS on top of the protruding resist posts (figure 3(c)). Removal of the photoresist posts effectively 'lifts-off' these thin PDMS residues, while leaving PDMS in the non-resist-containing etch holes, thereby anchoring the free-standing laminations. The sidewalls of the etch holes that originally contained photoresist are now exposed and available to facilitate sacrificial copper removal (figure 3(e)).

Figure 4(a) shows patterned PDMS anchors present in alternating etch holes of the multilayer structures. Figure 4(b) is a cross-section view of a polymeric anchor (SU-8),

demonstrating that the SU-8 is interlocked with the multilayer structure. In particular, it should be noted that the 10 μ m deep trenches created at the sidewalls of the metallic layers are completely filled by SU-8. It is empirically confirmed that such anchors were stable enough to support free-standing permalloy laminations after the sacrificial copper removal, thereby achieving nearly perfect interlamination insulation for the laminated structures presented in this work (the evaluation of interlamination insulation of fabricated laminated structures is detailed in section 3).

After anchoring, a selective removal of sacrificial copper layers from the permalloy/copper multilayer structures is performed. The multilayer structures are immersed into a selective copper etchant [8, 9]. The copper is etched beginning from the sidewalls of the multilayers which do not possess the polymeric anchors, as well as from the periphery of the multilayer structures. After the copper removal, samples are rinsed in isopropyl alcohol (IPA) for 5 min, and rapidly dried in a convection oven at 70 °C to minimize stiction between permalloy layers. The resulting structure, comprising individual lamination layers separated by air and held in place by polymeric anchors, is referred to as 'air-insulated laminations'.

Fabricated air-insulated laminations exhibit very high aspect ratio. The aspect ratio of a single lamination (or air gap) is defined by the ratio of the thickness of the layer, t (or the gap between two individual layers, g), to the distance between the



Figure 3. Fabrication for polymer anchoring. The sequence (a), (b), (d) depicts fabrication of SU-8 anchors, whereas (a), (b), (c), (e) represents PDMS anchoring process. (a) Electrodeposited multilayer structures, (b) partial etch of the multilayer structures to form microscale lateral trenches, (c) spin-cast of PDMS on photoresist post structures, (d) SU-8 anchor formation and (e) removal of the photoresist post structures.



Figure 4. Scanning electron microscope (SEM) images of polymeric anchors. (*a*) Top view of PDMS anchors fabricated by spin-cast micromolding. The locations of anchors are highlighted by dotted rectangles. (*b*) A cross-sectional view of an SU-8 anchor coupled to a multilayer structure of 1.5 μ m thick permalloy and 1.5 μ m thick copper. The sample was diced and chemically polished using a solution consisting of 5% nitric acid (65%), 5% hydrogen peroxide (35%) and 90% DI water for 10 s prior to the imaging.

periphery of the laminations and the nearest polymeric anchor (w) as depicted in figure 5. Aspect ratios of both permalloy layers and air gaps could be as high as 1:400 (t, $g = 1.5 \mu$ m, $w = 600 \mu$ m). The minimum air gap achieved in this work is 500 nm with an aspect ratio of 1:300.

To achieve electrical isolation between the laminations, the interlamination copper of the as-fabricated multilayer structures must be completely removed. Thus, a method for assessing the degree of copper removal is required. One approach is an *in situ* electrical characterization of the multilayer structures during the core release, as detailed in [10]. In this technique, the multilayer structure to be etched is packaged in a polymeric bobbin and wound with Litz-wire to form an inductor. The inductor is immersed in the copper



Figure 5. A schematic depiction of the sacrificial copper removal process.



Figure 6. A schematic for PVA infiltration into multilayer structures with copper fully removed. (*a*) DI rinse of the multilayer structures, (*b*) addition of PVA into the rinse solution and (*c*) drying or heating the sample to solidify PVA.

etchant, and periodically removed from the etchant to measure the inductance of the inductor as a function of frequency. The inductance of an air-core inductor (i.e. a bobbin with identical winding geometry but no magnetic material) is subtracted from the measured inductance, to estimate the contribution of the lamination material to the total inductance. This socalled 'effective inductance' is further normalized by dividing it by the value of effective inductance at low frequency. The normalized effective inductance of any laminated material is unity at the lowest frequency of interest ($\sim 100 \text{ kHz}$) and decreases as frequency increases, regardless of the total magnetic volume of the material and/or number of winding turns around the material.

Before the etching, the normalized effective inductance decreases as the frequency increases, due to the presence of substantial interlamination eddy currents. As the interlamination copper is etched, eddy currents are reduced (and high frequency performance is improved). The end point of the release process can be determined as the time after which the inductance of the inductor either: (1) no longer falls with frequency for frequencies at which the skin depth is greater than the lamination thickness; or (2) no longer changes with etching time for frequencies at which the skin depth is less than the lamination thickness. Based on this test, it is observed that the etching time can be as short as 3 h or as long as 48 h depending on the shape of the multilayer structures and the distribution of etch holes not occupied by polymeric anchors. Once the etch time for a given multilayer geometry has been established using this technique, this etch time can be taken as a process parameter for complete copper removal.

2.3. Polymer infiltration techniques

From a structural perspective, air-insulated laminations differ from conventional core laminations, as the interlamination space of conventional laminations is typically filled by an insulating solid. The aspect ratio of the airinsulated laminations easily exceeds 1:100; hence, individual laminations are mechanically fragile. It may therefore be desirable to develop solid interlamination insulators. Two methods to fill the air gaps of the air-insulated laminations with polymeric insulating materials are demonstrated, thereby providing mechanical reinforcement of the laminations. Two constraints on the filling processes were observed: (1) the process should occur at low temperature so as to not degrade the magnetic properties of the core; and (2) the process should be based on non-vacuum techniques so as to remain consistent with the low capital cost of electrodeposition.

2.3.1. PVA infiltration technique. The PVA infiltration technique gradually substitutes the multilayer rinse solution by a solution containing the water soluble polymer, PVA. Note that the sample is not dried prior to infiltration, which is beneficial in terms of preventing stiction between layers. Figure 6 illustrates the PVA infiltration process. Immediately after sacrificial copper etching is completed, the etched multilayer structure is removed from the etching bath, rinsed, and immersed in a DI water bath without any intermediate drying to remove copper etchant from the structure (figure 6(a)). A solution of PVA in DI water (1:5 by weight) is gradually added to the bath, approximately doubling the bath volume and allowing the dissolved polymer to diffuse into the gaps between the permalloy layers (figure 6(b)). Finally, the sample is dried (or heated at 95 °C) until the PVA is solidified (figure 6(c)). This approach is also extendable to other solvent/dissolved polymer pairs that are compatible with the permalloy layers.



Figure 7. Optical images of (*a*) PVA-infiltrated permalloy laminations (lamination thickness and interlamination spacing of 1 μ m) placed in a winding bobbin for inductor testing, and (*b*) freestanding PDMS-infiltrated permalloy laminations (lamination thickness and interlamination spacing of 1.5 μ m).



Figure 8. SEM images of PVA- and PDMS-infiltrated laminations. (*a*) Cross-sectional image of the sample shown in figure 7(*a*). (*b*) Cross-sectional image of the sample shown in figure 7(*b*). In (*c*) and (*d*), the PDMS-infiltrated structure is further dissected to show (*c*) a top view of the surface of a single layer of infiltrated PDMS and (*d*) the surface of the permalloy layer which was originally in contact with the PDMS layer shown in (*c*).

2.3.2. PDMS infiltration technique. The vacuum infiltration of PDMS is an established technique for filling complex structures possessing significant three-dimensionality [19]. The superior performance of PDMS in this application stems from not only its air-permeability but also its ability to be cast in a solventless fashion. To infiltrate the high aspect ratios of the air-filled laminations, PDMS is degassed under vacuum and dispensed onto the air-insulated laminations. The PDMS/lamination composite is held for 5 min, then placed in a vacuum chamber for 30 min at room temperature. As the air between the laminations is replaced by PDMS, air bubbles at the surface of the PDMS are observed during approximately the first 10 min of the procedure. The sample is held under vacuum an additional 20 min to ensure full PDMS infiltration, after which the sample is removed. The thickness of PDMS on top of the sample can then be adjusted by a subsequent spincoating step. After thickness adjustment, the sample is held for 48 h at room temperature to fully cross-link the PDMS.

2.3.3. Fabrication results. The fabrication results of polymer-infiltrated laminations detached from their respective substrates post-infiltration are shown in figures 7 and 8. Figure 7(a) shows a toroidal-shaped permalloy laminated structure comprising 40 lamination layers and PVA interlamination insulation placed in a polymeric winding bobbin, forming an inductor. The air gap thickness as well as the individual lamination thickness of this sample was 1 μ m prior to PVA infiltration. Figure 7(b) shows a permalloy laminated structure PDMS-infiltrated laminations comprising 21 lamination layers and PDMS interlamination insulation. The air gap thickness as well as the individual lamination thickness of this sample was $1.5 \,\mu$ m prior to PDMS infiltration. The resulting structure is flexible since both the interlayer insulators and the polymeric anchors are elastomeric PDMS. The PDMS infiltration method not only provides an effective route to package fragile laminations, but also may lead to the

realization of novel flexible devices such as magnetic actuators and flexible electronics.

The polymer-infiltrated laminations of figure 7 are crosssectioned to image the polymers filled in the laminations (figures 8(a) and (b)). In both cases, polymer layers (dark) can be observed between the permalloy layers (bright). In order to obtain better evidence of complete polymer infiltration, a portion of the multilayer structure was peeled back along a PDMS-permalloy interface to reveal a top view of the infiltration. The surface of an infiltrated PDMS layer is thereby exposed as shown in figure 8(c). It is observed that a thin PDMS almost completely covers the underlying permalloy layer. Figure 8(d) shows the surface of the permalloy layer which was originally in contact with the PDMS layer shown in figure 8(c). Note that the PDMS was infiltrated from the sites indicated by dotted lines (figure 8(c)), and the interlamination region was completely filled up to the PDMS anchor regions.

3. Electrical characterization of fabricated laminations

Although direct imaging of laminations to assess structural integrity is possible, such tests are time-consuming and destructive. Electrical characterization of laminations is therefore considered as a means to assess the overall quality of the laminations. As detailed in the previous section, electrical characterization of a laminated structure is performed by packaging the structure in a polymeric bobbin to form an inductor and extracting the normalized effective inductance $(L_{n,meas})$ of the inductor from the measured inductance. The quality of a laminated structure (including the thickness uniformity of individual laminations and the interlamination insulation conductivity) is evaluated by comparing $L_{n.meas}$, and its theoretical value $(L_{n,theo})$ which is calculated from a one-dimensional analysis of the electromagnetic diffusion in a packet of laminations with perfect interlamination insulation for sinusoidal excitation [20] as below:

$$L_{\rm n,theo} = \frac{L}{L_0} = \left(\frac{a}{2b}\right) \left\{ \frac{\sinh\left(\frac{2b}{a}\right) + \sin\left(\frac{2b}{a}\right)}{\cosh\left(\frac{2b}{a}\right) + \cos\left(\frac{2b}{a}\right)} \right\},\tag{1}$$

where *L* is the effective inductance of the material (H), L_0 is the low frequency effective inductance of the inductor (H), 2b is the thickness of a single magnetic layer (m), and *a* is the skin depth (m) of the magnetic material at the operating frequency. The skin depth is written as

$$a = \sqrt{\frac{2}{\omega\mu_0\mu_r\sigma}},\tag{2}$$

when ω is angular frequency (rad/s), μ_0 is the permeability of vacuum (H/m), μ_r is the relative permeability of the magnetic material, and σ is the conductivity of the magnetic material (S/m). Since the above equation was derived assuming perfect interlamination insulation, if the values of ($L_{n,meas}$) are similar to those predicted by the above equations ($L_{n,meas}$), confidence can be gained that the interlayer lamination insulation is performing appropriately.

Table 1 shows both $L_{n,meas}$ and $L_{n,theo}$ at 5 MHz for the laminated structures with different interlamination insulation

Table 1. The measured normalized effective inductance of fabricated laminated structures $(L_{n,meas})^a$ and its theoretical calculation $(L_{n,theo})$ for various lamination thicknesses, at 5 MHz.

Individual lamination thickness ^b (μ m)	$L_{\rm n},_{\rm theo}$	L _{n,meas}
5	0.453	0.483 (PDMS) ^c
2.5	0.908	0.860 (Air)
1.5	0.987	0.927 (PDMS)
1	0.997	0.983 (Air), 0.980 (PVA)
0.5	0.999	0.990 (Air), 0.978 (PDMS)

^a Each value of $L_{n,meas}$ presented in table 1 is the measurement result from a single sample that exhibited the highest normalized effective inductance (L_n) among the fabricated samples with the same individual lamination thickness and interlamination material. ^b For the samples of table 1, the air gap thickness and the

lamination thickness of the air-insulated laminated structure (prior to infiltration) is nominally identical. ^c The type of interlamination insulation for each laminated

structure is stated in parentheses.

materials, with different individual magnetic layer thicknesses. A μ_r of 1000 and a σ of 1.43 \times 10⁷ (S/m) is used for the calculation, which are typical values of electrodeposited permalloy [21]. It is observed that the discrepancy between $L_{n,theo}$ and $L_{n,meas}$ for all the laminated structures presented is within approximately 6%; the discrepancy may be attributed to the combination of minor fabrication error (i.e. laminations fabricated slightly thicker or thinner than expected) and estimation of the material properties of permalloy (i.e. relative permeability and resistivity). This indicates that the decrease of the normalized effective inductance mostly depends on the thickness of individual laminations; in other words, the eddy current loss from the laminated structures results solely from the skin depth effect within the individual permalloy laminations, and not from interlamination conduction, for all three interlamination insulation materials (air, PVA and PDMS). In particular, the laminations with individual film thicknesses of 0.5 and 1 μ m show negligible drop of $L_{n,meas}$ (<5%) at 5 MHz. This corresponds well to the fact that theoretical cut-off frequency (i.e. the frequency where $L_{n,theo}$ is 0.95) of such laminations is beyond 10 MHz. These results demonstrate that the frequency-dependent behavior of these laminated structures are consistent with excellent interlamination insulation performance.

4. Conclusion

A MEMS lamination technology based on sequential electrodeposition was demonstrated. The process exploited automated sequential electrodeposition of a multilayer structure comprised of structural permalloy layers and sacrificial copper layers. After the completion of electrodeposition, individual permalloy layers were electrically isolated by selective etching of copper. The resulting structure yielded air-insulated laminations mechanically supported by insulating polymeric anchor structures. Polymer infiltration techniques using PVA and PDMS were developed to fill the high aspect ratio air gaps of the air-insulated laminations. Electrical characterization of laminated structures with different individual lamination thickness and different interlamination insulation material (air, PVA and PDMS) were found by frequency characterization measurements to be comparable to theoretical laminations with perfectly insulated layers at a frequency of 5 MHz. These results indicated that both magnetic performance (i.e. suppression of lamination eddy currents) and insulation performance (i.e. full electrical isolation between laminations) were achieved. Such highly laminated structures have potential uses ranging from energy conversion to applications where composite materials with highly anisotropic mechanical or thermal properties are required.

Acknowledgments

This work was supported by the Advanced Research Projects Agency-Energy under the Agile Delivery of Electrical Power Technology program (Award DE-AR0000107). Microfabrication was carried out in part in the GeorgiaTech's Institute for Electronics and Nanotechnology.

References

- Lamovec J, Jovic V, Vorkapic M, Popvic B, Radojvic V and Aleksic R 2011 Microhardness analysis of thin metallic multilayer composite films on copper substrates *J. Min. Metall.* 47 53–61
- [2] Bakonyi I and Péter L 2010 Electrodeposited multilayer films with giant magnetoresistance (GMR): progress and problems *Prog. Mater. Sci.* 55 107–245
- [3] Ross C A 1994 Electrodeposited multilayer thin films *Annu. Rev. Mater. Sci.* 24 159–88
- [4] Leith S D and Schwartz D T 1999 *In situ* fabrication of sacrificial layers in electrodeposited NiFe microstructures *J. Micromech. Microeng*, 9 97–104
- [5] Arai S, Hasegawa T and Kaneko N 2003 Fabrication of 3-D Ni/Cu multilayered microstructure by selective etching of Ni J. Electrochem. Soc. 150 C798–801
- [6] Arai S, Hasegawa T and Kaneko N 2004 Fabrication of three-dimensional Cu/Ni multilayered microstructure by wet process *Electrochim. Acta* 49 945–50
- [7] Lim C-Y, Huang Q, Xie X, Safir A, Harfenist S A, Cohn R and Podlaha E J 2004 Development of an electrodeposited nanomold from compositionally modulated alloys *J. Appl. Electrochem.* 34 857–66
- [8] Galle W P, Kim S-H, Sha U and Allen M G 2010 Micromachined capacitors based on automated multilayer

electroplating IEEE MEMS (Whan Chai, Hong Kong) pp 332–5

- [9] Armutlulu A, Fang Y, Kim S-H, Ji C H, Bidstrup S A and Allen M G 2011 A MEMS-enabled 3D zinc-air microbattery with improved discharge characteristics based on a multilayer metallic substructure *J. Micromech. Microeng.* 21 104011
- [10] Kim J, Kim M, Galle W P, Herrault F, Shafer R, Park J Y and Allen M G 2013 Nanolaminated permalloy core for high-flux, high-frequency ultracompact power conversion *IEEE Trans. Power Electron.* 28 4373–83
- [11] Dubois S, Marchal C, Beuken J M, Piraux L, Duvail J L, Fert A, George J M and Maurice J L 1997 Perpendicular giant magnetoresistance of NiFe/Cu multilayered nanowires Appl. Phys. Lett. 70 396–8
- [12] Esmaili S, Bahrololoom M E and Kavanagh K L 2011
 Electrodeposition, characterization and morphological investigations of NiFe/Cu multilayers prepared by pulsed galvanostatic, dual bath technique *Mater. Charact.* 62 204–10
- [13] Herrault F, Galle W P, Shafer R H and Allen M G 2011 Electroplating-based approaches for volumetric nanomanufacturing *Proc. Tech. Dig. Technol. Future Micro-Nano Manuf.* pp 71–4
- [14] Park J W 2003 Core lamination technology for micromachined power inductive components *PhD Dissertation* School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA
- [15] Frazier A B and Allen M G 1993 Metallic microstructures fabricated using photosensitive polyamide electroplating molds J. Microelectromech. Syst. 2 87–94
- [16] Kim J, Kim J K, Kim M, Herrault F and Allen M G 2012 Integrated toroidal inductors with nanolaminated metallic magnetic cores *PowerMEMS (Atlanta, USA)* pp 18–21
- [17] Kim M, Herrault F, Kim J and Allen M G 2013 Monolithically-fabricated laminated inductors with electrodeposited silver windings *IEEE MEMS (Taipei, Taiwan)* pp 873–6
- [18] Maclain M A, LaPlaca M C and Allen M G 2009 Spun-cast micromolding for etchless micropatterning of electrically functional PDMS structures J. Micromech. Microeng. 19 10700
- [19] Ha Y-H, Vaia R A, Lynn W F, Constantino J P, Shin J, Smith A B, Matsudaira P T and Thomas E L 2004 Three-dimensional network photonic crystals via cyclic size reduction/infiltration of sea urchin exoskeleton *Adv. Mater.* 16 1091–4
- [20] Lammeraner J and Stafl M 1966 *Eddy Current* (London: Iliffe Books Ltd)
- [21] Park J Y 1997 Packaging-compatible micromachined magnetic devices: integrated passive components and modules *PhD Dissertation* School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA