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Electrical Characterization of a Microstrip Line Patterned by Electrohydrodynamic Jet Printing of Silver Nanoparticles

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Abstract. *Direct write technologies on circuits of printed circuit boards are attractive since the circuit pattern can be altered and manufactured almost instantaneously. In this article, microstrip lines were patterned by using electrohydrodynamic jet printing of silver nanoparticles as one type of direct write technologies. Characteristic impedance and insertion loss of a microstrip line were measured. The characteristic impedance was about 23 Ω, which agreed well with the calculated value of 21 Ω. The insertion loss was below 3 dB for frequencies below 1.8 GHz. This article demonstrated the possibility of using electrohydrodynamic jet printing of silver nanoparticles to obtain microstrip lines on circuit boards. © 2009 Society for Imaging Science and Technology.*
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INTRODUCTION

Direct write technologies are the latest approaches to form fine patterns whose line widths range from mesoscale to nanoscales.[1] With a direct write approach, patterns or structures can be obtained directly without the use of variable fabrication processes, masks, and liquids for etching. Direct write technologies, therefore, are the low cost, high speed, noncontact, and environmental friendly processes.[2] The direct writing of circuits on a printed circuit board is very attractive since circuit pattern designs can be altered and manufactured almost instantaneously.

As one of the direct write technologies, electrohydrodynamic jet printing can be used to obtain lines onto a substrate. Electrohydrodynamic jet printing is a pattern method that uses a nanocolloid jet generated at the apex of liquid cone in the cone-jet mode of an electrospray. Nanoparticle deposition by electrohydrodynamic jet printing offers advantages in 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 highly viscous colloid containing solid particles can be easily processed. Additionally, electrohydrodynamic jet printing creates patterns directly onto the surface of a substrate without lithography and does not require expensive equipment, while a laser-guided direct writing method or dip-pen nanolithography method requires a laser or atomic force microscope, respectively.

Recently, several studies[3–7] have recognized the potential of electrohydrodynamic jet printing of nanoparticles. Sekitani et al.[3] obtained organic transistors by using the electrohydrodynamic jet printing with subfemtoliter accuracy. Park et al.[4] attempted to structure complex patterns of conducting polymers, silicon nanoparticles, and carbon nanotubes by using the electrohydrodynamic jet printing. Lee et al.[5,6] structured one-dimensional (pattern widths: 32–165 μm, pattern heights: 0.3–5 μm) and two-dimensional patterns (pattern widths: 100–250 μm, pattern heights: 0.1–0.3 μm) of metallic nanoparticles, respectively, and showed that the resistivities of the patterns were low enough to be electrically conductive. Additionally, Lee et al.[7] obtained ceramic nanoparticle patterns with uniform widths as fine as 25 μm, although a nozzle diameter (920 μm) much larger than the conventional ink jet nozzle diameter (approximately 20 μm) was used.

The transmission line is a part of the design considerations of circuits in various applications including printed circuit boards, packages, and microwave multichip modules. Due to the importance of transmission lines in many applications, their electrical characteristics (characteristic impedance and insertion loss) should be analyzed. In this article, as one type of planar transmission line microstrip lines were printed by using electrohydrodynamic jet printing of silver nanoparticles. A microstrip line is a thin flat electrical conductor separated from a ground plane by a dielectric layer.[8] The electrical characteristics of the resulting lines were measured. Figure 1 shows the experimental setup of electrohydrodynamic jet printing.

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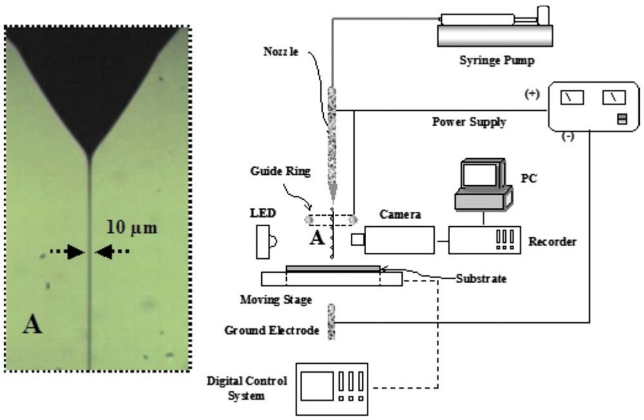

Figure 1. Experimental setup for electrohydrodynamic jet printing.

EXPERIMENTAL SETUP AND PROCEDURE

Electrohydrodynamic Printing

The experimental setup to obtain microstrip lines consisted of a liquid supply system including a syringe pump and nozzle, visualization system including camera and light-emitting diode (LED), electrical system, and moving stage system (Fig. 1). The electrical system consisted of a power supply, stainless steel nozzle, guide ring, and pin-type electrode. Both the nozzle and the guide ring were used as anode. The guide ring (inner diameter: 180 μm, outer diameter: 320 μm) was located 0.03 mm below the nozzle. The guide ring was installed to reduce the chaotic motion of the jet and prevented the jet from digressing from the centerline.[5] The 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 moving stage system consisted of an X-Y moving stage and digital control system. The stage was moved at 10 mm/s. The control system used a programmable motion-controller that communicated directly with a personal computer. The camera and LED in the visualization system were employed to monitor the cone-jet mode during the printing. The inset ("A") of Fig. 1 shows a Taylor[9] cone and a stable jet (cone-jet mode) when the applied voltage and flow rate were 5 kV and 2 μl/min, respectively. The diameter of jet was about 10 μm. The silver nanocolloid consisted of 20% silver nanoparticles (20 nm) and about 80% ethylene glycol in weight.

Figure 2 shows the experimental setup for electrical characterization. For structuring the lines, first the cone-jet mode was obtained with a high voltage, after silver nanocolloid was supplied to the nozzle by a syringe pump. Then, lines were printed on polyimide film (thickness: 25 μm), when the applied voltage and flow rate were 5 kV and 2 μl/min, respectively. After a set of silver lines was printed, the printed lines were sintered by heating at 220°C for 20 min in a convection oven. The polyimide film with sintered silver lines was placed on an aluminum block. The width and thickness of the lines were measured using a laser scanning microscope (5 Pa, Carl Zeiss) and an atomic force microscope (SPA 400, Seiko), respectively.

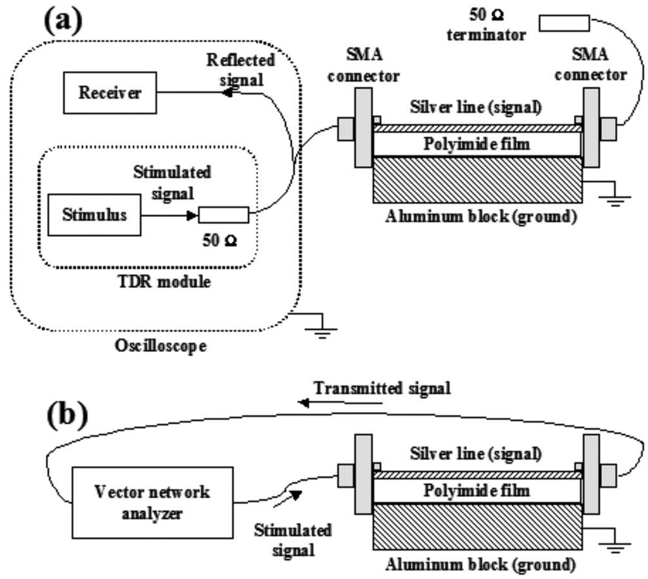

Figure 2. Experimental setup for electrical characterization.

Electrical Characterization

(1) Characteristic impedance. For the measurement of characteristic impedance, the time domain reflectometry (TDR) method was employed using an oscilloscope (86100C, Agilent) with TDR plug-in module (54754A, Agilent). Subminiature version A (SMA) connectors, on both sides of the block allowed reliable connection of the line sample with the measurement equipment. As shown in Fig. 2(a), a 50 Ω terminator was used for the reference. The diagram of the measurement setup is shown in Fig. 2(a). The characteristic impedance (Z_0) was also calculated by using

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_e}[W/h + 1.393 + 0.667\ \ln(W/h + 1.444)]}, \tag{1}$$

where W is the width of a line and ε_e is the effective dielectric constant of the line, which is given by

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} - \frac{1}{\sqrt{1 + 12h/W}} \tag{2}$$

in which h and ε_r are the thickness and relative permittivity of the substrate, respectively.[8]

(2) Insertion loss. To investigate the frequency characteristics of the line up to 6 GHz, we measured the insertion loss (S21 parameter) of the line by using a vector network analyzer (E8364A, Agilent). As shown in Fig. 2(b), the line was connected to the vector network analyzer using the SMA connectors. The S21 parameter of the line was also simulated by

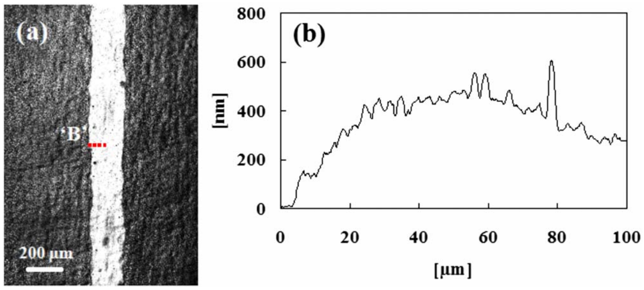

Figure 3. (a) Microphotographic image and (b) roughness profile of the silver line.

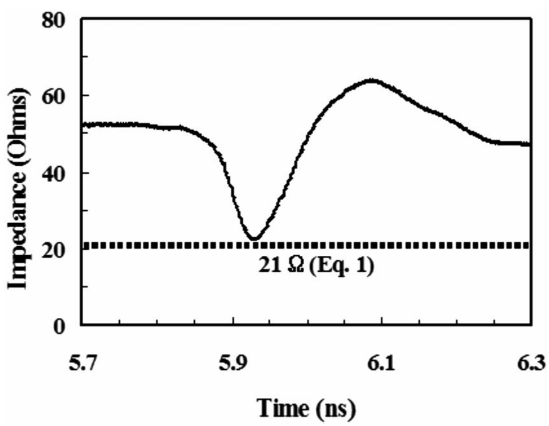

Figure 4. Characteristic impedance of a microstrip line.

using a commercial solver model [momentum in Advanced Design System (ADS) 2002, Agilent] based on the geometric characteristics of the line.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3(a) shows a magnified photo of a line after the sintering process. The average linewidth was about 200 μm. Fig. 3(b) shows the thickness profile of the dash line ("*B*") in Figure 3(a). The average thickness and root-mean-square roughness of the line were about 400 nm and 51 nm, respectively. Fig. 3 (color online) shows the (a) photoimage and (b) roughness profile of the silver line.

Figure 4 illustrates the characteristic impedance of a microstrip line while Figure 5 presents the insertion loss of microstrip line from 0 to 6 GHz. Fig. 4 shows that when the TDR module on the oscilloscope was stimulated for the TDR analysis, the characteristic impedance, which was initially about 53 Ω, decreased to 23 Ω, but recovered soon. The minimum value, corresponding to the characteristic impedance of the line, agreed well with the theoretical characteristic impedance of 21 Ω calculated by Eq. (1). The standard deviation of impedance for five repeated measurements was 0.8 Ω. The measurements were carried out for a finite length of the line, 20 mm. Fig. 5 shows the results of the insertion loss for applied frequencies of 0 to 6 GHz. The insertion loss was less than 3 dB for frequencies below 1.8 GHz but started to increase for frequencies above 2 GHz. Therefore, the printed microstrip line had a bandwidth of

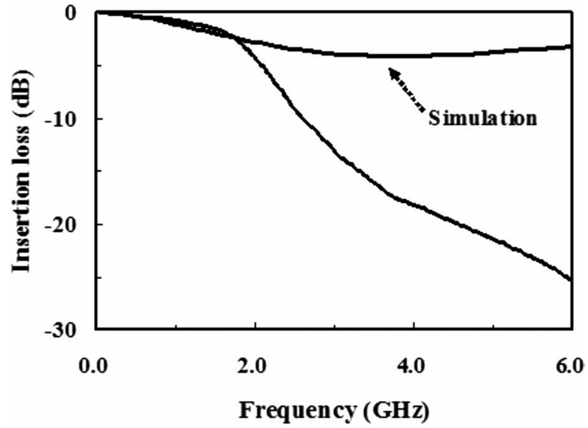

Figure 5. Insertion loss of the microstrip line from 0 to 6 GHz.

1.8 GHz. The standard deviation of bandwidth for five repeated measurements was 0.02 GHz. Fig. 5 also shows that the simulated results do not match the data for frequencies higher than 2 GHz. The simulation was based on a line having no roughness and porosity. However, when nanoparticles are printed onto a substrate, pores—which cause rough and porous morphology of a line—are inevitably generated.[10] The rough and porous morphology of the line causes additional losses in the electrical characteristics and the losses increase as the operating frequency increases.[11,12]

CONCLUSIONS

In this article, microstrip lines were patterned using electrohydrodynamic jet printing of silver nanoparticles, as a direct write technology. The microstrip lines were printed on a polyimide film (thickness: 25 μm) at applied voltage and flow rate of 5 kV and 2 μl/min, respectively. After the sintering process (220°C for 20 min), the average linewidth and thickness were about 200 μm and 400 nm, respectively. Characteristic impedance and insertion loss of a microstrip line were measured by using an oscilloscope and vector network analyzer, respectively. The characteristic impedance was about 23 Ω, which agreed well with the calculated value of 21 Ω. The insertion loss was below 3 dB for frequencies below 1.8 GHz but started to increase for frequencies above 2 GHz attributed to the roughness and porosity of the printed lines. The printed microstrip line had a bandwidth of 1.8 GHz.

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