MONOLITHICALLY-FABRICATED LAMINATED INDUCTORS WITH ELECTRODEPOSITED SILVER WINDINGS

Minsoo Kim, Florian Herrault, Jooncheol Kim, and Mark G. Allen
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA

ABSTRACT

This paper presents batch microfabrication and experimental characterization of solenoid inductors with electrodeposited silver windings and laminated core. To enable high-frequency operation, the metallic magnetic core consists of multiple air-insulated, electroplated micron-thick permalloy ($Ni_{80}Fe_{20}$) laminations, with total core thicknesses up to tens of microns. The core is achieved by sequential electrodeposition of permalloy and copper, followed by selective removal of the copper, thereby releasing the core laminations. Electroplated silver is selected as winding material for its low resistivity and to withstand the copper etching required during core release. Release of the core laminations is the final inductor fabrication step, reducing potential process-induced damage to the core. Two inductors sharing one laminated core in a transformer geometry are fabricated, and exhibit inductances of approximately 100 nH at 5 MHz, resulting in an inductance density of 29 nH/mm^2. This process demonstrates processing compatibility of using silver windings with highly-laminated, fully-integrated magnetics.

INTRODUCTION

The miniaturization of electrical power converters is often limited by bulky inductive components, which typically occupy the largest physical volume in a converter [1]. Together with attempts to reduce the required inductance (and therefore inductor physical size) by increasing switching frequency, there has been a steadily increasing effort to realize chip-scale inductors using micromachining technologies. High energy density magnetic materials (e.g., soft metallic magnetic materials [2] and ferrites [3]) can be integrated with micromachined windings in order to achieve the required inductance within a minimized footprint.

Recently, we have presented high energy density laminated cores comprised of tens of layers of electroplated submicron-thick soft magnetic metal alloy films, and demonstrated that the laminations suppress eddy currents up to several MHz operation frequency [4]. A critical part for successful core fabrication is the core release process, which is a selective removal of the copper from a multilayer permalloy/copper composite pre-fabricated by automated sequential electrodeposition. After the release step, individual permalloy layers are air-insulated while simultaneously being supported by insulating polymeric anchor structures.

The integration of such cores into conventional copper microwindings is a potential challenge, since the core release process is not compatible with pre-fabricated copper windings as well as copper seed layers. Core integration into micromachined windings has been achieved previously by manual placement of pre-fabricated laminated cores [4]; however, this approach requires hybrid manual assembly. Moreover, the post-processes performed on the laminated cores (e.g., photoresist casting) may deform the thin, free-standing individual laminations; this may result in either degradation of magnetic properties and/or increase of interlayer conductivity between individual laminations, thereby increasing the eddy current loss within the core.

In this paper, silver is utilized as a winding material to enable the monolithic fabrication of laminated permalloy cores and windings. The use of silver windings passivated in SU-8 exhibits superior compatibility to the core release process. Release of the core laminations is the final process step in inductor fabrication, reducing the possibility of post-processing-induced damage to the laminated core. Further, silver winding inductors may result in increased inductor Q-factor due to its superior electrical conductivity compared to copper [5].

DESIGN AND FABRICATION

Structure design

A pair of multi-turn solenoidal windings are coupled with a rectangular laminated core, comprising a transformer. A solenoidal geometry is selected for efficient utilization of magnetic material, as opposed to spiral integrated inductors typically exhibiting relatively limited inductance enhancement from the magnetic material [6].

The overall device design is shown in Figure 1. Figure 1(a) is a schematic top view of an integrated inductor with a rectangular laminated core. Figures 1(b) and 1(c) are schematic cross-sectional views of the inductor before and after the core release. Note that insulating SU-8 structures are (i) isolating the laminated core from the windings, (ii) passivating the windings from the outer environment, and (iii) anchoring individual core laminations after the core release.

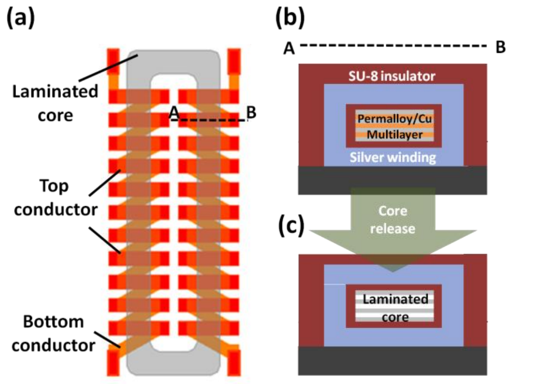

Figure 1. Schematics of an integrated inductor. (a) Top view, and cross-section view between A and B (b) before and (c) after the core release process.

Material selection

Silver is known to exhibit the highest electrical conductivity among all metals. In the field of micromachining, silver has been employed to maximize the Q-factor of high-frequency resonators [5]. In this work, silver is selected as a winding material to exploit its superior chemical resistance, along with the potential for Q-factor enhancement. SU-8 is chosen as an insulating material for its chemical stability and photopatternability. Permalloy is selected as the magnetic material since it exhibits superior saturation flux density as well as permeability. For the sacrificial material, copper is chosen because of its ability to be sequentially electrodeposited with permalloy as well as its ability to be selectively etched without damaging permalloy.

Fabrication process of integrated inductors

Microinductor fabrication is based on several repetitions of the steps: (i) through-mold electroplating; and (ii) SU-8 passivation. The through-mold electroplating occurs from a sputtered seed layer through a photoresist mold of thickness 50 µm (NR 21-20000P, Futurrex). The sputtered seed layer is a sandwich of titanium, silver, titanium, with thicknesses of 30 nm, 250 nm, and 30 nm, respectively. Note that the last titanium layer is indispensible for not only proper adhesion between photoresist mold and the substrate, but also to prevent the silver layer underneath from being oxidized by oxygen plasma descum process performed after photolithography. The silver electroplating is performed with current density of 2.5 mA/cm^2 in a cyanide-based bath. Copper and permalloy are plated as detailed in [7]. The mold is removed with acetone, and the seed layer is removed with diluted SC-1 (ammonium hydroxide/hydrogen peroxide) etchant. SU-8 is deposited and patterned to passivate the electroplated structures. The exposure dose for the SU-8 is 50~60 % of the recommended value [8], considering the superior UV reflectivity of silver. SU-8 hardbake is performed at a relatively high temperature of 170°C after development to prevent SU-8 structures from being deformed during any subsequent thermal processes.

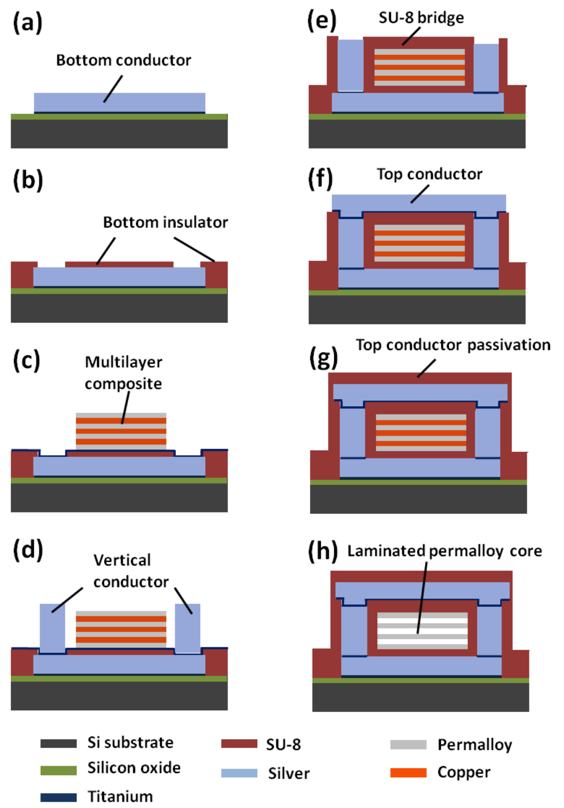

Figure 2. Fabrication process of an integrated inductor: (a) Bottom conductor fabrication, (b)bottom insulator patterning, (c) fabrication of multilayer permalloy/copper composites with an automated sequential electroplating, (d) vertical conductor fabrication, (e) SU-8 bridge formation, (f) top conductor fabrication, (g) top conductor passivation, and (h) core release.

The detailed integrated inductor fabrication procedure begins by electroplating and passivating the bottom conductors (Figure 2(a),(b)). Robot-assisted sequential electrodeposition is performed to build a multilayered core 40 µm in thickness comprised of alternating layers of 1 µm thick copper and 1 µm thick permalloy (Figure 2(c)). Vertical conductors are formed (Figure 2(d)), followed by patterning of SU-8 bridges which passivate the sidewalls of the vertical conductors as well as a portion of the top side of the multilayered composite core (Figure 2(e)). After the top conductors are plated along the bridges (Figure 2(f)), it is passivated with SU-8 (Figure 2(g)). After this step, the silver windings are completely encapsulated with SU-8. Finally, the core is released by a selective removal of copper from the multilayer composites (Figure 2(h))

[7]. Approximately 6 hours is required for the release. Problems such as winding disconnection, or delamination of structures are not observed during the core release, since the silver etch rate during the core release is less than 1% that of copper.

Fabrication Results

Images of fabricated inductors are shown in Figure 3 and Figure 4. Figure 3(a) shows two pairs of integrated inductors, while Figure 3(b) shows a close view of the laminated core and SU-8-passivated top windings. A single inductor has a footprint of less than 5 mm^2 and a device thickness of ~100 µm.

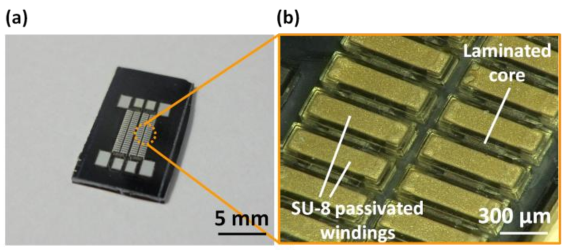

Figure 3. (a) Optical image of an integrated inductor; (b) close view imaged with a stereoscope.

Figure 4(a) shows the vertical conductors embedded in SU-8 bridges before the top conductor fabrication. Figure 4(b) show the SU-8 bridges isolating the silver windings from the laminated core. Both SU-8 bridges and bottom insulators provide greater than 10 µm separation between the windings and the core.

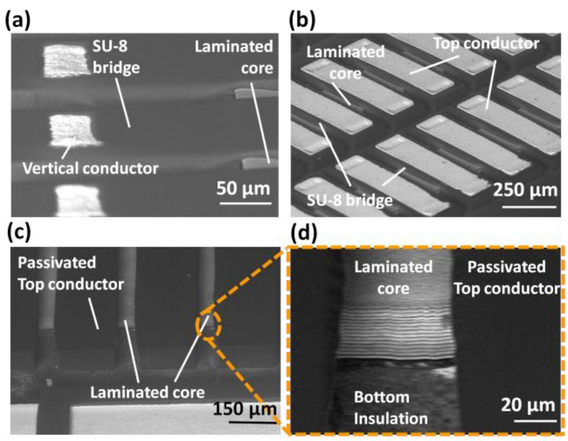

Figure 4. Close view of a integrated inductor(a) before the top conductor fabrication, (b) after the top conductor fabrication, (c) and after the final core release. (d) Magnified view of Figure 4(c).

Figures 4(c) and 4(d) show a side view of the released laminated cores. Individual permalloy layers in the picture are well-separated without suffering from stiction after the release process, validating that the layers are effectively anchored by SU-8 bridge structures.

CHARACTERIZATION OF INTEGRATED INDUCTORS

The magnetic characteristics of a fabricated inductor are measured using an impedance analyzer. Figure 5 shows the inductance and Q factor obtained from two identical 20-turn inductors sharing a single laminated core before and after the core release, at a constant magnetic flux of 2 mT. Before the core release, both inductors exhibit low inductances (~20 nH) as well as low Q factor (< 1) at frequencies above 5 MHz.

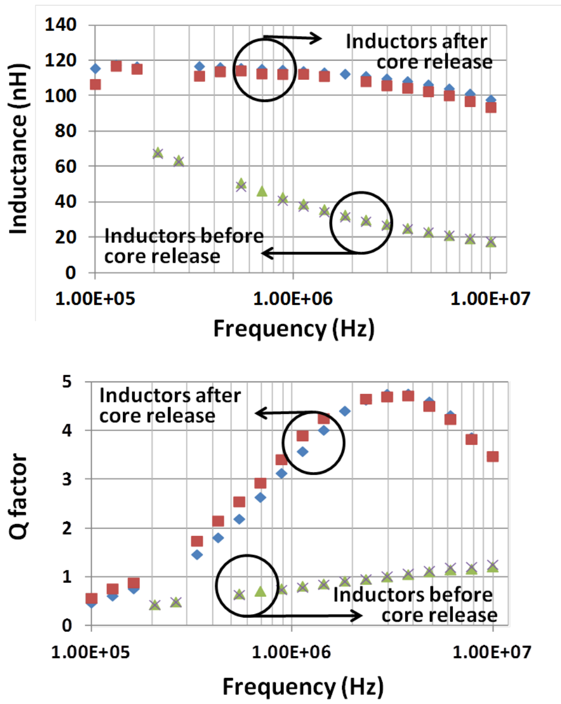

Figure 5. Inductance and Q-factor of two microinductors measured before and after the core release process.

This is due to the eddy current loss induced within magnetic cores thicker than the frequency-dependent magnetic skin depth [9]. However, the inductance and Q-factor of both inductors greatly increase after the copper release, as eddy currents can no longer flow in the laminated core.

The corresponding inductance density is 29 nH/mm^2, and the peak quality factor Q reaches 5 at 3 MHz, which is comparable to integrated inductors with sputtered permalloy laminations [10]. However, the electrodeposition-based lamination technology benefits from simplified core patterning, thick core electroplating capability, and low-stress electroplated films compared to sputtering approaches. Inductor performance can be further improved by (i) increasing the volume of the magnetic core material by constructing thicker cores, and (ii) by potentially using a magnetic material with higher permeability and lower coercivity (e.g., CoNiFe alloy [4]).

Furthermore, the usefulness of silver winding SU-8 passivation was evaluated by comparing the change of coil resistance during the core release process for windings with and without passivation. Figure 6 shows that the non-insulated silver windings can sustain up to approximately 20 hours of etching time, which is nearly 3 times longer than the etching time required for the core release of these inductors. This result suggests that the SU-8 passivation steps may be neglected to simplify the overall fabrication process by appropriately designing the core and winding dimensions.

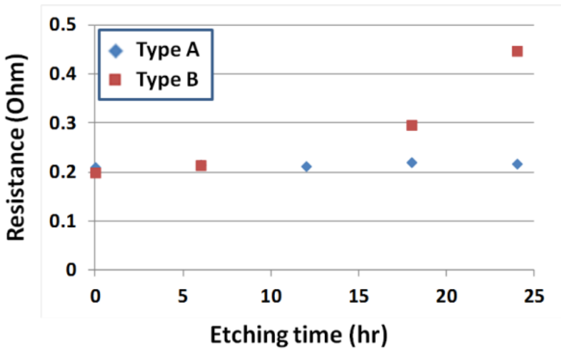

Figure 6. Resistance change during the core release process for two inductors with (Type A), and without (Type B) top conductor SU-8 passivation.

CONCLUSION

The monolithic integration of laminated permalloy cores with electroplated silver windings was demonstrated. Silver was employed as a winding material because of its compatibility with batch fabrication of laminated cores and three-dimensional windings. Release of the core laminations was the final process step in inductor fabrication, reducing the possibility of post-processing-induced damage to the highly-laminated core. Fabricated and functional solenoidal integrated inductors exhibited stable inductance in excess of 100 nH with quality factor reaching 5 at several MHz.

ACKNOWLEDGEMENTS

This work has been supported in part by the Advanced Research Projects Agency-Energy (ARPA-E) under the Agile Delivery of Electrical Power Technology (ADEPT) program (Award DE-AR0000107), and in part by Texas Instruments. The authors would like to thank David Anderson of Texas Instruments for helpful technical discussion and Richard Shafer of Georgia Tech for his assistance with the operation of the electroplating robot.

REFERENCES

[1] S. C. O'Mathuna, T. O`Donnell, N. Wang, and K. Rinne, "Magnetics on Silicon: An enabling technology for power supply on chip," *IEEE Trans. Power Electron*. vol. 20, pp. 585-592, 2005.
[2] D. S. Gardner, G. Schrom, F. Paillet, B. Jamieson, T. Karnik, and S. Borkar S, "Review of on-chip inductor structures with magnetic films," *IEEE Trans. Magn*. vol. 45, pp. 4760-4766, 2009.
[3] S. Bae, Y. -K. Hong, J. -J. Lee, J. Jalli, G. S. Abo, A. Lyle, B. C. Choi, G. W. Donohoe, "High Q Ni-Zn-Cu ferrite inductor for on-chip power module," *IEEE Trans. Magn*. vol. 45, pp. 4773-4776,
[4] J. Kim, J. K. Kim, M. Kim, F. Herrault, and M. G. Allen, "Integrated toroidal inductors with nanolaminated metallic magnetic cores," *PowerMEMS 2012*, Atlanta, Dec.2-5, 2012.
[5] M. Rais-Zadeh, P. A. Kohl, F. Ayazi, "A packaged micromachined switched tunable inductor," *IEEE MEMS 2007*, Kobe, Jan. 21-25, 2008, pp. 799-802.
[6] Lee D.-W, Hwang K.-P, and S. X. Wang, "Design and fabrication of integrated solenoid inductors with magnetic cores," *Elec. Comp. C. 2008*, Lake Buena Vista, May 27-30, 2008, pp. 701-705.
[7] A. Armutlulu, Y. Fang, S.H. Kim, C.H. Ji, S.A. Bidstrup Allen, and M.G. Allen, " A MEMS-enabled 3D zinc-air microbattery with improved discharge characteristics based on a multilayer metallic substructure," *J. Micromech. Microeng,* vol. 21, no. 10, pp. 1-6, 2011.
[8] http://microchem.com/pdf/SU82000DataSheet2000_5thru2015Ver4.pdf
[9] J. -W. Park, F. Cros, M. G. Allen, " A sacrificial layer approach to highly laminated magnetic cores," *IEEE MEMS 2002,* Las Vegas, Jan. 20-24, 2002. pp. 380-383.
[10] B. Orlando, R. Hida, R. Cuchet, M. Audoin, B. Viala, D. Pellissier-Tanon, X. Gagnard, and P. Ancey, "Low-resistance integrated toroidal inductor for power management," *IEEE Trans. Magn*. vol. 42, no. 10, pp. 3374-3376, 2006.

CONTACT

*M. Kim, tel: +1-404-630-6262; mkim354@gatech.edu