Inkjet Printing of Passive Microwave Circuitry

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***Abstract* — Inkjet printing technology was utilized to fabricate transmission lines on a glass substrate. 50 micron resolution was realized using 10 pL drop volumes on a Corning 7740 glass substrate. This can be further improved by applying other methods as described in this paper. The conductivity of the sintered silver structures were 1/6 that of bulk silver after sintering at a temperature much lower than the melting point of bulk silver. A comparison of the DC resistance of the sintered silver shows that it can be a match for electroplated and etched copper. Printed Coplanar lines demonstrated losses of 1.62 dB/cm at 10 GHZ and 2.65 dB/cm at 20 GHz.**

***Index Terms* — Inkjet printing, silver nano-particle, conducting ink, RF, coplanar waveguide, fluid surface interactions.**

I. Introduction

The past few decades have seen significant advances in technologies used to create passive wireless circuitry. These advances have ranged from the development of inexpensive printed-circuit board fabrication to the sophisticated manufacturing of RF integrated circuits. These techniques can be broadly categorized into thick-film, thin-film, and IC fabrication methods, and provide tradeoff between geometrical resolution and fabrication cost. These techniques all have the common modality of "subtractive" fabrication, utilizing repeated application of the "deposit/pattern/etch" technique to create multiple layers of patterned conductors by which passive microwave circuitry is constructed.

Alternatively, the advancement of inkjet printing for photographic applications has spawned the development of "additive" fabrication, where the deposited material is applied only to the desired areas. This eliminates the necessity for patterning and removal of deposited materials from undesired areas, decreasing the required materials and waste by-products. This fabrication technique has advanced to the point that machines capable of high resolution photographic printing can be easily purchased in retail venues. Exploiting this novel technology for the low-cost fabrication of passive wireless circuitry provides a unique opportunity to leverage the billions of dollars invested in technology for photographic applications.

The additive process of jet-deposition is currently being explored for constructing a variety of novel non-photographic applications, including deposition of 3-D structures, fabrication of plastic transistors and organic electronic displays, and as a methodology for creating biomedical devices. Companies are developing customized machinery for jet-printing of dielectrics, adhesives, solder beads for packaging, and ferrite particles for inductors. The possibility of jet printing passive microwave components has evolved dramatically with the development of metal-based inks from companies such as Advanced Nano Products, Cabot Corp, InkTec, and NovaCentrix. These metal-based inks enable the potential for low-cost, on-demand printing of passive microwave circuitry. This paper explores the efficacy of jet-printing of microwave transmission lines using metal inks, ultimately leading to low-cost jet-printing of passive microwave and millimeter-wave components for commercial wireless and defense applications.

II. Metallic Jet Printing Processes

We are using a drop-on-demand piezoelectric inkjet printing process to print conducting metallic lines. Here a piezoelectric actuator reduces the volume in a fluid reservoir causing an ink droplet to be ejected. The size of the droplet depends on the size of the nozzle orifice, as described below. Since the drop ejection process does not require the formation of a vapor bubble, as in thermal inkjet, the printer is able to use a broad range of solvent based inks. The ink used here contains silver nano-particles capped with a polymer coating that keeps the particles in a colloidal suspension. Inks with other metallic nano-particles such as gold are also available. Once the silver ink has been printed, it can be sintered at a low temperature (100˚C-300˚C) to form electrically conducting lines, enabling low temperature substrates such as paper [1] and polyimide to be used. The low processing temperature could also enable printing passive microwave circuitry on top of substrates with pre-existing microelectronics. An additional advantage of inkjet patterning is that it is possible to print on flexible and non-planar substrates since it is a direct-write process that does not require intimate contact between the substrate and a mask, as required in conventional photolithography. The gap between the inkjet head and substrate is approximately 1 mm which is large in comparison to the typical gap of several microns in photolithography.

The interaction between the ink and substrate is important for high resolution patterning in inkjet printing. Here capillary forces and surface wetting determine the spreading of the ink drop on the substrate. Printing on paper surfaces can result in drop spreading due to wicking of the ink along paper fibers.

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This spreading can be minimized by using surface coatings as are used in inkjet photopaper. When printing on glass or polymer substrates, the contact angle between the ink and surface determines drop spreading. Using surfactants and surface processing the contact angle can be optimized. Finally, the interaction between drops can impact the print resolution. If drops are printed in close proximity they can coalesce into a single drop, decreasing the print resolution.

III. MATERIAL USED AND EXPERIMENTAL CONDITIONS

The transmission lines were printed using a Dimatix DMP 2800 printer with a DMC-11610 cartridge [2]. The cartridge contains 16 nozzles that are 20 micrometer in diameter, and each nozzle generates 10 pL drops of ink that produces a 50 micrometer spot when printed on surface treated glass slides. The surface treatment rendered the glass slides hydrophilic thus producing the right conditions for printing. If the glass slides are hydrophobic poor resolution is attained since the fluid makes very poor contact with the surface. On the other hand, if the glass slides are too hydrophilic the ink spreads and the resolution once again suffers. Experiments in the lab have shown that only few degrees of contact angle are needed to produce 50 micron spot sizes with a 10 pL volume. The substrate used here was Corning #7740 (Pyrex) glass. Different surface treatments were applied to achieve the best resolution: oxygen plasma, nitrogen plasma, liquid surfactant application, and cleaning with different solutions. While the oxygen plasma showed encouraging results, the best treatment was to clean the surface with 75% ethyl alcohol and a 20 minute pre-bake at 60 degrees Celsius. The ink (CCI-300) used was produced by Cabot Corporation PEDs Materials [3]. A 0.2 um filter was used to filter the ink before the cartridge was loaded. A short post-bake ranging from 200˚C to 300˚C was used to sinter the silver nano-particles. The short duration of the post bake minimized the oxidation of the silver conductor while maximizing the conductivity. Figure 1 shows a chart of the sintering temperature versus conductivity for the post-bake process. Note that the bulk conductivity of silver is around $6.5*10^7$ Siemens per meter and that sintering the silver nano-particle ink at 300˚C (a small fraction of the melting temp. of silver) reproduces one sixth of that bulk conductivity. While increasing the sintering temperature would increase the conductivity of the devices it would also increase the residual mechanical stress and stress gradients. This is brought about by the difference in coefficient of thermal expansion of the cured silver and glass.

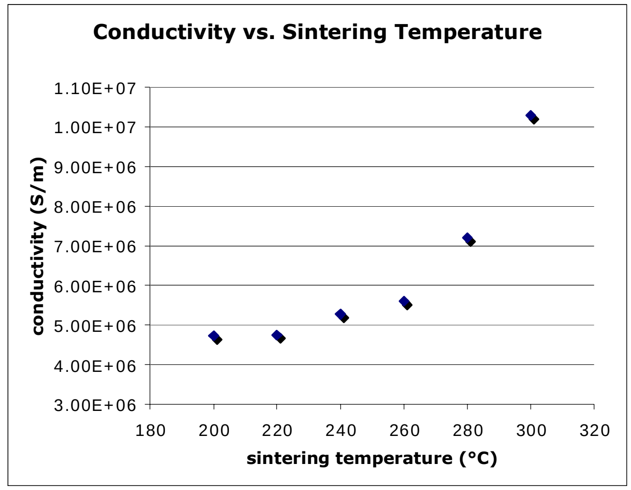

Figure 1. Conductivity vs. sintering temperature for Cabot silver nano-particles ink jetted with a Dimatix printer onto a surface treated glass substrate.

IV. RF PERFORMANCE

Sintered nanoparticles and polymers used for printing microwave circuits may not be able to duplicate the bulk material properties of solid inorganic materials (e.g. electrical conductivity). Therefore, conductivity of the transmission line is the major concern regarding insertion loss in a printed circuit. The electrical resistance of printed metal lines is dependent on a number of variables: type of nanoparticle, printed thickness, and sintering temperature. Printed thickness depends on: wetting characteristics of the substrate surface, dot size, substrate temperature, and viscosity.

In order to investigate conductor loss of printed microwave circuits, coplanar waveguide (CPW) transmission lines have been constructed using the proposed inkjet printing technique. The transmission lines were printed on 150 mm diameter Pyrex (relative permitivity=4.6) glass wafers using 10 pL drops of silver ink. The current drop size limits the size of the CPW slots to be greater than 100 μm. The constructed CPW lines are 20.5 mm in length and include 0.5 mm input and output tapered transitions to accommodate the 200 μm pitch of the Infinity I40 GSG probes. The input and output transitions utilize 100 μm slots and 100 μm center conductors which taper to 150 μm slots and 750 μm center conductors for the CPW lines. Figure 2 illustrates the CPW lines that were constructed and Figure 3 depicts the fabricated printed circuits.

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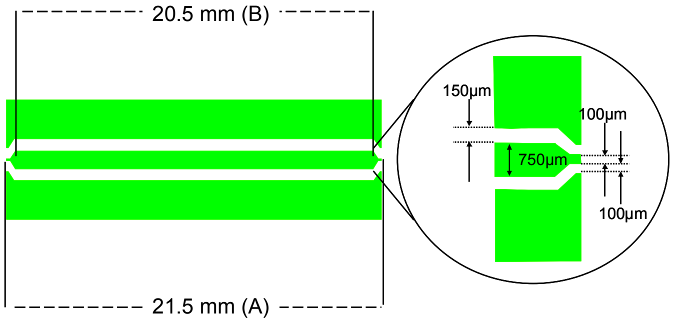

Figure 2. Layout of Ink-Jet Printed CPW Line

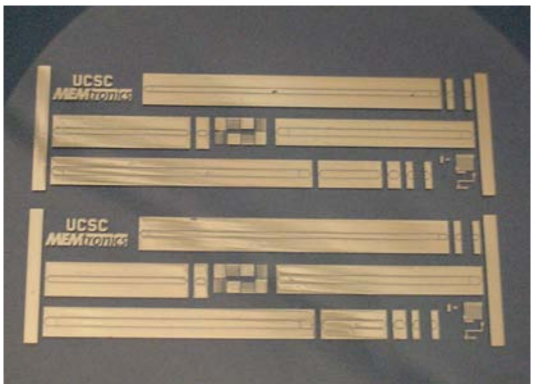

Figure 3. Photograph of Printed CPW Lines on Glass Substrate

DC resistance measurements were conducted using a Keithley 4200-SCS Semiconductor Characterization system to determine the resistivity of the printed material. Significant "thinning" of the printed material was observed in the area of the probe pads; therefore two resistances were measured: (1) the resistance of the signal line from the probe pads (denoted "A" in Figure 2), (2) the resistance of the signal line across the main body of the signal line (denoted "B" in Figure 2). The measured resistance across path (A) is 5.8 Ohms and across path (B) is 0.5 Ohms. This indicates that the observed "thinning" of the printed material has a dramatic effect on the resistance of the signal path. The calculated resistivity for path (A) is 0.130 Ohms/square and for path (B) is 0.018 Ohms/square. As a comparison, a 3 um tall electroplated copper, CPW transmission line (Width=230 µm, gap= 35 µm) has a resistivity of 0.0125 Ohms/square. While the total signal path (A) resistance in this case was quite high, measurement of path (B) indicates that resistivities on the order of those of copper are possible.

RF measurements were made using an Agilent N5230A-420 10 MHz to 40 GHz PNA-L vector network analyzer and a probe-tip SOLT calibration using Cascade Microtech's calibration substrate 101-190. Results indicate an insertion loss of 1.62 dB/cm and 2.65 dB/cm at 10 GHz and 20 GHz, respectively. As a comparison, the electroplated copper transmission lines discussed above yields losses of 0.5 dB/cm and 0.7 dB/cm at 10 GHz and 20 GHz, respectively. Figure 4 shows the measurement results.

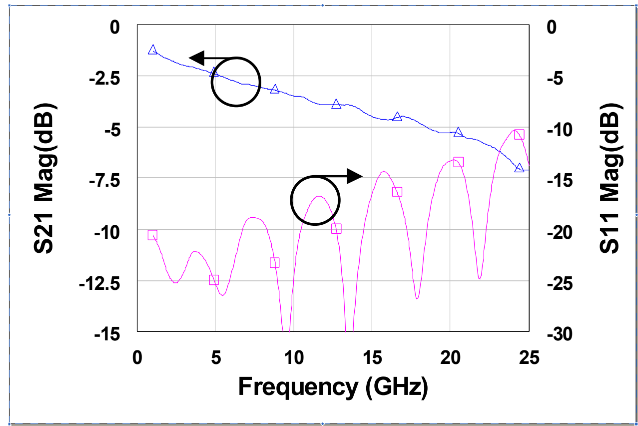

Figure 4. S11 and S21 of Printed CPW Line

In coplanar waveguide, the majority of the current flows along the edges of the conductive medium; therefore conductor losses are inherently susceptible to the edge profile of the transmission medium. Much of this loss can be attributed to a thinning of the printed conductive ink along the edges of the CPW slots and in the area of the probe pads. The surface tension of the ink as it cures causes a reduction in ink at the extremes of the printed region. Because a majority of the RF currents flow in this region of thin material, the loss increases. Improvements in printing techniques and surface preparation will provide for lower conductor losses.

V. JET PRINTING ISSUES

A. Resolution

The resolution required for passive microwave devices could be as small as 10 µm, although this is highly dependent on the design of each device. The current resolution of the DMC-11610 cartridge is around 50 µm but it can be improved to 20 µm by heating the substrate to 100˚C. This heating of the substrate sinters the ink in when it comes into contact with the substrate thus keeping it from spreading. Without further heating the conductivity of the sintered silver is variable but always lower than $5*10^6$ Siemens per meter. The conductivity can be further increased by baking the substrate for a short period at temperatures ranging from 200˚C to 300˚C as shown in the chart in Figure 1. The resolution can also be improved by using a cartridge with a lower drop ejection volume like the DMC-11601 which fires a 1 pL volume. The resolution of the DMC-11601 is around 25 µm but it can also be improved by heating the substrate as mentioned above. One of the disadvantages of printing with a lower drop volume is that the devices are considerably thinner. This can be overcome by multi-pass printing of the devices. Two layers have been successfully printed without sacrificing resolution. On the third overlayer, the ink begins spreading and the resolution suffers. On the other hand, printing on a heated substrate compensates for this since the ink sinters when it comes in contact with the substrate. Another advantage of heating the substrate is that no surface treatment in needed on the substrate since the fluid dynamic effects have been removed by sintering the ink in contact.

B. Silver Nano-Particle Fluid Interactions

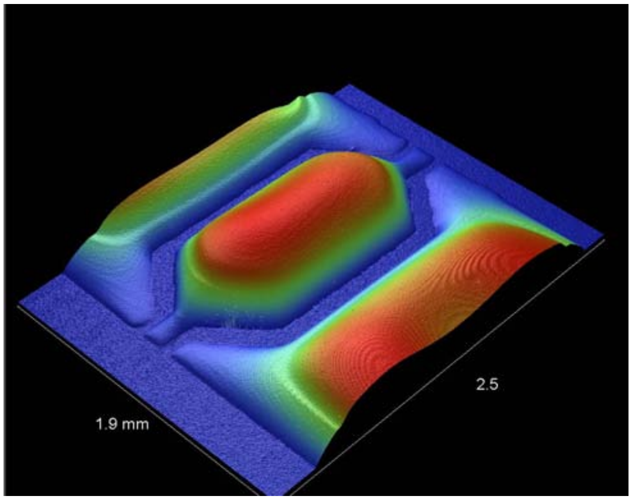

Figure 5. 3D image of CPW obtained with a Veeco white light interferometer.

Figure 5 shows a 3D image of a short CPW transmission line obtained with a white light interferometer. The maximum height of the device is 5 µm but the edges show considerable thinning. The thinning of the device edges is due to the interaction of the fluid and the substrate brought about by the contact angle and the surface tension of the fluid. If a single drop of fluid was ejected onto a substrate it would make a dome whose disk and rim would be the contact angle. As additional drops are added the surface tension of the fluid would pool the ink. The effects highlighted above have two major consequences. The first is that the edges of the devices are considerably thinner compared to the center which could cause some probing difficulties when probing the device with DC probes. The second major effect is that different parts of the device will have different thicknesses, which depend on the cross sectional area. Both of these effects can be observed in Figure 5. At the expense of a much rougher surface, substrate heating can overcome these effects. If the device is heated to lower temperatures, where the fluid is still allowed to pool and sinter at much slower rates, the surface roughness of the device would decrease and the minimum resolution would be preserved.

VI. Conclusion

While inkjet printing technology shows great potential for fabricating RF microwave circuitry and interconnects, more work is needed. Here we have studied silver metal nano-particle ink as a metal for printing coplanar waveguides transmission lines on glass substrates. Resistivities on the order of those of plated copper are possible if thickness of the lines can be controlled. The thinning is believed to be caused by fluid-substrate interactions which can be controlled using techniques described in this paper. Inkjet printing shows a very promising future for ultra-low-cost printing of passive microwave circuitry and interconnects. Low cost RF MEMS (Micro-electro-mechanical systems) are also envisioned in the future of inkjet printing.

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