



Enhanced performance of semi-transparent OPV with nanoparticle reflectors

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ABSTRACT

In order to overcome the decreased power conversion efficiency of semi-transparent organic solar cells, methods to prepare a simple external reflection layer were studied. A reflective layer was formed by blending a polymer with high refractive index materials and was fabricated on top of the device to enhance the power conversion efficiency of the semi-transparent device. When silver coated exfoliated montmorillonite, aluminum oxide nanoparticles, or magnesium oxide nano-particles were used as a reflective layer material, the enhancement in power conversion efficiency was imperceptible. A reflective layer formed by blending polymer and gold nanoparticles was tried to enhance the power conversion efficiency based on the plasmonic effect of gold. Two different sizes (2 nm and 30 nm in diameter) of gold nanoparticles were used as reflective layers to fabricate OPV devices and both devices showed an approximately 20% power conversion efficiency increase compared to the reference semi-transparent device. Better enhancement of power conversion efficiency was obtained by combining the gold plasmonic effect and the scattering effect from a reflective layer formed with a 1:1 mixture of 2 nm and 30 nm gold nanoparticles. Devices with the gold nanoparticle mixture layer as a reflective layer showed about 50% improvement in power conversion efficiency compared to the reference device. The process for preparing this polymer reflective layer is very simple and inexpensive to manufacture.

1. Introduction

Organic solar cells are flexible solar cells that can be manufactured by a roll-to-roll-based solution printing process, and thus they can be fabricated at low cost for applications in various fields. Recently, the efficiency of organic photovoltaic (OPV) devices through the development of photoactive layer materials (both n and p type) and improvements in device structures has reached a level appropriate for commercialization [1,2]. However if organic solar cells are to be used for energy generation, a large area is required due to the low power conversion efficiency. For this reason, at present solar power plants are being built on large plain areas or at sea. However, if power generation could be performed close to electric power consumers (known as small photovoltaics), the energy loss due to power transmission could be reduced. For this reason, there is a growing interest in building integrated photovoltaics (BIPV). Using organic solar cells that can transmit light, at low production cost and by a simple device fabrication process, is most suitable for building integrated solar power generator.

Semi-transparent organic solar cells are less efficient than conventional opaque solar cells because they transmit a significant amount of light. In general, opaque organic solar cells exhibit better efficiency than semi-transparent organic solar cells because of their higher

utilization of light due to opaque rear electrodes. In other words, the use of semi-transparent organic solar cells as a BIPV would further lower efficiency compared to using inorganic solar cells, thus reducing their attractiveness as a BIPV element. Therefore there have been many studies to improve the efficiency of semi-transparent organic solar cells [3–8]. Rear reflector methods typically use surface texture [9,10] (fabricating a rough surface or organized surface texture) and light interference [11] (adjust the optical thickness to achieve maximum reflectivity). These methods are very low in productivity and require a long processing time such that they are not adequate for mass production. Research [12–15] on reflective layers suitable for semi-transparent organic solar cells is very limited. Research using plasmonic effects with gold nanoparticles to enhance OPV devices is especially rare [16–19].

In this study, a semi-transparent organic solar cell was fabricated using silver nano wire, which is a transparent electrode, as an upper electrode of a semi-transparent organic solar cell device, instead of an opaque silver electrode in a conventional OPV. A study was performed to form a reflective layer on top of the semi-transparent electrode in order to reuse light passing through it without being reflected again due to usage of a semi-transparent electrode. The application of such an organic solar cell structure is expected to be an effective way to further

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improve the power conversion efficiency of a semi-transparent organic solar cell.

2. Experimental details

2.1. Nanoparticle synthesis

Gold nanoparticles (particle size ~ 2 nm) were synthesized by dissolving HAuCl_4 (purchased from Sigma-Aldrich) in deionized water at a concentration of 1 mM. Sodium citrate (purchased from Sigma-Aldrich) solution was prepared by dissolving 38.8 mM in deionized water. 20 ml of the HAuCl_4 solution was heated with stirring. When the solution began to boil, 2 ml of sodium citrate solution was slowly added. The mixture was heated for 10 min or more while stirring, and the synthesis was completed when the solution turned dark red. Silver coated montmorillonite was prepared by silver mirror reaction. First 0.1 M silver nitrate, 0.80 M potassium hydroxide and 0.25 M dextrose in de-ionized water were mixed, then 2–3 drops of concentrated ammonia solution were added to the solution, and the resulting brown precipitates were discarded. 7 ml of potassium hydroxide was added to the solution, and the mixture was stirred until the solution became clear. 0.1 g of montmorillonite (purchased from Sigma-Aldrich) was added to the stirred solution followed by another 2 ml of dextrose. The lid of the vial was closed and the mixture was shaken for 2–3 min. The surface of the vial and the montmorillonite were plated with silver. The montmorillonites were extracted by centrifugation.

2.2. Device fabrication

A patterned ITO cell ($8 \Omega/\square$ on glass) with an insulator was prepared by photolithography and was cleaned using acetone, isopropyl alcohol, and deionized water. The cleaned ITO was then treated by UV-Ozone for better coating characteristics. The electron transport layer was formed using ZnO nano particle solution (N-10 purchased from Avantama) by spin coating at 3000 rpm for 40 s and was dried for 10 min at 110 °C. 4 wt% of regioregular poly[3-hexylthiophene-2,5-diyl] (P3HT) (purchased from Solaris) and PCBM (purchased from Nano-C) blended at a 1: 0.6 wt ratio was dissolved in a 1:1 mixture of chlorobenzene and 1,2-dichlorobenzene at a concentration of 46.3 mg/ml. This active layer solution was spun cast onto the ZnO coated ITO at 1000 rpm for 80 s. The active layer film was dried in a vacuum oven for 10 min at 110 °C. The resulting active layer was approximately 400 nm thick.

For the hole transport layer of the opaque OPV device, poly(3,4-ethylenedioxythiophene): poly(4-styrene sulfonate) [PEDOT: PSS] (Orgacon EL-P5010) was formed by the bar coating method and dried at 110 °C for 10 min in a vacuum oven. PEDOT: PSS (PH-1000 purchased from Heraeus Clevios) was used as a hole transport layer in the semi-transparent solar cell, where a small amount (about 0.1 wt % of PEDOT:PSS) of surfactant (FS-31 purchased from DuPont) was added for better coating characteristics. PEDOT:PSS was spun cast onto the active layer at 2500 rpm for 40 s and dried at 130 °C for 5 min in a vacuum oven. The top electrode for the opaque OPV was screen printed using silver ink (Toyo UV) and was sintered using heat and UV light (110 °C for 10 min and 1 min with 2400 mJ photo-energy). The top electrode of the reference semi-transparent solar cell was screen printed using a silver nanowire solution (NovaWire-Ag-SP purchased from Novarials) and cured in a 130 °C vacuum oven for 10 min. The fabrication processes are presented in Fig. 1.

The nanoparticles used as the reflective material were dispersed in poly(vinyl alcohol) (PVA), a water-soluble polymer, which was used as a host to form a reflective layer film. The reflection layer solution was prepared by mixing 10 wt% PVA with nanoparticles in aqueous solution, and spin coated at 3000 rpm for 40 s. Since this reflective layer was formed from aqueous solution, a hydrophobic poly(methyl methacrylate) (PMMA) layer should be inserted as a protective layer

because coating of the reflection layer affects the already formed semi-transparent electrode. 3 wt% PMMA (MW of 120,000 g/mol) was spin coated at 3000 rpm for 40 s to form a protective layer with a thickness of approximately 100 nm.

2.3. Characterization

A Class AAA Xe solar simulator (McScience K3600) was used as a light source, and all measurements were performed under a 1 sun condition ($100 \text{ mW}/\text{cm}^2$). All data were obtained by averaging at least five devices measurements. Measurements were not corrected for reflection loss or absorptions from the ITO electrode. The I-V performance was measured with a Keithley 2400 source measurement unit. The thickness of the coated film was measured with a surface profiler (TENCOR®, P-10 a-step). Transmittance spectra of the devices were obtained using a photodiode array type UV-Vis spectrometer (HP 8453).

3. Results and discussion

In this study, semi-transparent organic solar cells using a silver nanowire as an upper electrode were fabricated, and a reflection layer was added on top of the device to enhance the efficiency of the OPV device by re-using escaping light. When adding a reflection layer to the device, attachment of the reflection layer outside the device was considered as an optimum structure in terms of easy processability and cost reduction. Therefore, the reflection layer to enhance the power conversion efficiency was overlaid after complete fabrication of the inverted type solution processed OPV.

High refractive index materials were considered as reflection materials since a higher refractive index results in a higher reflection, according to the Fresnel equation [20]. The chosen high refractive materials were aluminum oxide nano-sphere (purchased from Aldrich, size of the particles were 30–60 nm), magnesium oxide nano-sphere (purchased from Aldrich, size of the particles were < 50 nm), silver coated montmorillonite by the silver mirror reaction, home-made gold nano particles (size of the particles were ~ 2 nm) and gold nano-spheres (size of the particles were ~ 30 nm) purchased from Aldrich, and a gold nano particles mixture (1:1 mixture of 30 nm and 2 nm nano-particles). Since transparency is a very important factor for BIPV application of semi-transparent OPV, a transmittance study was performed first, as shown in Fig. 2. The transmittance of each reflective material was measured under the same conditions as the reflective layer to be applied to the device. In other words, after coating the PMMA layer on a glass substrate, the reflective material was blended with PVA according to the conditions described in the experimental section and then coated on top of the PMMA layer. As shown in Fig. 2, the average transmittance of the visible range (400–700 nm) of both 2 nm and 30 nm gold nanoparticles was about 89%, and the transmittance of the 1:1 mixture was improved to 91%. The transmittances of montmorillonite, MgO and Al_2O_3 were 79%, 52% and 36%, respectively. The transmittance was measured again after the reflective layer was coated over the Ag nanowire semi-transparent electrode. A silver nanowire solution (NovaWire-Ag-SP) was purchased from Novarials and followed manufacturer's suggested optimum fabrication condition (screen printed and cured in a 130 °C vacuum oven for 10 min), which resulting in 150 nm thick semi-transparent electrode with average visible transmittance of approximately 81%. If thickness of nano wire layer is thicker, the sheet resistance would decrease and the transparency would also decrease; therefore the thickness of electrode should be optimized. As shown in Fig. 3, the 2 nm gold nano-particles and gold nano-particle 1:1 mixture did not have a large influence on the transmittance of the Ag semi-transparent electrode, and the transmittance was similar to that of the Ag nano-wire semi-transparent electrode ($\sim 81\%$), but the transmittance of the 30 nm gold nano-particle reflection layer was slightly reduced to 78%. This slight reduction in transmittance was caused by the

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