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Simultaneous enhancement in both large-area coatability and photovoltaic performance of inverted organic solar cells with co-solvent

Yun-Ru Hong^a, Pin-Kuan Chen^b, Jen-Chun Wang^c, Ming-Kun Lee^b,
Sheng-Fu Horng^{b,*}, Hsin-Fei Meng^d

^a Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 300, Taiwan

^b Department of Electrical Engineering, National Tsing Hua University, Hsinchu 300, Taiwan

^c Department of Materials Science and Engineering, National Tsing Hua University, Hsinchu, 30013, Taiwan

^d Institute of Physics, National Chiao Tung University, Hsinchu, 30013, Taiwan

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ABSTRACT

We report our observation of simultaneous enhancement in large-area coatability and photovoltaic performance for blade-coated inverted P3HT:PCBM organic solar cells with DCB:hexane co-solvent. The addition of hexane improves greatly the wettability of P3HT:PCBM blend layer on Cs_2CO_3 treated ITO and leads to excessively higher P3HT surface concentration due to the incongruent evaporation of hexane and DCB. A post-processing light soaking was found to further improve the photovoltaic performance for blade-coated devices prepared with co-solvent by adjusting the P3HT surface concentration ratio for more favorable carrier transport, as evidenced by the disappearance of current suppression at forward bias and significant increase in V_{oc} after light soaking. Since large-area manufacturing is the key to full commercialization of organic solar cells, the use of co-solvent, combined with light soaking, may be crucial for the development of inverted organic solar cells.

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1. Introduction

Organic solar cell (OSC) is a very promising alternative for solar energy conversion due to their unique and attractive features of low-cost manufacturing, mechanical flexibility, light weight and fabrication feasibility [1–4]. Much progress on OSC has been made with impressive power conversion efficiency and the highest power conversion efficiency (PCE) reported exceeds 10.7% to date [5].

The key property which makes OSCs so attractive is the potential of roll-to-roll processing on low-cost substrates with standard coating and printing processes. This requires large-area high-quality coatings of organic semiconductors. Most of the reported efficient polymer solar cells are fabricated by spin coating technique because of its better control over the thickness and homogeneity of films. However, spin coating is unfavorable for large-area devices, inherently wasteful in material use and is incompatible with roll-to-roll process for high throughput production. To overcome these drawbacks of spin coating process, alternative techniques such as blade coating, slot-die coating,

gravure coating, ink-jet printing and spray coating were developed [6–12]. High-throughput continuous processing is crucial for OSCs to manufacture at sufficiently low cost to compete with other thin film solar cell technologies [12–19]. Krebs et al. developed full roll-to-roll processed polymer solar cell modules with a total active area of 35.5 cm^2 and the module PCE achieved 2.75% [20]. Recently, a module with 16 cm^2 aperture area and an efficiency as high as 5.5% was reported by Imec and Solvay [21]. An extensive survey of roll-to-roll technologies for various organic devices, organic solar cells included, by Søndergaard et al., can be found in Ref. [22].

To achieve full commercialization of OSCs, these continuous coating processes need to be carefully studied and various coating defects must be carefully controlled. Coating defects are mainly related to surface tension as well as surface flow and various additives or co-solvents may be used to match the surface tension to reduce the formation of coating defects. In spite of abundant work done in this regard in paint and compliant coating technologies [23,24], there is still little discussion of control over coating defects specifically for OSCs. This is especially important since change in solvent or additives to circumvent the coating defects may affect either the active layer/electrode interface [25] or the distribution and micro-morphology of donor–acceptor in the active layer and thus its photovoltaic properties.

* Corresponding author. Tel.: +886 3 574 2578; fax: +886 3 575 2120.
E-mail address: sfhorng@ee.nthu.edu.tw (S.-F. Horng).

Various types of co-solvents and additives have been proposed for use to improve the efficiency of organic solar cell in the literatures [26–28]; however, most of these previous work focused mainly on their effects on donor/acceptor phase separation. The effects of co-solvents on the film formation in large-area coating processes were little addressed. Schrödner et al. discussed recently the choice of solvent to optimize the photovoltaic performance of organic solar cells manufactured by roll-to-roll slot-die coating and found that CHCl_3 :DCB mixture can be effectively used to produce efficient large-area OSCs, yet only conventional OSCs are examined [29].

In this paper, we report our observation that the use of 1,2-dichlorobenzene:n-hexane (DCB:hexane) co-solvent can improve both the film formation in large-area coating process and the photovoltaic performance of the resulted inverted organic solar cells. X-Ray photoelectron spectroscopy (XPS) results reveal that the addition of hexane in the solution results in excessive increase in P3HT compositional ratio on the surface due to the incongruent evaporation of hexane and DCB. After a post-processing light soaking for 40 min with an AM 1.5G solar simulator, the PCE of the blade-coated inverted OSCs reaches 3.92%, thus demonstrating the possibility of simultaneous enhancement in both large-area manufacturability and photovoltaic performance for inverted OSCs.

2. Experiment

The schematic diagram of the device structure of OSC considered in this study is shown in Fig. 1. The devices were prepared as follows. Indium tin oxide (ITO) coated glass was cleaned by acetone, isopropanol (IPA) and de-ionized water for 10 min, respectively to remove residual organic materials. An electron transport material, 0.1 wt% Cs_2CO_3 (99%, purchased from ALFA, Inc.) dissolved in 2-ethoxyethanol, was blade-coated on the prepared ITO-coated substrates with coating speed of 20 mm/s and then dehydrated at 150 °C for 10 min. Two types of solvents for the blend layer of OSC were investigated in this work. The first is DCB and the other is a co-solvent consisting of DCB:hexane in 1:1 volume ratio. The blend solution was prepared by mixing P3HT (17 mg ml^{-1} , purchased from Rieke Metals, Inc.) and PCBM (17 mg ml^{-1} , purchased from Nano-C, Inc.) in either DCB or the co-solvent. Each blend solution was blade-coated on the Cs_2CO_3 -coated ITO substrate with typical coating speed of 13.3 mm/s and was subsequently annealed at 140 °C for 10 min. The area of ITO-coated glass substrate used to study large-area coatability was 7 cm by 8 cm. Two types of small-area solar cells with active area of 4 mm^2 (Device A and B) were fabricated to investigate the effects of co-solvent on photovoltaic performance. Both were

prepared following the same fabrication steps except for the preparation of blend solution. For Device A, the aforementioned blend solution prepared with DCB was used and for Device B, the blend solution with co-solvent. Each blend solution was blade-coated on the Cs_2CO_3 -coated ITO substrate with coating speed of 13.3 mm/s and annealed at 140 °C for 10 min. PEDOT:PSS (AI 4083, purchased from H. C. Starck, Inc.) solution diluted in IPA with the weight ratio of 1:10 (AI 4083:IPA) was blade-coated on top of the blend layer with the coating speed of 13.3 mm/s and was then annealed at 140 °C for 10 min. The doctor blade used in this study is purchased from Elcometer Co. Ltd. (model 3520) and is motorized by a linear motor system (model LMX1L-S, HIWIN Co. Ltd.). A photo of the coating system was shown in Fig. 2. The details of the setup of the blade coating system can be found in Ref. [30]. The polymer wet film was obtained by dragging the deposited solution with the coating blade and the solution concentration of polymer, the blade's speed and the gap between the doctor blade and the substrate determine the thickness of polymer films. In this work, 60 μm gap was employed for the Cs_2CO_3 as well as blend layers, and 30 μm gap was used for the diluted PEDOT:PSS. The thickness of various layers was measured by an Alpha Step Profiler (model. Alpha step 500, Tencor Inc.) For the small-area device, the thickness after annealing is $220 (\pm 20) \text{ nm}$ for the blend layer with both DCB and co-solvent, and $40 (\pm 5) \text{ nm}$ for PEDOT:PSS. Subsequently, a top metal electrode of Silver (100 nm) was thermally deposited under a pressure of $2.3 \times 10^{-6} \text{ Torr}$. The fabricated



Fig. 2. The picture of the coating system, consisting of a doctor blade motorized by a linear motor system and home-made supporting stage.

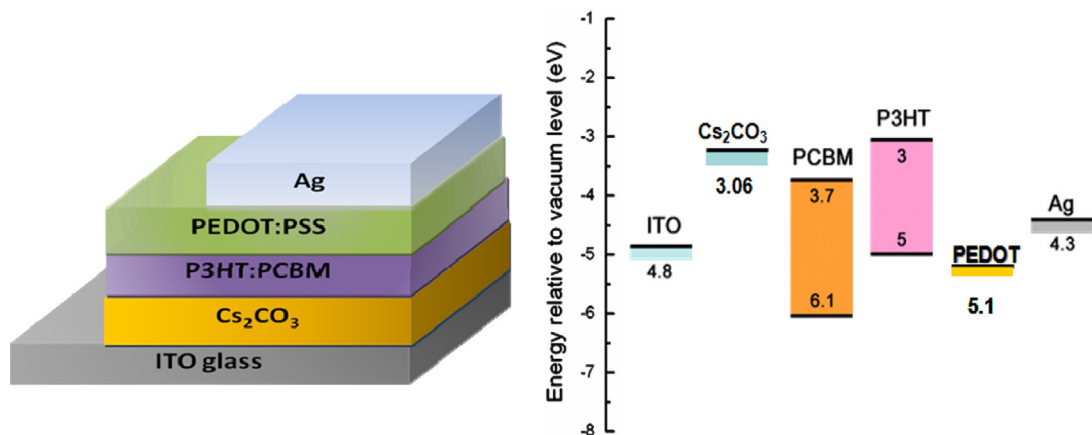


Fig. 1. (a) The device structure and (b) the energy band diagram of the inverted organic solar cell investigated in the present study.

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