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Transparent conducting films of silver hybrid films formed by near-field electrospinning

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ABSTRACT

Transparent conducting films (TCFs) are critical in the implementation of the low resistance TCFs of $<30\ \Omega$/square at the transmittance of $>90\%$ for the realization of commercial devices such as LEDs and solar cells. We fabricate the hybrid structures of the spin-coated silver nanowire film and the electro-spun silver nanoparticle mesh in order to reduce the sheet resistance of TCFs at high transmittance. After the patterning of the electro-spun Ag NP mesh, the Ag NW solution was spin-coated on the top of the electro-spun mesh pattern. The Ag NP mesh functioned as a backbone to connect the electrically non-connected spaces between the Ag NWs. The fabrication of TCFs on an insulating substrate by near-field electrospinning (NFES) is very difficult because the insulating substrate blocks the electric field between the nozzle and collecting plate during electrospinning. We successfully fabricated the low-resistance microscale electrodes with a line width narrower than 100 μm using NFES on an insulating substrate. In this study, we use a NFES as a tool for the easy and fast fabrication of microscale mesh electrodes without costly process steps.

1. Introduction

The output optical performance of semiconductor light-emitting diodes (LEDs) with light extraction via the top surface is adversely affected by the top metal electrode which prevents the extraction of the light generated beneath it. A remarkable enhancement of optical output has been reported for a blue GaN/InGaN LED with a top metal electrode designed as a mesh [1]. Indium tin oxide (ITO) is the material most commonly used to fabricate transparent conducting films (TCFs). However, its brittle ceramic structure, poor compatibility with organic materials, and the growing cost of indium seriously limit the use of ITO in TCFs, especially in emerging flexible electronics [2]. Therefore, metal nanostructures [3–6] and graphene-based structures [7] have been investigated as alternatives to ITO. In the practical applications such as LEDs and solar cells, TCFs using one-dimensional materials in large-scale fabrication of electro-optical devices is restricted by several specific drawbacks. First, it is difficult to achieve low resistance TCFs of $<30\ \Omega/\square$ at a transmittance of $>90\%$ using the one-dimensional material [8]. Second, the fabrication of the Ag stable and uniaxial patterns on the surface of the insulating substrate is very difficult [9]. In this study, we introduce a hybrid structure of spin-coated silver nanowires (Ag NW) and electro-spun Ag nanoparticles (NPs). The basic idea is to use near-field electro-spun Ag mesh as a backbone to connect the spaces between Ag NWs and reduce the sheet resistance of the hybrid films. To overcome the above drawbacks, we introduce near-field electrospinning (NFES) as a direct writing method for fabricating the low resistance TCFs. The hybrid patterns of spin-coated Ag NW films and electro-spun Ag NP meshes have been fabricated.

2. Experiments

First, 10 g of polyvinyl alcohol(PVA) and 100 ml of deionized (DI) water were put in a four-neck kettle reactor equipped with a mechanical stirrer, which was then placed in an oil bath at 90 °C. The concentration of PVA was 10 wt% (weight%). The Ag NW solution was spin-coated onto the top of insulating substrate. For the measurement of the thickness, half of the substrate was covered by vacuum tape and peeled off after spin-coat. After the initial

Abbreviations: Ag, silver; NW, nanowire; NP, nanoparticle; NFES, Near-Field-Electro-Spinning

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drying of spin-coated film at 70 °C for 10 min, annealed at 250 °C for 30 min to improve junction resistance between Ag NWs. Electro-spun Ag NP mesh was formed on insulating substrate surface (SiO_2 on silicon or glass). To fabricate the hybrid pattern, after the patterning of electro-spun Ag NP mesh, the Ag NW ink was spin-coated on top of electro-spun Ag mesh pattern. The structural properties were characterized by SEM (FEI SIRION-400). The sheet resistance was measured and compared using the four-probe van der Pauw method. The average film thickness was scanned using a surface profiler (Alpha step 500).

3. Results

The uniformity of the Ag NW films spin-coated onto a SiO_2 on silicon (SOI) substrate enhanced as the rotation speed was increased. As the rotation speed increased, the networks became less sparse and the films appeared more uniform. Fig. 1 show the changes in number densities of spin-coated Ag NW films taken from uniform and high-density (region-III), uniform but low-density (region-II), non-uniform and sparse (region-I) regions at the rotation speed of 1500 rpm. Open spaces between Ag NWs were clearly shown in the sparse region (black region) as shown in Fig. 1a-d. The sparse spaces result in poor percolation between the Ag NWs. Therefore, the electrical pathways between Ag NWs disconnected and increased the sheet resistance. To detect the element of Ag composite, EDX line scan for Ag NW and general EDX spectra for Ag NP at the point of cross mark were performed as shown in Fig. 1e (Ag NW) and Fig. 1f-g (Ag NP), respectively.

As described in the previous and this work, Ag mesh was produced on a collector by NFES as shown Fig. 2a–b [10]. The fabrication of the Ag fine mesh patterns on insulating substrates such as a SiO_2 on silicon (SOI), glass, polyethylene terephthalate (PET), or polyimide (PI) is very difficult because the electric field between the nozzle and the collecting plate was blocked by the insulting substrate [9]. Therefore, the cone-jet mode breaks into a spray mode of droplets before the jet contacts the insulating substrate. To obtain a stable jet, the radial growth rate of the jet should be decreased by applying radial electric fields using guide ring. Guiding ring reduced the chaotic motion of the jet in radial direction and prevented the jet from digressing from the center-line. We successfully obtained the Ag NP mesh with line width of ~70 μm using a NFES with guiding ring.

In the previous study, we reported the formation of dumbbell

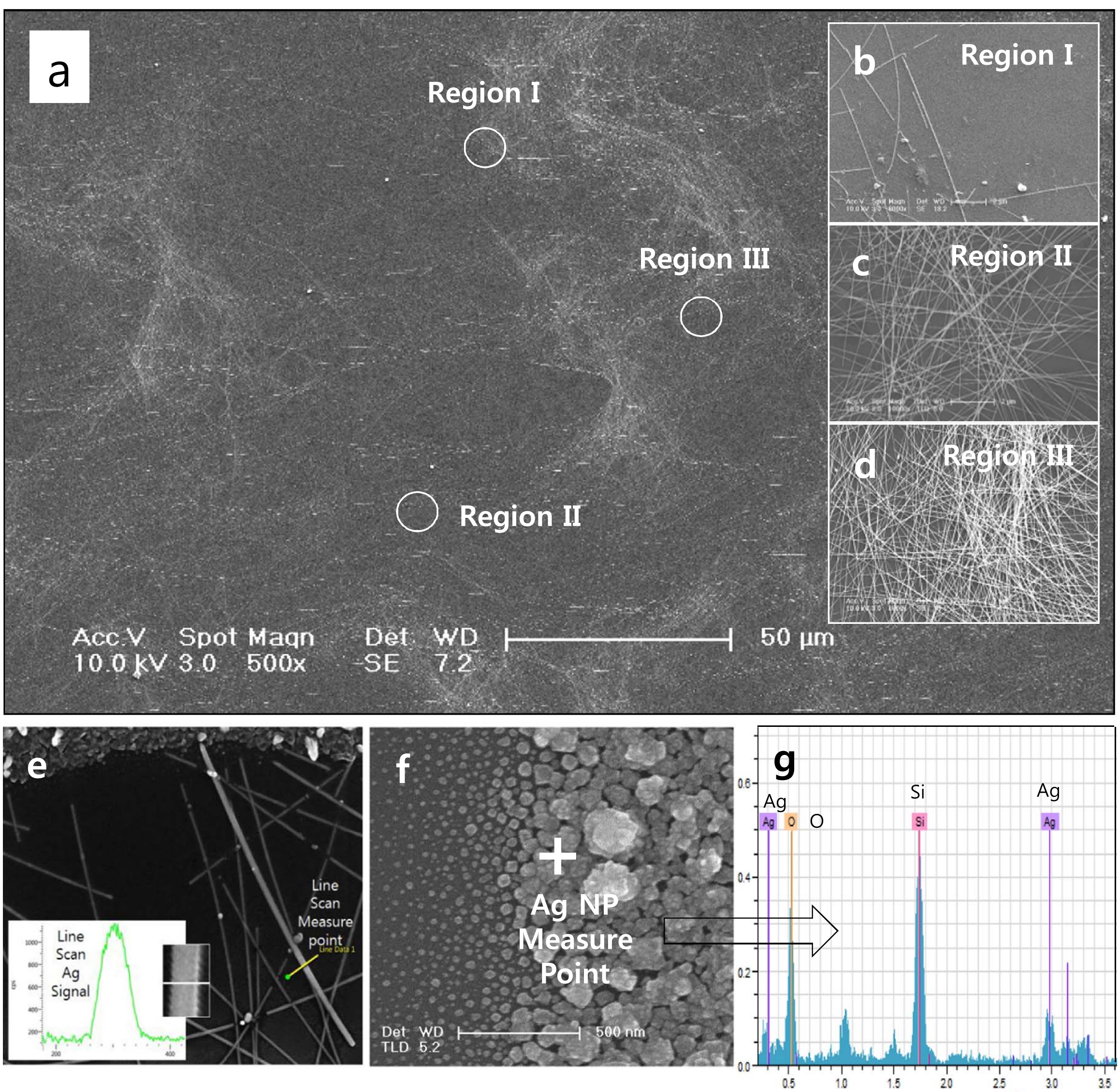

Fig. 1. SEM images and EDX spectra for Ag NW (Fig. 1e) and Ag NP (Fig. 1f and g).