Design of Electrohydrodynamic Lens for Stabilizing of Eletrohydrodynamic Jet Printing

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Abstract. The generation of micro patterns from conductive material suspensions is gaining significant interests for its usages in the fabrication of flexible display elements and flexible printed circuit boards. In this paper, we presented the results of line patterns of silver nanoparticles obtained by using various types of focusing lenses for electrohydrodynamic jet printing. The pattern widths were measured as 80~100 µm when the electrohydrodynamic lens having a cone-type inner hole and a cone-type outer wall was used. Electric field strengths were calculated by a commercial solver packages for the four types of electrohydrodynamic lenses. A lens having a cone-type inner hole and a cone-type outer wall of thinner thickness was found to be the best design.

1. Introduction
Direct write technologies are the most recent and novel approaches to form a fine pattern whose line width ranges from the meso to the nano scale [1]. As one of the direct write technologies, electrohydrodynamic jet printing uses the cone-jet mode of electrospray [2]. The deposition of nanoparticles by the electrohydrodynamic jet printing offers some advantages in fine patterning. First, by suitable fixing the flow rate and applied voltage and by optimizing the physical properties of the liquid, one can apply electrohydrodynamic jet printing to produce a narrow distribution (geometrical standard deviation ~ 1.1) of fine droplet (40 nm~1.8 µm) [3]. Second, the diameter of the nozzle (above 100 µm) is much larger than that used in ink-jet printing (about 20 µm in diameter). The use of a larger nozzle prevents blockage and allows easier processing of viscous suspensions containing high level (above 30 wt%) of solid particles [4]. Despite the use of much larger nozzles, the droplet sizes are much finer [5,6].

Numerous studies have been attempted to establish the principles of the cone-jet mode of electrospray and analyzed electric field strengths in electrohydrodynamic systems [7-10]. Recently, Poon [3] and Lee et al. [4] proposed printing technologies using the cone-jet mode of electrospray. They tried to make patterns by deposition of ceramic and metal suspensions. Especially, Lee et al. [4] tried to deposit silver nanoparticle suspension onto a polyimide film using the electrohydrodynamic jet printing including a guide ring and pin (nozzle)-to-pin (ground) electrodes. Deitzel et al. [11] indicated that the electric field was nearly uniform in a direction down the center of the electrode with hole,
when the electrode was located between the nozzle and the substrate. In this study, we designed and tested various types of electrohydrodynamic lenses for stabilizing the electrohydrodynamic jet printing. The electro-hydrodynamic lens was used to generate stable cone-jet mode and focus the jet to the target point of the substrate.

2. Experimental Setup

The experimental setup consisted of a liquid supply system, an electrical system, and a moving stage system. The liquid supply system included a syringe pump (minimum flow rate: 16.7 pl/min for 1ml syringe) and a stainless steel nozzle (inner diameter: 180 µm, outer diameter: 360 µm). A silver nanoparticle suspension was injected downward from the nozzle. The moving stage system consisted of an X-Y moving stage and a digital control system, in which a programmable motion-controller that communicated directly with a PC controlled the motion of a substrate. The electrical system consisted of a high voltage power supply (~DC 15kV) and two electrodes. The nozzle used for the liquid supply system was also used as an anode as well as an electrohydrodynamic lens, which was located 2.0 mm below the nozzle (Fig. 1). Figure 2 shows a magnified image of the rectangle ‘A’ in Fig. 1.

Figure 1. Schematic of experimental setup

Figure 2. Magnified image of rectangular in Fig. 1
Table 1. Geometries of electrohydrodynamic lens (unit : mm)

| EHD* lens | Upper part | | Lower part | | Height |
|-----------|------------|------------|------------|------------|--------|
|           | Outer Inner| Outer Inner|            |            |
| Type I    | 10         | 6          | 10         | 6          | 6      |
| Type II   | 10         | 6          | 10         | 4          | 6      |
| Type III  | 10         | 6          | 8          | 4          | 6      |
| Type IV   | 7          | 6          | 5          | 4          | 6      |

Figure 3 shows four types of electrohydrodynamic lenses. Type I lens has a cylinder-type inner hole and a cylinder-type outer wall while Type II lens has a cone-type inner hole and a cylinder-type outer wall. Type III lens has a cone-type inner hole and a cone-type outer wall. Type IV lens is basically same as Type III lens but has a thinner thickness than Type III lens. The detailed geometries of the four types are summarized at Table 1. Among the four types, Types I, II, and III were manufactured and tested. The material used was aluminum. Figure 4 shows lenses of Type II and Type III.
3. Results & Discussion

3.1. Feasibility testing of Type I lens.
Experiments were carried out when the Type I lens was used. Even though the pin-type ground electrode was not used, Fig. 5 shows that patterns of silver nanoparticles were successfully obtained. The pattern width was 150~170 µm.

![Figure 5. Optical image of a pattern (Type I lens)](image)

3.2. Patterning by using lenses (Type II, III)
Experiments were also carried out with lenses of Type II and Type III. Figure 6 shows patterns obtained by using the Type II and III. The pattern widths were about 100~120 µm and 80~100 µm when the Type II and III were used, respectively. The results show that pattern with lower width was generated when the Type III was used.

![Figure 6. Patterns obtained by using Type II and Type III lens](image)

3.3. 3D Simulation of electric field strength.
Electric field strengths near a lens were calculated by using a commercial solver package (Maxwell 3D, version 10). Figure 7 shows a cross-sectional view of electric field strengths between the nozzle and the lens in each of four types of lenses. The dotted lines in Fig. 7 indicate the degree of dispersion of electric field strength. When the Type IV lens was used for the calculations, the electric field strength was concentrated near the center of the lens and thus narrow electric fields were generated at the end of the lens. Consequently, it is expected that the jet break up would be minimized when Type IV lens is used.
4. Conclusions

This paper showed patterns of silver nanoparticles obtained by using various electrohydrodynamic lenses in electrohydrodynamic jet printing. The pattern width measured by using the Type I lens was 150~170\(\mu\)m. The pattern widths measured were about 100~120\(\mu\)m and 80~100\(\mu\)m when the Type II and III were used, respectively. The simulation results showed that the electric field strength was concentrated near the center of the lens and thus narrow electric fields were generated at the end of the lens, when the Type IV lens was used.

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