

Semitransparent inverted polymer solar cells using MoO₃/Ag/WO₃ as highly transparent anodes

Fumin Li, Shengping Ruan, Yang Xu, Fanxu Meng, Jialue Wang, Weiyu Chen, Liang Shen*

State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, Changchun 130012, People's Republic of China

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ABSTRACT

We demonstrate semitransparent inverted polymer solar cells with highly transparent anodes. The structure of the anode is made up of molybdenum trioxide (MoO₃)/silver (Ag)/tungsten oxide (WO₃). The inner MoO₃ layer is introduced as a buffer layer to improve hole collection, while the outer WO₃ layer serves as a light coupling layer to enhance optical transmittance of the photovoltaic device. The dependence of device performances on thickness of the outer WO₃ layer was investigated, and the transmittance and reflectance of MoO₃ (1 nm)/Ag (10 nm)/WO₃ ($x=0, 20, 40, 60,$ and 80 nm) electrode are compared. A high transmission of 90% was achieved for semitransparent inverted polymer solar cells with a 40 nm thick outer WO₃ layer.

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1. Introduction

Polymer solar cells, which are fabricated by conjugated polymer and fullerene derivative composite films [1–4], have become a highly attractive research topic during the last ten years. It has the advantage of solution processing capability, low-cost, large area device, and flexibility [5–8]. Although obvious progress in power conversion efficiency exceeding 7% has been made [9], there is still a long way to go for commercialization. One awkward cause is that the absorption spectrum of the electron donor is too narrow to match the solar spectrum, and poor absorption results in the low photocurrent. One efficient way to enhance broad spectral absorption of the polymer solar cells is to use a tandem structure [10–12] in which two or more cells with complementary absorption spectrum are stacked. The semitransparent electrode [13,14] used to connect cells plays an important role in forming tandem structure. A variety of semitransparent electrode structures have been developed in recent years. However, low transmittance and high series resistance are also introduced simultaneously [15,16]. An ideal transparent electrode for stacked devices must have high efficiency of carrier collection and high transparency simultaneously. In many organic electronic components, an ultrathin interlayer is usually inserted between the organic active layer and the metal electrode to enhance electron injection and to reduce the contact resistance [17]. It is usually self-defeating to reduce sheet resistance and compromise light transmittance. Here, we

report semitransparent inverted polymer solar cells with a multi-layer anode structure of MoO₃/Ag/WO₃. MoO₃ and WO₃ are both optically transparent and suitable for hole collection. The ultrathin MoO₃ layer inserted between the active layer and Ag serves as an anodic buffer layer to enhance hole collection. The outer WO₃ layer is used as a top-capping layer to enhance light coupling. It could also lower the series resistance of polymer solar cells.

2. Experimental

The photovoltaic device has a structure of ITO/nc-TiO₂/RR-P3HT:PCBM/MoO₃/Ag/WO₃, as shown schematically in Fig. 1. The ITO-conducting glass substrate (a sheet resistance of 15 Ω/□) was pre-cleaned using acetone, ethanol, and de-ionized water for 15 min. Anatase TiO₂ thin films were prepared as described in our previous papers [18,19]. The thickness of TiO₂ is 25 nm. P3HT (Nichem, used as received) was dissolved in 1,2-dichlorobenzene to produce an 18 mg/ml solution, followed by blending with PCBM (Nichem, used as received) in 1:1 weight ratio [20]. The blend was stirred for 72 h in air before spin coating on top of the TiO₂ 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. Finally 1 nm of MoO₃, 10 nm of Ag, and x nm ($x=0, 20, 40, 60, 80,$ and 100 nm) WO₃ were thermally evaporated in sequence under high vacuum (5×10^{-4} Pa) without disrupting the vacuum. The deposition rate was about 0.02 nm/s, which was monitored with a quartz-oscillating thickness monitor (ULVAC, CRTM-9000). The active area of the device was about 6.4 mm².

* Corresponding author.

E-mail address: shenliang@jlu.edu.cn (L. Shen).

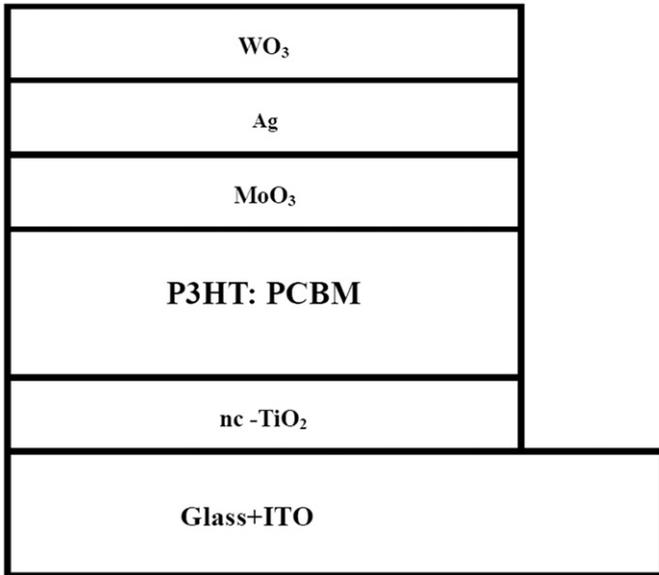


Fig. 1. Schematic structure drawing of semitransparent inverted polymer solar cells.

Current density–voltage (J – V) characteristics were measured using a computer-programmed Keithley 2400 source/meter under AM1.5G solar illumination using an Oriel 300 W solar simulator. The intensity of the solar simulator was 100 mW/cm^2 . Light intensity was measured with a photometer (International light, IL1400), which was corrected by a standard silicon solar cell. The transmission and reflection spectra were measured using 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 a 40 nm (device II) and without WO_3 (device I) under AM1.5G illumination of 100 mW/cm^2 . The incidence light was irradiated from the ITO side (bottom). The detailed results are given in Table 1. Device I shows a short circuit current density (J_{sc}) of 5.81 mA/cm^2 , open circuit voltage (V_{oc}) of 0.6 V, fill factor (FF) of 0.456, and power conversion efficiency (PCE) of 1.59. Device II shows a J_{sc} of 4.84 mA/cm^2 , V_{oc} of 0.6 V, FF of 0.619, and PCE of 1.80. It can be seen that J_{sc} of device II decreases, but FF increases dramatically compared to that of device I. We attribute the decrease of J_{sc} to the lower reflectance of $\text{MoO}_3/\text{Ag}/\text{WO}_3$ from 400 to 650 nm, which is shown in Fig. 3(b). It is evident that resistivity of the thin metal film (13 nm Ag here) is higher than that of the bulk metal due to scattering of electrons from the surface of the discontinuous film. The problem is solved by the introduction of WO_3 . The outer WO_3 decreases the series resistance (R_{sc}), which is defined by the slope of the J – V curve at $J=0 \text{ mA/cm}^2$. The series resistance is estimated to be 45.5Ω for device I and 23.2Ω for device II. The decrease of R_{sc} results in increase of FF from 0.456 to 0.619. 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 the $\text{MoO}_3/\text{Ag}/\text{WO}_3$ side (bottom). Here, the mixture of P3HT and PCBM, whose main absorption spectrum is from 400 to 650 nm, is chosen as an active layer. 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. 3a transmittance spectra of $\text{MoO}_3/\text{Ag}/\text{WO}_3$ from 300 to 1000 nm. It can be seen that transmittance becomes weak with

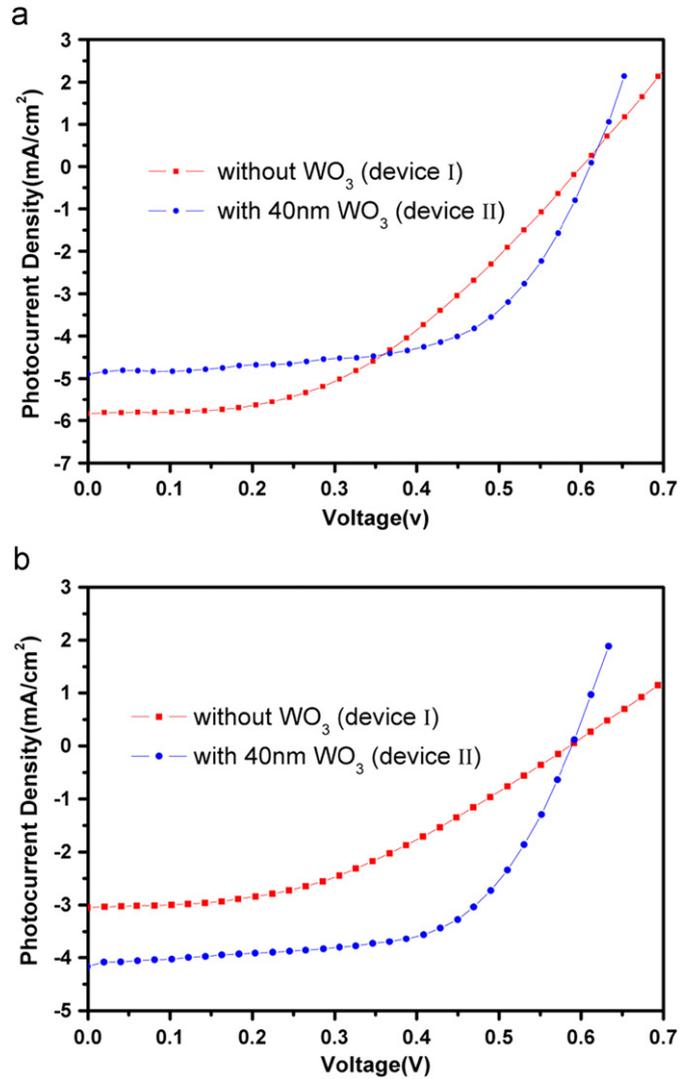


Fig. 2. J – V characteristics of device ITO/nc-TiO₂/P3HT:PCBM/MoO₃ (10 nm)/WO₃ ($x=0$ and 40 nm) when illuminated from (a) ITO side and (b) MoO₃/Ag/WO₃ side.

Table 1

Characteristic data of semitransparent inverted polymer solar cells with different thicknesses of the WO_3 capping layer illuminated from ITO (bottom) and $\text{MoO}_3/\text{Ag}/\text{WO}_3$ (top) side.

Device (nm)	Illumination	J_{sc} (mA/cm ²)	V_{oc} (V)	FF (%)	PCE (%)
0	Bottom	5.81	0.60	45.6	1.59
0	Top	3.03	0.58	42.7	0.75
20	Bottom	5.15	0.60	61.5	1.90
20	Top	3.76	0.58	61.5	1.34
40	Bottom	4.84	0.60	61.9	1.80
40	Top	4.11	0.58	61.9	1.48
60	Bottom	5.41	0.60	61.0	1.98
60	Top	3.46	0.58	61.2	1.23
80	Bottom	5.75	0.60	60.6	2.09
80	Top	3.17	0.58	60.4	1.11

increase of wavelength when the thickness of WO_3 is zero. However, with increase in thickness of the WO_3 capping layer, the transmittance peaks are redshifted, and a maximum transmittance of 90% is obtained when the thickness of WO_3 is 40 nm. With increasing thickness of WO_3 , transmittance gradually decreases. Meanwhile, additional transmittance peaks appear in the short

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