INTEGRATED TOROIDAL INDUCTORS WITH NANOLAMINATED METALLIC MAGNETIC CORES

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Abstract: This paper presents the fabrication and experimental characterization of microfabricated toroidal inductors with ferromagnetic metallic cores for on-chip power supply applications. A fabrication process was developed to integrate pre-fabricated nanolaminated cores with microfabricated toroidal windings via a core drop-in technique. The metallic magnetic cores consist of highly-laminated electroplated ferromagnetic CoNiFe material with sub-micron lamination thicknesses and total core thicknesses up to tens of microns. Microfabricated inductors 10 mm in diameter with 50 turns exhibited inductances of approximately 1.5 μH up to 30 MHz with peak quality factor on the order of 10 at 10 MHz. At 1 MHz, these inductors were experimentally tested at peak flux densities up to 0.5 T, an order of magnitude higher than the typical operation flux densities of conventional ferrites in DC/DC converter applications.

Keywords: Microfabrication, Laminated ferromagnetic metallic core, Toroidal inductor

INTRODUCTION

In today's power converters, the passive components (i.e., inductors and capacitors) typically occupy the largest volume of the total converter volume, limiting converter miniaturization [1]. As a result, in combination with improved switchers enabling higher frequency operation, advanced chip-scale inductors using microfabrication technology are being developed. These microfabricated inductors can greatly benefit from incorporating magnetic core materials including metallic alloys and ferrites, resulting in significant volume reduction for a given inductance [2, 3].

State-of-the-art microfabricated inductors with magnetic cores generally feature a spiral winding geometry surrounded by a layer of magnetic material on the order of a few microns [3, 4]. The selected magnetic materials include sputtered CoZrO materials, NiZnCu ferrites, and thin electroplated magnetic alloys such as NiFe and CoNiFe [2-4]. However, for high-efficiency 10-50 W power converter applications, microfabricated inductors not only need to exhibit low core material intrinsic losses (i.e., low hysteresis and low eddy current losses), but also typically need thick (tens of microns) magnetic cores to handle the large power levels. To address this need, we developed toroidal inductors with highly-laminated thick ferromagnetic metallic cores using a drop-in technique which differs from most current approaches. The laminated core is fabricated using automated sequential electrodeposition of alternating layers of magnetic material and sacrificial copper, followed by the selective removal of the copper, to form the laminations [5, 6].

In this paper, the fabrication technology to integrate highly-laminated, thick ferromagnetic metallic cores with microfabricated toroidal copper windings using a core drop-in technique is detailed. Toroidal copper winding fabrication is based on metalized polymer vertical windings [7]. The highly-laminated ferromagnetic metallic cores consist of 100 layers or more of sub-micron-thick CoNiFe. Functional 50-turn inductors, 10mm in diameter and integrated with nanolaminated CoNiFe cores, are experimentally characterized up to 30 MHz. The experimental results obtained from a series of devices are discussed.

FABRICATON

The inductor fabrication sequence consists of three major steps: (1) Microfabricating highly-laminated electroplated cores; (2) inserting them into partially-microfabricated windings; and (3) completing the inductor winding fabrication. Fig. 1 shows a conceptual rendering of the magnetic core integration with such microfabricated windings.

This approach alleviates several fabrication challenges as compared to a monolithic approach

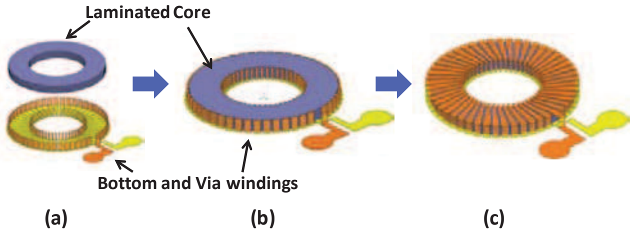


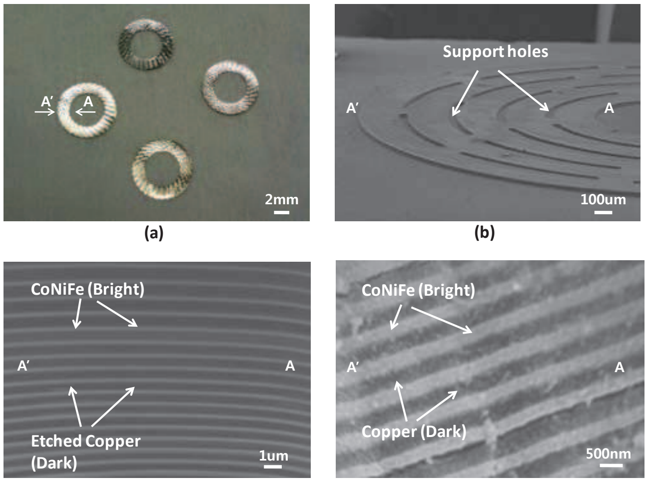
Fig. 1: Fabrication of integrated toroidal inductor with nanolaminated core. (a) Fabrication of the nanolaminated cores, (b) Core insertion into partially-microfabricated windings, and (c) Insulation of the nanolaminated core and top winding fabrication to form the toroidal inductor.

where the cores and windings would be co-fabricated sequentially on the same substrate [5]. The major difficulties in achieving monolithic fabrication of such toroidal microfabricated inductors with highly-laminated magnetic cores are associated with (1) the material selection for the core sacrificial layer being similar to the winding material (copper); (2) the challenges in passivating the copper coils from the core sacrificial wet etching process to prevent coil etching; and (3) the challenges in processing multiple layers of thick photoresists in order to achieve thick and integrated cores.

Nanolaminated Metallic Core Fabrication

Most magnetic cores including metallic alloys and ferrites can be suitable candidates for the drop-in technique. We previously demonstrated highly-laminated permalloy ($Ni_{80}Fe_{20}$) cores fabricated based on robotically-assisted sequential electrodeposition of alternating permalloy and sacrificial copper layers with precisely-controlled lamination thicknesses (on the order of 500 nm) [6]. Furthermore, we have also experimentally measured that such core materials exhibited high saturation flux densities, while simultaneously reducing eddy current losses in the core in the MHz frequency regime [8].

Using the same fabrication technology, nanolaminated CoNiFe metallic cores were batch-fabricated with lamination thicknesses on the order of 100-300 nm. CoNiFe alloys exhibit higher saturation flux density and lower coercivity than permalloy [9]. Core fabrication details can be found in [6, 8].



(a) (b)

(c) (d)

Fig. 2: (a) A picture of toroidal CoNiFe cores (OD = 10 mm, ID = 6 mm), (b) Scanning Electron Microscope (SEM) image of the core, (c) Cross-sectional view of a core with 500 nm thick CoNiFe layers after partial etch of sacrificial copper, and (d) Magnified cross-section view of nominally 300 nm thick layers of CoNiFe and copper.

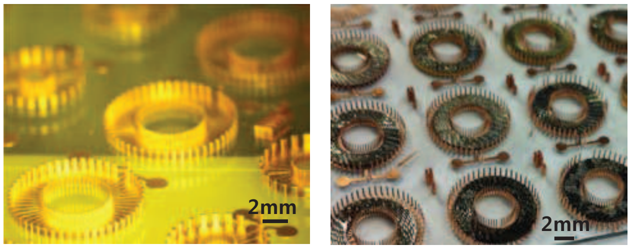
Fig. 2(a) shows an optical image of toroidal cores that were batch-fabricated and released from the substrate after electroplating. A scanning electron microscopy (SEM) view of such a core is shown in Fig. 2(b). The support holes consist of SU-8 filled holes that act to support individual laminations, thereby facilitating interlamination insulation. Fig. 2(c) and 2(d) show cross-sectional views of 300 and 500-nm-thick CoNiFe laminations with partially-etched sacrificial copper layers. After complete copper etch, the cores are fully-encapsulated in polydimethylsiloxane (PDMS) for lamination insulation and core handling.

Core Integration

These nanolaminated magnetic cores are inserted into partially-fabricated windings using a pick-and-place approach, as illustrated in Fig. 1(b). The bottom and vertical conductors were first fabricated on a glass substrate using a fabrication approach detailed in [7]. Vertical SU-8 pillars 1 mm in height were photo-defined and metalized. Using a spray-coated mold, both the bottom conductors and vertical windings were electroplated simultaneously. The vertical conductors need to be sufficiently tall to allow a large volume of integrated core, as well as to provide sufficient space between top conductors and the core to minimize capacitive parasitics.

In order to prevent electrical shorts between the windings and the core, either a thin insulating layer was added between them or the magnetic core was pre-packaged with PDMS. This drop-in approach is applicable for not only fabricated magnetic cores, but also any core material with suitable geometry.

Fig. 3(a) shows images of fabricated bottom and vertical windings before core integration. The bottom windings are approximately 250 μm wide, 30 μm thick, and feature 100 μm spacing between conductors. The vertical conductors are approximately 1 mm tall, and consist of SU-8 pillars surrounded by 30 μm thick copper layers. Fig. 3(b) illustrates the integration of nanolaminated cores into the partial windings.



(a) (b)

Fig. 3: Images of (a) partially microfabricated copper windings (bottom and vertical conductors), and (b) Integrated nanolaminated cores into the windings.

Fully-Fabricated Inductors

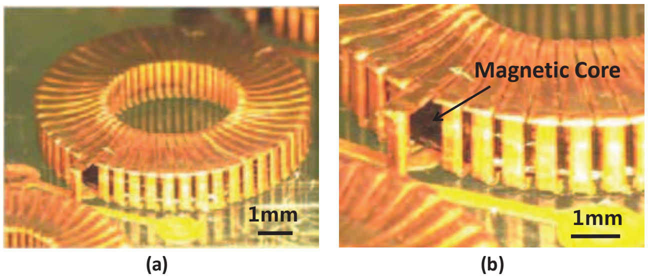
After core insertion, an additional layer of SU-8 is applied. The SU-8 is baked for 30 min at 110°C for planarization, and cured for 1 hour at room temperature. After SU-8 processing, the magnetic cores are embedded in the SU-8 layer while the vertical copper conductors protrude out of it, a critical requirement before top conductor fabrication. A Ti/Cu/Ti seed layer is then deposited and 30-µm-thick top windings are fabricated using standard through-resist electrodeposition. Photoresist and seed layer are removed after electroplating.

Fully-fabricated 50-turn toroidal inductors with nanolaminated CoNiFe cores are shown in Fig. 4(a). The inductor is 1 mm tall with a surface area of 88 mm^2. For these prototypes, only 3% of the total inductor volume was occupied by magnetic core material, as observed in Fig. 4(b). Thicker cores can be integrated into these toroidal winding structures to increase inductance. Incidentally, the inductor footprint could be decreased while maintaining similar inductance levels by taking full advantage of the winding fabrication process that enables high-aspect-ratio metalized vertical windings.

RESULTS AND DISCUSSION

The microfabricated inductors with nanolaminated CoNiFe cores were characterized using an impedance analyzer (HP 4194A).

Fig. 5 shows testing results of 50-turn inductors with 100 layers of 300-nm-thick CoNiFe cores. As a reference, the measurements from an air-core inductor featuring a similar winding geometry are also plotted. As indicated in Fig. 5(a), the measured inductance of both inductors with CoNiFe cores exceeded 1.5 µH up to 30 MHz demonstrating a 10X inductance increase over the air-core inductance. These measurements are consistent with a CoNiFe relative permeability of 200. The inductor resistance is plotted as a function of frequency in Fig. 5(b). The resistances of both inductors with CoNiFe cores are on the order of 1 Ω at 500 kHz, and increase at higher frequencies due to core and winding losses. In [8], we demonstrated that core losses in these highly-laminated magnetic alloys were dominated by hysteresis losses in the 1-3 MHz frequency range. At higher frequencies, eddy current losses potentially become non-negligible, but it should be noted that these cores were designed to operate in the MHz frequency regime.



(a) (b)

Fig. 4: Images of (a) fully-fabricated toroidal inductors integrated with nanolaminated core, and (b) its close-up view.

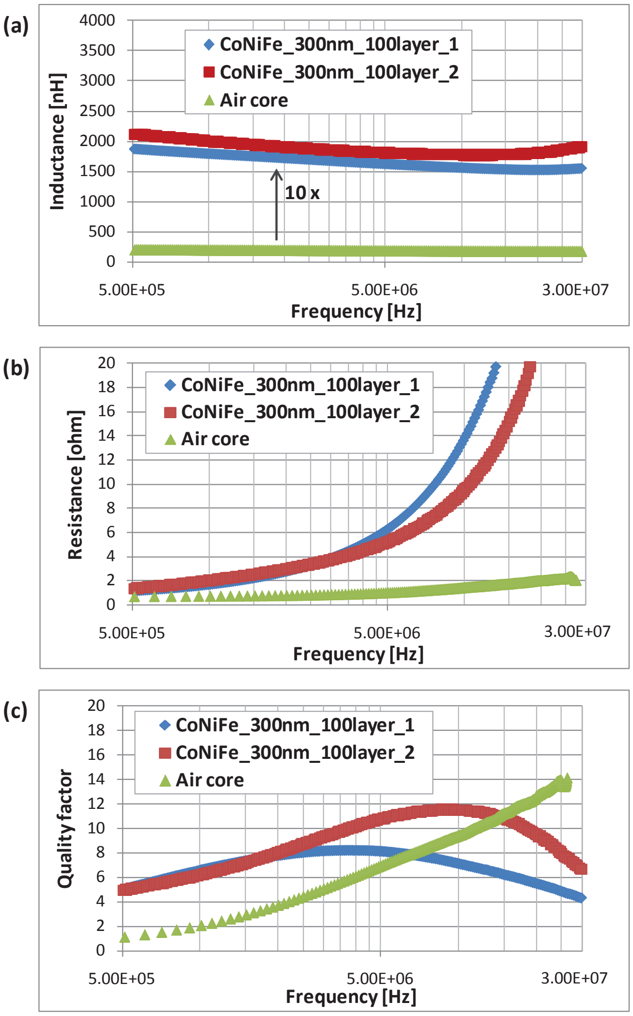


Fig. 5: Characterization of toroidal inductors with laminated CoNiFe core (300 nm x 100 layers) compared to air core inductor: (a) Inductance, (b) Resistance, and (c) Quality factor

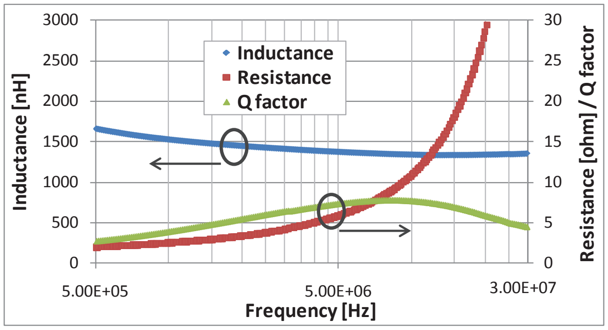


Fig. 6: Characterization of toroidal inductors with laminated CoNiFe core (100 nm x 300 layers)

As illustrated Fig. 5(c) measurements indicated quality factors on the order of 10 at 5-10 MHz. Discrepancies between the two similar inductors with CoNiFe cores are potentially due to the different heights and thicknesses of windings, as well as possible differences in core lamination thicknesses. Further, the low quality factor of the air-core inductor greatly affected the quality factor of the inductors with cores, suggesting that optimization of the winding geometry may allow further improvement in overall quality factor.

Fig. 6 demonstrates the performance of 50-turn microfabricated inductors with a CoNiFe core consisting of 300 laminations with 100 nm thickness. Measured inductance was approximately 1.4 µH from 1 MHz to 30 MHz with low frequency resistance measured at 1 Ω. At 10MHz, the quality factor of the inductor reached 8. The lower inductance could be due to several reasons, including but not limited to, electroplated material composition uniformity, lamination thicknesses, 100-nm-thick lamination mechanical integrity, electrical shorts between potentially-collapsed layers, and/or increased coercivity in 100-nm-thick magnetic layers.

During these measurements, these magnetic cores were operated at peak flux densities in the range of 5 to 10 mT. Additionally, these inductors were tested at high operating flux density using a high-power amplifier and operated at peak flux densities up to 0.5 T with negligible eddy current losses. This flux density is an order magnitude higher than the typical operation flux densities of conventional ferrites in DC/DC converter applications.

CONCLUSION

Design, fabrication, and performance of integrated toroidal inductors with nanolaminated CoNiFe metallic cores using a drop-in core approach are presented. Test results demonstrated inductor operation up to 50 MHz with stable inductance in the microhenry range and quality factors above 10 at 10 MHz. These results were achieved with 10-mm-diameter inductors with 30-µm-thick CoNiFe cores that were comprised of hundreds of sub-micron-thick layers, and 1-mm-tall 50-turn windings. Benefiting from the winding fabrication technology, which enables very high-aspect-ratio microfabricated conductors, the core volume, which only represented 3% of the total winding cross-sectional area in these prototype inductors, could be greatly increased to either increase inductance and power handling capabilities and/or reduce inductor footprint.

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