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Solution-processed vanadium oxide as an anode interlayer for inverted polymer solar cells hybridized with ZnO nanorods

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ABSTRACT

Solution-processed vanadium oxide (V_2O_5) as an anode interlayer is introduced between the organic layer and the Ag electrode for improving the performance of the low-cost inverted polymer solar cells hybridized with ZnO nanorods. Our investigations indicate that the solution-processed V_2O_5 interlayer as an electron-blocking layer can effectively prevent the leakage current at the organic/Ag interface. The power conversion efficiency is improved from 2.5% to 3.56% by the introduction of the V_2O_5 interlayer. The V_2O_5 interlayer also serves as an optical spacer to enhance light absorption, and thereby increases the photocurrent. Compared to the vacuum-deposited techniques, the fabrication of the solution-processed V_2O_5 interlayer is simple and effective. The solution-based approach makes it attractive for applications to mass production and potentially printed organic electronics.

1. Introduction

Polymer solar cells (PSCs) have attracted much attention due to their great potentials for large-area, lightweight, flexible, and low-cost devices [1–6]. Recently, bulk-heterojunction (BHJ) solar cells based on poly(3-hexylthiophene) (P3HT) and (6,6)-phenyl C_{61} butyric acid methyl ester (PCBM) with power conversion efficiency (PCE) of 4–5% have been reported [7–9]. However, control of the transportation of the charge carriers at interfaces is one of the most challenging issues in the improvement of PSCs. It has been reported that the insertion of an interlayer between the organic layer and the anode improves the device performance. To date, poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) [9,10] and transition metal oxides [11–14] have been employed for this purpose. However, only the deposition of PEDOT:PSS layer can be easily processed by solution-based coating techniques. Most transition metal oxides as the anode interlayers are deposited by the vacuum evaporation, which could detract from the advantage of the ease of PSC fabrication. Using solution-processed transition metal

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oxide as the anode interlayer for improving the PSC performance has seldom been reported.

The aim of this work is to realize a low-cost and high-efficiency inverted PSC hybridized with ZnO nanorod arrays by introduction of a solution-processed vanadium oxide (V_2O_5) as the anode interlayer. Our investigation shows that the photovoltaic device performance is improved by the introduction of the V_2O_5 interlayer due to the efficient suppression of the leakage currents at the organic/metal interface. Compared to the conventional BHJ structure (indium tin oxide (ITO)/PEDOT:PSS/active layer/Al), the use of the inverted structure overcomes some obstacles such as the facile oxidation of Al [15] and the electrical inhomogeneities of PEDOT:PSS as well as its corrosion to ITO [16]. The inverted PSCs utilize an air-stable high work-function electrode as the back contact to collect holes and metal–oxide nanostructures at the ITO to collect electrons [17–19]. Furthermore, it has been reported that the ZnO nanorods have beneficial effects of collecting and transporting electrons in the inverted PSCs hybridized with the ZnO nanorods [20]. Our works combine these advantages of V_2O_5 interlayer and ZnO nanorods, which thereby suppress the leakage currents and improve the collection and transportation of the charge carriers, resulting in enhancements of PCE, open-circuit voltage (V_{OC}), and fill factor (FF) of the devices. In addition, the V_2O_5 interlayer can serve as an optical spacer to increase light absorption, leading to an increased short-circuit density (J_{SC}). Moreover, the V_2O_5 interlayer and ZnO nanorod arrays both are fabricated from simple solution-based processes, which are well-suited for use in high-throughput roll-to-roll manufacturing.

2. Experimental

The structure and the energy level diagram of the inverted PSCs of ITO/ZnO/P3HT:PCBM/V_2O_5/Ag are schematically presented in Fig. 1. Devices were fabricated on cleaned ITO-coated glass substrates (~7 Ω/sq.). ZnO seed layer (~50 nm) was spin-coated from a 0.5-mol solution of zinc acetate dihydrate in 2-methoxyethanol followed by annealing at 200 °C for an hour in air. Hydrothermal growth of the ZnO nanorod arrays (~100 nm in length and ~50 nm in diameter) was achieved by suspending the ZnO seed-coated substrates in an aqueous solution of 50-mM zinc nitrate at 90 °C in an oven. Subsequently, a solution containing 20-mg P3HT and 20-mg PCBM in 1-ml *o*-dichlorobenzene (*o*-DCB) was spin-coated on top of the ZnO nanorods and dried slowly over the course of 40 min in air, forming the photoactive layer with a thickness of ~300 nm. V_2O_5 powder (Riedel-de Haën, 99%) was homogeneously dispersed and suspended in isopropanol at different concentrations by using ultrasonic agitation. During the process of the ultrasonic agitation, it was observed that the V_2O_5 powder was pulverized to smaller particles. After the ultrasonic agitation, the color of the V_2O_5 colloidal solution is uniformly orange. Then the V_2O_5 colloidal solution was spin-casted in air on top of the photoactive layer. Finally, silver film (~200 nm) was deposited on top in a vacuum of 2×10^{-6} torr.

Devices were unencapsulated, stored in air, and illuminated at 100 mW/cm^2 from a ThermoOriel 150 W solar simulator with AM 1.5G filters. The solar simulator was calibrated using a reference Si solar cell. All electrical measurements were carried out in air at room temperature. The active area of the device irradiated by the light was defined as 10 mm^2 by using a photomask, so no extra current outside of the defined area was collected. Current density–voltage (*J*–*V*) curves were measured with a Keithley 2400 source measurement unit. The surface morphologies of the photoactive layers were measured by atomic force microscopy (AFM). The reflectance spectra of the devices were obtained using a Perkin–Elmer Lambda 35 UV–vis spectrophotometer. The transmission spectrum of the V_2O_5 layer was measured using the same UV–vis spectrophotometer. The crystallinity of V_2O_5 was analyzed at room temperature by X-ray diffraction (XRD) using Cu Kα radiation.

3. Results and discussion

In order to avoid mixing or damaging the photoactive layer during the coating of V_2O_5, the selection of solvent

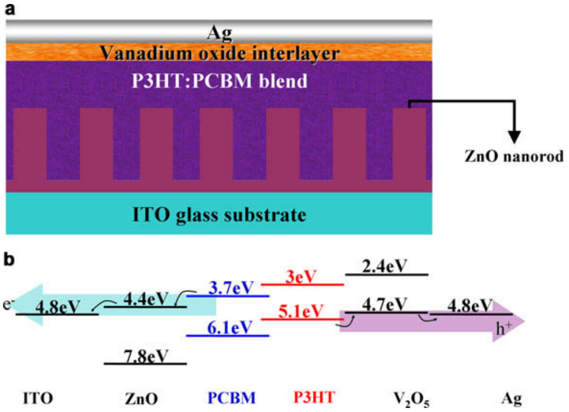

Fig. 1. (a) Device structure of the photovoltaic cells. (b) Energy band diagram for the photovoltaic cells in this study. The work function value of Ag is referred to the Ref. [28].

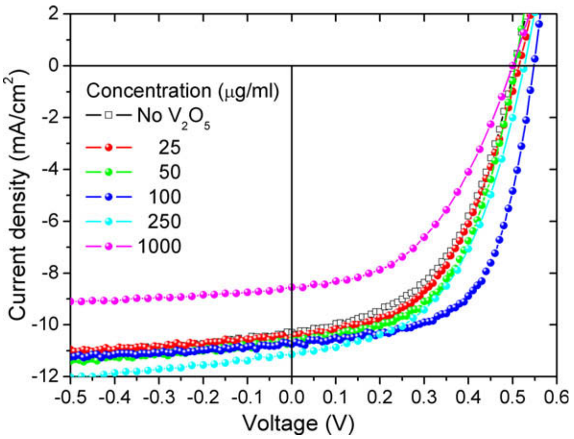

Fig. 2. The *J*–*V* curves of the photovoltaic devices with the V_2O_5 interlayer from various concentrations under 100 mW/cm^2 AM 1.5G irradiation.