Light trapping enhancement of inverted polymer solar cells with a nanostructured scattering rear electrode

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ABSTRACT

High performance inverted polymer solar cell is demonstrated by introducing a nanostructured backscattering rear electrode, which is fabricated by embedding silver nanoparticle (NP) arrays into the MoO_3 hole extraction layer. As verified by characterizing and simulating the electrical and optical properties, such a nanostructured rear electrode can achieve an improved cell performance by maintaining simultaneously high open-circuit voltage and fill factor values, while providing excellent short-circuit current enhancement through efficient backscattering-induced light trapping. A careful optimization of the nanostructured rear electrode can result in polymer solar cells with an enhanced power conversion efficiency of 7.21%, as compared to 6.26% of the reference cell with a flat electrode. It is noteworthy that the method described here offers a convenient and scalable way for inexpensive and high-performance polymer solar cell designs.

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1. Introduction

Polymer solar cells (PSCs) based on conjugated polymer/fullerene derivative bulk heterojunction (BHJ) are promising candidates for the deployment of cost-effective, lightweight photovoltaics, benefiting fully from simple solution processing of the active layer and mechanical flexibility for special substrates [1–8]. In recent years, significant progress on PSCs has been made with the power conversion efficiency (PCE) close to or over than 10% via the introduction of low band-gap materials, novel device structures, and the optimization of device fabrication processing [3,4,9–13]. Compared to the inorganic counterparts, the external quantum efficiency (η_{EQE}) of PSCs is limited due to the comparatively low carrier mobility and high probability of charge recombination, leading to poor charge transport and low charge collection efficiency

(η_{CC}). A thin active layer, usually in the range of 100–200 nm, is used in PSCs for efficient electron and hole extraction, which can decrease the carrier recombination losses and series resistance. However, the thickness of the active layer is typically an order of magnitude smaller than the optical absorption length of organic materials [3–9]. A large fraction of the incident light thus remains unabsorbed for photocurrent generation, limiting η_{EQE} and hence PCE of PSCs. Therefore, an essential aspect of developing of high-efficiency PSCs lies in increasing the light absorption of a polymer BHJ at a limited film thickness.

Recently, several advanced light trapping schemes have been implemented to realize absorption enhancement with a thin active layer in PSCs, including optical spacers [14–16], photonic crystals [17,18], optical cavities [19–21], and plasmonic nanostructures [9,22–32]. Employed in optimized devices, these approaches are capable of providing significant enhancement of the optical path length within the thin active layer of PSCs for efficient light trapping. In particular, an increased light harvesting in the active layer of PSCs has been experimentally realized by integrating metal nanostructures such as nanoparticles

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(NPs), gratings, and patterned electrodes to enhance the light absorption, which is ascribed to localized surface plasmons (LSPs) that leads to a strong near-field enhancement as well as highly efficient light scattering [22–29,33–36].

The commonly used approaches to introduce plasmonic effect in PSCs include the incorporation of metallic NPs into the interface between transparent front electrode and the active layer, or the direct incorporation of NPs inside the active layer to trigger the excitation of LSPs [24–27,35,36]. For instance, solution-processable Au NPs have been blended into an anodic buffer layer of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) or the polymer active layers to exploits near field enhancement of light absorption in the photoactive layer of PSCs [35,36]. However, these methods suffers from several drawbacks such as the influence on the active layer morphology, and the aggregation of metallic NPs in the polymer host [35], which induce the possibility of charge trapping and exciton quenching [33]. Additionally, metallic NPs embedded in the front electrode of the cell may give rise to destructive Fano interference and scatter the incident light in the reverse direction, leading to the inevitable loss of light into the active layer [37]. In general, as compared to the excitation of LSPs at the front electrode, to place metal nanostructures on the reflecting rear contact side of PSCs will be favorable to the light backscattering effect as well as surface plasmonic coupling effect [38]. The incident light will be preferentially trapped into the active layer by nanostructures-induced multiple and high-angle scattering at the rear electrode, and the light absorption is simultaneously enhanced by the excitation of LSPs with larger absorption cross-section. For Si solar cells, an efficiency enhancement by periodic arrays of nanostructured metal rear electrode has been reported [39]. For PSCs, however, it is quite challenging for the processing conditions compatible with the solution-processed polymeric materials without compromising their optical and electrical properties. Recently, high-efficiency PSCs have been demonstrated with patterned plasmonic nanostructured rear electrode on top of the active layer, leading to a significantly improved device performance [9,38].

In this study, we present an alternative, highly promising strategy to enhance the performance of PSCs by utilizing a nanostructured rear electrode, which achieve an electrical cell performance comparable to what we obtain on flat reference cells, while allowing for a powerful light trapping enhancement by backscattering and surface plasmonic effects due to the presence of metallic nanostructures adjacent to the active layer. The inverted structure is used for the PSC fabrication to satisfy the vertical phase separation in bulk-heterojunction polymer active layer and to avoid the degradation of reactive metal cathode in the regular structure induced by oxygen and water vapor. A careful optimization of the nanostructured rear electrode by a thermally deposited MoO_3/Ag NPs/MoO_3 sandwich structure can result in an excellent initial PCE of 7.21% with over 10% improvement of short-circuit current density as compared to the reference cell with a flat electrode.

2. Experimental section

2.1. Device fabrication

The device architecture of inverted PSC with a nanostructured rear electrode is schematically shown in Fig. 1. The devices were fabricated on ITO-coated glass substrates with a sheet resistance of 20 Ω/sq. Prior to the preparation of ZnO layer, the ITO substrates were subjected to a routine cleaning process and treated with UV-ozone. The ZnO precursor solution was prepared by dissolving 0.5 M zinc acetate and 0.5 M monoethanolamine in 2-methoxyethanol under vigorous stirring. The sol–gel–derived ZnO layer was formed by spin-coating the ZnO precursor solution onto ITO substrate, and then thermally annealed at 150 °C for 5 min during which the precursor was converted to dense ZnO film by the hydrolysis reaction at ambient conditions. The active layer with P3HT blended with ICBA at a 1:1 weight ratio dissolved in dichlorobenzene was spin-coated at 700 rpm for 50 s on top of the ZnO layer in a nitrogen-filled glove box, and thermally annealed at 110 °C for 10 min. Finally, to complete the device fabrication, a MoO_3/Ag NPs/MoO_3/Al nanostructured rear anode was thermally deposited on top of the active layer in a high vacuum system at a base pressure of 2×10^{-6} Torr. The deposition rate and film thickness were monitored by a quartz crystal oscillator. The Ag NPs and MoO_3 layer were deposited at rates 0.02–0.03 nm/s. A shadow mask was used to define the Al anode, and the device area determined by the overlap between ITO cathode and metal anode was estimated to be 0.1 cm^2.

2.2. Characterization of photovoltaic cells and thin films

Current density–voltage (J–V) characteristics of inverted PSCs without any device encapsulation were examined in air at room temperature using a programmable Keithley 2612 source measurement unit under illumination from a 150 W Newport 91160 solar simulator with an air mass (AM) 1.5G filter. The illumination intensity was adjusted to be 100 mW/cm^2, which was calibrated using a standard Si optical power meter. The incident photon to current conversion efficiency (IPCE) measurement was conducted with a photo-modulation spectroscopic setup (Newport monochromator). A calibrated monosilicon diode with known spectral response is used as a reference. Surface morphology and roughness were characterized with atomic force microscopy (AFM) (Veeco MultiMode V) in tapping mode. Absorption and transmission measurements were taken at room temperature using an UV/vis/near-IR spectrometer (Perkin Elmer Lambda 750). The steady state photoluminescence (PL) spectra were recorded in the transmission mode under air ambient conditions with a HORIBA JOBIN YVON Fluoromax-4 Fluorescence spectrometer.

2.3. Theoretical calculation

The near-field distribution of PSCs with flat and nanostructured rear electrodes was simulated based on