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Editorial

Special Issue on Printed Electronics 2017

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1. Introduction

Printed electronics is a new way of electronics, in which electronic system and components are directly produced on a rigid, flexible or stretchable substrate by low-cost coating and printing processes rather than traditional silicon-based processes. Not only have common printing technologies such as inkjet, flexography, gravure, screen printing and offset printing been utilized for printed electronics, but newly emerging additive manufacturing can also be considered a new platform for their applications. There are many advantages of using printing processes: low-cost manufacturing is achievable with low-temperature fabrication near ambient condition, and less wastes are generated. Since the advent of printed electronics in the early 2000's, it has attracted a great attention from research and industrial fields, and it is still considered one of the promising novel fabrication technologies for new functional electronic devices and systems such as flexible displays, smart labels, batteries and wearable electronics.

The purpose of this special issue was to disseminate the platform by highlighting challenges and recent advances in all the areas of printed electronics. All types of research articles with fundamental and applied nature were invited, and the invitation was open to all the related areas including, but not limited to, substrates, materials, printing and processing, equipment, fabrication of devices or systems, measurements and evaluations, and various applications. A total of 15 manuscripts were submitted to this special issue, and only 10 papers were finally published after rigorous peer review processes of *Applied Sciences*. The papers covers a wide range of topics including inkjet-printing, electrohydrodynamic (EHD) printing, nanoparticle production, plastic substrate, and applications for sensors, organic light emitting diode (OLED), and printed circuit boards (PCBs). This editorial briefly summarizes the primary contributions of the published papers.

2. Printed Electronics

The first topic is related to inkjet printing process. Kwon et al. investigated geometrical characteristics of the inkjet-printed nanosilver lines on plasma-treated substrates [1]. They analyzed the fluidic behavior and hydrodynamic instability during line formation by using various printing variables such as surface energy, droplet overlap ratio, printing frequency, substrate temperature and printing procedure. They also found the interlacing overprinting procedure is more advantageous to fabricate thick and narrow nanosilver lines on a hydrophobic substrate. Kim et al. conducted measurement of the dynamic properties of inkjet-printed Ag thin films on various substrates such as polyimide, silicon wafer and glass using flexural wave propagation [2]. They fabricated beam-shaped Ag-printed substrates using pico-second laser cutting and measured Young's modulus and loss factor of the Ag thin films using laser Doppler vibrometer without any damage to the thin films. Experimental results combined with wave propagation analyses showed that Young's moduli of Ag films are around 46 to 90% of those of bulk Ag depending on substrates, and loss factors tend to increase with an increasing modulus.

The second topic presents current progress in EHD printing, which uses a high DC voltage to charge ink and produce an electrical field for jetting. EHD printing can generate a droplet much

smaller than a nozzle diameter, so higher resolution printing is feasible as compared with inkjet printing even though it has a limitation of low-speed and non-uniform line printing. A new vector printing method for EHD printing was proposed by Phung et al. in order to overcome this limitation and obtain uniform EHD-printed lines [3]. They developed an encoder processing unit as well as a built-in computer-aided design software to consider both the acceleration or deceleration region and the constant speed region of the moving stage. They also validated their new method by comparing it with a conventional method and found the new method produced more uniform patterns even at much higher printing speed. In the viewpoint of meniscus deformation and oscillation of EHD printing, Kim et al. investigated the influence of damping ratio on the stability of EHD jetting performance [4]. Damping ratios were controlled by adopting different nozzle geometries, and a simplified linear damping model was used to describe the oscillating motion of Ag ink inside the nozzle. The effects of damping ratio and natural frequency were discussed, and the relationship between jetting frequency and pulsating frequency was experimentally examined.

The next topic is about nanoparticles. Ag nanoparticle is one of the materials which are widely used in the field of printed electronics. There is one paper dealing with production of nanoparticles. Jeon et al. investigated the effect of the laser pulse width ranging from femtoseconds to nanoseconds on the mean diameter and the yield rate of Ag nanoparticles [5]. Laser beam controlled by a galvanometer scanner was irradiated onto Ag target in distilled water, and Ag nanoparticle produced by laser irradiation were analyzed using a transmission electron microscopy and a particle size analyzer. The mean diameter tended to increase as the laser pulse width increased from femtoseconds to picoseconds to nanoseconds. However, the femtosecond and a few picosecond region showed a similar mean diameter due to similar mechanism of nanoparticle generation with little heat transfer effect at the particle surface. The yield rate was found to be higher at a shorter pulse width.

Flexible plastic substrates are also an important factor for reliable printing of functional inks. He et al. focused the tension of a plastic film in roll-to-roll gravure printing [6]. They constructed the mathematical model for the tension of plastic film considering temperature effects in a web tension system, and compared the numerical results with the experimental ones for various input and output parameters using a gravure printing system with PET film. It was found that the drying temperature significantly affected the tension settling time of plastic film. Since plastic substrate is weak for high temperature, deformation or warpage of substrate could occur by an excessive temperature change. The curvatures and warpages of PCBs during a thermal solder reflow process were investigated by Liao et al. [7]. They employed strain gage measurement, full-field shade Moiré fringe measurement and finite element analysis for estimating the curvature and warpage of PCB under thermal loads. The strain data measured from strain gages at the top and bottom surfaces of PCB were found useful to evaluate the deformation or warpage of PCB with help of a proposed simple beam model.

The last, but not least, topic of the special issue is applications of printed electronics such as sensors, OLEDs and PCBs. Tortorich et al. reviewed inkjet-printed and paper-based electrochemical sensors with a focus on the key components that support the low-cost, point-of-care fabrication [8]. They introduced that inkjet-printed and paper-based electrochemical sensors are suitable for healthcare diagnostic application provided that materials and fabrication method are carefully selected. In this review, various fabrication methods such as screen printing and inkjet printing were described as well as various ink materials and their requirements. Electrochemical detection and its applications were also summarized with a sufficient number of references. Inkjet printing allows for a low-cost fabrication with a relatively high accuracy, whereas capillary action could be used to make pump-free microfluidic devices on paper-based substrates; therefore, authors concluded, with further progress in the field of printed electronics, the inkjet-printed and paper-based low-cost sensors would be implemented in near future. Another application for OLED was presented with nozzle-printed PEDOT:PSS by Yoon et al. [9]. They investigated the influence of mixing ratio of ethanol to PEDOT:PSS on the quality of nozzle-printed patterns and eventually the performance of OLED device which used the diluted PEDOT:PSS as a hole injection layer. OLED devices with uniform quality of luminance

were demonstrated with a proper selection of mixing ratio of ethanol. For PCB application, Kim et al. proposed a compact, multi-stack electromagnetic bandgap structure for suppressing GHz noise in multilayer PCBs [10]. The effect of design parameters on the noise suppression characteristics was examined using a numerical analysis, and the suggested bandgap structure was experimentally tested and compared with simulated results. The proposed structure showed the superior performance than the previous stepped-impedance structure.

3. Conclusions

In summary, this special issue has covered a variety of topics in the field of printed electronics, which is rapidly advancing from research to commercialization and whose application area is expanding to new forms of electronics for flexible display, energy harvesting, medical engineering etc. There are still many challenges to overcome and further investigation is required for more complete study. As further progress is made in this field, the advances and increasing demand will contribute to propelling the research in this exciting field in near future. I hope that readership will find the selection of articles in this special issue as instructive and stimulating as I did, and the works presented here will pave the way towards high-quality research and innovation in this emerging and continuously progressing field of printed electronics to further expand their future applications.

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Conflicts of Interest: The author declares no conflicts of interest.

References

1. Kwon, J.-S.; Lee, D.J.; Oh, J.H. Formation and characterization of inkjet-printed nanosilver lines on plasma-treated tlass substrates. *Appl. Sci.* **2018**, *8*, 280. [CrossRef]
2. Kim, D.; Kwak, Y.; Park, J. Effect of substrates on the dynamic properties of inkjet-printed Ag thin films. *Appl. Sci.* **2018**, *8*, 195. [CrossRef]
3. Phung, T.H.; Nguyen, L.N.; Kwon, K.-S. A vector printing method for high-speed electrohydrodynamic (EHD) jet printing based on encoder position sensors. *Appl. Sci.* **2018**, *8*, 351. [CrossRef]
4. Kim, S.H.; Kang, H.; Kang, K.; Lee, S.H.; Cho, K.H.; Hwang, J.Y. Effect of meniscus damping ratio on drop-on-demand electrohydrodynamic jetting. *Appl. Sci.* **2018**, *8*, 164. [CrossRef]
5. Jeon, J.-W.; Yoon, S.; Choi, H.W.; Kim, J.; Farson, D.; Cho, S.-H. The effect of laser pulse widths on laser—Ag nanoparticle interaction: Femto- to nanosecond lasers. *Appl. Sci.* **2018**, *8*, 112. [CrossRef]
6. He, K.; Liu, S.; Wang, K.; Mei, X. Thermal characteristics of plastic film tension in roll-to-roll gravure printed electronics. *Appl. Sci.* **2018**, *8*, 312. [CrossRef]
7. Liao, M.-C.; Huang, P.-S.; Lin, Y.-H.; Tsai, M.-Y.; Huang, C.-Y.; Huang, T.-C. Measurements of thermally-induced curvatures and warpages of printed circuit board during a solder reflow process using strain gauges. *Appl. Sci.* **2017**, *7*, 739. [CrossRef]
8. Tortorich, R.P.; Shamkhalichenar, H.; Choi, J.-W. Inkjet-printed and paper-based electrochemical sensors. *Appl. Sci.* **2018**, *8*, 288. [CrossRef]
9. Yoon, D.G.; Kang, M.; Kim, J.B.; Kang, K. Nozzle printed-PEDOT:PSS for organic light emitting diodes with various dilution rates of ethanol. *Appl. Sci.* **2018**, *8*, 203. [CrossRef]
10. Kim, M.; Ahn, S. A compact and multi-stack electromagnetic bandgap structure for gigahertz noise suppression in multilayer printed circuit boards. *Appl. Sci.* **2017**, *7*, 804. [CrossRef]

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