Low-temperature laser sintering of printed nano-silver electrodes for flexible electronics

Weibing Gu , Jian Lin and Zheng Cui*

Printable Electronics Research Centre, Suzhou Institute of Nanotech, Chinese Academy of Sciences, Suzhou 215123, PR China

* Tel：+86 512 62872705, Fax：+86 512 62603079, E-mail：zcui2009@sinano.ac.cn

ABSTRACT

In this paper, we demonstrated the continuous wave (CW,1064nm) laser sintering of nano-sliver electrode patterns printed by an aerosol jet printer on polyethylene terephthalate (PET) substrate. A laser sintering apparatus has been constructued which has precise control of laser spot size to 15um and can effectively minimize the damage of substrates and other functional layer in multilayer devices. The effects of the laser processing parameter on the sintering results including scanning speed and power were investigated. The electrical resistivity of laser sintered nano-silver electrode was measured to be $2.4\times10^{-6}\Omega$m which is similar to that achieved in conventional oven sintering.

Keywords: flexible electronics, printed electronics, nano-silver ink, laser sintering

1 INTRODUCTION

Printed electronics has received significant attention as a technology of low cost, large-scale, and sustainable production for device such as display, RFID tags, and sensors on flexible substrates. In printed electronics, components and patterns are formed from several layers of different functional inks. These inks contain additives to separate nanoparticles in order to achieve good printing properties. After printing, the ink is still wet. Hence, a thermal process is necessary to sinter the ink into a solid trace pattern before the next layer is printed. The heating evaporates the additives and dispersing agents and causes the nanoparticles to densify to form a solid thin layer.

Generally, sintering is implemented with a convection oven or hot plate. It can also be done with a laser, or a microwave oven. Oven sintering causes thermal stress on the surrounding materials, and the sintering temperature is limited by the most fragile material on the substrate. High thermal stress is a reliability risk and may damage the flexible substrate or destroy the function layer in a multilayer device because of the long duration of thermal load. As for nanosliver ink, low sintering temperature may prevent thermal damage to the substrates, but will lead to low electrical conductivity of electrodes, which has serious impact on the electrical performance of printed devices.

In order to overcome the drawback, we investgated laser sintering of nanosliver electrode patterns on PET substrate. Laser sintering is a selective sintering method, which can treat material locally and makes it possible to process only the printed ink patterns at higher temperature than the substrate material can tolerate.

2 EXPERIMENT

Materials: Nanoparticle silver ink from Bayer Corporation (TPS 50) was used for printing silver electrodes. The substrate that used throughout this work is flexible, transparent, 125um thick polyethylene terephthalate(PET, HS435) foil from Bayer MaterialScience.

Experimental set-up: The printer used is an aerosol jet printer (Optomec, Aerosol Jet 300P), where a pneumatic atomizer generates a aerosol droplet from a liquid solution and prints on a PET substrate. The deposition temperature were set at 60℃, and then the electrodes were sintered by a laser system. Nanoparticles were used to exploit the significant depression of sintering temperature (sintering is observed to occure in the range of 130-140℃) compared to the melting temperature of bulk sliver (961.78℃) due to thermodynamic size effect.

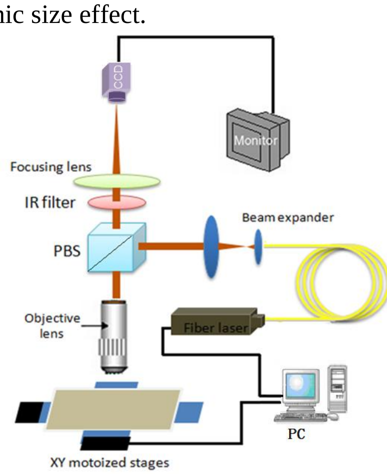

Fig 1: schematic diagram of Laser sintering system

The laser sintering apparatus is schematically shown in Fig. 1. The output wavelength of the laser (fiber laser, IPG, YLM-5-SC) is 1064nm with a power range of 0.5~5W in continuous wave mode. Mitutoyo long working distance objective lens, 10×, were used to focus the laser beam down to diffraction limit. The same objective lens was used for in-situ monitoring of the sample surface combined with a zoom lens and a CCD camera. The setup of laser sinter systerm is shown in Fig.2. With this apparatus, the laser spot size can be controlled to less than 15um (Fig 3). So the laser power density expressed as power per unit area(W/cm^2) is large enough (greater than $5kW/cm^2$) to sinter sliver nanoparticles.

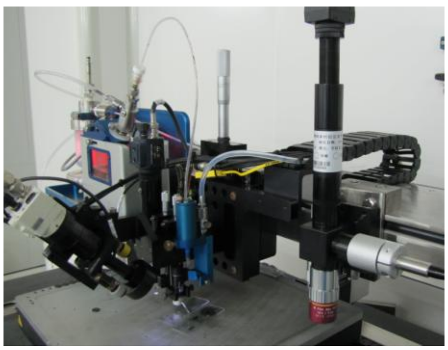

Fig 2: Setup of laser sintering system with Aerosol jet printer

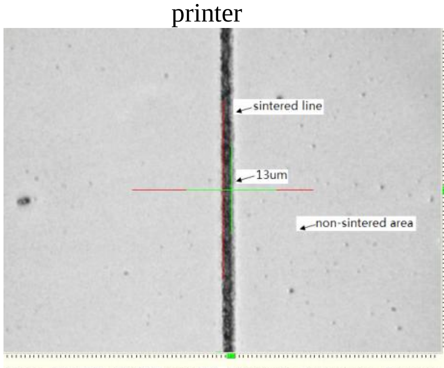

Fig.3: Image of line width sintered with laser focal point which is about 13um

The important parameters in the laser processing of nano-silver electrodes are laser power P, scanning speed V and laser size D. In this paper, we fixed the laser spot size at 15um. The mophology of nanosilver electrodes before and after laser sintering were characterized using scanning electron microscope(SEM, FEI, Quanta 400 FEG).

3 RESULTS AND DISCUSSION

3.1 Effect of laser scanning speed

To investigate the effect of laser scanning speedon sintering results, the laser power is fixed at 0.75 W while the scanning speed varied in the range 4-16mm/s as listed in Table 1, and corresponding sintering results are shown as in Fig.4 which are the SEM micrographs of surface morphology.

Table 1: Different laser scanning speeds used for sintering nano-silver electrodes

samples	D(um)	V(mm/s)	P(W)	J=P/VD(J/ cm^2)
a	15	4	0.75	12.5
b	15	8	0.75	6.25
c	15	16	0.75	3.125

When sintered at the scanning speed of 16mm/s, the electrodes had a porous and clustered microstructure, as shown in Fig.4(c) and (f). This behavior was attributed to partial sintering of sliver nanoparticles. As the laser irradiating on the ink, additives are evaporated from the ink. If the laser scanning speed is too fast, partially sintered nanoparticles rapidly solidifies to form the porous structure. For the same reason, nanoparticles in the electrodes can not gain enough energy to yield more liquid phase to form densified structure, resulting in a clustered microstructure.

Fig.4(b) and (e) show that when the laser scanning speed was reduced to 8mm/s, the porous microstructure was eliminated and relatively dense and lager particles were formed. However, at this scanning speed the laser energy was not high enough to fully densify the nanopartciles.

The SEM micrograph in Fig.4(a) and (d) show that as the laser scanning speed was further decreased to 4mm/s, more nanoparticles were sintered to form a dense and uniform microstructure. However, a wave-like morphology appeared on the surface, this is due to the high energy yielding more melting and liquid phase during laser spot scanning.

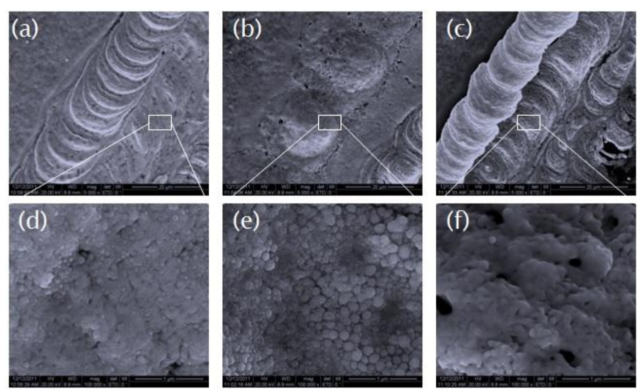

Fig.4 SEM micrographs of Ag electrodes using laser scanning speed of (a) 4mm/s, (b) 8mm/s and (c) 16mm/s with laser power of 0.75W. (d), (e) and (f) are magnified micrographs, respectively.

3.2 Effect of laser power

To investigate the effect of laser power on sintering results, the scanning speed was fixed at 8mm/s while laser power varied from 0.5W to 1.5W as listed in Table 2, and corresponding sintering results are shown as in Fig.5 which are the SEM micrographs of surface morphology.

Table 2: Different laser power used for sintering nanosilver electrodes

samples	D(um)	V(mm/s)	P(W)	J=P/VD(J/ cm^2)
a	15	8	0.5	4.16
b	15	8	0.75	6.25
c	15	8	1	8.3
d	15	8	1.5	12.5

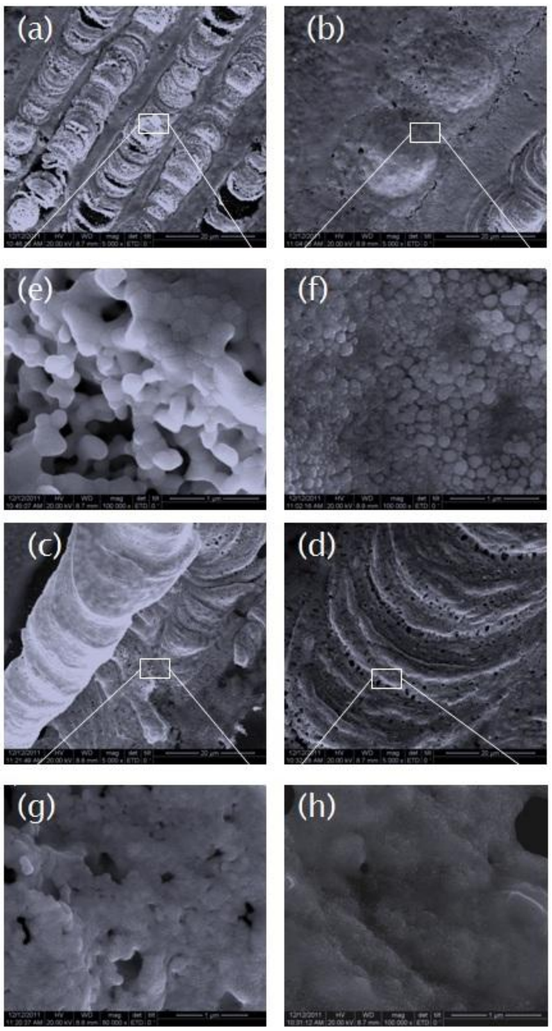

Fig.5 SEM micrographs of Ag electrodes using laser power of (a) 0.5W, (b) 0.75W, (c) 1W and (d) 1.5W with scanning speed of 8mm/s. (e), (f), (g) and (h) are magnified micrographs, respectively.

At laser power of 0.5W, the SEM micrograph in Fig.5(a) and (e) show that the electrode has a porous and clustered microstructure. It is again the aforementioned partial sintering effect. At laser power of 0.75W, the SEM micrograph in Fig.6(b) and (f) show that the nanoparticles in the electrodes were better sintered and formed denser structure. However, Fig.6(c, g) and Fig.6(d, h) show that with the further increase of laser energy, the surface became porous again, where nanoparticles have been ablated partially. From the experimental results and analysis, it was concluded that a laser power of 0.75W was optimum for the sintering.

The effect of higher scanning speed (16m/s) and higher laser power （0.5-2W）were also investiged. The optical micrographs of sintered silver lines are shown in Fig.6. It can be seen that the morphology of electrodes appears bubble-like with the increase of laser power. This phenomenon is due to excessive laser energy effect on the electrodes and the nanoparticles in the electrodes were ablated partially. When the laser power was adjusted to 2W, the PET substrate was damaged and nanoparticles were evaporated from the ink.

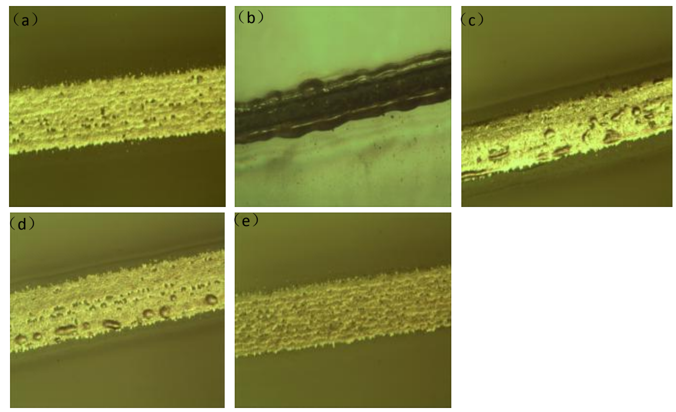

Fig.6 The morphology of printed Ag lines without sintered (a), sintered laser powers of (b) 2W, (c) 1W, (d) 0.75W, (e) 0.5W with scanning speed of 16mm/s.

The above results indicate that the laser power is a key parameter affecting the microstructure of nano-silver electrodes sintered by a laser irradiation. When the laser power is adhjusted with a fixed spot size, an appropriate laser energy density can be obtained, and a fine and dense microstructure can be achieved. The variations in laser scanning speed, laser spot size and laser power results in the changes of energy density. Therefore, there has to be a fine balance among the three processing parameters in order to achieve the optimum sintering results.

3.3 Conductivity measurement

Electrical resistivity(ρ) measurement was carried out to characterize the conductivity of the electrodes. The resistivity(ρ) is calculated from RA/L. The resistance R was measured with a probe station. A is the cross sectional area of electrode measured from confocal microscopy and L is the length of the test sample (10mm). In our experiment, the electrical resistivity was calculated to be $2.4\times10^{-6}\Omega m$ which similar to that achieved in conventional oven sintering. With the optimum laser sintering parameters, nanosilver electrodes with fine and uniform morphology have been obtained.

4 CONCLUSION

Laser sintering of nanosliver electrode patterns on PET substrate has been demonstrated. The optimized laser sintering parameters are the laser focal spot size of 15um, laser scanning speed of 8mm/s and laser power of 0.75W. Excellent quality of laser-sintered nanosliver electrodes have been achieved on PET substrate. The resistance of laser sintered conductive patterns is very close to that using conventional oven sintering. It proves that laser sintering is a promising alternative for sintering materials and substrates which cannot be subject to a high thermal load. This approach is also a faster curing method and is suitable for the fabrication of conductive patterns in flexible electronics.

5 ACKNOWLEDGEMENT

The authors thank the support of the Natural Science Foundation of China (Grant 91123034) and the Chinese Academy of Sciences (Grant KJCX2-EW-M02).

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