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Room temperature fabrication of silver nanowire transparent electrodes

Takehiro Tokuno, Masaya Nogi, Makoto Karakawa, Jinting Jiu and Katsuaki Suganuma

Osaka University
Mihogaoka 8-1, Ibaraki, Osaka, 567-0047, Japan
Phone: +81-6-6879-8521 E-mail: takehiro_tokuno@eco.sanken.osaka-u.ac.jp

1. Introduction

Materials with a remarkable combination of high electrical conductivity and optical transparency are important components of various optoelectronic devices such as organic light emitting diodes and solar cells. Doped metal oxide films such as tin doped indium oxide (ITO) have single-handedly dominated the field. However, the next generation of optoelectronic devices requires not only transparency but also flexibility due to the development of printable manufacturing methods on plastic substrates with roll-to-roll processes. These requirements severely limit the use of ITO for transparent electrodes because ITO films fail under bending. Fortunately, there are several emerging alternatives to ITO, including single-walled carbon nanotubes [1], graphenes [2], and metal nanowires [3-10]. Great efforts have been made to improve the performance, such as carbon nanotube films. A typical sheet resistance for a carbon nanotube network on plastic is 100–300 ohms/sq, with an optical transparency of 70–90% have been obtained [1]. Graphene electrodes are another candidate, with a best performance of 10^2–10^3 ohms/sq and 80% transmittance using a simple coating method [2]. Graphene electrodes have a significantly lower cost because of the abundant material source. However, significant improvement is needed before the sheet resistance can reach the low values of ITO for current-driven devices. Excitingly, a random network of silver nanowires has recently been put forward as a leading candidate material and various devices are fabricated using transparent electrodes with silver nanowires [3-10]. Lee *et al.* have fabricated silver nanowires films exhibiting performances that rival those of ITO, with sheet resistances approaching 16 ohms/sq at a transparency of 86% [3]. Unfortunately, the fabrication process could not be applied to temperature-sensitive polymeric substrates such as PET films due to over 200°C annealing treatment. A filtration/transport method had been developed by De and Madaria to form silver nanowire transparent electrodes on a PET film which indicated that the removal of the polyvinylpyrrolidone (PVP) capping agent is important for high conductivity [4,5]. A simple coating method has been used by Hu to fabricate silver nanowire transparent electrodes on a PET film [6]. The silver nanowire suspension was coated on a PET film by mayer bar and heated it at 65°C and 120°C. The silver nanowire transparent electrodes showed sheet resistances of 50 ohms/sq with a transparency of 80%.

Until now, a heating process has been used to fabricate silver nanowire transparent electrodes. However, the high process temperature above the glass-transitions point of plastic substrates is a problem for roll-to-roll processes. For example, the glass-transition point of PET films is 69°C. Plastic films such as PET films are pulled in roll-to-roll processes and change their shapes at a high temperature and high tensile force. Thus, room temperature processing is very important and significant. We report, therefore, silver nanowire transparent electrodes with a remarkable combination of high electrical conductivity and optical transparency at room temperature. The silver nanowire networks on PET substrates exhibited a high transparency of 80% and a sheet resistance of 10 ohms/sq.

2. Experimental

Silver nanowires were synthesized using the polyol method [11]; 16 g of $FeCl_3$ solution (6×10^{-4} M, in ethylene glycol), 1.08 g of $AgNO_3$, and 0.98 g PVP (average molecular weight 360 k in term of monomeric units) were added to 125 g of ethylene glycol in a round-bottom flask. The reaction mixture was kept at 150 °C until all of the $AgNO_3$ was completely reduced which took approximately 1.5 h. After the reaction was completed, the solution was cooled to room temperature. Then, the suspension was diluted 8 times with ethanol and filtrated to obtained sediments of silver nanowires which were dispersed. The suspension was drop-coated on PET substrates and air-dried and then cold-pressed at 25 MPa for 5 seconds. The sheet resistance was measured using the four-probe method (LorestaGP T610, Mitsubishi Chemical Analytech). The transparency at a wavelength of 550 nm was measured using a UV-Vis-NIR spectrophotometer (V670, JASCO) and the PET film without silver nanowires was used as a reference.

3. Result and discussion

The obtained silver nanowires had an average length of 8 μm and an average diameter of 70 nm. The air-dried PET substrates exhibited a random network structure (Fig. 1) and the transparency was around 80%.

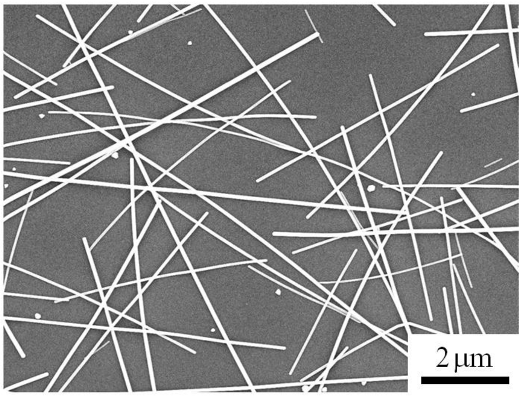

Figure 1. SEM image of silver nanowire transparent electrodes on a PET substrate.

The air-dried silver nanowires on the PET film showed a sheet resistance of 1,000 ohms/sq, without any heating process (Fig. 2). Excitingly, when the air-dried PET substrates with silver nanowires were pressed at 25 MPa, the sheet resistance was drastically decreased to 10 ohms/sq. When a smaller amount of silver nanowires was used to coat the PET films, we obtained electrodes with a high transparency of 85% and a sheet resistance of 20 ohms/sq after the cold-press process.

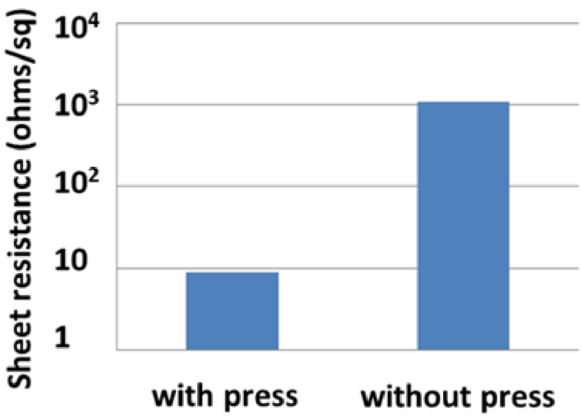

Figure 2. Sheet resistance of silver nanowire transparent electrodes on a PET film with transparency of 80% with and without press process.

Hu *et al.* also showed that the mechanical pressing of silver nanowires can fuse the nanowire junctions [6]. The sheet resistance decreased from several hundred ohms per square to several tens of ohms per square by mechanical pressing at 81GPa. Mechanical pressing not only increased the conductance but also greatly improved the film morphology. We succeeded in fabricating silver nanowire transparent electrodes at a far lower pressure than that used by Hu. We believe the PVP maybe play an important role. It is worthwhile to be noted that well-washed silver nanowires incredibly decrease the sheet resistance without loss in transparency. It is guessed the electrical connections between the silver nanowires were formed by cold-pressing without heating. The obtained transparent electrodes with silver nanowires on the PET film exhibited high flexibility equal to that of PET films without silver nanowires.

4. Conclusions

The authors successfully fabricated silver nanowire transparent electrodes on a PET film at room temperature by cold-press method. The electrodes gave a high electrical conductivity of 10 ohms/sq and transparency of 80%. This technique will be applied to develop flexible devices such as organic solar cells, flexible displays and flexible organic light emitting diodes.

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