

Enhanced efficiency of bilayer polymer solar cells by the solvent treatment method



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ABSTRACT

We successfully facilitated an enhancement in the efficiency of polymer bilayer solar cells using the solvent treatment method. Specifically, after creating a poly(3-hexylthiophene-2,5-diyl(P3HT))/[6,6]-phenyl-C61-butyrac-acid-methyl-ester (PCBM) bilayer structure by the use of an orthogonal solvent, we applied the solvent treatment method to the bilayer solar cell to improve the device performance. When the interfaces between the P3HT layer and the PCBM layer and between the PCBM layer and the Al electrode were treated with methanol, the bilayer SCs showed significantly enhanced device performance with improved J_{sc} , FF, and PCE.

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1. Introduction

Polymer solar cells (PSCs) based on semiconducting and metallic polymers have drawn considerable attention due to their low cost, flexibility, and viability in printable energy devices [1–4]. PSCs are classified into two types of devices based on the structure of their active layers: simple planar heterojunctions (bilayer) and bulk heterojunctions (BHJs) [5]. BHJ devices consist of a blend of an electron-donating conjugated polymer (P-type) and an electron-accepting fullerene derivative (N-type) in the bulk volume, while bilayer devices consist of sequentially stacked P-type and N-type materials [6–8].

To date, most of the research regarding PSCs has been primarily focused on the development of BHJ devices, due to advantages including facile fabrication, self-assembling nanoscale morphologies, and greater interface areas for charge separation, which lead to significant enhancements in the photocurrent of the device [9,10]. However, in spite of such advantages, BHJ devices still suffer from several critical issues which must be resolved prior to

commercialization. In the BHJ geometry, electron-donating conjugated polymers and electron-accepting fullerene derivatives spontaneously form nanoscale phase separations and bicontinuous interpenetrating networks. Since the separated charges (electrons and holes) are transported to the electrode via self-assembled bicontinuous charge channels, the device performance is sensitive to the nanoscale morphology of the BHJ blend. Moreover, difficulties in controlling the nanoscale morphologies of both phases debase the reproducibility of the device performance required for commercialization [11].

In contrast, bilayer devices with sequentially stacked donor and acceptor layers are conceptually more straightforward in regard to commercialization [12,13]. Because the bilayer architecture allows each layer to be controlled and optimized independently, controlling the morphology of each phase is more facile as compared to BHJs. Consequently, the reproducibility of the device performance is increased. Several research groups have demonstrated bilayer SCs including small molecule devices consisting of small molecular donors and fullerene acceptors, in addition to polymer devices based on soluble polymer donors and fullerene derivatives acceptors [14,15]. However, small molecule SCs fabricated by thermal evaporation are hardly regarded as printable SCs, and solution-processable bilayer PSCs exhibit a relatively low power conversion efficiency (PCE) compared to BHJ devices.

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Therefore, the development of solution-processable bilayer PSCs with a high performance is crucial in order to realize printable SCs and to simultaneously develop useful methods to improve the performance of printable bilayer PSCs.

Towards that end, simple and useful methods that improve the performance of BHJ-based devices have been reported by several groups [16–18]. Interestingly, Zhou et al. described the simultaneous enhancement in the open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), and fill factor (FF) of a BHJ device by methanol coating on the active layer prior to cathode deposition [19]. They concluded that the additional methanol coating on top of the BHJ layer may have altered the properties of the interface between the BHJ layer and the metal electrode, and filled trap sites at the surface resulting in an increase in the surface charge density [19]. Considering these results, it is expected that the solvent treatment method can be utilized in bilayer PSCs to improve device performance. Moreover, we believe that its utility would be more evident in bilayer structures as compared to BHJ structures because of the additional interface between the donor polymer and fullerene derivatives.

As such, in this work, we utilized the solvent treatment method to improve the device performance of printable bilayer PSCs. After achieving a poly(3-hexylthiophene-2,5-diyl (P3HT)/[6,6]-phenyl-C61-butyrac-acid-methyl-ester (PCBM) bilayer structure using an orthogonal solvent, we utilized the solvent treatment method to the bilayer SC by using alcohol-based solvents. When the interface between the P3HT layer and the PCBM layer in addition to the interface between the PCBM layer and Al electrode were treated with ethanol, isopropanol, and methanol, the bilayer SCs showed a significant enhancement in their device performance with improved J_{sc} , FF, and PCE.

2. Experimental

After clarifying the bilayer structure, the solvent treatment method was applied in order to improve the SC efficiency. P3HT/PCBM bilayer PSCs were fabricated on an indium tin oxide (ITO)-coated glass substrate in the following structure: ITO-coated glass substrate/poly(3,4-ethylenedioxythiophene) (PEDOT:PSS)/P3HT:PCBM/Al. The ITO-coated glass substrate was first cleaned with detergent, ultrasonicated in acetone and isopropyl alcohol, and subsequently dried overnight in an oven. PEDOT:PSS (Baytron PH)

was spin-cast from an aqueous solution to form a 40 nm-thick film. The substrate was dried for 10 min at 140 °C in air and then transferred into a glove box for spin-casting of the charge separation layer. For the fabrication of the bilayer PSC, the P3HT solution in Dichlorobenzene (DCB) was cast on the PEDOT:PSS layer and dried at room temperature for 30 min. PCBM dissolved in Dichloromethane (DCM) was spin-coated on the P3HT layer with a spin speed of 4000 rpm for 10 s. For the fabrication of the BHJ PSC, a solution containing a mixture of P3HT:PCBM (1:0.8) in DCB (2 wt. %) was spin-cast on top of the PEDOT:PSS layer. Then, an aluminum (Al, 100 nm) electrode was deposited by thermal evaporation in a vacuum (5×10^{-7} Torr). Current density–voltage (J – V) characteristics of the devices were measured using a Keithley 2400 Source Measure Unit. Irradiation was carried out using an Air Mass 1.5 Global (AM 1.5 G) solar simulator with an irradiation intensity of 1000 W m^{-2} .

3. Result and discussion

One of the main issues in the generation of the P3HT/PCBM bilayer structure is the formation of a completely separate PCBM film on top of the underlying P3HT film. Because the P3HT film is easily dissolved in common organic solvent such as DCB, Chlorobenzene (CB), Chloroform (CF), and Tetrahydrofuran (THF), the use of these solvents for preparing the PCBM solution damages the P3HT layer when PCBM is casted on top of the P3HT layer. Therefore, a solvent that does not dissolve P3HT, yet dissolves PCBM is required in order to produce the bilayer structure. The use of DCM as a solvent for the PCBM solution enabled the realization of the bilayer structure [14]. Specifically, the orthogonal solubility of P3HT in DCM enables the fabrication of a completely separate PCBM film on the underlying P3HT film. Fig. 1 illustrates the fabrication process of the bilayer structure of the P3HT/PCBM using DCB and DCM as solvents. As shown in the upper portion of Fig. 1, DCB easily removed the P3HT layer when the PCBM-DCB solution was dropped on top of the P3HT film. In contrast, the use of DCM as the solvent for the PCBM solution yielded complete P3HT/PCBM bilayer films as shown in the lower portion of Fig. 1, while PCBM was soluble in DCM, P3HT was not. As such, the P3HT layer underneath was preserved when the PCBM solution was dropped.

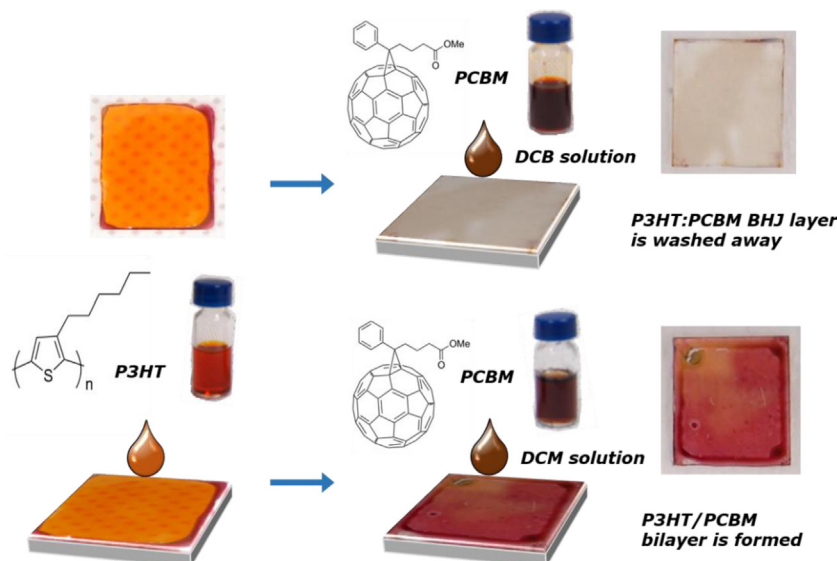


Fig. 1. Scheme of the fabrication process of the bilayer structure of the P3HT/PCBM using DCB and DCM.

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