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Editorial

The Investigations of Novel Circuits Printing on Substrates by Aerosol Jet Printing

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Aerosol jet printing (AJP) is a straightforward write–fabrication technique with high resolution, design flexibility, and integration capabilities [1]. AJP is capable of printing elaborate material textures on complex, flexible, and stretchable substrates, like delicate and intricate electronic and biocompatible sensors, bio-electrodes, antennas, LEDs, RFID tags, 3D interconnects, and even micro-coils for electronic packaging [2]. Specifically, AJP possesses the potential to enable novel and efficient chip packaging solutions, such as low-loss micro-strip lines (MSLs) and multi-material microwave package printing. Even the interconnect and chip-level stiffness gradients can also be elaborately fabricated by direct printing [2,3]. Moreover, AJP is capable of printing circuits on chip ceramic substrates for high-frequency applications, such as millimeter wave transmission lines [4,5].

In the AJP process, material compatibility, process optimization, and fabrication reliability are critical to maintain a smooth circuit printing process with excellent performance [1]. Ink selection is based on solutions or nanoparticle suspensions, including metals, alloys, ceramics, polymers, etc. [6]. However, suitable inks for printing on ceramic substrates attribute excellent adhesion, wetting, and compatibility with the substrate and also fulfill the electrical, mechanical, and thermal requirements [2]. Skarżyński et al. [7] explored silver nanoparticle ink with special parameters for micro-scale printed electronics, using AJP to enhance electrical conductivity and printability. Results showed that surfactants and dispersing agents were positive for improving ultrasonic atomization efficiency, the uniform structure of printed lines, and narrowing the width of patterns, with a significant decrease in resistivity compared to initially prepared inks. Pradeep et al. [8] applied aqueous silver ink to successfully and commercially print full-wave rectifiers (AC to DC conversion) and voltage bridge oscillators (DC to AC conversion). Hung et al. [9] further exploited the low-viscosity and high-compatibility ink with metals, non-metallic conductors, and polymers to finish the high-precision printing with a minimum resolution of up to 10 μm. Consequently, ink properties directly impact the quality of printed interconnects, passive components, and thin-film transistors. Proper ink selection ensures extraordinary deposition and adhesion during the printing process, which enhances the electrical conductivity and the resistivity of metallic patterns in uniform geometry and high-resolution on 3D substrates.

Moreover, critical process parameters, such as nozzle size, aerosol flow rate, jetting distance, substrate temperature, and relative humidity, assist in achieving contactless micrometer-scale feature size via adjusting the ink deposition, jetting, and curing [10,11]. Jeong et al. [12] exerted soluble silver clusters as the conductive ink to accomplish the line electrode formation process, aiming at establishing an operability window with optimized conditions for high-quality lines. Results showed that the line width could be statistically

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regressed and estimated by integrating sheath flow rate, atomizer flow rate, and dispensing speed. Lall et al. [13] successfully achieved the least amount of line resistance while maintaining print consistency by optimizing sheath rate, mass flow rate, nozzle size, and chiller temperature. Successively, Lall et al. [14] further applied atomizers to resoundingly print bi-material, multi-layer circuitry by investigating process parameters to acquire reliable multi-layer printing performance. In addition, the key parameters directly impact the morphology of the printed line when printing flexible circuits, which helps to understand the behavior of the printhead during deposition for achieving desired line characteristics on planar and even curved substrates.

Moreover, circuits with complex geometry and multiple functions on ceramic substrates require dependable circuit resistance, capacitance, inductance, voltage, current, etc. [15]. Such performance seriously depends on the printed materials, structures, and even post-processing, such as annealing, sintering, coating, etc. [2]. Wang et al. [16] introduced a novel post-treatment method to achieve high-performance electric circuits on an ULTEM substrate fabricated via fused deposition modeling (FDM). After post-treatment, surface property changes from scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS) revealed a significant improvement in printed electrical resistance. Hines et al. [17] elaborately discussed the post-testing conditions for AJP in optimally fabricating the hybrid electronic circuits. Zhao et al. [18] further investigated the effects of temperature, humidity, and bias on electrochemical migration to investigate situations in AJP circuit printing. Such treatments and testing enhance circuit conductivity, reduce resistance, optimize overall performance, and further ensure the printed circuits remain stable under various conditions. Specifically, post-treatment improves the adhesion between the printed lines and the substrate to strengthen the circuit's resistance to bending, stretching, and wear.

In summary, such corresponding investigations indicate that the appropriate ink selection dominates the printing precision and accuracy, influences conductivity, printability, and overall circuit quality, and is essential for achieving reliable, high-performance printed electronics. Optimized parameters, as a critical aspect of flexible electronics manufacturing, lead to low linewidth characteristics and improved conductivity, further ensuring precise, reliable, and efficient circuit printing. Moreover, post-treatment and testing verify the circuit's functionality, electrical parameters, and overall reliability and assess their long-term behavior to meet specifications and standards, consolidating the fabrication's reliability and circuit performance.

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