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Interdigitated electrode geometry effects on the performance of organic photoconductors for optical sensor applications

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ABSTRACT

This paper studies the electrical characteristics of solution-processed organic photosensors (OPSs) made from organic materials of poly-3-hexylthiophene (P3HT) and [6,6]-phenyl-C61 butyric acid methyl ester (PCBM), with four-type of interdigitated electrodes for achieving high photo-sensing performances. The thin layers of organic material are deposited by spin-coating methods. The current of the OPSs through the semiconductor organic films is measured under light intensities ranging from dark to 300 mW/cm^2. At 10 V bias and 300 mW/cm^2 illumination, the currents obtained from pristine P3HT and blended P3HT/PCBM, both spin-coated, are 6.9×10^{-5} mA, and 3.6×10^{-5} mA, respectively. Finally, in order to evaluate the response characteristics under illumination, the current characteristics of the OPS are measured as a function of time and results confirm good reproducibility and fast response times of the OPSs.

1. Introduction

The fields of photoluminescence (PL)-based chemical and biological sensors have been widely investigated in recent years [1,2]. Such sensors, which are generally used for monitoring a single analyte, are sensitive, reliable, and suitable for a wide range of applications, such as medical, biological, environmental, and industrial [3–5]. The sensors are typically composed of a luminescent sensing component, whereby the PL is monitored before and during exposure to the analyte, a light source that excites the PL, a photodetector (PD), a power supply, and the electronics for the signal processing. Thus, organic light emitting diodes (OLEDs) have been introduced as promising light sources for PL-based sensing applications. The multianalyte detection methods include using the electrochemical [6], piezoelectric [7], electrical resistance [8] and optical [9] properties. Here, in other to analyze the detection of light as OLEDs, the conjugated polymers have been widely used in organic photodiodes, and organic photovoltaic devices based on organic semiconductor materials for their advantages in simplified fabrication processing of devices, low-temperature process, having good flexibility, high-quantum efficiencies, and high-absorption coefficients. The organic photodiodes and organic photovoltaic cells, utilizing higher photosensitivity, have been actively studied since a large photocurrent, lower dark current, and high speed responses can be achieved [10,11]. Also, inline mass production has received special attention from the scientific community and industry because solution process-ability enables low-cost fabrication processes, such as drop-casting, spin-coating, screen-printing, and spray-coating [12–14] for large areas.

This paper studies the electrical characteristics of solution-processed OPSs made from organic materials of pristine P3HT and P3HT:PCBM 1:0.8 blended with four-type interdigitated electrodes for achieving high photo-sensing performances. Also, in order to evaluate the response characteristics under illumination, the current characteristics of the OPSs are measured as a function of time.

2. Experimental

Fig. 1 shows the schematic device structure of the OPSs for four-type interdigitated electrodes, such as channel widths of 200 um (S1), 2 mm (S2), 7.8 mm (S3), and 13.3 mm (S4). The channel lengths of the OPSs are fixed at 100 μm. Because organic compounds have high resistance, the electrode of the OPSs is used as the interdigitated electrodes in order to reduce the sensor resistance and to increase the sensor performance. P3HT and PCBM, purchased from Sigma-Aldrich Co, have been used as the electron donor and the electron acceptor, respectively. The solution of P3HT (12 mg/ml) is dissolved in chlorobenzene. The blend is prepared with P3HT:PCBM 1:0.8 ratio, and dissolved in a 22 mg/ml solution with chlorobenzene with the blended solution being homogenized for 4 h. The cleaning of the glass

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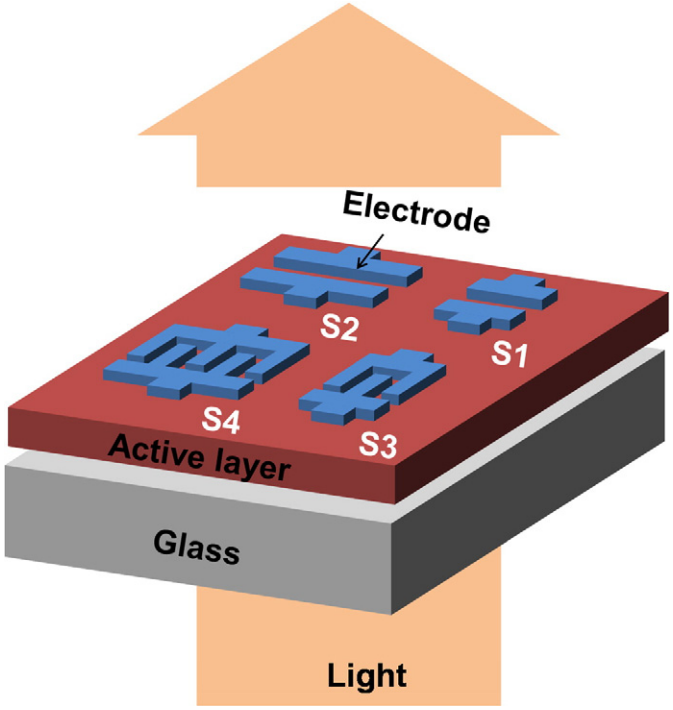

Fig. 1. Cross section of OPSs devices on glass.

substrate is carried out chemically according to the method based on successive baths of methanol and acetone, using ultrasonic waves for 10 min, and then rinsed in deionised (DI) water. A thin film is coated on the glass substrate by the spin-coating method and the thickness of the deposited film is found to be about 200 nm. The aluminum contact of the interdigitated four-type electrode is deposited on the glass substrate through a shadow mask, by thermal evaporation (DOV Co., Ltd), under 2×10^{-6} Torr at room temperature. Finally, the device is annealed, using a hot-plate at 150 °C, for 10 min. UV/visible spectrophotometer (Lambda 35, PerkinElmer) was used to study absorption spectra of the pristine P3HT, pristine PCBM and blended P3HT:PCBM films on the glass substrate. The current–voltage (I–V) characteristics of the device under dark and illuminated states are measured using a KEITHLEY 237 source meter. The applied voltage is scanned between 0 and +10 V and the OPSs measurements are employed under light intensities ranging from 10 mW/cm^2 to 300 mW/cm^2, using a xenon lamp. The effect of the interdigitated electrodes is investigated by comparing the responses of the OPSs for the four-type interdigitated electrodes under illuminated powered conditions. The changes in current of the OPSs, when exposed to the xenon lamp, are also measured for two different materials of pristine P3HT and blended P3HT/PCBM.

3. Results and discussion

Fig. 2(a–c) shows atomic force microscope (AFM, XE-100 system) images of the surface morphology of the pristine P3HT film, the pristine PCBM film, and the blended P3HT/PCBM film, deposited on the glass substrate by the spin-coating method. Usually, the sensing performance of the organic semiconductor sensors can influence various factors, such as the composition of the film, the organic semiconductor molecular structures, the degree of crystallization, the surface morphology, and the grain boundaries [15]. Thus, the surface morphology leads to the result that the organic photodiode has higher electrical performances for smooth surfaces than for rough surfaces [16,17]. As can be seen in Fig. 2, the AFM images demonstrate that a surface roughness of about 1.2 nm is grown directly on the glass

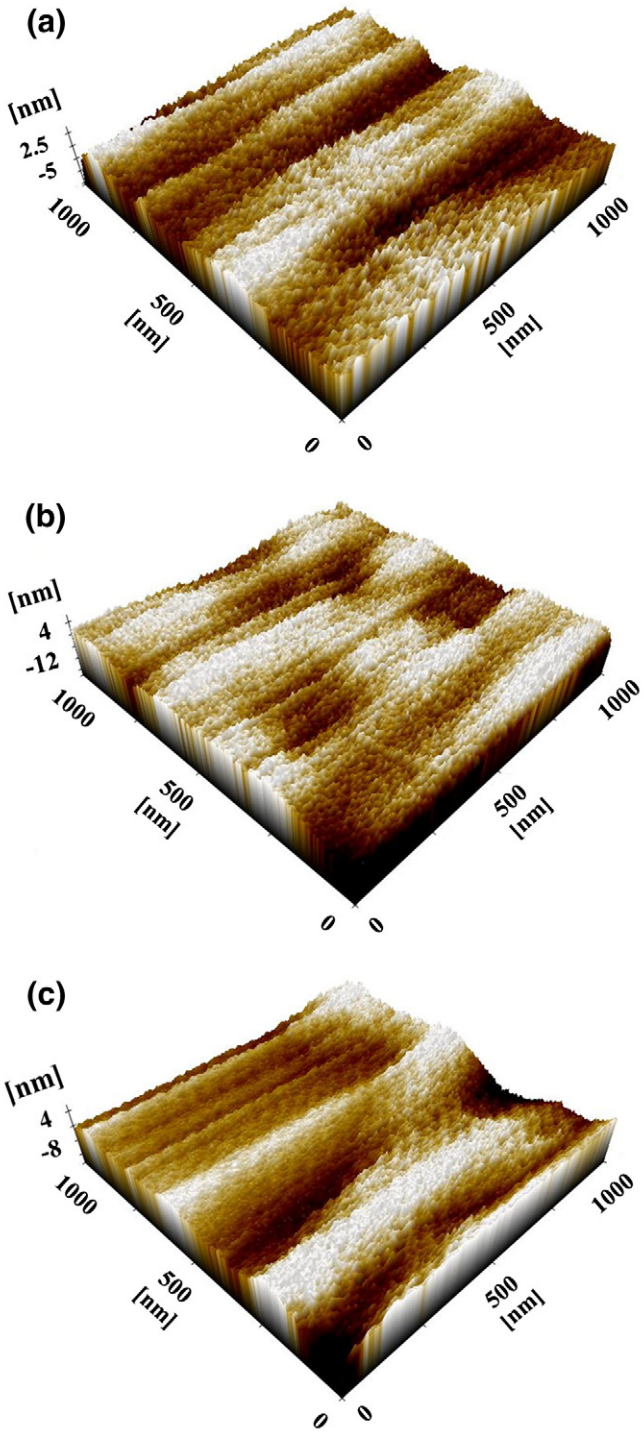

Fig. 2. AFM images for the surface morphology of (a) P3HT, (b) PCBM, and (c) bended P3HT/PCBM thin films deposited on glass by the spin-coating method.

substrate and the surface of the spin-coated organic film is both homogeneous and smooth.

The molecular structures of the organic compounds pristine P3HT and pristine PCBM, are shown in Fig. 3(a–b), and the measured absorption spectrum of each material is shown in Fig. 3(c). The absorption spectrum of the pristine P3HT shows the features of strong absorption in the visible spectrum, with an absorbance peak at 530 nm, and two small shoulders at ~550 nm and ~600 nm, respectively. The pristine PCBM film shows the typical absorption peak at 340 nm whereas the spectrum of the blended P3HT/PCBM shows one broad peak at 510 nm, as a contribution of the polymer,

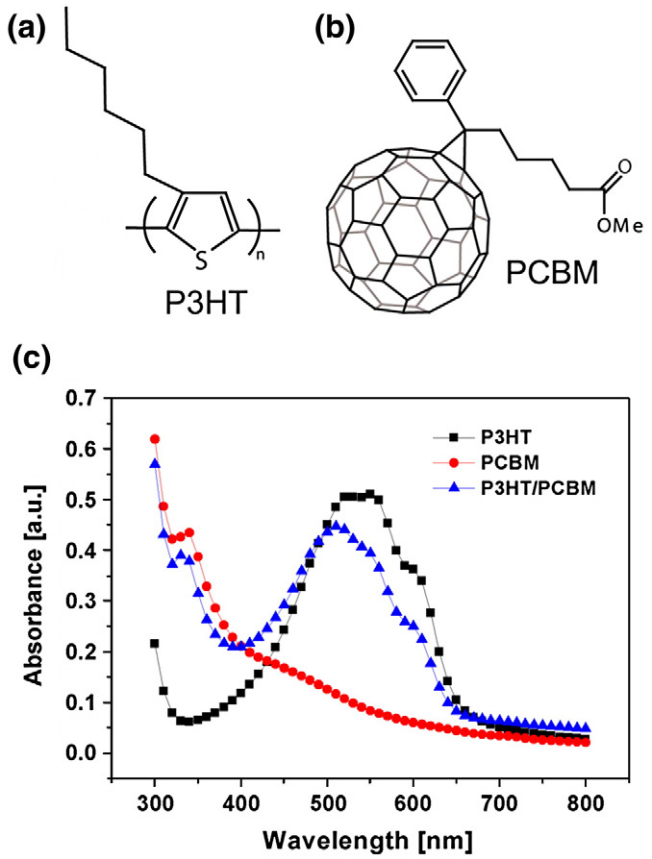

Fig. 3. The molecular structures of organic compounds, namely, (a) pristine P3HT and (b) pristine PCBM, and (c) the absorption spectrum of each material.

and one at 330 nm due to the absorption of the PCBM. With respect to the pristine P3HT, the absorption peak of the blended device is blue-shifted, and the whole spectrum is less structured due to the presence of the PCBM, which strongly limits the self-organizing property of the P3HT. However, blending the P3HT and the PCBM has been found to cover a wider visible spectral range.

Fig. 4 shows the current–illumination (I–L) characteristics of the OPSs, based on (a) pristine P3HT, and (b) blended P3HT/PCBM, under dark and light illuminated conditions. The current of the OPSs through the semiconductor organic films is measured under light intensities ranging from 10 mW/cm^2 to 300 mW/cm^2. At 10 V bias and 300 mW/cm^2 illumination, the current obtained from the pristine P3HT and the blended P3HT/PCBM films, both spin-coated, are 6.9×10^{-5} mA and 3.6×10^{-5} mA, respectively. The current of the OPS based on the pristine P3HT is higher than that of the blended P3HT/PCBM. However, as shown in Fig. 3(c), blended OPS can be used in a wider visible spectrum range because those based on blended P3HT/PCBM films can cover a wider visible spectral range than the ones based on pristine P3HT films. Here, when the OPSs are exposed under illumination power, the many photons are absorbed within organic molecules, such as P3HT and PCBM. The electrons are excited to a higher occupied molecular orbital (HOMO) level, from a low unoccupied molecular orbital (LUMO) level, and this transition induces the generation of an exciton. Such excited electrons are bound to the hole due to the low dielectric constant of the organic material at room temperature so that the excitons can only diffuse a few nanometers before they recombine, and consequently their contribution charges are lost. The result being that the current, at a given voltage for organic thin film under illumination, is higher than that of a dark state, indicating that the light illumination increases the production of the electron-hole pairs.

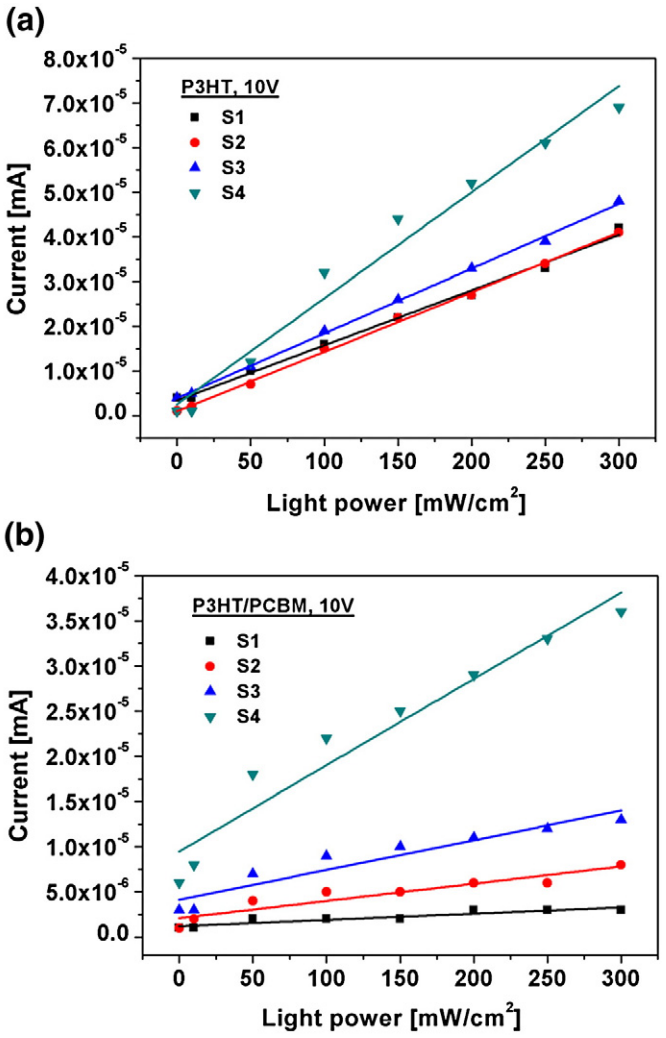

Fig. 4. The current–illumination (I–L) characteristics of OPSs based on (a) pristine P3HT and (b) blended P3HT/PCBM films under dark and light illumination conditions.

In order to investigate the reproducibility of the OPSs, three sensing cycles are tested by repeating the sensing and recovery. Fig. 5 shows the change in the current as a function of time, when the OPSs of the four-type interdigitated electrodes are exposed to exposure/intercept three-cycles, under an illumination power of 300 mW/cm^2, performed at room temperature in the atmosphere. The variation current of the OPSs based pristine P3HT, and the blended P3HT/PCBM films are shown in Fig. 5(a) and (b), respectively. The measurements of the time dependence of the current in the OPSs measure the applied voltage of 10 V under an illuminated power of 300 mW/cm^2 for 100 s. Also, the channel lengths of the OPSs are fixed at 100 um, and the channel widths are varied from 200 um to 13.3 mm. Recovery is obtained by using the light-off condition for 100 s. The measured current for the OPSs of the four-type interdigitated electrodes is achieved more rapidly under higher illumination power where it can be clearly observed that the current of the OPSs increases due to an increase in the light illumination power. The current for three sensing cycles decreases by degrees for the OPS based on pristine P3HT, is as shown in the 'A' point of Fig. 5(a) but the bended P3HT/PCBM shows no decrease of current. The cause of the decreased current is largely due to the electron trap effect for the applied voltage, and the thermal effect from the illumination power. Thus, reliability is one of the major issues slowing the development of sensors based on organic semiconductors. Some organic semiconductor films are not very

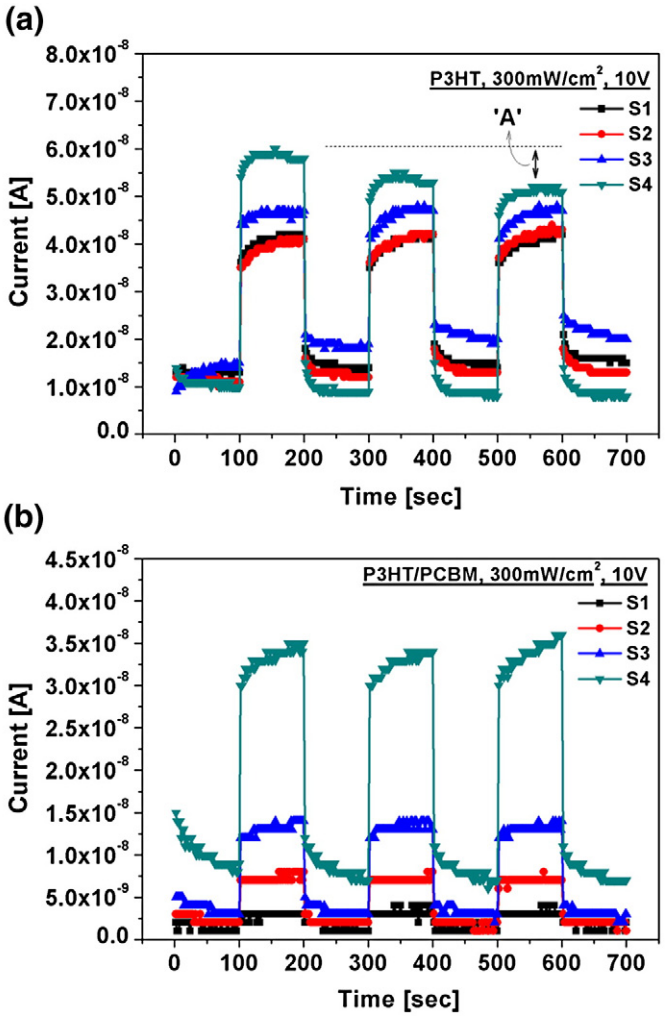

Fig. 5. The change in the current for OPSs of the (a) pristine P3HT and (b) blended P3HT/PCBM as a function of time when the photosensors of different channel widths exposed to exposure/intercept three-cycles under illumination power of 300 mW/cm^2 at room temperature.

stable once a current passes through them, especially in highly doped electrochemically grown films. The sensors based on organic semiconductors can be very helpful in this respect, particularly

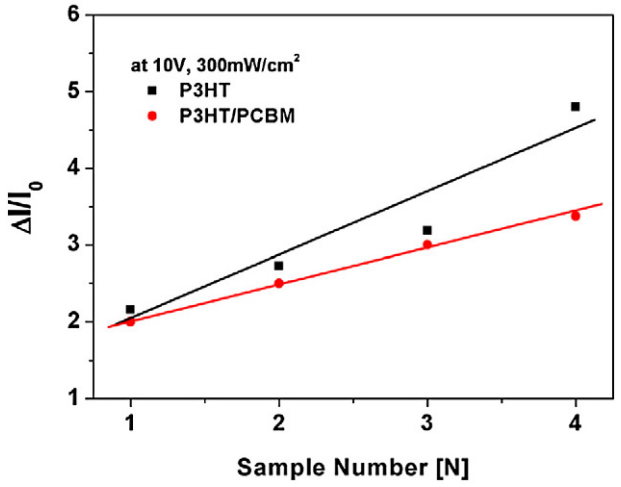

Fig. 6. The response characteristics of OPSs for four-type channel widths vs. active materials of pristine P3HT and blended P3HT/PCBM films.

Table 1
Response characteristics of OPSs devices for active materials of pristine P3HT and blended P3HT/PCBM films under the dark and under light illumination conditions.

	S1	S2	S3	S4
P3HT ($\Delta I/I_0$)	2.15	2.73	3.18	4.8
Blended P3HT/PCBM ($\Delta I/I_0$)	2	2.5	3.00	3.38

when they are operated in the pulse mode. Toris et al. reported that sensors exhibit extremely good response repeatability in the pulse mode [18].

Finally, the response characteristics of the OPSs are shown in Fig. 6, after being calculated from the graph curve of Fig. 5. The relative current change, $\Delta I_{rep} = I_{light}/I_{dark}$ is plotted against time for each illumination power level, with I_{dark} being the current baseline before exposure to the illumination power. For a comparison of the response characteristics when the OPSs based on pristine P3HT and blended P3HT/PCBM are exposed to various illumination powers, the parameters for all the devices are summarized in Table 1. As shown in Fig. 4(a–b), among the OPSs with different channel widths exposed under illumination power, those with long channel widths show higher response characteristics than those with short channel widths. Also, the response characteristics of the OPSs based on an active layer of pristine P3HT and blended P3HT/PCBM shows higher response characteristics for the OPS of pristine P3HT active layer than for the OPS based on the blended P3HT/PCBM active layer. These results confirm good reproducibility and short-time responses of the organic photosensor, as shown Fig. 5(a–b). It is forecast that, the simplicity and low cost of this OPSs fabrication technique, as well as its adaptation to photosensor manufacturing, will provide a very promising technology for industrial processes.

4. Conclusions

The electrical characteristics of solution-processed OPSs, made from organic materials of P3HT and PCBM films, with four-type of interdigitated electrodes for achieving high photo-sensing performances have been studied. The current from the OPSs through the semiconductor organic films has been measured under light intensities ranging from dark to 300 mW/cm^2. As a result, the current of the OPS based on pristine P3HT is higher than that of the blended P3HT/PCBM films. However, the blended OPS device can be used in a wide visible spectrum range, through the result of the absorption spectrum. The measured current for different channel widths is achieved more rapidly under higher illumination powers. Those with long channels widths show higher response characteristics than those with short channel widths. Also, the response characteristics of the OPSs based on active layers of pristine P3HT and blended P3HT/PCBM films show higher response characteristics for the OPS of pristine P3HT active layers than for the OPS based on blended P3HT/PCBM active layers. These results show good reproducibility and fast response time of the OPSs devices.

Acknowledgements

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