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Flash light sintering of ag mesh films for printed transparent conducting electrode

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ABSTRACT

Transparent conducting electrodes (TCEs) are fabricated through the flash light sintering of reverse-offset printed Ag mesh patterns. Interestingly, the narrower printing lines require a higher flash light energy to obtain an equivalent sheet resistance even if the same Ag nanoparticle ink is used. The microstructural development of sintered Ag nanoparticles is also retarded with the decrease of line width after the same flash light sintering. The temperature calculation in the Ag mesh patterns clearly reveals that heat dissipation is affected by the print dimension. To improve the performance of Ag mesh TCEs with 3 μm wide lines, a preheating step comprised of multi-pulses is inserted before a main flash light sintering. The multi-pulsed flash light sintering is effective in decreasing the sample temperature and in removing the substrate damages or microstructural defects. As a result, the flash light-sintered Ag mesh TCEs shows a sheet resistance of 27 Ω/□ and an optical transmittance of 84.7% including an optical transmittance of substrate.

1. Introduction

Transparent conducting electrodes (TCEs) are a key component in various display and photovoltaic devices [1–6]. Indium tin oxide (ITO) has been mainly used for TCEs to satisfy both optical transparency and electrical conductivity in spite of the high cost that originates from the vacuum coating and photolithograph etching processes as well as the material scarcity of indium [7–10]. In recent years, as an alternative to ITO, printed metal mesh films have attracted substantial attention due to their practical advantages of having a simple process, which is composed of printing and sintering, and the ease in controlling sheet resistance and optical transparency by changing the design parameters [11–14]. Printing on a flexible polymer substrate can facilitate the introduction of a roll-to-roll(R2R)-based mass production system. Thus, besides metal mesh films, various solution-based materials, such as metal nanowires, graphene, and carbon nanotubes (CNTs) have been simultaneously adopted for electronic devices as ITO-free approaches [15–17]. However, post-heat treatment requires a temperature that is higher than the glass transition temperature (Tg) of conventional polymer substrates, which plays a technical obstacle for fabricating flexible TCEs on polymer substrates [18,19].

The flash light sintering technique has a remarkably fast sintering time that is compatible with the R2R-based printing speed [20–32]. In recent years, R2R-based photonic sintering has been carried out on flexo- or inkjet-printed silver nanoparticles by optimizing web speed, flash frequency, energy, and overlapping exposure areas [30–32]. Printed silver or copper films were converted to highly conductive electrodes after being exposed for only a few milliseconds at room temperature under an ambient condition and they showed excellent bending strength [33]. As a main mechanism of flash light sintering, it has been considered that the absorbed light energy through the plasmonic resonance of metal nanoparticles was converted to thermal energy [34,35]. The rapid increase of temperature inside printed films was monitored in real time during the flash light sintering process [28,36]. The side effects of surface cracks and film delamination were observed to originate from the abrupt evaporation of organic residues [28]. Two-step flash light sintering was suggested to remove microstructural defects and substrate warpage [27,28].

The conversion and release of thermal energy plays a critical role on the practical application of flash light sintering process but is still an unexplored field. In this study, we employed flash light sintering to the fabrication of printed silver mesh TCEs. We investigated the effect of print dimension on flash light sintering by analyzing the electrical and optical properties of printed Ag mesh patterns. The temperature

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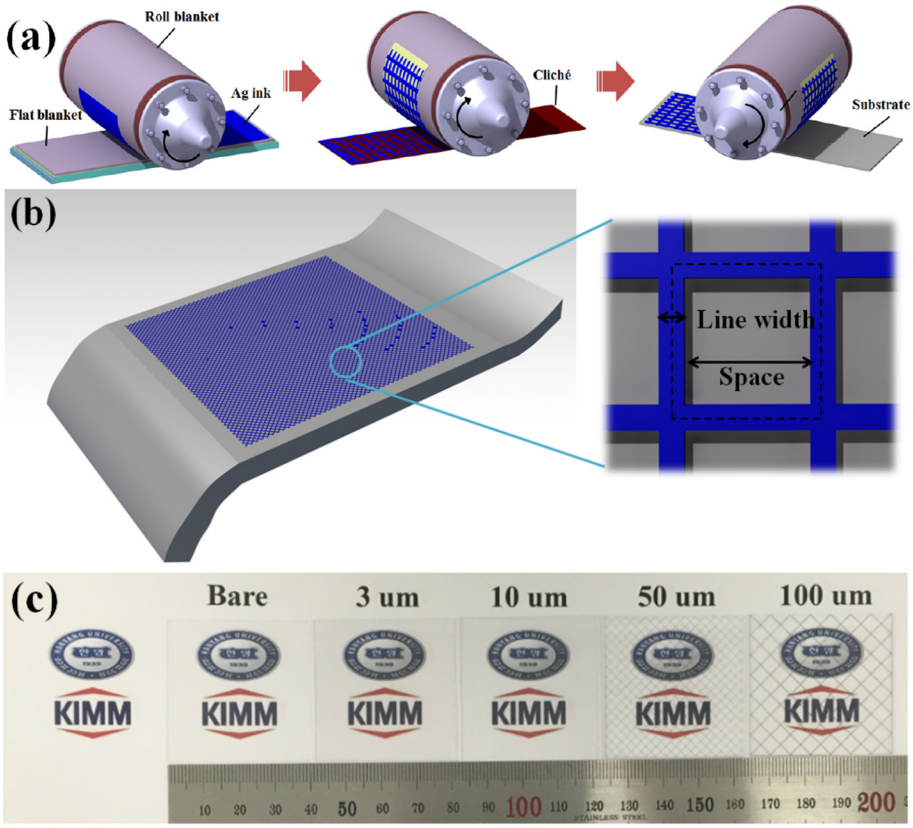

Fig. 1. Schematic diagrams of (a) reverse-offset printing and (b) Ag mesh film with design factors. (c) Optical images of printed Ag mesh film with different line widths.

changes that occurred during sintering were calculated by using a 2-D heat transfer model to understand the relationship between heat dissipation and print dimension. Based on our experimental results and calculations, we propose the use of the multi-pulsed flash light sintering process for finely printed silver mesh film for TCEs.

2. Experimental procedures

2.1. Reverse-offset printing of silver mesh patterns for TCEs

Commercial Ag nanoparticle ink (Silverjet DGP for reverse-offset, ANP Co.) is formulated with a solid content of 25 wt% and then stirred with a magnetic bar for one day. Using this nanoparticle ink, we reverse-offset printed Ag mesh patterns with different line widths on 180 μm thick polycarbonate (PC) films, as shown in Fig. 1 (a). First, the Ag ink was spin-coated on a flat blanket at a speed of 6000 rpm for 10 s. The spin-coated Ag ink on the flat blanket was transferred to a roll blanket at a speed of 8 mm/s under a contact pressure of 6 kgf. Then, the transferred Ag ink was patterned using a cliché at a speed of 2 mm/s under a contact pressure of 2 kgf. Finally, the Ag mesh patterns on the roll blanket were printed on a PC substrate at a speed and force of 5 mm/s and 13 kgf, respectively.

As illustrated in Fig. 1 (b), the printed Ag mesh films with a line width of 3, 10, 50, and 100 μm, respectively, were designed to have 95% optical transmittance by controlling the space between lines. The optical transmittance of printed Ag mesh can be calculated from the opening ratio (OR) as follows [13]:

$$OR = \frac{s^2}{(w+s)^2} \tag{1}$$

$$T_{Ag\ mesh}[\%] = OR \times 100 \tag{2}$$

where, w is line width and s is space, as shown in Fig. 1 (b). The optical transmittance including the substrate can be obtained by multiplying the transmittance of substrate and Ag mesh together:

$$T_{Total}[\%] = T_{substrate}[\%] \times T_{Ag\ mesh}[\%] \div 100 \tag{3}$$

Fig. 1 (c) shows images of Ag mesh films with different line widths. The sample size was 40 × 40 mm^2 and the thickness of the Ag layer was fixed at 300 nm through the same coating process. The optical properties of printed Ag mesh TCEs are summarized in Table 1 with respect to print dimension. The printed Ag mesh films were dried at 130 °C for 10 min using a hot plate to evaporate the solvent of Ag ink.

2.2. Flash light sintering

Flash light sintering was conducted on the reverse-offset printed Ag mesh films using a photonic curing system (PulseForge 1300, Novacentrix Co.). To optimize the electrical and optical properties of Ag mesh films for the printed TCEs, single-pulsed irradiation energy was varied from 3 to 21 J/cm^2, which was measured using a bolometer.

Table 1
Optical properties of printed Ag mesh film with respect to print dimensions.

Print dimension	Linewidth (μm)	3	10	50	100
	Space (μm)	120	400	2000	4000
	Thickness (μm)	0.3	0.3	0.3	0.3
Optical properties	Opening ratio (OR)	0.95	0.95	0.95	0.95
	Fraction of Ag area (1-OR)	0.5	0.5	0.5	0.5
	Measured transmittance (%) including substrate before sintering	85.6	85.5	85.7	85.8
	Bare PC film	90.3% transmittance, 0.22% Haze			
	Measured haze before sintering (%)	1.8	0.78	0.42	0.31