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Microfabrication of toroidal inductors integrated with nanolaminated ferromagnetic metallic cores

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Abstract

We report microfabricated toroidal inductors with nanolaminated ferromagnetic metallic cores for chip-scale, high-power switching converters. The fabrication process of the toroidal inductor is based on individual manufacturing of partial windings (i.e. bottom and vertical conductors) and nanolaminated magnetic core, and integrating them by means of a drop-in approach. The nanolaminated ferromagnetic metallic cores presented in this paper consist of many multilayers of electrodeposited CoNiFe films, each layer with sub-micron thickness, with a total core thickness exceeding tens of microns. The beneficial magnetic properties (i.e. high saturation flux density and low coercivity) of CoNiFe alloys are well suited for chip-scale inductors as they achieve both large energy storage capacity as well as minimized volumetric core losses at high operating frequencies due to their nanolaminated structure. A drop-in integration approach, introduced to combine the microfabricated toroidal inductor windings with the magnetic cores, allows ease of integration. An advantage of this hybrid approach over monolithic fabrication in this application is the potential use of a wide variety of core materials, both microfabricated and bulk-fabricated, and which may or may not ultimately be CMOS-compatible. Exploiting this drop-in approach, 30-turn- and 50-turn-toroidal inductors integrated with nanolaminated CoNiFe cores, having 10 mm outer diameter and 1 mm thickness, have been successfully developed. Both types of inductors exhibit inductances higher than 1 μ H at frequencies up to tens of MHz, showing ten times the inductance of an air core device with the same nominal geometry. The peak quality factor of the 30-turn-toroidal inductor reaches 18 at 1 MHz.

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

1. Introduction

Compact, multi-functional personal electronic devices (e.g., smart phones and tablet PCs), which often employ multiple internal voltage levels and require the recharging of internal batteries, should employ high-power density switching converters to maintain their compactness. However, the miniaturization of dc/dc converters is often made more challenging by their need for passive components, especially inductors, which can consume large physical volumes [1, 2]. Consequently, significant efforts have been made to develop chip-scale inductors using advanced microfabrication technology, exploiting the trends of increasing switching frequencies as well as incorporation of inductor magnetic materials to reduce physical size [3–5]. Although conventional ferrites have been mostly used in these applications, soft ferromagnetic alloys (e.g., NiFe, NiFeMo and CoNiFe) are gaining increased attention due to their superior magnetic properties (i.e. higher saturation flux density and lower coercivity) as well as their potential for CMOS-compatible integration. However, as switching frequencies increase, such ferromagnetic alloys can possess significant eddy-current losses at high-frequency operation, limiting the use of the magnetic cores to small overall thicknesses [6, 7]; this is

in contrast to non-electrically conducting ferrites. Therefore, most microfabricated inductors integrated with magnetic cores are either planar spiral windings [8, 9] or solenoid windings [10, 11] with limited total magnetic core thicknesses. Such small thicknesses are typically insufficient to meet the power handling needs of portable electronics, e.g., in the 10–50 W range. To realize microfabricated inductors that can handle such high power, it is required to develop (1) magnetic materials with sufficiently large volume and minimized losses, (2) microfabricated windings providing a large magnetic flux path where the large volume core could be placed and (3) a fabrication technique to integrate the large volume core into the windings.

We recently developed highly laminated ferromagnetic metallic cores via automated sequential electrodeposition, demonstrating sufficient magnetic volumes with significant reduction in eddy-current losses up to 10 MHz operation frequency [12]. In addition, 650 μ m tall air core toroidal inductors have been fabricated based on metal-encapsulated polymer vias, yielding large cross-sectional area, thereby large magnetic flux path [13]. In this paper, we provide a fabrication technique to incorporate these types of large volume magnetic cores into toroidal windings by means of a core drop-in approach, where pre-fabricated cores are incorporated as an intermediate step in the fabrication of toroidal windings. This fabrication technology allows not only the use of the thick magnetic core for high-power handling, but it also alleviates process compatibility issues in the monolithic fabrication of toroidal inductors with highly laminated magnetic cores (e.g., defect-free insulation of copper coils during the laminated core fabrication and multiple processing of thick photoresist layers potentially causing stress issues) [14]. Although the fabrication technology is illustrated by means of the incorporation of laminated CoNiFe cores in the microfabricated windings, it should be noted that the technique can be generalized to other core materials, including conventional ferrites, if desired.

2. Fabrication

The fabrication process for the integrated toroidal inductor with drop-in nanolaminated core can be divided into three main steps as illustrated in figure 1. First, the nanolaminated ferromagnetic metallic cores and partially formed windings (i.e. bottom and vertical windings) are individually prepared (figure 1(a)). Second, the cores are integrated with the partially formed windings by means of a drop-in approach (figure 1(b)). In order to prevent electrical shorting between the metallic cores and the bottom windings, a 100 μ m thick insulating spacer is placed within the windings prior to core insertion. Third, top windings are fabricated to complete the toroidal inductor (figure 1(c)). The top windings can be built either on a sacrificial insulating layer, which will be removed after top conductor fabrication (temporary core embedding approach), or on a non-sacrificial insulating layer to reinforce the mechanical stability of the toroidal windings and core (permanent core embedding approach).

 Table 1. Electrodeposition conditions for nanolaminated CoNiFe core.

Component	Quantity
$CoSO_4 \cdot 7H_2O$	0.08 (mol L ⁻¹)
$NiSO_4 \cdot 6H_2O$	$0.2 \pmod{L^{-1}}$
FeSO ₄ · 7H ₂ O	$0.03 \pmod{L^{-1}}$
NH ₄ Cl	$0.3 \pmod{L^{-1}}$
Boric acid	$0.4 \pmod{L^{-1}}$
Sodium saccharin	$0.02 \pmod{L^{-1}}$
Sodium lauryl sulfate	$0.004 \pmod{L^{-1}}$
Anode	Nickel sheet
pH	2.8
Current density	20 (mA cm ⁻²)

2.1. Nanolaminated metallic core fabrication

Nanolaminated ferromagnetic metallic cores are batchfabricated based on automated sequential electrodeposition of alternating ferromagnetic material and sacrificial copper layers on a sputtered titanium/copper seed layer [15]. In this sequential electrodeposition system, a robotic arm, which holds a substrate (cathode), moves alternately between a CoNiFe bath and a commercial copper bath (Grobet, Clean Earth Cu-mirror solution) with two steps of DI water rinsing in between these baths. The electroplated CoNiFe typically exhibits high saturation flux density (>1.8 T) and low coercivity (<2 Oe), and several electrodeposition approaches have been established [16, 17]. The electrodeposition conditions for this work are detailed in table 1. At a current density of 20 mA cm⁻² for both the CoNiFe and the commercial copper baths, deposition rates are 0.25 μ m min⁻¹ and 0.5 μ m min⁻¹, respectively. The thickness of each electrodeposited layer is precisely controlled by monitoring the electrodeposition time. Furthermore, the thickness of the magnetic layer is designed to be smaller than the skin depth (δ), expressed as

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}},\tag{1}$$

where *f* is the operating frequency (Hz), μ is the magnetic material permeability ($\mu_r \cdot \mu_o$) (H m⁻¹), and σ is the conductivity of the magnetic material (S m⁻¹). Considering typical properties of an electrodeposited CoNiFe film (relative permeability of approximately 1000 and conductivity of approximately 45 000 S cm⁻¹) [16, 17], a CoNiFe/copper multilayer core is fabricated with single lamination thickness less than 500 nm (i.e. below the skin depth of the material, 1 μ m at 30 MHz), while the total magnetic layer thickness (i.e. sum of the individual magnetic layer thicknesses) exceeds 30 μ m. With the electrodeposition conditions mentioned above, it takes approximately 4.5 h to achieve the total magnetic layer thickness.

After sequential electrodeposition, the cores are separated from the substrate by removing the titanium seed layer in a 49% hydrofluoric acid solution. Then, the freed multilayer cores are affixed using cyanoacrylate adhesive onto a 150 μ m thick polyester insulator film that has been patterned in the same shape as the toroidal core by use of laser micromachining as illustrated in figure 2(*a*). The insulator film acts as a



Figure 1. Conceptual integration approach for microfabricated toroidal inductor with drop-in core.

physical spacer between the nanolaminated metallic core and the bottom conductors. Once the on-insulator CoNiFe/copper multilayer cores are prepared, it is critical to selectively remove the copper layers without damaging the magnetic CoNiFe layers. A saturated solution of copper sulfate in ammonium hydroxide $(NH_4OH + CuSO_4)$ is utilized as a copper etchant since it provides excellent selectivity to nickel-based soft magnetic alloys (e.g., CoNiFe and NiFe) [15, 18]. The sacrificial copper material is partially removed in the copper etchant, leaving lateral trenches between the CoNiFe layers. SU-8 insulating polymer is then applied through the 'support holes' as shown in figure 2(b), underfilling space formerly occupied by the partially etched copper. After the SU-8 curing, the remaining sacrificial copper layers are entirely removed to form air-insulated CoNiFe laminations in which each lamination is supported by SU-8 insulating polymer as depicted in figure 2(c). The detailed fabrication process to create the air-insulated laminated cores is described in [12]. The nanolaminated CoNiFe cores are further packaged in polydimethylsiloxane (PDMS) to improve mechanical reinforcement and prevent stiction between laminations as shown in figure 2(d). In order to ensure the infiltration of PDMS into the nanolaminated structure, the core is immersed in uncrosslinked PDMS and vacuum is applied for approximately 10 min. The infiltrated PDMS is fully crosslinked in 48 h at room temperature. As the PDMS is firmly confined between the CoNiFe layers due to the vacuum process, excess PDMS around the core is easily stripped manually, providing a PDMSlaminated CoNiFe multilayer core.

Figure 3 shows various images of nanolaminated CoNiFe toroidal cores. Figure 3(a) shows optical images of nanolaminated toroidal cores and polyester insulator films. The cores have an outer diameter of 10 mm and an inner diameter of 6 mm. Figure 3(b) shows an inclined top-view scanning electron microscope (SEM) image. Note that support holes are utilized to facilitate partial removal of the sacrificial copper layers as well as to apply the SU-8 supports. Figure 3(c) shows a cross-sectional view of the nanolaminated core, comprising 70 CoNiFe layers, each with a thickness of 500 nm. (The sacrificial copper layers are partially etched to enhance their visibility.) A magnified view of the 500 nm CoNiFe laminations is shown in figure 3(d), demonstrating that each CoNiFe layer has uniform thickness and exhibits no interlayer stiction.



Figure 2. Fabrication sequence for PDMS-encapsulated CoNiFe core. (*a*) Electrodeposited CoNiFe/copper multilayer cores on an insulator film, (*b*) multilayer core after partial removal of copper, (*c*) multilayer core supported by SU-8 after entire removal of copper, (*d*) multilayer core encapsulated with PDMS.

2.2. Winding fabrication and core drop-in

A typical microfabricated toroidal inductor winding consists of bottom, vertical and top conductors. For the proposed dropin approach, the vertical conductors are based on copper metallization of high-aspect-ratio SU-8 pillars, followed by lithographic patterning [13]. Figure 4(a) shows fabricated 50turn bottom and vertical conductors on the glass substrate. For the bottom windings, approximately 250 μ m wide, 30 μ m thick conductors are positioned with 100 μ m interconductor lateral spacing. For the vertical windings, 1 mm tall SU-8 pillars with 100 μ m diameter are lithographically formed and coated with a 30 μ m thick electrodeposited copper layer. These high aspect ratio vertical windings enable placement of large volume magnetic cores. Once the partially fabricated windings (i.e. bottom and vertical windings) are prepared, the PDMSinfiltrated CoNiFe multilayer cores are manually pick-andplaced and affixed as shown in figure 4(b). No observable winding damage was caused by this drop-in core approach. In figure 4(b), the thickness of the PDMS-infiltrated CoNiFe laminations including the insulator film is approximately $300 \ \mu m$, which is lower than the height of vertical windings.



Figure 3. Images of nanolaminated CoNiFe cores. (a) Toroidal cores and insulator films with outer diameter of 10 mm, (b) SEM image of inclined top view, (c) SEM cross-sectional image of 70 layers of 500 nm thick CoNiFe, (d) magnified view of (c).



Figure 4. (a) Batch fabricated 50-turn partial windings on a glass substrate. (b) Magnetic cores integrated with the partial windings.

2.3. Core integration

Prior to top winding fabrication, it is critical to form an insulating layer on top of the nanolaminated core where the top windings will be deposited and patterned. The insulating layer should possess a planar surface for top conductor deposition as well as sufficient thickness to avoid parasitic capacitance between the metallic core and top windings. Two methods, a temporary core embedding approach and a permanent core embedding approach, are explored as shown in figure 5. Also, both approaches are summarized in table 2.

The temporary core embedding approach utilizes non-photopatternable EPON SU-8 epoxy pellets (Miller-Stephenson, Inc.), which will be removed in acetone after top winding fabrication. In this approach, epoxy pellets in a sufficient quantity to cover the nanolaminated core are distributed on the partially fabricated inductors (i.e. bottom and vertical windings, and magnetic cores) and melted at 130 °C on a hotplate as shown in figure 5(*b*). In this step, it is critical to obtain an appropriate insulating layer thickness (600–900 μ m from the bottom winding) so as not to cover the top of the vertical windings since the SU-8 epoxy pellet is not photopatternable. However, due to the lack of solvent and crosslinker in the SU-8 epoxy pellet, long softbaking times are not required even for thick films, resulting in reduced process time. After melting, the SU-8 epoxy is brought to room temperature for approximately 1 h until it is re-solidified. Figure 6(*a*) shows the inductor after the epoxy sacrificial layer step has been completed. Note that the top of the vertical windings is exposed, while the laminated metallic core is embedded within the SU-8 sacrificial epoxy.

In contrast, the permanent core embedding approach utilizes photo-definable SU-8 2025 (MicroChem). After casting SU-8 on the sample by weight as shown in figure $6(b)^*$,



Figure 5. Core integration approaches after (*a*) core drop into the partially fabricated windings. (*b*)–(*e*) Temporary core embedding approach, $(b)^*$ –(*e*)* permanent core embedding approach.



Figure 6. Optical images of fabricated additional layers with (*a*) EPON SU-8 epoxy using temporary core embedding approach, and (*b*) photopatternable SU-8 2025 using permanent core embedding approach.

	Temporary core embedding approach	Permanent core embedding approach
Insulating material	EPON SU-8 epoxy pellets (Miller-Stephenson, Inc.)	SU-8 2025 (MicroChem)
Process sequence	Melted at 130 °C Solidified at 23 °C for 1 h	Softbake at 95 °C for 12 h Expose at 30 mW cm ⁻² for 30 min Postbake at 95 °C for 30 min Develop for 25 min in Thinner P
Top conductor seed layer deposition Advantages	E-beam evaporation Fast process time	Sputtering or E-beam evaporation Mechanical reinforcement
Disadvantages	Non-photopatternable	More complex process steps

Table 2. Comparison of temporary core embedding and permanent core embedding approaches.

it is planarized and softbaked at 95 °C for 12 h on a hotplate. Note that 1 g of cast SU-8 corresponds to 1 mm thickness on a 6.45 cm² glass substrate after the softbaking. Since the softbaked SU-8 covers the vertical windings, it is patterned to expose the vertical windings to connect with top windings. After 4 h cooling, the SU-8 is exposed with a UV light intensity of 30 mW cm⁻¹ for 30 min as shown in figure $5(b)^*$, followed by post-bake at 95 °C for 30 min. The sample is then developed in PGMEA (propylene glycol methyl ether acetate)-based Thinner P (MicroChem) for 25 min leaving the vertical windings exposed as shown in figure $5(c)^*$. Figure 6(b)shows that patterned SU-8 insulating layers encapsulate the lower and vertical windings as well as the core, and that the tops of the vertical conductors protrude. Since the SU-8 is fully crosslinked, it potentially provides higher mechanical robustness for the inductor.

2.4. Top winding fabrication

For the two approaches, top windings are fabricated in a similar process. First, a 300 nm thick copper seed layer is deposited by e-beam evaporation. Then, a 20 μ m thick photoresist layer is spray-coated on the seed layer and photolithographically patterned to serve as a mold for electrodeposition of top copper conductors as shown in figures 5(*c*) and (*d*)*. After a 30 μ m thick copper electrodeposition, the photoresist and the copper seed layer are removed to complete the toroidal inductor fabrication as shown in figures 5(*d*) and (*e*)*. For the temporary core embedding approach, the embedding SU-8 epoxy can be removed in acetone as shown in figure 5(*e*).

3. Fabricated inductors and characterization

3.1. Fabricated toroidal inductors integrated with nanolaminated cores

Optical images of integrated toroidal inductors with nanolaminated CoNiFe cores are shown in figure 7. Figure 7(*a*) shows a 1 mm tall, 50-turn-toroidal inductor fabricated by means of the temporary core embedding approach and a dense winding mask. The sacrificial SU-8 epoxy has been removed upon completion of the top winding fabrication. The laminated magnetic core inside the toroid is comprised of 100 layers of CoNiFe with individual lamination thickness of 300 nm. Figure 7(*b*) shows a 1 mm tall, 30-turn-toroidal inductor fabricated using the permanent core embedding approach and a

 Table 3. Parameters of integrated inductor with nanolaminated cores.

	50-turn inductor	30-turn inductor
$\overline{A_{\rm air}({\rm m}^2)}$	2.3×10^{-6}	2.3×10^{-6}
$A_{\rm core} ({\rm m}^2)$	6×10^{-8}	7×10^{-8}
r_i (m)	2.85×10^{-3}	2.85×10^{-3}
$r_o(m)$	2.3×10^{-3}	5.15×10^{-3}
2 <i>b</i> (m)	3×10^{-7}	5×10^{-7}
μ_e	250	330
Ν	50	30

sparse winding mask. The crosslinked SU-8 underlying the top windings enhances the mechanical robustness of the inductor.

3.2. Characterization of toroidal inductors integrated with nanolaminated cores

The inductance, resistance and quality factor of the inductors fabricated using two different approaches were characterized as a function of frequency at typical core magnetic flux densities between 2 and 10 mT using an impedance analyzer (HP 4194 A). Figure 8 shows the measured result from a 50 turn microfabricated inductor integrated with nanolaminated CoNiFe core using the temporary core embedding approach, and an air core inductor with the same nominal geometry. The nanolaminated core consists of 100 layers of 300 nm thick CoNiFe laminations with 300 nm tall interlamination gaps. Measured inductances of these two inductors are shown in figure 8(a). The microfabricated air core inductor exhibits a constant inductance of approximately 210 nH (inductance density of $2.52 \times 10^{-3} \ \mu \text{H mm}^{-2}$) up to 30 MHz. To validate this measured inductance, the theoretical inductance of the 50 turn toroidal inductor has been estimated using the theoretical expression [19]

$$L_{\rm air} = \frac{\mu_0 \cdot A_{\rm air} \cdot N^2}{\pi (r_i + r_o)},\tag{2}$$

where μ_0 is the permeability of vacuum, $4\pi \times 10^{-7}$ H m⁻¹, A_{air} is the cross-sectional area of the magnetic flux path (m²), N is the number of windings, and r_i and r_o are the inner and outer radii of the toroid (m), respectively. With the parameters presented in table 3, the theoretical air core inductance is estimated as 280 nH. The calculated and measured inductances agree within 25% up to 30 MHz. The lower measured inductance from the microfabricated inductor could be due to



Figure 7. Microfabricated toroidal inductors integrated with nanolaminated CoNiFe cores by means of (*a*) temporary core embedding approach and (*b*) permanent core embedding approach. Note that in (*b*) the encapsulating SU-8 possesses a rim that extends to the periphery of the picture, resulting in additional mechanical stability.

leakage flux between the windings and fabrication tolerances between the microfabricated inductor and the original design. The measured inductance of the integrated inductor with laminated CoNiFe core exceeds 1.6 μ H (inductance density of $1.9 \times 10^{-2} \mu$ H mm⁻²) up to 30 MHz, showing an approximately ten times inductance increase from the air core inductor. The measured inductance is also analyzed by comparing with theoretical prediction. To estimate the frequency-dependent inductance of the integrated inductor with nanolaminated CoNiFe core, the effective permeability of the CoNiFe core is first extracted using a theoretical expression of low-frequency inductance of integrated inductor with a magnetic core, where eddy-current loss is negligible:

$$L_{\text{core, dc}} = \frac{\mu_0 \cdot \mu_e \cdot A_{\text{core}} \cdot N^2}{\pi \left(r_i + r_o\right)},\tag{3}$$

where μ_e is the effective permeability of the magnetic core and A_{core} is the cross-sectional area of the magnetic core (m²). Considering that the total magnetic thickness of the nanolaminated core (30 μ m) occupies approximately 3% of the total inductor thickness (1 mm), the effective permeability of the core is estimated as 250, which is in the range of typical soft magnetic material permeability (50–2000) [4]. Then, the frequency-dependent inductance (L_{core}) can be calculated based on a one-dimensional analysis of the electromagnetic diffusion in a laminated core with ac sinusoidal excitation [6, 7] and is expressed as

$$L_{\text{core}} = L_{\text{core, dc}} \left(\frac{a}{2b}\right) \left(\frac{\sinh\left(\frac{2b}{a}\right) + \sin\left(\frac{2b}{a}\right)}{\cosh\left(\frac{2b}{a}\right) + \cos\left(\frac{2b}{a}\right)}\right), \quad (4)$$

where 2b is the thickness of a single lamination layer (m) and *a* is the skin depth (m) of the magnetic material at the operation frequency as expressed in equation (1). Finally, the overall inductance (L_{total}) is expressed by adding inductances from air and magnetic core:

$$L_{\text{total}} = L_{\text{air}} + L_{\text{core}} = \frac{\mu_0 \cdot N^2}{\pi (r_i + r_o)} \left(A_{\text{air}} + A_{\text{core}} \mu_e \left(\frac{a}{2b} \right) \left(\frac{\sinh\left(\frac{2b}{a}\right) + \sin\left(\frac{2b}{a}\right)}{\cosh\left(\frac{2b}{a}\right) + \cos\left(\frac{2b}{a}\right)} \right) \right).$$
(5)

From equations (1) and (5), the single lamination thickness (300 nm) of the core is well below the skin depth at



Figure 8. Characterization of 50-turn-integrated inductors with nanolaminated magnetic cores as well as an air core inductor by means of a temporary core embedding approach. (*a*) Measured inductance, (*b*) theoretical inductance, (*c*) measured resistance, (*d*) measured quality factor.

30 MHz ($\sim 1 \mu$ m); thereby, the theoretical total inductance of the integrated inductor with the nanolaminated CoNiFe

core exhibits the constant inductance of 2.1 μ H up to 30 MHz. However, use of a bulk (non-laminated) core with the same magnetic volume (30 μ m) would cause significant inductance decrease after 300 kHz due to the eddy currents flowing in the magnetic core. Compared with the theoretical inductance, the measured inductance shows slight inductance decrease as frequency increases. Since the theoretical equation assumes perfect insulation of identical CoNiFe laminations, the decreasing inductance of fabricated inductor is possibly due to (1) lamination thickness and material composition uniformity, (2) potentially collapsed CoNiFe layers causing electrical short, (3) parasitic capacitance between lamination layers, as well as between the dense 50-turn windings and the core. It is also shown that the measured inductance tends to increase after 20 MHz, implying a self-resonance of the integrated inductor with nanolaminated CoNiFe core. In figure 8(b), the resistance of both inductors at low operation frequency is near 1 Ω , and increases at higher frequency with growing winding and core losses. The different resistances at low frequency, where the losses from the magnetic core should be negligible, are mainly due to the different winding losses from the microfabrication winding tolerances. The increasing resistance of the integrated inductor with a nanolaminated CoNiFe core at higher frequency is attributed to frequencydependent magnetic core losses including hysteresis losses, eddy-current losses and anomalous losses [7]. However, the quality factors of the integrated inductor with a nanolaminated core is approximately 12 at 6 MHz and higher than that of the air core inductor up to 15 MHz as shown in figure 8(c), indicating an effective energy storage/transfer capacity by utilizing nanolaminated magnetic cores.

Figure 9 shows the measurement result from a 30-turn microfabricated inductor integrated with a nanolaminated CoNiFe core consisting of 70 layers of 500 nm thick CoNiFe laminations (and 500 nm tall interlamination gap) using the permanent core embedding approach, as well as an air core inductor with the same nominal geometry. Measured inductances of these two types of inductors are shown in figure 9(a). The microfabricated air core inductor exhibits a constant inductance of approximately 96 nH (inductance density of $1.15 \times 10^{-3} \ \mu \text{H} \ \text{mm}^{-2}$) up to 30 MHz. The theoretical inductance of the 30-turntoroidal inductor using equation (2) is estimated as 104 nH, demonstrating reasonable agreement with measured inductance up to 30 MHz. The 30-turn inductor integrated with a laminated CoNiFe core exhibits constant inductance of 1.15 μ H (inductance density of $1.4 \times 10^{-2} \ \mu \text{H} \text{ mm}^{-2}$) up to 30 MHz, showing an approximately 12 times inductance increase over the air core inductor. From equation (3), the effective permeability of the nanolaminated CoNiFe core is estimated as 330. The measured inductance is also compared with theoretical prediction using equations (1) and (5). Since the single lamination thickness (500 nm) of the core is still below the skin depth at 30 MHz $(\sim 1 \ \mu m)$, the theoretical total inductance of the integrated inductor with nanolaminated CoNiFe core predicts a constant inductance of 1.15 μ H up to 30 MHz. The good agreement of measured inductance with theoretical prediction indicates improved insulation from thicker interlamination gap as well



Figure 9. Characterization of 30-turn-integrated inductors with nanolaminated magnetic cores, as well as an air core by means of a permanent core embedding approach. (*a*) Inductance, (*b*) resistance, (*c*) quality factor.

as uniform lamination thickness, resulting in suppressed eddycurrent flow in the nanolaminated core. It is also expected that the sparsely distributed 30-turn-windings compared to the densely distributed 50-turn-windings minimize the capacitive effect between the core and the windings. In figure 9(b), the resistances of both inductors at 500 kHz are less than 1 Ω due to the fewer number of turns compared with figure 8(b), and increases as a function of operation frequency due to winding and core losses. The similar resistance of both inductors in the low-frequency region indicates the achievement of the same winding thickness and height and improved mechanical integrity between vertical and top windings. In figure 9(c), the quality factor of the integrated inductor with a nanolaminated CoNiFe core is approaching 20 at 5 MHz, and is greater than that of the air core inductor up to 15 MHz. Compared to the peak quality factor frequency (~6 MHz) from the 100 layers

of 300 nm thick CoNiFe laminations shown in figure 8(c), the peak quality factor appears at lower frequency (~4.5 MHz) due to the thick lamination (500 nm) indicating that the operational frequency can be adjusted by controlling a single lamination thickness. Also, the higher quality factor implies that optimization of winding geometry (e.g., winging width, thickness and height) as well as core design (e.g., lamination thickness, gap between the laminations) can improve the quality factors of the integrated inductors with a nanolaminated magnetic core.

4. Conclusion

The design, fabrication and characterization of integrated toroidal inductors with nanolaminated ferromagnetic metallic cores by means of a drop-in approach are presented. Nanolaminated CoNiFe, potentially usable at higher operation fluxes than conventional ferrites, is utilized as a demonstration core material. Two different approaches to core integration, the temporary core embedding approach and the permanent core embedding approach, are provided and compared. Thirty-turn and 50-turn-toroidal inductors integrated with the nanolaminated CoNiFe cores are fabricated and tested. The resulting toroidal inductors exhibit an approximately $10 \times$ inductance increase from nominally identical air core inductors at operation frequencies up to 30 MHz. The inductor peak quality factor approaches 20 at low MHz frequency. Since the CoNiFe nanolaminated material has high saturation flux density compared to ferrites and low-eddycurrent losses due to lamination, microfabricated inductors based on these materials have the potential to enable ultracompact dc/dc power conversion operation at high power and high frequency. Although the integration approach is illustrated using nanolaminated alloys, it is also potentially applicable to commercial ferrites and silicon steels with suitable geometries.

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