Parylene-Insulated Ultradense Microfabricated Coils

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***Abstract*—This paper details the microfabrication and characterization of electrodeposited coils with high packing density. The process consists of electroplating a first sequence of metal microstructures, followed by conformal insulation of these conductors by a thin vapor-deposited layer of parylene, and subsequent electrodeposited metal filling between the first-layer conductors. Using this approach, the packing density limitation due to photoresist aspect ratio is overcome. The microcoils, which are fabricated onto a dummy substrate, are released and embedded into a parylene layer to reduce parasitic substrate losses at high frequencies, as well as to facilitate the device integration. Comblike test structures were designed and fabricated in order to validate the approach and to explore the electrical properties of such microconductors. Furthermore, ultradense parylene-insulated spiral windings were fabricated and electrically characterized. A large number of turns per volume can be fabricated because of this fabrication approach, which is a requirement for highly efficient small-scale magnetic actuators. Finally, an array of substrateless parylene-coated 2-D coils were built, then folded on top of each other, and electrically connected to form 3-D coil devices. A 14.6-mm-diameter 96-turn three-layer copper winding was fabricated and characterized. The packing density of the 3-D fabricated coil was 81%. [2010-0045]**

***Index Terms*—Chemical vapor deposition, high aspect ratio, metal microelectromechanical systems (MEMS), microcoils, parylene.**

I. Introduction

IN HIGHLY efficient high-current devices, such as electromagnetic actuators, it is desirable to produce winding coils with maximal packing density (i.e., percentage of copper per unit volume). Consequently, it is required not only to control the geometric shape and alignment of the individual conductors but also to minimize the insulation surrounding each conductor [1]. In conventional wire wrapping, cylindrical wires are stacked in a relatively inefficient fashion. Furthermore, the insulation thickness for fine magnet wires is on the order of the thickness of the conductor itself [2]. Microelectromechanical systems (MEMS) fabrication technologies offer the possibility of an efficient and controlled stacking. Standard fabrication processes of microcoils consist of electrodeposition of copper material through a photoresist mold [3]. An efficient arrangement can be achieved because of the square cross-sectional geometry of the copper conductors. However, the gap between the coil turns is commonly limited by the maximum aspect ratio that is achievable with the photoresist mold. Furthermore, the fabrication of 3-D electrodeposited metal coils using standard MEMS approaches is challenging, primarily due to the difficulties associated with forming multiple layers of reasonably thick high-aspect-ratio-patterned molds on top of each other. Generally, the number of conductor layers is limited to two or three layers [4]. Other techniques have been reported to fabricate 3-D coils with controlled stacking. For example, the use of an automated wire bonder enables high-throughput fabrication of small-scale 3-D solenoids with insulated gold wires wound around SU-8 posts [5]. However, round geometries do not offer the highest packing density.

In this paper, we present a MEMS-enabled approach to fabricate such 3-D microcoils with high-aspect-ratio electroplated conductors exhibiting micrometer-sized interconductor gaps. Electroplating through resist mold coupled with a sidewall insulation scheme is utilized. This process greatly differs from conventional planar coil microfabrication because the gap between the metal conductors is not limited by the maximum aspect ratio of the photoresist mold. Instead, the gap is controlled by the thickness of a chemically vapor-deposited insulation material [6], [7]. Furthermore, the three dimensionality of copper coils is achieved by a folding process. Two-dimensional arrays of copper coils are fabricated on a planar and rigid substrate. The coils are then released and folded onto each other to form a 3-D coil device. The polymer material provides electrical insulation as well as mechanical support between the multiple layers of copper windings.

Fig. 1 shows the comparison of the packing density of conventionally wrapped magnet wires [2] with that of square coils insulated with a thin layer of nonconductive material. Configuration #1 corresponds to a standard arrangement where the cylindrical coils are aligned on top of each other. The higher packing density of configuration #2 is due to the staggered arrangement, as shown in Fig. 1(b). It should be noted that the thickness of the insulation layer also increased as the coil diameter increased, as referred in [2]. The data labeled as "MEMS coil" correspond to a coil fabricated using the proposed approach. The conductors have a square geometry and are insulated by a 5-μm-thick layer of conformally deposited polymer. Such concept results in a 50%–100% enhancement in packing density. This improvement is due to the change from cylindrical to square wires, as well as a reduction of the

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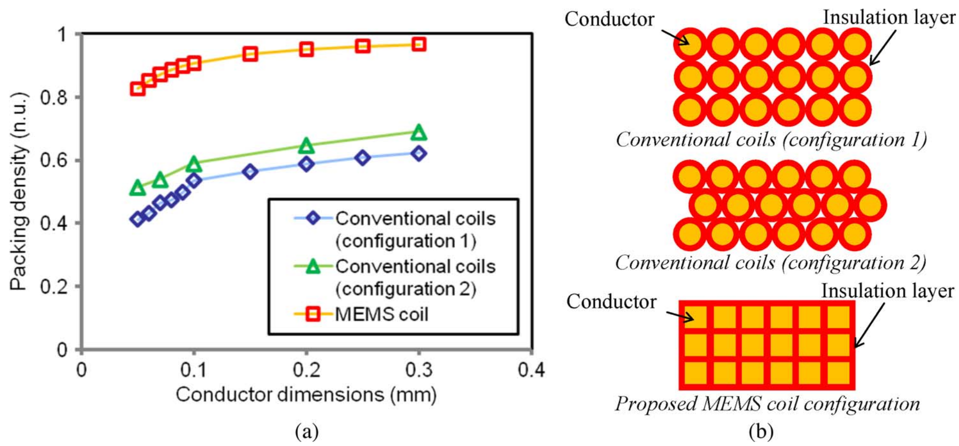


Fig. 1. (a) Packing density as a function of the conductor dimensions calculated over an array of conductors and (b) schematics of the three configurations. The round magnet wires have standard insulation [1], while the MEMS-fabricated square coils have a 5-μm-thick parylene insulation.

thickness of the insulation layer. In many high-current low-voltage magnetic applications, such considerations are essential to improving coil performance and, thus, the overall efficiency of the device. For example, the potential benefits of higher packing densities are reduced dimensions of the coil or better device performance due to larger number of turns in a given volume.

First, the fabrication process used to build ultradense copper microconductors is described. Second, the design and fabrication of comblike test structures are presented, followed by capacitance measurements and insulation voltage breakdown characterization. Using these test devices, process limitations have been investigated. Finally, the design of fabricated spiral microcoils and standard electrical measurements are reported. The performance of ultradense microfabricated coils compared to wrapped wires is also discussed.

II. Fabrication Concept

The fabrication of 3-D ultradense microcoils relies on the conformal deposition of thin layers of parylene insulating material onto nonplanar metal microstructures, followed by copper filling and subsequent release of the windings. The fabrication process flow is shown in Fig. 2.

The process started with the deposition of a Ti/Cu/Ti seed layer onto an oxidized silicon substrate. Using standard plating-through-resist techniques, a first layer of copper conductors was formed, as shown in Fig. 2(a). The photoresist mold was removed by acetone, while the layers of titanium and copper were etched away using diluted hydrofluoric acid and a solution of ammonium hydroxide saturated with copper sulfate, respectively. As shown in Fig. 2(b), the metal conductors were then coated with a vapor-deposited insulating material such as parylene C. This material provides excellent conformal deposition and pinhole-free films [8]. Next, a second Ti/Cu/Ti seed layer was deposited, as shown in Fig. 2(c). Using a manual spray-coating technique [9], a negative-tone photoresist layer (NR9-8000P, Futurrex) was subsequently formed onto the microstructures. The negative photoresist was first diluted using cyclohexanone, which is the principal solvent contained in this photoresist (1 : 1 weight ratio). The purpose of the dilution

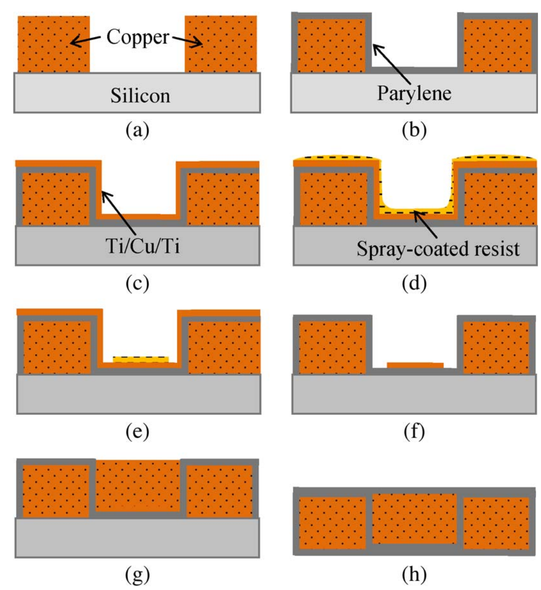


Fig. 2. Fabrication process flow of ultradense microcoils. (a) Standard through-resist mold electroplating. (b) Parylene insulation. (c) Ti/Cu/Ti deposition. (d) Spray coating of negative-tone photoresist. (e) Photoresist patterning. (f) Seed layer patterning. (g) Second electroplating sequence. (h) Release and insulation of the fabricated coils.

was to decrease the resist viscosity in order to facilitate the spray coating. Although it is usually challenging to achieve a conformal photoresist layer onto nonplanar topographies using spin coating, a thickness-controlled photoresist layer can be achieved at the bottom of such microtrenches using the spray-coating technology [9]. In order to obtain the desired thickness (~5 μm at the bottom of the channels), multiple coatings were necessary. Using a dark-field photomask, the photoresist layer was patterned so that the photoresist etch mask remains between the copper structures, as shown in Fig. 2(e). Next, the seed layer was patterned by wet etching. Although this is not shown in Fig. 2(f), the patterned seed layer was continuous, enabling the electrodepostion of a second sequence of copper conductors, as shown in Fig. 2(g). The first layer of insulated metal structures was used as a plating mold, which resulted in insulated metal lines spaced by the thickness of the vapor-deposited material on the order of several micrometers or less.

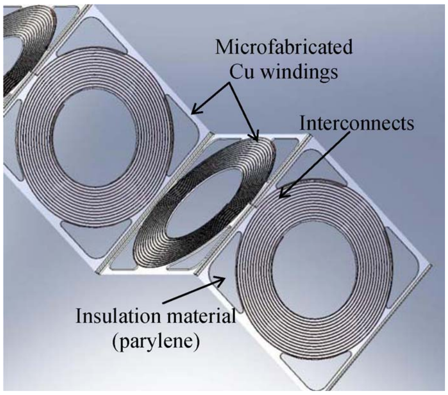


Fig. 3. Rendering of the folding concept to create 3-D MEMS-based coils from a flexible array of planar microfabricated windings.

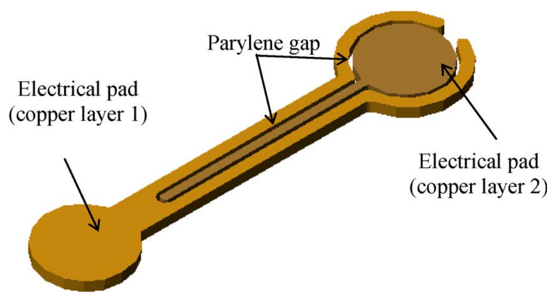


Fig. 4. Rendering of the comblike test structure.

The ultradense metal microstructures are now fabricated. Next, the structures were released from the rigid substrate by underetching the silicon oxide layer in hydrofluoric acid. Finally, both surfaces were insulated with another layer of parylene material, as shown in Fig. 2(h). Such a process created substrateless ultradense 2-D coils. In order to build a 3-D structure, arrays of 2-D coils were fabricated. The structures were then folded together and electrically connected to form 3-D microcoils. The folding concept is shown in Fig. 3.

III. Ultradense Test Structures

A. *Design and Fabrication*

Comblike test structures were designed and fabricated so as to validate the fabrication concept. Using these structures, the optimum width of the patterned seed layer relative to the spacing between first-layer conductors was determined. Furthermore, various thicknesses of insulation material were also tested in order to vary the copper packing density and investigate the limitations of this fabrication technique. A schematic of the comblike test structure is shown in Fig. 4.

Arrays of such microstructures were fabricated. The first-layer copper conductors were 100 μm wide and 80 μm tall. Because the second layer of copper is electroplated using the sidewalls of the first-layer conductor, a design with two-finger-like structures was utilized for the first layer. The lateral spacing between these two fingers was 125 μm, and the width of the patterned seed layer varied between 30 and 120 μm [cf. Fig. 2(f)]. Two 800-μm-diameter electrical pads were implemented for resistance and capacitance measurements.

From a fabrication standpoint, it was observed that the seed-layer-patterned narrow combs (30–60μm) were mechanically weak and tended to break or delaminate during the patterning of the seed layer. Oversized combs (100–120μm) were poorly defined because of the thicker spray-coated photoresist near the bottom of the first copper layer [cf. Fig. 2(d)]. This caused nonuniform plating of the second copper layer. Fig. 5(a) shows an optimum seed layer pattern for electrodeposition of the second copper conductor. In this case, the patterned seed layer is 80 μm wide. SEM micrographs of the ultradense comblike test microstructures are shown in Fig. 5(b) and (c). The presented images demonstrate that the fabrication process can be utilized for both straight and curved geometries, validating its suitability for planar spiral coils. For imaging purposes, the parylene layer on top of the first-layer metal microstructures was etched away. However, the insulating gap is still visible and can be seen as a dark line between the copper conductors. Fig. 5(c) shows a close-up view of the conductors separated by the high-aspect-ratio micrometer-sized gap.

B. *Experimental Results*

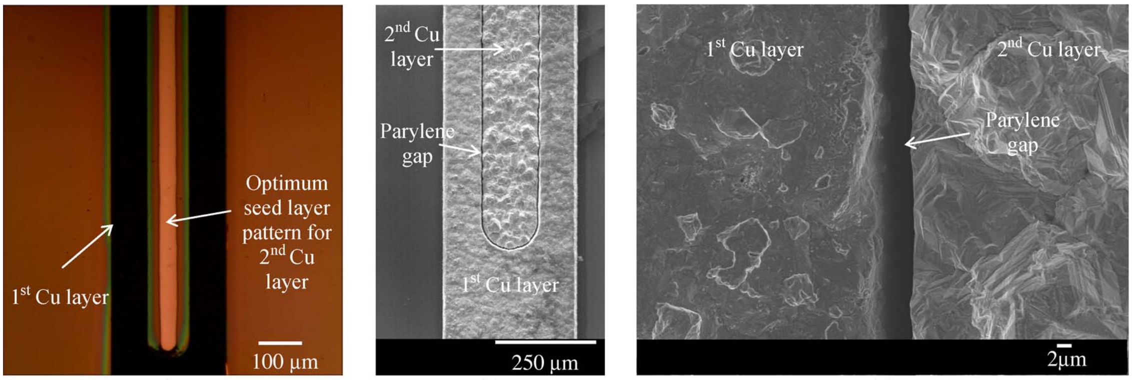
In order to confirm that electrical insulation was achieved, both resistance and capacitance measurements were performed between the first- and second-layer copper conductors using an impedance analyzer. The resistance measurements indicated that there was no electrical connection between the two layers, as the resistance was superior to several megaohms. Using a high-voltage low-current source, the voltage breakdown of the test devices was measured. The results are shown in Fig. 6(a). As expected, the voltage breakdown increases linearly with increasing parylene thickness. The device with a 5-μm-thick parylene layer exhibited a voltage breakdown of approximately 1800 V or 360 V/μm, which is comparable to that in [10].

The capacitance measurement results are shown in Fig. 6(b). As predicted by the theory, the capacitance is inversely proportional to the gap between electrodes. For this device, the gap is defined by the thickness of the parylene layer. This further confirmed that there was a proper electrical insulation between the two copper layers. Experimental results and capacitance calculations were in good agreement. In this calculation, the relative dielectric constant ε_r of parylene C was 3.1 [7]. The area A utilized in the capacitance theoretical calculations corresponded to the measured thickness of the electroplated copper layers multiplied by the length of the capacitor, which, in turn, corresponds to the perimeter of the second copper layer which includes the copper finger and the electrical pad. Second, parylene gaps as small as 1 μm were achieved with these microstructures. It corresponded to an aspect ratio of 1 : 80. This is much higher than the aspect ratio achieved using standard photolithography techniques on thick photoresists.

IV. Ultradense Microcoils

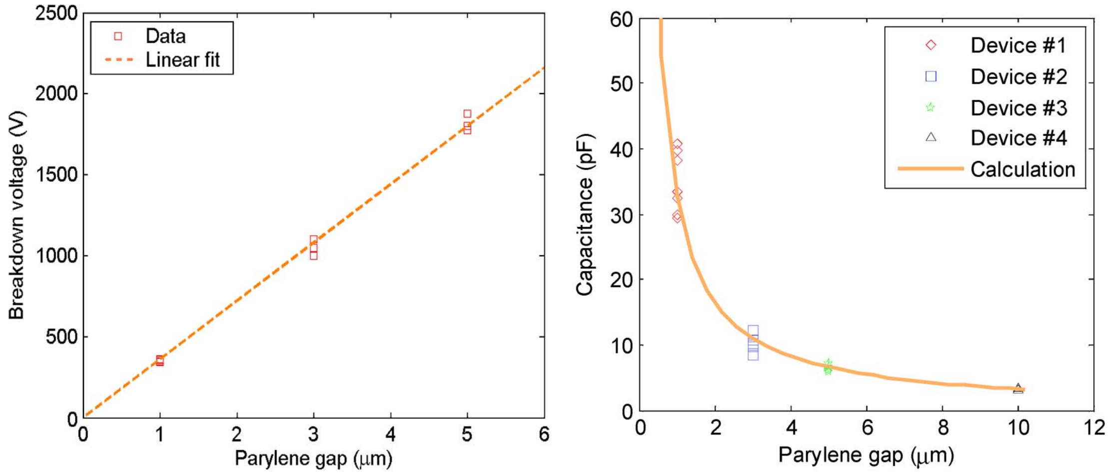
A. *Microfabricated Coils*

Intended to be used as a driving coil in a highly efficient permanent-magnet linear actuator, the dimensions of the



(a) (b) (c)

Fig. 5. Ultradense comblike electroplated test structures. (a) Before and (b) and (c) after plating. (b) and (c) Parylene was removed by plasma etching after the second copper electroplating for imaging purposes.



(a) (b)

Fig. 6. (a) Voltage breakdown and (b) capacitance measurements between the first and second electroplated layers of the comblike structures as a function of the parylene thickness.

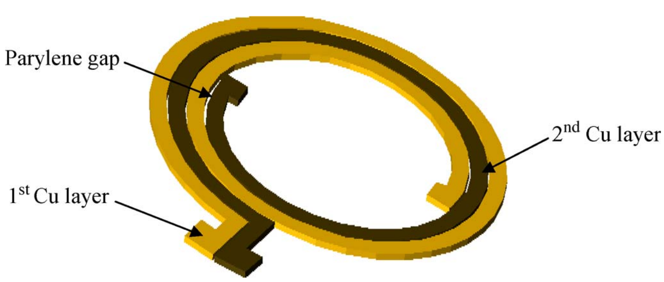


Fig. 7. Rendering of the microfabricated ultradense spiral coil.

ultradense parylene-encapsulated microcoils were set by the application requirements. The inner and outer diameters were 14.6 and 21.5 mm, respectively. The width of the conductors was 100 μm, and the parylene insulation thickness was approximately 5 μm. This corresponded to a spiral coil having two parallel conductors of 16 turns each. The height of the electroplated copper coils was measured at 110–120 μm in average. Fig. 7 shows a rendering of the ultradense spiral coils. As presented, the two conductors run along each other in a parallel fashion. With appropriate wiring, the parallel conductors can be connected in series. The fabrication results are shown in Fig. 8. Fig. 8(c) shows a cross-sectional view of the ultradense conductors. Such a photograph demonstrates that there is no need to achieve perfectly vertical sidewalls in order for this process to work. Using similar cross-sectional views, the measured packing density of the microfabricated planar coil with top and bottom insulation layers was estimated at approximately 88%, which is much higher than that of manually wound conventional coils (Fig. 1).

B. Electrical Characterization

After fabrication, the device consisted of two parallel microcoils that are electrically insulated from each other with individual electrical pads. As a result, the resistance and inductance of each coil, as well as the capacitance between the two conductors, were measured using an impedance analyzer. The results are reported in Table I. The capacitance between the two copper conductors exhibited a value of 530 pF. Based on the measurements of the fabricated copper conductors mentioned in Section IV-A (i.e., coil and parylene thicknesses), a capacitance value of 543 pF was analytically calculated. The theoretical value is in good agreement with the measured data because the discrepancy was less than 5%. The large value is mainly caused by the length of the coil ($\sim$0.9 m for

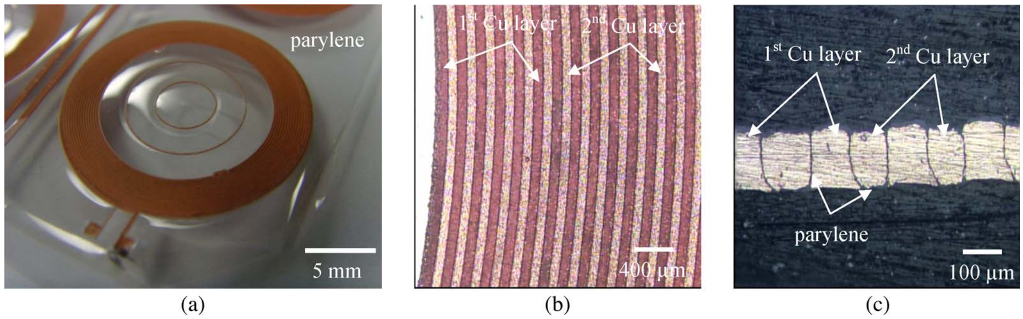


Fig. 8. Images of the ultradense parylene-encapsulated spiral coils. (a) Front side. (b) Close-up view. (c) Cross-sectional view.

TABLE I
ELECTRICAL MEASUREMENTS FOR THE FIRST AND SECOND COPPER COILS

		Calculated	Measured
Resistance *(Ω)*	1st Cu layer	1.3	1.13
	2nd Cu layer	1.4	1.30
Inductance (μH)	1st Cu layer	7.5	7.4
	2nd Cu layer	7.5	7.4
Capacitance (pF)	Between 1st/2nd layer	543	530

each conductor) and the thin parylene insulation layer (several micrometers). The resistance and inductance of each conductor were approximately measured at 1.2 Ω and 7.35 μH at low frequencies, respectively. Analytically, a resistance of 1.3 Ω was calculated using a resistivity of 17.6 n$\Omega \cdot$m, which has been experimentally determined for our copper electroplating solution [9]. In [11], an analytical expression of the inductance of spiral planar inductors was determined using current sheet approximation. The formula, which is reported in (1), relates the inductance to several geometrical parameters, where n is the number of turns, OD is the outer diameter, and ID is the inner diameter

$$L = \frac{\mu_0 \cdot n^2 \cdot \left(\frac{OD-ID}{2}\right)}{2} \cdot \left(\ln\left(2.46 \cdot \left(\frac{OD+ID}{OD-ID}\right)\right) + 0.2 \cdot \left(\frac{OD-ID}{OD+ID}\right)^2\right). \quad (1)$$

Using this equation, the theoretical inductance value was 7.46 μH, which corresponds to less than 2% discrepancy from the measured inductance.

The two parallel spiral microconductors were connected in series by manually soldering short magnet wires onto the appropriate electrical pads. Both the resistance and the inductance were measured as functions of frequency using an impedance analyzer. The results are shown in Fig. 9. At low frequencies, the ultradense coil exhibited a resistance of 2.4 Ω and an inductance of 29 μH. As expected, the dc resistance of the coil goes up by a factor of two when the two interleaved copper layers are connected in series. It is also essential to note that the ultradense coil configuration corresponds to a single inductor with 32 turns, as opposed to two 16-turn inductors connected in series. The reason is that the two copper conductors are interleaved, thus contributing to the same inductor. As a result, the inductance L of the ultradense coil is four times higher than that of the first-layer coil, as predicted by (1), where the inductance varies as the square of the number of turns. The ultradense windings exhibited a self-resonance at 2.65 MHz. The quality factor Q of the inductor reached a maximum value of 57 at 1.15 MHz. At this frequency, the coil resistance and inductance were 4.5 Ω and 35.5 μH, respectively. The calculated parasitic capacitance Cp corresponded to a 530-pF value. Although this ultradense coil has been designed to operate in the 50–400 Hz frequency range, thus not accounting for the inductance due to a negligible inductive reactance compared to the resistance of the coil, this experimental characterization provides insights for the design selection of high-frequency ultradense inductors. Near an operating frequency of 1 MHz, the coil suffers from eddy current and proximity losses, as a result of which the ac resistance increases by 85% compared to the dc resistance. Furthermore, the parasitic capacitance is large because of the high coil packing density and thin insulation layer, thus decreasing the inductor resonant frequency. For higher operating frequencies, thicker parylene layers or air gaps should be used to minimize the capacitance between neighboring turns.

V. 3-D ULTRADENSE COILS

Three spiral planar coil structures were also designed and fabricated to demonstrate the multilayer folded coil concept, as shown in Fig. 10. Note that the dimensions and the number of turns were modified for better clarity of the schematic. In this initial experiment, the dimensions and parameters of the three coils were similar to the ones presented before. The three first-layer coil structures were connected in series by soldering electrical pads from one structure to the other one. The same process was applied to the second-layer coils. Finally, the two copper layers were connected to each other.

First, the resistances of the six planar coils were measured, as shown in Table II. The results confirmed that the two layers of ultradense conductors were correctly insulated throughout the entire device. Once the three planar coils were folded and electrically connected to each other, a total resistance of approximately 14.6 Ω was measured for this 96-turn microcoil. This compared favorably with calculations, as shown in

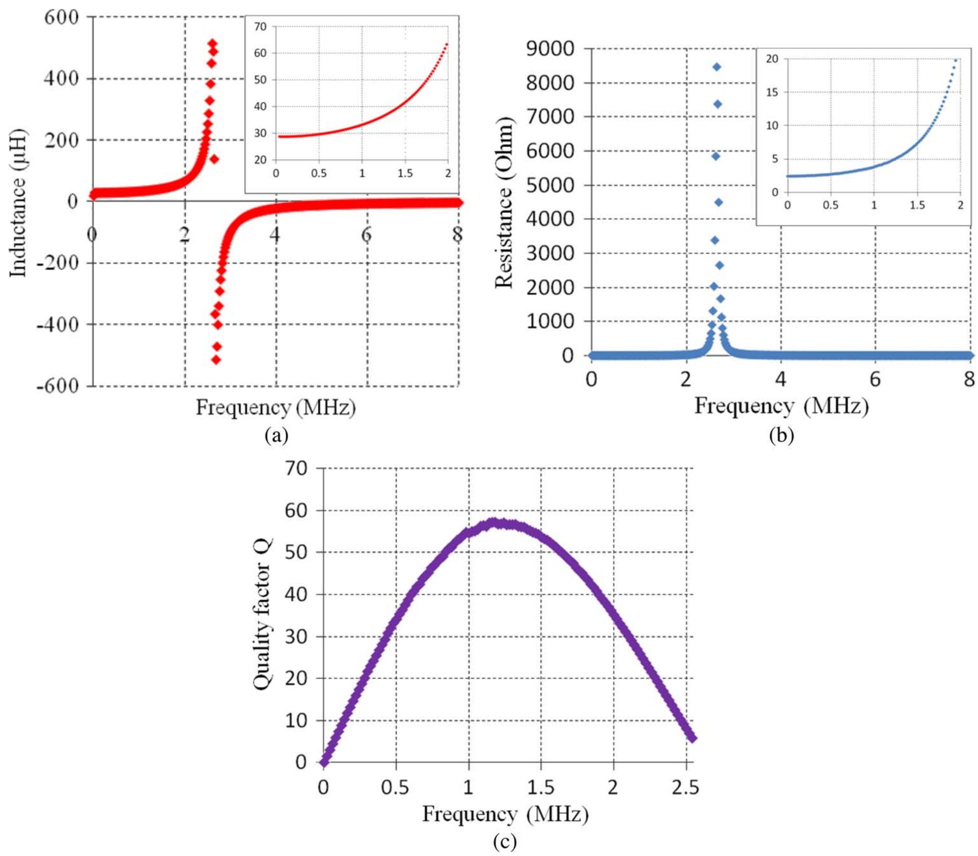


Fig. 9. Impedance characterization of ultradense parylene-encapsulated microcoils. (a) Inductance. (b) Resistance. (c) Quality factor as a function of frequency.

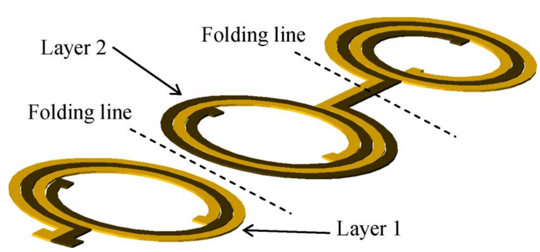


Fig. 10. Three-dimensional conceptual rendering of an ultradense three-layer spiral coil structure before folding.

TABLE II
RESISTANCE MEASUREMENTS AND CALCULATIONS OF THE 3-D ULTRADENSE COILS BEFORE AND AFTER FOLDING

	Resistance (Ω)	
	Calculated	Measured
Single-coil structures (before folding)	2.6	2.4-2.5
3-D folded windings	15.6	14.6

Table II, validating the design of the coil interconnects, as well as suitable insulation of the winding turns.

For comparison, calculations were made with a similar coil using conventional magnet wire with a comparable number of turns, similar copper coil cross-sectional area, and identical inner diameter. Based on [1], it corresponded to a cylindrical magnet wire with an overall diameter of 121 μm and a 100-μm-diameter copper wire. The winding volumes for the MEMS-enabled and conventional coils were 52.8 and 81.6 mm^3, respectively. Consequently, the MEMS-fabricated ultradense coils exhibited a 65% improvement over the conventional wire-wound coils in packing density.

VI. SUMMARY AND CONCLUSION

We have demonstrated the fabrication of microcoils with packing densities higher than that of conventional magnet wires. The approach relied on the conformal deposition of a thin insulation layer onto a first layer of copper conductors, followed by copper filling of the gap in between these conductors. To demonstrate the conception of ultradense microcoils, series of 100-μm-wide and 80-μm-tall insulated copper conductors were fabricated on a rigid substrate with a gap as small as 1 μm between neighboring conductors. Both the capacitance and the breakdown voltage were measured. The data, which varied depending on the insulation layer material and thickness, were in good agreement with previously reported measurements. Flexible arrays of 2-D spiral coils with a 5-μm-thick insulation layer were also fabricated and experimentally characterized. DC resistance measurements have confirmed the proper fabrication and insulation of the windings. At high frequencies, the coil exhibited a self-resonance at 2.65 MHz. This was due to the large parasitic capacitance during neighboring turns. Furthermore, a 3-D coil device, which consisted of multiple planar coils folded on top of each other, was fabricated. Such devices are suitable for high-current, low-voltage, and low-frequency applications. The fabrication concept could ultimately be applied to other types of applications, such as coil laminations, to reduce eddy current losses, magnetic laminations, or nonplanar capacitors.

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