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Si/PEDOT:PSS hybrid solar cells incorporated with silver plasmonic nanospheres

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ABSTRACT

We study the incorporation of periodic silver nanospheres on planar hybrid Si/PEDOT:PSS solar cell for absorption enhancement based on the plasmonic effect. The impact of the periodicity and diameter of the silver nanospheres on the light absorption of the hybrid cell is systematically simulated using the finite element method. The light absorption is found to improve significantly in the presence of the silver nanospheres, achieving a maximum ultimate efficiency of 22.6% when the periodicity is 600 nm and the nanosphere diameter to periodicity ratio is 0.45. This is 23.8% higher than that of the planar hybrid thin cell without the silver nanospheres. The physics behind the enhanced light absorption in the hybrid cell arising from the introduction of periodic silver nanospheres is also discussed.

1. Introduction

During the last decade, significant research effort has been dedicated towards Si nanostructures based solar cells [1–3]. The strong trapping of light by the nanostructures can substantially increase light absorption and improve cell performance. However, such nanostructure based solar cells are costly as their fabrication at nanoscale involves complicated processes such as photolithography, high temperature thermal diffusion, reactive ion etching, etc. This has prompted research on hybrid nanostructures based solar cells in recent years, such as the SiNWs/PEDOT:PSS solar cell, which leverages on the advantages of both Si nanostructures and organic materials that include high power conversion efficiency, low temperature and low cost simple solution based processes [4–6]. Currently, the highest efficiency reported for hybrid solar cell is based on a Si nanowire structure with a cell efficiency of 13.01% [6].

The introduction of nanostructures can substantially increase light absorption and result in a higher short circuit current density. However, due to the large surface area introduced that is generally defective and promotes carriers recombination, the open circuit voltage and fill-factor are degraded, conceding the cell performance that is expected from the use of nanostructures [7]. Therefore, alternative approaches should be explored to improve the performance of hybrid solar cells without the use of Si nanostructures. We have previously demonstrated that it is possible to obtain hybrid solar cells with good performance without the use of nanostructures [8]. The cells were fabricated on planar Si substrate and have a high efficiency of 10.6%, attributed to the high open circuit voltage arising from the good Si surface quality and passivation [8]. This approach is attractive as it eliminates the need of nanostructure and substantially simplifies the fabrication process.

To further improve the efficiency of such planar hybrid cells without nanostructures for light trapping, one possible approach is to incorporate plasmonic silver (Ag) nanospheres (NS) to improve their light absorption. Incorporation of metallic plasmonic nanospheres into solar cells for light absorption enhancement has been demonstrated previously [9–11]. The sunlight can be effectively guided within the absorbing layer due to the collective oscillations of electrons at the surface of the metal nanospheres [12–14]. The improved light absorption is achieved through the following mechanisms: Firstly, when the plasmonic nanoparticles are placed at the interface between air and Si, they effectively trap the sunlight into the underlying Si material by forward scattering [15,16]. It has been demonstrated that this scattering induced light absorption enhancement has a strong dependence on the shape and size of the plasmonic nanoparticles [9,12]. Secondly, the plasmonic nanoparticles function as antennas to enhance the local field around the nanoparticles [15], and hence the incident light can be effectively trapped into this localized surface plasmon modes. This mechanism works well mainly for very small diameter nanoparticles of less than 20 nm, but is very useful for materials with short diffusion length [15]. Thirdly, by using a metallic grating at the back surface of Si, the incident light can be coupled into the surface plasmon modes induced at the interface between the Si thin film and the metal structure

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[15,17]. For sunlight with frequency close to that for plasmonic resonance, the light is effectively guided and trapped within the structure. This mechanism is critical for the long wavelength sunlight, which generally has a small light absorption coefficient in Si [18]. Although the introduction of plasmonic nanoparticles can increase light absorption, it also induces light loss due to absorption within the nanoparticles themselves [15]. Therefore, a balance must be struck with a proper design of their shape, dimension and structure. To date a number of such metal nanoparticles incorporated photovoltaic devices have been demonstrated experimentally. A 13% increment in the power conversion efficiency has been reported by incorporating monofunctional poly (ethylene glycol) (PEG)-capped gold nanoparticle into the PEDOT:PSS layer in organic solar cells [19]. The gold nanoparticle solution was added into the PEDOT:PSS and then spin coated onto the glass substrate for the formation of the organic solar cell. Kim et al. has introduced another method of depositing silver nanoparticle using the spin coating processing [20]. The silver nanoparticle solution was dropped onto the substrate followed by spinning coating. After that, a thin layer of SiO_2 was deposited on top of the silver nanoparticles to passivate the surface. Chen et al. has reported a 23% enhancement in the power conversion efficiency for thin film amorphous silicon solar cell incorporated with silver nanoparticles using a similar spin coating method [21]. A silver metal mesh film with ordered pores introduced at the back surface of Si has been reported by Wu et al. [22]. Closed packed polystyrene particles were initially deposited, followed by the deposition of silver seeds in the voids of the polystyrene particles, and the subsequent removal of the polystyrene particles [22]. It is noted that all the above mentioned approaches are low cost and simple to implement, indicating a promising future on the application of plasmonic effect in solar cell for enhanced light absorption. Todate, the incorporation of plasmonic nanospheres into Si/PEDOT:PSS hybrid solar cell has not been reported.

In this paper, we report for the first time a detailed study on the incorporation of Ag NS into planar hybrid Si/PEDOT:PSS thin film solar cells to improve the light absorption using optical simulation based on the finite element method. In contrast to most other studies in this field where the Ag nanoparticles are in direct contact with the Si material, the plasmonic scattering would be very different in the case of hybrid Si/PEDOT:PSS solar cell, due to the presence of a layer of PEDOT:PSS located between the Ag nanoparticles and the Si material. There is optical absorption in the PEDOT:PSS across certain bands of the solar spectrum. However, the optical absorption does not lead to photocurrent generation because of the short diffusion length of the carriers in the PEDOT:PSS. As a result, the optimum design for the Ag nanoparticles would be very different for the Si/PEDOT:PSS hybrid cells as compared to the conventional Si solar cells. The effects of the diameter and the structural periodicity of the Ag NS on light absorption enhancement are systematically investigated to provide a design guideline for the fabrication of high performance hybrid Si/PEDOT:PSS solar cells. It is found that light absorption is maximized at a Ag diameter of 270 nm and periodicity of 600 nm, which gives rise to the highest ultimate efficiency of 22.6%. This reflects an improvement of ~23.8% as compared with planar hybrid Si thin film cells without the Ag NS.

2. Simulation methodology

The commercial software High Frequency Structure Simulator (HFSS) based on the finite element method has been used to simulate the light absorption of Ag NS incorporated planar hybrid Si/PEDOT:PSS solar cell [23]. Fig. 1(a) shows the schematic of the thin film hybrid cell structure used in this study. The height H of the planar Si thin film is fixed at 2 μm. As we have previously demonstrated that the optimal thickness for the PEDOT:PSS layer (T) ranges from 60 nm to 80 nm, we have chosen T = 60 nm in the simulation [8]. The cell structure is optimized for light absorption by varying the diameter (D) and periodicity (P) of the Ag NS. The incident light with wavelength (λ) ranging from

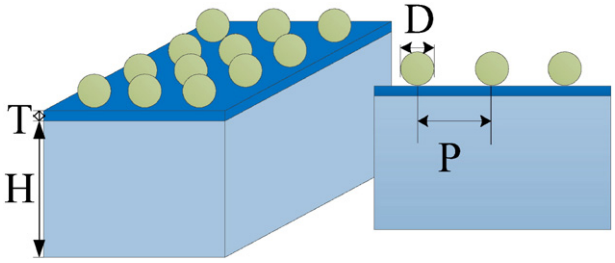

Fig. 1. Schematics of the hybrid Si/PEDOT: PSS cell structure incorporated with Ag nanospheres on the top surface.

300 nm to 1100 nm is normally incident on the surface of the hybrid Si solar cell. By solving the Maxwell's equations from the interaction between the incident light and the hybrid thin film structure, the spatial distribution of the energy flux can be obtained, from which the light reflectance (R), transmittance (T) and absorption (A) within Si, PEDOT:PSS and Ag NSs can be deduced. The optical constants of Si, Ag and PEDOT:PSS used in our simulation are taken from the literature [24,25]. To determine the optimized geometric configuration for absorption of sunlight, the ultimate efficiency (η) is calculated as follows by assuming an internal quantum efficiency of 100% [26]:

$$\eta = \frac{\int_{300}^{1130} \frac{E_g P(\lambda) A(\lambda)}{E} d\lambda}{\int_0^{\infty} P(\lambda) d\lambda}$$

In the above, E_g is the band gap of Si, E is the photon energy, λ is the incident light wavelength, $A(\lambda)$ is the absorption efficiency and $P(\lambda)$ is the spectral irradiance of the standard AM1.5G solar spectrum.

3. Results and discussion

Fig. 2 (a), (b) and (c) show the light absorption in Si (ASi), PEDOT:PSS (APEDOT:PSS) and Ag (AAg) respectively, while and Fig. 2 (d) and (e) display the overall reflectance and transmittance of the hybrid structure with a fixed D/P ratio of 0.5 and varying P from 300 to 800 nm. The corresponding results for a planar hybrid structure without Ag NS are also plotted for comparison. For the planar cell, A_{Si} is high for 300 nm < λ < 600 nm, and it reduces significantly at longer wavelengths. For the cell incorporated with Ag NS having small P of 300 nm, A_{Si} is poor over the range 300 nm < λ < 600 nm, and is even lower than the cell without Ag NS. As the Ag NS diameter of this cell is relatively small at 150 nm, therefore mainly the dipolar mode has been excited, resulting in enhanced A_{Ag} and weak induced scattering of sunlight. This can be seen from the strong A_{Ag} of 47% at the resonance frequency of ~400 nm and the larger overall reflectance in the same wavelength range. As P increases to 400 nm, there are two A_{Ag} absorption peaks at 370 nm and 450 nm, indicating that higher order modes have been excited. Hence, the light absorption within Ag NS is reduced while the scattering effect is enhanced over the range 300 nm < λ < 600 nm. Consequently, the light reflection is reduced and A_{Si} is increased compared to the structure with P = 300 nm. Nevertheless, the result is still not better than the cell without Ag NS. When P is further increased to 600 nm, the resonance frequencies for absorption in Ag NS and scattering are further separated apart, with the latter shifts towards the center of the solar spectrum, resulting in strong scattering of light for λ around 600 nm–800 nm. This is consistent with the fact that induced plasmon resonance will be broader and red-shifted as the dimension of the metal nanoparticle increases [12]. Consequently, A_{Si} is strong for 600 nm < λ < 800 nm as compared to the cell without Ag NS. It is also noted that A_{Si} for λ < ~500 nm is lower than that of the cell without Ag NS due to the absorption within