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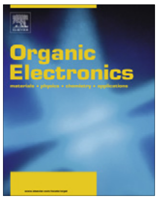

Organic photovoltaics with V_2O_5 anode and ZnO nanoparticles cathode buffer layers

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ABSTRACT

We report the hybrid inorganic–organic photovoltaics incorporating vanadium pentoxide (V_2O_5) as hole and zinc oxide (ZnO) nanoparticles (NPs) as electron extraction layers. This device demonstrates high open circuit voltage of about 0.89 V with considerably high short-circuit current density of 10.13 mA/cm^2 along with fill factor of about 61.03%. Combining all these parameters, the power conversion efficiency is 5.53% which is higher compared to that (3.6%) of the cell without ZnO NPs.

1. Introduction

Polymer solar cells (PSCs) have attracted huge attentions due to its potential to be implemented onto large area, cost effective and also flexible light-weight substrates [1–7]. Recently, the power-conversion-efficiency (PCE) has surpassed the 10% barrier in the tandem solar cells architecture consisting of a polymer donor and fullerene acceptor blend that is inserted between the bottom and top electrodes. However, although we have seen such a fast improvement for the last few years, the stability of the PSCs is still poor and further improvement is needed. For instance, in the case without encapsulation, longer exposure of the PSCs to air may lead to oxidation of the metal electrode and degradation to the photoactive layer. The oxidation and degradation are likely from the diffusion of oxygen and moisture through the grain boundaries and pinholes of the metal electrode [8]. Moreover, the semiconducting properties of the photoactive layer will be affected due to the diffusion of thermally evaporated metal [9,10]. A simple method can be implemented to prevent or to assuage the diffusion of metal is to introduce a suitable buffer layer between the photoactive layer and top electrode in order to diminish the amount of damage and oxygen and moisture diffusion into the photoactive layer. Recently, a thin (~7.5 nm) solution-processed sol–gel graphene oxide (GO) has been used as a versatile buffer layer in the conventional and inverted architectures to improve device performance and at the same time to reduce any physical and chemical damages as well as an effective barrier for oxygen permeation to improve device stability in ambient [11].

Another method to prolong device stability is to make use of less reactive and sensitive high work function metals such as Ag and Au as the hole collecting electrode and air-stable inorganic metal–oxide semiconductor (TiO_x, ZnO, AZO) as the electron selective layer at the ITO interface. One of the biggest advantages of using an inverted architecture is the ability to avoid the use of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS). It has been proven that the use of PEDOT:PSS degrades the performance of device.

In 2011, Reynolds and co-workers have fabricated a bulk hetero-junction (BHJ) solar cell using a thin (30 nm) of ZnO. In their study, they obtained high efficiency (PCE) of about 8.1% along with 14.1 mA/cm^2, 0.86 V, and 67.3% of current density (J_{sc}), open circuit voltage (V_{oc}), and filling

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factor (FF), respectively. They attributed this high J_{sc} to the UV-ozone treatment on ZnO nanoparticles films, where it can successfully passivate the defect, thus, enhanced the J_{sc} [12]. Despite a successful attempt to achieve high performance solar cells, the fabrication procedures required them to use high annealing temperature (about 200 °C) to the crystallized ZnO. It simply makes them disqualified to be used for printed plastic electronics. A few requirements for plastic solar cells are as follows; (i) the device needs to be processed under low temperature using simple methods; (ii) sustain high flexibility, and (iii) retain a thin form factor. Recently, zinc oxide nanoparticles (ZnO NPs) have been demonstrated to be easily processed to form thin layer via spin coating at room temperature [13]. These ZnO NPs also have relatively good mobility of about $\sim$0.17 $cm^2/V\,s$ [14]. Therefore, in the present work we employed ZnO NPs as cathode buffer layer. Stability and performance of encapsulated conventional devices incorporating ZnO NPs was compared to those of the conventional devices without ZnO NPs layer.

2. Experimental

2.1. Materials

V_2O_5 was purchased from Sigma Aldrich ($\sim$99.99%) and used as received. ZnO NPs was purchased from Alfa Aesar. P3HT and PCBM were supplied by Sigma Aldrich.

2.2. Fabrication of PSCs

PSCs were fabricated on ITO-coated glass substrates. The ITO-coated glass substrates were first cleaned with detergent, ultrasonicated in water, acetone, and isopropyl alcohol, and subsequently dried using air compressor. Before the preparation of hole transport layer (HTL), all ITO substrates were treated with UV/O_3 for 15 min in order to increase wettability of ITO surface. First, for the conventional device architecture, V_2O_5 layer with a thickness of $\sim$30 nm was coated onto ITO substrates by spin-coating in a glove-box followed by annealing at 120 °C for 10 min. A solution containing a mixture of P3HT:ICBA (1:0.6) using dichlorobenzene solution with a concentration of 7 $mg\,mL^{-1}$ was spin-casted on top of V_2O_5 films. The thickness of the active layer and V_2O_5 films were measured with a profilometer. Then, the BHJ films were heated at 70 °C for 10 min. After annealing process, a thin ZnO NPs layer was spin-casted on top of active layer, followed by baking at 80 °C for 10 min in air. For the control device, no ZnO NPs is coated instead. Finally, the cathode (Al, $\sim$100 nm) was deposited through a shadow mask by thermal evaporation in a vacuum of about 1×10^{-8} Torr. The active area of device was 0.04 cm^2. During the measurement, no aperture was used. Current density–voltage (J–V) characteristics were measured using a Keithley 236 Source Measure Unit. Measurements of solar cell performance used an Air Mass 1.5 Global (AM 1.5 G) solar simulator with an irradiation intensity of 100 $mW\,cm^{-2}$. To investigate the effect of ZnO NPs on the stability of fabricated devices, changes of cells performances were recorded as a function of exposure time in air using the same identical equipment setup. The stability measurements were carried out in air over 2880 h of exposure according to the ISOS-L-1 procedures [15].

3. Results and discussion

Current density–voltage (J–V) characteristics under AM 1.5 G irradiation (100 $mW\,cm^{-2}$) of P3HT:ICBA solar cells fabricated with and without ZnO NPs as ETL are demonstrated in Fig. 1. The extracted device performance data obtained with a BHJ layer thickness of 80 nm are tabulated in Table 1. The optimal thickness of ZnO NPs was found to be 9 nm. This cell documents a PCE of 5.53%, a short-circuit current density J_{sc} of 10.13 mA/cm^2, an open-circuit voltage V_{oc} of 0.89 V, and a filling factor of 61.03%. On the contrary, the control device (fabricated without ZnO NPs) demonstrates a PCE of 3.62%, along with J_{sc}, V_{oc}, and FF of about 6.73 mA/cm^2, 0.84 V, and 64.02%, respectively. The introduction of ZnO NPs ETL prevents the direct quenching of photogenerated excitons in the photoactive layer by the Al top electrode. At the same time, it also prevents the diffusion of Al atoms into the photoactive layer upon deposition or post-deposition annealing, which would otherwise lead to recombination sites for excitons and/or carriers. As we can see from the energy levels alignment, the deep valence band of ZnO NPs presents a large barrier height to prevent the leakage of photogenerated holes in the photoactive layer to the cathode. Furthermore, the heterojunction between P3HT and ZnO NPs also facilitates the dissociation of excitons generated in P3HT, enhancing their contribution to the photocurrent. Although our fabricated device shows much lower efficiency compared to the previously reported device based on P3HT:ICBA [16,17], but, this new structure creates a new pathway for the development of high efficiency organic solar cells.

Fig. 2 displays external quantum efficiency (EQE) spectra of two different devices. The maximum EQE is higher 60% which indicates the highly efficient photon-to-electron conversion. In the device fabricated with ZnO NPs,

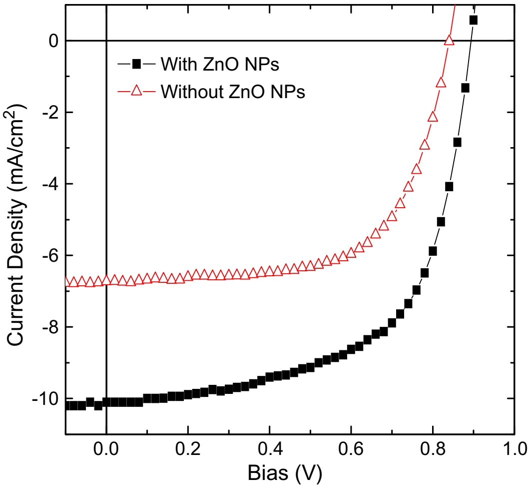

Fig. 1. J–V characteristics of P3HT:ICBA solar cells. The control device was fabricated without ZnO NPs.