Solar Energy Materials & Solar Cells 94 (2010) 1835–1839

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Letter

Effects of embedding non-absorbing nanoparticles in organic photovoltaics on power conversion efficiency

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ARTICLE INFO

Article history:
Received 28 March 2010
Received in revised form
24 May 2010
Accepted 25 May 2010
Available online 17 June 2010

Keywords:
Organic photovoltaics
Nanoparticles
Photon scattering

ABSTRACT

The three essential requirements for increasing the power conversion efficiency of organic photovoltaics include a thick active layer for sufficient photon absorption, a lot of interfaces between donor and acceptor materials for efficient exciton separation, and a thin, high-mobility material for enhanced electron–hole transport. We propose the embedding of non-absorbing nanoparticles into organic photovoltaics for photon scattering as a way to meet the challenge of satisfying all three requirements simultaneously. We applied this concept to P3HT/PCBM bilayer cells containing ZnO nanoparticles and demonstrated an increase in power conversion efficiency. We chose a bilayer structure because it is simple enough to isolate the effects of photon scattering. Photon absorption was enhanced, leading to an increase in the short circuit current density. We applied this method to bulk heterojunction solar cells and demonstrated that thickness of the active layer could be reduced by half without sacrificing power conversion efficiency.

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1. Introduction

Organic photovoltaics (OPVs) have received much attention due to their low cost and amenability to mass-production on flexible substrates [1–3]. Krebs [4] and Krebs et al. [5] used roll-to-roll (R2R) process and screen printing to make flexible OPVs in the ambient atmosphere under industrial conditions . Also, Krebs and Norrman [6] used light-induced thermocleavable materials for ITO or vacuum processing free R2R process. Furthermore, recent research finding has showed that industrial application of OPVs is now possible as "Lighting Africa" [7] and encapsulated flexible OPV devices are stable for over 4 months by the round robin (RR) study [8]. However, OPVs suffer from low efficiency, prompting most research efforts to focus on improving their power conversion efficiency (PCE). The PCE of OPVs depends primarily on three parameters: (i) a thick active layer for sufficient photon absorption, (ii) large interfaces between donor and acceptor materials for efficient exciton separation, and (iii) thin, high-mobility materials and morphological considerations for efficient electron/hole transports. It has been challenging to satisfy all three requirements simultaneously since the three requirements partially conflict with one another. Fabricating OPVs with a thin active layer that is able to sufficiently absorb photons would enhance its efficiency. Optical spacers [9–11] have been used to modulate the incident light; by using the optical interference effect of the optical spacer, the active layer absorbs more incident light, thus increasing power conversion efficiency. The surface relief grating method has also been proposed for efficient light management in OPVs [12,13]. Specifically, the surface relief grating endows the otherwise smooth metal a cathode surface with periodic gratings that reflect the light, which is then able to travel a greater distance than the incident length.

In this paper, we propose a method for decreasing the active layer thickness for light management by embedding nanoparticles for photon scattering. There are other ways of scattering incoming photons, such as patterning of ITO or glass. However, to avoid the vacuum process and to simplify the process, we used ZnO nanoparticles because we can just simply use the spinning process. We applied this concept in bilayer OPVs to simplify the problem and to extract important physics, but the basic concept should be applicable to bulk heterojunction OPVs. We placed nanoparticles near the transparent electrode to scatter the incoming photons, while the surface relief grating scattered the reflected photons from the metal cathode electrode [12,13]. The embedding of metallic nanoparticles in OPVs was recently achieved [15–18]. The metallic nanoparticles absorb photons and generate surface plasmons. While the surface plasmon enhances light absorption in OPVs and scatters the incoming photons, it also generates phonons and is dissipated as heat. Senkovskyy et al. [14] grew P3HT from nanoparticles, the so-called hairy nanoparticles with end-tethered P3HT chains. These hairy nanoparticles

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doi:10.1016/j.solmat.2010.05.049

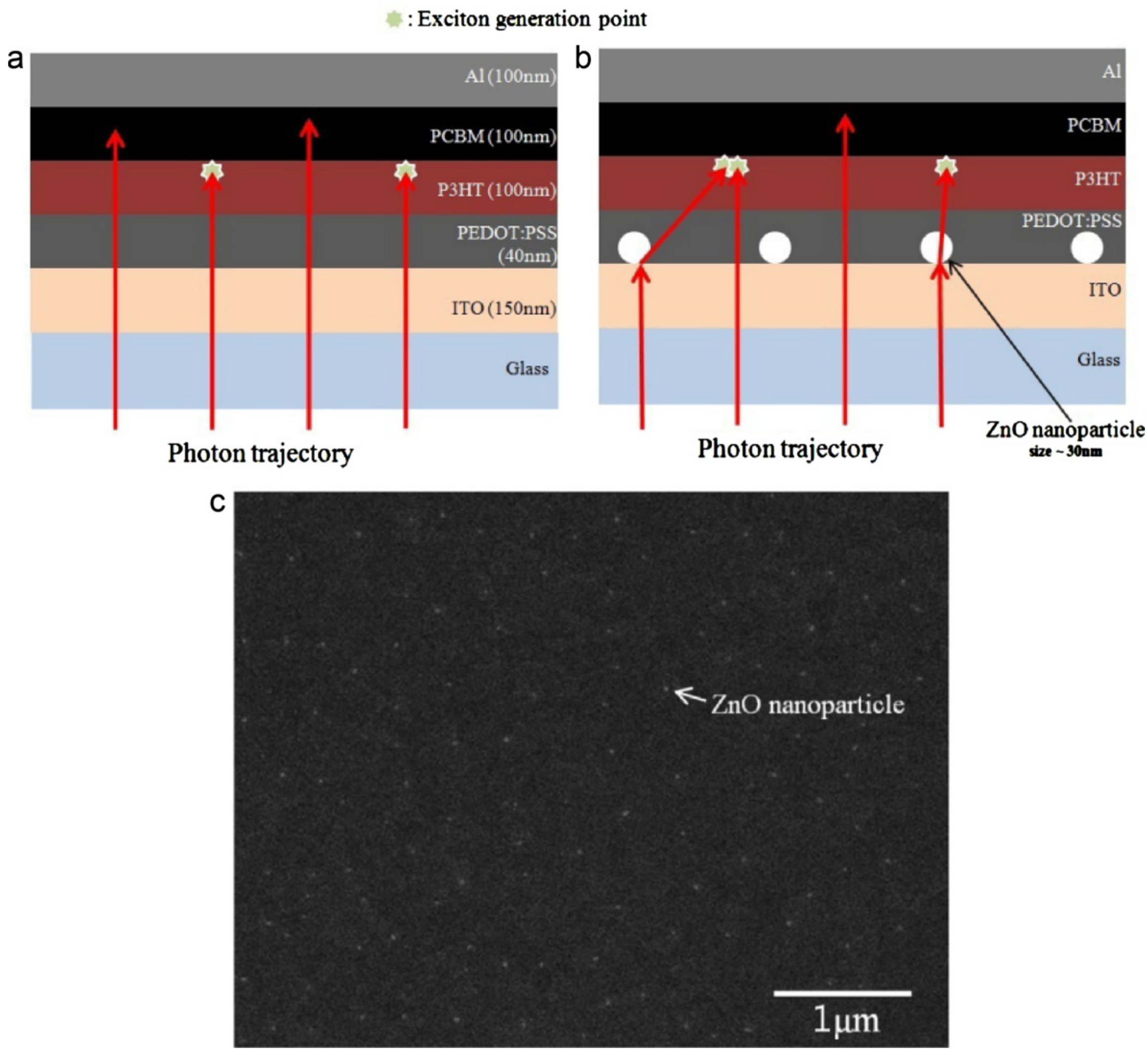

Fig. 1. Schematic of (a) a reference bilayer cell, and (b) a bilayer cell with embedded ZnO nanoparticles. Photon trajectories are shown in the schematics to explain how the ZnO nanoparticles scatter incoming photons. (c) SEM image of ZnO nanoparticles (white dots) on the ITO substrate (top view); 1 mg of ZnO nanoparticles in 8 ml IPA solution was dispersed.

exhibited red shift in absorption. They used these nanoparticles in the bulk heterojunction solar cells. Also, Krebs [19] and Krebs et al. [20] used ZnO nanoparticles as active layer for air stable and mass producible OPVs. In this paper, we used nanoparticles that are non-absorbing materials to determine the effects of photon scattering. The energy bandgap of ZnO is about 3.3 eV [21,22], so it scatters light rather than absorbing it. By embedding ZnO nanoparticles into the OPVs, the incident photons are scattered, thus increasing the traveling distance to a given active layer. Through these actions, we improved the absorbance of the donor polymer, P3HT, which should increase the probability of exciton dissociation. Consequently, we demonstrated an increase in power conversion efficiency.

2. Device fabrication

For the transparent anode substrate, patterned indium tin oxide (ITO, ~10 Ω/□) glass was used. The ITO glass was cleaned with detergent, DI water, acetone, and isopropyl alcohol (IPA). The substrate was then treated with UV ozone for 10 min and moved into a glove box for spin coating and application of the active

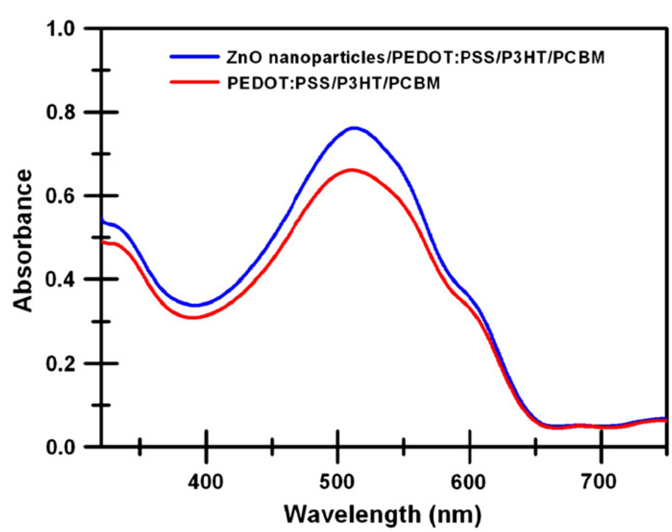

Fig. 2. Absorbance data of ITO/PEDOT:PSS/P3HT and ITO/ZnO nanoparticles/PEDOT:PSS/P3HT structures; 1 mg of ZnO nanoparticles in 8 ml IPA solution was dispersed.

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