Effect of Porosity on Specific Resistance of Inkjet-Printed Silver Nanoparticles during Laser Sintering

Yoon Jae Moon[*,**], Heuiseok Kang[*], Kyungtae Kang[*], Sang Ho Lee[*], Jun Young Hwang[1*] and Seung Jae Moon[**]

[*]Korea Institute of Industrial Technology, Micro/Nano Scale Manufacturing R&BD Group
143, Hanggaul-ro, Sangnok-gu, Ansan-si, Gyeonggi-do, 426-910, Korea, jyhwang@kitech.re.kr
[**]Hanyang University, Seoul, Korea, smoon@hanyang.ac.kr

ABSTRACT

The printed electrode should be sintered to enhance electrical conductivity. The most commonly adopted sintering method is heating the whole substrate using an oven or hot plate. However, in this whole-substrate heating, the temperature-sensitive substrate and/or other already-printed layers frequently restrict the maximum temperature. Laser irradiation is ideal for the selective heating of two-dimensional patterns on a substrate. By scanning or tracking a focused laser beam, the precise amount of energy can be selectively transferred to the designed pattern. In nano-metal sintering, the electrical resistivity of nano-metals is related to their structure. Electrical resistivity is affected by grain size and density. Larger grains and denser films yield lower electrical resistivity. This work investigated the effect of porosity on specific resistance of silver nanoparticles with various laser intensities and irradiation durations. Conducting lines were printed on a glass substrate by a drop-on-demand (DOD) inkjet printer and silver nanoparticle ink. The conductivity and morphology of the laser sintered silver patterns were measured.

Keywords: Laser sintering, specific resistance, silver nanoparticles, porosity

1 INTORDUCTION

Photolithography is generally used to fabricate microstructures. This process requires many steps after thin film deposition. Recently, inkjet printing, a direct writing technology, has attracted growing interest for the production of micropatterns. In particular, inkjet printing of metal nanoparticles for electronic applications has been studied for decades[1, 2]. The printed electrode should be sintered to enhance electrical conductivity. The most commonly adopted sintering method is heating the whole substrate using an oven or hot plate [3]. However, in this whole-substrate heating, the temperature-sensitive substrate and/or other already-printed layers frequently restrict the maximum temperature. Additionaly, as the component materials advance and become more accurate and as the substrate becomes larger, which are the universal trends in displays and solar cells manufacturing, the heating process is apt to be more time-consuming, less energy-efficient, and more difficult to conduct accurately. Therefore, a locally selective and more rapid heating process, such as laser [4], microwave [5], or electrical sintering [6], is needed to sinter a target pattern with minimal thermal damage to the adjacent areas. Laser irradiation is ideal for the selective heating of two-dimensional patterns on a substrate. By scanning or tracking a focused laser beam, the precise amount of energy can be selectively transferred to the designed pattern. Electrodes with high electrical conductivity are advantageous to printed electronics because they can reduce the resistance-capacitance time delay to achieve high-speed circuits. In nano-metal sintering, the electrical resistivity of nanometals is related to their structure. Electrical resistivity is affected by grain size and density [7]. Larger grains and denser films yield lower electrical resistivity.

This work investigated the effect of porosity on specific resistance of inkjet-printed silver nanoparticles during laser sintering. Conducting lines were printed on a glass substrate by a drop-on-demand (DOD) inkjet printer and silver nanoparticle ink. Selective sintering of the printed silver nanoparticles was then performed using a laser beam to enhance electrical conductivity. A focused laser beam was irradiated normally to the silver layer printed on the transparent substrates with various beam intensities. The conductivity and morphology of the laser sintered silver patterns were measured..

2 EXPERIMENT

The ink (Advanced Nano Products, DGP 40LT-15C) contains 31 wt% spherical silver nanoparticles (with an average diameter of 50 nm), dispersed in triethylene glycol monoethyl ether (TGME). The suggested sintering duration ranges from 30 to 60 min at 150°C. The Eagle XG (Samsung-Corning) glass substrate was used to eliminate the diffusion effect of alkali metals into the ink during the sintering process. A DOD inkjet printing device (Dimatix, DMP-2831) consists of a cartridge-type jetting head and a controller that generate a series of droplets with a volume of approximately 10 pl, as well as a 2-D traverse stage, a monitoring camera, and a working bed. The patterned line size of the printed ink was 3000 x 130 x 0.3 μm (length x width x thickness), and contacting pads (1000 x 1000 μm) were also printed at both ends of the line for probes of an ohmmeter. The light source of the present laser sintering system is a laser (Coherent, Verdi-V5) with a wavelength of 532 nm and maximum output power of 5 W. Using a circular convex lens with a focal length of 500 mm, a circular beam and scanning method was used to sinter the printed lines. The laser beam size was measured using the knife edge method. The circular beam diameter was 360 µm. Maximum laser intensity was 5.2 kW/cm^2. The laser irradiation time was determined by the beam diameter and scan speed. Initial porosity was 0.243, which was calculated from the mesured volume of a known number of the droplets.

After sintering, the resistance of the sintered line was measured using a probe station (Signatone, 1160 series) and a milliohmmeter (Agilent, 4338B), and the cross-sectional area of the sintered line was measured using a profiler (KLA tensor, Alpha-step ASIQ). Using field emission electron microscope (FESEM), the morphology change of the laser-sintered silver nanoparticles was observed. Grain size was measured from the FESEM images

3 RESULTS

Figure 1 shows the change of specific resistance of inkjet printed silver nanoparticles with various intensities for 0.1 sec. Specific resistance decreased with increasing laser intensities. The decreasing rate of specfic resistance was reduced above 2.5 kW/cm^2 laser intensity. At this intensity, specific resistance was 3.4 x 10^{-8} Ωm. The minmum specific resistance was 2.1 x 10^{-8} Ωm at 5.2 kW/cm^2 laser intensity, which is 1.3 times higher than specific resistance of Bulk Ag

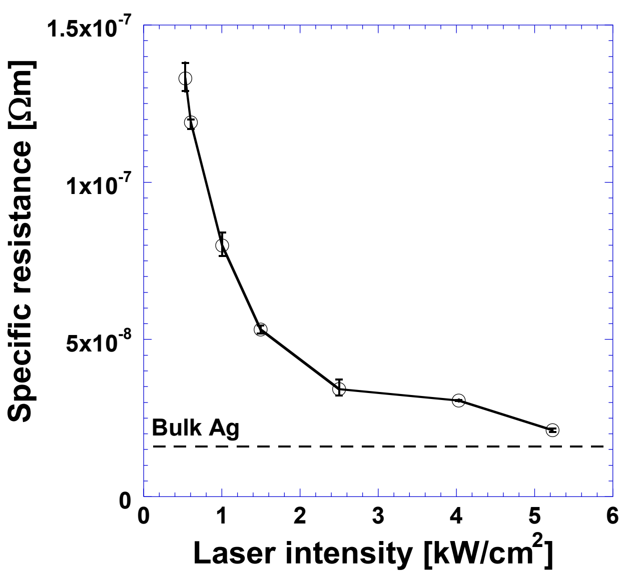

Figure 1: The change of specific resistance of silver nanoparticles with various laser intensities for 0.1 sec

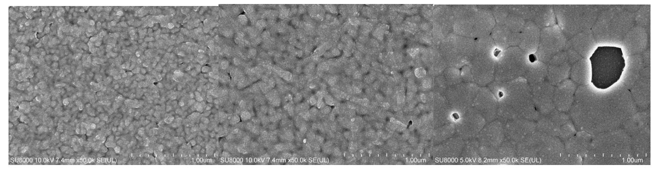

Figure 2: FESEM images of silver nanoparticles with various laser intensities for 0.1 sec; (a) 0.6 kW/cm^2, (b) 2.5 kW/cm^2, and (c) 5.2 kW/cm^2

Figure 2 shows the FESEM plan view images of silver nanoparticles with various laser intensities for 0.1 sec. As laser intensity increases, the connectivity between silver nanoparticles increases and neck formationa and growth occurred. At 5.2 kW/cm2, grains and pores grew.

Figure 3 shows the specific resistance which the porosity is zero and porosity as a function of average grain size. In Fig. 3, porosity decreased as average grain size increases. But, as average grain size exceeded the thickness of line, porosity increased. Specific resistance which porosity is zero was calculated by following equation[8].

$$\rho = \rho_0 \frac{1+kP}{1-P} \tag{1}$$

where ρ is resistivity of the porous pattern, ρ_0 is resistivity which prorosity is zero, P is porosity, and k is constant (when pore shape is spherical, k=0.5). When grain size exceeded the thickness of line, resistivity which porosity effect is removed from the porous pattern of silver nanoparticles reached that of bulk Ag. Specific resistance of. silver nanoparticles does not decrease any more due to the increase of porosity

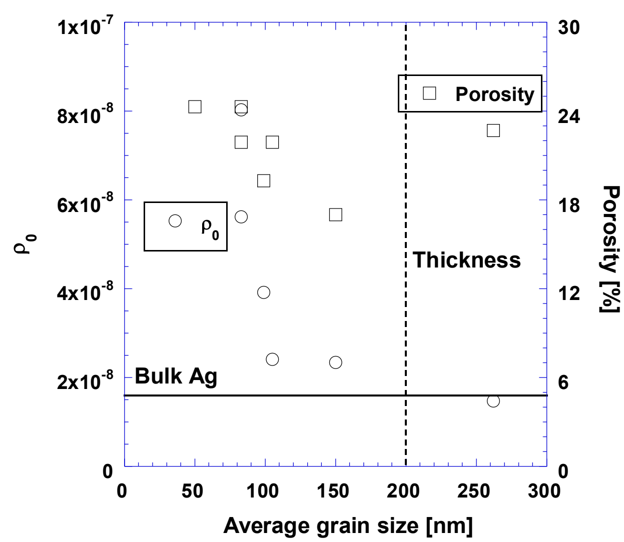

Figure 3: Specific resistances which the porosity is zero and porosity as a function of average grain size

4 CONCLUSION

Effect of porosity on specific resistance of inkjet printed silver nanoparticles sintered using 532 nm continuous wave laser was investigated. As grain size exceeded the thickness of line, porosity increased. As the effect of porosity is removed from the measured specific resistance, specific resistance of silver nanoparticles reached that of bulk Ag. Specific resistance of silver nanoparticles does not decrease any more due to the increase of porosity.

ACKNOWLEDGEMENT

This reaserch was supported by "Development of mask free process materials for the efficient manufacturing of a largesize LCD" and "Development of Non-lithography Manufacturing Technology for Flexible IT Devices".

REFERENCES

[1] J. Kwon, S. Park, M. M. Haque, Y. S. Kim, and C. S. Lee, J. Nanosci. Nanotechnol., 12, 3434, 2012

[2] P. Xu, X. Ji, V. Abetz, and S. Jiang, J. Nanosci. Nanotechnol., 11, 1135, 2011

[3] A. L. Dearden, P. J. Smith, D. Y. Shin, N. Reis, B. Derby and P. Brien, *Micromol. Rapid Commun.*, 26, 315, 2005

[4] N. R. Bieri, J. Chung, S. E. Haferl, D. Poulikakos, and C. P. Grigoropoulos, Appl. Phys. Lett., 82, 3529, 2003

[5] Y. S. Kim, T. J. Lee, W. H. Yoo, B. G. Chang, S. Y. Park, and Y. S. Oh, J. Microelectronics & Packaging Society, 14, 43, 2007

[6] M. L. Allen, M. Aronniemi, T. Mattila, A. Alastalo, K. Ojanpera, M. Suhonen and H. Seppa, Nanotechnology, 19, 175201, 2008

[7] X. Y. Qin, W. Zhang, L. D. Zhang, and L. D. Jiang, Phy. Rev. B, 56(19), 10596, 1997

[8] T. Mori and K. Tanaka, Acta Met., 21, 571, 1973