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Light absorption by a layered structure of silicon particles as applied to the solar cells: Theoretical study

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Absorption of a layered system (multilayer) consisting of monolayers of monodisperse crystalline silicon (c-Si) spherical particles is studied using the transfer matrix method. The wavelength range from 0.28 μm to 1.1 μm and the particle size range from 1 μm to 1000 μm are considered. The results for the particulate multilayer are compared with the ones for a homogeneous plane-parallel plate of the equivalent amount of silicon (equivalent plate). It is shown that at strong absorption of silicon the absorption coefficient of the plate is larger than the one of a single monolayer of particles. In the spectral range of small and middle absorption index of silicon absorption coefficient of the monolayer can exceed the one of the plate. Absorption coefficient of the system consisting of three and more monolayers exceeds the one of the equivalent plate. The integrated over the solar spectral irradiance ("Global tilt" ASTM G173-03) absorption coefficient is calculated. It is shown that the integral absorption of the particulate structure consisting of three and more monolayers of silicon particles is more than the one of the equivalent plate. Integral absorption coefficient of the four-monolayer system composed of particles with diameter of 1 μm is approximately 1.7 times larger than the one of the plate. It increases with the particles size and the number of monolayers increasing. The maximum value is close to 0.9. The scheme of the possible design of solar cell based on the particulate structure of active layer is proposed. The described method can be applied for light absorption optimization in solar cells based on silicon and other materials.

1. Introduction

The most suitable semiconductor materials for solar cells (SCs) have the values of the band gap $E_g = 1\text{–}2$ eV [1]. One of the most commonly used materials for creating solar cells is silicon due to its relatively low cost, non-toxicity, etc. Because silicon is a nondirect gap semiconductor, the probability of an electron transition from valence to conduction band due to absorbing the photon (its energy must be larger than the band gap of silicon: $h\nu > E_g$) is small. For example, attenuation of the radiation with a photon energy $h\nu = 1.5$ eV due to absorption in bulk silicon in e times occurs at thickness of 10 μm, while in the direct band gallium arsenide (GaAs) it takes place at thickness of 1 μm [1]. Therefore, to increase the absorption of light by a homogeneous silicon layer, it is necessary to increase its volume. This reduces the efficiency of solar cell based on such a layer.

One of the ways for increasing the efficiency of solar cells is reducing the optical losses at the interaction of light with a semiconductor material. To attain this end different approaches allowing to decrease reflection, increase the path length of the radiation in the structure, and, consequently, increase the light absorption are developed [1–11]. Another way is creation of the cell structure that absorbs

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light most effectively from a standpoint of photoelectromotive force (photo-emf) [11–14]. Photo-emf is caused by spatial separation of the light-generated charge carriers by the electric field of the p–n junction. Only carriers generated in the space–charge (depletion) region and adjacent areas, that are determined by the diffusion length of the minority carriers, are separated [1,11–17].

In this paper we theoretically investigate the possibility of increasing both absorption coefficient and the efficiency of light absorption in silicon solar cell by creating the active layer as a particulate (disperse) layered structure (multilayer) consisting of monolayers of spherical silicon particles with size of the diffusion length order. Such a structure can reduce the reflection and increase the path length of light in system due to scattering and multiple reflections. These lead to increase light absorption by the layer. The particles with size of the order of the diffusion length of minority carriers provide most efficient light absorption from a standpoint of the photo-emf generation.

Here we calculate the absorption, transmission, and reflection coefficients of the individual monolayer of monodisperse spherical crystalline silicon particles [18,19] and the layered system consisting of such monolayers, under normal lighting. We consider the particles in a wide range of their sizes which match the diffusion length of the minority carriers in silicon. The obtained results are compared with those for a homogeneous plane-parallel layer of the equivalent amount of silicon (equivalent plate). It is shown that particulate structure can absorb more light than the equivalent plane-parallel homogeneous plate.

2. Monolayer of spherical particles and plane-parallel plate: basic relations

Consider a monolayer of monodisperse spherical particles of crystalline silicon. Let us calculate spectra of its absorption, coherent (directional) and incoherent (diffuse) transmission and reflection coefficients.

We use the single scattering approximation (SSA) [20–22]. Absorption coefficient A_{ml} of monolayer of particles in this approximation is

$$A_{ml} = \eta Q_{abs}, \tag{1}$$

where η is the monolayer surface filling coefficient (the ratio of the area of particle projections onto the monolayer plane to the area where particles are located); absorption efficiency factor of particle

$$Q_{abs} = Q_{ext} - Q_{sc}. \tag{2}$$

Extinction Q_{ext} and scattering Q_{sc} efficiency factors of spherical particle are found by equations [21]

$$Q_{ext} = \frac{2}{x^2}\mathrm{Re}\sum_j (2j+1)(a_j+b_j), \tag{3}$$

$$Q_{sc} = \frac{2}{x^2}\sum_j (2j+1)(|a_j|^2+|b_j|^2). \tag{4}$$

Here $x=\pi D/\lambda$ is the size parameter of particles with diameter of D, λ is the wavelength of the incident light, a_j and b_j are the Mie coefficients [21,22].

Equations for the coherent transmission T_c and reflection R_c coefficients of monolayer in the SSA can be written in the form [22]

$$T_c = |t_c|^2 = \left|1 - \frac{\eta}{x^2}\sum_j (2j+1)(a_j+b_j)\right|^2, \tag{5}$$

$$R_c = |r_c|^2 = \left|-\frac{\eta}{x^2}\sum_j (-1)^j(2j+1)(a_j-b_j)\right|^2, \tag{6}$$

where t_c and r_c are the amplitude coherent transmission and reflection coefficients. To calculate the incoherent components of light transmitted T_{inc} and reflected R_{inc} by a monolayer we can write the following equations:

$$T_{inc} = (1 - T_c - R_c - A_{ml})F_{fs}, \tag{7}$$

$$R_{inc} = (1 - T_c - R_c - A_{ml})F_{bs}. \tag{8}$$

Here functions F_{fs} and F_{bs} determine parts of light scattered in the forward and backward hemispheres, respectively:

$$F_{fs} = \frac{\int_0^{\pi/2} i(\theta)\sin\theta\, d\theta}{\int_0^{\pi} i(\theta)\sin\theta\, d\theta}, \tag{9}$$

$$F_{bs} = \frac{\int_{\pi/2}^{\pi} i(\theta)\sin\theta\, d\theta}{\int_0^{\pi} i(\theta)\sin\theta\, d\theta}, \tag{10}$$

where $i(\theta)=[i_1(\theta)+i_2(\theta)]/2$, θ is the polar scattering angle, $i_1(\theta)$ and $i_2(\theta)$ are the dimensionless Mie intensities [21]:

$$i_1(\theta) = \left|\sum_j \frac{(2j+1)}{j(j+1)}(a_j\tau_j(\cos\theta) + b_j\pi_j(\cos\theta))\right|^2, \tag{11}$$

$$i_2(\theta) = \left|\sum_j \frac{(2j+1)}{j(j+1)}(a_j\pi_j(\cos\theta) + b_j\tau_j(\cos\theta))\right|^2. \tag{12}$$

Angular functions $\pi_j(\cos\theta)$ and $\tau_j(\cos\theta)$ are

$$\pi_j(\cos\theta) = \frac{P_j^{(1)}(\cos\theta)}{\sin\theta}, \tag{13}$$

$$\tau_j(\cos\theta) = \frac{dP_j^{(1)}(\cos\theta)}{d\theta}, \tag{14}$$

where $P_j^{(1)}(\cos\theta)$ are the associated Legendre functions.

Absorption coefficient of the homogeneous plane-parallel plate A_{pl} is calculated by equation

$$A_{pl} = 1 - T_{pl} - R_{pl}, \tag{15}$$

where T_{pl} and R_{pl} are transmission and reflection coefficients of the plate.

Taking into account the multiple-beam interference we can write the equations for the transmission T_{pl} and reflection R_{pl} coefficients of a thin plate for the normal illumination as follows:

$$T_{pl} = |t_{pl}|^2 = \left|\frac{t_{01}t_{12}e^{ikh}}{1 - r_{12}r_{10}e^{2ikh}}\right|^2, \tag{16}$$

$$R_{pl} = |r_{pl}|^2 = \left|r_{01} + \frac{t_{01}t_{10}r_{12}e^{2ikh}}{1 - r_{12}r_{10}e^{2ikh}}\right|^2. \tag{17}$$

Here t_{pl} and r_{pl} are the amplitude transmission and reflection coefficients of the plate, t_{01}, t_{10} and r_{01}, r_{10} are