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Semitransparent inverted polymer solar cells using $MoO_3/Ag/V_2O_5$ as transparent anodes

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ABSTRACT

We demonstrate semitransparent inverted polymer solar cells with highly transparent anodes. The structure of the anode is molybdenum trioxide (MoO_3)/silver (Ag)/vanadium pentoxide (V_2O_5). The inner MoO_3 layer is introduced as a buffer layer to improve holes collection, while the outer V_2O_5 layer served as a light coupling layer to enhance optical transmittance of the photovoltaic device. The maximum transmittance of 90% from 400 nm to 700 nm is obtained when the thickness of V_2O_5 is 40 nm. When the thickness of V_2O_5 is 40 nm, under AM1.5G illumination of 100 mW/cm^2 illuminated from ITO side (bottom), the J_{sc} is 5.01 mA/cm^2, the V_{oc} is 0.591 V, the *FF* is 61.8%, and the PCE is 1.83%; from $MoO_3/Ag/V_2O_5$ side (top), the J_{sc} is 4.28 mA/cm^2, the V_{oc} is 0.585 V, the *FF* is 61.9%, and the PCE is 1.55%. The trend of the optical electric field distribution is highly consistent with the J_{sc}, which is dependent on the thickness of the V_2O_5 top capping layer.

1. Introduction

Polymer solar cells (PSCs) have been studied intensively as a energy substitute due to their advantage of low-cost, flexible, and large area electronic devices [1–3]. Recently there has been some progress in bulk heterojunction solar cells, and the power conversion efficiency (PCE) has reached 6–8% [4–6]. However, PCE is still limited by a few factors, such as narrow absorption range, short exciton diffusion length, and small charge carrier mobility [7]. The tandem structure [8], which is formed using a semitransparent electrode, is composed of two or more cells with complementary absorption spectra, and it is considered as an effective way to improve the efficiency. The problems of semitransparent electrode structures are low transmittance and high series resistance, which results in low efficiency of tandem solar cells. Here, we report semitransparent inverted PSCs with a multilayer anode structure of $MoO_3/Ag/V_2O_5$. In this work, we present a multilayer transparent anode with optimized functionality in a multiple-device stacking structure. For the transparent anode, the two most important properties are transparency and efficient holes collection. We have demonstrated that the MoO_3/Ag electrode could form efficient holes collection contact in polymer solar cells in our recent paper [9]. Recently Han et al. [10] have demonstrated a simple but highly effective strategy to enhance the power conversion efficiency of semitransparent solar cells by utilizing the partial internal reflection from a multilayer top anode structure of WO_3/Ag/ZnS. It has been reported that the outer layers (ZnS, WO_3, and MoO_3) could improve incident light transmittance to enhance light coupling. V_2O_5 film is transparent and stable, so we use V_2O_5 as a top-capping layer. The V_2O_5 layer virtually has no electrical role and is used primarily for tuning the optical properties of the anode as well as the overall device. The $MoO_3/Ag/V_2O_5$ is optically transparent with high transmittance and suitable for holes collection. An ultrathin MoO_3 layer acts as an anodic buffer layer to enhance holes collection, and the outer V_2O_5 layer is used as a top-capping layer to enhance light coupling.

2. Experimental details

The photovoltaic device has the structure ITO/nc-TiO_2/RR-P3HT:PCBM/$MoO_3/Ag/V_2O_5$, as shown schematically in Fig. 1. The ITO-conducting glass substrate (a sheet resistance of 15Ω/□) was precleaned by acetone, ethanol, and de-ionized water for 15 min. TiO_2 thin films were prepared as described in our previous paper [11]. P3HT (Lumtec Corp, used as received) was dissolved in 1,2-dichlorobenzene to produce 18 mg/ml solution, followed by blending with PCBM (Lumtec Corp, used as received) in 1:1 weight ratio. The blend was stirred for 72 h in air before spin coating on top of TiO_2 film surface. Then the samples were baked in low vacuum (vacuum oven) at ~160 °C for 20 min. The typical film thickness of P3HT:PCBM is about 200 nm. MoO_3 and V_2O_5 were successively evaporated under a high vacuum (5×10^{-4} Pa) without disrupting

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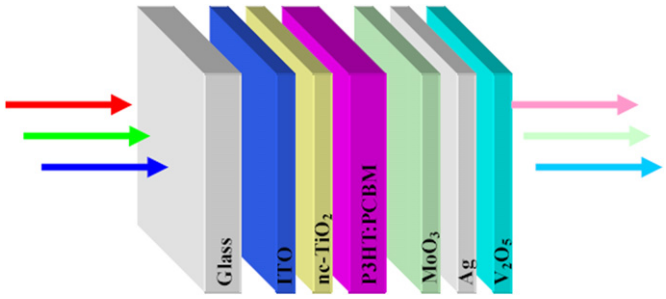

Fig. 1. Schematic structure drawing of the semitransparent inverted polymer solar cells.

the vacuum. The deposition rate was about 0.02 nm/s, which was monitored with a quartz-oscillating thickness monitor (ULVAC, CRTM-9000). Finally 1 nm MoO_3, 10 nm Ag, and x (x=0, 20, 40, 60, 80, and 100 nm) V_2O_5 were thermally evaporated in sequence. The active area of the device was about 6.4 mm^2.

Current density–voltage (J–V) characteristics were measured with a computer-programmed Keithley 2400 source/meter under AM1.5G solar illuminations with an Oriel 300 W solar simulator intensity of 100 mW/cm^2. The light intensity was measured with a photometer (International light, IL1400) corrected by a standard silicon solar cell. The transmission spectra and the reflection spectra were measured by means of an ultraviolet/visible spectrometer (UV 1700, Shimadzu).

3. Results and discussion

Fig. 2(a) shows the J–V characteristics of semitransparent inverted polymer solar cells with outer 40 nm (device II) and without V_2O_5 (device I) under AM1.5G illumination of 100 mW/cm^2. The incidence light is irradiated from the ITO side (bottom). The detailed results are given in Table 1. Device I shows short circuit current density (J_{sc}) of 5.81 mA/cm^2, open circuit voltage (V_{oc}) of 0.601 V, fill factor (FF) of 0.456, and power conversion efficiency (PCE) of 1.59. Device II shows J_{sc} of 5.01 mA/cm^2, V_{oc} of 0.591 V, FF of 0.618, and PCE of 1.83. It can be seen that the PCE of device I is bigger than that of device II. The J_{sc} of device II decreases, but its FF increases dramatically compared to that of device I. We attribute the decrease of J_{sc} to lower reflectance of MoO_3/Ag/V_2O_5 from 400 to 650 nm, which is shown in Fig. 3(b). It is evident that the resistivity of the thin metal film (10 nm Ag here) is higher than that of the bulk metal due to the scattering of the electrons from the surface of the discontinuous film. The outer V_2O_5 decreases the series resistance (R_{sc}), which is defined by the slope of the J–V curve at J=0 mA/cm^2. The series resistance is estimated to be 33.6 Ω for device I and 18.9 Ω for device II. The decrease of R_{sc} results in the increase of FF from 0.456 to 0.618. Fig. 2(b) shows the J–V characteristics of semitransparent inverted polymer solar cells (devices I and II) under AM1.5G illumination of 100 mW/cm^2 when illuminated from MoO_3/Ag/V_2O_5 side (bottom). Here, the mixture of P3HT and PCBM that has the main absorption spectrum from 400 to 650 nm is chosen for active layers. The photocurrent density is in direct proportion to light absorption of the active layer. Since device II has higher transmittance from 400 to 650 nm, as shown in Fig. 3(a), it has bigger J_{sc} than device I.

Fig. 3(a) shows the transmittance spectra of the Glass/ITO and the MoO_3/Ag/V_2O_5 from 300 nm to 900 nm. The ITO film is deposited onto the glass as an electrode with high transparency in the visible region of solar spectrum, and a high transmittivity of $>$95% appears from 450 nm to 900 nm. It means that the ITO film is almost transparent in the visible range. Therefore, there is

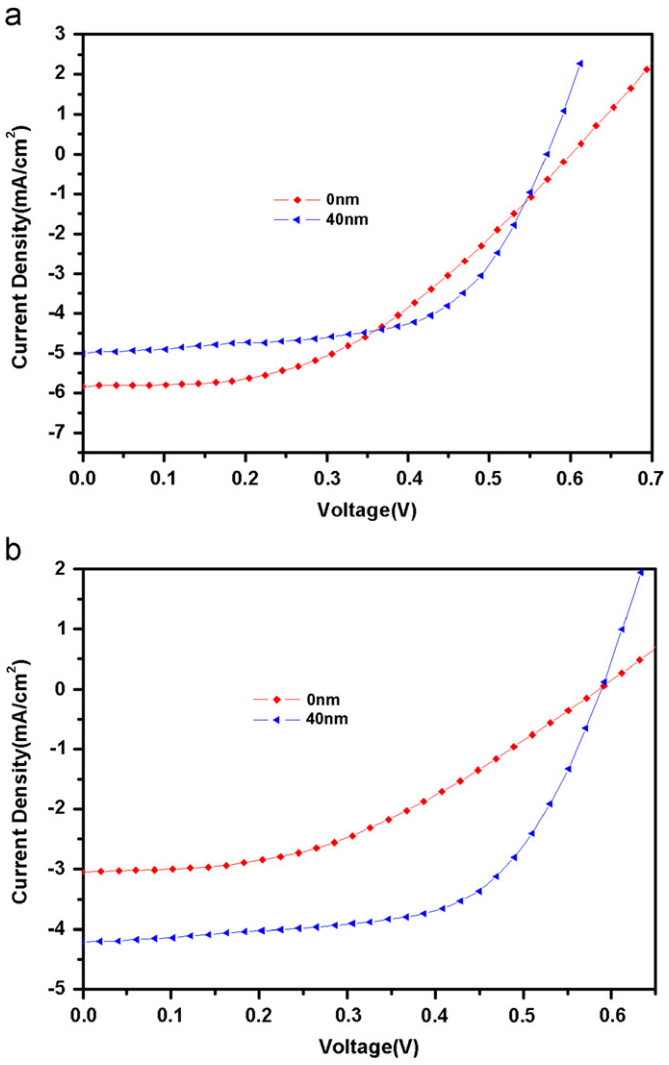

Fig. 2. J–V characteristics of device ITO/nc-TiO_2/P3HT:PCBM/MoO_3 (1 nm)/Ag (10 nm)/V_2O_5 (x=0, 40 nm) when illuminated from (a) ITO side and (b) MoO_3/Ag/V_2O_5 side.

Table 1
Characteristic data of semitransparent inverted polymer solar cells with different thicknesses of the V_2O_5 capping layer illuminated from ITO (bottom) and MoO_3/Ag/V_2O_5 (top) side.

Device (nm)	Illumination	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	PCE (%)
0	Bottom	5.81	0.601	45.6	1.59
0	Top	3.03	0.579	42.7	0.75
20	Bottom	5.25	0.595	61.5	1.92
20	Top	3.88	0.583	61.6	1.39
40	Bottom	5.01	0.591	61.8	1.83
40	Top	4.28	0.585	61.9	1.55
60	Bottom	5.48	0.597	61.1	1.99
60	Top	3.59	0.582	61.1	1.28
80	Bottom	5.76	0.598	60.5	2.08
80	Top	3.33	0.581	60.4	1.17

no reflection effect when the reflected electrode is ITO. For the MoO_3/Ag/V_2O_5, it can be seen that the transmittance becomes weak with the increase of wavelength, and high transmittance of 90% appears in short wavelength range when the thickness of V_2O_5 is zero. When introducing outer V_2O_5 (capping layer), the transmittance is changed dramatically. With the increase of the thickness of V_2O_5 capping layer, the transmittance peaks are