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Effect of temperature on electrical conductance of inkjet-printed silver nanoparticle ink during continuous wave laser sintering

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ABSTRACT

To determine the effect of temperature on the specific electrical conductance of inkjet-printed ink during continuous wave laser sintering, the temperature of the sintered ink was estimated. The ink, which contained 34 wt.% silver nanoparticles with an average size of approximately 50 nm, was inkjet-printed onto a liquid crystal display glass substrate. The printed ink was irradiated with a 532 nm continuous wave laser for 60 s with various laser intensities. During laser irradiation, the *in-situ* electrical conductance of the sintered ink was measured to estimate the transient thermal conductivity of the ink. The electrical conductance and thermal conductivity of the ink was coupled to obtain the transient temperature by applying the Wiedemann–Franz law to a two-dimensional transient heat conduction equation. The electrical conductance of laser-sintered ink was highly dependent on the sintering temperature of the ink.

1. Introduction

The sintering process of metal nanoparticle ink is an important research area of inkjet printing technology. Printed metal nanoparticle ink on a circuit board may have a low conductance that degrades the performance of the circuit by increasing the RC-delay [1]. To improve the specific electrical conductance of the ink, a smooth path between metal nanoparticles should be formed to establish a path for electrons during heat treatment from 373 to 573 K.

During the sintering process of metal nanoparticles, the process temperature is known to be an important parameter. To adjust the temperature, a furnace is usually used for sintering metal nanoparticle ink; the furnace sintering temperature corresponds to an increase in the specific electrical conductance of the printed ink [2]. This process is completed at 473 K for an hour on flexible electronics, and has been described by Osch et al. [3]. The furnace and hot-plate sintering process can manage the large area substrate; however, the long process time may damage the glass or flexible substrate, making it vulnerable to excess heat. As an alternative, a laser sintering process concentrates laser energy on the printed ink for a shorter process time. Biery et al. used a continuous wave laser sintering process to heat ink with gold nanoparticles that are directly ejected from the piezoelectric inkjet nozzle at room temperature [4]. Chiolerio et al. concluded that continuous wave laser sintering of printed silver nanoparticle ink generally improved the specific electrical conductance of the radio frequency identification device compared with that of one treated by a hot-plate sintering process [5]. Until now, no study has been carried out to determine the relationship between the specific electrical conductance and the transient temperature of the conductive ink during the continuous wave laser sintering process.

In this study, the transient temperature of the silver nanoparticle ink during the continuous wave laser sintering process was estimated by solving a two-dimensional heat conduction equation. The *in-situ* transient specific electrical conductance was measured to estimate the transient temperature of the sintered ink by adopting the Wiedemann–Franz law during the continuous wave laser sintering process. The surface morphology was investigated by field emission-scanning electron microscopy (FE-SEM). The transient temperature of the laser annealing significantly affects the specific electrical conductance and surface morphology of the ink during the laser sintering process.

2. Experimental details

The conductive ink used had 34 wt.% silver nanoparticles with an average size of 50 nm. Eagle-XG (Samsung–Corning) glass substrates were used to eliminate the diffusion effect of alkali metals into the ink during the sintering process. Before we printed the ink onto the glass substrates, they were cleaned in an ultrasonic cleaner for 5 min. The substrates were then baked in an oven at 423 K for 900 s to remove any surface moisture.

Fig. 1 shows a schematic diagram of the laser sintering system and the pattern shape of printed ink. Silver nanoparticle ink was printed on Eagle-XG (Samsung–Corning) glass using a DMP-2831 inkjet printer (Dimatix). The patterned line size of the printed ink was

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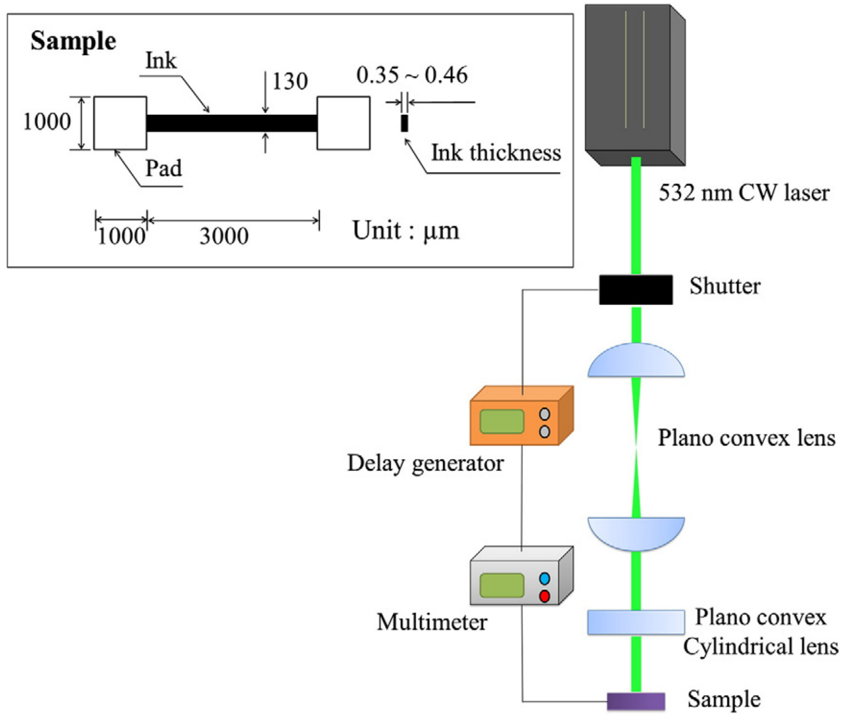

Fig. 1. Schematic diagram of the employed laser sintering system and pattern shape of printed ink.

3000 × 130 ×0.36 μm (length × width × thickness) and that of a pad was 1000 × 1000 μm. To reduce the pad resistance, the printed pads were furnace sintered at 323 K for 1800 s and then sintered at 523 K for 1800 s. The patterned line was printed after the pad sintering. Table 1 shows the initial resistances of the samples. An average value of the initial resistance was 226 Ω and the standard deviation was 21 Ω. During the laser sintering process, the printed ink was irradiated by a 532 nm continuous wave laser (Coherent). The shape of the laser beam was an ellipse, formed by using a convex spherical lens and cylindrical lens. To adjust the laser irradiation time and position of the laser beam, a shutter and an automatic translation stage were used. The *in-situ* electrical resistance of the conductive ink during laser sintering was measured from an L4411A multimeter (Agilent) which was connected to two S-725 micro positioners (Signatone) and probe tips (Signatone). To control the delay time between the multimeter and the shutter, a DG535 delay/pulse generator (Stanford Research Systems) was used. The laser beam power was measured with a power meter (FieldMax-Ⅱ, Coherent).

The printed ink was sintered with various laser intensities, 121, 222, 348, 467, and 585 W/cm^2, for 60 s. After continuous wave laser sintering, the cross-sectional area of the sintered ink was measured using the Alpha step IQ (Kla Tencor). The cross-sectional areas of the ink were measured at 5 different locations along the length of the ink. The average value of the area was used to obtain the specific electrical conductance of the ink. To investigate the surface morphology of the sintered ink, which is expected to cause electrical property variation, an FE-SEM (Hitachi S-4800) was used. Image analysis (Image Xpert) was conducted to determine the porosity of the sintered ink.

To find the normal reflectivity of the sintered ink as the temperature varied, the samples were spin-coated on glass substrates by an SC-80P spin coater (E-flex). The thickness of 10 μm was controlled by spinning at 250 rpm with a spin coater. The samples were sintered in a furnace at 323, 373, 423, 473, and 523 K for 1800 s. The refractive indices, n and the extinction coefficient, κ of the samples were measured by ellipsometry at room temperature.

Table 1
Measured initial resistance of inkjet-printed silver nanoparticle ink before continuous wave laser sintering.

Initial resistance [Ω]	Laser intensity [W/cm^2]
210	121
249	222
226	348
249	467
196	585

3. Temperature calculation

Fig. 2 shows a schematic diagram for temperature calculation. The x-axis and y-axis indicate width and thickness direction of ink and glass substrate, respectively. To determine transient behavior as a

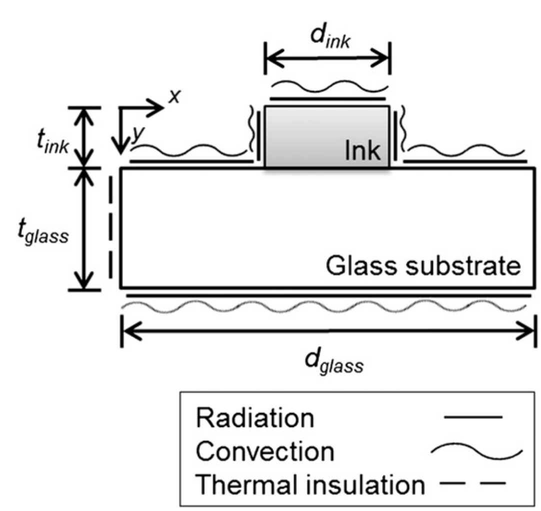

Fig. 2. Two-dimensional numerical simulation model for temperature calculation.