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Original research article

Simultaneously improving efficiency and transparency of semitransparent organic solar cells by constructing semitransparent microcavity

Jinyao Zhong, Wenyue Liang, Yongbing Long*

Department of Applied Physics, College of Electronic Engineering, South China Agricultural University, Guangzhou 510642, PR China

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ABSTRACT

Semitransparent microcavity is constructed by sandwiching an active layer between the WO_3/Ag/WO_3 multilayer electrode and the thin Ag electrode capped by one-dimensional photonic crystals (1DPCs) to simultaneously improve light absorption and transmission of the semitransparent organic solar cells (OSCs). Optical simulations demonstrate that the upper limit to power conversion efficiency (PCE_{max}) of the semitransparent OSCs is improved up to 8.37%, an improvement of 14.0% from that of the conventional device without the microcavity; simultaneously, the transparency of the device reaches a relatively high value of 21.7% with an improvement of 8.0%. In addition, it is revealed that PCE_{max}, transparency and see-through color of the devices bear strong relevance to the photonic bandgap of 1DPCs. Transparency for the semitransparent OSCs can be tuned from 2.4% to 33% and the see-through color of the semitransparent OSCs can be tuned in a broad range by tailoring the center wavelength of the photonic bandgap. Results from the paper demonstrate the semitransparent microcavity is an efficient light trapping structure for semitransparent OSCs and can find application in the design and fabrication of semitransparent OSCs with high efficiency and high transparency.

1. Introduction

Semitransparent organic solar cells (OSCs) have attracted much attention due to such advantages as low-cost, easy-fabrication and flexibility, as well as potential application to power-generating windows of buildings and automobiles [1–5]. One of the key issues in fabricating this type of devices is to secure suitable transparent electrode to maintain both high transparency and high efficiency of the devices. In previous studies, transparent conducting oxide [6], thin metal film [7–9], conductive polymer [10,11], graphene [12,13] and nanotube films [14] have been deposited on top of the photoactive layer as transparent electrode to construct semitransparent devices. However, when these transparent electrodes are used, high device efficiency is usually accompanied by low transmission in the visible wavelength range [7]. A trade-off occurs between efficiency and transparency of the devices.

To circumvent the trade-off, one-dimensional photonic-crystals (1DPCs) is capped on the top electrode of the semitransparent OSC devices [15–20]. Although the fabrication of the 1DPCs with a few to a dozen layers is a challenge and generates additional fabrication cost, the advantage of this light trapping structure is also apparent since the 1DPCs can powerfully manage the optical performance of the semitransparent OSCs. The 1DPCs can reflect all the photons within the photon bandgaps (PBGs) back for re-absorption in the active layer and increase device efficiency; simultaneously, the photons within the passband of the 1DPCs can

* Corresponding author.
E-mail address: yongbinglong@126.com (Y. Long).

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transmit through the semitransparent OSCs, which can help to maintain high transparency of the devices. Based on this approach, L. Shen et.al have fabricated the 1DPC-based semitransparent OSCs with an efficiency of around 5% and the average transmission of the device remains over 40% [18,19]. More recently, 1DPCs are also used to improve the color rendering index of the semitransparent OSCs and the color rendering index are optimized to approach 100 [21,22]. Generally, previous studies have focused on investigating how to employ the 1DPCs to improve efficiency and color rendering index of the semitransparent OSCs. Other properties of the 1DPCs-based semitransparent OSCs such as transparency weighted by eye sensitivity and see-through colors, however, have received little attention even though these properties are, in fact, very important factors concerning performance of semitransparent OSCs when used as power-generating windows [4–6,9].

Another issue for the 1DPCs-based semitransparent OSCs is that the active layer can not completely absorb the light reflected by the 1DPCs since thickness of the active layer is limited by the short exciton diffusion lengths and low carrier mobility of the organic material. To maximize photon absorption in the active layer with limited thickness, former studies have developed light trapping approaches based on surface plasmons, optical spacers and optical microcavity [23–29]. It is found that optical microcavity combined with optical spacers can confine large photons within the device and significantly improve light absorption in the active layer [25,29]. However, these structures have been applied to only conventional opaque OSCs. Little literature has studied and reported their application to semitransparent OSCs. Considering improvement in absorption for semitransparent OSCs is usually accompanied with reduction in transparency, it is even more challenging to develop light trapping structures which can improve photon absorption without reducing the transparency of semitransparent devices.

This paper aims to develop light trapping structure to enhance both photon absorption and transparency of semitransparent OSCs. For this purpose, a semitransparent microcavity structure is constructed by sandwiching an active layer between the WO_3/Ag/WO_3 multilayer electrode and the Ag electrode which is capped by 1DPCs. Optical simulations based on transferred matrix method [30,31] demonstrate that the semitransparent microcavity can simultaneously improve the upper limit to power conversion efficiency (PCE_{max}) and transparency weighted by eye sensitivity (T_{eye}) for the semitransparent OSCs. The effects of the 1DPCs on PCE_{max}, T_{eye} and color coordinates of the semitransparent OSCs are also investigated. It is found that semitransparent OSCs with transparency and see-through colors varying in a wide range can be obtained by tailoring the photonic bandgap of the 1DPCs.

2. Device structure and theoretical model

2.1. Device structure

The 1DPCs-based semitransparent OSCs with microcavity are assumed to have a structure of Glass/WO_3(I)/Ag/WO_3(II)/active layer/TiO_2/Ag/LiF/1DPCs. Within the devices, WO_3(I) acts as the antireflection layer with thickness assumed to be 40 nm and WO_3(II) acts as the hole transport layer with thickness set as 20 nm [32]. Thin Ag films are used as both cathode and anode to construct semitransparent microcavity and then improve the optical performance of the semitransparent OSC devices. The thickness of Ag cathode, Ag anode and electron transport layer (TiO_2) is set as 10 nm. The active layer is assumed to be made from a blend of benzodithiophene polymers (PTB7) and [6,6]-phenyl-C71-butyric acid methyl ester ($PC_{71}BM$) and the thickness is assumed to be 80 nm. LiF film with varied layer thickness is sandwiched between the Ag cathode and the 1DPCs to adjust the reflection phase of the 1DPCs and this layer is named as phase matching layer (PML).

The 1DPCs are assumed to be composed of 8 pairs of WO_3/LiF, as is illuminated in Fig. 1(a). The layer thicknesses of the WO_3 and the LiF are determined by [33]:

$$n_{WO3}\ d_{WO3} = n_{LiF}\ d_{LiF} = \frac{\lambda_0}{4} \tag{1}$$

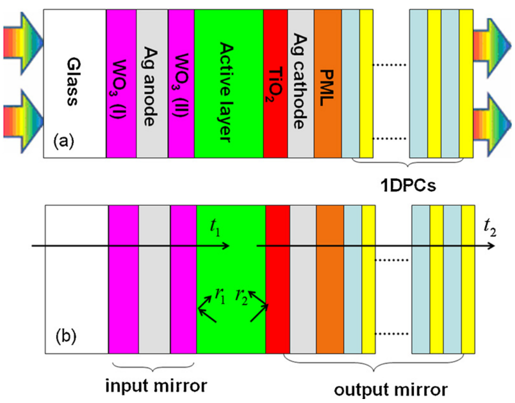

Fig. 1. (a) Structure of 1DPCs-based semitransparent OSCs with microcavity structure; (b) Structure of the microcavity within the device. t_1 and t_2 respectively denote the transmission coefficient of input and output mirrors; r_1 and r_2 respectively denote the reflection coefficient of input and output mirrors.