Solar Energy Materials & Solar Cells 127 (2014) 27–32

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

# Light harvesting enhancement toward low IPCE region of semitransparent polymer solar cells via one-dimensional photonic crystal reflectors

Wenjuan Yu [a], Shengping Ruan [a], Yongbing Long [b], Liang Shen [a,*], Wenbin Guo [a], Weiyou Chen [a]

[a] State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, Changchun 130012, People's Republic of China
[b] School of Applied Physics and Materials, Institute of Thin Film and Nanomaterials, WuYi University, No. 22, Dongchen Cun, Jiangmen 529020, People's Republic of China

ARTICLE INFO

*Article history:*
Received 3 January 2014
Received in revised form
22 February 2014
Accepted 8 April 2014
Available online 4 May 2014

*Keywords:*
Light harvesting
Semitransparent polymer solar cells
One-dimensional photonic crystals
Distributed Bragg reflector

ABSTRACT

In this study, we demonstrate a light harvesting method to achieve efficient semitransparent polymer solar cells (STPSCs) based on PCDTBT: $PC_{70}BM$ by employing one-dimensional photonic crystals (1DPCs) as reflector. The 1DPCs were constructed by N pairs of $WO_3$/LiF, a pair means a combination of $WO_3$ and LiF, including a layer of $WO_3$ film and a layer of LiF film. By optimizing the number of pairs, a 1DPC with high reflectance region (400–500 nm), which is exactly matched with the weak region of the (incident photon-to-electron conversion) IPCE spectrum of the reference STPSC is obtained. In contrast, the excellent STPSC with 8 pairs of 1DPC exhibited a high efficiency about 4.84% and hold an average transmittance of 25.4% in the visible range (400–700 nm).



## 1. Introduction

Polymer solar cells (PSCs) have drawn considerable attention due to the prospect of flexibility, low-cost and solution-based fabrication process [1–3]. With a high power conversion efficiency (PCE) of exceeding 10% based on a tandem structure, this novel photovoltaic technology is getting closer to commercialization [4,5]. An attractive feature of PSCs is their diverse applications, including stretchable PSCs, [6] photonic color filters integrated PSCs [7–9] and semitransparent PSCs (STPSCs). [10] STPSCs can potentially integrate into windows panes to generate electricity, which require a part of light to be transmitted through the windows with different colors [11]. The transparent top electrode is the key factor for STPSCs. In recent years, some efforts have been done to develop the metallic microgrid electrode, [12] transparent graphene electrode, [13] and dielectric/metal/dielectric multilayer electrode. [14–17] Among them, the dielectric/metal/dielectric multilayer electrode, such as $WO_3$/Ag/ZnS, [14,15] $V_2O_5$/Ag/$V_2O_5$, [16] $MoO_3$/Ag/$WO_3$, [17] $WO_3$/Ag/$WO_3$, [18] has attracted more attention due to its favorable optical and electrical performance. For instance, in the $WO_3$/Ag/ZnS electrode reported by Han et al., [14,15] $WO_3$ layer positioned next to active layer is used as a buffer layer making $WO_3$/Ag layers work effectively as an anode. In contrast, ZnS layer virtually has no electrical role and is used primarily for tuning the optical properties of the electrode as well as the overall device. Recently, one-dimensional photonic crystals (1DPCs) have been used to substitute the ZnS layer and take advantage of the photonic bandgap to tune the absorption and transmittance. 1DPCs, which act as a back reflector, [19,20] could not only tune the optical properties of the device, but also improve the light harvesting dramatically. Yu et al. reported the STPSC with $WO_3$/Ag/1DPCs electrode and the PCE reached to 5.16%. [21] Similar STPSC based on $MoO_3$/Ag/1DPCs electrode was also reported by Zhang et al. [22] However, the absorption enhancement caused by 1DPCs are always around the strong absorption region of the active layer to improve IPCE. The study on light harvesting toward the low IPCE region of STPSC, which has great potential to improve the PCE, has not been reported until now. Therefore, in this work, we design 1DPCs with a fine photonic bandgap which matches with the low IPCE region of active layer.

The efficient STPSC based on PCDTBT: $PC_{70}BM$ with a distributed Bragg reflector (DBR) is shown in Fig. 1. PCDTBT is a kind of promising low bandgap polymer of PSCs [23–25]. The DBR is one-dimensional photonic crystals (1DPCs) with quarter-wave stack in the periodic

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

http://dx.doi.org/10.1016/j.solmat.2014.04.007
0927-0248/

structure ($[WO_3/LiF]^N$), which can reflect part of transmitted light back into the device to capture the incident light twice or more [26,27]. In previous studies, the 1DPCs, which are capped on STPSCs, are used to enhance the absorbance in strong absorption region. [21,22,26–29] But in this region, the inherent absorption of active layer is so high that the enhancement is not remarkable. In this paper, the 1DPCs are designed to enhance light harvesting towards weak absorption range of PCDTBT: $PC_{70}BM$ which locates in 400–500 nm. This region has great potential to harvest more photons compared to the range of strong absorption. At the same time, the other wavelength range of light can smoothly transmit to maintain the total device transmittance. Therefore, the light harvesting enhancement towards weak absorption can realize higher PCE and transmittance simultaneously. The pairs (N) of $WO_3$/LiF are optimized by simulated calculation, the current density vs voltage characteristics (*J–V*), and incident photon-to-electron conversion (IPCE) test of STPSCs. The STPSC exhibits a high PCE about 4.84% and an excellent transmittance of 61.3% at 650 nm with 8 pairs of 1DPC.

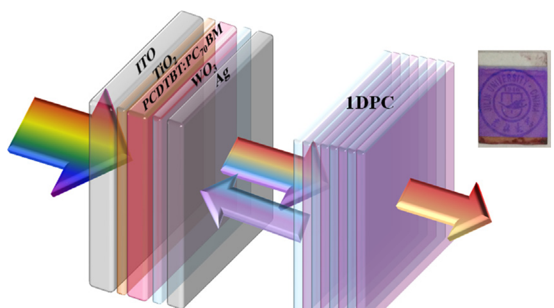


**Fig. 1.** Device architecture of STPSC with 8 pairs of 1DPC. Inset: a photograph of real STPSC with 8 pairs of 1DPC.

## 2. Experimental section

### *2.1. Fabrication and characterization of STPSCs with 1DPCs*

As shown in Fig. 1, the reference device structure is Glass/ITO (150 nm)/$TiO_2$(25 nm)/ PCDTBT: $PC_{70}BM$ (80 nm)/$WO_3$(10 nm)/Ag (15 nm) (Device A) and the structure of 1DPCs-based STPSCs is Glass/ITO(150 nm)/$TiO_2$(25 nm)/PCDTBT:$PC_{70}BM$ (80 nm)/$WO_3$ (10 nm)/Ag(15 nm)/$[WO_3/LiF]^N$ (Device B–E). In the fabrication, the ITO-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 followed by treatment with oxygen plasma for 10 min. Anatase $TiO_2$ thin films were prepared as described in our previous papers [30]. PCDTBT (Lumtec Corp) was dissolved in 1, 2-dichlorobenzene to produce 7 mg/ml solution, followed by blending with $PC_{70}BM$ (Lumtec Corp) in 1:4 weight ratio. The blend was stirred for 72 h in glove box filled with argon. The PCDTBT: $PC_{70}BM$ active layer with a thickness of 80 nm was prepared by spin coating on top of $TiO_2$ film surface at 2000 rpm for 30 s. The samples were annealed at ~70 °C for 25 min in glove box. Then, the devices were evaporated of 10 nm $WO_3$ and 15 nm Ag in sequence under a high vacuum ($5 \times 10^{-4}$ Pa) without disrupting the vacuum. For the semitransparent devices with 1DPCs, N pairs of $WO_3$ (53.8 nm)/LiF (78.1 nm) were alternately evaporated under a high vacuum ($5 \times 10^{-4}$ Pa) without disrupting the vacuum. *N* is equal to 2, 4, 6, and 8. Correspondingly, the devices are referred to as Device B, Device C, Device D, and Device E. The real photograph of Device E is shown as an inset in Fig. 1.

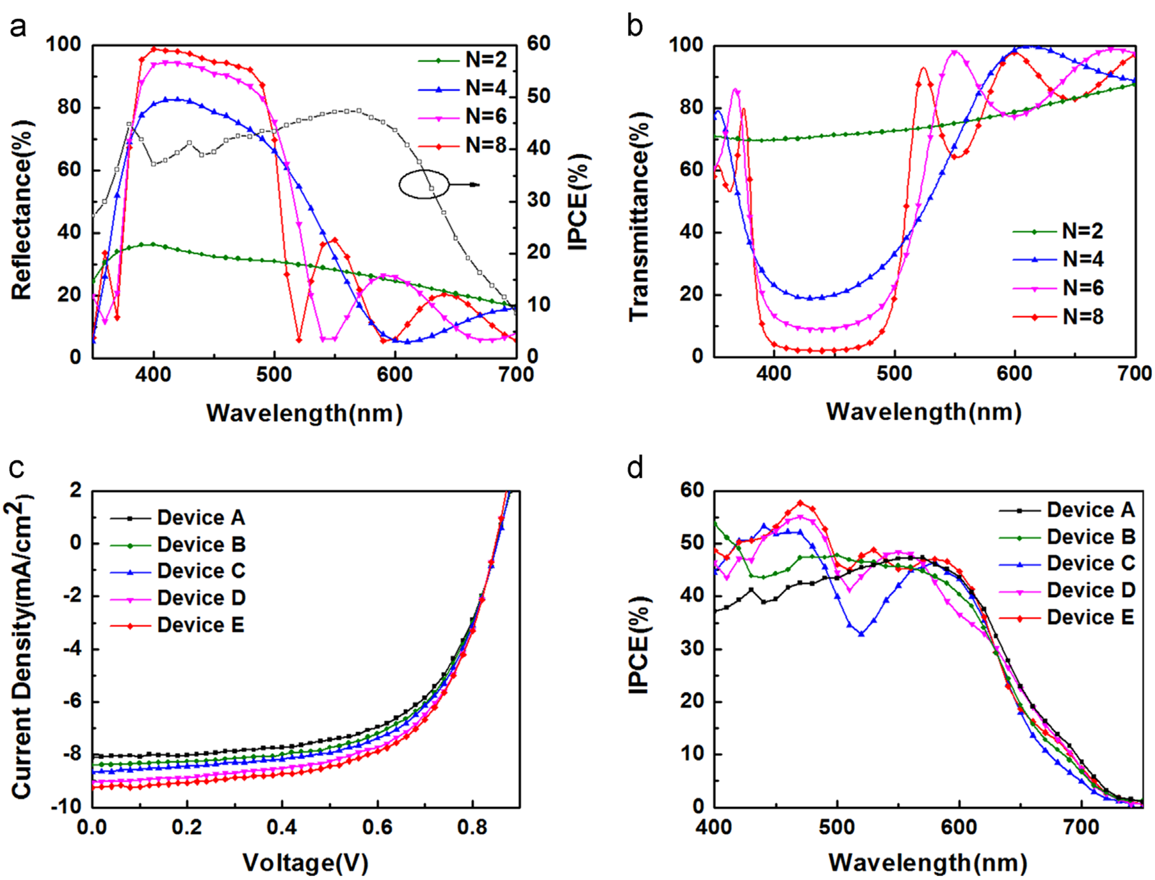


**Fig. 2.** (a) Reflectance spectra of 1DPCs and the IPCE spectrum of Device A. (b) Transmittance spectra of 1DPCs. (c) *J–V* characteristics of Devices A–E, under 100 mW/cm$^2$ simulated AM1.5G in ambient air. (d) IPCE characteristics of Device A–E.