A Sacrificial Layer Approach to Highly Laminated Magnetic Cores

Jin-Woo Park, Florent Cros, and Mark G. Allen

School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332 USA
Phone: (404) 894-9909, Fax: (404) 894-5028, E-mail: gte764c@prism.gatech.edu

ABSTRACT

The incorporation of laminations into micromachined magnetic components has the potential to reduce eddy current losses induced in the cores of these components. This paper reports a manufacturing technique for the fabrication of highly laminated cores. The approach is based on an alternating, conformal sequential electroplating of layers of NiFe and Cu, followed by selective sacrificial etching of the Cu. Since the copper sacrificial interlayer is itself conducting, it can act as a plating base for the subsequent deposition of NiFe without the necessity of multiple vacuum steps, multiple coating of insulating layers, or multiple photolithography steps. Highly laminated structures can therefore be achieved merely by alternating plating baths during fabrication, followed by selective removal of the Cu layers to provide electrical insulation between the magnetic layers. The fabrication approach can be readily adapted to a wide range of core geometries. To illustrate the improvements in magnetic properties achievable using this technique, the magnetic core fabrication technology has been successfully combined with integrated solenoid-like coils in order to fabricate a complete integrated inductor, which has been designed to operate in the low MHz range for power conversion applications. Inductors with highly laminated cores fabricated using the sacrificial layer approach exhibit quality factors exceeding those of unlaminated core devices by a factor of 2-3 at a frequency of 1 MHz.

INTRODUCTION

Conductive, electroplated NiFe alloys such as permalloy have been widely used for the fabrication of electromagnetic MEMS components. One example of their application has been as energy storage elements in switched-mode power converters. As switching frequencies increase, it is possible to reduce the values and overall dimensions of the magnetic components in these converters [1]. However, as frequencies increase (e.g., into the low MHz region and beyond), core losses (e.g., due to eddy currents) in unlaminated conducting cores also increase, driving the use of low conductivity core materials such as ferrites. Since many ferrites have lower saturation flux densities than NiFe alloys the overall dimensions of the device resist further miniaturization. Thererfore, there is a need for processes to fabricate laminations in conducting, micromachined permalloy cores. It should be noted that core losses can result from both hysteresis effects and eddy current effects. This paper focuses primarily on the reduction of eddy current effects.

In macro-scale magnetic devices, low-loss laminated cores are typically achieved by stacking alternating layers of core material and insulating material (which blocks eddy current flow), and laminating the entire stack together. Laminations have also been utilized in micromachined magnetic components. Previous approaches to micromachined laminations include one-step electroplating of vertical high-aspect-ratio structures [2]; repeated deposition of insulator, seed layer, and NiFe films [3]; multiple sputtering of thin magnetic and dielectric layers [4]; and mechanical lamination of polymer-coated NiFe foils [5].

Although these approaches have demonstrated improvement in device performance, processability and scaling remain as unaddressed issues. As permeabilities and desired operation frequencies increase, lamination thicknesses should be reduced to the micron range (i.e., on the order of the magnetic skin depth) while simultaneously maintaining total core thicknesses of tens to hundreds of microns to prevent saturation. These requirements dictate large numbers of thin, high-aspect-ratio laminations, which are difficult to achieve using the previously-proposed approaches. For example, in the case of vertically-laminated structures, the required aspect ratio of the mold laminations increases, making mold fabrication difficult. Horizontal lamination using repeated deposition of magnetic thin films and insulators, e.g., by sequential sputtering, overcomes this difficulty but may not be able to achieve the required overall stack thicknesses due to stress issues. Electroplating of horizontal laminations offers the possibility of fabricating structures of sufficient overall thickness, but the repeated switching of substrates between plating bath and vacuum system as detailed in [3] becomes unmanageable as the number of layers increases. Finally, conventional foil lamination becomes difficult as the foil thickness approaches the micron range, especially since mechanical strain of magnetic foils has been demonstrated to degrade magnetic properties.

In this paper, a manufacturable approach allowing micron-scale (or smaller) laminations and large total core thickness without the need for interposing vacuum steps or sub-micron lithography is presented. The approach is based on

0-7803-7185-2/02/$10.00 ©2002 IEEE

sequential electroplating to form densely alternating stacks of magnetic and nonmagnetic material. Previous work in sequential electroplating has produced compositionally-modulated stacks, which have been proposed as fabrication aids [6] or nanostructured materials with improved wear characteristics [7]. In this work, the focus is on the exploitation of this technique to create laminations. The approach is based on an alternating, conformal sequential electroplating of layers of NiFe and Cu, followed by selective sacrificial etching of the Cu. Since the copper sacrificial interlayer is itself conducting, it can act as a plating base for the subsequent deposition of NiFe without the necessity of multiple vacuum steps, multiple coating of insulating layers, or multiple photolithography steps. Highly laminated structures can therefore be achieved merely by alternating plating baths during fabrication, followed by selective removal of the Cu layers to provide electrical insulation between the magnetic layers. Additional features are also incorporated in the fabrication sequence to ensure mechanical integrity of the lamination stack after removal of the sacrificial layer.

CORE DESIGN CONSIDERATIONS

Lamination of the core of an inductor is particularly effective when the thickness of an individual lamination layer is on the order of (or smaller than) the skin depth of the given material at a given frequency of operation. The magnetic material used in this work is electroplated NiFe. Its reported relative permeability and conductivity are 800 and $5X10^6(\Omega.m)^{-1}$, respectively [2]. Using these values, the skin depth of NiFe is approximately 5 microns at a frequency of 2 MHz. Therefore, each individual NiFe lamination will be fabricated in this thickness range in order to determine the utility of this approach for integrated inductors in the low MHz frequency range. Figure 1 illustrates examples of cores fabricated in this work. Figure 1.1/ is a schematic cross section of a solid core inductor that suffers from eddy currents, and which will be used as a comparison benchmark to assess the laminated cores. Fig 1.2/ is a 'perfectly' laminated core (i.e., complete electrical and, ideally, physical separation between laminations). Figures 1.3/ and 1.4/ represent the cross section of two laminated cores, fabricated using the sequential lamination process, which include supporting structures to hold each lamination in place. These supporting structures are utilized in order to maintain structural integrity of the core. Since the supporting structures will also be fabricated from NiFe for process convenience, the central V-shaped structure of (fig 1.4/) has been chosen, since it does not provide a closed electrical path for eddy currents to flow.

Initially, laminated cores were fabricated as described below and hand-wound with coils for testing purposes. Once the utility of the core was demonstrated, the core fabrication sequence was combined with fabrication of integrated coils to form fully integrated inductors.

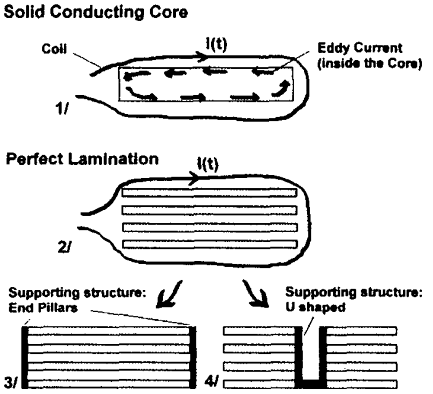

Figure 1: Configurations for laminated and unlaminated magnetic cores

FABRICATION OF LAMINATED CORE

Using standard techniques, a seed layer is deposited on a substrate and a thick photoresist layer is processed in order to create a core mold. The mold is formed of two low aspect ration trenches:30 µm deep and 500 µm wide. The mold is a 4mm*4mm square ring. The ring is 1 mm wide (see fig 2). The mold is filled with sequential electrodeposition of NiFe (80%-20%) and Cu layers (fig 2.1/). Three 4 µm thick layers of NiFe are deposited. Each layer of NiFe is separated from the next NiFe layer by a 6 µm layer of Cu. Note that during the formation of the stack, each layer provides a good electrical base for the electrodeposition of the subsequent layer. Two adjacent Cu/NiFe multi-layered structures separated by a central trench are hence created (fig 2.2/). The mold is removed and a new layer of photo-resist is patterned (fig 2.3/), opening a central trench between the two structures. A final NiFe layer is then electrodeposited. This 4 µm thick layer coats the sidewalls inside the trench as well as the upper surface of each structure (fig 2.4/).

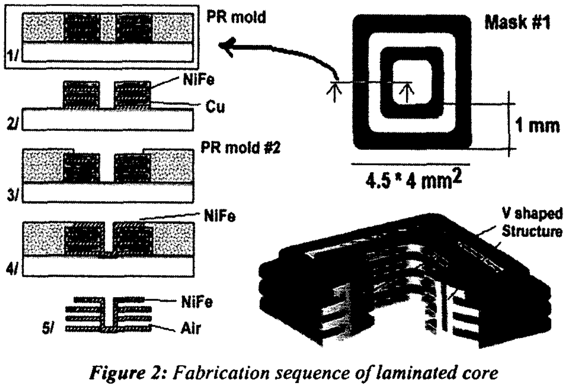

Figure 2: Fabrication sequence of laminated core

After removing the photo-resist mold (fig 2.5/), the fabrication of the core ends with the selective etching of the copper between the NiFe layers. As described earlier, the

V-shaped central NiFe layer is supporting each individual NiFe lamination once the Cu is removed.

Successful freestanding core structures were fabricated using the above process. Figure 3 shows a detail of the NiFe laminated core after Cu removal. The layers of NiFe are separated from each other by 6 μm of air.

***Figure 3:** Scanning Electron Micrograph of a laminated NiFe structure after Cu removal (detail)*

DISCUSSION AND PRELIMINARY TESTS

One potential limitation of this process is that as the horizontal aspect ratio of the laminations increases, the compliance of each lamination layer may also increase. For example, in some structures fabricated using the above process, visual inspection of some cores showed that some NiFe layers were touching at the periphery of the structure. If significant layer-to-layer electrical conductivity occurs at these contact points, the efficacy of the lamination structure is reduced. To assess the effects of unwanted mechanical contact between adjacent NiFe layers, three different cores were fabricated. Test core 'A' was fabricated using the technique described in the previous section, with four 4-μm-thick NiFe laminations. Test core 'B' was fabricated using multiple individual NiFe rings of the same thickness, fabricated separately, and stacked together with thin insulating films between them to most closely approach the 'perfect lamination' case of Figure 1.2. Test core 'C' was a solid NiFe ring fabricated using a single-step electroplating, with a total thickness equal to the sum of the lamination thicknesses in either core 'A' or core 'B'.

Each core was hand-wound with insulated magnet wire in order to create a test inductor. The frequency response of these cores was then tested (Figure 4), using an HP4194A impedance analyzer. The results show that core 'A' (the micromachined laminations) favorably compares to core 'B' (the 'perfect' laminations). It should be noted that this result was obtained in spite of the fact that during the hand-winding process, core 'A' was subjected to significant mechanical compression. Both laminated cores exhibited significantly superior performance over that of solid core 'C', which showed a rapid decrease in inductance with frequency, characteristic of the limiting effects of eddy currents [8].

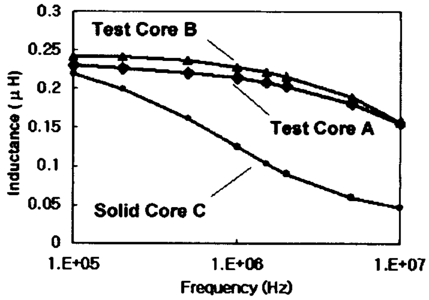

***Figure 4:** Inductance vs frequency for 3 different test cores*

FABRICATION OF INTEGRATED INDUCTORS WITH LAMINATED CORE

Since lamination using this approach was demonstrated to produce magnetically-superior cores, the process of Figure 2 was combined with a standard integrated coil process to achieve fully-integrated, laminated inductors. This combined process is described below. The bottom conductor lines of the coil are fabricated first using conventional micro-molding and electroplating of Cu. The lines are passivated under a layer of photosensitive epoxy, which is patterned in order to create electrical vias (fig 5.1/). A single Ti-Cu-Ti seed layer is deposited and the fabrication of the laminated core is performed as described earlier (fig 5.2/). Before removing the sacrificial Cu, a thin photoresist is spin-cast and patterned in order to clog the electrical via and protect the underlying Cu lines during the sacrificial Cu etch step (fig 5.3/). Once the laminated core is fabricated (fig 5.4/), a thick layer of epoxy resist (SU-8) is then deposited, in order to further structurally reinforce the core as well as to allow completion of the coil (fig 5.5/).

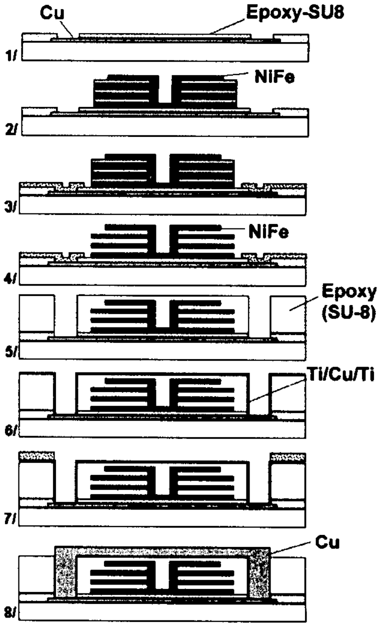

***Figure 5:** Fabrication sequence for a complete integrated inductor*

The layer of epoxy is patterned using photolithography. The core is now embedded under a structure of cross-linked epoxy and is surrounded by vertical vias. The vertical vias will later allow the fabrication of the vertical sections of the 3D conductor. The entire structure is coated with a conformal layer of Ti/Cu/Ti using DC sputtering. (fig 5.6/). A thick layer of conventional photoresist is patterned to create horizontal openings connecting each vertical via at the upper surface of the epoxy structure (fig 5.8/). A final Cu electrodeposition yields the simultaneous fabrication of the vertical as well as the upper horizontal parts of the Cu conductor. The photoresist and seed layer is removed (fig 5.9/). A photomicrograph of the fabricated device is given in Fig. 6.

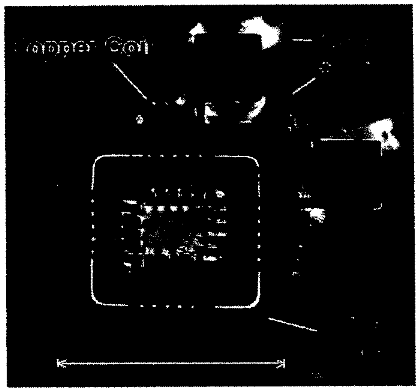

***Figure 6**: Photomicrograph (top view) of a complete integrated inductor with laminated NiFe core*

INTEGRATED INDUCTOR CHARACTERIZATION

To illustrate the improved characteristics of a laminated core, a solid core integrated inductor with the same cross-sectional core area as the device of Fig. 6 was fabricated, and both devices were tested using an HP4194A impedance analyzer. Their respective inductances and Q-factors are shown in Figure 7. Figure 7 shows that the inductance of both devices decreases with increasing frequency. However, the inductance of the solid core inductor decreases faster than its counterpart, suggesting that eddy current effects are significantly reduced in the case of the laminated core inductor.

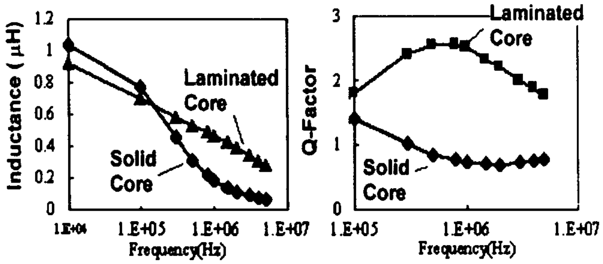

***Figure 7**: Inductance and Q factor of solid and laminated core integrated inductors as a function of frequency*

Figure 7 also shows that the Q-factor of the laminated core inductor is approximately 2-3 times larger than that of the solid core inductor at 1MHz.

CONCLUSION

Using a sequential electroplating and sacrificial selective etching technique, laminated cores have been fabricated for magnetic microsystems. This fabrication approach yields laminated cores with reduced eddy current losses. Fully integrated inductors based on these cores have been fabricated and tested in the low MHz range. As expected, laminated inductors show significantly improved performance over solid-core devices. Since highly laminated structures can be achieved merely by alternating plating baths during fabrication, it is expected that this approach will enable the incorporation of laminations into magnetic micromachined devices in a manufacturable manner.

ACKNOWLEDGEMENTS

This work was supported in part by the Defense Advanced Research Projects Agency and the Army Research Office MURI Program. Microfabrication was carried out at the Georgia Tech Microelectronics Research Center with the assistance of the staff.

REFERENCES

[1] C. R. Sullivan and S. R. Sanders, “Microfabrication of transformers and inductors for high frequency power conversion,” in *24th Annu. Power Electronics Specialists Conf.*, June 1993, pp. 33–40.

[2] 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,” *IEEE Trans. Magn.*, vol. 34, pp. 1369-1371, July 1998.

[3] J. Park, S. H. Han, and M.G. Allen, “Batch-fabricated microinductors with electroplated magnetically anisotropic and laminated alloy cores,” *IEEE Trans. Magn.*, vol. 35, no. 5, pp.4291-4300, 1999.

[4] C. R. Sullivan and S. R. Sanders, “Microfabrication process for high-frequency power-conversion transformers,” in *26th Annu. Power Electronics Specialists Conf.*, June 1995, pp. 658-664.

[5] J. Park, J. Y. Park, Y. Joung, and M. G. Allen, “Fabrication of high current and low profile micromachined inductor with laminated Ni/Fe core,” *IEEE Trans. Component and packaging Technology*, submitted.

[6] S. Leith and D. T. Schwartz, “In situ fabrication of sacrificial layer in electrodeposited NiFe micro-structures,” J. Micromech. Microeng. , 9 1999, p 97-104

[7]C. Yang and H. Y. Cheh, “Pulsed Electrodeposition of Copper/Nickel multilayers on rotation disk electrodes,” J. Electrochem. Soc., Vol. 142, no.9, sep. 1995 3034-3039

[8] J. Lammeraner, and M. Stafl, *Eddy current*. London: Iliffe Books Ltd., 1966, Chapter 2