Structuring of Conductive Silver Line by Electrohydrodynamic Jet Printing and Its Electrical Characterization

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Abstract. A set of silver lines with a few hundred nanometers in thickness and with a few hundred micrometers in width were obtained using the electrohydrodynamic jet printing. The lines exhibited about three times higher resistivity (4.8 µΩcm) than that of bulk silver after thermal sintering process. The characteristic impedance of the silver line was about 18 Ω, while the value calculated was 20 Ω. This paper demonstrated the possibility of using electrohydrodynamic jet printing of silver nanoparticles to obtain conductive line onto circuit boards.

1. Introduction
Some novel printing methods of nanoparticles have been suggested in recent years. The printing methods for manufacturing circuits of a PCB (printed circuit boards) are very attractive since circuit pattern designs can be altered.

As one of the printing methods, electrohydrodynamic jet printing of nanoparticles can be used to obtain micro-sized lines onto a substrate [1]. When a liquid including nanoparticles is supplied to a nozzle and the interface between air and the liquid is charged to a sufficiently high electrical potential (~kV), the liquid meniscus has the shape of a stable cone, whose summit emits a microscopic jet. This is referred to as cone-jet mode in electrospray. Electrohydrodynamic jet printing is a printing method using the cone-jet mode of electrospray [1].

Deposition of nanoparticles by electrohydrodynamic jet printing offers some advantages in fine patterning. Because the diameter of the nozzle (> 100 µm) used is much larger than that of ink-jet printing (about 20 µm), blockages are prevented and the high viscous colloid containing solid particles can be easily processed [2]. Additionally, electrohydrodynamic jet printing directly creates patterns onto the surface of a substrate without lithography and does not require expensive equipments, while a laser-guided direct writing method or dip-pen nanolithography method requires a laser or AFM (atomic force microscope) equipment, respectively [3]. In the last few years a considerable number of studies have been made on principles and forces in electrohydrodynamic phenomena [4-7]. Lee et al. [3,8,9] made 1-D and 2-D patterns of metallic or ceramic nanoparticles using electrohydrodynamic jet printing, respectively, and showed that the resistivities of the patterns were low enough to be...
electrically conductive [3, 8]. Park et al. [10] showed the use of electrohydrodynamically induced fluid flows through fine microcapillary nozzles for jet printing of patterns and functional devices with submicrometer resolution. This paper demonstrated impedance of electrically conductive silver line printed using electrohydrodynamic jet printing.

2. Experimental setup

2.1. Electrohydrodynamic jet printing
Electrohydrodynamic jet printing system used in this study consisted of a nozzle, electrodes, power supply, and X-Y stage, as shown in Fig. 1 (a). A stainless steel nozzle (inner diameter: 180 µm, outer diameter: 320 µm) was used to produce a jet containing silver nanoparticles, which were uniformly supplied to the nozzle by a syringe pump (kds-100, KD Scientific Inc.) The nozzle was also used as anodes as well as a guide ring (inner diameter: 3.2 mm, outer diameter: 5.2 mm), which was located 0.03 mm below the nozzle. A pin-type electrode (400 nm in diameter) located 3.8 mm below the nozzle was used as the ground electrode to focus the jet onto the substrate, which was located 1.08 mm below the guide ring. The silver colloid, which consisted of 20 % silver nanoparticles and about 80 % ethylene glycol in weight with very small amounts of surfactants to prevent agglomeration between silver nanoparticles, was used. The geometric diameter of the silver nanoparticles was below 20 nm.

The experiments were conducted as follows. First, a jet was obtained by applying high voltage after silver colloid was supplied to the nozzle using the syringe pump. Using the jet, a set of lines were printed onto a substrate made of polyimide (thickness: 25 µm) when the stage was moved at 10 mm/s. Then, sintering process was conducted by heating at 230°C with atmospheric pressure for 1 hour at a constant heating rate of 2°C/min.

2.2. Measurement of electrical characterization
After sintering process, specific electrical resistivity, ρ, of the line was calculated by a formula, ρ = RA/l, where R is the electrical resistance of line, l is the length of the line, and A is the cross section area of the line. The resistance was calculated from an I-V curve measured by an I-V meter (4145B, HP). To calculate the cross section area (A = wt), the line width (w) and thickness (t) were measured by a laser scanning microscope (LSM 5 Pascal, Carl Zeiss) and an atomic force microscope (SPA 400, Seiko), respectively.

Characteristic impedance measurements of the conductive lines were performed with time domain reflectometry (TDR) using a serial data analyzer (Agilent 86100C). A block made of aluminum and SMA (Sub Miniature version A) connectors on the both sides of the block allowed reliable connection of the conductive line sample with the measurement equipment (Fig. 1 (b)). As shown in Fig. 1(b), a 50 Ω terminator was used for the reference of characteristic impedance when the characteristic impedance of the silver line was measured. The characteristic impedance (Z0) was also calculated by a formula (Eq.1) where h is the thickness of the substrate and εr is the effective dielectric constant [11].

\[
Z_0 = \frac{120\pi}{\sqrt{\varepsilon_r [W/h+1.393+0.667\ln(W/h+1.444)]}}
\]

\[\varepsilon_r = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1+12h/W}}\]
3. Results and discussion

Figure 2 shows images of the silver lines printed onto a polyimide substrate. It is shown that continuous silver lines were formed. Width and thickness of the lines were about 200 µm and 300 nm, respectively.

Figure 3 shows that I-V characteristic of a silver line was linear. The DC resistance of the silver line calculated from the slope of the line (Fig. 2) was about 20 Ω. The resistivity was approximately 4.8 μΩcm, which was about three times larger resistivity than that (1.6 μΩcm) of bulk silver after sintering process. Figure 4 shows that characteristic impedance measured by TDR method. When the TDR module on the oscilloscope was stimulated for the TDR analysis, the characteristic impedance, which was initially about 51 Ω, decreased to 18 Ω, but recovered soon. The minimum value, corresponding to the characteristic impedance of the line, agreed well with the theoretical characteristic impedance of 20 Ω calculated by the equation (1). The measurements were carried out for a finite length of the line, 20 mm.

4. Conclusions

A set of silver lines with a few hundred nanometers in thickness and with a few hundred micrometers in width were obtained using the electrohydrodynamic jet printing. The lines exhibited about three times higher resistivity (4.8 μΩcm) than that of bulk silver after thermal sintering process. The characteristic impedance of the silver line was about 18 Ω, while the value calculated was 20 Ω. This paper demonstrated the possibility of using electrohydrodynamic jet printing of silver nanoparticles to obtain conductive line onto circuit boards.
Figure 3. I-V curve of line printed onto polyimide substrate after sintering process.

Figure 4. Characteristic impedance of lines printed onto polyimide substrate after sintering process.

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References
[1] Poon H F 2002 Electrohydrodynamic Printing (Ph. D. Thesis, Department of Chemical Engineering, Princeton University)
[2] Yu J H, Kim S Y, Hwang J 2007 Appl. Phys. A-Mater. 89 157
[3] Lee D Y, Hwang E S, Yu T U, Kim Y J, Hwang J 2006 Appl. Phys. A-Mater. 82 671
[4] Fernandez De La Mora J, Loscertales I G 1994 J. Fluid. Mech. 260 155
[5] Ganan-Calvo A M 1997 Phys. Rev. Lett. 79 217
[6] Hartman R P A, Brunner D J, Camelot D M A, Marijnissen J C M, Scarlett B 2000 J. Aerosol. Sci. 31 65
[7] Jaworek A, Krupa A 1999 J. Aerosol Sci. 7 873
[8] Lee D Y, Shin Y S, Park, S E, Yu T U, Hwang J 2007 Appl. Phys. Lett. 90 081905
[9] Lee D Y, Yu J H, Shin Y S, Park D, Yu T U, Hwang J 2008, Jpn. J. Appl. Phys., in press
[10] Park J U, Hardy M, Kang S J, Barton K, Adair K, Mukhopadhyay K D, Lee C Y, Strano M S, Alleyne A G, Georgiadis J G, Ferreira P M, Rogers J A, 2007 Nature Materials 6 782
[11] Pozar D M 2003 Microwave Engineering (Wiley, 3rd edition) p 145