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# An Efficient Triple-Tandem Polymer Solar Cell

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**Abstract**—We present an efficient triple-tandem polymer solar cell with identical poly(3-hexylthiophene) (P3HT) and 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6,6) $C_{61}$  (PCBM) bulk heterojunction as the active layers and highly transparent Al (1 nm)/MoO<sub>3</sub> (15 nm) as the intermediate layer. This intermediate layer is structurally smooth as characterized by atomic force microscopy. Although identical organic active layers are used to construct such triple-tandem cell, a tripled open-circuit voltage of 1.73 V and power conversion efficiency of 2.03% are obtained under simulated solar irradiation of 100 mW/cm<sup>2</sup> (AM1.5), demonstrating a viable technique for fabricating triple-tandem polymer cell with the intermediate layer of Al/MoO<sub>3</sub>.

**Index Terms**—Intermediate layer, MoO<sub>3</sub>, polymer solar cells (PSCs), tandem PSCs.

## I. INTRODUCTION

POLYMER solar cells (PSCs) have been intensively studied because of their advantages of low cost, light weight, flexibility, and easy fabrication. The power conversion efficiency (PCE) of the bulk heterojunction of poly(3-hexylthiophene) (P3HT) and 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6,6) $C_{61}$  (PCBM) has reached 5% with an improved morphology of the interpenetrating networks [1], [2]. For a standard P3HT:PCBM single cell, the open-circuit voltage ( $V_{oc}$ ) is only around 0.60 V. On the other hand, the tandem structure of PSCs [3]–[5], i.e., two or more cells with complementary absorptions stacked in series by optical and electrical connections, is an effective approach to raise the  $V_{oc}$  and further improve the efficiency. A few double-tandem polymer cells with identical active layers have been demonstrated with increased  $V_{oc}$ , using identical MEH-PPV/PCBM ( $V_{oc} = 1.64$  V) [6] and MDMO-PPV/PCBM ( $V_{oc} = 1.34$  V) [7] bulk heterojunction. However, there are problems associated with the tandem structure such as incompletely stacking cells [6] and large voltage drop [7]. To truly avoid these problems, an effective intermediate layer is a must. A good intermediate layer has to meet the challenges of stacking solution-processed polymer layers repeatedly, which brings the complexity and difficulty by the requirements

of preventing the existing polymer layer from being dissolved, as well as light loss caused by the added intermediate layer. Thus, an intermediate layer with simple and controllable processes, high transparency, efficient electric connection, and protection of prior-deposited polymer layer is desired. The commonly used intermediate layer in solution-processed tandem cell comprises the combination of metal Al/Au and poly(3, 4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS). However, it has to be pointed out that either the metal layer causes significant light loss [8] or the PEDOT film needs to be formed and baked outside the glove box [5], [9], which would degrade the performance of existing polymer layers. For triple-tandem polymer cell, to date, only one has been reported [3] where a solution-processed ZnO/PEDOT intermediate layer was used to connect identical MDMO-PPV/PCBM active layers. However, the resulting  $V_{oc}$  of devices without UV irradiation is much lower than expected due to large voltage loss across the ZnO/PEDOT layer. Meanwhile, the fill factor (FF) also suffers a remarkable decrease induced by high series resistance. In addition, PEDOT has to be modified neutrally before spin coating it onto the ZnO layer, which further complicates the fabrication process.

In our previous study [10], we developed an Al (1 nm)/MoO<sub>3</sub> (15 nm) intermediate layer with high transparency (98%) and low voltage loss (efficient electric connection). More importantly, this intermediate layer can effectively protect the prior-deposited polymer layer from dissolving in the wet process, which is very suitable for multiple-tandem photovoltaic devices. In this letter, we present a triple-tandem solar cell with this Al/MoO<sub>3</sub> intermediate layer. The enhanced  $V_{oc}$  reaches 1.73 V in the triple-tandem polymer cell with identical P3HT/PCBM active layers. The PCE (2.03%) of the triple-tandem cell is comparable to those of single- and double-tandem cells.

## II. EXPERIMENTAL SECTION

All cells were fabricated on indium-tin-oxide (ITO)-coated glass substrates with a sheet resistance of 20  $\Omega/\square$ . PEDOT:PSS (Baytron P 4083) was first spin coated onto a precleaned ITO glass with a thickness of 40 nm and was baked at 120 °C for 20 min. The polymer active layer was fabricated by spin coating the blend solution, made of P3HT (Rieke Metals, Inc.) and PCBM (Nano-C) with a weight ratio of 1:0.8 in chlorobenzene (18 mg/mL), onto PEDOT- or MoO<sub>3</sub>-coated substrates. MoO<sub>3</sub>, Al, and Ag were deposited under a base pressure of  $2.0 \times 10^{-4}$  Pa, respectively. All cells were postannealed at 150 °C for 5 min with the active area of 0.1 cm<sup>2</sup>. The film morphology was evaluated by atomic force microscopy (AFM)

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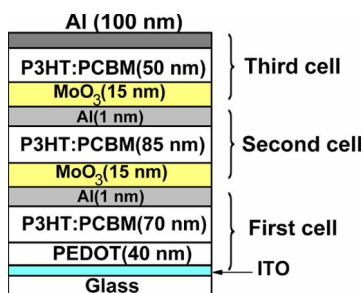
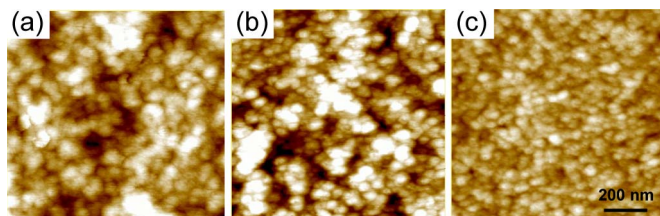


Fig. 1. Device structure of the triple-tandem PSC.

Fig. 2. AFM images of (a) P3HT:PCBM, (b) P3HT:PCBM/Al (1 nm), (c) P3HT:PCBM/Al (1 nm)/MoO<sub>3</sub> (15 nm) films. The scale bar is 200 nm (applicable to all images).

(NanoScope IIIa). The current–voltage ( $I$ – $V$ ) characteristics were measured with a Keithley 2400 SourceMeter in the dark and under 100-mW/cm<sup>2</sup> (AM 1.5 G) irradiation of a solar simulator (Solar Light Company, Inc.). The transmittance spectra of the used films were characterized by an HP 8453 UV–VIS spectrometer. The thickness was measured with a surface profiler (Tencor P15). The incident photon-to-electron conversion efficiencies (IPCEs) (spectral response) were measured using a 200-W Xenon lamp light source with a motorized monochromator (Oriel). The resulting structure of the triple-tandem polymer cell is shown in Fig. 1.

### III. RESULTS AND DISCUSSION

Fig. 2(a)–(c) shows the AFM images of P3HT:PCBM, P3HT:PCBM/Al (1 nm), and P3HT:PCBM/Al (1 nm)/MoO<sub>3</sub> (15 nm) films, respectively. The 1-nm-thick Al should be in the form of nanocluster, as pointed out by other researchers [11]. The root-mean-square surface roughness of the P3HT:PCBM/Al film [Fig. 2(b)] is 0.861 nm, which is slightly higher than that of the P3HT:PCBM film (0.662 nm) [Fig. 2(a)]. However, with the deposition of 15-nm MoO<sub>3</sub>, the roughness of P3HT:PCBM/Al/MoO<sub>3</sub> [Fig. 2(c)] reduces to 0.366 nm, indicating that the Al/MoO<sub>3</sub> intermediate layer is structurally smooth.

The identical polymer blend (P3HT:PCBM) was used as the three active layers to constitute the triple-tandem cell. To realize tripled  $V_{oc}$  and relatively high efficiency, the thickness of each active layer was carefully adjusted so as to simultaneously maximize light absorption and realize matched short-circuit current in each subcell.

Fig. 3(a) compares the  $I$ – $V$  characteristics of all cells covered in the triple-tandem cell under 100-mW/cm<sup>2</sup> irradiation. The photographic image of the device under test is shown as the inset of Fig. 3(a). The PCEs of the first [the P3HT:PCBM thickness (the same hereinafter) is 70 nm], sec-

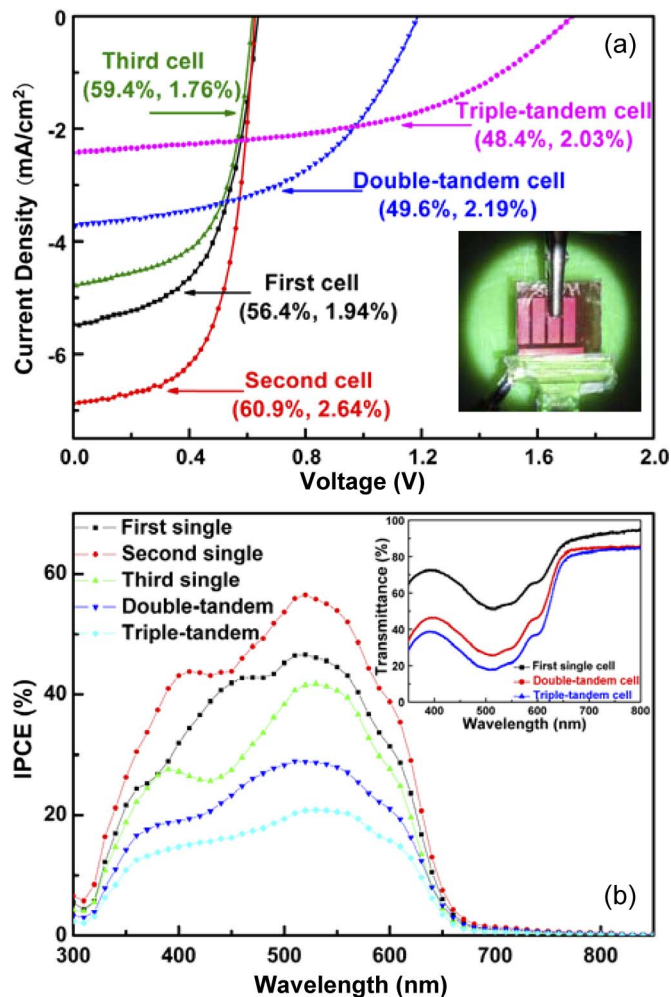


Fig. 3. (a)  $I$ – $V$  characteristics of the first (70 nm), second (85 nm), third (50 nm) single-, double-, and triple-tandem cells under a simulated solar irradiation of 100 mW/cm<sup>2</sup>. The corresponding FF and PCE are shown in the form of (FF, PCE). The inset is a photographic image of the device under test. (b) IPCE spectra of each single-, double-, and triple-tandem cells. The inset shows the transmittance spectra of the first single film (70 nm), double-tandem film (70 nm/85 nm), and triple-tandem film (70 nm/85 nm/50 nm).

ond (85 nm), and third (50 nm) single cells are 1.94%, 2.64%, and 1.76%, respectively. The double-tandem cell has a PCE of 2.19% with  $V_{oc}$  of 1.19 V and short-circuit current density ( $J_{sc}$ ) of 3.71 mA/cm<sup>2</sup>. The triple-tandem cell achieves a  $V_{oc}$  of 1.73 V with  $J_{sc} = 2.41$  mA/cm<sup>2</sup>, FF = 48.4%, and PCE = 2.03%. The  $V_{oc}$  almost triples that of a single cell (0.62 V), demonstrating a relatively good ohmic contact between Al and MoO<sub>3</sub> layer [3]. The inset of Fig. 3(b) shows the transmittance spectra of the first (70 nm), double-tandem (70 nm/85 nm), and triple-tandem (70 nm/85 nm/50 nm) films. Obviously, the triple-tandem cell absorbs more solar irradiation in the main absorption range of P3HT/PCBM blend. However, as we are using the same polymer materials for the stacked device, the light intensity becomes weaker when it passes through the stacks. As the final current in serially connected cells is determined by the smallest current, the photocurrent generated in each subcell in the tandem device will be scaled down in proportion to the number of stacked subcells for an optimized tandem device.

Consequently, compared to a  $J_{sc} = 4 - 7 \text{ mA/cm}^2$  of a single cell, a  $J_{sc}$  of  $2.41 \text{ mA/cm}^2$  for a triple-tandem cell is pretty good [Fig. 3(a)]. Meanwhile, the  $J_{sc}$  is expected to be less affected by stacking different polymer layers with complementary absorptions. It can also be seen from Fig. 3(a) that the FF reduces slightly as the number of cells increases, which can be largely attributed to the increase of series resistance in the multiple-tandem cell. However, with a simultaneously increased shunt resistance, reduction in FF is not significant. In fact, our FF (48.4%) is higher compared to those previously reported triple-tandem cells [3]. The overall PCE of the triple-tandem cell (2.03%) is comparable to those of the single- and double-tandem cells. Thus, this intermediate layer is feasible to be applied in tandem PSCs with complementary absorption spectra.

The spectral response (IPCE) of each of the single-, double-, and triple-tandem cells are shown in Fig. 3(b). It can be seen that, with the increase of stacked cells, the capability of converting harvested photons into extracted charges becomes weaker at all wavelengths across the absorption spectrum of the active layers, which is in agreement with the  $I-V$  characteristics shown in Fig. 3(a).

Last, with nearly tripled  $V_{oc}$ , our triple-tandem cell with a  $0.1\text{-cm}^2$  active area was able to turn on a red light-emitting diode under a simulated  $100\text{-mW/cm}^2$  irradiation (not shown here), demonstrating that our tandem cell is advantageous compared to three individual cells connected in series by external wiring in that it has a three times smaller footprint that is beneficial for area-limited applications.

#### IV. CONCLUSION

In conclusion, we have implemented the triple-tandem polymer cell with an enhanced  $V_{oc}$  of 1.73 V and a comparable PCE of 2.03%. With the highly transparent, efficiently protecting, and structurally smooth intermediate layer (Al/MoO<sub>3</sub>), such

stacked identical active layers can fully absorb in their main corresponding range. Such high  $V_{oc}$  by the multiple-cell tandem structure will provide the potential application of PSCs in area-limited low-power electronics. Furthermore, this intermediate layer would be the most potentially applied one in multiple-tandem polymer cells with ideal complementary absorptions.

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