Optimizing aerosol jet printing process of silver ink for printed electronics

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Abstract. Aerosol jet is an additive manufacturing technique that writes electronic inks directly onto the surface. The process has great potential for printed electronics as it is non-contact method that works well with variety of materials- metals, insulators, semiconductors, epoxy and encapsulation materials for conformal writing. This paper explores the effect of some parameters like ultrasonic power and atomizer flow on overall print quality, thus establishing a process window.

1. Introduction
The growing complexity of devices and emergence of multifunctional structures has made research and industrial community to look for alternate method of fabrication and material processing. Additive manufacturing has emerged as the promising candidate for creating complex 3D structures with easy processing [1]. Additive manufacturing builds an object through layer-by-layer deposition, and can embed functional elements in every single layer [2, 3]. Aerosol jet is an additive manufacturing technique that is based on droplet-deposition method and is widely explored for printed electronics. There are only few reports available where authors exploit aerosol jet for printing polymers and carbon based materials [4-6]. Seifert et al. do talk about differences between inkjet and aerosol jet [7], but none of the reports delve on the parameter influences of aerosol jet. Studying various parameters helps to establish guidelines for materials and contributes towards multi-material printing. Understanding parameter processing also give users an idea on what dimensions can be realistically printed.

This paper explores aerosol jet printing technique for printing silver electronic tracks on polyimide substrate. Both qualitative and quantitative analysis is carried out to determine the process window parameters to have controlled, repeatable and good line quality.

2. Aerosol jet printing
The basic schematic of aerosol jet printer is shown in figure 1. The Aerosol Jet process uses aerodynamic focusing to precisely deposit inks onto the substrates. The ink is placed into an atomizer, which creates a dense mist of material loaded droplets between 2- 5 µm in diameter. The aerosol mist is then delivered to the deposition head, where a sheath gas focuses it. When the sheath gas and aerosol pass through the nozzle, they accelerate and are focused into a tight stream of droplets flowing inside the sheath gas. The sheath gas also serves to insulate the nozzle from material contact preventing clogging. The resulting high velocity particle stream remains focused during its travel from...
the nozzle to the substrate over a distance of 2 to 5 mm maintaining feature resolution on non-uniform and 3D substrates. The system is driven by standard CAD data.

![Aerosol Jet Printer Schematic](image-url)

**Figure 1.** Schematic of Aerosol jet printing process.

Aerosol Jet printing is fast becoming an alternative for screen-printing and direct write methods like inkjet, as it allows smaller print resolution and deposition on non-planar surfaces [8, 9]. Such features give aerosol jet added flexibility, scalability and to print conformal multifunctional features in when compared to traditional technologies. Wide range of ink viscosities (1-1000 cP) and materials like metals, polymers, ceramic powders, semiconductors and insulators can be printed using aerosol jet.

### 3. Experimental section

Commercial silver nanoparticle ink (PRELECT TPS 50, Clariant) was used to print desired tracks on polyimide film substrate. Substrates were cleaned using ethanol prior to printing. The electronic tracks were designed in CAD and printed using aerosol jet (Optomec). Silver ink was dried at room temperature and later annealed at 200 °C for 60 min. Contact angle measurement was done to determine the wettability of silver ink on polyimide using an Attement Theta optical tensiometer and accompanying Biolin Scientific software. Inverted microscope (Olympus CKX41) was used for imaging the samples. Image J Software was used to quantify and measure the dimensions of printed part. Scanning electron microscope (SEM, Joel JSM-5600LV) was employed to determine surface morphology. All physical measurements were performed at least five times to achieve statistically significant results.

### 4. Results and discussion

The surface roughness of the polyimide film is measured to be 0.6 µm. The measured contact angle of the silver nanoparticle ink after printing is about 38°, indicating hydrophilic nature of the surface. There are many factors that will influence the quality of the final printed lines. In particular, substrate/ink combination, number of printed layers and print head speed are relevant to the printing quality. The width control of the aerosol beam and thus the line width of the deposited line are controlled by various parameters, but the most important of them are atomizer flow rate and ultrasonic power. This work investigates the effect of these two parameters on the overall print quality achieved using aerosol jet. The aim is to establish process window to allow printing close to designed values. It is to be noted that sheath gas flow (0), ink temperature (30 °C), platen temperature (70 °C) and process speed (10 mm/s) are kept constant throughout the experiments.

Figure 2a shows how the line width of printed line changes with ultrasonic current at constant atomizer flow of 14 ccm3. The thickness of the printed line increases with increasing ultrasonic
current. It is to be noted that 0.65 A is the maximum current that can be achieved with this aerosol jet printer. Also investigated is the change in line width with atomizer flow rate under constant ultrasonic current of 0.5 A (figure 2b). The curve in figure 2b tells us that when flow rate is below 16 ccm3, very less ink is deposited leading to discontinuous and breaking lines. For flow rate above 20 ccm3, excess ink is dispensed leading to bulging features on the substrate.

Figure 2. Line width as a function of (a) Ultrasonic current at constant atomizer flow of 14 sccm and (b) Atomizer flow rate under constant ultrasonic current of 0.5 A.

A good quality printed line is homogenous, continuous and adheres to the designed value. Figure 3a shows the process parameter combinations required to achieve a good printed line. Red, yellow and green zones signify discontinuous line, bulging line and good printed line quality respectively. The optical image of various printed lines is shown in figure 3. As discussed earlier, less ink in mist will lead to broken and irregular features. An overspray will form swollen and expanded prints. The overspray phenomenon is usually caused by the smallest droplets in the aerosol. However, changes in atomizer flow rate have much higher impact on the print quality than ultrasonic power. This means a small change in atomizer flow is enough to change the line width as against ultrasonic power. The table gives an indication of parameters that need to be used to have good printability. Atomizer flow rate between 15-20 sccm and ultrasonic current in range 0.4-0.6 A gives the best features for silver nanoparticle ink on polyimide substrate. It is to be noted that these parameters will change if ink, substrate and other parameters (that are kept constant) are varied.

Figure 4a shows a strain gauge pattern printed successfully on polyimide substrate. The aerosol jet has an added capability to write on curved surfaces, as shown in inset of figure 4a. Same strain gauge pattern is printed conformably on the dome shaped object using silver nanoparticle ink. The objective of printing the design is to get good print quality and narrow line-width of around 20 μm. The printed ink is further characterized using SEM to analyze the microstructure. Figure 4b shows sintered silver ink parallel tracks on polyimide. The printed pattern of strain gauge containing parallel lines depicts a good print quality as expected, with line width approaching 20 μm as desired. Such narrow and fine feature size is highly desirable for microelectronic and Nanoelectronic applications. The higher magnification image shows the particle size to be in the range of approximately 20-50 nm (figure 4c). The deposited silver film on polyimide is homogeneous and crack-free. Figure 4d also depicts 2.5 dimensional (2.5D) image of the pattern depicting the consistency of the printed features.

Hence, it was observed that when ultrasonic current was kept in the range of 0.3-0.6 A and atomize flow restricted to 16-20 sccm the print quality for silver is good. The deposited lines are close to design value and homogenous. The established parameters can also be used to write directly on 3D surfaces also, as shown for the dome structure.
| (a) | Line width (µm) |
|-----|----------------|
|     | 0.3 | 0.4 | 0.5 | 0.6 |
| Ultrasonic current (A) |     |     |     |     |
| Atomizer flow (sccm) | 14  | 14.9| 15.2| 17  |
| 16  | 20.7| 18.8| 21.8| 22.3|
| 20  | 37.5| 51.2| 31.1| 42.9|
| 25  | 90.5| 74.5| 73.6| 55.3|

**Figure 3.** (a) Print quality determination for two parameters in aerosol jet printing. Red, yellow and green zones signify discontinuous line, bulging line and good printed line quality respectively. (b), (c) and (d) Optical image of the good and bad features of printed silver ink.

**Figure 4.** (a) Image of printed strain gauge on polyimide substrate. Inset shows the same design written on a dome shaped object. SEM micrographs showing printed silver lines after annealing, (a) low- and (b) high magnified image. (d) 2.5D image obtained using optical microscope.
5. Future works
The future work may involve studying the effect of print passes and thickness variation for fabricating functional devices like antenna, sensors and transistors.

6. Conclusion
Aerosol jet printing is a unique additive manufacturing technique for fabricating miniaturized electronic circuits and components on various substrates for printed electronics. The process works with wide range of materials to create functional components on 2d and 3D surfaces. This paper investigates the effect of ultrasonic current and atomizer flow on the print quality of the silver tracks, and establishes the best parameter combination for the material. For the ultrasonic current ranging between 0.3-0.6 A, an atomizer flow of 16 sccm prints homogenous, continuous and crack-free tracks. Optical microscope and SEM are used to ascertain the quality of printed lines. Aerosol jet capability of direct-write is also demonstrated on a curved dome shaped structure.

References
[1] Chua C K and Leong K F 2015 3D printing and additive manufacturing-principles and applications, World Scientific
[2] Lopes A J, MacDonald E and Wicker R B 2012 Rapid Prototyping Journal 18 129
[3] Goh G L, Ma J, Chua K L F, Agarwala S, Yeong W Y and Zhang Y P 2016 Virtual and Physical Prototyping 11 1
[4] Yang C, Zhou E, Miyamishi S, Hashimoto K and Tajima K 2011 ACS Applied Materials and Interfaces 3 4053
[5] Liu R, Shen F, Ding H, Lin J, Gu W, Cui Z and Zhang T 2013 Journal of Micromechanics and Microengineering 23 065027
[6] Tait J G, Witkowska E, Hirade M, Ke T H, Malinowski P E, Steudel S, Adachi C and Heremans P 2015 Organic Electronics 22 40
[7] Seifert T, Sowade E, Roscher F, Wieme M r, Gessner T and Baumann R R 2015 Industrial & Engineering Chemistry Research 54 769
[8] Hong K, Kim Y H, Kim S H, Xie W, Xu W D, Kim C H and Frisbie C D 2014 Advanced Materials 26 7032
[9] Liu R, Ding H, Lin J, Shen F, Cui Z and Zhang T 2012 Nanotechnology 23 505301