Soft Magnetic Materials

Highly Laminated Soft Magnetic Electroplated CoNiFe Thick Films

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Abstract—The fabrication and characterization of highly laminated (~40 layers), thick (~40 μm) films of magnetically soft cobalt–nickel–iron are presented. Thick film fabrication is based on automated sequential electrodeposition of alternating CoNiFe and copper layers, followed by selective copper removal. The film, comprised tens of 1 μm thick laminations, exhibits saturation flux density of 1.8 T and coercivity of approximately 1.3 Oe. High-frequency film characterization took place in a 36-turn test inductor, which demonstrated constant inductance of 1.6 μH up to 10 MHz, indicating suppressed eddy-current loss. Quality factor exceeding 40 at 1 MHz, surpassing the performance of similarly fabricated Permalloy ($Ni_{80}Fe_{20}$) films.

Index Terms—Soft magnetic materials, eddy-current losses, laminated CoNiFe film, magnetic core inductor.

I. INTRODUCTION

The continual reduction in size and increase in functionality of portable electronic devices drives the development of ultra-compact electrical power converters and therefore their associated inductors, which typically occupy the largest volume within the converter. This inductor size reduction can be achieved by increasing both the converter switching frequency as well as inductor operating flux density, e.g., by utilizing appropriate magnetic core materials [Gardner 2009, Meere 2011, Mathuna 2012]. Magnetically soft metallic alloys (e.g., NiFe, CoNiFe) are good core material candidates due to their superior magnetic properties (e.g., high saturation flux density and low coercivity) compared to conventional ferrite. However, to minimize eddy current losses, the core thickness is limited to the skin depth ($\delta = \sqrt{2/\omega\sigma\mu}$), where ω is the angular frequency [rad/s], σ is the conductivity [S/m], and μ is the permeability [H/m]. The high conductivity (~45000 S/cm) of these otherwise suitable metallic alloys results in decreasing inductance as well as significant losses at high (MHz) switching frequency [Lammeraner 1966]. Advances in materials such as CoZrTa or CoZrO granular thin films, which exhibit lower conductivity (<3000 S/cm), offer promise but it is still challenging to achieve film thicknesses suitable for high power conversion using sputtering deposition [Ikeda 2002, Xu 2011, Yao 2013]. Recently, we have demonstrated laminated soft magnetic Permalloy ($Ni_{80}Fe_{20}$) films with sufficient total magnetic volume for high flux, high-frequency power conversion by means of automated sequential electrodeposition, demonstrating suppressed eddy-current loss up to 10 MHz operation frequency, while maintaining the superior magnetic properties of Permalloy when compared to ferrite [Kim 2013]. Further improvement of such laminated films is achievable by exploiting advanced soft magnetic materials exhibiting higher saturation flux density and reduced coercivity, potentially resulting in higher efficiency power conversion. In this letter, we present laminated soft magnetic CoNiFe films exhibiting both higher saturation flux density and lower coercivity than laminated Permalloy films, and their performance as an inductor core material for high-frequency power conversion applications.

II. FABRICATION AND CHARACTERIZATION OF CoNiFe FILMS

Electroplated CoNiFe is a widely researched magnetic material due to its high saturation flux density (>1.8 T) and low coercivity (<2 Oe) [Osaka 1998]. Several electrodeposition approaches for this material have been established [Osaka 1998, Liu 2003]. In this letter, these electrodeposition approaches were investigated for compatibility with automated sequential multilayer deposition. Table 1 details the electrodeposition conditions (i.e., bath composition and plating parameters) for this letter. Although it has been reported that sulfur-containing additives such as sodium saccharin and sodium lauryl sulfate may increase the coercivity of CoNiFe [Osaka 1999], they are critical to relieve the deposition stress and improve ionic mass transfer throughout the multistep deposition of the films. Ammonium

Table 1. Electrodeposition conditions.

Component	Quantity
$CoSO_4 \cdot 7H_2O$	0.08 [mol/L]
$NiSO_4 \cdot 6H_2O$	0.2 [mol/L]
$FeSO_4 \cdot 7H_2O$	0.03 [mol/L]
NH_4Cl	0.3 [mol/L]
Boric acid	0.4 [mol/L]
Sodium saccharin	2.1 [g/L]
Sodium lauryl sulfate	0.01 [g/L]
Temperature	23 °C
pH	2.7 - 2.9
Current density	5-30 [mA/cm^2]

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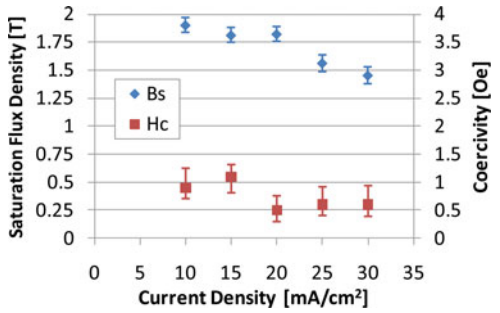


Fig. 1. Saturation flux density and coercivity of 1-μm-thick CoNiFe as a function of current density.

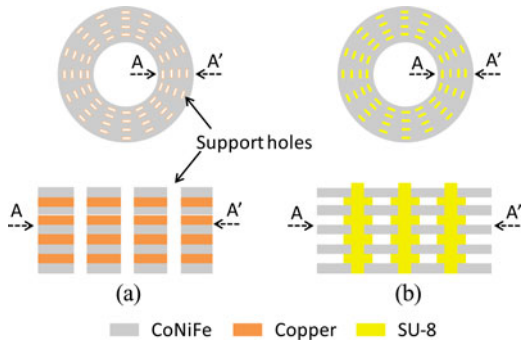


Fig. 2. Schematic top view and cross-sectional view of toroidal shape multilayer film: (a) CoNiFe/copper multilayer and (b) CoNiFe/air multilayer sustained by SU-8 support.

chloride enhances electrolyte conductivity, and boric acid provides pH buffering. A 5 cm $\times$ 5 cm nickel sheet anode is utilized and a pH of approximately 2.8 is maintained to prevent precipitation of cobalt in the electrolyte. Agitation of the electrolyte is not applied to minimize the convective mass-transfer effect [Leith 1999].

Based on these conditions, 1-μm-thick CoNiFe single laminations were deposited with various current densities (10–30 mA/cm^2). In excess 20 samples were prepared at each current density. The coercivity and saturation flux density of each sample were measured using a vibrating sample magnetometer (VSM) (LakeShore, 7300 VSM). Fig. 1 shows the dependence of the magnetic properties of these films as a function of current density. Data points represent average values for a given current density; error bars represent the data range. It is observed that the saturation flux densities of the deposited CoNiFe exceed 1.4 T and the coercivities are lower than 1.5 Oe. Over this current density range, 20 mA/cm^2 was selected for further use as it provided both high saturation flux density (1.82 T) as well as the lowest coercivity (0.5 Oe). For comparison, typical electrodeposited Permalloy exhibits saturation flux density of 1.25 T and coercivity higher than 2 Oe [Park 2003]. At the selected current density, the deposition rate is 0.25 μm/min and the atomic composition of the deposited material is 44% cobalt, 37% nickel, and 19% iron. It is also observed that the composition of nickel increases as the current density increases, while the other components (i.e., cobalt and iron) exhibit the opposite tendency, which is in agreement with previous reports [Osaka 1998, Leith 1999, Liu 2003].

The electrodeposition of CoNiFe/copper multilayer films is performed onto a sputtered copper seed layer and guided by a prepatterned photoresist mold. Once a first CoNiFe layer is deposited in a first magnetic material electroplating bath, the cathode bearing the film is robotically moved to a rinse followed by a second, commercially available copper electroplating bath (Grobet, Clean Earth Cu-mirror solution). This process is then repeated as many times as desired to achieve a large number of multiple lamination layers (and thereby large magnetic volume) while simultaneously allowing for precise control of the individual lamination thicknesses [Herrault 2011, Kim 2013]. The electrodeposited CoNiFe/copper multilayer film is shown in Fig. 2(a). After the multilayer deposition is completed, the sacrificial copper layer is entirely removed, while each CoNiFe layer is sustained by SU-8 epoxy insulating supports to prevent electrical connection or mechanical collapse between the magnetic layers as illustrated in Fig. 2(b). If further mechanical robustness is required, encapsulation or infiltration of insulating material between the laminations can be performed [Kim 2013]. More details of automated sequential electrodeposition and multilayer film fabrication are found in Kim [2013]. Fig. 3 shows a scanning electron microscope image of laminated toroidal shape CoNiFe/copper multilayers on a silicon substrate. The laminated film consists of 30 layers of alternating CoNiFe/copper, each with a 1-μm layer thickness. The support holes are utilized to apply SU-8 insulating posts. From the side views (left and right micrographs), individual CoNiFe laminations are separated from each other, having uniform lamination thicknesses of 1 μm throughout the entire film thickness.

In order to assess the magnetic properties (i.e., saturation flux density and coercivity) of laminated CoNiFe films, VSM measurement has been conducted on films with differing numbers of laminations. For all films, the individual lamination thickness is maintained at 1 μm. Fig. 4 shows the magnetic properties of the laminated films as a function of number of laminations, demonstrating that saturation flux density of the laminated film remains approximately 1.8 T and does not change with increasing numbers of lamination layers. The coercivity of the laminated film tends to increase compared to a single lamination deposited directly on a sputtered copper seed layer, possibly due to the higher roughness of electrodeposited copper compared to sputtered seed copper [Rhen 2008]. In order to investigate the effect of the CoNiFe film roughness, atomic force microscopy measurements have been conducted on the two different seed layer (i.e., sputtered copper and electroplated copper) as well as the CoNiFe films deposited on the two seed layers. The average roughness of the sputtered copper is 2.78 nm, while that of the electrodeposited copper is 10.9 nm. Consequently, it is observed that the average roughness of the CoNiFe film on the electrodeposited copper layer is 17.1 nm, which is higher than that of the CoNiFe film on the sputtered copper of 10.6 nm. Fig. 5 illustrates an example of 3-D surface topology of electrodeposited CoNiFe films on the two different seed layer. Although the increased average roughness of the CoNiFe film deposited on electrodeposited copper may degrade the mag-

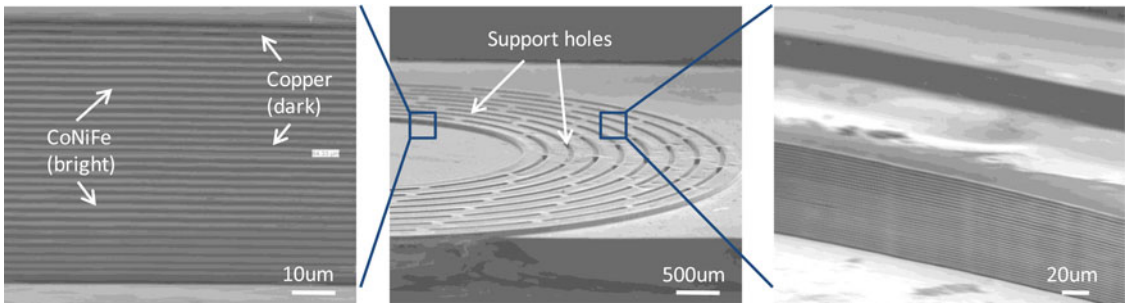


Fig. 3. Laminated core consisting of 30 layers of 1 μm-thick-CoNiFe films. Copper layers were partially etched toroidal shape CoNiFe to distinguish each CoNiFe layer.

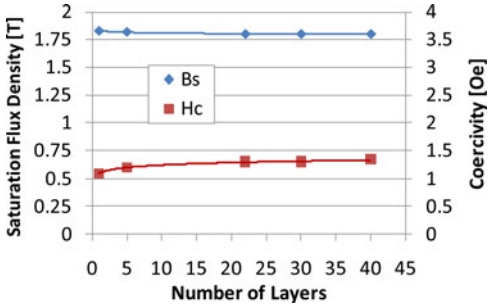
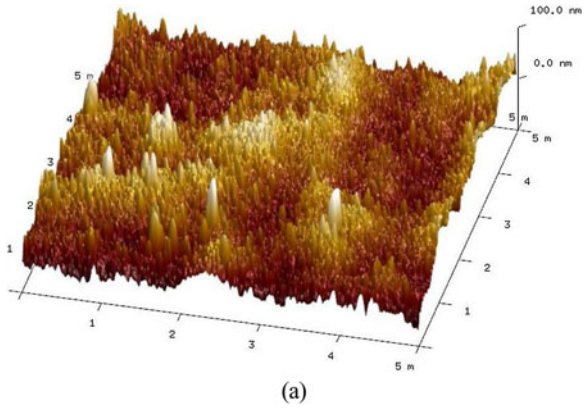


Fig. 4. Saturation flux density and coercivity of laminated CoNiFe films as a function of number of laminations.



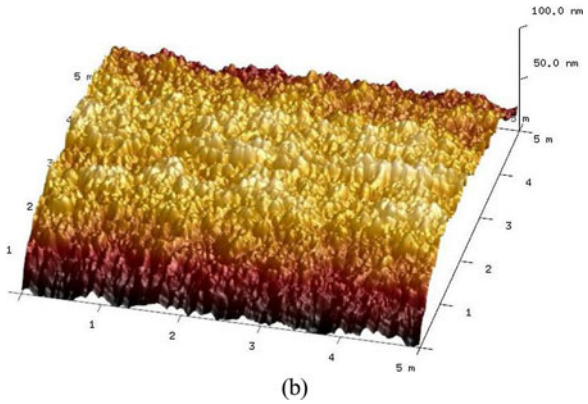


Fig. 5. Surface topology of electrodeposited CoNiFe films (a) on sputtered copper seed layer and (b) on electrodeposited copper seed layer.

netic property of the film (increased coercivity), the measured coercivity is maintained less than 1.5 Oe up to 40 lamination layers as shown in the Fig. 3.

In order to assess the magnetic properties of the laminated CoNiFe as an energy storage element, laminated toroidal shape CoNiFe cores with 10 mm outer diameter and 6 mm inner diameter have been prepared and formed into test inductors by winding 36 turns of litz wire around the cores. The electrical properties of the inductor (e.g., inductance and resistance) are measured using an HP 4194 A impedance analyzer. Details of this characterization approach are explained in Kim [2013]. Fig. 5 shows the performance of the laminated CoNiFe core comprised of 40 layers of 1-μm-thick CoNiFe laminations, and compares the performance to laminated Permalloy cores with the same geometry. Both laminated CoNiFe and Permalloy cores exhibit constant inductances up to 10 MHz operation frequency as shown in Fig. 6(a), demonstrating that eddy currents in the metallic core are suppressed in the laminated structures [Lammeraner 1966]. However, the inductance of the laminated CoNiFe core is approximately 1.7$\times$ higher than that of the Permalloy core, implying a higher effective relative permeability of approximately 200. Fig. 6(b) shows volumetric power losses from both laminated core materials, showing that the volumetric power loss of the laminated CoNiFe core is approximately half that of the volumetric power loss of the laminated Permalloy core in the low megahertz frequency region at the same operating flux density of 5 mT. Fig. 6(c) also demonstrates that the laminated CoNiFe core shows a higher quality factor throughout the entire frequency region.

III. CONCLUSION

We developed and characterized laminated CoNiFe films and magnetic cores. Highly laminated CoNiFe films are fabricated using automated sequential electroplating, allowing large numbers of stacked magnetic lamination layers with precisely controlled thickness. The laminated CoNiFe film consists of 40 layers of CoNiFe laminations with 1 μm individual lamination thickness, and exhibits a high saturation flux density reaching 1.8 T, and low coercivity of less than 1.5 Oe. The laminated CoNiFe core is demonstrated to operate in the megahertz frequency regime without suffering from eddy-current losses. Compared to the same geometry Permalloy core, higher inductance as well as lower volumetric power losses at the same operating flux level are achieved. Furthermore, the high saturation flux den-

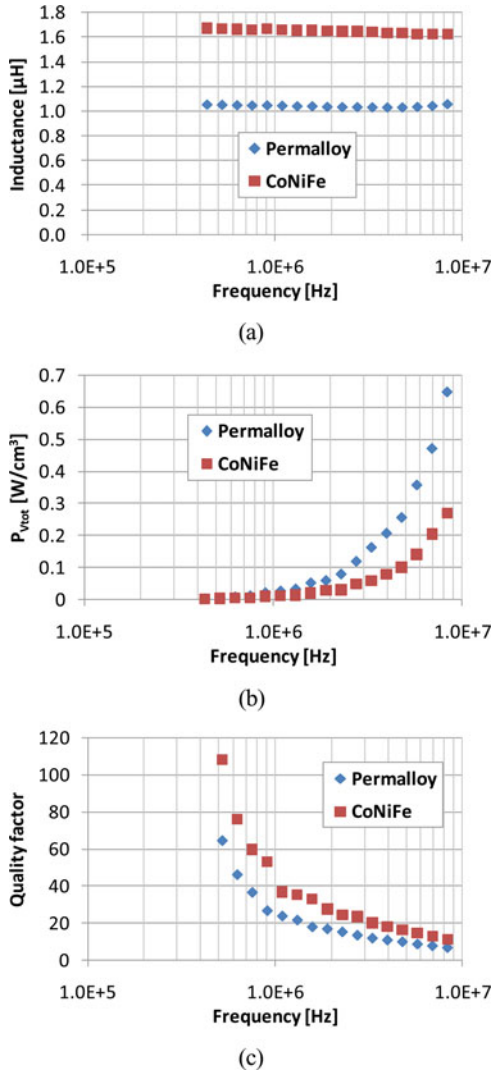


Fig. 6. Characterization of 36-turn inductor with laminated CoNiFe and Permalloy cores. (a) inductance, (b) volumetric core loss, and (c) core quality factor.

sity of CoNiFe, enabling high flux operation, potentially leads to the development of compact energy conversion devices.

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