Solar Energy Materials & Solar Cells 117 (2013) 198–202

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Simultaneous improvement in efficiency and transmittance of low bandgap semitransparent polymer solar cells with one-dimensional photonic crystals

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ARTICLE INFO

Article history:
Received 6 May 2013
Received in revised form
31 May 2013
Accepted 3 June 2013

Keywords:
One-dimensional photonic crystals
Low bandgap polymer
Semitransparent solar cells

ABSTRACT

One-dimensional photonic crystals (1DPCs) with the structure of $(WO_3/LiF)^N$ are employed to simultaneously improve the efficiency and transmittance of low bandgap semitransparent polymer solar cells (PSCs). Within the photonic bandgap(PBG) of 580–780 nm, 1DPCs with 8 pairs of WO_3/LiF act as distributed reflectors (DBR), which reflects light wavelength of 580–780 nm back into the PSCs for reabsorption by active layers. Power conversion efficiency (PCE) of 2.46% is obtained for the semitransparent PSCs and there is an improvement of 28.1% in the PCE when compared with that of the device without 1DPCs. Within the photonic passband of 380–580 nm, the 1DPCs act as antireflection coatings. An average transmittance of 40% is remained within the wavelength range and the value is improved by 33% when compared with that of the device without the 1DPCs. Finally, it is demonstrated that the efficiency and transmittance of the device are dependent on the number of the repeated period (N).

1. Introduction

Polymer solar cells (PSCs) have attracted intensive attentions due to the tunable electronic and optical properties of polymer materials and their potential for flexibility, low cost, and roll-to-roll manufacturing [1–3]. Nowadays, the research of PSCs focuses not only on improving the efficiency, but also on some other applications, such as semitransparent PSCs [4], stretchable PSCs [5], and photonic color filters integrated PSCs [6,7]. Semitransparent PSCs have many applications, such as energy-harvesting window [8] and integrated photovoltaic chargers for portable electronics [9]. Some efforts have been done in semitransparent PSCs, which concentrate on the synthesis of polymer materials and the fabrication of transparent electrode [10–13]. These efforts are aiming to achieve both high efficiency and transmittance simultaneously, which is an investigation handicap because there is a contradiction between them [14]. To maintain high transmittance of the semitransparent PSCs, the thickness of the active layer has to be thinner. But the followed weaker absorption would result in a reduction of PCE.

The conventional electron donor material in PSCs is P3HT [15]. However, the relatively large bandgap and high highest occupied molecular orbital (HOMO) energy level of P3HT limit the possibility of further improvement of PCE. Hence, the synthesis of low bandgap polymer has attracted more interest due to the fine absorption ability [16,17]. PSBTBT, which has been reported by Hou et al. [18], is regarded as a kind of promising low bandgap polymer as electron donor for PSCs. In this paper, we introduce a light trapping structure into semitransparent PSCs based on PSBTBT: PCBM blend and resolve the contradiction of efficiency and transmittance successfully. The light trapping structure consists of a photonic crystals [19] (PCs) reflector, which uses one-dimensional photonic crystals (1DPCs) as a distributed Bragg reflector [20,21] (DBR). The PCs have been applied in PSCs previously, such as the fabrication of highly ordered arrays of nanoscale active layer, or the semitransparent electrode in P3HT: PCBM-based polymer solar cells [22–24]. However, the application of 1DPCs in low bandgap PSCs is not taken into consideration in previous studies.

In our study, the reference device is glass/FTO/TiO_2/PSBTBT: PCBM/WO_3/Ag. The structure of $(WO_3/LiF)^N$,which is used as

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http://dx.doi.org/10.1016/j.solmat.2013.06.002

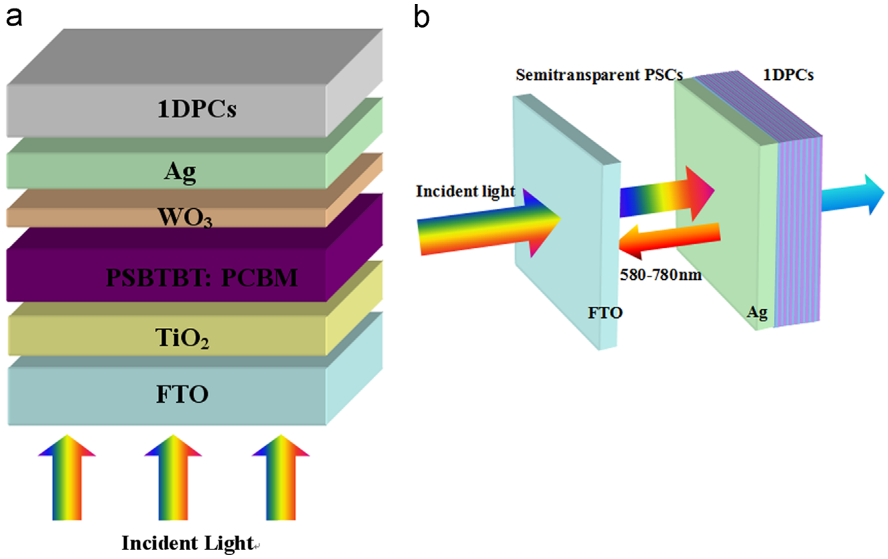

Fig. 1. (a) The structure of the semitransparent low bandgap PSCs with 1DPCs. (b) The optical schematic diagram of semitransparent low bandgap PSCs with 1DPCs.

1DPCs, is capped on the transparent Ag anode of the reference device (Fig. 1(a)) to improve the device efficiency and transmittance simultaneously. Current density–voltage (*J*–*V*) test, incident photon-to-electron conversion efficiency (IPCE) test and transferred matrix simulation (TMM) [25] are employed to investigate the device performance. It is revealed that the efficiency is improved by 28.1% for the device with $(WO_3/LiF)^8$ 1DPCs, due to the high reflectance of the 1DPCs within the photonic bandgap of 580–780 nm. In the remaining wavelength range of 380–580 nm, the transmittance remains at a relatively high value of about 40% as a result of the high transmittance within the passband of the 1DPCs.

2. Methods

2.1. Fabrication and characterization (experimental section)

As shown in Fig. 1(a), the reference device structure is Glass/FTO(150 nm)/TiO_2(25 nm)/PSBTBT:PCBM(80 nm)/WO_3(10 nm)/Ag (20 nm) (Device A). The structure of 1DPCs-based semitransparent PSCs is Glass/FTO(150 nm)/TiO_2(25 nm)/PSBTBT: PCBM(80 nm)/WO_3(10 nm)/Ag(20 nm)/$[WO_3/LiF]^N$ (Devices B–E). In the fabrication, the FTO-conducting glass substrate (a sheet resistance of 15 Ω/sq) was first pre-cleaned by acetone, ethanol and de-ionized water for 15 min, respectively. Anatase TiO_2 thin films were prepared as described in our previous papers [26]. PSBTBT (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 solution was stirred for 72 h in the air before spin coating on top of TiO_2 film surface. Then the samples were annealed at ~120 °C for 20 min in the glove box. Finally WO_3 and Ag were evaporated in sequence under a high vacuum (5×10^{-4} Pa) with a deposition rate of about 0.2 nm/s, which was monitored by a quartz-oscillating thickness monitor (ULVAC, CRTM-9000). *N* pairs of WO_3 (81.6 nm)/LiF (118.3 nm) were alternately evaporated on the Ag anode. *N* is the number of repeated period and equals to 2, 4, 6, and 8. The devices are referred as Devices B, C, D, and E, correspondingly. The device dimension was 6.4 mm^2.

J–*V* characteristics were measured with a computer-programmed Keithley 2601 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 photo-meter (International light, IL1400) corrected by a standard silicon solar cell. The absorption, reflectance and transmittance spectra were measured by means of an ultraviolet/visible spectrometer (UV1700, Shimadzu). IPCE was measured with a Crowntech QTest Station 1000AD.

2.2. Theoretical model

PCs are materials patterned with a periodicity in index of refraction, which can create a range of "forbidden" frequencies called a photonic bandgap [27]. If the index of refraction of the constituent materials has great difference, Bragg scattering off the dielectric interfaces can produce many of the same phenomena for photons as the atomic potential does for electrons. Photons with energies lying in the bandgap cannot propagate through the PCs. Typical quarter-wave stack 1DPC has an index of refraction that is periodic in one-dimensional and consists of an many repeating stack of dielectric flats, which alternate in thickness from d_1 to d_2 and in index of refraction from n_1 to n_2 [28]. The n_1 and n_2 have a great difference in numerical value. For a quarter-wave stack in the periodic structure, there is a fixed relationship between n_1, n_2, d_1 and d_2, respectively [29]. The optical path of every layer is exactly 1/4 of the center wavelength λ_0 which is corresponding to the mid-gap frequency ω_0. The relationship formulation is as follows:

$$n_1 d_1 = n_2 d_2 = \frac{\lambda_0}{4} = \frac{\pi c}{2\omega_0} \qquad (1)$$

where *c* is the vacuum speed of light. When Eq. (1) is met, the reflected light from every interface have an identical phase and then the constructive interference start up. For this quarter-wave stack 1DPC, a high reflectivity that is approaching 100% around center wavelength λ_0 is expected.

In this letter, the 1DPCs act as a DBR. It is used to reflect the part of visible light, which is matched well with absorption range of the active layer. The optical schematic diagram of semitransparent low bandgap PSCs with 1DPCs is shown in Fig. 1(b). The absorption spectrum of PSBTBT: PCBM, which is from 580 nm to 780 nm with the peak at 680 nm, is illustrated in Fig. 2(a). We set 680 nm as center wavelength λ_0 and select WO_3 with a high index of refraction, LiF with a low index of refraction as the periodicity repeat unit components. The indexes of refraction of WO_3 and LiF are 2.08(n_1) and 1.44(n_2) respectively. According to Eq. (1), the thickness of WO_3 and LiF can be calculated, which is 81.6 nm and 118.3 nm respectively.