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G. Li
*University of California at Los Angeles*

C.-W. Chu
*University of California, Los Angeles*

V. Shrotriya
*University of California at Los Angeles*

Jinsong Huang
*University of Nebraska-Lincoln, jhuang@unc.edu*

Y. Yang
*University of California at Los Angeles*

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Efficient inverted polymer solar cells

G. Li, C.-W. Chu, V. Shrotriya, J. Huang, and Y. Yang

Department of Materials Science and Engineering, University of California at Los Angeles, Los Angeles, California 90095-1595

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We investigate the effect of interfacial buffer layers—vanadium oxide (V_2O_5) and cesium carbonate (Cs_2CO_3)—on the performance of polymer solar cells based on regioregular poly-(3-hexylthiophene) and [6,6]-phenyl C_60 butyric acid methyl ester blend. The polarity of solar cells can be controlled by the relative positions of these two interfacial layers. Efficient inverted polymer solar cells were fabricated with the structure of indium tin oxide (ITO)/Cs_2CO_3/polymer blend/vanadium oxide (V_2O_5)/aluminum (Al). Short-circuit current of 8.42 mA/cm^2, open-circuit voltage of 0.56 V, and power conversion efficiency of 2.25% under a AM1.5G 130 mW/cm^2 condition were achieved. The interfacial layers were also used to fabricate polymer solar cells using ITO and a thin gold (Au) layer as the transparent electrodes. The thickness of V_2O_5 layer (10 nm) makes it an effective protective layer for the active layer so that ITO can be used for both the electrodes, enabling highly efficient transparent polymer solar cells (i.e., polymer solar cells with transparent electrodes). Application of this structure for multiple-stacking polymer solar cells is also discussed. © 2006 American Institute of Physics. [DOI: 10.1063/1.2212270]

Fast improvement in polymer solar cells (PSCs) performance in recent years has distinguished this technology as a promising cost effective alternative to silicon based solar cells. PSCs can be utilized to generate truly clean and renewable energy from sunlight. Recently, our group demonstrated efficient transparent polymer solar cells (PSCs) can be utilized to generate truly clean and renewable energy from sunlight. Recently, our group demonstrated efficient transparent polymer solar cells.
In the device with no buffer layer (ITO/blend/Al), reasonable photovoltaic effect was observed with short-circuit current density \(J_{SC}\) of 4.75 mA/cm\(^2\). However, open-circuit voltage \(V_{OC}\) and fill factor (FF) are poor at 0.22 V and 28.5%, resulting in PCE of only 0.23%. Modifying the ITO anode by PEDOT:PSS provides significant improvement in the device performance where \(J_{SC}\) increases to 7.44 mA/cm\(^2\), \(V_{OC}\) to 0.42 V, FF to 51.8%, and the overall efficiency to 1.25%.

Furthermore, insertion of 1 nm thermally evaporated Cs\(_2\)CO\(_3\) layer at the polymer/Al interface leads to a reduction in \(J_{SC}\) at 5.95 mA/cm\(^2\). However, the \(V_{OC}\) increases to 0.52 V, and an excellent FF of 65.6% is achieved. This results in a PCE of 1.55%, a 25% improvement. These results clearly show that Cs\(_2\)CO\(_3\) can act as a functional interfacial layer to enhance polymer solar cell efficiency. The work function of PEDOT:PSS is 5.0 eV, which is 0.3 eV higher than that of ITO (4.7 eV). This work-function increase can explain the increase in \(V_{OC}\) by 0.2 eV according to the metal-insulator-metal (MIM) model. This apparently contradicts the common belief that the energy level difference between the donor highest occupied molecular orbital (HOMO) and the acceptor lowest unoccupied molecular orbital (LUMO) levels dominates the \(V_{OC}\) in the polymer BHJ solar cell. However, the contact changes from non-Ohmic in the case of ITO to Ohmic for PEDOT:PSS, and both electrodes being Ohmic is a necessary condition for the above belief to be valid. Earlier study on Cs\(_2\)CO\(_3\) indicated that during thermal evaporation, Cs\(_2\)CO\(_3\) decomposes into cesium oxide. Depending on the film thickness, the resulting cesium oxide has a field-emission work function of \(\sim 1.1\) eV because of thermionic emission. Ultraviolet photoemission spectroscopy (UPS) measurements conducted in our laboratory on thermally evaporated Cs\(_2\)CO\(_3\) films show a work function of 2.2 eV. The polymer/Cs\(_2\)CO\(_3\) contact is therefore Ohmic. An increase in \(V_{OC}\) by only 0.1 V, despite the work-function difference between Cs\(_2\)CO\(_3\) and Al of 2 eV, agrees well with the earlier observation by Brabec et al. and indicates Fermi-level pinning. The ITO/V\(_2\)O\(_5\)/blend/Al device shows the same polarity as that of ITO/PEDOT:PSS/blend/Al device. The \(V_{OC}\) for the former \((J-V\) curve not shown here\) is 0.38 eV, also significantly higher compared to bare ITO electrode. The HOMO level of a thermally evaporated V\(_2\)O\(_5\) film was determined by UPS to be 4.7 eV which is identical to that of ITO. The most plausible reason for \(V_{OC}\) enhancement is the formation of surface dipoles between V\(_2\)O\(_5\) and an active layer, which causes an upward shift in work function of at least 0.2 eV. These results indicate that V\(_2\)O\(_5\) can be considered as an effective hole injection layer, like PEDOT:PSS, with a similar effective work function. This is further evidenced by the \(J-V\) curves for an ITO/PEDOT:PSS/polymer blend/V\(_2\)O\(_5\)/Al device, where no photovoltaic effect was observed (see Fig. 2). The anode contact therefore has an important effect on polymer solar cell performance.

Figure 3 shows \(J-V\) curves for various inverted polymer solar cell structures. The ITO/polymer blend/V\(_2\)O\(_5\)(10 nm)/Al inverted solar cell has \(J_{SC}=6.97\) mA/cm\(^2\), \(V_{OC}=0.30\) V, FF=41.2%, and PCE of 0.66%. This provides further evidence for the presence of surface dipoles that enhance the V\(_2\)O\(_5\) work function by \(\sim 0.3\) eV. Based on the results so far, an efficient inverted polymer solar cell can be achieved with the structure ITO/Cs\(_2\)CO\(_3\)/polymer blend/V\(_2\)O\(_5\)/Al, where Cs\(_2\)CO\(_3\) was either thermally evaporated or spin coated. The \(J-V\) curves in Fig. 3 for solar cells with thermally evaporated (1 nm, open circle) and solution pro-
cessed (solid triangle) Cs$_2$CO$_3$ clearly demonstrate efficient inverted solar cells. The $J_{SC}$, $V_{OC}$, and FF are very similar for the evaporated (8.42 mA/cm$^2$, 0.56 V, and 62.1%) and the solution processed (8.78 mA/cm$^2$, 0.55 V, and 56.3%) device. The overall efficiencies are 2.25% and 2.10%, respectively. Therefore, inserting V$_2$O$_5$ and Cs$_2$CO$_3$ interfacial layers can result in efficient conventional as well as inverted polymer solar cells. LiF (1 nm, electron injection layer) and V$_2$O$_5$ (10 nm, hole injection layer) were also used to fabricate inverted solar cells. This device has a current density comparable to the device with Cs$_2$CO$_3$ and V$_2$O$_5$, but an antidiode behavior results in low $V_{OC}$ (0.39 V), FF (40.7%), and PCE (0.99%). A thin LiF layer has been reported to work well with a wide range of metals (Ca, Al, and Au) in conventional device configuration. The presence of an antidiode in the inverted configuration indicates that the LiF growth pattern (on ITO versus on polymer) might have a significant impact on device performance.

In conventional device structure, introducing 1 nm thermally evaporated Cs$_2$CO$_3$ reduces the device photocurrent but improves $V_{OC}$ and FF significantly, indicating possible physical damage. However, in the inverted structure, where Cs$_2$CO$_3$ is deposited on ITO substrates, all three parameters are improved.

Based on information collected, we can treat V$_2$O$_5$ as a hole injection layer with “effective” work function of $\sim$5.0 eV and Cs$_2$CO$_3$ as an electron injection layer with very low work function, both of which provide Ohmic contacts. The polarity of the device is decided by the relative positions of these two interfacial layers and is insensitive to the conducting electrodes. The energy level diagrams for various inverted configurations are illustrated in Fig. 3(b).

Due to the presence of a thick (10 nm) V$_2$O$_5$ layer which protects the underlying polymer, the inverted configuration is especially suitable for making transparent solar cells. We replaced a thick Al top electrode with 12 nm of Au in the inverted structure. The J–V curves for this transparent polymer solar cell, with light incident from ITO and the Au side, are shown in Fig. 4. When illuminated from the ITO side, the device shows an overall efficiency of 0.85%. However, when illuminated from the semitransparent Au electrode, the PCE is 0.52%. The difference between the two J–V curves is due to the partial loss by the reflection and absorption at the semitransparent Au electrode. In a transparent solar cell, the light absorption is less than that in a device with a reflecting metal electrode. Similar to inorganic solar cells, the $V_{OC}$ of organic solar cells also increases with increasing incident light intensity. The slight reduction in the $V_{OC}$ of transparent solar cells can therefore be explained by the less effective light intensity. When designing a tandem polymer solar cell, the optical losses due to the first transparent solar cell should be reduced. To provide sufficient electrical conductance, Au layer thickness has to be sufficient and the optical loss at Au electrode becomes significant. However, the inverted solar cell structure has a metal oxide layer that is not transparent but also provides effective protection to the polymer layer. A transparent conductive oxide electrode, such as ITO, can therefore be deposited without compromising device performance. This structure thus provides a very efficient method for realizing tandem polymer solar cells for improving device efficiency.

To summarize, we have fabricated efficient conventional and inverted polymer solar cells by using different functional interfacial layers. Efficiency up to 2.25% has been achieved for an inverted polymer solar cell with FF as high as 62.1%. Preliminary efforts have also demonstrated transparent polymer solar cells with 0.85% efficiency.

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**FIG. 4.** J–V curves for transparent polymer solar cells illuminated from two transparent electrodes—ITO and Au.