3D inkjet printing of conductive structures using *in-situ* IR sintering

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Abstract

In this study we investigate the inkjet printing of a silver nanoparticle ink and the optimization of IR sintering conditions to form 3D inkjet-printed conductive structures. The understanding of the interaction between the silver layers and the sintering conditions are key elements to successfully build conductive tracks in 3D.
The drop size of conductive ink on glass substrates as well as on sintered conductive film was measured to optimize the printing resolution. The resistivity of the sintered deposition was studied in a planar X-Y direction as well as in a vertical Z direction to analyze the effects of stacking hundreds of silver layers in different deposition orientations.
Using the results of the optimized printing and sintering conditions, conductive tracks were demonstrated forming simple 3D inkjet-printed structures powering electronic components.

Introduction

3D printing of electronic components and circuitries are key target areas of additive manufacturing (AM) technologies. Taking electronics outside the traditional two-sided or limited layers printed circuit boards (PCB) into the 3rd dimension will enable various new electronic applications. Similar to 3D integrated circuits (3DIC), compact and flexible electronics are amongst those applications that 3D technologies could enable, where conductive tracks can move in a volumetric manner rather than a 2D surface allowing more freedom of track routing [1-3]. Antenna design is another area that has benefited from 3D technologies where conductive tracks printed on 3D surfaces showed better performance and higher efficiency antenna than conventional fabrication methods[4, 5].
Most common form of conductive inkjet inks are precursors of silver nanoparticles dispersed in solvents [6, 7]. A challenge to 3D-print conductive inks is the sintering process which is usually a heating process to evaporate the solvent of the conductive ink and sinter the nanoparticles to form a percolated path[6].
In this study we report using infrared (IR) heating to sinter multilayer tracks of inkjet-printed silver ink. IR sintering has been reported in roll-to-roll processes where the inkjet-printed patterns are sintered using high power IR lamps to form 2D conductive circuits [8-11].

Experimental

In order to understand the printing conditions the silver ink was jetted at different substrates to optimize the droplet size and the printing resolution. Upon inkjet printing, the IR lamp was configured to sinter the deposition when each layer of deposition is complete. Tracks containing layers from 1 to 20 were printed and IR sintered using these conditions. The resistance of the tracks was measured as the number of layers increase. Finally 300 layers of an array of single pixels were printed to study the effect of printing large number of layers on the overall resistance in the *z* direction and compare it to the *x-y* planer patterns.

Materials: A commercial silver nanoparticle conductive ink from Advanced Nano Product (ANP) – product number: DGP 40LT-15C - was used in this study. The ink contains 38.5 wt% of <50 nm silver nanoparticles dispersed in triethylene glycol monomethyl ether (TGME). Glass slides used as substrates were soda lime glass slides from Cole-Parmer Instrument Co. Ltd.

Apparatus: The ANP silver ink was inkjet-printed from a Spectra SE128 print-head installed in a bespoke printer from PixDro (commercial name Toucan). An IR lamp from Heraeus (Heraeus 4114) was installed 800 mm away from the print-head in the direction of printing, which occurs by moving the substrate under the IR lamp for a number of passes as shown in figure 1.

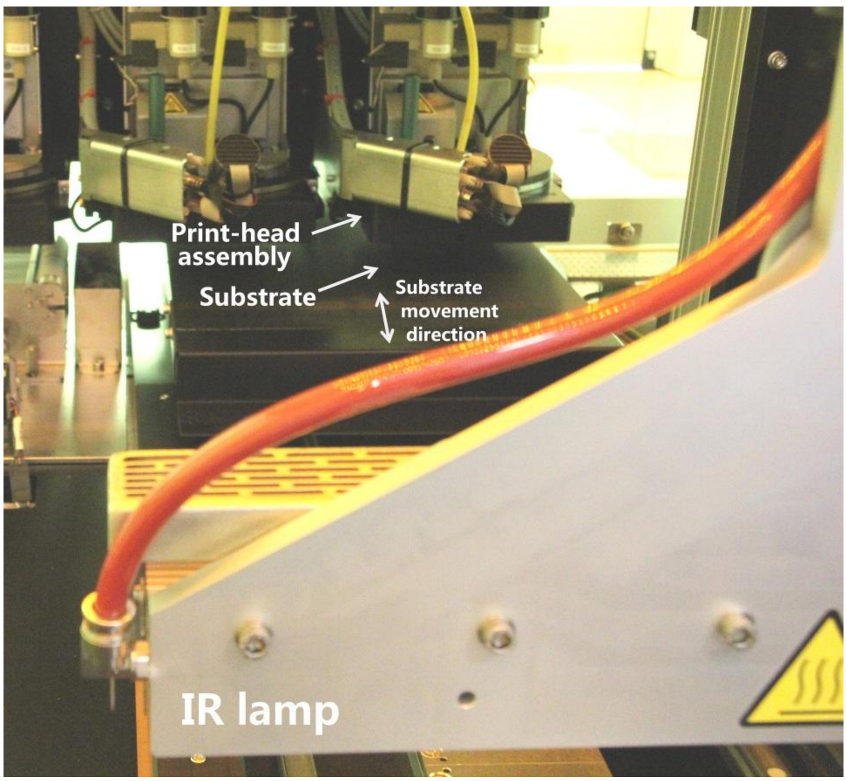


Figure 1, Toucan inkjet printer with IR sintering unit.

The jetting conditions of the ANP ink were 90 V jetting pulses each is 12 µs (2 µs ramp, 8 µs dwell time and 2 µs falling time). The ink was jetted at 30 ºC to tune the viscosity, and the ink pressure on the print-head was maintained at -20 mBar.
The height of the print-head from the substrate was 1 mm and the height of the IR lamp was kept at 7 mm away from the substrate which corresponds to a temperature of 290 ºC measured at the surface of a glass substrate.

Results

Drop size and printing resolution: The size of the droplet size at the substrate is determined by many factors, one is the substrate material. In 3D inkjet printing, using a glass substrate as an example, the droplet size on the glass substrate would change in the second layer after the first layer of the ink was formed if the materials have different surface energies. To evaluate the printing resolution the droplet size of the ANP ink was measured on soda lime glass slide and also on sintered silver ink. Figure 2 shows a comparison of the droplet size on the two materials.

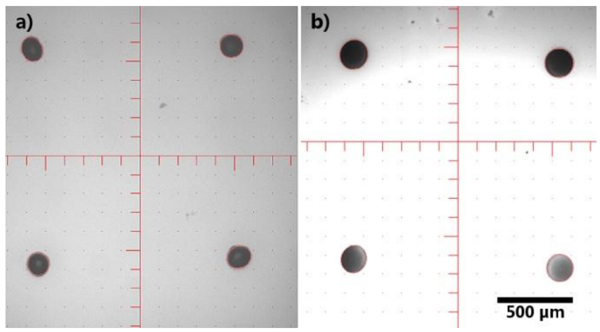


Figure 2, Droplet size of the ANP conductive ink on a) soda lime glass substrate. b) Sintered silver substrate.

The average droplet size of the ANP on glass was 118 μm whereas on silver it was 145 μm. Assuming droplets overlap of 70% the resolutions on glass and silver substrates are 308 dpi and 250 dpi, respectively.

Electrical characterization: To measure the electrical resistivity of the sintered ink tracks of 7 by 0.5 mm were printed and sintered using the printing conditions described in the experimental section. Square pads were also printed at the end of the tracks to act as measurement points as shown in figure 3.

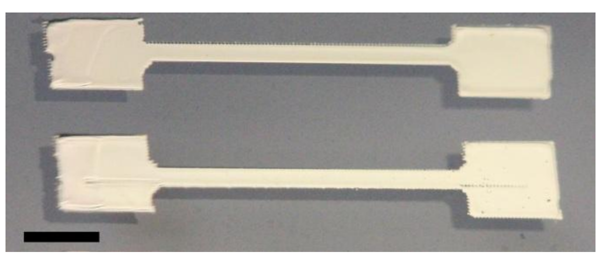
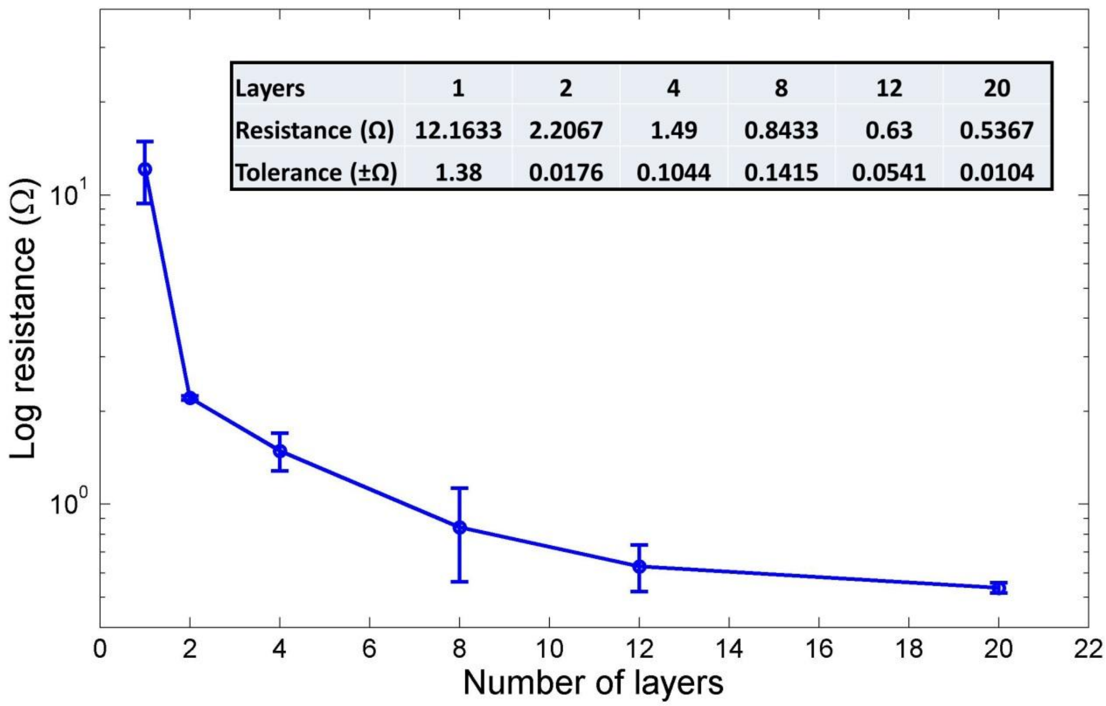


Figure 3, Multi-layer tracks of IR sintered silver ink printed on glass substrate (5mm scale bar).

The resistance of each track was measured using Hameg LCR high precision meter to evaluate the development of the resistance as the number of layers increase.
Figure 4 shows the average resistance of the tracks taken from multiple samples; each track was sintered by applying 10 passes of IR over the deposition which corresponds to 60 seconds of IR exposure.



Layers	1	2	4	8	12	20
Resistance (Ω)	12.1633	2.2067	1.49	0.8433	0.63	0.5367
Tolerance (±Ω)	1.38	0.0176	0.1044	0.1415	0.0541	0.0104

Figure 4, The resistance of the tracks as it changes with the number of layers.

A number of observations can be made on figure 4. The change in resistance with the increase of layers is nonlinear although in theory the increase is geometry dependent so assuming the volume of each layer is the same the resistance trend should have been linear. This nonlinear trend can be due to different deposition volumes per layer as the layers increase; however the most likely reason of this nonlinearity can be due to the presence of organic residue between the layers. The organic materials between the layers usually come from any additives in the ink other than the solvent (surfactants and viscosity modifiers) which don't evaporate during the sintering process.

To measure the resistance of the sintered ink vertically 300 layers of single pixels array were printed and sintered on brass substrate using the same printing and sintering conditions as the planer tracks. The resistance of the tracks was measured between the brass substrate and the tip of the silver as shown in figure 5.

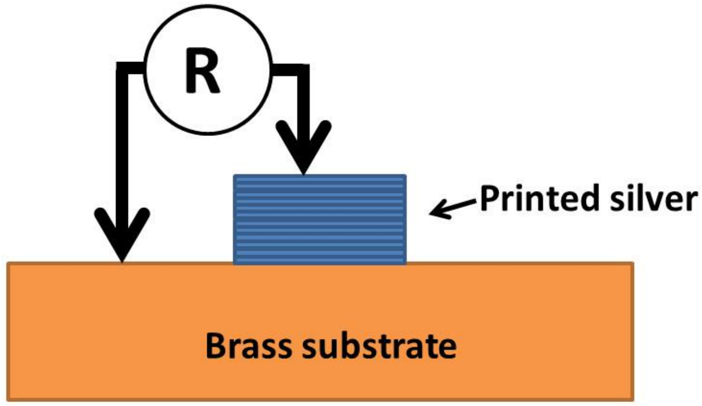


Figure 5, The configuration of measuring the resistance of 300 sintered silver layers vertically.

The measured resistance of the 300 layers was 21±4 mΩ. The diameter of each pixel was around 150 µm and the height was around 200 µm. Comparing that to the estimated resistivity for less number of layers (1-20 layers), the overall resistivity increases when the number of layers increase. This confirms the influence of the interlayering organic materials acting as small resistors between the layers.

The conclusion of the presence of organic interlayers needs further study to include an accurate surface profile of the tracks to measure the resistivity quantitatively and compare it to higher aspect ratio silver pillars in order to draw a further rigorous conclusion and a mathematical model of the resistivity as it changes with the number of layers.

Conclusion

Printing and sintering multilayer conductive ink was achieved using an inkjet print-head with IR post-processing. The droplet size on glass substrate and silver film was measured to evaluate the influence of the substrate and determine the optimal printing resolution.

Multiple layers of silver tracks were printed and sintered for each layer at the same conditions. The resistance of tracks was measured and showed a nonlinear behavior. A hypothesis of this nonlinearity as the number of layers increase was introduced. Organic interlayers from various additives in the ink add a fine resistance between the silver layers increasing the overall resistivity of the structure. This conclusion needs further investigation to quantitatively measure the resistivity of the sintered tracks in addition to the vertical resistance that was introduced in this study.

Acknowledgments

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