An Electrohydrodynamic (EHD) Jet Printing Method for Increasing Printing Speed

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Abstract
It is well known that drop-on-demand electrohydrodynamic (EHD) jet printing can make small dots and fine line patterns thereby. However, it is believed that drop-on-demand based EHD printing is only limited to very slow printing applications due to small dot size and limited jetting frequencies. In this study, we propose using the change of printed relic shape to enhance printing speed. For this purpose, high molecular polymer was mixed into the silver nanoparticles ink for printing. The proposed method could help to increase the printing speed and reduce the line-pattern width as well. The video of our recent development can be found from website: https://youtu.be/ak6Zl-9yE-c.

Introduction
In the field of nano-/micro-patterning applications Electrohydrodynamic (EHD) inkjet printing has drawn attention due to its high-resolution printing capability [1,2]. In printed electronics, line-patterns are required in various applications, such as conductive interconnects, sensors, and RFID [2]. To print the complicated patterns, drop-on-demand (DOD) printing with pulsed-triggering is preferred [2-5]. However, due to the small size of the droplets and limited jet frequency, the connected line patterns usually takes long time, which has been a critical drawback of EHD technology.

In this study, we investigate the use of the printed droplets shape to increase the printing speed as well as reduce the pattern linewidth. Herein, we proposed the high speed EHD printing method for the fine line patterns. For this purpose, the high molecular polymer solutions are added into the conventional silver nanoparticle ink. In this way, we can achieve higher printing speed by enhancing the controllability of deposited relics shape.

Materials and method for high speed patterning
The Ag-nanoparticles ink used in experiments is Harima Ink NPS-JL (Harima Chemical Inc., Japan), which has 53.5wt% of silver. Polymer solution used in the experiments includes 10wt% Polyvinylpyrrolidone (PVP, M_w = 1,300,000 – Sigma Aldrich, USA) in 90wt% Chloroform (Sigma Aldrich, USA). 2wt% polymer solution is mixed with 98wt% Harima Ink using magnetic bar to get the final material for printing process.
To form EHD jetting, a negative trapezoidal pulse voltage is applied to the substrate holder while superposed high DC voltage is applied to the nozzle part [5]. The maximum triggering frequency should depend on the pulse durations. For instance, when a pulse duration of 500 µs was considered, the maximum jetting frequency would be less than f_{limit} = 2 kHz [5]. The meniscus at the glass capillary nozzle tip is control by air pressure applied to the ink reservoir. The printing ability could be investigated by combination of jet-triggering frequency and moving speed of the substrate. The jetting was carried out on untreated glass substrate.

Results and discussion
Conventionally, in vector DOD printing, when the pulse-trigger signal is used, the distance between the droplets on substrate $d = v/f$, where v and f are printing speed and frequency, respectively. Assuming that the droplets are in round shape, overlapping of droplets is necessary to form continuous lines. However, the EHD pulsating jet has jet duration related to pulse voltage [5, 6]. It was shown that the duration of jet stream can be increased via pulse voltage. In this study, we are using ink to increase length of jet stream and thereby stretched relic can be obtained on the substrate. The relic shape is dependent on jetting frequency and printing speed. For example, the relic shape is likely to be round as shown in Fig. 1 (a) when the jetting frequency and moving speed was low (less than 750 Hz and 10mm/s). However, the moving speed increase could lead to the less round relic shape on the substrate. Here, the high frequency takes an important role, higher frequency shows more distinct effect. For instance, with the frequency of 1 kHz jetting and printing speed higher than 25 mm/s, the droplets formed as “bean shape” rather than round as shown in Fig.1 (b). If the frequency is above 1.25kHz, the continuous lines could be printed with the speed up to 50mm/s as shown in Fig. 1 (c). The printing method has additional advantages of reduction in the linewidth. The linewidth could change from ~20µm to 4µm when printing with the speed of 50mm/s and frequency higher than 1.25kHz are used. Here, as discussed in [5], the jetting stream occurs during a period of time Δt when the falling time of the pulse applies. The added high molecular polymer could help to increase the stretching as well as the jetting duration due to its stretchability. The triggering frequency could help to change equivalent DC voltage. In high frequency jetting, the equivalent DC voltage take over pulse effect, that could produce continuous and thin jetting like near-field electrospinning printing. Nonetheless, it has on-off controllability because the proposed method is based on DOD printing schemes.

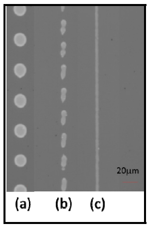

Figure 1. *Printed results (a) round shape droplets at printing speed 10mm/s and frequency 250Hz, (b) "bean shape" droplets at printing speed 30mm/s and frequency 1kHz (c) like-continuous high speed printing at 50 mm/s and 1.5kHz*

Concluding remarks

We discuss the ink modification effects on EHD printed relics shape on the substrate. The effects can be used to enhance the printing speed for line pattering. For this purpose, proper amount of high molecular polymer was added to ink. In low printing speed and low jetting frequency, the jetting behavior and round relic shape on substrate is equivalent to that of conventional DOD EHD printing. However, in case of higher printing speed, the jet behavior and relic shape becomes similar to continuous jet. In this way, high speed line printing using EHD can be achieved. In addition, the line width can be further reduced by using our proposed method. We are improving ink and other printing processes to use the method for industry applications.

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