# On-chip 3D air core micro-inductor for high-frequency applications using deformation of sacrificial polymer

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## ABSTRACT

A novel on-chip 3D air core micro-inductor, utilizing deformation of sacrificial thick polymer and conformal photoresist electrodeposition techniques, is reported. The bottom conductors are formed on silicon or glass substrate by metal electroplating through SU-8 polymeric mold. A thick SJR 5740 photoresist is then spun on and patterned to be a supporting mesa. Hard curing of such polymer mesa could significantly deform it into a cross-sectional bell-shape sacrificial core with graded profile in which is used to support top conductors formation. A layer of conformal electrodeposited photoresist (PEPR 2400) is then coated along the core's surface profile, patterned by standard optical lithography and filled up by metal electroplating. Finally, all polymeric molds including significantly deformed sacrificial core and electroplating bases are removed, resulting in an on-chip solenoid-type 3D air core micro-inductor. Since this new inductor has an air core and has only two contact points per turn, the core loss and equivalent series resistance are expected to be small, and hence, to give higher quality factor at high-frequency operation. Currently, high-frequency characterization of this on-chip inductor is under way.

**Keywords:** Inductor, RF, MEMS, on-chip, high-Q, air core, wireless, polymer

## 1. INTRODUCTION

Wireless communications including mobile personal communication devices, global positioning systems (GPS) and wireless computing are advancing very rapidly in modern societies. Because of the growing demand of wireless applications but limited resources, very selective, low-noise radio transceivers operated at higher frequencies are desirable. In order to achieve these high performance RF circuits, passive components such as inductors and capacitors need high quality factor (high-Q), high self-resonant frequency (SRF) and low insertion loss. Currently, many off-chip discrete passive elements are widely used as key components to meet these requirements. Due to problems in packaging complexity, large final system area and increasing cost in systems utilizing off-chip passive components, there have been many investigations to realize high performance on-chip passive components which are monolithically integrated with active circuitry. Such monolithically integrated on-chip components are very beneficial in many aspects but yet technically challenging.

Since GaAs substrate has semi-insulating characteristic and high mobility, GaAs monolithic microwave integrated circuit (MMIC) technologies are widely used for monolithic RF and microwave circuits where planar spiral inductors could be integrated on-chip to give acceptable performance[1]. On the other hand, modern silicon technologies provide high-performance active devices with high enough operating frequency, but integration of planar spiral inductors on silicon substrate usually suffers performance degradation from lower self-resonant frequency and quality factor. Due to its planar structure, spiral inductor has large parasitic capacitance to silicon substrate and is likely to have low self-resonance frequency. In addition, the magnetic flux along the center of the coil (passing perpendicularly into the substrate) causes substrate loss due to eddy current. These effects reduce the Q-factor of integrated planar spiral inductors[1-6]. There have been efforts to increase Q-factor and self-resonant frequency of on-chip inductors on silicon substrates in many ways including the use of low resistivity conductor such as copper for equivalent series resistance reduction, the use of low-loss substrate or high-resistivity materials such as high-resistivity silicon (HRS), thick polyimide on silicon[1], the use of thick buried oxide (SOI)[5], and silicon on sapphire (SOS)[6]. Other solutions include partial removal of the substrate underlying the inductor[2], insertion of perforated ground plate beneath the inductor[3], and increasing the space between the inductor and silicon substrate using insulative materials[4] or air by sacrificial layer etching[7]. Spiral inductors with a Q-factor of up to 40 at 5.8 GHz have been demonstrated using copper on sapphire configuration[6] while most integrated inductors give Q-factors below 20.

Recently, endeavors to minimize the size of inductors occupied on the substrate area as well as the reduction of substrate parasitic capacitance paved the ways toward three-dimensional on-chip solenoid-type micro-inductors[7-10]. In comparison to planar spiral inductors, 3D solenoid inductors have less substrate parasitic capacitance since only partial parts of the coil, the bottom conductors, are facing or touching the substrate. In addition, 3D solenoid inductors have significantly less eddy current induced substrate loss than planar spiral inductors since the core center is in the direction parallel to the substrate. Furthermore, core-loss can be minimized using low loss-tangent core such as alumina. An alumina core solenoid inductor with Q-value of 30 at 1 GHz has been realized for a low-noise RF voltage-controlled oscillator[8].

Due to the loss-free nature of the air, with a goal of achieving high Q-factor inductors, a variety of solenoid 3D air core on-chip inductors have been investigated[7, 9, 10]. One type of such inductors uses polymeric sacrificial layer to create an air gap between the inductor and the substrate, yielding the Q factor of nearly 60 at 7-8 GHz[7]. Another type use thin metal strips as bottom conductors and freestanding bonded wire as top conductors[9] yielding Q-factor in the range of 20 at 3 GHz. Various micromachining techniques have been investigated in realization of integrated on-chip inductors. Most common approach is to integrate on-chip inductors on top of the wafer with already-fabricated electronics circuits (a so-called post-IC integration approach). In such an approach, the post-IC processing sequences must have compatibility with already-fabricated circuits such as chemical processing compatibility and low temperature processing which must not exceed approximately 450°C.

In this work, we investigated the deformation of thick polymer and applied the polymer deformation characteristic to create a sacrificial core to realize a novel on-chip 3D air core micro-inductor. Although the current inductor has been fabricated directly on a substrate, our ultimate goal is to realize a 3D suspended on-chip air core solenoid inductor on a circuit containing substrate.

## 2. FABRICATION

Figure 1 shows a brief fabrication sequence of the on-chip 3D air core solenoid inductor and Figure 2 shows optical photomicrographs of such inductor under fabrication. The fabrication starts with substrate insulation by thermal oxidation of Si substrate, followed by a sputtering of electroplating base (2000 Å Cu / 1000 Å Ti) for bottom conductors of the coil as shown in Figure 1-a. A 15 μm thick SU-8 (MicroChem Corp.) resist then has been spin-coated and patterned to be used as a polymeric mold for bottom conductor electrodeposition as shown in Figure 1-a. Figure 2-a shows a corresponding optical photomicrograph. Metal (either Cu or Ni) has been electroplated through the SU-8 mold and the next layer of electroplating base has been deposited (Figure 1-b and Figure 2-b).

The next step is to deposit a polymeric mesa which must have two distinctive features: easy deformation to have a smooth surface profile and easy to be stripped. It is well known that positive photoresists can be stripped, simply by rinsing in acetone. SJR 5740 (Shipley Company) is a thick positive photoresist which satisfies the requirements. It can be patterned as a thick rectangular mesa using normal UV lithography and can then be reflowed at elevated temperatures. A 40 μm thick SJR 5740 positive photoresist has been spun on the wafer and patterned to form a rectangular mesa on top of the bottom conductors (Figure 1-c and Figure 2-c). This temporary core has been successively hard cured at 120 °C for 6 hours to deform its cross-sectional profile into a bell-shape as shown in Figure 1-d and 2-d. Alternatively the temporary core can be hard cured at 200 °C for 3 hours. After long curing, the SJR 5740 deformed core is stable enough to stand the next electroplating base sputter coating. Figure 3 shows scanning electron microscopy (SEM) photomicrographs of polymeric mesa before and after the hard curing. The rectangular polymeric mesa shown in Figure 3-a has been reflowed during the sputter coating of gold thin film for SEM. Before then it is our belief that the polymeric mesa has nearly perfect rectangular shape. After the hard curing, the polymeric mesa has been significantly deformed to form a bell-shape with a smooth surface profile (Figure 3-b). A sputtering of electroplating base (2000 Å Cu / 1000 Å Ti) for top conductors of the coil has been carried out on top of the bell-shape sacrificial polymeric core.

In formation of the top conductors, the photoresist cannot be spin-coated conformally onto the wafer due to the significant height difference between the core and the rest of the wafer. To solve this problem, the resist is applied using electrodeposition. The PEPR 2400 (Shipley Company) photoresist is positive working water borne resist which is applied by anodic electrodeposition. Upon application of a direct current, charged micelles form a conformal coating. We have tested the electrodeposition of PEPR 2400 using an array of patterned polyimide grooves to check the conformal deposition

characteristic. Figure 4 shows SEM photomicrographs of Ni lines which have been electroplated through conformally deposited PEPR 2400. After such test, we use this conformal photoresist deposition process to delineate the top conductors.

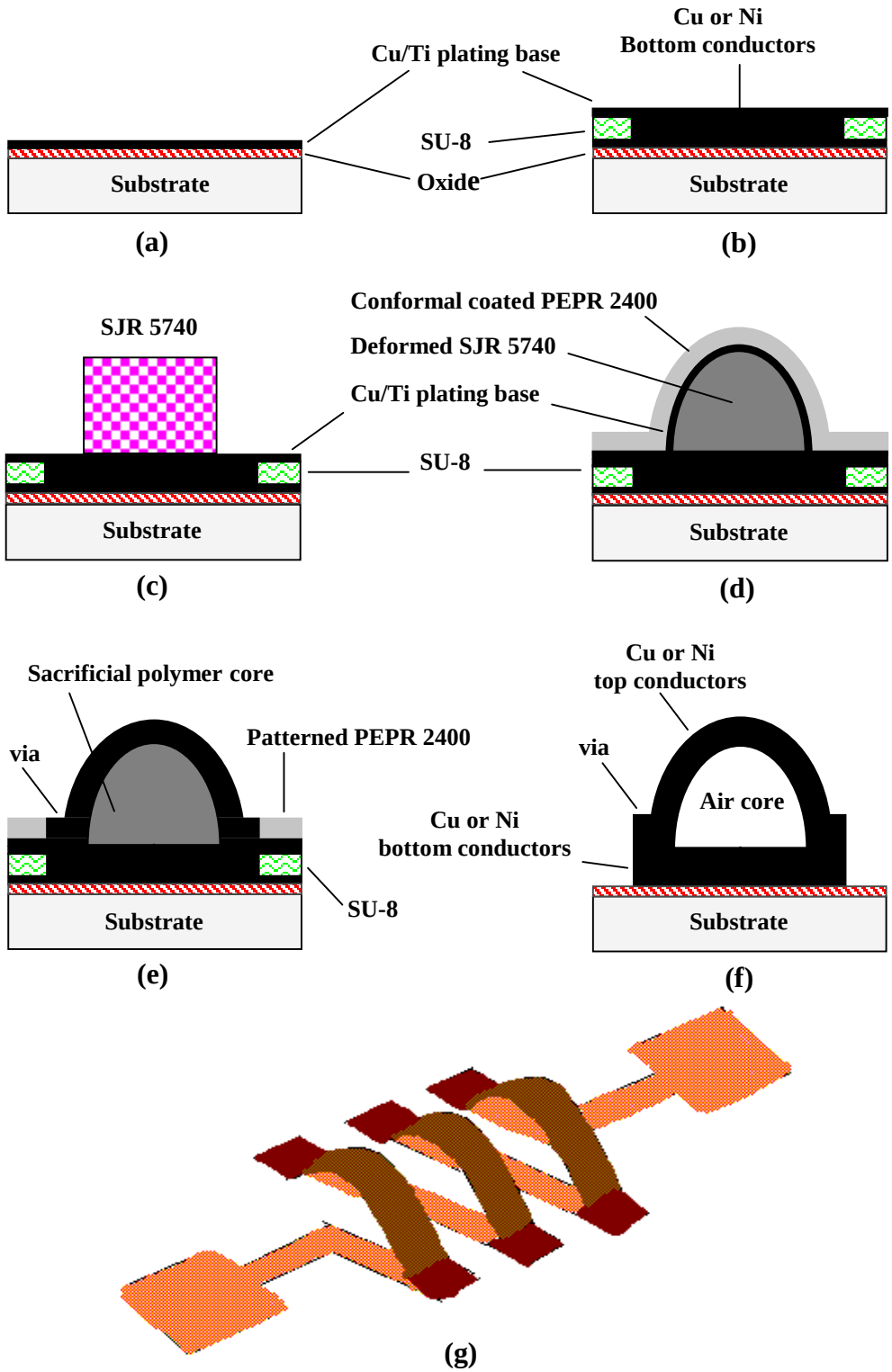



Figure 1. Fabrication sequence for 3D air core on-chip inductor using deformed sacrificial polymer core.

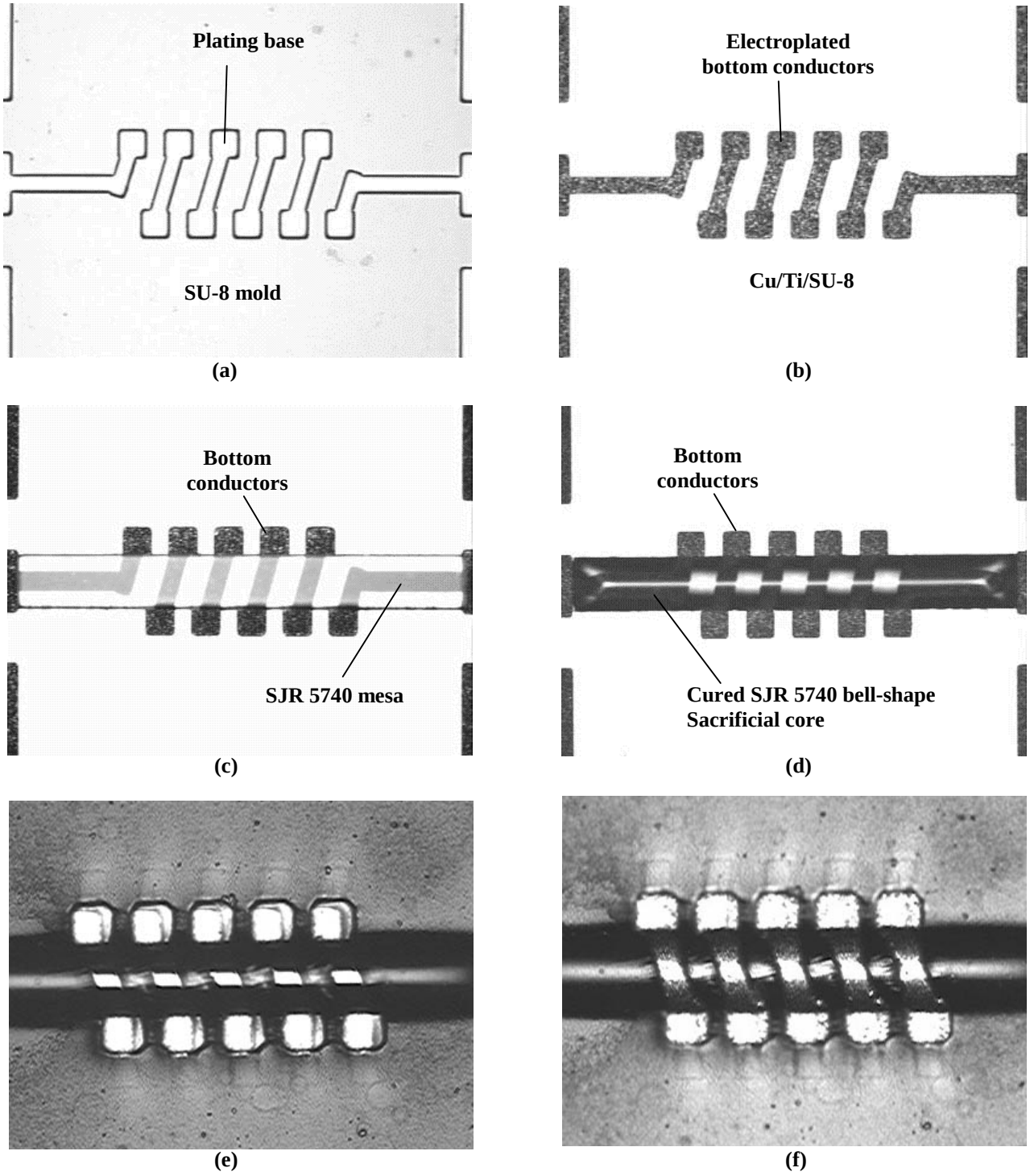
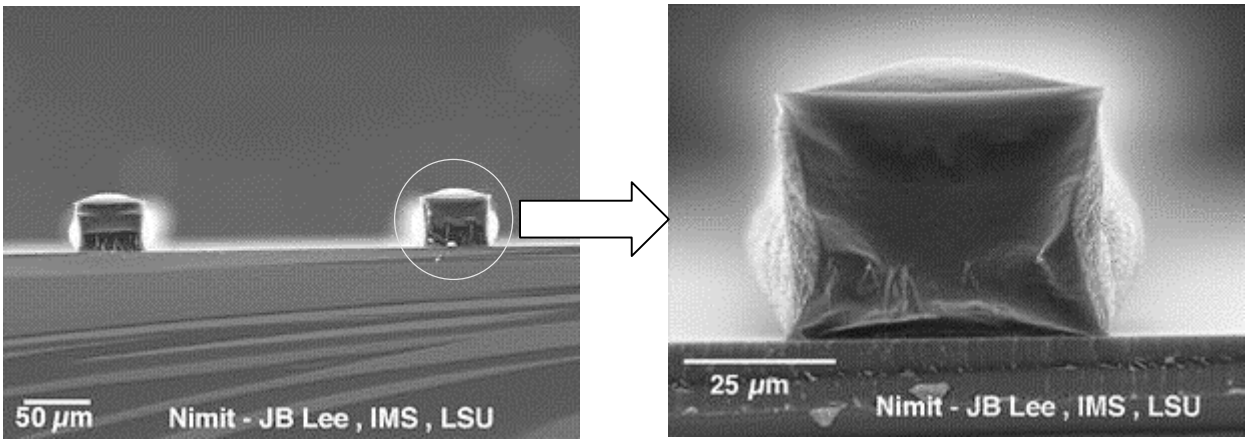


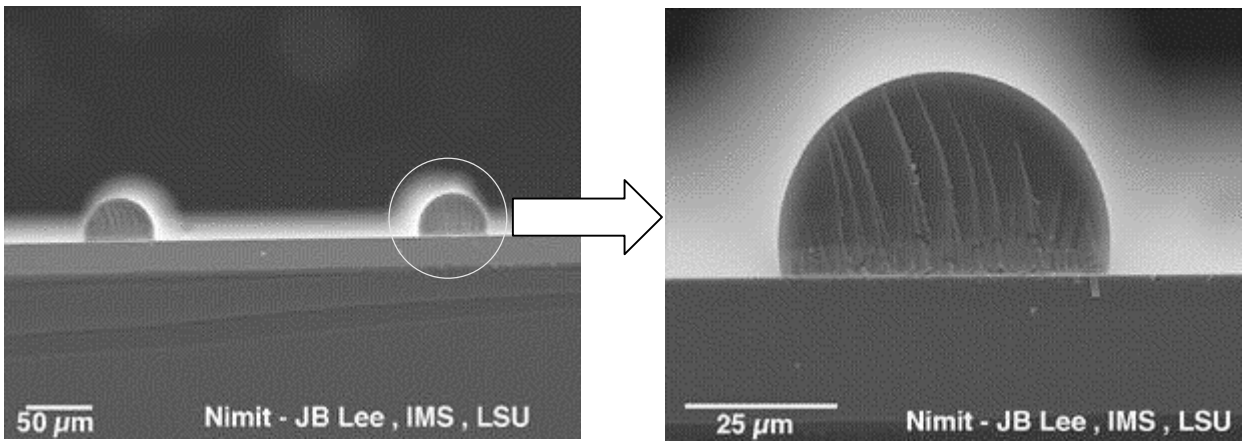

Figure 2. Optical photomicrographs for 3D air core on-chip inductor under fabrication: (a) SU-8 polymeric mold for bottom conductors; (b) Electroplated bottom conductors; (c) Uncured SJR 5740 mesa; (d) Deformed bell-shape sacrificial core; (e) PEPR 2400 mold for top conductors; (f) Electroplated top conductors with PEPR 2400 mold.

A mixed solution of PEPR 2400 and de-ionized (DI) water (with a volume mixture ratio of 1:7) has been used to conformally electrodeposit polymeric layer on top of the bell-shaped sacrificial core. A DC voltage of 250V has been applied between the wafer (anode) and the stainless steel reference electrode (cathode). After approximately 4 minutes of electrodeposition of PEPR 2400, the wafer has been rinsed briefly in DI water and dried by spinning at 1000 rpm for about one minute. The wafer then has been baked in a convection oven by ramping up the temperature from 50°C to 105°C, holding at 105°C for 10 minutes, and cooling down on an insulator for 10 minutes. At this point, the pattern of top conductors has been transferred to the wafer with UV exposure with a dose of 400 mJ/cm$^2$. The exposed wafer has been developed in 1 % sodium carbonate solution at 35°C. The pattern then becomes a polymeric mold for electroplating of top conductors (Figure 2-e). Ni or Cu has been electroplated through the PEPR 2400 mold to form top conductors on top of bell-shape polymeric core (Figure 1-e and Figure 2-f).

Once both bottom and top conductors are interconnected to form a solenoid coil, all polymeric molds and the sacrificial core have been removed using a two-step etch process. First, a wet etching process has been carried out using heated (70 °C ~ 90 °C) 1-methyl-2-pyrrolidinone to quickly remove most areas of polymers. Then, a dry etching process has been performed by oxygen plasma using a plasma etcher to remove the remaining polymers which could not be etched away in the wet etchant. The copper layer in the electroplating base has been removed in a solution of ammonium hydroxide ($NH_4OH$) saturated with copper sulfate ($CuSO_4 \cdot 5H_2O$). Finally, the Ti layer in the electroplating base has been etched away in 5 % hydrofluoric acid (HF) solution. After all sacrificial layers and electroplating base were removed; the remaining structure is a 3D solenoid-type air core inductor as shown in Figure 1-f and Figure 1-g.




(a)




(b)

Figure 3. Deformation of sacrificial polymer cores: (a) Cross-sectional rectangular polymer mesa before hard curing, some reflow occurred during gold sputter coating for SEM; (b) Cross-sectional bell-shape polymer mesa after hard curing at 120 °C for 6 hours.

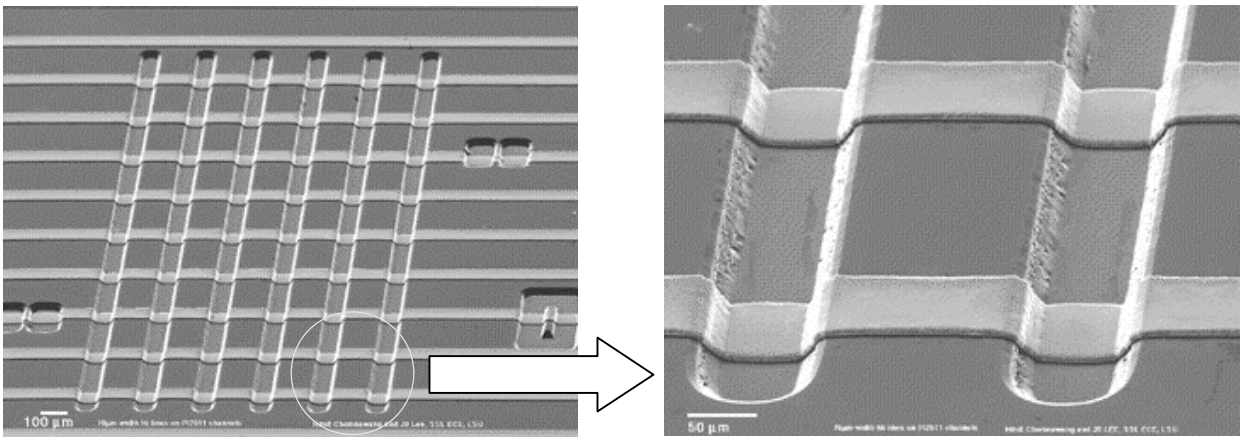



Figure 4. SEM photomicrographs of conformally electroplated Ni lines across polyimide grooves using PEPR 2400 electrodeposition.

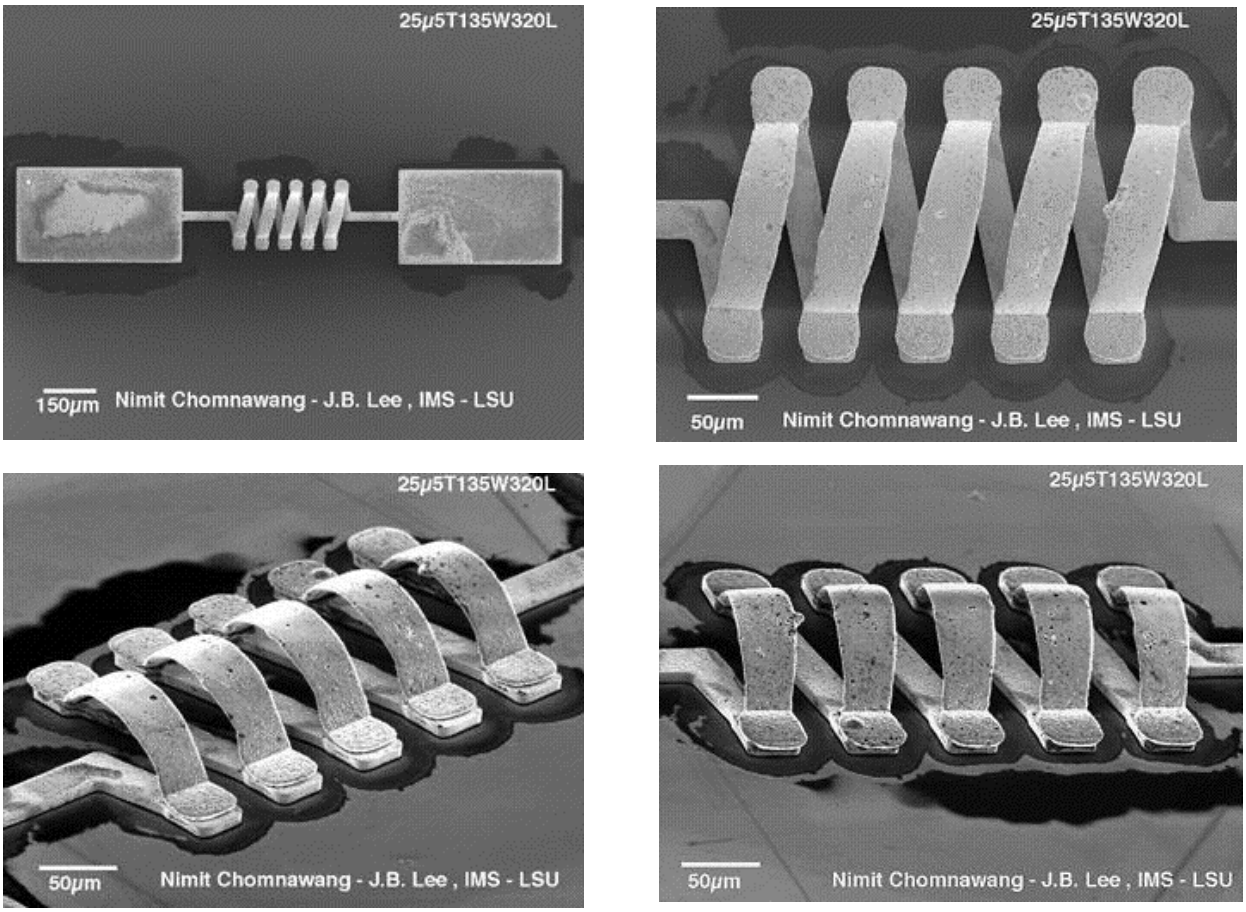
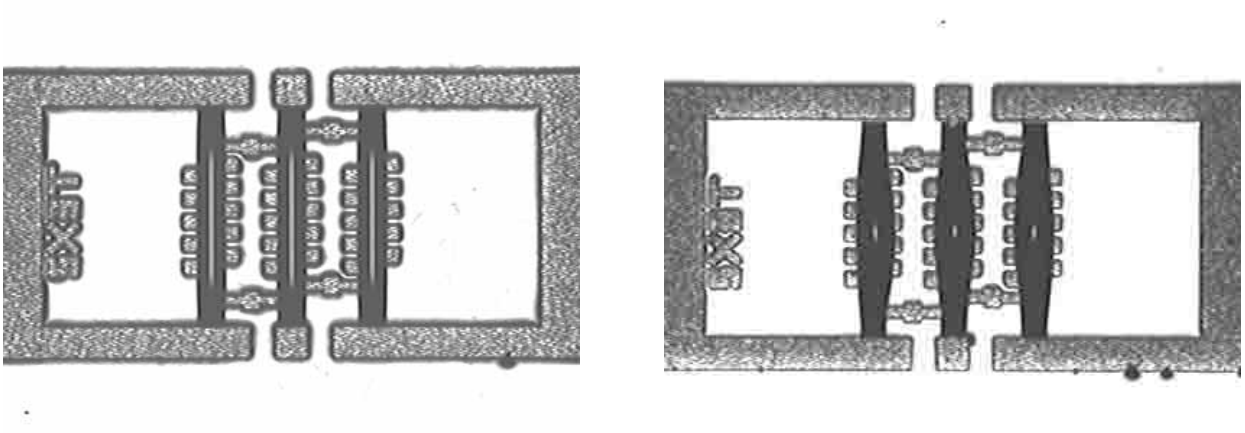



Figure 5. SEM photomicrographs of 3D air core on-chip inductor using deformed sacrificial polymer core.

## 3. RESULTS AND DISCUSSION

Figure 5 shows SEM photomicrographs of fabricated 3D air core inductor. The width of the core is 135 μm, the size of the via is 50 μm, the linewidth of the bottom conductor is 25 μm, and the height of the core at the center is approximately 40 μm. The linewidth of the top conductor varies from 25 μm (at the bottom edge of the sacrificial polymeric core) to 30 μm (at the top of the sacrificial polymeric core). This linewidth variation is caused by thickness variation of the deposited PEPR 2400. Although PEPR 2400 is conformally deposited on top of the bell-shape sacrificial core, the thickness of deposited PEPR 2400 at the bottom edge of the core is relatively thicker than that at the top of the core. Due to the thickness variation, the top part of the PEPR 2400 is over developed to widen the linewidth.

Figure 6-a shows an optical photomicrograph of the top view of an another design of micro-inductor after the curing of sacrificial rectangular polymeric mesa, where the width of the core is 70 μm and the height of the core is 40 μm. In order to increase the aspect ratio of the inductor, we have tried to use much thicker (70 μm) sacrificial polymeric mesa. For thicker polymeric mesa, during hard curing the polymeric mesa tends to reflow toward its center and significantly deformed from its original position (Figure 6-b). Apparently such deformed polymeric mesa covered the via area of the bottom conductors so that it cannot be used to form a bell-shape inductor. Based on this observation, we concluded that the maximum aspect ratio (core height with respect to the core width) for the bell-shape air core inductor using this process would be 1:1.



**(a)** **(b)**

Figure 6. Optical photomicrographs of top view of the hard cured polymeric mesa (a) with core width of 70 μm and core height of 40 μm, (b) with core width of 70 μm and core height of 70 μm.

## 4. MEASUREMENT

Measurements of inductance, series resistance, and quality factor of fabricated on-chip 3D air core inductor have been carried out using HP 4275A multi-frequency LCR meter with a custom designed electromagnetic interference (EMI) shielded probe station for the frequency range between 10 KHz and 10 MHz. Figure 7 shows preliminary measurement results for 5 turns, 15 turns, and 20 turns inductor. Since the air core inductor has been designed to be used in high frequency (> 1 GHz) applications, low frequency characteristic of the inductor is relatively less important. Currently, we are fabricating similar inductors with ground planes to be measured in a ground-signal-ground on-wafer microwave load-pull system for high frequency characterization.

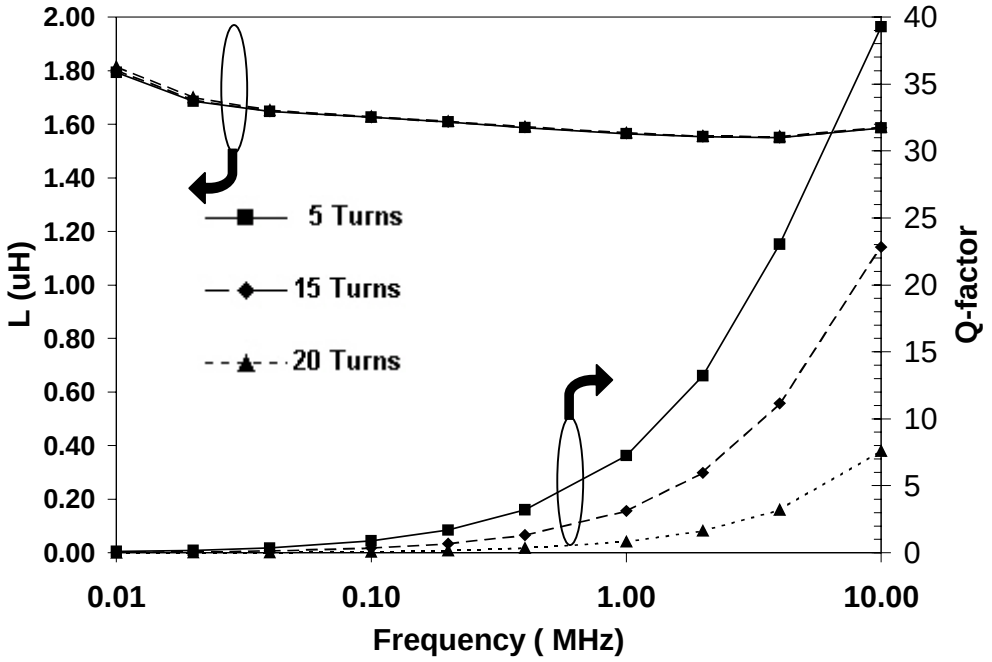



Figure 7. Inductance and Q-factor of Ni bell-shape on-chip 3D air core inductor.

## 5. CONCLUSIONS

A novel on-chip 3D air core micro-inductor has been designed, fabricated, and characterized based on the deformation of polymeric sacrificial layer. The inductor has bottom conductors sitting on the substrate while the top conductors have an arch-like structure with an air-bridge. The deformation characteristic of polymeric core has been studied to find out the maximum achievable aspect ratio of this process and it has been found to be 1:1 height to width ratio. Inductance and Q-factor has been measured for the inductor in low frequency range (10 KHz ~ 10 MHz). Currently, high frequency (> 1 GHz) characterization of this device is under way. One of logistical next steps includes the investigation of suspended air core inductor using sacrificial polymeric layer underneath the bottom conductors.

## ACKNOWLEDGMENT

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