3D PRINTED RF PASSIVE COMPONENTS
BY LIQUID METAL FILLING
Chen Yang¹, Sung-Yueh Wu¹,², Casey Glick¹, Yung Seok Choi³, Wensyang Hsu², and Liwei Lin¹
¹University of California, Berkeley, USA
²National Chiao Tung University, Hsinchu, Taiwan
³Samsung Electronics Co., Ltd., Hwaseong-si, Korea

ABSTRACT
We present three-dimensional (3D) micro-scale electrical components and systems by means of 3D printing and a liquid-metal-filling technique. The 3D supporting polymer structures with hollow channels and cavities are fabricated from inkjet printing. Liquid metals made of silver particles suspension in this demonstration are then injected into the hollow paths and solidified to form metallic elements and interconnects with high electrical conductivity. In the proof-of-concept demonstrations, various radio-frequency (RF) passive components, including 3D-shaped inductors, capacitors and resistors are fabricated and characterized. High-

INTRODUCTION
3D printing is a polymer direct-write technology which has attracted great interests for various applications in rapid prototyping due to its geometric flexibility in design and manufacturing [1]. Recently, researchers have started to use 3D printing and other technologies to make 3D micro devices such as microfluidic systems [2-8] but few have studied in the rapid metallization for 3D micro systems. Ideally, metal-embedded 3D micro systems could enable various new applications. For example, a solenoid coil can serve as the inductor in LC-resonant circuits, as an actuator in solenoid actuation devices, or an inductive coupling component in electrical transformers. Currently, most published works still have the lithography-defined planar electrodes in these micro systems using rather complicated fabrication and bonding processes.

Several efforts have been explored to use bonding wires or direct-written liquid metals to form 3D conductive structures [9-12]. These metallic structures are suspended in air and difficult to fabricate. Here we propose a novel method to generate arbitrary 3D microstructures with embedded metallic elements by the liquid-metal-filling technique for a variety of possible applications. In this work, we demonstrate several 3D RF passive devices and systems as the proof-of-concept.

DESIGN
Figure 1 illustrates the proposed 3D design and fabrication steps. First, functional 3D structures are designed and constructed by the 3D printing technique. The hollow micro channels and cavities are embedded in the 3D structures to be filled with liquid metal pastes. As an example, a hollow solenoid-shaped channel is formed as shown in Figure 1. Second, in order to facilitate the liquid metal filling step in the next fabrication process, injecting holes are designed and fabricated with solenoid channels. For example, the solenoid-inductor structure as shown has designated cavities as the ground-signal-ground (G-S-G) pads on the top surface of the device. Third, after the 3D printing process, liquid metal paste is injected via the injecting hole into the designed channels and cavities to form electrical structures. The overflow of the liquid metal at the outlets on the top surface can be used as the contact pads. Forth, the solidification process cures the liquid metal to form solid structures and the top surface of the device is planarized to remove the injection hole and overflowed liquid metal.

An array of RF passive components has been designed, as shown in Figure 2, including resistors, inductors and capacitors with various geometries. The goal is to demonstrate and test the system-level performance of 3D micro devices fabricated by the proposed methodology and filled with liquid metal. Specific issues to be investigated include the precision and accuracy of the physical structure, the electrical conductivity of the liquid filled metal, and the characteristics of the fabricated components and systems.
FABRICATION AND EXPERIMENTS

The fabrication process uses the 3D printing machine, ProJet™ HD 3000, based on the fused deposition modeling (FDM) technology [13] with a printing resolution of 30 μm. During the printing process, polymer materials are heated and ejected from the nozzles of the inkjet printer. Building (VisiJet® EX 2000 [14]) and sacrificial materials (VisiJet® S100 [15]) are deposited alternatively from the dual nozzles to form the printed samples, in which the building material defines the molding structure while the sacrificial material occupies the hollow channels.

A post-printing process is conducted to remove the sacrificial materials. First, the whole 3D printed sample is immersed in a mineral oil bath at 80 °C to dissolve the sacrificial material. Second, the residual mineral oil is removed by detergent and water in sequence thoroughly. Afterwards, the liquid metal, silver suspension (Pelco® 16040-30) is injected into the micro channels and cavities. The as-filled sample is kept at room temperature for 2 hours for the solidification process.

The fabricated passive components are shown in Figure 3. It is noted that the volume of silver suspension shrank after the solidification process, and therefore leads to voids inside the metal traces. By optimizing the silver suspension concentration and repeating the filling operations, the voids could be minimized for better electrical conductivity. The cross-section view in Figure 3c indicates the metal filling inside the solenoid coil.

The electrical performances of the fabricated passive components are characterized. The DC I-V curves of resistors are measured by a semiconductor parameter analyzer (HP 4145B). The RF S-parameter spectra of the inductors and capacitors are measured by a Cascade G-S-G probe station and a network analyzer (Agilent E5071A). The parasitic effects of G-S-G pads are de-embedded accordingly.

RESULTS

Resistors

The DC I-V curves of two resistors with different designs are shown in Figure 4. The equivalent conductivity $\sigma$ of the filled metal is calculated as:

$$\sigma = \frac{1}{R} \times \frac{L}{S}$$

(1)

where $R$ is the total resistance, $L$ is the length of the conductor, and $S$ is the cross-sectional area by considering the void effect. The cross-sectional shape of the metal...
Traces is circular with a diameter of 600 μm and the length is 21.4 mm and 47 mm for resistor R1 and R2, respectively. The calculated average $\sigma$ is $2.30\times10^6$ S·m⁻¹, which is about 86% of the ideal conductivity of silver paste at $2.67\times10^6$ S·m⁻¹ [16]. This difference may result from the remaining solvent of the injected metal, which could be further improved by optimizing the solidification process in the future.

**Inductors**

The measured $S$-parameters of the fabricated inductors are converted to $Y$-parameters and then the inductor performances are extracted as [17]:

$$L = \frac{\text{Im}\left(\frac{1}{Y_{ii}}\right)}{2\pi f},$$

$$Q = \frac{\text{Im}\left(\frac{1}{Y_{ii}}\right)}{\text{Re}\left(\frac{1}{Y_{ii}}\right)},$$

where $L$ is the total inductance, $Q$ is the quality factor, and $f$ is the frequency.

Figure 5 shows the measured inductance and quality factor of inductors with different numbers of coil turns, $N$. These solenoid-shaped inductors have a designed diameter of 4 mm. The cross-sectional shape of the metal traces is circular with a diameter of 600 μm. Line spacing between adjacent winding is 400 μm. In Figure 5a, the measured total inductance $L$ increases as $N$ increases. For example, the inductances at 0.8 GHz are 19 nH, 36 nH and 66 nH for inductors with 1.5, 2.5 and 3.5 turns, respectively. For each inductor, the $L$ increases first as the frequency increases, and reaches up to maximum due to self resonance. For example, the inductance of the 2.5-turn inductor increases from 36 nH at 0.8 GHz to over 1500 nH around 1.14 GHz. Then the inductance drops quickly. The frequency at which the $L$ drops to zero, i.e., the self-resonance frequency $f_0$ is 1.24 GHz, 1.15 GHz and 1.04 GHz for these inductor samples, respectively. It is noted that larger $N$ corresponds to smaller $f_0$ due to larger inductance and parasitic capacitance. Figure 5b shows the measured quality factors. The $Q$-factor first increases as the frequency increases and then drops down to zero due to the high loss at self-resonance frequency. It is noted that higher inductance leads to lower quality factor due to higher energy losses. For example, the 1.5-turn inductor has the smallest inductance and highest $Q$ about 31 at 0.95 GHz, while the 3.5-turn inductor shows maximum $Q$ of 11 at 0.72 GHz. During the magnetic energy storage cycles in the inductors, the energy loss mechanisms mainly include the skin-effect induced ohmic losses in the conductor and the electric field energy losses due to parasitic capacitance.

**Capacitors**

The measured $S$-parameters of the capacitors are converted to $Y$-parameters and then the capacitor performances are extracted as [18]:

$$C = \frac{1}{2\pi f} \text{Im}(Y_{ii}).$$

where $C$ is the total capacitance.

**CONCLUSION**

The design and fabrication steps and processes to construct three-dimensional (3D) micro-scale components and structures by the combination of 3D printing and liquid metal filling technique have been developed. The 3D structures with hollow channels and cavities are first built using the polymer inkjet printing process. Silver particles in the form of suspension pastes are injected into the hollow channels and solidified to form metallic elements.
and interconnects inside the 3D structures. By optimizing the silver suspension concentration and repeating the filling operation, the voids inside the cured silver paste could be minimized for good conductivity. Various RF passive components (including inductors, capacitors and resistors) are fabricated and characterized. As such, this paper has developed and demonstrated a new class of manufacturing process to construct arbitrary 3D structures with the metallization process. Possible applications could extend to different kinds of 3D micro electromechanical systems with embedded metallic components, such as 3D packaging and lab-on-a-chip to name a few.

ACKNOWLEDGMENT

This work is partially supported by Samsung Electronics, Inc. Mr. Sung-Yueh Wu is supported by the Ministry of Science and Technology of Taiwan under Grant 103-2917-I-009-192. The authors would also like to thank the help from Prof. Albert P. Pisano for the measurement equipment.

REFERENCES


CONTACT
*C. Yang, tel: +1-510-642-8983; chenyang@berkeley.edu. C. Yang and S.-Y. Wu contributed equally to this work.

Figure 6: Measured total capacitance C of 3D printed RF capacitor. The device's self-resonance frequency is 1.1 GHz.