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Investigation of Gold Quantum Dot/Plasmonic Gold Nanoparticle System for Improvement of Organic Solar Cell

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Abstract

Light management allows enhancement of light harvesting in organic solar cells (OSCs). In this paper, we describe the first investigation of OSCs enhanced by the synergistic effect of gold quantum dots (AuQDs) and localized surface plasmons, obtained by blending a AuQD layer and plasmonic gold nanoparticles (AuNPs) in a hole-transport layer (HTL). Different AuQDs emitting blue, green, and red fluorescence were examined in this study. The best synergistic effect was found with OSCs consisting of a green-emitting AuQD layer and a HTL containing AuNPs, resulting in the highest improvement in PCE of 13.0%.

1. Introduction

Metallic nanostructure-induced plasmonic properties have been used to improve light harvesting in photovoltaic devices [1-4]; in particular, the introduction of gold nanoparticles (AuNPs) into OSCs enhanced the photocurrent and PCE.[5-7] We also reported the use of AuNPs to improve the performance of OSCs [5]. Plasmonic nanoparticles (NPs) are usually dispersed into photoactive or hole-transport layers as well being deposited at the interfaces of organic layers in photovoltaic devices [8]. AuNPs with particle sizes from 2 to 100 nm typically enhance the electric field and optical absorption through excitation of localized surface plasmon resonance, which depends on the particle size, shape, and surrounding environment. When the size of gold nanoparticles is further reduced (<2 nm), they are known as gold nanoclusters or gold quantum dots (AuQDs), on which localized plasmons cannot be excited. Instead, due to the quantum confinement effect, electrons in AuQDs are excited from the ground state by absorbing near-UV light, and the AuQDs emit fluorescence in the visible range. The size of the AuQDs, i.e., the number of gold atoms, determines the wavelength of the fluorescence emission [9-10]. This implies that AuQDs can harvest light from the UV region and convert it into visible light. AuQDs were previously shown to be effective in the operation of dye-sensitized solar cells, being employed both as a photosensitizer and catalyst. AuQDs deposited on a TiO2 electrode improved the light absorption capacity, increased the photocurrent, and enhanced charge transport [11]. Because most organic photoelectric conversion materials harvest light mainly in the visible range, an important challenge is to apply AuQDs to organic light harvesting systems, which absorb light in the near-UV region and convert it to visible light as fluorescence emission [12]. In combining AuQDs and AuNPs, synergistic effects are expected because the fluorescence from AuQDs enhances the localized plasmon effect of the AuNPs, and simultaneously the enhanced electric field on AuNPs enhances the fluorescence of AuQDs by localized plasmon excitation.[13] Based on the optical properties of AuNPs, the enhancement of the photovoltaic properties of plasmonic organic thin-film solar cells by introducing AuNPs and AuQDs (blue, green, and red) was investigated in this work. AuQDs/plasmonic solar cells with an Al/poly(3-hexylthiophene-2,5-diyl) (P3HT): [6,6]-phenyl C61 butyric acid methyl ester (PCBM)AuNP:poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS)/ AuQD/indium tin oxide (ITO) glass substrate structure exhibited an improved performance. Our results demonstrated that the AuQDs/AuNPs in the organic solar cell played an important role in improving its photovoltaic properties, leading to a 13% increase in the PCE.

2 Photovoltaic performances of AuQD/plasmonic AuNP solar cells

The proposed device structure of the AuQD/plasmonic AuNP solar cells consists of Al/P3HT:PCBM/PEDOT:PSS:AuNP/AuQD/ITO glass substrate as shown in Fig. 1(a). AuQDs emitting fluorescence at different wavelengths, B-AuQDs, G-AuQDs, and R-AuQDs, were used to improve the properties of plasmonic AuNP-enhanced photovoltaic devices. Under the same experimental conditions, AuNPs were added into the hole-transport PEDOT:PSS layer for photon trapping, and each AuQD layer was used for UV light harvesting. The current density-voltage (*J-V*) characteristics of different AuQD/plasmonic AuNP systems in fabricated solar cells are presented in Fig. 1(b), and the important photovoltaic parameters of the devices are given in Table 1. A device with no metal nanoparticles was used as a reference cell. Specifically, AuNPs enhanced the performance due to a localized surface plasmon effect, which enhanced the optical path lengths via light scattering as well as increasing light absorption by the photoactive layer [1,5]. Moreover, a AuQD layer inserted into the OSCs increased the efficiency by absorbing light in the UV region and converting it to visible light in the cells, in which a higher photogenerated carrier density could be obtained via higher absorption of visible light by the active layer. It should be noted that the

P3HT:PCBM exhibits almost no absorption or photoelectric conversion in the UV region but exhibits absorption peak between 500 and 600 nm. We found that the AuQD/AuNP complex system presented synergistic benefits in light management of the developed OSCs. After incorporating a AuQD layer, B-AuQDs, G-AuQDs, or R-AuQDs, and/or a AuNP:PEDOT:PSS layer into the polymer solar cells, the open-circuit voltage (V_{oc}) and the fill factor (FF) were found to be similar, while the short-circuit current density (J_{sc}) increased from 2.92% to 11.1%, and the power conversion efficiency (PCE) increased from 2.47% to 13.0% in comparison with the corresponding values for the reference cell. Of the three AuQDs without added plasmonic AuNPs, incorporating G-AuQDs in the solar cell gave the best performance, with a J_{sc} of 7.33 mA/cm^2 and PCE of 3.50%.

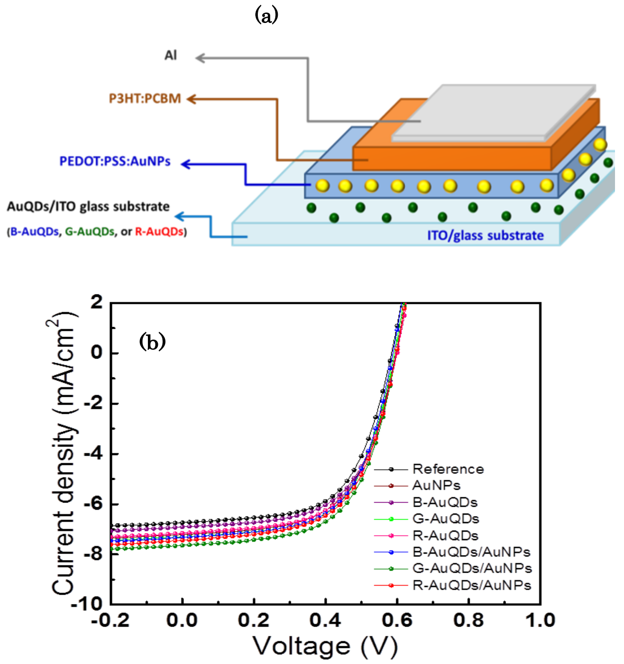

Fig. 1. (a) Schematic of the fabricated OSCs and (b) *J-V* characteristics of the OSCs compared with the reference cell.

Table 1. Photovoltaic parameters of the developed OSCs

Devices	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	PCE (%)	Enhancement (%)
Reference	6.85±0.08	0.59	0.59	3.24	-
AuNPs	7.28±0.05	0.59	0.60	3.42	5.56
B-AuQDs	7.05±0.15	0.59	0.59	3.32	2.47
G-AuQDs	7.33±0.02	0.59	0.60	3.50	8.02
R-AuQDs	7.21±0.07	0.60	0.60	3.45	6.48
B-AuQDs/AuNPs	7.20±0.11	0.59	0.60	3.44	6.17
G-AuQDs/AuNPs	7.61±0.04	0.60	0.60	3.66	13.0
R-AuQDs/AuNPs	7.38±0.05	0.60	0.60	3.54	9.26

The presence of both a G-AuQD layer and AuNPs in the PEDOT:PSS film produced the greatest increase in the J_{sc} from 6.85 to 7.61 mA/cm^2 and enhanced the PCE from 3.24% to 3.66%, followed by the R-AuQD/plasmonic AuNP and B-AuQD/plasmonic AuNP-OSCs. The latter two solar cell systems exhibited J_{sc} values of 7.38 and 7.20 mA/cm^2 and PCE values of 3.54% and 3.44%, respectively.

3. Conclusions

We designed an efficient AuQD/plasmonic AuNP system to manage light harvesting to enhance OSCs. A AuQD layer with green fluorescence emission and a AuNP:PEDOT:PSS HTL with localized plasmon excitation achieved the best light harvesting in OSCs. A G-AuQD/AuNP complex system exhibited enhanced photovoltaic performances (J_{sc} of 7.61 mA/cm^2 and a PCE of up to 3.66% (13% improvement)), compared to those of reference OSCs. AuQDs could broaden light harvesting in the UV region and emit light in the visible region, which could be absorbed in the active layer as well as inducing energy transfer to the plasmonic AuNPs, resulting in more light harvesting in OSCs. Hence, the AuQD/AuNP complex system designed for OSCs has the potential to synergistically enhance OSC performances. Our strategy for light manipulation in OSCs using AuQDs and AuNPs is promising and could be applied to the development of other types of solar cells.

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References

[1] H. A. Atwater, A. Polman, Nature Mater. **9** (2010) 205.
[2] A. Baba, N. Aoki, K. Shinbo, K. Kato, F. Kaneko, ACS Appl. Mater. Interfaces **3** (2011) 2080.
[3] S. Nootchanat, A. Pangdam, R. Ishikawa, K. Wongravee, K. Shinbo, K. Kato, F. Kaneko, S. Ekgasit, A. Baba, Nanoscale **9** (2017) 4963.
[4] T. Thepudom, C. Lertvachirapaiboon, K. Shinbo, K. Kato, F. Kaneko, T. Kerdcharoen, A. Baba, MRS Comm. **8** (2018) 107.
[5] A. Pangdam, S. Nootchanat, R. Ishikawa, K. Shinbo, K. Kato, F. Kaneko, C. Thammacharoen, S. Ekgasit, A. Baba, Phys. Chem. Chem. Phys. **18** (2016) 18500.
[6] Y.-S. Hsiao, S. Charan, F.-Y. Wu, F.-C. Chien, C.-W. Chu, P. Chen, F.-C. Chen, J. Phys. Chem. C **116** (2012) 20731.
[7] S. Nootchanat, H. Ninsonti, A. Baba, S. Ekgasit, C. Thammacharoen, K. Shinbo, K. Kato, F. Kaneko, Phys. Chem. Chem. Phys. **16** (2014) 24484.
[8] E. Stratakis, E. Kymakis, Mater. Today **16** (2013) 133.
[9] H. Kawasaki, K. Hamaguchi, I. Osaka, R. Arakawa, Adv. Funct. Mater. **21** (2011) 3508.
[10] K. G. Stamplecoskie, Y.-S. Chen, P. V. Kamat, J. Phys. Chem. C **118** (2014) 1370.
[11] A. Kogo, Y. Takahashi, N. Sakai, T. Tatsuma, Nanoscale **5** (2013) 7855.
[12] A. Pangdam, S. Nootchanat, C. Lertvachirapaiboon, R. Ishikawa, K. Shinbo, K. Kato, F. Kaneko, S. Ekgasit, A. Baba, Part. Part. Syst. Charact. **34** 2017() 1700133.
[13] K. G. Stamplecoskie, P. V. Kamat, J. Phys. Chem. Lett. **6** (2015) 1870.