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Modeling of optimum light absorption in random plasmonic solar cell using effective medium theory

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ABSTRACT

Random plasmonic nanostructures are very suitable candidates for light trapping in thin film solar cells because of their ability of efficient transportation and localization of light in a broad spectrum. In this work, besides the introducing of a novel structure of plasmonic thin-film solar cell, in which metal nanoparticles are randomly distributed through the photoactive layer of solar cell, we are presenting a new simple calculation method which can predict the behavior of plasmonic solar cells.

To avoid the difficulty of analytical calculation and due to small size of constituents of the structure, we have used the effective medium theory to describe its optical properties. We have used a general description of effective dielectric function that can support each effective medium theory named spectral density theory, which takes into account the percolation of metal component and also interaction among inclusions. Using this method, the optimum values of nanoparticle's filling fraction for each wavelength within the active layer can be found where the solar cell can have the maximum absorption of light, thereupon the optimum external quantum efficiency.

1. Introduction

Wafer based solar cells have the potential to make a large contribution to overcome the energy crisis among the Photovoltaic systems [1]. But they are relatively expensive kind of photovoltaic energy supplying sources. A good promising way to price reduction is to use thin-film solar cells instead of conventional wafer-based cells. In such cells, thickness of the photoactive layer is in order of a few micrometers and below [2]. However, due to reduced thickness of these kind of solar cells, their light absorption is insufficient compared to wafer-based solar cells, and some light trapping mechanisms are required in order to achieve a satisfying performance. Usual light trapping methods such as surface texturing cannot be applied to thin-film cells because of increasing the surface area and hence the minority carrier recombination on the surface [3]. A promising way found recently is to use the rapidly emerging field of plasmonics and especially nanoplasmonics, to enhance the optical absorption of the photoactive layer [4].

Studies on plasmonic solar cells have been shown that their performance can be significantly improved by metallic nanoparticles deposited on top of the photoactive layers. It was shown that the enhanced performance of such cells is attributed to the improved optical absorption of thin-film photoactive layer [5–7]. This additional optical absorption is caused by scattering from the metallic nanoparticles, which intensely increases the light trapping within thin-film cells by coupling with waveguide modes of the photoactive layer [8].

Other advantage of metallic nanoparticles is their resonant nature that makes them an opportune option for solar cell applications. By tuning the plasmon resonance frequencies of the nanoparticles (that is dependent on their material, size, or distribution), one can modify spectral profiles of the absorbed power of photoactive layer. However, despite numerous attempts to enhance the solar cell performance using different nanoparticle materials, sizes, shapes, and surface coverage, there isn't still any analytical study on the optimum light trapping situation that can be achieved by adjustment of nanoparticle's distribution [9,10].

In this work we have introduced a novel structure in which metal nanoparticles are randomly distributed in photoactive layer of solar cell, i.e. a random plasmonic solar cell. Random plasmonic

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nanostructures were expected to efficiently transport and localize light by manipulating plasmonic scattering channels [11,12]. They are known to provide a broad spectrum of overlapping plasmon modes that confidently would be appropriate for solar cell applications [13].

2. Methods and materials

The analytical calculation of random metal-semiconductor nanocomposites, requires to compute the local fields inside the nanocomposite and their distortions caused by the inhomogeneities using Maxwell's equations. In the general case of a spatially random structure, it appears as a formidable task to solve analytically this problem. These difficulties have led numerous groups to study the partial differential equations for the local fields using different computational techniques [14]. However, if the size of each constituents of the structure is much smaller than the smallest optical wavelength in the host material, then the structure can be described as an effective medium [15]. Effective medium theories define an effective dielectric function for a composite material in terms of the dielectric function of its components and their geometrical arrangement. Over the last century numerous effective medium theories have been proposed. For the mixture consists of isolated and poorly interacting spherical metal inclusions embedded in a dielectric matrix, the Maxwell-Garnett and the Bruggeman expressions are most successful to explain the effective behavior of a large number of nanocomposites [16]. A more general description of the geometry-related features contained in each effective medium theory was defined in the context of the spectral density theory. This theory states that any effective dielectric function of a composite made of two components with dielectric functions ε_1 and ε_2 can be expressed as [17]:

$$\varepsilon_{eff} = \varepsilon_1 \left(1 - p \int_0^1 \frac{g(u,p)}{t-u} du\right) \tag{1}$$

where in our work, ε_1, ε_2 are the dielectric functions of the silicon and silver nanoparticles respectively. p is the filling fraction of silver nanoparticles, that is the ratio of volume occupied by silver nanoparticles to the total volume of nanocomposite, u is an integral variable, $t = \varepsilon_1/\varepsilon_1 - \varepsilon_2$ and $g(u,p)$ is the spectral density function. For the Bruggeman effective medium theory, the spectral density function reads as:

$$g_{BG}(u,p) = \frac{3p-1}{2p}\delta^+(u)\theta(3p-1) + \frac{3}{4\pi p u}\sqrt{(u-u_L)(u_R-u)}\theta(u-u_L)\theta(u_R-u), \tag{2}$$

with,

$$u_{R/L} = \frac{1}{3}\left(1 + p \pm 2\sqrt{(2p-2p^2)}\right),$$

where θ is the Heaviside step function. The first term of equation (2) describes the percolation of metal component that increases with p and is zero below the percolation threshold ($p_c = 1/3$). The second term is a continuous distribution of resonances between u_L and u_R accounts for the interaction among inclusions. The structure we have used has been showed schematically in Fig. 1. To demonstrate the suitability of presented design for high-performance solar cells, we calculated its ultimate quantum efficiency (QE), with assumption that every absorbed photon with energy larger than the electronic band gap, produces exactly one electron-hole pair. The

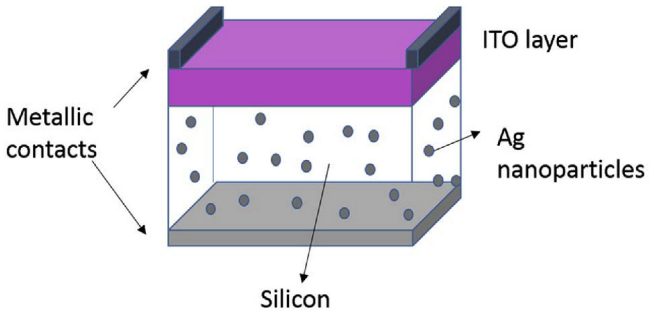

Fig. 1. Schematic structure of random plasmonic Ag-Si solar cell.

ultimate QE is calculated according to:

$$QE = \frac{\int_{\lambda_1}^{\lambda_2} \frac{\lambda}{\hbar c} A(\lambda) I_{AM1.5}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{\lambda}{\hbar c} I_{AM1.5}(\lambda) d\lambda} \tag{3}$$

where λ is the incident wavelength, $\hbar$ is Plank's constant, c is the light speed in free space, $A(\lambda)$ is the Absorbance of Silicon layer along with Ag nanoparticles and $I_{AM1.5}$ (λ) is the air mass 1.5 solar spectrum as usually adopted [18].

After calculating the effective dielectric function, it's possible to find out the absorption coefficient of system using relation (4);

$$n_{eff} = \sqrt{\varepsilon_{eff}} \quad , \quad \alpha = \frac{2n''_{eff}\omega}{c} \tag{4}$$

where, n''_{eff} is the imaginary part of effective refractive index, ω is angular frequency and c is the speed of light in vacuum. Absorbance of a light trapping system can be calculated as:

$$A(\lambda) = 4n^2_{eff}(\lambda) h \alpha(\lambda) \tag{5}$$

where h is the thickness of layer, n_{eff} is effective refractive index of nanocomposite [19].

Therefor in this method, the impacts of random metal nanoparticles entirely is applied on absorbance of the system using an effective dielectric function. In fact we have introduced an absorption coefficient for nanocomposite using the effective medium theory. So, one may introduce this absorption coefficient as an effective absorption coefficient, which involves the role of both randomly distributed Ag nanoparticles and the host medium. Absorption coefficient is related to carrier's generation rate is shown as (6)

$$G(x,\lambda) = \phi(\lambda)(1 - R_{ITO})\alpha(\lambda)e^{-\alpha(\lambda)\cdot x} \tag{6}$$

$\phi(\lambda)$ is the photon flux density and R_{ITO} is the reflectance of ITO layer and x is the position in nanometer [20].

3. Results

Fig. 2 shows the real and imaginary part of effective dielectric function of random Ag-Si nanocomposite with 400 nm thickness, as a function of wavelength and filling fraction. Dimension of the surface is 800 × 800 nm^2 and the radius of Ag nanoparticles considered 40 nm.

It can be comprehend from Fig. 2(a) that, by increasing the filling fraction, the effective dielectric function behaves as the bulk silver, as in short wavelengths, the real part of effective dielectric function