

MICROFABRICATED, ULTRA-DENSE, THREE-DIMENSIONAL METAL COILS

F. Herrault^{1}, S. Yorish², T. Crittenden², and M.G. Allen¹*

¹Georgia Institute of Technology, Atlanta, Georgia, USA

²Virtual AeroSurface Technologies, Atlanta, Georgia, USA

ABSTRACT

This paper focuses on the fabrication of three-dimensional 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 vapor-deposited parylene layer, and subsequent electrodeposited metal filling between the first-layer conductors. The windings are microfabricated as an array of two-dimensional coils, which are later released from the substrate, folded and electrically connected to form a three-dimensional coil device. The MEMS-fabricated, ultra-dense coils exhibited a 62% improvement in packing density over conventional wire-wound coils.

KEYWORDS

Micro-coils, chemical vapor deposition, parylene, high aspect ratio, metal MEMS

INTRODUCTION

In highly-efficient high-current devices, it is desirable to produce winding coils with maximal packing density (i.e., percentage of copper per unit volume). Consequently, it is required to not only control the geometric shape and alignment of the individual conductors, but also to minimize the insulation surrounding each conductor. Unlike conventional wire wrapping, in which cylindrical wires are stacked in a relatively inefficient fashion, and where insulation thickness (for fine magnet wire) is on the order of the thickness of the conductor itself, MEMS fabrication techniques offer the possibility of an efficient and controlled stacking, as well as ultra-thin, vapor-deposited insulation layers. Figure 1 compares the packing density of conventionally-wrapped magnet wires [1], with that of square coils insulated with a thin layer of non-conductive material. The use of this approach 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 thickness of the insulation layer. In many high-current, low-voltage magnetics applications, such considerations are essential to improving coil performance, and thus the overall efficiency of the device.

In this paper, we present a MEMS-enabled approach to fabricate such three-dimensional micro-coils with high-aspect-ratio electroplated conductors exhibiting micron-sized interconductor gaps. An 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 the chemically vapor-deposited insulation material [2, 3]. Moreover, the fabrication of three-dimensional 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. An alternative approach is proposed, and consists of fabricating two-dimensional arrays of copper coils on a planar and rigid substrate, followed by the release, and folding of these microstructures to form a three-dimensional coil device. The polymer material provides electrical insulation as well as mechanical support between the multiple layers of copper windings.

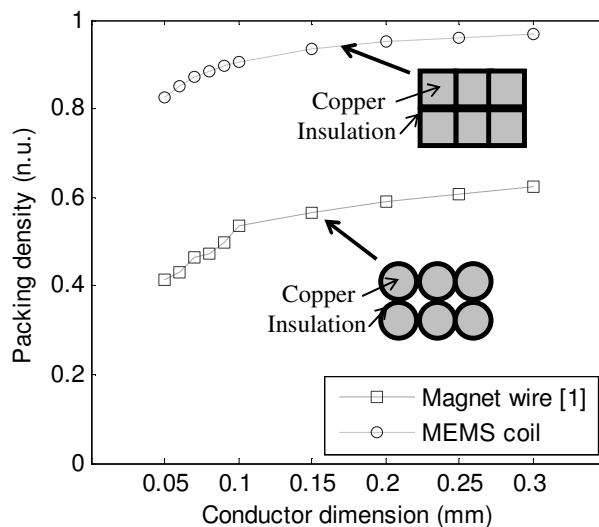


Figure 1: Packing density as a function of the conductor dimensions calculated over an array of conductors. The round magnet wires have standard insulation [1], while the MEMS-fabricated square coils have a 5- μ m-thick parylene insulation.

FABRICATION CONCEPT

The fabrication of three-dimensional, ultra-dense micro-coils relies on the conformal deposition of thin layers of parylene insulating material onto non-planar metal microstructures, followed by copper filling, and subsequent release and folding of the windings. The fabrication process flow is shown in Figure 2.

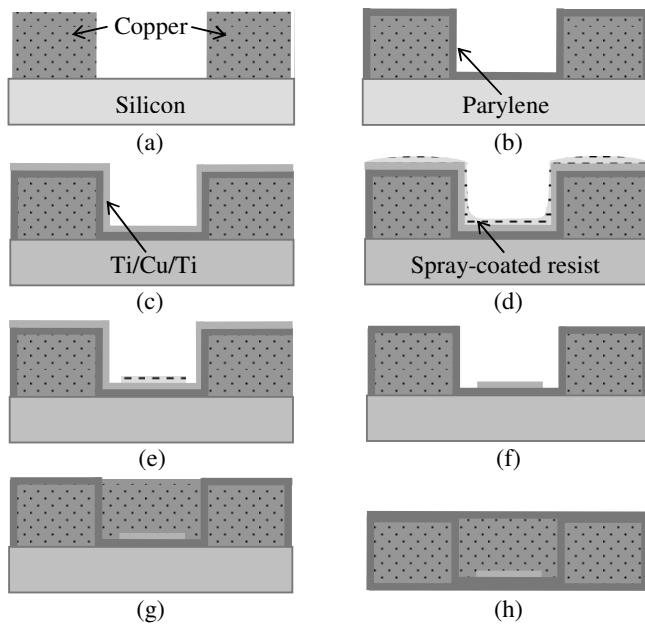


Figure 2: Fabrication process flow of ultra-dense micro-coils: (a) Standard through-resist mold electroplating, (b) Parylene insulation, (c) Spray coating of negative-tone photoresist, (d) Photoresist patterning, (e) Seed layer patterning, (f) Second electroplating sequence, (g) Release and insulation of the fabricated coils.

The process starts with the deposition of a Ti/Cu/Ti (20/300/20 nm) seed layer onto an oxidized silicon substrate. Using standard plating-through-resist techniques, a first layer of copper conductors is formed, as shown in Figure 2(a). The photoresist mold is removed by acetone, while the layers of titanium and copper are etched away using diluted hydrofluoric acid, and a solution of ammonium hydroxide saturated with copper sulfate, respectively. As depicted in Figure 2(b), the metal lines are then coated with a vapor-deposited insulating material such as parylene C. This material provides excellent conformal deposition and pin-hole-free films [4]. Next, a second Ti/Cu/Ti seed layer is deposited, as represented in Figure 2(c). Using a manual spray-coating technique [5], a negative-tone photoresist layer (NR9-8000P, Futurrex) is subsequently formed onto the microstructures. The negative photoresist is first diluted using cyclohexanone, which is the principal solvent contained in the photoresist (1:1 weight ratio). This decreases the resist viscosity and facilitates the spray-coating. Although it is difficult to achieve a conformal photoresist layer onto non-planar topographies using spin-coating, a thickness-controlled photoresist layer can be achieved at the bottom of such micro-trenches using spray-coating technology [5]. In order to obtain the desired thickness, multiple coatings are necessary. Using a dark-field photomask, the photoresist layer is patterned so that the mold remains between the copper structures, as shown in Figure 2(e). Next, the seed

layer is patterned by wet etching. Although this is not represented in Figure 2(f), the patterned seed layer is continuous, enabling the electrodeposition of a second sequence of copper conductors, as indicated in Figure 2(g). The first layer of insulated metal structures is used as a plating mold, which results in insulated metal lines spaced by the thickness of the vapor-deposited material on the order of several microns or less. The ultra-dense metal microstructures are now fabricated. Next, the structures are released from the rigid substrate by under-etching the silicon oxide layer in hydrofluoric acid. Finally, both surfaces are insulated with another layer of parylene material, as depicted in Figure 2(h). Such a process creates a flexible array of ultra-dense two-dimensional coils. The structures are then folded together, and electrically connected to form three-dimensional micro-coils. The folding concept is schematized in Figure 3.

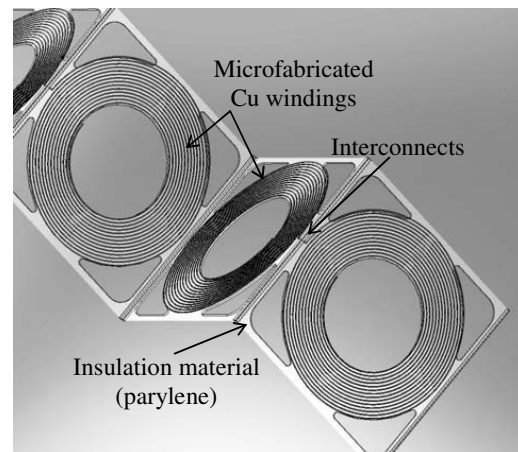


Figure 3: Rendering of the folding concept to create 3-D MEMS-based coils from a flexible array of planar microfabricated windings.

ULTRA-DENSE MICRO-COIL TEST STRUCTURES

Design and Fabrication

Comb-like test structures were designed and fabricated in order 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 so as to increase the copper packing density, and investigate the limitations of this fabrication technique. A schematic of the comb-like test structure is shown in Figure 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 fingers-like structures was

utilized for the first layer. The lateral spacing between these two fingers was $125\text{ }\mu\text{m}$, and the width of the patterned seed layer varied between 30 and $120\text{ }\mu\text{m}$ (cf. Figure 2(f)). Two $800\text{-}\mu\text{m}$ -diameter electrical pads were implemented for resistance and capacitance measurements.

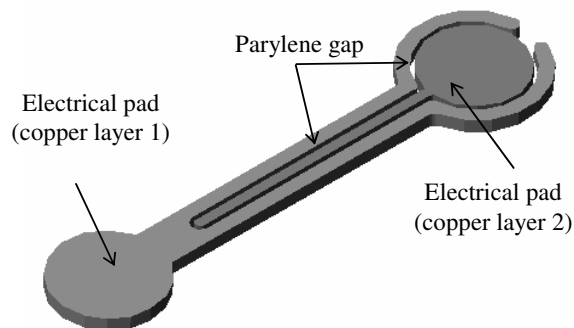


Figure 4: Rendering of the comb-like test structure.

From a fabrication standpoint, it was observed that the seed-layer-patterned narrow combs ($30\text{-}60\text{ }\mu\text{m}$) were mechanically weak, and tended to break or delaminate during the patterning of the seed layer. Oversized combs ($100\text{-}120\text{ }\mu\text{m}$) were poorly defined because of the thicker spray-coated photoresist near the bottom of the first copper layer (cf. Figure 2(d)). This caused non-uniform plating of the second copper layer. Figure 5(a) shows an optimum seed layer pattern for electrodeposition of the second copper conductor. In this case, the patterned seed layer is $80\text{ }\mu\text{m}$ wide. A SEM micrograph of the result after electroplating is presented in Figure 5(b). 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. The inset depicts a close-up view of the conductors separated by the thin layer of parylene.

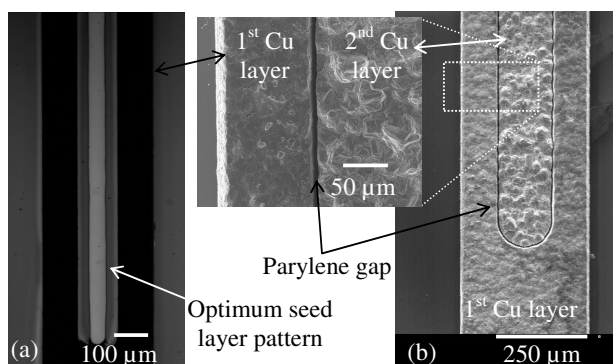


Figure 5: Ultra-dense, comb-like, electroplated test structures: (a) before, and (b) after plating. The inset shows a close-up view of the gap between two conductors.

Experimental Results

In order to confirm that electrical insulation was achieved, both resistance and capacitance measurements were performed between the first-layer 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 $\text{M}\Omega$. Using a high-voltage, low-current source, the device insulated with a $5\text{-}\mu\text{m}$ -thick parylene layer exhibited a voltage breakdown of approximately 1800V , or $360\text{ V}/\mu\text{m}$, which is comparable to [6]. The capacitance measurement results are presented in Figure 6. As expected by the theory, the capacitance is inversely proportional to the parylene gap. This further confirmed that there was a proper electrical insulation between the two copper layers. Experimental results and capacitance calculations are in good agreement. Secondly, parylene gaps as small as $1\text{ }\mu\text{m}$ 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.

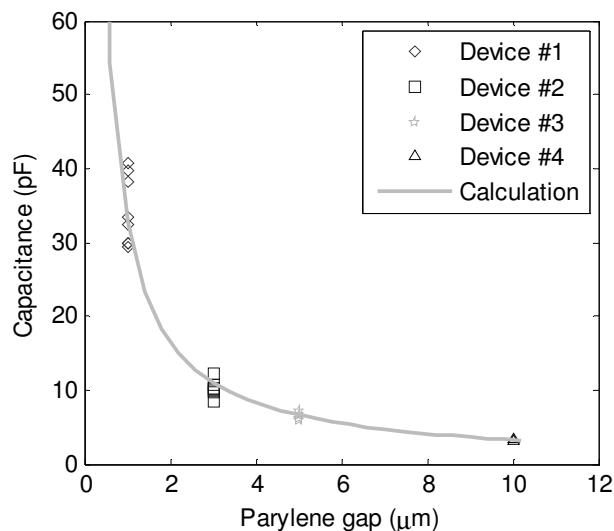


Figure 6: Capacitance measurements between the first and second electroplated layers of the comb-like structures as a function of the parylene thickness.

3-D ULTRA-DENSE COILS

Three spiral planar coil structures were also designed and fabricated to demonstrate the multi-layer folded coil concept, as illustrated in Figure 7. Note that the dimensions and the number of turns were modified for better clarity of the schematic.

In this initial experiment, the copper conductors were $80\text{ }\mu\text{m}$ thick, and the parylene insulating layer was of a thickness of $5\text{ }\mu\text{m}$. The inner and outer diameters of each coil structure were 13.7 mm and 17.8 mm , respectively. Ten turns per coil and per copper layer were designed,

which corresponded to a total of 60 turns electrically connected in series. 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.

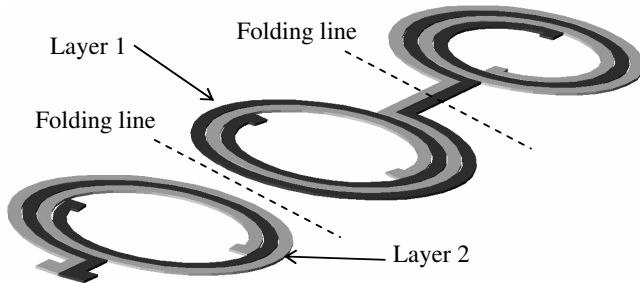


Figure 7: Three-dimensional conceptual rendering of an ultra-dense three-layer spiral coil structure before folding.

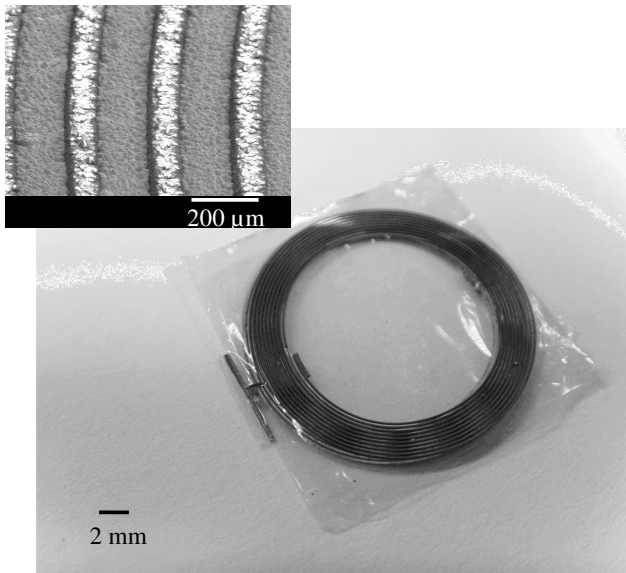


Figure 8: Three-dimensional folded windings from three planar coils. The inset shows a close-up view of ultra-dense multi-turn coils.

First, the resistances of the six planar coils were measured, as indicated in Table 1. The results confirmed that the two layers of ultra-dense 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 5 Ω was measured for this 60-turn micro-coil. This compared favorably with calculations as shown in Table 1. This validated 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 and the same copper volume. 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 the conventionally-fabricated coils were 27.4 mm^3 and 44.5 mm^3 , respectively. Consequently, MEMS-fabricated, ultra-dense coils exhibited a 62% improvement over conventional wire-wound coils in packing density.

Table 1: Resistance measurements and calculation of the microfabricated ultra-dense coils before and after folding.

	Resistance (Ω)	
	Calculated	Measured
Single-coil structures	0.75	0.79 - 0.84
3-D folded windings	4.6	5.04

SUMMARY AND CONCLUSION

We have introduced the fabrication of three-dimensional coils with high packing density using MEMS technologies. To demonstrate the conception of ultra-dense micro-coils, 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. Flexible arrays of two-dimensional spiral coils with a 5- μm -thick insulation layer were also fabricated, and followed by substrate release, coil folding and electrical connections to form a three-dimensional coil device suitable for high-current, low-voltage applications. The fabrication concept could be applied to other areas such as magnetic laminations, or non-planar capacitors.

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CONTACT

* F. Herrault, tel:+1-404-894-9909; fh59@mail.gatech.edu