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Nanolaminated CoNiFe Cores with Dip-Coated Fluoroacrylic Polymer Interlamination Insulation: Fabrication, Electrical Characterization, and Performance Reliability

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***Abstract*— We present fabrication, electrical characterization, and performance reliability of electrodeposited, nanolaminated soft magnetic metallic cores with dip-coated flouroacrylic polymer interlamination insulations. The nanolaminated cores are comprised of hundreds of submicron-thick CoNiFe layers that are electrically-insulated from the neighboring layers by ~100 nm-thick fluoroacrylic polymer layers. A fluoropolymer coating solution is utilized to achieve electrical insulation between the individual magnetic layers while the layers are being assembled into a single core. Superior magnetic energy densities, surpassing that of conventional ferrite materials, are achieved even at high operating frequencies up to 10 MHz while the eddy current losses within the individual magnetic layers are suppressed. For the ultimate miniaturization of an inductor, the microfabrication of coil is achieved "on" the surface of the core. Reliability tests, i.e., temperature cycling test and corrosion test, are performed to study potential performance degradation of the nanolaminated cores in actual operation environments.**

Keywords- laminations, soft magnetic materials, microfabricated inductors, reliability test

I. Introduction

The growing demand for multifunctional, miniaturized electronics (e.g., cell phone, lab top) has motivated the miniaturization of power conversion devices. Multiple DC-DC power converters are required to shift the voltage from a battery, powering different chips that are operating at different voltage levels. Reducing the form factors of these converters while achieving Watt-level power handling at high conversion efficiencies is critical.

In particular, inductors and transformers are among the largest components of a switched-based, DC-DC buck converter. To achieve proper power handling based on smaller passive devices, the state-of-the-art converters are designed to operate at high frequencies exceeding several hundreds of kilohertz, or even exceeding 1 MHz [1]; consequently, the inductors should exhibit (1) superior magnetic energy densities and (2) minimal power losses at such high frequencies.

Typically, a magnetic core is employed inside an inductive device to achieve high magnetic energy density. Ferrite materials are chosen for the inductors operating at high frequencies, since their high electrical resistivities lead to suppressed eddy current losses. However, the miniaturization of ferrite core inductors is limited by the relatively low saturation flux densities of the materials. On the other hand, soft, ferromagnetic metallic alloys exhibit high saturation flux densities, at the expense of eddy current losses at high frequencies. The eddy current losses can be suppressed in laminated cores, i.e., cores comprising alternating magnetic and insulation layers. The thicknesses of the individual magnetic layers within the laminated core should be smaller than the skin depth of the material at operating frequencies. A proper magnetic volume can be achieved by increasing the number of laminations.

The skin depths of representative soft ferromagnetic metallic alloys are 3~10 μm at 1-10 MHz; hence, nanolaminated ferromagnetic cores, i.e., cores comprising submicron-thick, soft magnetic alloys/interlamination insulation layers, become potential candidates for the magnetic core material for high frequencies. However, the fabrication of such materials into a laminated core with significant overall thickness is not a trivial task. The conventional method which involves milling, stacking and pressing is challenging to create laminations with micron, or submicron-thick individual layers. Sequential physical vapor deposition (e.g., CoZrO) has been reported; however, the total thickness of the core is limited due to the slow deposition speed and high built-in stress of the deposited materials [2,3].

We have previously reported a nanolamination process based on sequential multilayer electrodeposition [4,5]. This process involves (1) sequential deposition of alternating magnetic layers (NiFe or CoNiFe) and sacrificial Cu layers, (2) formation of polymeric, electrically-insulating SU-8 anchor structures, and (3) selective removal of sacrificial layers. The individual magnetic layers are electrically insulated after the copper etch; this approach is referred to as an "SU-8 anchor approach." The eddy current losses from the cores were suppressed up to 10 MHz, being negligible compared to the hysteresis losses. Watt-level power conversion at 1 MHz was demonstrated with power conversion efficiency over 80%. However, the overall

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thickness of the core was limited to the maximum achievable thickness of the plating mold (~ 0.1 mm).

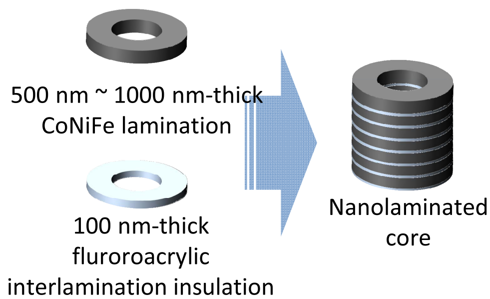


Figure 1. Schematic of a nanolaminated core.

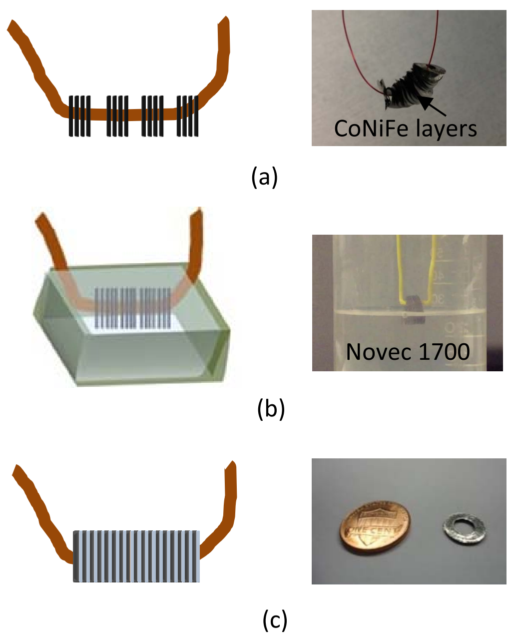


Figure 2. Fabrication of a nanolaminated core based on surface tension-driven assembly.

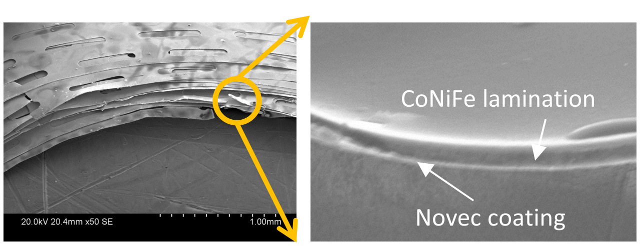


Figure 3. Scanning electron microscope image of a nanolaminated core. The core is manually cross-sectioned to observe Novec coating (Left). The magnified view of the cross-section of a single magnetic layer (Right).

To overcome such limitation, and thereby to create nanolaminated cores with unlimited total thickness, a surface tension-driven approach is presented. The individual magnetic layers, separated by the removal of sacrificial Cu layers, are dipped in a fluoroacrylic polymer solution. While the magnetic layers are pulled out from the solution, the layers are self-assembled to form a single core due to surface tension. Microwindings are directly patterned "on" the surfaces of the cores to minimize the additional volume contributed by the windings. The fabricated nanolaminated cores are subjected to reliability tests (i.e., temperature cycling test and corrosion test) to assess robustness and failure modes of these cores.

II. FABRICATION

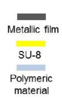
A. Nanolaminated Core

The present nanolaminated core comprises alternating layers of single micron, or submicron-thick CoNiFe alloy and ~100 nm thick fluoroacrylic polymer (Novec 1700^{TM}, 3M)(Figure 1). CoNiFe is selected as the magnetic material since it exhibits high saturation flux density (i.e., 1.8 T). Novec 1700 is a solution comprising 2% fluoroacrylic materials and 98% of solvent. The material is commonly utilized to rapidly coat electronics to improve environmental stability (e.g., improved corrosion resistance). The low viscosity of the solution enables facile self-assembly of magnetic layers, while a conformal, electrically-insulating coating is formed between the individual magnetic layers.

Fabrication of nanolaminated cores begins with a multilayer deposition of CoNiFe and Cu. First, a photoresist mold is patterned on a Cu/Ti seed layer coated, oxidized Si substrate. Electrodeposition is performed to form a desired number of magnetic layers within the molds. Current densities of both electrodeposition processes are set to 20 mA/cm^2 to (1) achieve specific magnetic material composition within the alloy and (2) achieve Cu layers with smooth surfaces. After that, the silicon oxide layer is etched using hydrofluoric acid (49% by volume) to detach the multilayer structures from the substrate. Then, a number of detached multilayer structures are linked together using an enamel coated copper wire. A selective copper etch follows, removing the copper from all the multilayer structures while the CoNiFe layers remain intact. The individual CoNiFe layers are separated from each other, while they are still coupled to the string (Figure 2(a)). After rinsing in deionized water, these layers are transferred to a bath filled with Novec 1700 (Figure 2(b)). Then, the layers are slowly pulled out from the bath. If the interlayer spacing between separated layers is (on average) closer than a critical distance, the surface tension between the layers is strong enough to assemble the layers into a single nanolaminated core (Figure 2(c)). The process is detailed in [6]. The Figure 3(c) shows a single millimeter-thick, nanolaminated core. Since multiple numbers of multilayer can be utilized to form a single core, nanolaminated cores comprising virtually unlimited numbers of individual magnetic layers can be assembled based on a single step process. Figure 3 shows the cross-sectional scanning electron microscope (SEM) image of the layers. The light grey layer coated over the metallic film corresponds to Novec coating.

Table 1 summarizes the differences between the previous method (SU-8 anchor approach) and the presented approach. The thicknesses of the nanolaminated cores based on the previous method were strictly limited by the achievable thickness of a plating mold, whereas core thicknesses exceeding 1 mm could be achieved by the present method. The previous magnetic layer insulation process involved polymeric anchoring and copper removal followed by sample drying, which could lead to stiction between the layers (since the air gaps between the layers after the drying are virtually identical to the thicknesses of the sacrificial copper layers). On the contrary, the individual layers are electrically insulated while they are assembled, leading to better production yield. Some of the limitations of the present process include (1) difficulties in fabricating cores comprised of very thin (<300 nm) magnetic layers (mainly due to manual handling), (2) achieving perfect alignment between the layers, and (3) designing a monolithic fabrication process, which enables the realization of microwinding and magnetic core on a single substrate.

TABLE I. COMPARISON BETWEEN THE NANOLAMINATION APPROCHES

	SU-8 anchor approach	Surface tension-driven assembly
Core cross-section 		
Insulation material	SU-8 and air	Novec 1700 polymer
Insulation thickness	300 nm ~ 5 µm	Down to 100 nm
Achievable total thickness	Limited to photoresist mold (~100 µm)	Potentially unlimited

B. *Microfabrication of Inductors*

The fabricated cores are integrated with windings, forming inductors. Two winding approaches have been demonstrated previously and will be discussed briefly; the third approach, so-called direct patterning method, will be presented in more detail here.

Laser machined plastic bobbins have been utilized for the manual fabrication of inductors [4,5]. Acrylic plastic sheets are cut and assembled to make a bobbin with a trench, within which a laminated core is placed. Then, a Litz wire is wound along the notches that are patterned along the periphery of the bobbin. Although this approach offers an easy route to fabricate an inductor, the miniaturization of the device cannot be achieved. Tightly wound windings with uniform, high spatial density are challenging to be achieved. This motivated a winding process based on microfabrication techniques, referred to as a "drop-in approach."

The drop-in approach begins with the creation of SU-8 pillar structures. After the sputtered copper layer is formed on the SU-8 and substrate, photolithography, followed by copper electrodeposition, is performed to form vertical and bottom conductors, simultaneously. Note that the vertical conductors are formed around the previously-patterned SU-8 pillars. This approach of fabricating tall (> 100 µm), high aspect ratio vertical conductors is much faster than the traditional approach [8], where the conductors are formed by through-mold, bottom-up electrodeposition. After the core is dropped within the array of the vertical windings, SU-8 epoxy is dispensed and patterned, leaving the topside of the vertical conductors exposed [9]. The top winding is formed based on a conventional, through-mold electrodeposition. Although this approach can be used to form a microinductor with reduced form factor, the process is limited to nanolaminated cores with moderate total thicknesses (< 300 µm) mainly because the maximum achievable SU-8 pillar height is approximately 1 mm.

The "direct patterning approach" presented in this paper can be utilized to fabricate microwindings "on" the nanolaminated cores. This approach is useful to create microfabricated windings around the thick (> 1 mm) cores. The core is first potted in SU-8 epoxy (Figure 4(a),(b)); a thin (100~200 µm) and conformal, electrically-insulating layer is formed on the nanolaminated core. After a copper seed layer is sputtered on the sample surface (Figure 4(c)), the sample is again dip coated in a negative photoresist (NR7-3000P, Futurrex) (Figure 4(d)). The coated resist is baked in an oven, and subjected to photolithography (Figure 4(e)). The four sides of the sample are sequentially exposed under a proper mask, and a single step development is performed to create patterned molds around the sample. Subsequent through-mold copper electrodeposition forms microwindings within the patterned molds on every side of the sample, simultaneously (Figure 4(f)). The negative photoresist is removed and the seed layer is blanket etched to form an inductor (Figure 4(g)).

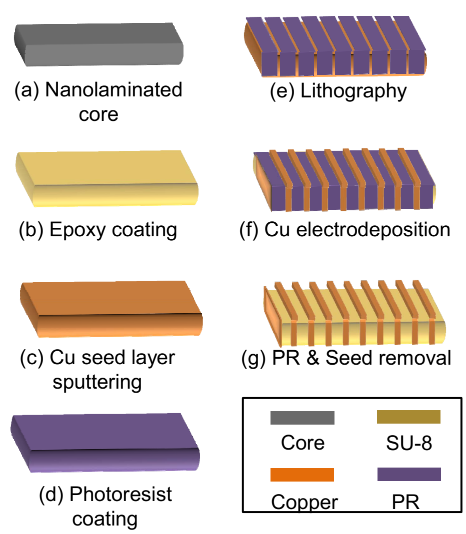


Figure 4. Microfabrication of a coil based on direct patterning method.

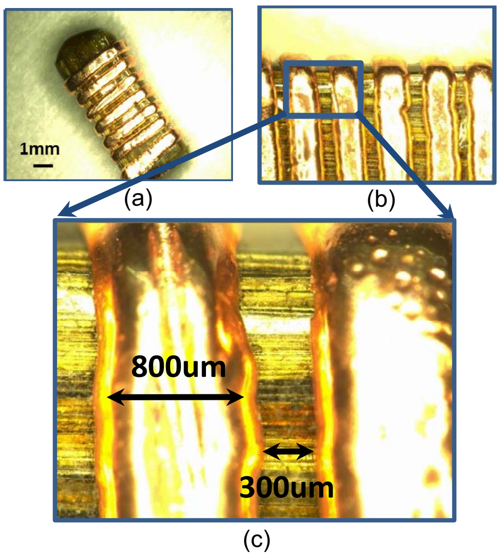


Figure 5. (a) Low magnification, (b),(c) high magnification optical images of the nanolaminated core wound by directly-patterned coils.

Figure 5 shows a 7 turn coil wrapping around a nanolaminated core. The thickness of the coil is approximately 50 µm, which does not add significant volume to the packaged core. From Figure 5(c), the layered nature of the core can be observed through the transparent SU-8 package. By further optimization of the process (such as spray coating to achieve thinner photoresist mold), smaller windings with sub-100 µm lateral dimensions (i.e., winding width, gap between winding turns) could be achieved.

III. Characterization

A. *Electrical Characterization of Direct-Patterned Winding Inductors*

The electrical characterization of the fabricated nanolaminated cores is performed based on impedance measurements. We previously observed that bobbin-wound inductors based on the nanolaminated cores exhibit 500 nH-2500nH inductances with Q factors exceeding 20 up to 10 MHz [6]. Here, we present the measurement results for the microfabricated inductor based on the direct winding approach.

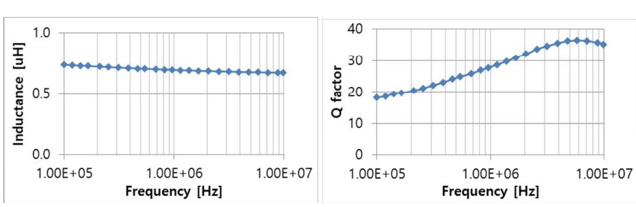


Figure 6. Inductance (Left) and Q factor (Right) of a microfabricated inductor with directly-patterned windings.

The inductance and Q factor of the microfabricated inductor is measured (Figure 6). The core comprised 2000 layers of 1 µm-thick CoNiFe layers. The total thickness of the fabricated inductor was 3 mm. The measured inductance is almost constant up to 10 MHz (690-750 nH), indicating negligible eddy current losses. It is also important to note that the peak of the Q factor is 35 observed at 5 MHz; the inductor performance is optimal at a few MHz. The additional fabrication processes for the microfabricated coils are compatible with the electric/magnetic properties of the nanolaminated cores.

B. *Reliability Test Using Bobbin Wound Inductors*

Bobbin-wound inductors were utilized in reliability testing to facilitate access to the core during and after test. To assess the reliability of the nanolaminated cores, tests are performed based on standard methods. Exposure to high (or low) temperature may negatively affect the electrical performance of nanolaminated cores. In particular, exposure to high temperature may degrade the insulation quality of the Novec polymer as well as cause oxidization of the magnetic layers. In addition, a sudden change of temperature may lead to the delamination of the layers, since the coefficients of thermal expansion (CTE) of the polymer and metal are significantly different.

The temperature cycling test is performed based on Mil-Std-883 Method 1010-B. The device-under-test (DUT) is a bobbin wound inductor with a nanolaminated core. The DUT undergoes 10 cycles of test, where a single cycle is comprised of a 10 minute long exposure to 120 ºC (in a convection oven) and a 10 minute long exposure to -55 ºC (in a customized ice box). After each step, the inductance of the inductor is measured (at room temperature). Note that an isopropyl alcohol (IPA) bath, placed on a volume of dry ice (measured surface temperature: -78 ºC), is used to cool the DUT; the temperature of the bath is accurately set (-55 ºC ±1) by controlling the volume of the IPA bath (Figure 7(a)).

The measurement results are presented in Figure 7(b). Through 10 cycles, the measured normalized inductances (i.e., measured inductances within a specific cycle, divided by the initial measured inductance of the DUT) do not vary more than 5%. The air core inductors (i.e., a bobbin wound inductor without nanolaminated cores) show a similar trend. The nanolaminated cores are sufficiently reliable to withstand these temperature changes.

Another important measure of the nanolaminated core reliability is corrosion resistance. Most ferromagnetic metallic alloys suffer from corrosion, mainly due to their high iron content. As the corrosion continues, iron is oxidized, leading to a decrease of magnetic volume within the inductive device. Hence, the corrosion rate could be tracked by measuring the decreasing inductance of the device as a function of time.

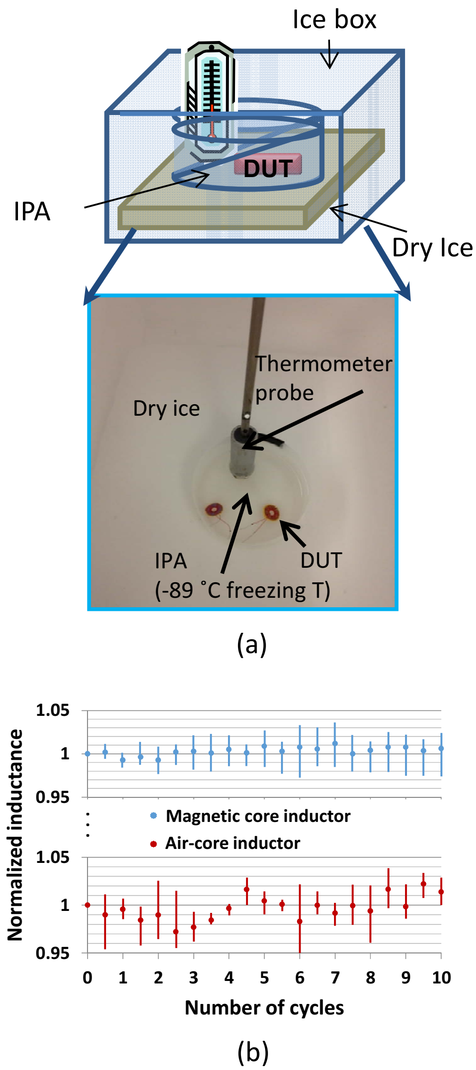


Figure 7. Temperature cycle test. (a) Test setup, (b) measured inductances of the test devices throughout 10 cycles.

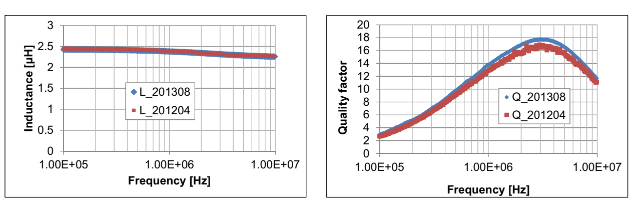


Figure 8. Inductance (Left) and Q factor (Right) of a device after 16 months at ambient conditions (L_201308, Q_201308).

The impedance of the inductor is tracked over more than a year, while the device was placed at ambient conditions (i.e., 21 ºC, 55% humidity). Figure 8 shows the measured inductance and Q of the inductor 16 months after the device was fabricated; the initial measurement results have been superimposed. No significant change is observed. In addition, the corrosion resistance of the inductors is evaluated in a highly corrosive environment, i.e., high humidity (80%) and high temperature (50 ºC). The DUT is placed in an enclosure containing a wet sponge together with temperature and humidity sensors (Figure 9). After the box is sealed, it is placed in an oven. The sample was periodically removed, and the impedance of the inductor measured (Figure 10). Four types of samples are prepared: (1) air-core inductors (inductance of the sample referred to as "L_air"); (2) inductors with the nanolaminated cores based on the previous SU-8 anchoring method ("L_core"); (3) inductors with the self-assembled nanolaminated cores ("L_Novec"); and (4) inductors with self-assembled cores, completely passivated by photocrosslinked SU-8 ("L_SU-8"). Note that the "L_core" represents the degradation of the bare nanolaminated cores without coating material around the individual layers, while the "L_Novec" represents that of the cores with Novec interlayer insulations. It is interesting that both "L_core" and "L_Novec" decrease as a function of time (0.25% and 0.21% decrease per day, respectively). The decreasing trends of the inductances are attributed to the oxidization of iron since both inductance and Q factor measured from the air core inductor are constant throughout the experiment.

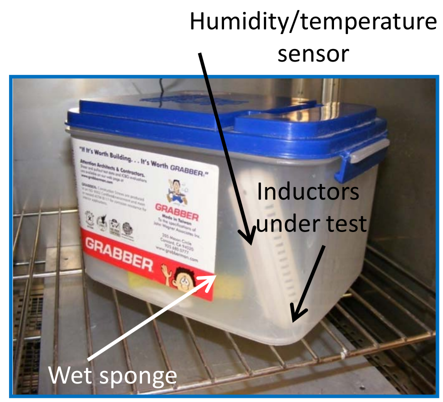


Figure 9. Corrosion test setup.

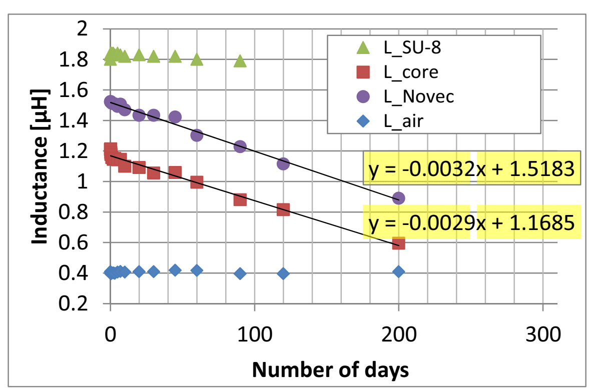


Figure 10. Measured inductances of the devices (at 3 MHz) throughout 200 days in the corrosion chamber.

Figure 11 shows the optical image of an SU-8 anchor core and a self-assembled core, after the samples stayed 90 days in the corrosion chamber. The surfaces of both cores are significantly roughened while their colors changed to light brown, indicating the corrosion. The corrosion resistivity of the self-assembled nanolaminated cores can be improved by additional epoxy potting; the measured "L_SU-8" is constant for least until 100 days. Impermeable potting materials with better mechanical toughness and thermal stability should further improve the reliability of self-assembled nanolaminated cores.

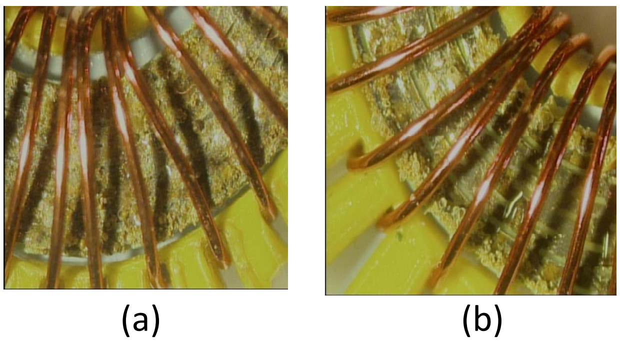


Figure 11. Optical microscope images of an (a) SU-8 anchor core and a (b) self-assembled core after 90 days of corrosion test.

IV. CONCLUSIONS

Nanolaminated cores with very large total thickness (> 1mm) were achieved by surface tension-driven assembly of individual, submicron-thick CoNiFe magnetic layers. While the separated magnetic layers are pulled together due to surface tension between the layers and a fluoroacrylic polymer solution, the layers are electrically insulated, thereby forming the nanolaminated cores with proper interlamination insulation. Electrical characterization was performed based on impedance measurement. The inductance of the inductors were constant as a function of frequency up to 10 MHz, validating negligible eddy current losses within such a large volume. Using such a thick core, a proper level of inductance (> 500 nH) was achieved with minimal winding turns and footprint. In order to microfabricate a coil around the thick nanolaminated core, a direct patterning approach was presented: (1) Plating molds are directly patterned "on" the electrically-insulated surfaces of the core; and (2) a single step electrodeposition of copper was performed to form the coil around the core. Reliability tests, i.e., temperature cycling test and corrosion test, were performed to assess the functionality of the cores in simulated operating environments. Additional epoxy potting was required to further decrease the corrosion of the Novec polymer-insulated, nanolaminated core. Thick, nanolaminated cores can be a practical solution for the miniaturized inductive components in Watt-level DC-DC converters and circuit isolators.

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