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The annealing effects of tungsten oxide interlayer based on organic photovoltaic cells

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ABSTRACT

We investigated the effect of tungsten oxide (WO_3) interlayer as a hole collection layer on the performance of organic photovoltaic cells according to the thickness and temperature of the interlayer. The characteristics of organic photovoltaic cells such as fill factor, current density, and open circuit voltage are continuously improved by increasing the temperature of the WO_3 interlayer. The surface of a treated WO_3 film promotes the crystallization of P3HT because a treated WO_3 film is more hydrophobic than a pristine WO_3 film. Furthermore, the energy barrier between P3HT and the WO_3 interlayer is minimized since the work function of the WO_3 film after annealing progressively increases until a hole can be smoothly transferred. Therefore, organic photovoltaic cells using an interlayer of treated WO_3 film have higher hole mobility and better efficiency. The efficiency of an organic photovoltaic cell with a 40 nm-thick WO_3 interlayer is significantly enhanced from 0.94 to 3.04% as the temperature changes from room temperature to 350 °C under AM 1.5G illumination.

1. Introduction

Organic photovoltaic cells (OPVs) have been studied as a type of next generation energy source because they are lightweight and flexible, showing much potential for large scale fabrication through a low-cost process [1]. During the past 30 years since the development of OPVs, OPVs technologies have focused on increasing power conversion efficiency (PCE), lifetime and reliability. Many methods have been proposed to improve the performance of OPVs, such as the use of a bulk heterojunction structure [2], the use of an optical spacer over the active layer using titanium oxide (TiO_2) [3], annealing to improve the crystallization of poly-3 (hexylthiophene) (P3HT) polymer [4], and O_2-plasma treatment on indium tin oxide (ITO) for work function modification [5].

Also, thin interlayers between the active layer and the electrodes were introduced to extract diffused holes or electrons, easily. A polymer complex of poly(3,4-ethylenedioxythiophene) and poly (styrene sulfonate) (PEDOT:PSS) has been preferred for OPVs [6,7] because it has flexibility, high transparency and good hole mobility on an ITO layer. Furthermore, it has a high work function, which can be used to match the band structure between the donor layer and the anode. However, the PEDOT:PSS interlayer has several disadvantages that reduce the performance of OPVs, such as stability and life-time due to the fact that PSS, which is highly acidic, corrodes the ITO layer chemically and that PEDOT:PSS degrades under UV illumination [8–11]. For solving these problems, several proposals such as alternative materials of PEDOT:PSS, ITO-free devices [1,12,13], and inverted architecture device [14] have been studied.

Recently, as replacement for PEDOT:PSS, metal oxides have been used to form attractive hole extracting layers because they do not have side effects such as degradation and chemical reaction with ITO. Nickel oxide (NiO) [15], vanadium oxide (V_2O_5), molybdenum oxide (MoO_3) [16] have been researched as materials for the interlayer, such as the hole-selective or electron-selectivity layer. Especially, tungsten oxide (WO_3) has been investigated as an effective hole collection layer because it has a high work function, high ionization potential (IP) and p-type electronic property [17]. Also, the surface morphology of a WO_3 layer is much smoother than those of MoO_3 and V_2O_5 layers. It can also reduce the leakage current because the bias-dependent carrier recombination is prevented because the local high electric fields were not formed at a smoothened surface of an interlayer or electrode [18]. The WO_3 interlayer deposited by thermal evaporation as an anodic interlayer was reported to have increased the performance of OPVs [19]. In inverted OPVs, the WO_3 layer between the active layer and the top electrode improved the efficiency of the OPVs from 0.13 to 2.58% [20].

In this work, OPVs are fabricated with WO_3 interlayers, instead of the PEDOT:PSS layer, between the active layer and the anode to collect holes. We investigated the effect of WO_3 layers of various

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thickness and annealing temperatures which changes from room temperature to 350 °C on the performance of organic photovoltaic cells. We discussed the function of an annealed WO_3 interlayer, which significantly improved the performance of an OPVs device. The physical, optical and electronic properties of a thermal evaporated WO_3 thin film are measured by AFM, IPCE, XPS and XRD.

2. Experimental

Fig. 1 shows the structures of OPVs with WO_3 interlayers of different thicknesses and temperatures. The patterned ITO substrates of 25 Ω/square were ultra-sonically cleaned several times in acetone, methanol and de-ionized water sequentially. The cleaned substrates underwent UV-Ozone treatment for 15 min and treated with oxygen plasma at 90 W for 240 s. A WO_3 (purchased from KOJNDO KOREA, 99.99%) thin film was deposited onto an ITO substrate by thermal evaporation in vacuum of about 1×10^{-6} Torr at evaporation rate of 4.0 Å/s. The thicknesses of the WO_3 films were detected in situ by a quartz monitor.

The deposited WO_3 thin films were annealed in Ar atmosphere in a glove box at different temperatures (room temperature (RT), 200 °C, and 350 °C) for 30 min using a hot plate. The ITO glass substrate below WO_3 was kept in the glove box of Ar environment for 10 h after thermal annealing to cool down.

In order to fabricate bulk hetero-junction organic solar cells, P3HT (purchased from Rieke metals, Inc.) and PCBM (purchased from Nano-C, Inc.) were dissolved in mono-chlorobenzene (CB, 40 mg/ml) for 14 h and blended at a mixing ratio of 1:0.6 for 2 h in a glove box (Ar atmosphere). The blended active mixture was spin coated at 900 rpm for 30 s to form a film, which was then thermally annealed at 140 °C for 15 min in Ar atmosphere. The Al cathode (100 nm) and the interlayer (LiF 0.6 nm) were thermally evaporated in vacuum greater than 5×10^{-7} Torr.

The current–voltage (*I–V*) characteristics of the fabricated devices were subjected to simulated AM 1.5 global solar irradiation of 100 mW/cm^2 incident power density using a 300 W Xe lamp (Mc science) and measured using a Keithley 2400 source meter. Moreover, Incident-Photon-to-electron Conversion Efficiency

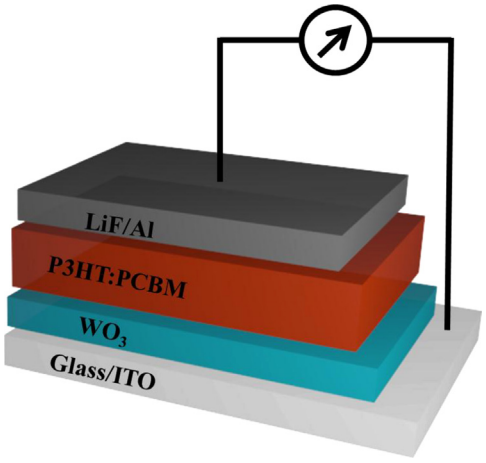

Fig. 1. Structure of OPVs with WO_3 interlayer of different thicknesses for different temperatures: ITO/WO_3/P3HT:PCBM/LiF/Al.

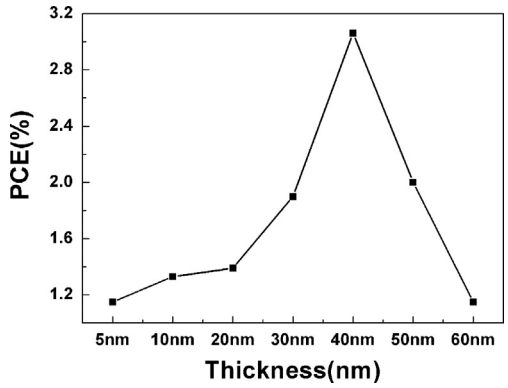

Fig. 2. *J–V* characteristics under 100 mW/cm^2 white light illumination in air for devices with WO_3 interlayers of different thicknesses between the active layer and ITO.

Table 1
Short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), FF, and power conversion efficiency (PCE) of OPVs according to the thickness of WO_3.

Thickness	Jsc	Voc	FF	PCE
5nm	6.94	0.53	31	1.15
10nm	7.10	0.53	35	1.33
20nm	7.18	0.52	36	1.39
30nm	7.74	0.55	44	1.90
40nm	7.79	0.60	64	3.04
50nm	7.46	0.58	46	2.00
60nm	6.91	0.51	32	1.15

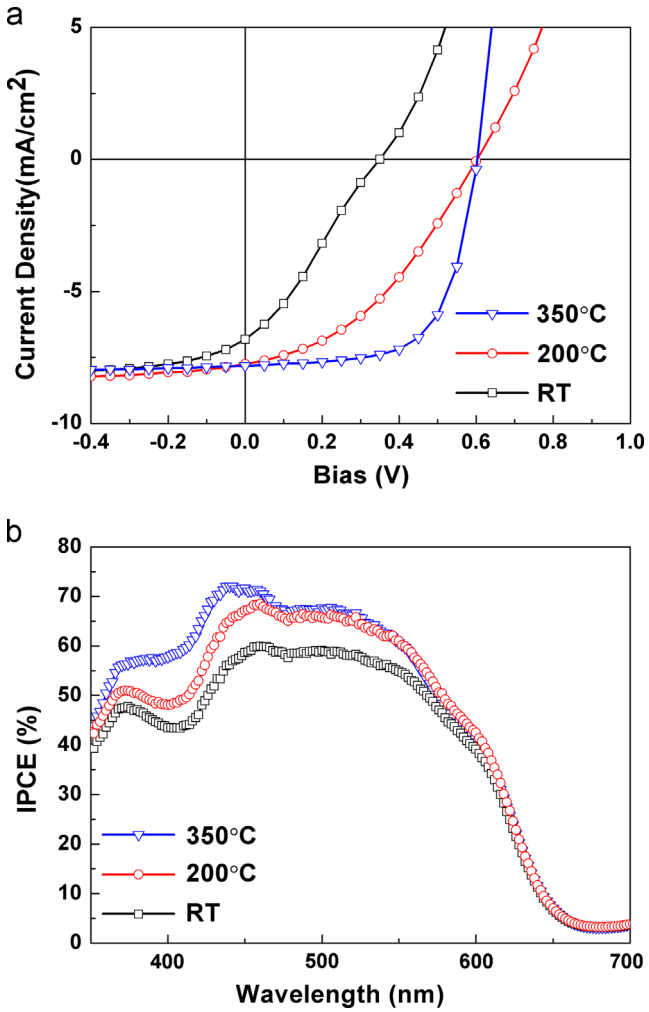

Fig. 3. (a) The *J–V* characteristics under 100 mW/cm^2 white light illumination in air for devices according to different temperature. (b) The Incident-Photon-to-electron Conversion Efficiency (IPCE) according to different temperatures.