Deposition Characteristics and Electrical Properties of Silver and Carbon Nanotube Inks Deposited by Aerosol Jet

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Abstract

3D printing on the microscale has the ability to significantly reduce fabrication time of MEMS devices allowing for more innovation between design cycles. Another advantage provided is the conservation of material during printing. For example, instead of sputtering metal onto a surface and then removing the majority of it, direct and targeted deposition allows only the necessary metal to be printed onto the substrate. Specifically, aerosol jet printing allows the deposition of features and lines down to 10 um. This poster will focus on the physical and electrical properties of a silver ink and a carbon-nanotube (CNT) ink printed using aerosol jet deposition. The resistivity of the inks is analyzed for deposition of features and lines down to 10 um. This poster will focus on the physical and electrical properties of a silver ink and a carbon-nanotube (CNT) ink printed using aerosol jet deposition.

The resistivity of the inks is analyzed for deposition of lines constructed from a varying number of passes of the printer. This method has been shown to achieve around 35x the bulk resistivity of silver itself. Interestingly, the resistivity appears to vary with the number of passes in which the line is deposited. The main plots shown on the poster will include resistivity vs. Ag/CNT inks for a defined structure and the quantification of contact resistance. Contact resistance was analyzed in order to increase accuracy of the resistivity calculations. The variability in contact resistance is thought to be an artifact probing a topographic and particulate structure.

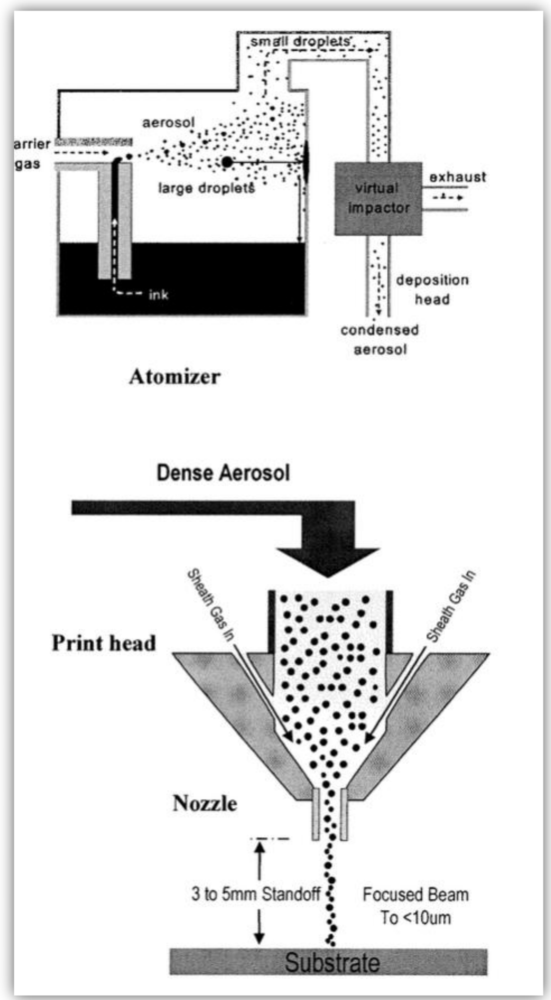
- Aerosol jet allows for targeted, high resolution material deposition.
- Additive manufacturing methods enable time and cost reduction in the design and fabrication cycle.
- Deposition parameters can influence the conductor's effective electrical properties.
- Silver represents the standard printed conductor while CNTs are interesting as non-metallic tunable conductors.

Introduction and Motivation

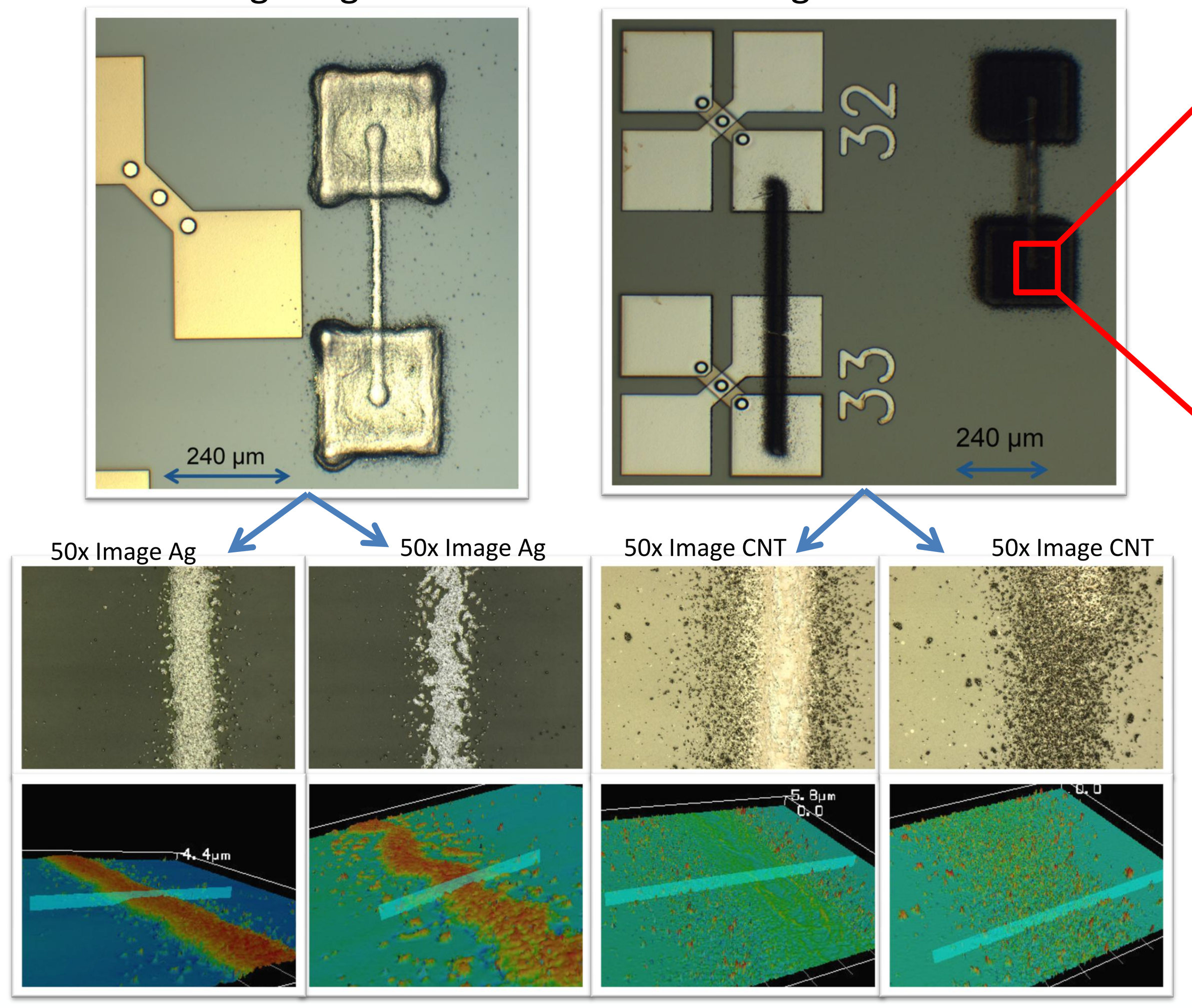
The 3-D printing industry, including aerosol ink jet technology, is evolving rapidly with over a \$3 billion market in 2013[1]. As Singh et. al. write, "The organic electronics roadmap identifies organic and printed electronics market to exceed \$300 billion in the next 20 years" [2]. Prior technology includes ink jet printing where the ink is simply pushed through a nozzle by the constriction of its reservoir chamber. Ink jet printing typically yields traces ≥ 20 μm^2. This technology has yielded resistivity for silver inks of approximately 5x that of bulk silver[3,4]. For carbon nanotube inks, literature has reported achieved sheet resistances of 40-115 kΩ/sq [5,6]. One of the latest developments has been the aerosol ink jet which allows for the printing of metals, dielectrics and other materials typically giving a resolution of up to 10 µm. The following poster will present resistivity data for a CNT ink and an Ag ink designed for aerosol jet deposition.

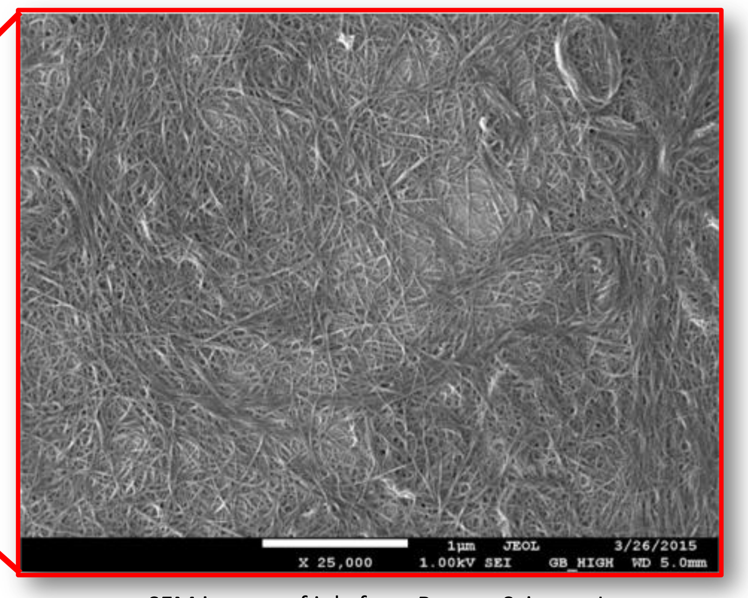
Aerosol Jet Printing: Technology & Results

The picture on the right outlines the aerosol jet printing process. In the upper picture, an ink is atomized through introduction to a carrier gas. Then the atomized material, in the form of a dense aerosol, is separated by particle size through a virtual impactor. The resulting aerosol is then pushed through the print head and deposited on the substrate.



Schematic of the Aerosol Jet printing process[7]

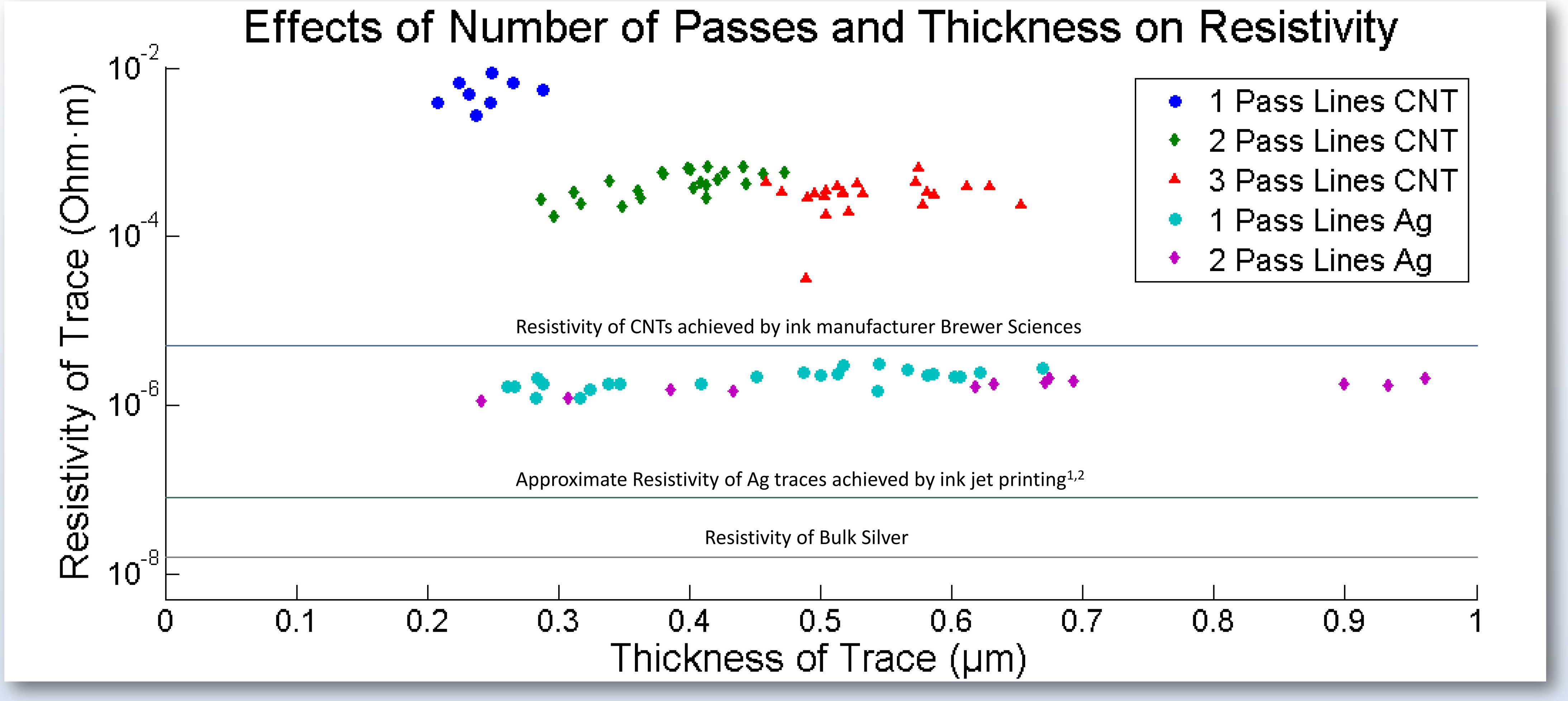




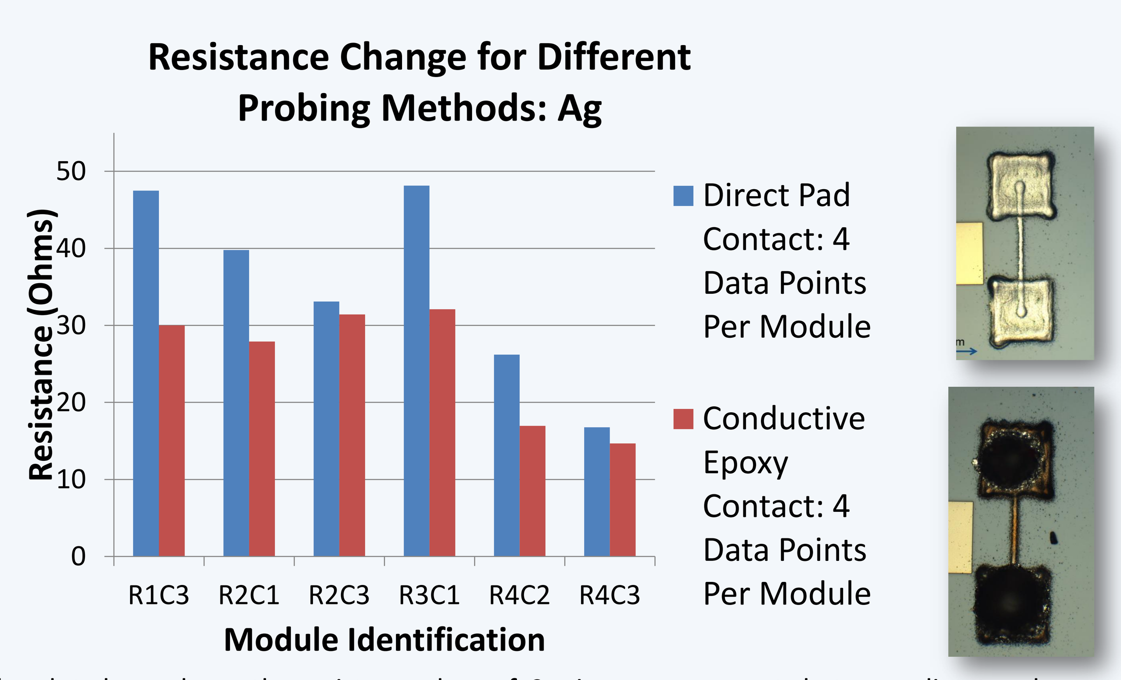
SEM images of ink from Brewer Science, Inc

The image on the left shows the CNT network after aerosol jet deposition. Larger rings of CNTs appear to form randomly on top of the material.

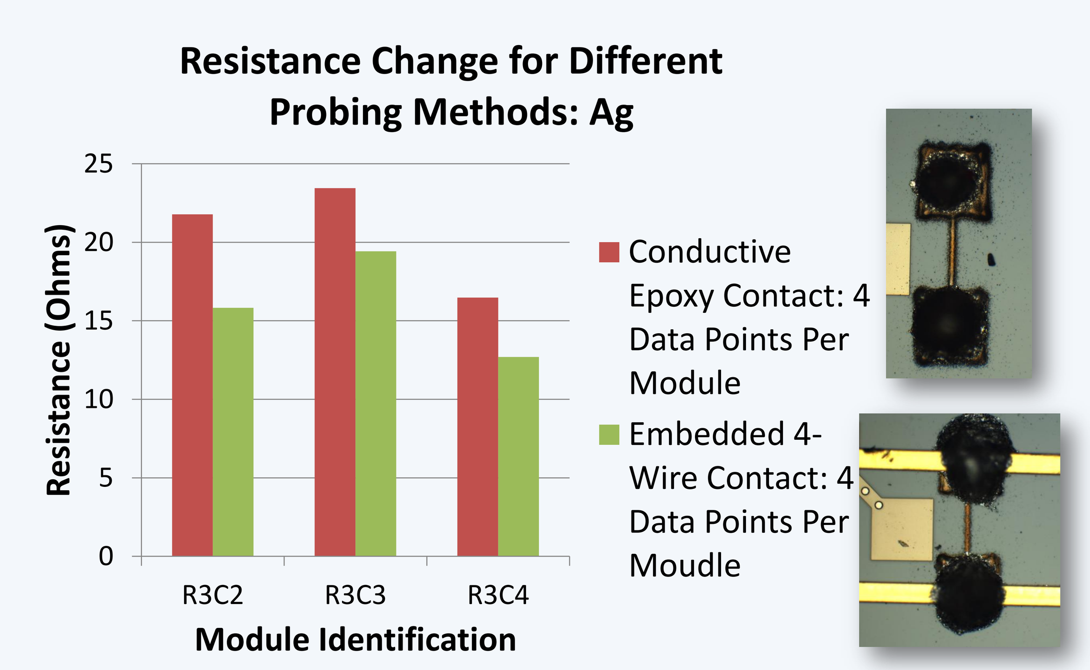
The pictures on the left show the pattern printed with both inks. 2 techniques were used to create the conductive traces: Either lines were printed onto Cu/Ti Pads or lines were printed along with pad structures. This can clearly be seen in the print image of the CNT structures on the left. Below the large picture of a printed unit with the Ag and CNT inks is a 50x microscope picture of two different lines for each ink. There can be a noticeable output drift when using aerosol jet deposition as shown in these pictures. Below the microscope pictures are 3-D confocal images of the lines.



- Both Ag and CNT inks are significantly less conductive than their respective printed benchmarks. Ag printed lines are approximately 2 orders of magnitude more resistive than bulk and 20 times more resistive than lines achieved by inkjet printing[1,2]. CNT printed lines are approximately 60 times more resistive than obtained by Brewer Sciences
- The CNT ink appears to show a dependence on pass number between 1 and 2+ passes. This is expected to be an artifact of material output drift during printing. Areas of less deposition have smaller cross-sectional area thus effecting resistivity.
- Further research is being done on the effects of aging on the resistivity
- SEMs of the CNTs were analyzed to determine the visual deposition characteristics of the tubes.



The plot above shows the resistance drop of 2-wire measurements between direct pad contact and contact onto conductive silver epoxy with probes. As can be observed, a substantial resistance change occurs. This demonstrates the significance of contact resistance in these measurements. Images of the two test cases are shown on the right.



The plot above shows the resistance drop between 2-wire probe measurements onto conductive silver epoxy with probes versus a four wire measurement done by embedding gold wire into the conductive silver epoxy. The difference is approximately the resistance of the wires in the probing station. Images of the two cases are shown on the right.

Materials

Conductor

- CNTRENE® 3023 A7-R SWCNT
  - Brewer Science, Inc
  - ~1.5 µm length, ~1.1 nm diameter
- Novacentrix® HPS-030AE1 Silver Ink
  - 143 nm particle size

Substrate and insulator

- Silicon
- Spin-on dielectric
  - DOW Intervia 8023

Conclusion

- **Resistivity of inks are not yet comparable to their respective benchmarks**
- **Pass variability to CNTs attributed to non-uniform deposition**
- **With these inks, replacement of MEMS fabrication techniques to achieve similar specs is not practical**
- **Prototyping with these inks can still provide useful data and expedite the design cycle**

Acknowledgements

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