

# HIGH RESOLUTION AEROSOL JET PRINTING OF CONDUCTIVE INK FOR STRETCHABLE ELECTRONICS

GUO LIANG GOH<sup>1</sup>, SHWETA AGARWALA<sup>1</sup>, WAI YEE YEONG<sup>1</sup>

<sup>1</sup>*Singapore Center for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore*

**ABSTRACT:** Stretchable electronics is gaining wide spread attention due to its application in many applications such as wearable devices, soft robotics, biomedical and consumer products. Aerosol jet printing, which is capable of printing very fine features, can be used to fabricate high performance flexible electronic devices. In this paper, we explore aerosol jet process technique to print conductive stretchable ink for fabricating new-age electronic circuits. Functional composite ink made of silicone and silver composite were used to print directly on stretchable silicone rubber substrate. Electronic functional devices such as flexible circuit and strain gauge were successfully printed, characterized and tested for stretchability.

**KEYWORDS:** Aerosol jet printing, stretchable electronics, 3D printing, Additive manufacturing, Printed electronics.

## INTRODUCTION

Flexible and stretchable electronics is an emerging technology that is revolutionary and developing fast. (Kim et al. 2012, Lu et al. 2014). Flexible and stretchable electronics can be used for smart electronic products such as flexible RFID tags (Kim et al. 2014, Shao et al. 2014), low cost sensors on food package (Zhang et al. 2013), and wound monitoring (Zhang et al. 2013). Stretchable electronics can be fabricated using various printing technologies such as gravure printing (Secor et al. 2014), flexographic printing (Leppäniemi et al. 2015) and screen printing (Pardo et al. 2000). These technologies are able to give acceptable print resolution (approximately 50 microns) for general electronic applications. For instance, Hrehorova et al. achieved a resolution of 75 microns using gravure printing and Hyun et al. achieved a printing resolution of 40 microns using screen printing (Hrehorova et al. 2011, Hyun et al. 2015). However, new-age and high performance electronic devices require better print resolution (Chang et al. 2012). Thus far, various printed flexible electronic components such as circuitry (Kim et al. 2008), resistors, capacitors (Li et al. 2012), transistors (Baeg et al. 2012), photodiode (Pierre et al. 2015) and OLED (Pardo et al. 2000) have been successfully demonstrated.

Among these printing technologies, aerosol jet printing is a relatively new and less-established additive manufacturing (AM) technology for printed electronics (Saengchairat et al. 2017, Tan et al. 2016), wherein researchers are still developing and trying to understand the process (Goth et al. 2011). Aerosol jet printing belongs to a class of AM technology where patterning of the functional inks is done by additively depositing the functional inks at desired location on substrates. Using the unique aerodynamic focusing technique, aerosol jet printing is capable of printing resolution as small as 10-20  $\mu\text{m}$  (Wang et al. 2013). Due to the nature of the printing process, aerosol jet printing technology is capable of doing conformal printing (Paulsen et al. 2012) and processing wide range of materials such as graphene (Song et al. 2017), carbon nanotube (Cao et al. 2017), metals (Krzeminski et al. 2017), etc. To date, aerosol jet printing has been reported as a fabrication tool for flexible solar cells (Mette et al. 2007), thin-film transistors (Jones et al. 2010), molded interconnect devices (Paulsen et al. 2012) and sensors (Liu et al. 2012).

This work explores aerosol jet printing to deposit stretchable ink on silicone rubber substrate. A parametric study of process parameters (sheath flow, atomizer flow, process speed) for printing of the stretchable ink with pneumatic atomizer is carried out to optimize the process. Both qualitative and quantitative analyses have been done to investigate the process window for controlled, repeatable and good quality print. Using the optimized parameters, a stretchable circuit was fabricated demonstrating flexible and stretchable electronic devices.

## **EXPERIMENTAL SECTION**

### **Ink and Substrate Preparation**

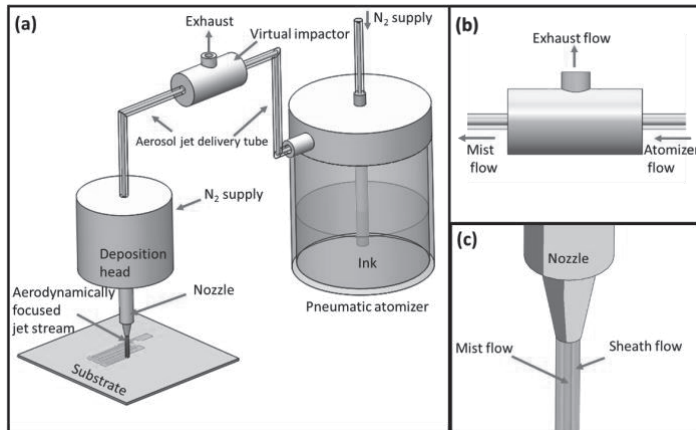
The ink used in this work is the electrically conductive stretchable ink (127-30, Creative Materials) specially tuned for Optomec aerosol jet printer. The ink is repeatedly stirred and sonicated for 30 minutes to ensure homogeneous solution. The ink contains silver particle fillers dispersed in liquid silicone ink with viscosity of 250 cps, which adheres well to substrate such as silicone substrate which normally has low surface energy. The ink turns conductive after sintering for few minutes at 170-180°C in a heat convection oven. The silicone rubber substrate is cleaned by sonicating in ethanol to remove dust and contaminants prior to printing.

### **Aerosol jet printing**

Aerosol jet printing technique comprises 3 stages, which are (i) atomization stage, (ii) aerosol delivery stage, and (iii) deposition stage as shown in Figure 1a. The first stage, which is the atomization stage, involves the formation of aerosols or droplets of the ink. The ink is normally placed in an ink reservoir and secured in place inside the pneumatic atomizer. The pneumatic atomizer consists of a venture tube and a nozzle, which is used to generate aerosol of ink. Tiny droplets of ink are formed when it is forced through the nozzle at high speed. The atomization rate is dependent on the atomizer air flow and the ink viscosity. The viscosity of the ink can be tuned by regulating the temperature of the water bath. Once the aerosol is formed, it is then transported to the deposition head via a delivery tube. At the deposition head, the aerosol flow is then aerodynamically focused by sheath flow. The sheath flow also helps eliminate clogging issue by acting as a barrier for the aerosol ink from sticking to the inner wall of the nozzle as shown in figure 1c. Once focused aerosol flow comes out of the nozzle, the flow can remain focused up to approximately 5 mm, which is the standoff distance of the nozzle from the substrate. In order to pattern the ink, the deposition head and the build platform are controlled by motion controller forming 5-axis motion. As aerosol jet printing is a single nozzle direct write technique, patterning of the ink is done by printing line after line. The toolpath of a pattern can be generated by using VMTools® plugin for AutoCAD®.

### **Characterization**

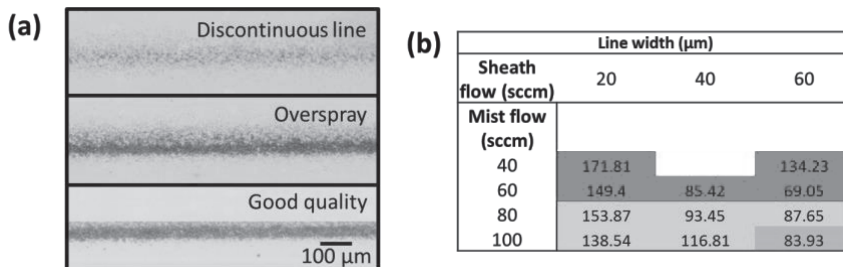
Scanning electron microscope (SEM), JOEL JSM-5600LV model, was employed to determine the surface morphology of the printed films. Aerosol Jet (Optomec 5X) 3D Printing system is utilized to print the line pattern. AutoCAD® software is used to create the line pattern and the toolpath is generated by VMTools®. The printed line is then measured using Olympus SZX7 optical microscope. All physical measurements are performed at least five times to achieve statistically significant results.



**Figure 1.** (a) Aerosol jet printing with pneumatic atomizer, (b) Atomizer, exhaust, and mist flows flowing through the virtual impactor, (c) the mist and sheath flows at the nozzle.

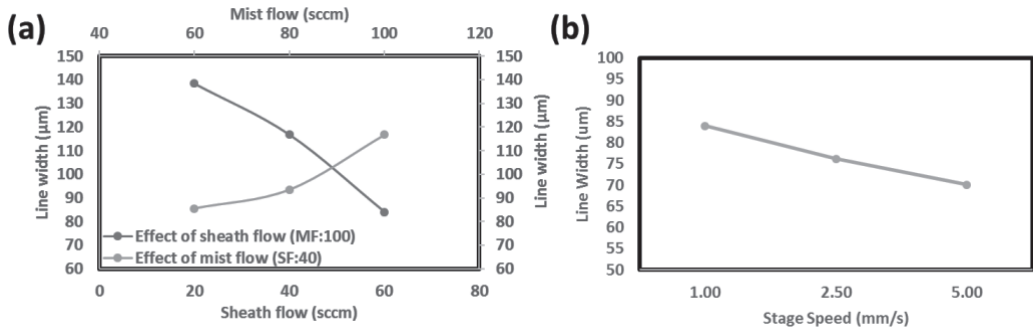
## RESULT AND DISCUSSION

In this work, the aerosol jet printing parameters that were investigated are the mist flow (MF), sheath flow (SF) and the print speed (PS). The mist flow is made up of highly dense aerosol of ink that flows out from the virtual impactor and the difference between the atomizer flow and exhaust flow through the virtual impactor determines the mist flow. Here, the mist flow is increased (40, 60, 80, and 100 sccm) by decreasing the exhaust flow (960, 940, 920, and 900 sccm) and the atomizer flow is kept constant (1000 sccm) to ensure similar aerosol generation rate at all conditions. Besides, the sheath flow is controlled at 20, 40, and 60 sccm to investigate its effect on the line width. For each condition, the 3 lines of 1 cm length were printed at print speed of 1 mm/s and the line width and features were observed using optical microscope. Figure 2a shows the different features (discontinuous line, overspray, and good quality) of aerosol jet printed lines using different process parameters. Figure 2b shows the process window of the aerosol jet printing parameters (sheath and mist flows) when using a 300  $\mu\text{m}$  nozzle and substrate temperature of 50  $^{\circ}\text{C}$ . The red cells indicate that the lines are discontinuous, the blue cells indicate that the lines have overspray issue, and the green cell indicates that the line has good quality. It also shows that the minimum printed line width of 84  $\mu\text{m}$  can be achieved using sheath flow of 60 sccm and mist flow of 100 sccm.



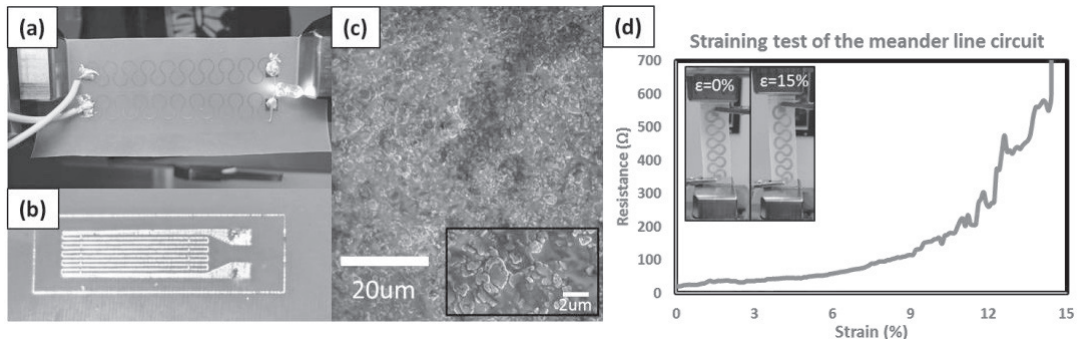
**Figure 2.** (a) Optical images showing the features of aerosol jet printed lines such as discontinuous line, overspray line, good quality line, (b) the process window of aerosol jet printing parameters (sheath and mist flows)

Figure 3 shows the trend of varying SF, MF, and PS respectively. Figure 3a shows that the line width decreases with increasing sheath flow and line width increases as the mist flow increases. The decreasing line width is due to the narrowing of the aerosol jet stream when more sheath flow going through the nozzle. On the other hand, the increasing line width is due to more ink being deposited onto the substrate when mist flow increases. Figure 3b shows the line width decreases with increasing print speed. This is because the substrate will receive lesser ink per unit time as the print speed increases and hence smaller line width.



**Figure 3.** Trends of the line width with (a) sheath flow (SF) and mist flow (MF) and (b) print speed (PS).

As proof-of concept, a stretchable circuit with meander line design is printed on a silicone rubber substrate. Following printing, the circuit is sintered at 120 °C for 2 hours. Finally, connecting wires and LED bulb are attached to the contact pads on the circuit using conductive silver epoxy. The circuit can be powered using a battery or a voltage source. Figure 4a shows a functional stretchable meander line circuit printed on silicone rubber substrate with LED still lighting up while being stretched. Potentially, the same technique can be used to print stretchable strain gauges with fine features as small as 80 μm as shown in figure 4b. A strain test is conducted to test the strain limit of the meander line circuit, and it is found that the stretchable meander line can be strain up to 15% before breaking. This shows that the stretchable ink and the silicone rubber substrate are suitable for making functional stretchable electronics.



**Figure 4.** (a) Optical image showing functional meander line circuit with LED lighting up while being stretched, (b) Strain gauge with very fine features, (c) Surface morphology of the sintered conductive silicone/silver composite ink (d) Straining test of meander line circuit.

## CONCLUSIONS

Aerosol jet printing, an additive manufacturing technique, is explored to print flexible and stretchable electronic device such as a stretchable circuit and a strain sensor. The fine resolution and conformal printing of aerosol jet printer allows new feasibility of designing and producing high performance devices. Parameters like sheath flow, mist flow and print speed are optimized to obtain a good print quality of the printed line traces. A homogeneous and continuous conductive stretchable silver-silicone composite material line trace with line width of 80  $\mu\text{m}$  is printed with optimized parameters. Strain analysis reveals the printed stretchable circuit can function normally within strain of 15%. A stretchable meander line circuit with LED is fabricated and remained functional while being stretched.

## ACKNOWLEDGEMENTS

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore under its Medium-Sized Centre funding scheme.

## REFERENCES

- Baeg, K. J., Khim, D., Kim, J., Yang, B. D., Kang, M., Jung, S. W., You, I. K., Kim, D. Y. and Noh, Y. Y. (2012). "High-performance top-gated organic field-effect transistor memory using electrets for monolithic printed flexible NAND flash memory", *Advanced Functional Materials*, **22**(14), 2915-2926.
- Cao, C., Andrews, J. B. and Franklin, A. D. (2017). "Completely Printed, Flexible, Stable, and Hysteresis-Free Carbon Nanotube Thin-Film Transistors via Aerosol Jet Printing", *Advanced Electronic Materials*, **3**(5).
- Chang, J., Ge, T. and Sanchez-Sinencio, E. (2012). Challenges of printed electronics on flexible substrates. Circuits and Systems (MWSCAS), 2012 IEEE 55th International Midwest Symposium on, IEEE.
- Goth, C., Putzo, S. and Franke, J. (2011). Aerosol Jet printing on rapid prototyping materials for fine pitch electronic applications. Electronic Components and Technology Conference (ECTC), 2011 IEEE 61st, IEEE.
- Hrehorova, E., Rebros, M., Pekarovicova, A., Bazuin, B., Ranganathan, A., Garner, S., Merz, G., Tosch, J. and Boudreau, R. (2011). "Gravure printing of conductive inks on glass substrates for applications in printed electronics", *Journal of Display Technology*, **7**(6), 318-324.
- Hyun, W. J., Secor, E. B., Hersam, M. C., Frisbie, C. D. and Francis, L. F. (2015). "High-resolution patterning of graphene by screen printing with a silicon stencil for highly flexible printed electronics", *Advanced Materials*, **27**(1), 109-115.
- Jones, C. S., Lu, X., Renn, M., Stroder, M. and Shih, W.-S. (2010). "Aerosol-jet-printed, high-speed, flexible thin-film transistor made using single-walled carbon nanotube solution", *Microelectronic Engineering*, **87**(3), 434-437.
- Kim, D.-H., Ahn, J.-H., Choi, W. M., Kim, H.-S., Kim, T.-H., Song, J., Huang, Y. Y., Liu, Z., Lu, C. and Rogers, J. A. (2008). "Stretchable and foldable silicon integrated circuits", *Science*, **320**(5875), 507-511.
- Kim, D.-H., Ghaffari, R., Lu, N. and Rogers, J. A. (2012). "Flexible and stretchable electronics for biointegrated devices", *Annual review of biomedical engineering*, **14**, 113-128.
- Kim, J., Wang, Z. and Kim, W. S. (2014). "Stretchable RFID for wireless strain sensing with silver nano ink", *IEEE Sensors Journal*, **14**(12), 4395-4401.

- Krzeminski, J., Wroblewski, G., Dybowska-Sarapuk, L., Lepak, S. and Jakubowska, M. (2017). Nanosilver conductive lines made by spray coating and aerosol jet printing technique. Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2017, International Society for Optics and Photonics.
- Leppäniemi, J., Huttunen, O. H., Majumdar, H. and Alastalo, A. (2015). "Flexography-Printed In2O3 Semiconductor Layers for High-Mobility Thin-Film Transistors on Flexible Plastic Substrate", *Advanced Materials*, **27**(44), 7168-7175.
- Li, Y., Torah, R., Beeby, S. and Tudor, J. (2012). An all-inkjet printed flexible capacitor on a textile using a new poly (4-vinylphenol) dielectric ink for wearable applications. Sensors, 2012 IEEE, IEEE.
- Liu, R., Ding, H., Lin, J., Shen, F., Cui, Z. and Zhang, T. (2012). "Fabrication of platinum-decorated single-walled carbon nanotube based hydrogen sensors by aerosol jet printing", *Nanotechnology*, **23**(50), 505301.
- Lu, N. and Kim, D.-H. (2014). "Flexible and stretchable electronics paving the way for soft robotics", *Soft Robotics*, **1**(1), 53-62.
- Mette, A., Richter, P., Hörteis, M. and Glunz, S. (2007). "Metal aerosol jet printing for solar cell metallization", *Progress in Photovoltaics: Research and Applications*, **15**(7), 621-627.
- Pardo, D. A., Jabbour, G. E. and Peyghambarian, N. (2000). "Application of screen printing in the fabrication of organic light-emitting devices", *Advanced Materials*, **12**(17), 1249-1252.
- Paulsen, J. A., Renn, M., Christenson, K. and Plourde, R. (2012). Printing conformal electronics on 3D structures with Aerosol Jet technology. Future of Instrumentation International Workshop (FIIW), 2012, IEEE.
- Pierre, A., Deckman, I., Lechêne, P. B. and Arias, A. C. (2015). "High Detectivity All-Printed Organic Photodiodes", *Advanced Materials*, **27**(41), 6411-6417.
- Saengchairat, N., Tran, T. and Chua, C.-K. (2017). "A review: Additive manufacturing for active electronic components", *Virtual and Physical Prototyping*, **12**(1), 31-46.
- Secor, E. B., Lim, S., Zhang, H., Frisbie, C. D., Francis, L. F. and Hersam, M. C. (2014). "Gravure printing of graphene for large-area flexible electronics", *Advanced materials*, **26**(26), 4533-4538.
- Shao, S., Kiourti, A., Burkholder, R. and Volakis, J. (2014). Flexible and stretchable UHF RFID tag antennas for automotive tire sensing. Antennas and Propagation (EuCAP), 2014 8th European Conference on, IEEE.
- Song, D., Mahajan, A., Secor, E. B., Hersam, M. C., Francis, L. F. and Frisbie, C. D. (2017). "High-Resolution Transfer Printing of Graphene Lines for Fully Printed, Flexible Electronics", *ACS nano*, **11**(7), 7431-7439.
- Tan, H., Tran, T. and Chua, C. (2016). "A review of printed passive electronic components through fully additive manufacturing methods", *Virtual and Physical Prototyping*, **11**(4), 271-288.
- Wang, K., Chang, Y.-H., Zhang, C. and Wang, B. (2013). Evaluation of Quality of Printed Strain Sensors for Composite Structural Health Monitoring Applications. SAMPE Fall Technical Conference, Wichita, KS, Oct.
- Zhang, B., Dong, Q., Korman, C. E., Li, Z. and Zaghoul, M. E. (2013). "Flexible packaging of solid-state integrated circuit chips with elastomeric microfluidics", *Scientific reports*, **3**.