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Plasmonic effect of gold nanoparticles in organic solar cells

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Abstract

Light trapping, due to the embedding of metallic nanoparticles, has been shown to be beneficial for a better photoabsorption in organic solar cells. Researchers in plasmonics and in the organic photovoltaics fields are working together to improve the absorption of sunlight and the photon–electron coupling to boost the performance of the devices.

Recent advances in the field of plasmonics for organic solar cells focus on the incorporation of gold nanoparticles. This article reviews the different methods to produce and embed gold nanoparticles into organic solar cells. In particular, concentration, size and geometry of gold nanoparticles are key factors that directly influence the light absorption in the devices. It is shown that a careful choice of size, concentration and location of gold nanoparticles in the device result in an enhancement of the power conversion efficiencies when compared to standard organic solar cell devices.

Our latest results on gold nanoparticles embedded in on organic solar cell devices are included. We demonstrate that embedded gold nanoparticles, created by depositing and annealing a gold film on transparent electrode, generate a plasmonic effect which can be exploited to increase the power conversion efficiency of a bulk heterojunction solar cell up to 10%.

Keywords: Gold nanoparticles; Organic solar cell; Surface plasmon; Bulk heterojunction

1. Introduction

Organic photovoltaics developed rapidly in the last decade due to its potential to achieve a faster, lower-cost and larger volume process to manufacture devices compared to the silicon technology (Kalowekamo and Baker, 2009; Powell et al., 2009). Specifically, the potential of printing or coating solar cells, using roll to roll machinery, makes this technology very attractive for future mass production (Kippelen and Brédas, 2009; Krebs, 2009a,b).

The power conversion efficiency (PCE) (Dennler et al., 2009), the device lifetime (Jørgensen et al., 2008) and the large scale production (Brabec and Durrant, 2008) are three problems that sill need to be solved in this technology in order to compete with the technologies already present on the market.

The PCE in organic solar cells is controlled by the absorption of light and the collection of charges at the electrodes (Schilinsky et al., 2002). Increasing the light absorption is crucial in order to increase the PCE of these devices. Due to low carrier mobilities of the conducting polymer (Street et al., 2010) and short lifetime of the excitons (Halls et al., 1996; Theander et al., 2000), the optimum thickness of the active layer is often limited to ~100 nm or less (Kirchartz et al., 2012; Min Nam et al., 2010; Namkoong et al., 2013). For larger thicknesses, the recombination of free charge carriers becomes predominant with a consequent decrease of the PCE. Lowering the thickness limits the

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absorption of all the photons with a consequent low photocurrent.

For these reasons, increasing the optical path length of the light in the device becomes crucial in order to increase the PCE. In fact, the increase by guiding the light multiple times in the active layer of the organic solar cells can increase the absorption probability in the device (Mokkapati and Catchpole, 2012). The light trapping can be achieved with structures that are similar or smaller in size to the wavelength of the light of interest and with specific materials that interact strongly with the light such as semiconductors or metals.

In particular, collective oscillation of electrons in metallic nanoparticles are generated by the light at a specific frequency leading to a strong absorption or scattering of the light as function of particle size (Catchpole et al., 2011). Metallic nanoparticles have already been used to enhance the photocurrent by 33% of thin film silicon solar cells (Pillai et al., 2007).

Recently, the usage of the metallic nanoparticles in organic photovoltaics has been exploited because they can be easily incorporated without compromising the architecture of the device.

This review article presents a summary of organic photovoltaics, a description of the physical mechanisms of light trapping in organic solar cells through metallic nanoparticles and recent results on the incorporation of gold nanoparticles in organic photovoltaics devices.

2. Organic photovoltaics

A typical organic solar cell is composed of different layers that can be organic and/or inorganic. A solar cell is defined as organic if the active absorbing layer is composed by only organic material. The most common structure of an organic solar cell consists of two electrodes (in which one of the two has to be transparent) with an active layer between them, where the generation of free charge carriers will occur. Sometimes, a buffer layer is included between each electrode and the active layer, to ensure that a charge selective transport occurs preventing charge recombination effects that reduce the performance of the device.

The generation of a photocurrent from an incident light in organic solar cells can be summarized in the following way: photon absorption in the conducting polymer; creation of an exciton (bound state of an electron and a hole which are attracted to each other by the electrostatic Coulomb force); exciton separation at the interface of the heterojunction (interface between the donor and the acceptor material). Due to the built-in electric field at the interface of the heterojunction, the electron is transferred to the acceptor material and the hole to the donor material causing the creation of a photocurrent (Krebs, 2010; Nunzi, 2002).

The excitons generated by the light typically have very short lifetimes with a recombination distance between 4 nm and 20 nm (Halls et al., 1996; Theander et al., 2000). Because of this problem, the bulk heterojunction (BHJ) solar cell (mixture of the donor and acceptor material) is the best solution in terms of performance because it provides a larger volume of interaction between the acceptor and the donor, more efficient charge separation and separate paths for the transport of free carriers (Erb et al., 2005; Li et al., 2005; Mihailetchi et al., 2005). The first kind of BHJ solar cell was originally proposed by Sariciftci et al. (1992). It was composed of on an active layer made out of a conducting polymer that was the electron donor material mixed with fullerenes derivatives that was the electron acceptor material (Umnov and Korovyanko, 2005). The active layer morphology is an important parameter to be considered for the performance of the device (Pivrikas et al., 2011; Su et al., 2012; Watkins et al., 2005).

At present, the most studied BHJ solar cells are the ones based on fullerene derivative [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) as acceptor material and conducting polymer poly(3-hexylthiophene-2,5-diyl) (P3HT) as donor material (Lee et al., 2011; Seemann et al., 2011; Tao et al., 2013). P3HT and PCBM have been commonly used as reference materials for organic solar cells because they are readily commercially available and guarantee stable devices. In the regular structure (Fig. 1a), Indium Tin Oxide (ITO) is mostly used as the transparent conducting anode, poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) is the electron blocking layer, lithium fluoride (LiF) is the hole blocking layer and aluminum (Al), is used as the cathode because of its low work function (Bindl et al., 2011; Nelson, 2011). In this device, the holes are collected at the ITO and the electrons are collected at the Al electrode. This structure can be reversed (Fig. 1b) by inserting a hole blocking layer between the ITO and the active layer in order to collect electrons at the ITO electrode and inserting an electron blocking layer on the metal electrode in order to collect holes. The metal electrode in this case is made of a high work function metal that is usually gold or silver. A typical inverted structure is composed of ITO as the cathode, zinc oxide (ZnO) as the hole blocking layer, PCBM:P3HT as the active layer, the PEDOT:PSS as the electron blocking layer and gold (Au) as the anode (Hau et al., 2010).

Currently, many stable devices based on the P3HT:PCBM mixture have a PCE of about 4% (Dang et al., 2011). Some research groups are replacing the PCBM with other fullerene derivatives, such as phenyl-C71-butyric acid methyl ester ($PC_{71}BM$), obtaining PCEs higher than 7% (Liang et al., 2010). After the discovery of the high carrier mobility, intrinsic one-dimensionality, and tuneable optical and electronic properties of carbon nanotubes (CNTs) (Zhu et al., 2009), many groups are trying to use this material in organic solar cells (Sgobba and Guldi, 2008). Some groups are trying to replace either partially (Lu et al., 2013) or completely (Ren et al., 2011) the PCBM compounds with carbon nanotubes (CNTs). In particular, they observed that when the P3HT is mixed with the CNTs, the polymer chains tend to wrap the CNTs