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Optical, electrical and mechanical properties of indium tin oxide on polyethylene terephthalate substrates: Application in bulk-heterojunction polymer solar cells ☆

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ABSTRACT

We investigated optical, electrical and mechanical properties of indium tin oxide (ITO) on flexible polyethylene terephthalate (PET) substrate, considering bulk-heterojunction (BHJ) polymer solar cells applications. Encapsulation of flexible solar cells with the architecture PET/ITO/PEDOT:PSS/P3HT:PCBM (or P3HT:PCBM:AZ-NDI-4)/Al was done by direct brush-painting with nail enamel. Active cell layer blends of [6,6]-phenyl C_{61} butyric acid methyl ester (PCBM) with regioregular or regiorandom poly(3-hexylthiophene-2,5-diyl) (P3HT) were applied. Additionally for this role the mixture of regioregular P3HT:PCBM with naphthalene diimide–imine with four thiophene rings AZ-NDI-4 was tested. Obtained photovoltaic (PV) and optical (UV–vis) results of the flexible polymer solar cells were compared with the same architecture of devices on the glass/ITO substrate.

1. Introduction

Organic photovoltaics (previously also called as polymer photovoltaics) are very widely investigated at the scientific and industrial level [1–7]. Presently the highest power conversion efficiency (PCE) value for bulk heterojunction (BHJ) device was observed to be approximately 12%, as reported by Heliatek [8]. In the meantime, a lot of work concerning the manufacturing and processing was done by Krebs et al. [9–11]. For flexible polymer solar cells (FPSC) the highest value of PCE was found at 4.2% for ultrathin and lightweight organic solar cells [12]. Based on the literature dedicated to FPSC we can conclude that presently not a lot of scientists are working on this subject [12–28] compared to the huge amount of papers dedicated to polymer solar cells on the glass substrate [1–7,29–37]. Recently, among flexible organic solar cells, graphene (or graphene oxide) was utilized as a potential flexible electrode [23–28,32]. This kind of substrate was applied to FPSC with such polymer as polyethylene terephthalate (PET) with PCE=0.84–4.2% [12–15,20,21], polyethylene naphthalene (PEN) with PCE=0.30–1.93% [16,18,20], polyethersulfone (PES) with PCE=1.12% [17] or polypropylene (PP) with PCE=0.33% [19]. Although possibly beneficial, this type of electrode formation is still expensive and does not lead to top conversion efficiencies due to material production, deposition and contacting problems. Alternatively standard indium tin oxide (ITO) technology, applied for real flexible devices of various constructions, was experimentally verified by the authors.

In this work, we investigated flexible polymer solar cells based on PET as a substrate and three kinds of active

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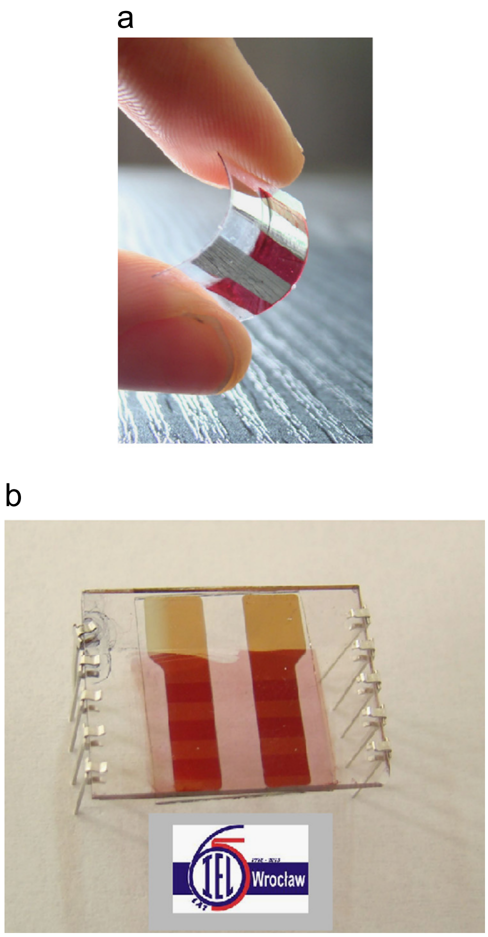

Fig. 1. Picture of constructed flexible polymer solar cell on the PET/ITO substrate (a) and polymer solar cell on the glass/ITO substrate (b).

layers including: (i) influence of regioregularity of P3HT on the photovoltaic (PV) parameters, (ii) influence of addition of naphthalene diimide–imine AZ-NDI-4 to P3HT:PCBM, (iii) influence of brush-painting hermetization with nail enamel on the efficiency of devices and (iv) stability of the constructed flexible devices in air after 16 h. Additionally for flexible applications electrical, optical and mechanical properties of PET substrate with ITO applied as an anode were tested.

2. Experimental

2.1. Materials and methods

Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), poly(3-hexylthiophene-2,5-diyl) (P3HT, regioregular and regiorandom) and [6,6]-phenyl C_{61} butyric acid methyl ester (PCBM) were purchased from Sigma-Aldrich and used as received. Methanol, acetone, and chloroform (98%) were purchased from POCH and used as received. Glass with ITO was purchased from Ossila company. Surface resistance of ITO on the glass substrate was about 20 Ω/sq. ITO on PET substrate from Zhuhai Kaivo Electronic Components Co., Ltd. was used. The 130 nm oxide layer was manufactured by magnetron sputtering on the PET substrate with thickness of 125 μm. The average resistance of 45 Ω/sq was obtained for ITO on PET. Synthesis of naphthalene diimide–imine AZ-NDI-4 is described in [38].

UV–vis spectra of P3HT:PCBM and P3HT:AZ-NDI-4 on PET/ITO were recorded as thin films on the flexible substrate by using a Jasco V670 spectrophotometer. The solutions were spread on flexible substrate using a spin-coating method. Characteristic parameters related to speed (10,000 rpm) and time (25 s) of rotation were applied to spin-coating equipment.

Resistance per square of ITO samples on PET was determined using a four probe measuring setup. The dynamic change of resistance was tested by a multi-cylinder rotor machine with on-line resistance acquisition system, based on a RIGOL DM3062 multimeter logger. The surface analysis was done by HRSEM (Tm-3000), optical microscope and Dektak profilometer.

3. Fabrication and characterization of polymer photovoltaic cells

3.1. Flexible solar cells

Solar cells were fabricated on indium tin oxide-(ITO)-coated PET substrate, with the structure PET/ITO/PEDOT:PSS/P3HT:PCBM (or P3HT:PCBM:AZ-NDI-4)/Al in air. PEDOT:PSS was spin cast (5000 turns/min, 20 s) from aqueous solution, to form a film on the PET/ITO substrate. A mixture of P3HT:PCBM with weight ratio 1:0.8 or P3HT:PCBM:AZ-NDI-4 in chloroform solution was then spin cast on top of the PEDOT:PSS layer. Active layer consisting of random P3HT:PCBM or P3HT:PCBM:AZ-NDI-4 was annealed for 2 h at 60 °C. Then, an aluminum electrode was deposited by thermal evaporation in vacuum of 5×10^{-4} Torr. Measurements were done for non-encapsulated devices and for the encapsulated devices by brush-painting with nail enamel. The active area of each cell was about 0.64 cm^2. Fig. 1a shows a picture of constructed flexible polymer solar cell on the PET/ITO substrate.

3.2. Solar cells on the glass substrate

Solar cells were fabricated on ITO coated glass substrate with the structure glass/ITO/PEDOT:PSS/P3HT:PCBM (or P3HT:PCBM:AZ-NDI-4/)Al in air, which was described in detail in our previous papers [29–34,39]. The area of one photovoltaic pixel was about 4.5 mm^2. Fig. 1 shows a picture of constructed polymer solar cell on the glass/ITO substrate.

Current density–voltage (*J*–*U*) characteristics of all devices were measured using a Solartron Potentiostat/Galvanostat Model SI 1260. Sunlight simulator utilized a xenon lamp with an irradiation intensity of 100 mW/cm^2 and standardized AM1.5G spectrum.

4. Results and discussion

In our study we used P3HT as a p-type semiconducting polymer, PCBM as a n-type semiconductor and AZ-NDI-4 as an n–p type compound. PEDOT:PSS was used as an