



Optical absorption and electrical properties of enhanced efficiency in organic solar cells as interfacial layer with Au NPs



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ABSTRACT

The effects of the gold nanoparticles (Au NPs) on performance of organic solar cells (OSCs) are systematically investigated based on blend of the low band gap polymer and fullerene. The localized surface plasmon resonance (LSPR) induced by the Au NPs enhance the light absorption in the active layer and the photoluminescence spectra showed a significant enhancement in their intensity which mainly contribute to increased light absorption of active layer induced by LSPR. The impedance spectroscopy study revealed that the introduction of Au NPs as interfacial layer decreases the sheet and charge-transport resistance between ITO/PEDOT:PSS or PEDOT:PSS/active layer. From the results, the introduction of Au NPs increased the rate of exciton generation and the probability of exciton dissociation, thus enhancing the short-circuit current density and the fill factor. The optimized OSCs incorporated with Au NPs were found to have power conversion efficiency of 5.40% compared to control device (4.65%), measured by using an AM 1.5 G solar simulator at 100 mW/cm² light illumination intensity.

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1. Introduction

Organic solar cells (OSCs) have attracted much attention because of their great potentials, such as for large-area, light-weight, low-temperature fabrication, and mechanical flexibility [1–3]. Recently, many research groups have investigated that the introduction of a donor/acceptor bulk heterojunction (BHJ) concept, where a large phase separated interfacial for sufficient exciton dissociation, which dramatically improves the device performance [4–8]. However, compared with inorganic solar cells, OSCs usually suffer from the insufficient light absorption due to the thin active layer restricted by the low carrier mobility and short exciton diffusion length, resulting in low device performance [9,10]. Thus, there is a need to increase the absorption of the active

layer without increasing the film thickness, motivating the development of a variety of light-trapping techniques. For efficient light trapping in the active layer, several approaches including the synthesis of low-band gap polymers that absorb red and near infrared region [11–13], the application of periodic nanostructures to increase the optical path length in the active layer [14–17], and the introduction of an optical spacer to redistribute the light intensity in the device have been reported [18–20]. Recently, metallic nanostructures have been introduced into thin-film inorganic solar cells (e.g., Si, GaAs, quantum dot, dye-sensitized solar cells) for efficient light harvesting by exploiting plasmonic light-scattering effect causing an increase in the effective optical path length and/or localized surface plasmon resonances (LSPR) enhancing strong local field around the nanoparticles (NPs) to increase absorption [21]. In OSCs applications, the metallic NPs were dispersed into active layer and/or poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) or at various interfaces within the OSC cell architecture with observable improvement in power conversion efficiency (PCE) [22–32]. The above mentioned approaches of NPs in OSCs are fundamentally

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different in terms of absorption and performance enhancement mechanism. Although PCE enhancements in OSCs have been investigated experimentally, the degree of contribution of LSPR or light-scattering effects remains inconclusive. There are limitations using incident photon to electron conversion efficiency (IPCE) enhancement as the evidence for LSPR or light-scattering effects, because IPCE is highly affected by the electrical characteristics of the OSCs [27].

Recently dual plasmonic nanostructures in BHJ OSCs have gained importance due to accumulated improvements in device performance [32]. The most effective method for realizing dual plasmonic structure would be to blend metal NPs in the both the photoactive and buffer layers simultaneously. The fabrication of dual layers with metallic NPs usually requires orthogonal solvents to avoid the case of intermixing. Also, the higher miscibility in the organic matrix is prominent factor to prepare dual nanostructures in single BHJ OSCs in order to overcome the NPs aggregation when they are blended directly into a photoactive layer. Furthermore, the morphology of the photoactive layer is often affected when metallic NPs are directly blended with photoactive layer, leading to serious phase separation which may degrade the device performance [33]. Alternatively, the metallic NPs are placed between the ITO/PEDOT:PSS layer or between PEDOT:PSS/active layer and in combination of both shows more scope. The main advantage of the NPs at the interfaces is that the exciton quenching by non-radiative energy transfer between the active layer and the NPs can be avoided [33]. The incorporation of NPs at the interfaces within OSCs may excite LSPR at their vicinity of the planar surfaces and leading to enhancement in performance of OSCs [32].

In this study, we systematically explored how metallic NPs influence the electrical and optical characteristics of OSCs based on blend of low band gap polymer, poly[4,8-bis-alkyloxy-benzo[1,2-*b*:4,5-*b'*]dithiophene-2,6-diyl-alt-4-(alkyl-1-one)thieno[3,4-*b*]thiophene-2,6-diyl] (PBDTTT-C) and [6,6]-phenyl-C₆₁-butyric acid methyl ester (PC₆₁BM). To investigate the effects of metallic NPs on the performance of OSCs, we added the 15 ± 4 nm diameter Au NPs at the interface of the indium tin oxide (ITO) and/or PEDOT:PSS layer, and investigated the impact of Au NPs on the optical and

electrical properties of OSCs. As a result, under optimized condition, the improvement in PCE by ~16% was achieved for Au NPs based device.

2. Experimental

The indium tin oxide (ITO) glass substrate with a sheet resistance of 12 Ω sq⁻¹ was washed in turn with a substrate-cleaning detergent, deionized water, acetone, and isopropyl alcohol, and finally treated with UV-ozone chamber for 10 min. The PEDOT:PSS (40 nm, CLEVIOS P) was spin-coated directly onto the patterned ITO glass and baked at 150 °C for 10 min. The Au NPs (0.01% in HAuCl₄) with a size of ~15 ± 4 nm were purchased from Sigma-Aldrich. Then, an Au NPs solution was spin-coated on the ITO substrate or PEDOT:PSS layer, followed by thermal annealing at 150 °C for 10 min in glove box. In a nitrogen-filled glove box, a solution of PBDTTT-C (10 mg mL⁻¹) and PCBM (20 mg mL⁻¹) dissolved in 1,2-dichlorobenzene (DCB) was spin-coated on top of the PEDOT:PSS layer. The thickness of the active layer was ca. 100 nm. Thicknesses of the thin films were measured using a surface profilometer (KLA Tencor Alpha-step IQ) with an accuracy of ±1 nm. The active solutions used in the device fabrication were filtered with 0.20 mm PTFE syringe filter. The device fabrication was completed by thermal evaporation of 100-nm-thick Al as the cathode under vacuum at a base pressure of 2 × 10⁻⁶ Torr. The device area, defined through a shadow mask, was 0.36 cm². The current density versus voltage (*J*-*V*) characteristics of the devices were measured using a Keithley 2400 source measure unit under a calibrated AM 1.5 G solar simulator (Pecell Technologies Inc., PEC-L11) at a 100 mW/cm². The intensity of sunlight illumination was calibrated using a standard Si photodiode detector with a KG-5 filter. The IPCE measurement system (Oriol IQE-200) composed a 250 W quartz-tungsten-halogen lamp as the light source, a monochromator, an optical chopper, a lock-in amplifier, and a calibrated silicon photodetector. The dimensions of the Au NPs were measured using an ultra-high resolution field emission scanning electron microscope (UHR FE-SEM, S-5500, Hitachi). Absorption spectra were measured using an UV/vis/near-IR

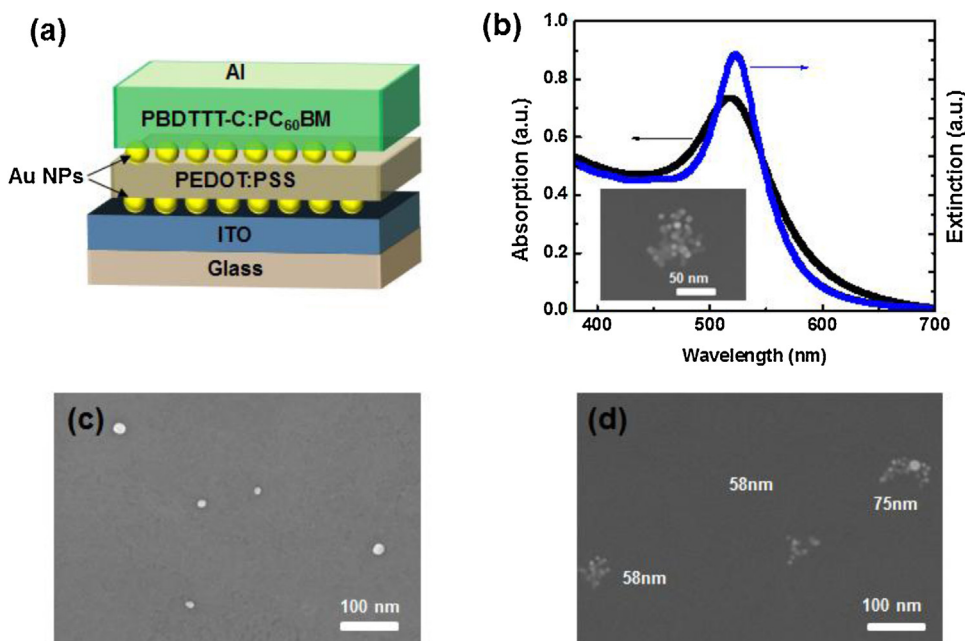


Fig. 1. Device structure of the OSCs incorporating Au NPs as the interfacial layer (a). UV-vis absorption spectrum of Au NPs and theoretically calculated extinction spectrum of Au NPs (along with FE-SEM image of Au NPs in the inset) (b). SEM images of interfacial layer with (c) Au NPs on ITO substrate and (d) PEDOT:PSS layer. The Au NPs are indicated as white dots in (c).

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