MICROFABRICATION OF AIR-CORE TOROIDAL INDUCTOR WITH VERY HIGH ASPECT RATIO METAL-ENCAPSULATED POLYMER VIAS

J.K. Kim, F. Herrault, X. Yu, and M.G. Allen
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA, USA

Abstract: This paper presents a very high aspect ratio metalized polymer via approach for the realization of microfabricated toroidal inductors with large magnetic cross-section. The inductor consists of lower and upper radial conductors formed from solid electroplated metal, and vertical via interconnections formed by photosensitive epoxy polymer cores bearing electroplated metal on their surfaces. An approach to enhance the lithographic performance of these epoxy materials is implemented in which an acrylic filter is used to remove wavelengths shorter than h-line (405 nm) from impinging on the epoxy. This filtering approach significantly improves the achievable aspect ratio. Utilizing this process, together with an SU-8 dry film resist, arrays of 1000 µm tall micropillars with 30 µm typical lateral feature size are uniformly fabricated. Based on this approach, 70-turn toroidal inductors are successfully fabricated and characterized. The fabricated devices had inductances of 660 nH in the frequency range of 0.1~100 MHz, AC resistance of 1.6 Ω at 0.1 MHz, and quality factor of 19 at 50 MHz.

Keywords: Microfabricated toroidal inductor, very high aspect ratio, Micropillar array, SU-8 dry film

INTRODUCTION

As inductors are often the single largest components in switching converter systems, reduction of inductor size is essential for the continued miniaturization of these systems. Although higher converter operating frequency typically reduces the required inductance value and therefore the number of turns and/or the inductor size, very high frequency operation can often result in higher system losses [1]. As a result, the operating frequency of most commercial switching converters is typically in the range of 0.5-10 MHz. Miniaturized inductors, therefore, with sufficient inductance and power handling capability in the range of 0.5-10 MHz are of great interest [2, 3]. However, the challenge is to achieve higher degrees of miniaturization in this frequency range without sacrificing performance.

Microfabrication of inductors may enable not only physical size reduction but also reduced parasitics and the ability to integrate these devices with other microfabricated devices on a single chip or substrate. Microfabricated toroidal inductors are appealing due to the geometric confinement of the generated magnetic flux within the windings, potentially resulting in reduced electromagnetic interference (EMI) [4] and low induced losses in the substrate [5,6]. However, a microfabrication challenge for this geometry is to achieve a substantial cross-sectional area for flow of the magnetic flux, as this area is defined in part by the height of the inductors.

Previously reported miniaturized toroidal inductors have achieved significant cross-sectional areas by exploiting heights in the 100 ~ 500 micron range by using various available microfabrication technologies [6-8]. However, larger height extents would lead to higher inductances. In addition to total height, aspect ratio must also be considered, as higher aspect ratios can potentially lead to a larger number of turns in a given area. Recent microfabrication study based on lithographic patterning of cast SU-8 resist to realize high aspect ratio structures have been reported, including a fabrication method utilizing exposure wavelength selection with an acrylic filter [9]. In that work, total thicknesses of 1000 µm and aspect ratios of almost 100:1 could be achieved. However, the use of these resists typically requires extremely long softbaking time (15 ~ 30 hours), and significant care must be taken to avoid coating non-uniformity in practical applications.

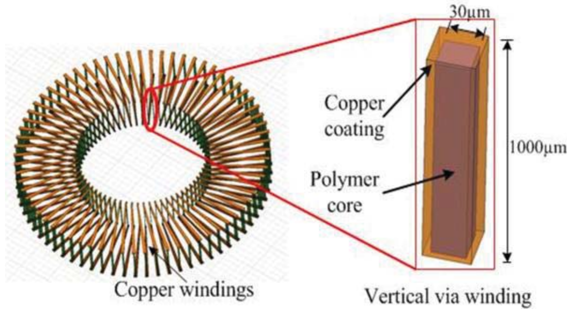


Fig. 1: Schematic diagram of a 70 turn toroidal inductor and a metalized polymer via comprising a vertical winding segment of the inductor.

The conventional approach to vertical winding fabrication in toroidal inductors would entail the deposition of an electroplating mold with a trench via, followed by electroplating to fully fill the via. A very thick plating mold is thus required to increase the height of the inductor. Such high aspect ratio, thick (~ 1000 μm) trench or via molds are more difficult to fabricate than their high aspect ratio pillar complements, due to lithographic and development nonidealities such as optical diffraction and resist swelling. Even if such high aspect ratio trenches could be achieved, the long softbaking time for such thick resists is still an issue. Also, even if by sacrificing lithographic resolution and enduring very long softbaking times suitable trench via molds can be achieved, a long electroplating time must still be endured to completely fill the molds with metal. Further, electroplating through thick molds often requires substantial optimization to achieve plated structures of uniform thickness over a large substrate area.

In this work these issues are addressed by introducing a pillar mold instead of a trench mold to form the vertical vias, and by adopting an SU-8 dryfilm process for the pillar fabrication to eliminate the long softbaking time. The relatively long electroplating time required to fill trenches is then replaced by a relatively short electrodeposition that occurs everywhere on the external surface of the conductor. This external pillar plating approach has been successfully implemented previously for RF inductors [10].

Based on the above process, a 70-turn densely-wound toroidal inductor is microfabricated. In this inductor, the lower and upper radial conductors are formed by solid electroplated metal, and the vertical via interconnections are formed by polymer cores with electroplated metal layers on their surfaces as shown in Figure 1.

DESIGN AND FABRICATION

Inductor design

The inductor has 70-turn windings with an inner diameter of 4 mm and an outer diameter of 8 mm. An interwinding spacing of 100 μm has been chosen in part to accommodate the constraints of proximity lithography on highly nonplanar surfaces. The bottom and top windings are solid electroplated metal and the vertical windings are metal-encapsulated polymer vias as discussed above. The thickness of the bottom and top metal windings is chosen to be 30 μm, given the skin depth of copper at the operating frequencies of interest.

The calculated inductance of the toroidal inductor is approximately 650 nH from the equation as following:

$$L = \mu \frac{N^2}{l} A \qquad (1)$$

where L, μ, N, l , and A are inductance, permeability, number of windings, average toroidal inductor length, and cross-sectional area of the winding, respectively.

Inductor fabrication

The overall sequence of the inductor microfabrication is described in Figure 2. The first fabrication step involves forming the pillar arrays that will comprise the vertical windings. This is achieved by adopting an SU-8 dry film process and acrylic UV filtering exposure method, coupled with backside exposure. An SU-8 dry film (SUEX 1000, DJ DevCorp.), 1000 μm in thickness, is placed on a chromium- patterned glass substrate, and then bonded on a hot plate at 60°C for 3 minutes. The film is exposed through the glass and patterned chromium layer using a backside exposure scheme. A 0.22 inch-thick acrylic board (G11, Professional Plastics, Inc.) is used as a UV filter which blocks wavelengths shorter than 400 nm. A UV light intensity of 35 mW/cm^2 at 405 nm was applied with an exposure dose of 18 J. A post-exposure bake is performed at 95°C for one hour on a hot plate, followed by development using PGMEA (Propylene Glycol Methyl Ether Acetate) for 40 minutes (Figure 2a). The pillar array is metalized using sputtered titanium and copper (Fig. 2b), followed by spray-coating with negative photoresist (NR9-8000, Futurrex, Inc.) and patterning using proximity UV lithography to form an electroplating mold for the bottom and vertical windings (Fig. 2c).

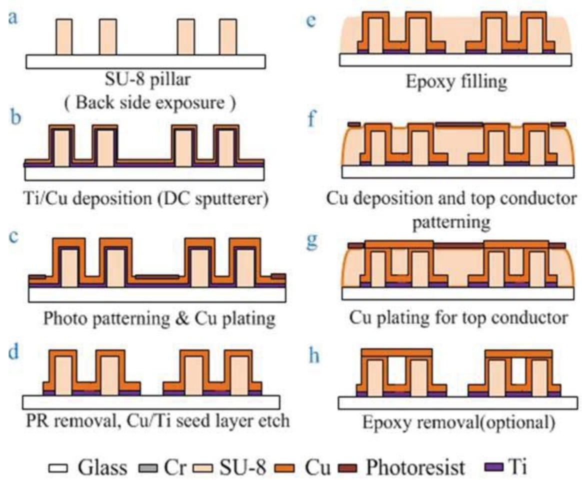


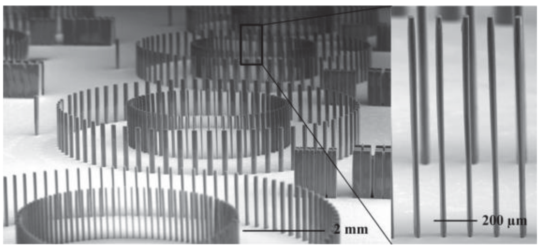
Fig. 2: Fabrication process of the toroidal inductor.

The bottom and vertical windings are simultaneously formed by 30 µm-thick copper electrodeposition, followed by photoresist mold removal and seed layer etch (Fig. 2d). A solid SU-8 epoxy without crosslinker (EPON SU-8, Momentive Performance Materials Inc.) is melted into the structure and re-solidified to fill the volume of the inductor and provide a foundation for the formation of the upper windings (Fig. 2e). The top conductors are copper-plated through a photoresist mold (Fig. 2f and 2g), and the PR mold, the copper seed layer and the SU-8 epoxy are removed (the epoxy removal being optional) (Fig. 2h).

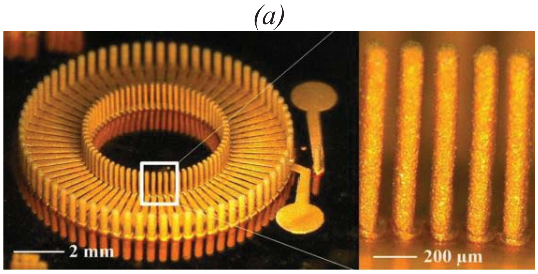
RESULTS

Fabrication results

The scanning electron microscopy (SEM) image of a micropillar array is shown in Figure 3a. More than 1000 micropillars are uniformly fabricated with 1000 µm height and 30 µm lateral feature size. The inset of Figure 3a shows a magnified view of the fabricated SU-8 pillars with an aspect ratio of approximately 33. Figure 3b shows the bottom and vertical windings of the inductor after simultaneous Cu-electroplating where the electroplated copper thickness is approximately 30 µm. The inset of Figure 3b shows a magnified view of the uniform Cu electrodeposition on the vertical SU-8 pillars. Fully microfabricated air-core inductor is shown in Figure 4. Two electrical pads are formed with the inductor for ease of potential integration to other circuitry as well as ease of characterization.



(a)



(b)

Fig. 3: Partially completed samples at selected steps: (a) Very high aspect ratio pillar array (1000µm tall 30µm feature size), (b) Cu plated vertical and bottom windings.

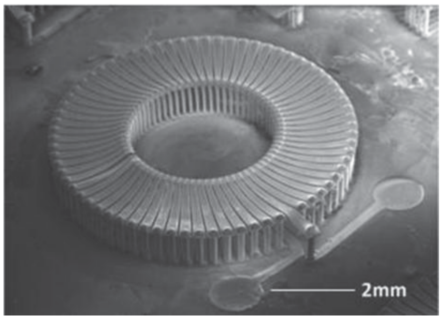
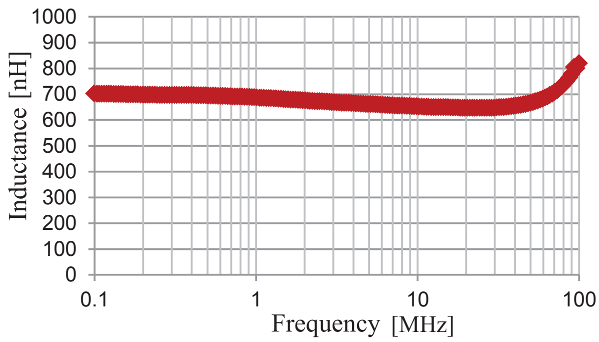


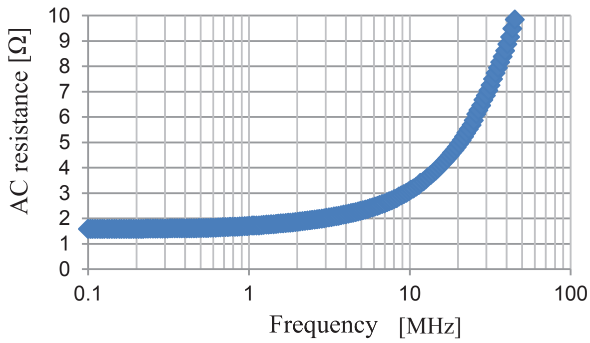
Fig. 4: SEM image of microfabricated 70 turn toroidal inductor.

Inductor characterization

The microfabricated inductors have been electrically characterized by an impedance analyzer (HP4194) in terms of inductance, resistance, and quality factor as a function of frequency as shown in Figure 5 and Figure 6. An average inductance of approximately 660 nH was measured in the frequency range of 0.1 to 50 MHz as shown in Figure 5a. At higher frequencies, a resonant behavior was observed. The inductor resistance, shown in Figure 5b, measures approximately 1.6 Ω at 0.1 MHz. The quality factor is plotted in Figure 6 and increases with frequency up to 50 MHz. At this frequency, the quality factor reaches 19.



(a)



(b)

Fig. 5: Characterization results of fabricated inductor: (a) Inductance, (b) AC resistance.

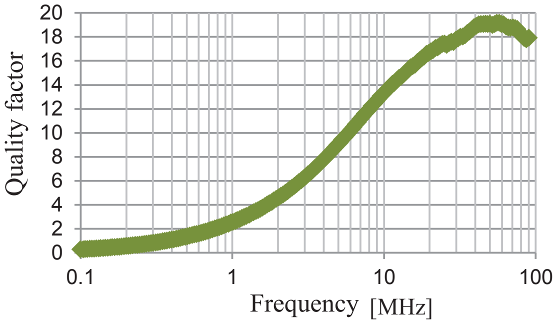


Fig. 6: Characterization results of fabricated inductor: Quality factor.

CONCLUSION

A fabrication process for 3-D, densely wound, toroidal inductors with substantial height and large magnetic cross-section has been demonstrated. This process has the advantage of being relatively simple with reduced processing time compared to the traditional plate-through-mold approaches. In particular, a dry film resist process assisted with an acrylic UV filter for the vertical pillar fabrication enabled the fabrication of thousands of millimeter-tall uniform pillars, avoiding 15-30 hour-long softbaking times. A metal encapsulated polymer via design, which exploited simultaneous metallization on the bottom and vertical windings, also replaced a relatively long bottom-up electroplating step with a relatively short coating electroplating step. Non-photosensitive SU-8 pellets served as a thick sacrificial layer allowing a successful top winding fabrication. The capability of the process has been demonstrated through the fabrication of 70-turn toroidal inductors. The fabricated inductor demonstrated inductances of 660 nH in the frequency range of 0.1 ~100 MHz, AC resistance of 1.6 Ω at 0.1 MHz, and maximum quality factor of 19. The micromachined air-core inductors with high inductance values are potentially suitable for the chip scale power converters operating in the tens of MHz frequency range.

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REFERENCES

[1] Musunuri S., Chapman P. L. 2002 Optimization Issues for Fully-Integrated CMOS DC-DC Converters, *Proc. Conf. Record IEEE Industrial Applications Society Annu. Conf., 2002, pp. 2405–2410.*

[2] Malkinski L., 2012 Advanced Magnetic Materials, *In Tech. ISBN 978-953-51-0637-1.*

[3] O'Donnell T., Wang N., Brunet M., Roy S., Connell A., Power J., O'Mathuna C., McCloskey P., 2008 Thin-Film-Integrated Power Inductor on Si and Its Performance in an 8-MHz Buck Converter, *Transactions on Magnetics, **vol. 44**, NO. 11, pp. 4096 – 4099.*

[4] Cheng K. W. E, Evans P. D., 1994 Calculation of winding losses in high-frequency toroidal inductors using single strand conductors, *IEE Proceedings - Electric Power Applications, **vol. 141**, 2, pp. 52-62.*

[5] J. Phinney, J. Lang, and D. Perrault, Multi-resonant microfabricated inductors and transformers, *IEEE 35th Annual Power Electronics Specialists Conference (PESC), **vol. 6,** June 2004, pp. 4527 – 4536.*

[6] Yu X. Araghchini M., Herrault F., Kim J. K., Lang J. H., Allen M. G. 2012 Fabrication, Modeling, and Performance analysis of Silicon embedded 3-D Toroidal inductors, *PowerMEMS 2012.*

[7] Yu X., Kim M., Herrault F., Ji C.-H., Kim J., Allen M., 2012 Silicon-embedded 3D toroidal air-core indctor with through-wafer interconnect for on-chip integration, *MEMS 2012. France, Paris, pp. 325 – 328.*

[8] Hahn R., Krumbholz S, Reichl H.,Izm F., 2006 Low Profile Power Inductors Based on Ferromagnetic LTCC Technology, *Electronic Components and Technology Conference pp. 529-533.*

[9] Yang R., Wang W., 2005 A numerical and experimental study on gap compensation and wavelength selection in UV-lithography of ultra-high aspect ratio SU-8 microstructures, *Sensors and Actuators B, **vol.110**,pp. 279–288*

[10] Yoon Y.-K., Park J.-W., Allen M. G., 2005 Polymer-core conductor approaches for RF MEMS, *Journal of Microelectromechanical Systems **vol. 14**, no. 5. pp. 886-894.*