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Anisotropic nanolaminated CoNiFe cores integrated into microinductors for high-frequency dc–dc power conversion

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Abstract

This paper presents a rectangular, anisotropic nanolaminated CoNiFe core that possesses a magnetically hard axis in the long geometric axis direction. Previously, we have developed nanolaminated cores comprising tens to hundreds of layers of 300–1000 nm thick metallic alloys (i.e. $Ni_{80}Fe_{20}$ or $Co_{44}Ni_{37}Fe_{19}$) based on sequential electrodeposition, demonstrating suppressed eddy-current losses at MHz frequencies. In this work, magnetic anisotropy was induced to the nanolaminated CoNiFe cores by applying an external magnetic field (50–100 mT) during CoNiFe film electrodeposition. The fabricated cores comprised tens to hundreds of layers of 500–1000 nm thick CoNiFe laminations that have the hard-axis magnetic property. Packaged in a 22-turn solenoid test inductor, the anisotropic core showed 10% increased effective permeability and 25% reduced core power losses at MHz operation frequency, compared to an isotropic core of the identical geometry. Operating the anisotropic nanolaminated CoNiFe core in a step-down dc–dc converter (15 V input to 5 V output) demonstrated 81% converter efficiency at a switching frequency of 1.1 MHz and output power of 6.5 W. A solenoid microinductor with microfabricated windings integrated with the anisotropic nanolaminated CoNiFe core was fabricated, demonstrating a constant inductance of 600 nH up to 10 MHz and peak quality factor exceeding 20 at 4 MHz. The performance of the microinductor with the anisotropic nanolaminated CoNiFe core is compared with other previously reported microinductors.

Keywords: laminated soft magnetic alloy, anisotropic CoNiFe, suppressed eddy current losses, microinductor

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

1. Introduction

Recently, there has been tremendous effort towards dc–dc converter miniaturization by developing advanced magnetic cores and chip-scale microinductors using microfabrication techniques [1, 2]. Thus, magnetically soft metallic alloys (e.g. NiFe or CoNiFe) are gaining much attention due to their high saturation flux density as well as CMOS-compatible fabrication processes (e.g. sputtering or electroplating), resulting in compact power supplies on chip [3, 4]. Specifically, the use of

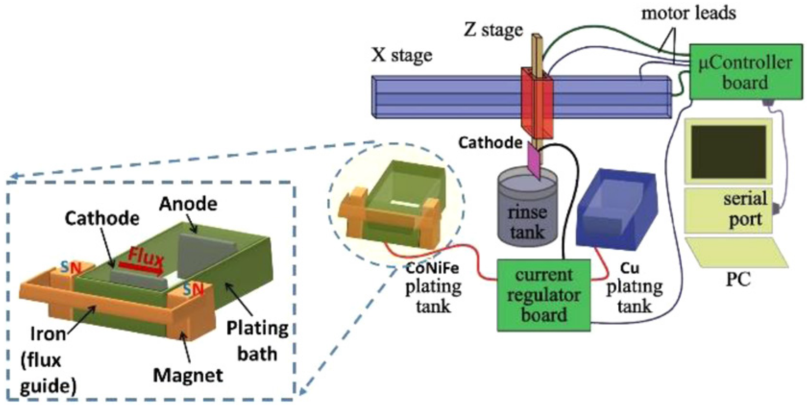

Figure 1. Schematic of in-field sequential electrodeposition system.

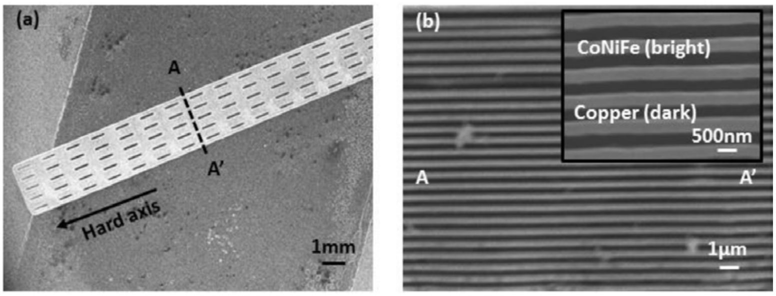

Figure 2. Bar-type nanolaminated CoNiFe core. (a) SEM image and (b) cross-sections.

laminated soft metallic alloy cores with appropriate lamination thickness simultaneously enables high power density and suppressed eddy-current losses at high frequencies [5]. The magnetic properties of such metallic alloys can often be improved by induction of magnetic anisotropy (i.e. easy and hard axes). It is reported that the anisotropic magnetic cores exhibit higher permeability and lower magnetic losses in the MHz frequency range and above when magnetic flux flows in the direction parallel to the hard axis during operation [6, 7].

In this work, anisotropic nanolaminated CoNiFe cores featuring a hard magnetic axis in the length direction are presented. The properties (i.e. relative permeability and magnetic power losses) of the anisotropic nanolaminated core was investigated using a 22-turn test inductor and compared with the isotropic, nanolaminated core of the identical geometry. The 22-turn test inductor with the anisotropic, nanolaminated core was then characterized in a dc–dc buck converter evaluation board at a switching frequency above 1 MHz. Finally, the anisotropic nanolaminated core was incorporated into microfabricated solenoid windings for on-chip power supply applications.

2. Core fabrication

Rectangular, anisotropic nanolaminated CoNiFe cores were batch-fabricated based on automated sequential electroplating [8] as shown in figure 1. The electrodeposition of alternating CoNiFe and copper films is performed on a silicon wafer substrate bearing a titanium/copper seed layer to a desired number of layers through a lithographically-patterned, rectangular shape photoresist. The thickness of each film is precisely controlled to be less than the skin depth ($\delta = (1/f\pi\sigma\mu)^{0.5}$) of the operation frequency (i.e. 3 μm for 10 MHz) by adjusting the deposition time. Magnetic anisotropy was induced by applying an external magnetic field (50–100 mT) during CoNiFe electrodeposition by placing two permanent magnets across the substrate (figure 1). The orientation of the magnetic field was perpendicular to the long axis of the rectangular core so as to realize a hard magnetic axis in the length direction. This robot-assisted electrodeposition system allows not only ease of fabrication, but also precise lamination thickness in the nanoscale range compared to previously reported manual sequential electrodeposition [9]. After the sequential electroplating, solenoid CoNiFe/copper multilayer structures were separated from the substrate by removing the underlying titanium layer in a 49% HF solution. Then, the copper layers in the multilayer structures are selectively wet-etched in a saturated solution of copper sulfate in ammonium hydroxide ($NH_4OH + CuSO_4$), while the individual CoNiFe layers are anchored by non-conducting materials (e.g. SU-8), preventing interlamination electrical current flow. More details of the core fabrication (e.g. electrodeposition conditions, selective copper etching, and SU-8 anchoring process) are described in [5, 10].

Figure 2 shows SEM (scanning electron microscope) images of 2 mm wide and 15 mm long rectangular cores comprising 70 layers of 500 nm-thick CoNiFe films. Figure 2(b) shows the cross-section of the core demonstrating that 500 nm-thick individual CoNiFe layers are separated from each other, suggesting suppressed eddy-current losses at MHz frequencies.

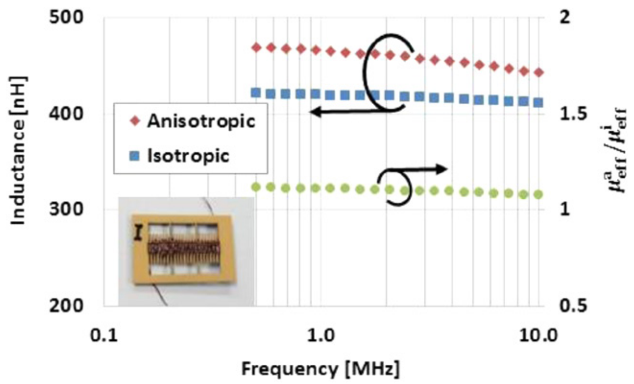

Figure 3. Measured inductance of test inductors and ratio of effective permeabilities of nanolaminated CoNiFe cores.

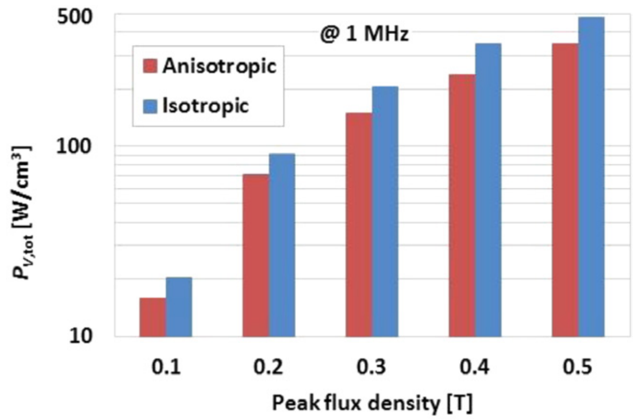

Figure 4. Total volumetric power losses of nanolaminated CoNiFe cores at 1 MHz as a function of peak flux density. Note that *y*-axis is in log-scale.

3. Core characterization

3.1. Permeability and core losses at high frequency

The anisotropic nanolaminated CoNiFe core comprising 70 layers of 500 nm-thick laminations was packaged in a solenoid test inductor by winding 22 turns of magnet wire (inset of figure 3) around the core for characterization. The number of windings has been determined based on the inductance (~450 nH) that is required for the converter operation in section 3.2. For comparison, an isotropic nanolaminated CoNiFe core of the identical geometry electrodeposited without external magnetic field was also prepared. Both inductors were characterized using an impedance analyzer (HP 4194A).

As shown in figure 3, the test inductor with the anisotropic core shows approximately 10% higher inductance than the test inductor with the isotropic core at 0.5–10 MHz frequency range. The constant inductance from both cores indicates that the eddy currents are suppressed in each nanolamination. Considering the identical geometry of both cores, the higher inductance is attributed to the higher effective permeability of the anisotropic core; i.e. the ratio of effective permeability of both cores (i.e. μ_{eff} of anisotropic core divided by μ_{eff} of isotropic core ($\mu^{a}_{\mathrm{eff}}/\mu^{i}_{\mathrm{eff}}$)) can be estimated from the ratio of measured inductances of the test inductors.

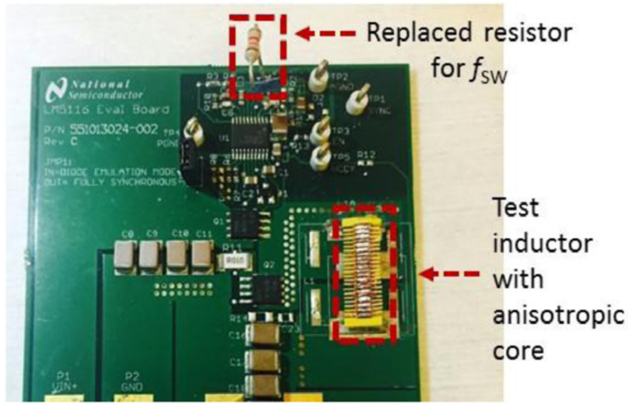

Figure 5. Converter evaluation board with replaced resistor and test inductor with anisotropic core.

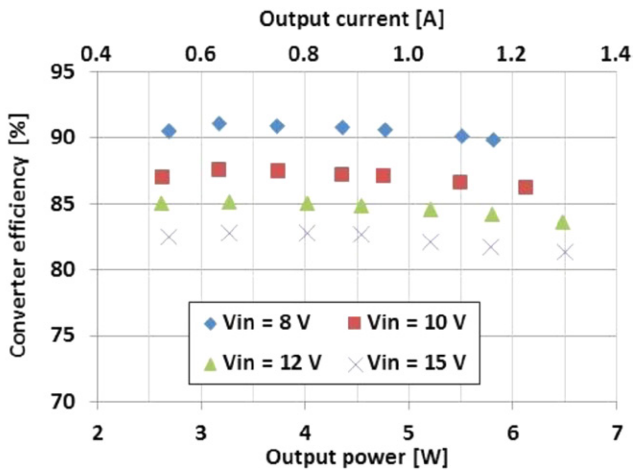

Figure 6. Experimental results of dc–dc converter performance (in discontinuous conduction mode) tested with an anisotropic, nanolaminated CoNiFe core inductor. Converter efficiency as a function of output power and output current at 5 V fixed output voltage.

Further investigation of volumetric power losses on both magnetic cores at high flux density (0.1–0.5 T) at 1 MHz was performed based on a high flux and high frequency characterization method proposed by Han *et al* in 2008 [11]. This method relies on a series resonance between the 22-turn test inductor with the magnetic cores and a reference capacitor, enabling a calculation of core losses as a function of operation flux density at the resonant frequency determined by the reference capacitor. Measured core losses are then decomposed into hysteresis losses and eddy-current losses based on the frequency-dependent magnetic loss characteristic [12]. Details of the high flux characterization and the loss decomposition are described in [5].

Figure 4 shows volumetric power losses of both anisotropic and isotropic cores at 1 MHz, demonstrating that the anisotropic core exhibits approximately 25% reduced total volumetric power losses (i.e. sum of the hysteresis losses and the eddy-current losses) compared to the isotropic core at the same peak flux density levels. Note that both cores were operated up to 0.5 T peak flux density which would be challenging

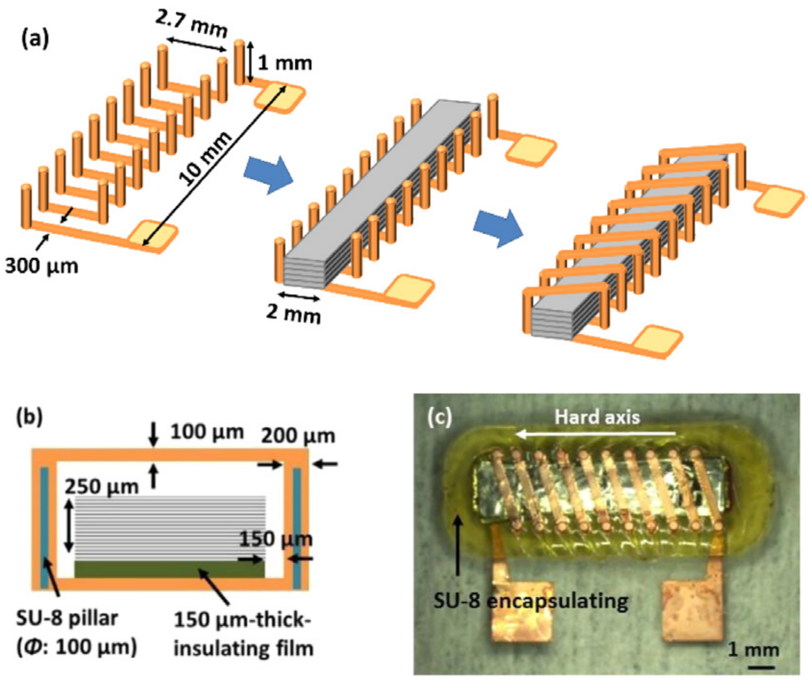

Figure 7. 10-turn solenoid microinductor with a nanolaminated, anisotropic CoNiFe core. (a) Fabrication steps, (b) cross section, and (c) optical image.

to achieve using conventional ferrite cores. Since eddy-current losses of both cores are suppressed to a negligible level (less than 2% of the total losses), the reduced volumetric power losses of the anisotropic core are mainly attributed to the reduced hysteresis losses resulting from the induced anisotropy.

3.2. DC–DC converter test

In order to characterize the anisotropic nanolaminated CoNiFe core in a dc–dc converter system, the 22-turn test inductor with the anisotropic core that exhibits 500 nH was operated in a dc–dc converter evaluation board (LM 5116, TI) by replacing a commercial inductor in the board with the test inductor. A diagram of the evaluation board and typical component values can be found in [13]. By modifying the resistor that sets the switching frequency, the converter operated at switching frequencies above 1 MHz and output power higher than 2 W. Figure 5 shows the evaluation board with the replaced resistor and the 22-turn test inductor.

During the measurement, applied input voltages were ranging from 8 V to 15 V, and output voltage was fixed at 5.3 V with a switching frequency 1.1–1.5 MHz. Converter efficiencies as a function of output power are shown in figure 6. With an input voltage of 8 V, the converter efficiency exceeds 90% up to 5 W output power. Decreasing converter efficiency was observed with increasing voltage regulation ratio, and the converter efficiency was approximately 81% with a 15 V input voltage at 6.5 W output power.

4. Solenoid microinductor with nanolaminated CoNiFe core

The developed nanolaminated CoNiFe cores are further integrated into microfabricated solenoid windings by means of a core drop-in approach. As shown in figure 7(a), the nanolaminated cores are placed into partial windings (i.e. bottom and vertical windings) that were fabricated based on SU-8 photolithography and copper metallization [14]. Then, the partial windings and the core are encapsulated with SU-8, followed by top winding fabrication forming a solenoid microinductor. More details of the fabrication process are described in [15]. Figure 7(b) illustrates the cross section of the solenoid microinductors, showing specific dimensions of the device. The 150 μm-thick polyester insulating film is placed between the core and the bottom winding to prevent an electrical short circuit. A fully-fabricated 10-turn solenoid microinductor with an anisotropic nanolaminated CoNiFe core is shown in figure 7(c). Dimensions of the microinductor are specified in table 1.

Microfabricated solenoid inductors with both anisotropic and isotropic nanolaminated CoNiFe cores were characterized in the 0.1–10 MHz frequency range using an impedance analyzer. Both cores comprise 200 layers of 1000 nm-thick CoNiFe laminations. As shown in figure 8, the microinductor with the anisotropic core shows a constant inductance of 600 nH up to 10 MHz, indicating suppressed eddy-current losses in the measured frequency range. This is approximately 15% higher inductance over that of the microinductor with the isotropic nanolaminated CoNiFe core, demonstrating the higher effective permeability of the anisotropic, nanolaminated CoNiFe core at MHz frequency operation. The microinductor

Table 1. Dimension of the microinductor with core.

Microinductor	
Number of turns	10
Height	1 mm
Length	10 mm
Width	2.7 mm
Surface area	$27\,\text{mm}^2$
Total Volume	$27\,\text{mm}^3$
Microfabricated winding	
Width (bottom and top)	300 μm
Thickness (bottom and top)	100 μm
Diameter (vertical)	200 μm
Laminated core	
Number of laminations	200
Lamination thickness	1 μm
Length	10 mm
Width	2 mm
Magnetic thickness	200 μm
Cross section area	$0.4\,\text{mm}^2$
Magnetic volume	$4\,\text{mm}^3$

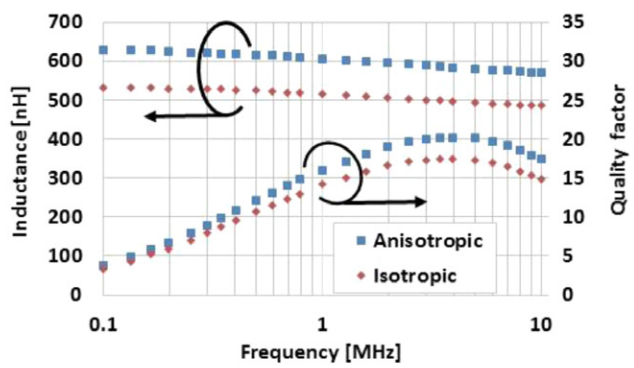

Figure 8. Characterization of solenoid microinductors with nanolaminated CoNiFe cores. Inductance and quality factor.

with the anisotropic core also exhibits higher quality factor over the measured frequency than the microinductor with the isotropic core, suggesting that the use of the anisotropic core is beneficial for MHz frequency operation. Peak quality factor of the microinductor with the anisotropic core exceeds 20 at 4 MHz.

Performance of the microinductor with the anisotropic nanolaminated CoNiFe core is also compared with other microinductors with electrodeposited magnetic cores [4, 9, 15–23]. These microinductors feature solenoid, spiral, or race track geometries and the magnetic cores comprise typically alloys of nickel, iron, and cobalt. Several figures of merit have been proposed to compare such microinductors based on inductance density, quality factor, saturation current density, and energy density ($E_D = Li_{sat}^2/2A$) [1]. $E_D = Li_{sat}^2/2A$ figure 9 compares the microinductors based on energy density and peak quality factor at 0.3–10 MHz. Generally, increasing magnetic core thickness for high energy density causes significant magnetic losses (e.g. eddy-current losses) at high frequency operation, resulting in low quality factor. Therefore, the thickness of the metallic alloy cores is typically limited to

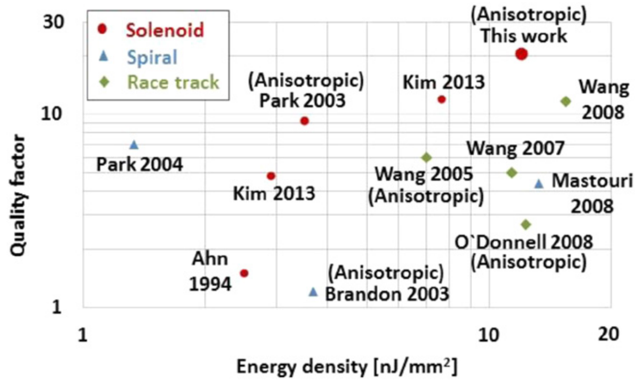

Figure 9. Comparison of microinductors with electroplated magnetic cores. (Anisotropic) represents the inductors with anisotropic cores.

a few microns for MHz frequency range and above. The use of nanolaminated cores allows large overall magnetic thickness with suppressed eddy-current losses, simultaneously enabling high energy density and quality factor at high frequency as shown in the graph.

5. Conclusion

Inducing magnetic anisotropy in nanolaminated CoNiFe cores results in increased inductance and reduced magnetic power losses. A solenoid microinductor with anisotropic nanolaminated CoNiFe core demonstrates high energy density and quality factor at MHz frequency operation. The improved high frequency characteristics of anisotropic CoNiFe, together with the fabrication technology for nanolaminated cores and microinductors will enable high-frequency, high-power ultracompact dc–dc converters.

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