Ultralow-Profile Micromachined Power Inductors With Highly Laminated Ni/Fe Cores: Application to Low-Megahertz DC–DC Converters

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***Abstract*—Micromachined inductors with submillimeter profiles and comparable electrical performance to thicker, commercially-available surface-mount devices, have been fabricated and characterized for low-megahertz dc–dc converters. The fabrication approach involves micron-scale lamination of Ni/Fe cores, combined with three-dimensional micromachined copper windings. The magnetic core of the fabricated inductor has 72 laminations of 1-μm-thick Ni/Fe films. The inductor dimension is 11.5 $\times$ 5.7 $\times$ 0.7 mm, and the dc resistance is 150 mΩ. A maximum Q of 9.2 at 3 MHz with an inductance value of 2.3 μH and a dc saturation current (I80) of 0.2 A were obtained. Use of this inductor in a regulated dc–dc boost converter circuit (7–12 V) operating at 2.2 MHz yielded 1.9-W power output at 71% efficiency.**

***Index Terms*—DC–DC converter, eddy current, magnetic core lamination, micromachining, power inductor.**

I. INTRODUCTION

THERE HAS BEEN an increasing demand for compact power converters in portable applications. For example, battery-operated electronic systems such as notebooks and PDAs require multiple driving voltages for different internal functional blocks, and multiple power converters specialized to power each functional block is often necessary. Miniaturized dc–dc switching converters operating at high frequency are one of the highest efficiency power conversion solutions in these applications. The key challenge in implementing miniaturized switching converters is to realize micromachined magnetic components with small dimension (especially low profile for compact packaging) and high efficiency.

One of the major problems for realization of micromachined magnetics originates from magnetic materials. Nonconducting ferromagnetic materials such as ferrite cores are often used in order to minimize eddy current losses at high frequency. However, metallic alloys such as Ni–Fe show higher magnetic permeability and saturation flux density than many ferrites, allowing for the storage of larger amounts of magnetic energy per unit volume. The typical disadvantage of these metallic alloys is linked to their low-electrical resistance, which can cause substantial eddy-current loss at high frequency, resulting in low efficiency.

Reduction of eddy current loss is usually achieved through appropriate lamination of the magnetic core. Due to the relatively high permeability of these films, the laminations must be exceedingly fine (1–5 μm, i.e., on the order of the magnetic skin depth) for operation in the low-megahertz regime. Previous approaches to micromachined laminations include one-step electroplating of vertical high-aspect-ratio structures [1]; repeated deposition of insulator, seed layer, and magnetic films [2]; multiple sputtering of thin magnetic and dielectric layers [3]; and mechanical lamination of polymer-coated magnetic foils [4]. Although these approaches have demonstrated improvement in device performance, previous approaches to produce highly laminated films have not been able to produce the total magnetic cross-sectional area (e.g., many tens to hundreds of microns) necessary to achieve large magnetic flux handling [5].

In this work, a simple manufacturable laminated core fabrication technique has been used for reducing eddy currents in the megahertz operating regime while simultaneously preserving large total magnetic cross-sectional area. The manufacturing approach is based on an alternating, conformal sequential electroplating of layers of Ni–Fe and Cu, followed by selective sacrificial etching of the Cu [5]. This approach is applied to realize an inductor with the core consisting of 72 laminations of 1-μm-thick electroplated Ni/Fe films. To make a core with the above lamination, alternating electrodeposition of Ni–Fe and Cu can be done 72 times, which might be performed by automated sequential (e.g., robotic) processing. An alternative approach for demonstration purposes is the stacking of nine units of laminated cores, each of which is fabricated in a single batch of eight alternating platings, which is within the capability of nonrobotic standard processing (and which is the method utilized in this work). In order to realize a complete power inductor, this highly laminated core-fabrication technology is combined with microelectromechanical system (MEMS)-based toroidal conductor winding technology.

II. INDUCTOR DESIGN

Widely used Ni_{80}–Fe_{20} was chosen as a magnetic material since it has high relative permeability (~ 800) and high saturation flux density $(\sim 1\ \mathrm{T})$.

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The lamination thickness can be chosen to be on the order of or less than the skin depth [1]. For a given magnetic material and frequency, the skin depth (δ_c) of the core can be calculated as [6]

$$\delta_c = \frac{1}{\sqrt{\pi f \mu_c \sigma_c}} \qquad (1)$$

an, the effective resistance (R_e) from eddy current loss can be approximated as [6]

$$R_e \approx \frac{\pi^2}{3} L_0 \mu_c \sigma_c f^2 t^2 \text{ for } \frac{t}{\delta_c} < 0.5 \qquad (2)$$

where f is the frequency of the alternating magnetic flux, μ_c is the permeability of the core material, σ_c is the conductivity of the core material, L_0 is the low-frequency static inductance, and t is the thickness of the lamination. The skin depth at a frequency of 5 MHz calculated from (1) is approximately 3.6 μm with a conductivity of 5×10^6 $(\Omega\text{m})^{-1}$. Generally, 3.6-μm-thick laminations should be sufficient to prevent substantial eddy current losses in the low-megahertz regime. However, it can be seen from (2) that the effective resistance from the eddy current is proportional to the square of the thickness of the laminations for laminations thinner than 1.8 μm (half the skin depth) at 5 MHz. Consequently, the loss can be substantially reduced by further reducing the thickness of the laminations. In this work, a 1-μm-thick lamination was chosen for the further reduction of eddy current loss since thinner laminations do not introduce much fabrication complexity in this fabrication approach. The large cross section (50 $\times$ 300 μm) of the inductor coils is designed to ensure low-electrical dc resistance. Also, a coil thickness of 50 μm is chosen to avoid significant ac resistance increases resulting from the skin effect at low-megahertz frequencies, since the skin depth of Cu at 5 MHz is approximately 30 μm. For vertical Cu posts, thick (300 $\times$ 300 μm) conductors are designed to ensure good electrical contact between bottom and top conductors. Although these thick conductor portions could interact with magnetic leakage fields to produce eddy-current loss in the megahertz region, this loss is expected to be small compared to total core loss at the frequency of interest.

III. Fabrication

The fabrication of the power inductors with highly laminated cores includes two major processes: laminated magnetic core fabrication and three-dimensional (3-D) toroidal winding fabrication. As mentioned previously, the laminated cores are batch-fabricated separately in units of eight laminations, stacked, and combined with integrated winding technology to realize complete power inductors.

A. Batch Fabrication of Laminated Cores

Using conventional UV lithography and sequential electroplating of Ni–Fe and Cu through molds, the multilayered core structure is fabricated [Fig. 1(a)]. Only two UV lithography steps are required regardless of the number of Ni–Fe layers. Then, the Cu layers are selectively etched leaving the laminated Ni–Fe structure [Fig. 1(b) and (c)]. Note that all the magnetic

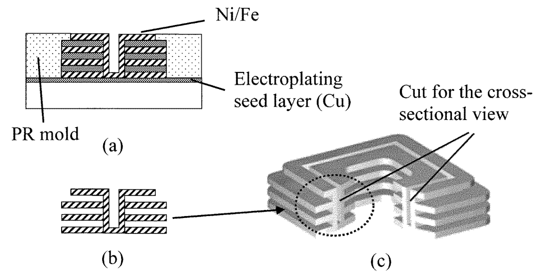

Fig. 1. Fabrication sequence of a laminated core.

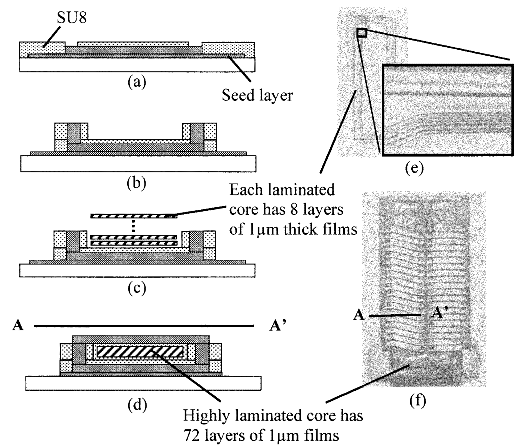

Fig. 2. Fabrication sequence and photograph of a power inductor with a highly laminated core.

layers in the final laminated Ni–Fe structure are mechanically connected. However, the mechanical support is carefully designed not to yield an effective eddy-current path in the core structure even though the magnetic films are electrically and mechanically connected. The detailed core fabrication steps can be found in [5]. Electroplating of Ni–Fe layers has been performed in a dc magnetic field of 20 mT to introduce magnetic anisotropy in the films and thereby improve high frequency characteristics [3].

B. Completion of Inductors Using the Prefabricated Cores

A seed layer (Cr–Cu–Cr) is deposited and patterned to form a mesh type seed layer on a glass substrate. This mesh-type seed layer allows electrical current to flow to each inductor winding during electroplating, and allows electrical insulation at the completion of the process by etching the mesh. Negative photoresist (NR9-8000, Futurrex) is patterned and electroplating of Cu is performed to form the bottom conductor lines of the coils. After removal of the photoresist mold, the lines are passivated under a layer of photosensitive epoxy (SU8), which is patterned in order to create electrical vias [Fig. 2(a)]. The new layer of 500–600-μm-thick SU8 is applied and patterned to form the vertical walls which will contain prefabricated laminated cores in a drop-in fashion. These vertical walls also extend the electrical vias from the first epoxy layer. The Cu is electroplated through the electrical vias after covering the seed layer with photoresist [Fig. 2(b)]. Then, the required number of prefabricated laminated cores are dropped into the core location, which

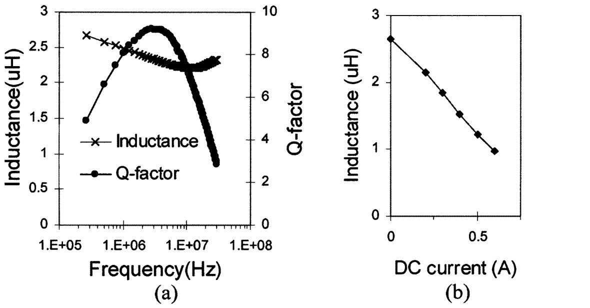

Fig. 3. Measured inductance, Q-factor, and dc saturation characteristics of the fabricated inductor.

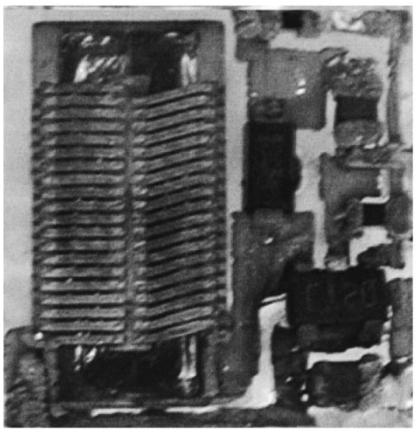

Fig. 4. Photograph of a miniaturized dc–dc converter.

is defined by epoxy vertical walls [Fig. 2(c)]. After passivation of the laminated cores with SU8, the top conductor lines of coils are fabricated with Cu electroplating, and finally the electroplating seed layers are timed-etched [Fig. 2(d)]. Since portions of the mesh-type seed layer in the nonpassivated areas are much thinner (0.3 μm) than the electroplated conductor lines, the timed-etch does not significantly affect the conductor lines Fig. 2(e) shows a photograph and the side closeup SEM of a unit-laminated core. A photograph of a complete inductor with highly laminated core is shown in Fig. 2(f).

IV. Experimental Results and Discussion

The inductance and Q-factor of the fabricated inductors were measured using an HP4194 A impedance analyzer with an internal oscillation level of 0.5 V. The achieved inductance and Q-factor is shown in Fig. 3(a). A maximum Q-factor of 9.2 was obtained at 3 MHz with an inductance value of 2.3 μH. This high Q-factor of the fabricated inductor results from the lamination of the magnetic core [5]. Self-resonance due to stray capacitance was observed at 70 MHz, which is far from our frequency of interest. The saturation characteristic with a dc current superimposed on a 300-kHz ac signal was measured using a Wayne–Kerr 3245 precision inductance analyzer and is shown in Fig. 3(b). The dc saturation current $(I_{80\%})$ was 0.2 A. The dc resistance of the inductor winding was 150 mΩ.

After characterization, the inductor was utilized along with a commercially available switching regulator chip (LT1930 A, Linear Technology) operating at 2.2 MHz, a Schottky diode, capacitors, and resistors, to realize a miniaturized dc–dc boost converter module. The photograph of the fabricated converter module (11.5 $\times$ 12 mm in lateral dimension) is shown in Fig. 4. The demonstrated converter has a 1.9 W output with 71% efficiency converting from 7 to 12 V, as shown in Fig. 5.

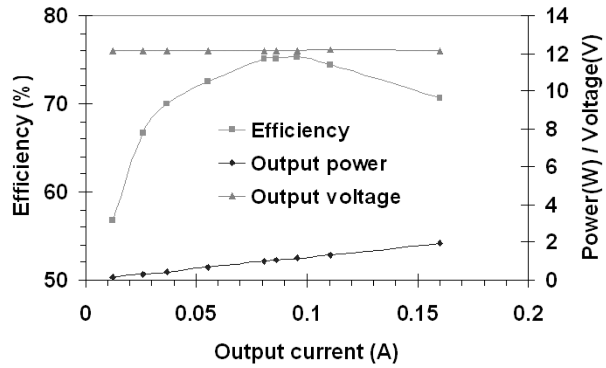

Fig. 5. Output performance of a miniaturized dc–dc converter (input voltage: 7 V).

V. Conclusion

Ultralow-profile micromachined power inductors with highly laminated cores are designed, fabricated, and characterized for low-megahertz power applications. A simple manufacturable laminated core fabrication technique has been used for reducing eddy currents in electroplated Ni–Fe cores and combined with 3-D-MEMS winding technology to realize high efficiency power inductors. The fabricated inductor has a Q-factor of 9.2 at 3 MHz. This inductor can be directly fabricated on top of prefabricated silicon circuitry since only CMOS-compatible low temperature fabrication is used. The high Q-factor, high-saturation current, and low-dc resistance of the developed inductors shows strong potential for high-efficiency power conversion and conditioning applications. The demonstrated switching dc–dc converter utilizing the fabricated inductor has a 1.9 W output with 71% efficiency converting from 7 to 12 V.

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