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Preparation of transparent conducting films with improved haze characteristics using single-wall carbon nanotube-silver nanowire hybrid material

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ABSTRACT

Transparent conducting films (TCFs) were fabricated using single-wall carbon nanotube (SWCNT)–silver nanowire (AgNW) hybrid materials on flexible substrates. The hybrid solution was prepared with various weight ratios of SWCNTs and AgNWs, followed by bar-coating on polyethylene terephthalate (PET) film. As the SWCNT content increased, the haze of the film decreased markedly, while transparency and sheet resistance were a little bit impaired. As a result, the prepared hybrid TCFs exhibited a sheet resistance of 120 Ω/sq and a transparency of 90.8%, with a haze of as low as 1.6% when the weight ratio of SWCNTs to AgNWs was 2:3. These properties appear suitable for the application of TCFs in high-performance, flexible capacitive touch panels.

1. Introduction

Transparent conducting films (TCFs) have been widely used in electronic applications such as touch screen panels, flat panel displays, and photovoltaics [1–3]. Indium tin oxide (ITO) has been one of the most popular TCF materials [4–6]. However, with the advent of flexible electronic devices, there has been increasing demand to replace ITO films by novel, flexible films. Single-wall carbon nanotubes (SWCNTs) and silver nanowires (AgNWs) are amongst the most promising candidates to prepare flexible TCFs [7–10]. In order to use TCFs in capacitive touch-screen panels (c-TSPs), the transmittance (including the base film) and the sheet resistance should be higher than 89% and lower than 300 Ω/sq, respectively [11]. However, most of previously reported sheet resistances of TCFs based on SWCNTs did not match the requirements of c-TSPs. SWCNTs are unexceptionally composed of metallic and semiconducting nanotubes. This coexistence results in a high sheet resistance, thus preventing the use of SWCNTs in high-performance TCFs. On the other hand, AgNWs have attracted much attention owing to their high electrical conductivity [9,10]. However, AgNW-based TCFs suffer from excessive haze due to light scattering from the Ag surface [12,13]. The low conductivity and high haze of TCFs based on SWCNT and AgNW, respectively, hinder their practical application in flexible electronic devices.

Nonetheless, the high conductivity of AgNW- and the low haze of SWCNT-based films are attractive characteristics for TCF applications. For this reason, hybrid films prepared using both SWCNTs and AgNWs have recently been proposed [14,15]. However, in order to develop these hybrid materials and use them to produce TCFs, further studies on the fabrication and properties of the hybrid films are needed. In the present study, we prepared a hybrid solution of SWCNTs and AgNWs, and coated it onto poly(ethylene terephthalate) (PET) films using bar-coating method, and then, systematically investigate the relationship between SWCNT:AgNW ratio, surface properties, and performance of the hybrid films.

2. Experimental

SWCNTs with diameters ranging from 1.0 to 1.2 nm were synthesized by arc-discharge and then purified by thermal treatment. The detailed experimental procedures for the synthesis and purification were reported previously [8]. The thermally treated SWCNTs (0.2 wt%) were dispersed in de-ionized (DI) water with the assistance of a dispersant (0.7 wt%, Tamol® NN8906)

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purchazased from BASF. The dispersion of the solution was carried out by probe sonication, followed by centrifugation for removing metal catalysts and non-dispersed SWCNTs. Ink containing dispersed AgNWs with an average diameter of 50 nm (0.15 wt%) was purchased from Cambrios Technology Corporation. Then, the hybrid solution was prepared by mixing the SWCNT and AgNW solutions with nanotube contents ranging from 0 to 100 wt%. In order to improve the dispersion stability of the hybrid solution, 2.5 wt% of a dispersing agent (DISPERBYK 192) was added to the solution. The SWCNT–AgNW hybrid solution was then bar-coated onto a PET film. A $6 \times 6\,cm^2$ PET film was placed on the coater, and 0.25 ml of the hybrid solution was spread on the top of the film, followed by coating using a Mayer bar. The thickness of the film was controlled by using different types of Mayer bars (#8, #10, and #12). The coated films were dried in the oven at 130 °C for 5 min, followed by washing and drying with DI water and air gun, respectively.

The surface morphologies of the coated films were investigated by scanning electron microscopy (SEM, JEOL JSM-7500F) and atomic force microscopy (AFM, Park System XE-100). The four-point probe method was used to measure the sheet resistance of the films. Transmittance and haze were evaluated at 550 nm using a haze meter (Nippon Denshoku, NDH-5000). We also measured the visible light transmittance (300–750 nm) using an UV–vis spectrophotometer (Shimadzu UV-2450). X-ray photoelectron spectroscopy (XPS, VG Multilab 2000) was used to monitor the shift of the Ag binding energy.

3. Results and discussion

Hybrid solutions of various SWCNT:Ag ratios were bar-coated using three different Mayer bars (#8, #10, and #12). The measured thickness of films coated using #8, #10, and # 12 bars were 54, 68, and 95 μm, respectively. It is well known that the sheet resistance of a metallic thin film decreases with increasing thickness [16]; thicker films showed lower sheet resistance in the case of AgNW [17] and SWCNT [18] films too. We found that the sheet resistance of the present SWCNT–AgNW hybrid films also decreased with increasing film thickness, as shown in Fig. 1. As expected, the sheet resistance of the hybrid film increased with decreasing AgNW content. The figure also highlights another intriguing phenomenon: the sheet resistance of the films showed first a gradual increase with increasing SWCNT content from 0 to 40%, followed by a drastic increase when the SWCNT content further increased from 40% to 60%, especially for thinner films. The present hybrid films have three types of contact points: AgNW–AgNW (A–A), AgNW–SWCNT (A–S), and SWCNT–SWCNT (S–S). It is believed that the electrical conduction in the hybrid film occurs mainly through the A–A contact points for SWCNT content of 40% or lower. On the other hand, we can speculate that in 60%-SWCNT films, not only A–A but also A–S or S–S contacts contribute to the electrical conduction owing to the insufficient AgNW content. This phenomenon might explain the rapid increase in sheet resistance observed for the 60%-SWCNT film.

In order to use a transparent film in a touch-screen panel, key prerequisites are not only high transmittance and low sheet resistance, but also low haze. The total transmittance (T.T) is composed of parallel transmittance (P.T) and diffuse transmittance (D.T), where D.T originates from scattered light. The haze (H) is given by $H(\%) = (D.T/T.T) \times 100$. Fig. 2 shows the haze of the

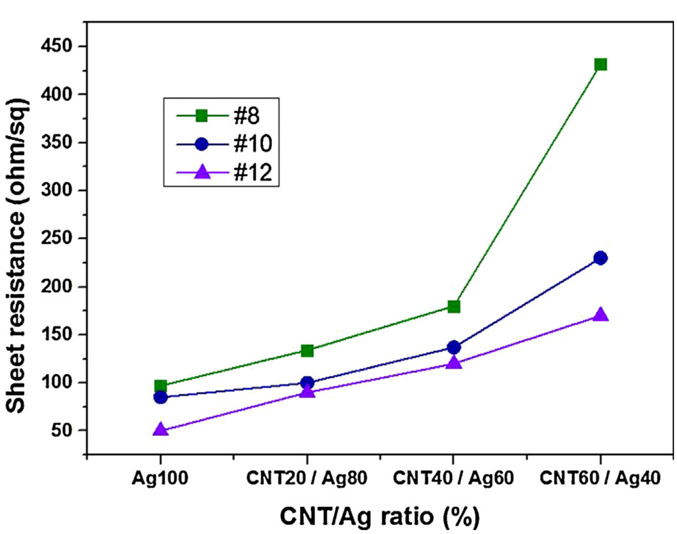

Fig. 1. Sheet resistances of hybrid films prepared using three different (#8, #10, and #12) Mayer bars. The SWCNT content ranges from 0 to 60%.

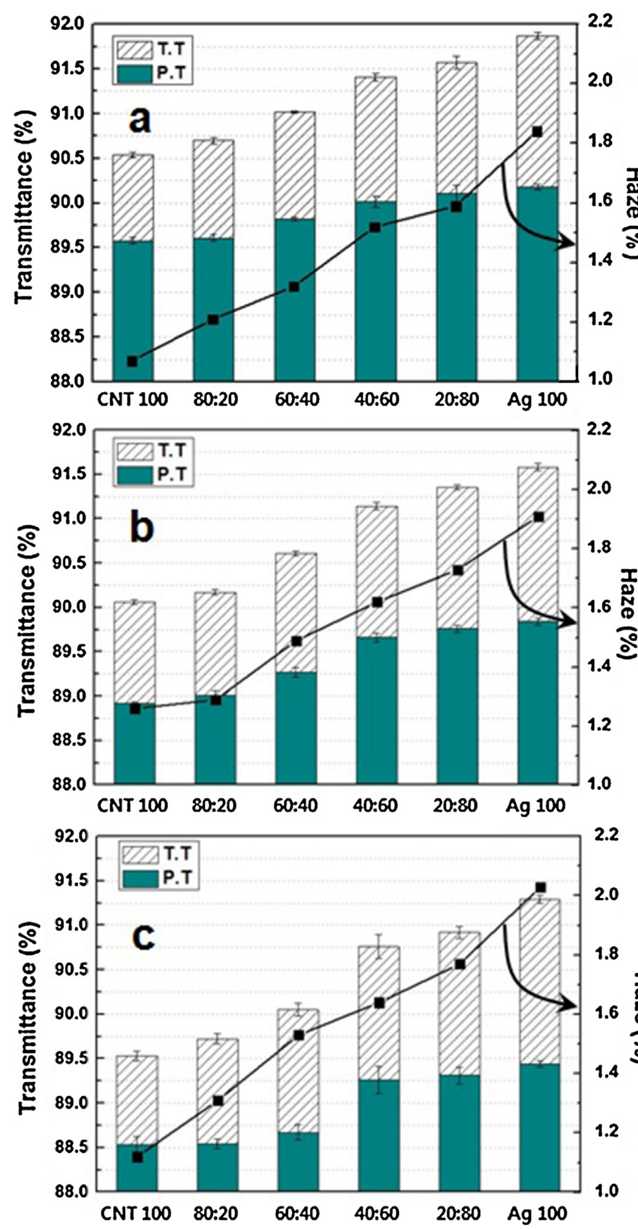

Fig. 2. Transmittances (total and parallel) and hazes of hybrid films with different SWCNTs:AgNWs ratios. The films were prepared by bar-coating method using (a) #8, (b) #10, and (c) #12 Mayer bars.