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NOTE

Potential application of highly conductive and transparent poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate) thin films to touch screen as a replacement for indium tin oxide electrode

Hu Yan, Toshihiko Jo and Hidenori Okuzaki

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INTRODUCTION

Poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate) (PEDOT/PSS) has been extensively studied from in both its academic and technological aspects.[1–5] The PEDOT/PSS has been a widely available conductive polymer because the colloidal dispersion of the PEDOT/PSS in water can easily provide films on various substrates by simple means such as solution-casting and spin-coating techniques.

We recently investigated the correlation between the sizes of colloidal particles and the minimum thicknesses of spin-coated thin films of PEDOT/PSS.[6,7] The PEDOT/PSS thin films spin-coated at 3000 r.p.m., are suggested to be primary nanoparticle-'monolayers'. The PEDOT/PSS primary nanoparticles, however, do not pack compactly within the thin films. Such thin films showed high transparency but poor conductivity.

Poly(4-styrenesulfonate)-layer-removed PEDOT/PSS nanoparticles with narrow size distributions would result in compactly packed nanoparticle-thin films, which can be expected to show both high conductivity and transparency. On the basis of this strategy, we achieved significant enhancement in the electrical conductivity of spin-coated PEDOT-PSS thin films on smooth silicon wafers by centrifuge and solvent effects,[8] whereas high transparency was maintained.[9] A 93-nm thick PEDOT/PSS thin film showed electrical conductivity of 443 $S\,cm^{-1}$ and visible light-transmittance of 89%.[9]

Resistive touch screens are composed of two transparent electrodes and separated by an air gap. When pressure is applied to the surface of the touch screen, the two electrodes are pressed together. The two electrodes contain horizontal and vertical lines. When the electrodes are pushed together, the precise location of the touch screen is registered.[10] The two electrodes, especially the front electrode should be very flexible. In terms of flexibility, PEDOT/PSS thin layers on plastic films are superior compared with indium tin oxide (ITO) thin layers on the plastic films. A PEDOT/PSS thin layer on a plastic film, prepared by conventional techniques, however, has a high sheet resistance, which prevents applications to the touch screens.

In this study, we present the electrical and optical properties of a highly conductive PEDOT/PSS thin layer on polycarbonate (PC) film, and its potential applications in touch screens as a replacement for transparent ITO electrodes.

EXPERIMENTAL PROCEDURE

Materials

PEDOT/PSS dispersion (BAYTRON PH500, from HC Starck, München, Germany) and ethylene glycol (EG, from Wako Chemical Co., Osaka, Japan) were used as received. Polycarbonate film and silicon dioxide/silicon wafer were commercially purchased.

Preparation of PEDOT/PSS thin layer on PC films

The PEDOT/PSS thin layer was prepared on the PC film following a procedure previously reported by us.[9] The typical procedure is as follows: 20 ml of PEDOT/PSS (BAYTRON PH500) solution was separated by a centrifuge at 5000 r.p.m. and the upper layer of the solution was decanted. The upper-layered solution was freeze-dried to obtain PEDOT/PSS powder. The powder was re-dispersed in deionized water under ultrasonication, resulting in PEDOT/PSS solution with a concentration of 2 wt%. Nine milliliters of the solution containing 2 wt% of PEDOT/PSS and 7 wt% of EG was dropped onto the PC films (8×8 cm). Spin-coatings were applied at a rotational speed of 3000 r.p.m. for 1 min under atmospheric conditions. After the spin coating, the samples on the PC films were dried at 160 °C for 1 h in vacuum. For comparison, a PEDOT/PSS/PC film was also prepared in the same manner but without the addition of EG. The thickness of the PEDOT/PSS thin layer on the PC film was measured with an optical ellipsometer (Otsuka FE-5000-S, Otsuka Electronics Co., Ltd., Osaka, Japan).

Department of Applied Chemistry, Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Japan
Correspondence: Professor H Yan or H Okuzaki, Department of Applied Chemistry, Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, 4-4-37 Takeda, Kofu 400-8511, Japan.
E-mail: yanhu@yamanashi.ac.jp or okuzaki@yamanashi.ac.jp
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Measurements of atomic force microscopy (AFM) current images of the PEDOT/PSS films

For atomic force microscopy (AFM) current imaging, PEDOT/PSS films were prepared on a Silicon wafer in the same manner. Atomic force microscopy measurements were carried out with a scanning probe microscope (SPM-9600, Shimadzu Co., Kyoto, Japan), equipped with a conductive probe. The AFM current images were measured under contact mode at a bias of 0.5 V.

Measurement of electrical resistance when bending

The electrical resistances of the PEDOT/PSS on PC films, when bending, were measured by a two-point technique with a multimeter. The degree of the bending was expressed as a bending angle with the same film length defined in Figure 2. The bending angle was changed using cylindrical bars with various diameters. The electrical resistance of the PEDOT/PSS/PC film at bending angle of 29° was measured 100 times.

Measurement of electrical linearity and optical haze

The electrical linearity of the sample films was measured, at 10 points, along each direction (X and Y), using a linearity evaluation equipment (Touchpanel Lab. 001-29, Tokyo, Japan). The optical haze of the sample films was measured using a haze meter (NDH2000, Touchpanel Lab.). On the other hand, the transparency of the PC film was measured at a wavelength of 550 nm with an ultraviolet–visible spectroscope (V-670 JASCO, Tokyo, Japan).

Preparation of touch screen using the PEDOT/PSS/PC film as a transparent electrode

Silver lines were formed on the four edges of the PEDOT/PSS/PC film (8×8 cm) using a silver paste-printing method coupled with curing at 90 °C for 30 min. A four-point resistance-type touch screen device was prepared using the PEDOT/PSS/PC film and an ITO-sputtered PC film as front and rear electrodes, respectively. For comparison, a touch screen device with all ITO-sputtered PC films was also prepared in the same manner.

The four-point touch screens were operated on a personal computer (Windows XP) using the driving software (Touchkit Version 4).

RESULTS AND DISCUSSION

AFM current images of the PEDOT/PSS films

The AFM current images of the PEDOT/PSS films are shown in Figure 1. The highly conductive spots were densely packed with each other in the PEDOT/PSS film prepared after centrifuging and adding 7% EG (Figure 1b), whereas few highly conductive spots were observed in the PEDOT/PSS film prepared directly from a commercially available PH500 solution (Figure 1a). It should be noted that the sheet resistance was as high as 10 MΩ cm^{-2}, even for the PEDOT/PSS film prepared after addition of EG but without centrifuging because of loose packing of the clusters or particles, although the conductivity within the individual grains (vertical conductivity estimated by the AFM current image) was much high.[7] The results support our idea that primary nanoparticles, with less PSS on the particle surface, could pack densely with each other, resulting in high conductivity, without the loss of the transparency of the PEDOT/PSS film.

Change in electrical resistance of the PEDOT/PSS/PC film when bending

The changes in electrical resistance of the PEDOT/PSS/PC film when bending are shown in Figure 2. Both the resistance and the normalized values were held in constant within an error margin when the bending angle was changed from 0 to 180°. The resistance at a bending angle of 29° was repeatedly measured 100 times. In terms of the electrical resistance, the initial and final values were 837 and 836 Ω, respectively, with an average value of 841 Ω, indicating the fairly good durability and stability of bending of the PEDOT/PSS/PC film.

Electrical linearity and optical haze of the PEDOT/PSS/PC film

The main properties of the PEDOT/PSS/PC films as a transparent electrode for touch screens are summarized in Table 1. The surface resistance (or sheet resistance) was 351–449 Ω cm^{-2}, which fulfills the requirements for touch-screen applications.[11] The thickness of the PEDOT/PSS thin layer was preliminarily evaluated by the optical ellipsometer. As a result, the thickness was 194 nm, which is twice as thick as the thickness of the PEDOT/PSS thin layer on a silicon wafer, which was measured by a scanning transmission electron microscopy.[9] The conductivity was estimated to be 115–147 S cm^{-1}, which is much lower than that on the silicon wafer.[9] The thermal stability of the PEDOT/PSS/PC films, in terms of the resistance, was good in the aging test, conducted at 150 °C for 1 h. The linearility of the sheet resistance was 1.2–1.7%, which is close to the standard value of 1.0%.

On the other hand, the optical transmittance and haze were 81 and 15.6%, respectively, which needs to be improved because the standard values are 86 and 1.0%, respectively. The transmittance of the PC film was measured separately by a different spectrometer. The transmittance at a wavelength of 550 nm was 73%, which is even lower than that of the PEDOT/PSS/PC film. This is probably because of the poor quality and inhomogeneity of the PC film (as a roll of one-meter wide and several meters long) used in this work. Therefore, it is considered that the transmittance of the PEDOT/PSS/PC films can be easily

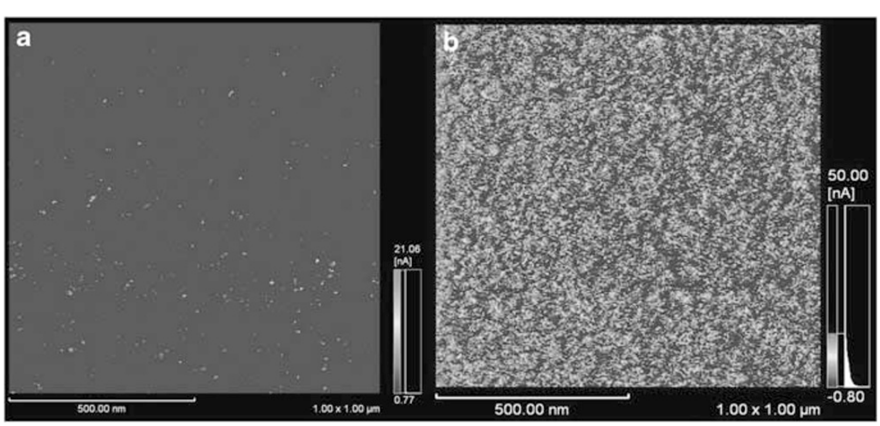

Figure 1 Atomic force microscopy current images of the poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate) (PEDOT/PSS) films spin-coated from PEDOT/PSS dispersion without any treatment (**a**) and with a centrifuge and the addition of 7% ethylene glycol (EG) (**b**). A full color version of this figure is available at *Polymer Journal* online.

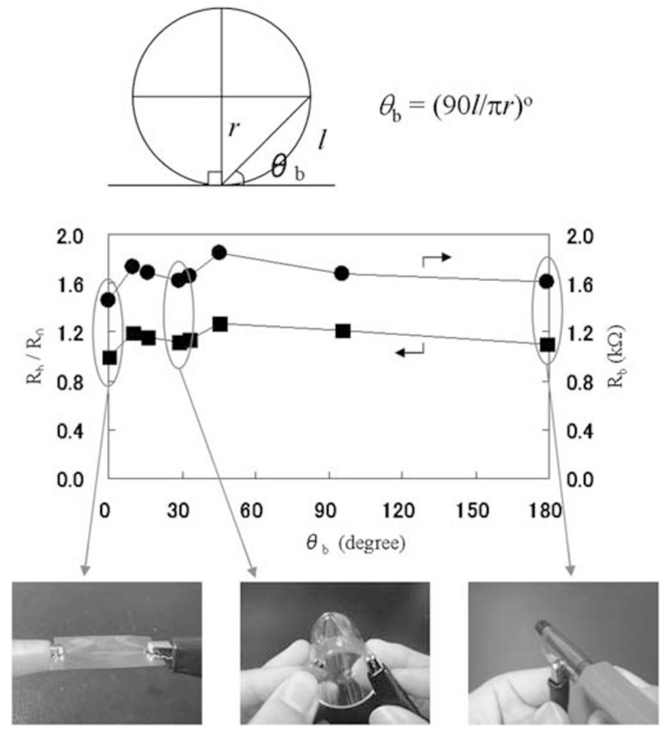

Figure 2 Plots of electrical resistance (right) and normalized resistance (left) of the poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate) (PEDOT/PSS/PC) films against the bending angle. A full color version of this figure is available at *Polymer Journal* online.

Table 1 Electrical and optical properties of the PEDOT/PSS/PC films

Sample no.	*Surface resistance* (Ω cm^{-2})	*Linearity (%)*	T^{total} *(%)*	T^{550nm} *(%)*	*Haze (%)*
1	351	1.2			
2	414	1.7			
3	449	1.3			
4	387		80.9	81.3	15.6
4[a]	397		80.5	81.0	16.6

Abbreviations: PC, polycarbonate; PEDOT, poly(3,4-ethylenedioxythiophene); PSS, poly(4-styrenesulfonate).
[a]Sample no. 4 after aging at 150 °C for 60 min.

improved simply by choosing highly transparent PC films because the transmittance of the PEDOT/PSS layer is close to 90%.[9] The optical haze may also be improved simply by choosing the correct PC film, and especially by further optimizing the coating. Because the PC film is usually slightly hydrophobic, a plasma etching or surfactant coating on the PC film would improve the wetting of the PEDOT/PSS dispersion on the surface of the PC film, resulting in a more homogeneous PEDOT/PSS thin layer.

Prototype touch screen fabricated using the PEDOT/PSS/PC film as a transparent electrode

The touch screen fabricated using the PEDOT/PSS/PC film as the top electrode, was transparent as that using ITO, as shown in Figure 3. We have tested finger and pen inputs by displaying them on a PC screen by using a driving software. As a result, the number '2' was well inputted, as shown in Figure 4. The results indicate that the PEDOT/PSS/PC films can basically work as the transparent electrode of the touch screens. However, it is noted that the influence of some factors, for instance, the mechanical and electrical durability on the operation of these touch screens should be further investigated for the practical use of the PEDOT/PSS/PC films in touch screens.

Figure 3 Prototype touch screens fabricated using a poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate/polycarbonate) (PEDOT/PSS/PC) film (top) and indium tin oxide (ITO) film (bottom), respectively. A full color version of this figure is available at *Polymer Journal* online.

Figure 4 The number '2' on a polycarbonate (PC) screen written using a finger, or pen input by the touch screen fabricated using the poly(3,4-ethylenedioxythiophene)/poly(4-styrenesulfonate/polycarbonate) (PEDOT/PSS/PC) film as the top electrode. A full color version of this figure is available at *Polymer Journal* online.

CONCLUSION

In conclusion, we have investigated on the practical application of highly conductive and transparent PEDOT/PSS films, prepared on a PC sheet by a spin-coating coupled with a centrifuge and a solvent-treatment, to resistance-type touch screens. The results show that the PEDOT/PSS/PC films principally work well as transparent electrodes in the touch screens in which a number '2' was well written by a simple finger- or pen-input.

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