Non-lithographic and scalable fabrication of one-turn-like inductor having laminated NiFe core for power converters operating at high frequency

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***Abstract*—We fabricated one-turn-like wire inductor via electrodepositing magnetic core materials, NiFe, on the surface of cylindrical copper wires. The current was applied to flow through a copper wire which generated circumferential magnetic flux around the wire. Control of core thickness and wire lengths showed tunability of inductance values. Compared to an air-core wire inductor (no magnetic core on a wire), 50 µm thick NiFe electroplated wire inductor had 144 times higher inductance values. We also achieved sequential electroplating of NiFe and interlamination layer, polypyrrole, on wire surfaces. Laminated cores showed higher retention of inductance compared to a single layer NiFe core, demonstrating wire inductor's applicability in high frequency applications. Our one-turn-like wire inductors provide an effective strategy to fabricate micro-inductors in a simple and scalable manner to be integrated for Power system-in-package.**

Keywords—Inductors, NiFe, Lamination, Power converters, Power System in Package, High Frequency, MEMS

I. Introduction

Power system-in-package (PwrSiP) enables economical, compact, and modular solutions for power conversion in complex electronic systems, that requires different voltage and current levels to efficiently drive various subsystems [1], [2]. In order to fully realize the potential of the PwrSiP concept, all key components need to be scaled down. Since many PwrSiP architectures are based on switching power converters, one effective means to reduce size is to operate the switch at a higher frequency. Advancements in SiC and GaN transistors have enabled power switches that can operate in the several MHz frequency range and higher [3], [4].

One of the key components and also the largest component in power converters is an inductor [5], [6]. Thus, inductor size reduction is critical. Up to now, ferrite has been the most commonly used magnetic core for inductors due to its inherent resistivity-based suppression of eddy currents that would otherwise cause unacceptable losses [7]. However, the limited saturation flux density and frequency limitations of ferrite's permeability make it difficult to further miniaturize, especially in a higher power or high frequency systems. Recent studies on the lamination of higher performance metallic magnetic core materials, such as NiFe alloys, have shown that micromachined laminations can suppress eddy currents even in the MHz frequency range [8]. Using NiFe as a magnetic core material, few millimeter-scale lateral dimensions with multiple micron-scale thickness laminations are sufficient to achieve tens of µH inductance.

Micron-scale thick inductors raise the problem of winding coils around the magnetic core. Conventional large winding equipment is difficult to wind such thin micro-inductors due to their inherent fragility. Wire bonding is one way to wind, but as wire bonding is a serial process, it has limitations in scalability and cost [9]. Lithographic windings have also been demonstrated but will require substantial additional fabrication steps [10]. Therefore, there is a need for a simple means to wind wires for micro-inductors having laminated cores.

We propose a strategy of making a one-turn-like wire inductor while simultaneously maintaining the ability to electrodeposit laminations and interlamination insulation. Consider a cylindrical copper wire having a magnetic core circumferentially arranged on its surface. Flowing current through the copper wire will create a circumferential magnetic flux around the wire in the magnetic core. Such a device is effectively a one-turn inductor that does not require a separate winding; instead, the winding (i.e., wire) is the substrate upon which the core is formed. Such a process does not require photolithography, further simplifying the inductor fabrication. We have validated this concept by showing that the laminated magnetic core can be electrodeposited and has reasonable inductance values to be used by itself or as a bundle.

II. Results and Discussion

We fabricated cylindrical wire inductors by winding enamel-insulated copper wires on a frame, sputtering seed layer, and electroplating magnetic core materials, as depicted in Figure 1. As inductance increases by the square of the number of turns, cylinder inductors have disadvantages in achieving high inductance values compared to a solenoid or planar spiral inductors. Thus, we used highly permeable magnetic material, NiFe, to coat the copper wire. It was

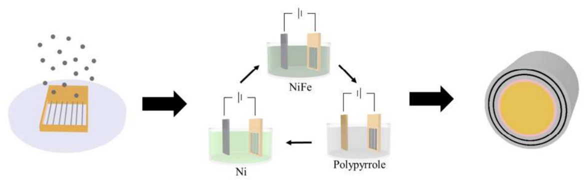

Figure 1. Schematics of wire inductor fabrication method.

confirmed with EDS that the electroplated magnetic material is NiFe having a composition of approximately $Ni_{75}Fe_{25}$. However, NiFe is conductive and thus has high eddy current loss as the operating frequency increases. In order to suppress eddy current loss, polymer interlayers were added to create a circumferentially laminated core structure. More details on laminations will be discussed later in the paper. Commercial enamel-coated copper wire was chosen instead of bare copper wire to better model the magnetic and electrical properties of wire inductors. Complete electrical isolation between Cu and magnetic material due to enamel avoids eddy currents that flow from the first magnetic layer, NiFe to Cu. In practical application, an insulation layer may not be required, which would eliminate the need for the sputtering process, leaving only scalable and continuous electroplating fabrication steps to produce the proposed wire inductors.

A simplistic theoretical model of cylindrical inductance value can be calculated by (1).

$$L = \frac{h\mu_0\mu_r}{2\pi}\left(\ln\frac{r_{copper} + t_{core}}{r_{copper}}\right) \quad (1)$$

where L is inductance, h is cylinder length, μ_r is relative permeability, μ_0 is vacuum permeability, r_{copper} is radius of copper wire, t_{core} is the NiFe thickness.

As presented in the equation, there are three different parameters we can manipulate to control inductance of cylinder inductors: permeability, wire length, and NiFe thickness. As a change in permeability requires a change in magnetic material, we have investigated inductance manipulations by changing NiFe thickness and inductor lengths. We successfully controlled NiFe thickness from 5 μm to 50 μm by changing the NiFe electroplating duration. Cross-sectional images of the fabricated wire inductors of different NiFe thicknesses are shown in Figure 2a-d. The center circle is the commercial copper while the silvery ring surrounding copper is NiFe. The black gap in between copper and NiFe is the wire's enamel coating. Seed-layers are too thin (~100 nm) to be seen in the provided magnification. An increase in NiFe thickness translates to a rise in inductance as shown in Figure 2e. When equation (1) was plotted, one could see a close approximation of our experimental data with the theoretical values. Compared to 5 μm thick NiFe wire inductor, 50 μm NiFe wire inductor presents about 15 times higher inductance, showing that there is a wide window of inductance values controllable by changing magnetic coating thickness. It is also important to note that a 50 μm radius wire inductor has an inductance value over 141 times larger than that of air-core at low frequency, validating the means to achieve a high inductance inductor to overcome geometric limitations with a thin magnetic coating material. We would be able to achieve higher inductance by increasing electroplating time or electroplating current density.

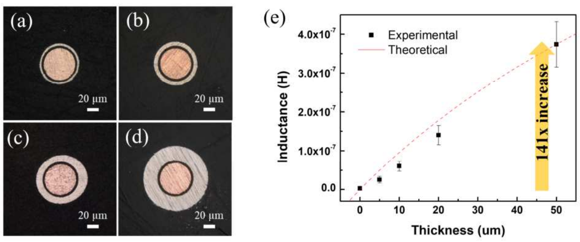

Figure 2. Cross-section images of wire inductors taken using an optical microscope having thicknesses of (a) 5 μm, (b) 10 μm, (c) 20 μm, and (d) 50 μm. (e) Inductance over a range of frequency for different NiFe thickness wire inductors at 50 kHz.

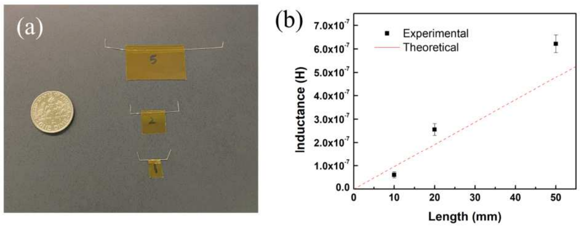

Figure 3. a) wire inductors of different lengths and (b) inductance over a range of frequency for different wire inductor lengths at 50 kHz.

Wire inductor lengths were also successfully controlled from 10 mm to 50 mm as presented in figure 3a. All length varied inductors tested had 10 μm thick NiFe. Wire inductor of 50 mm long was about 10 times higher in inductance than 10 mm long wire inductors as shown in Figure 3b. Magnetic core thickness and wire inductor lengths are two nobs to control inductance value, providing a practical and effective method to control the inductance values of the proposed wire inductors.

However, the inductance of these wire inductors falls quickly as frequency increases. This is caused by the generation of eddy currents in the conducting NiFe magnetic core material, which occurs when the core thickness exceeds the skin depth of the magnetic material at the frequency of interest. These eddy currents, which increase with frequency, not only increase loss, but also reduce the effective area for the flow of flux (and therefore inductance). Breaking the magnetic core into a large number of smaller laminations, in which each lamination is thinner than the skin depth, and adding an insulating layer between the laminations, is a well-known strategy to suppress eddy currents. Therefore, we have fabricated laminated wire inductors of NiFe core and polypyrrole insulator using the reported continuous and additive electroplating method [11]. Aiming to compare lamination effects, we fabricated three different wire inductors as shown in Figure 4a-c: one layer of 20 μm, two layers of 10 μm each, and four layers of 5 μm each. Ni interlayer is too thin (~100 nm) to be seen in that scale, while the thin black lines

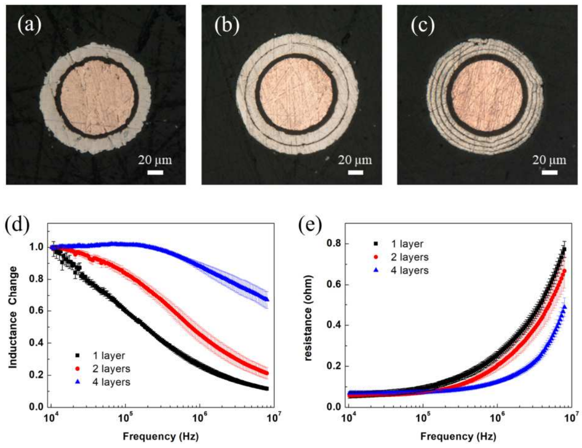

Figure 4. Cross-sections images of NiFe having a total thickness of 20 μm: (a) one-layer NiFe, (b) two-layer NiFe, and (c) four-layer NiFe. Dependence of the (d) inductance and (e) AC resistance, respectively, of the wire inductors as a function of frequency.

in between NiFe are the eddy-current-hindering polypyrrole interlayers.

As shown in Figure 4d, while the inductance of the one-layer wire inductor decreased continuously even from low frequency, the multilayer inductors possessed more stable frequency behavior, indicating the suppression of eddy currents by the laminations was successful. Further, as the number of laminations increased (and therefore the thickness of each lamination decreased), the high frequency inductance roll-off behavior showed continuous improvement. For the four-layered wire inductor, inductance was retained up to approximately 300 kHz, demonstrating the successful hindering of eddy current via a multi-layered structure. The concomitant difference in loss of 1, 2, 4 layered wire inductors is also depicted in Figure 4e. Such a trend provides a potential for inductance retention at an even higher frequency regime by decreasing individual lamination thickness.

III. CONCLUSION

We have fabricated a single-turn winding micro-inductor having a lamination of a metallic magnetic core, NiFe, and interlamination insulation layer, polypyrrole. Tunability of inductance was demonstrated by changing the wire lengths and electroplated core thicknesses. Suppression of eddy-current through lamination was also shown. We believe our work proposed an effective strategy to overcome the challenges of winding on inherently fragile micro-inductor cores for high frequency operations. Building wire inductors avoids the use of complex lithographic processes or non-scalable serial fabrication steps. Further studies on incorporating wire micro-inductors will help develop PwrSiP.

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