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Enhanced light absorption of silicon solar cells with dielectric nanostructured back reflector

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ABSTRACT

This paper investigates the light absorption property of nanostructured dielectric reflectors in silicon thin film solar cells using numerical simulation. Flat thin film solar cell with ZnO nanostructured back reflector can produce comparable photocurrent to the control model with Ag nanostructured back reflector. Furthermore, when it is integrated with nano-pillar surface decoration, a photocurrent density of 29.5 mA/cm^2 can be achieved, demonstrating a photocurrent enhancement of 5% as compared to the model with Ag nanostructured back reflector.

1. Introduction

Nanostructured silicon solar cells have recently attracted great interest. Nanostructures can be decorated on both the top and rear surface of the solar cells [1–3]. There has been considerable experimental evidence that nanostructured surface which serves as anti-reflection layer and light trapping scheme can increase the photocurrent of thin film solar cells [4–8]. Nanostructured metal reflector, which is sputtered onto its back side of the device, serves both as a back reflector and a contact electrode [9–11]. The incident photons with short wavelength are nearly fully absorbed by the semiconductor substrate, while the photons with long wavelength penetrate through the semiconductor layer and interact with the rear metal nanostructures [12]. The oscillating electromagnetic field of the light excites coherent collective oscillations of the electron gas density at surfaces of metal nanostructures [13]. The resonances of these coherent collective oscillations are called localized surface plasmon polaritons (LSPP). The non-radiative decay of LSPP causes absorption of incident light, leading to optical losses, while the radiative decay of LSPP causes the scattering of incident light into the embedded dielectric layers at high scattering angles, resulting in increased optical path of light in semiconductor layer and therefore improved photoelectron generation [14]. The LSPP is very sensitive to the properties of the nanostructures (shape, size and material type) as well as the surrounding dielectric medium. Hence, nanostructure design is crucial to the performances of solar cells. Plenty of research has been carried out on metal nanostructured back reflector for silicon [15–18], CIGS [19], and organic solar cells [20]. However, improved light trapping of thin films due to scattering is not limited to metal nanostructures, and such enhancement can also be achieved with dielectric nanostructures, on which less work has been undertaken. Since such dielectrics exhibit very low absorption at visible spectrum, the use of dielectric structures in solar cells can achieve efficient light trapping with minimized parasitic absorption loss. Hence, lossless dielectric structures provide great potential for improving the performance of the solar cells.

In this paper, we investigate the absorption enhancement behavior of dielectric and metallic nanostructured reflector for solar cell application. Numerical analysis of the optical response is carried out using the FDTD method. According to our simulation, the model with ZnO nanostructured back reflector can achieve comparable photocurrent density to the model with Ag nanostructured back reflector. In particular, with nanopillar surface decoration, a photocurrent enhancement of 5% is achieved as compared to the model with Ag nanostructured back reflector.

2. Solar cell structure and modeling method

In this study, we investigated the influence of dielectric and metallic nanostructures on light trapping in silicon thin film solar cells. Fig. 1(a) depicts the geometry of solar cell model under investigation, in which Al doped ZnO (ZnO:Al) hemisphere nanostructures were embedded in silicon substrate with underlying Ag back reflector (ZnO-NS). ZnO:Al is a transparent conducting material widely used in photovoltaic device for its good electrical and optical properties. ZnO:Al have a high electrical conductivity thus can be incorporated with silver back mirror as electrode. Meanwhile, ZnO:Al is almost transparent among entire

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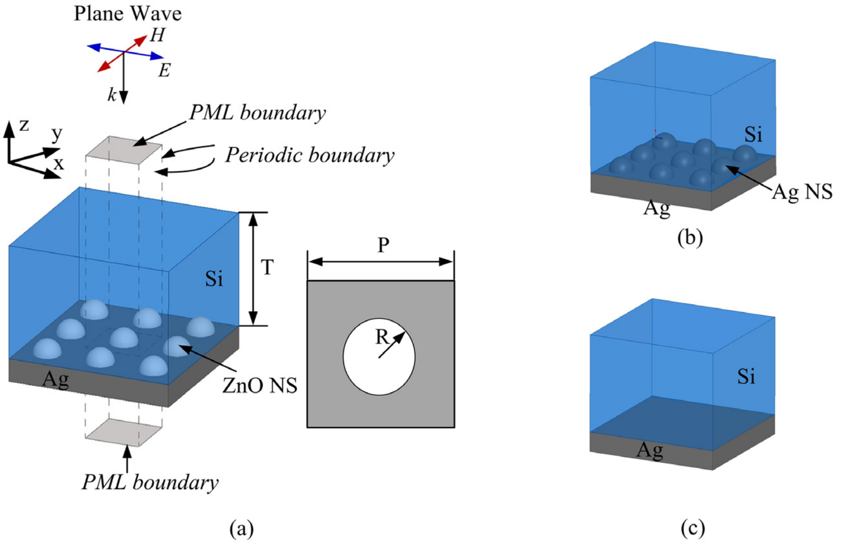

Fig. 1. Schematic illustration of geometries used in the simulation: (a) ZnO nanostructures embedded in silicon film integrated with underlying Ag back reflector, (b) silicon film with Ag nanostructured back reflector, (c) silicon film with planar back reflector.

solar spectrum, which ensures minimal optical losses in it. The nano-hemisphere is periodically arranged on silver film. The radius (R) and period (P) of the nano-hemisphere are 100 nm and 400 nm, respectively. The thickness of the top silicon substrate is 1 μm. For comparison, we also consider silicon film with Ag nanostructured back reflector (Ag-NS) and silicon film with planar back reflector (Planar), which are shown in Fig. 1(b) and (c) respectively. The interaction of light with nanostructured back reflectors were studied via numerical simulations based on finite-difference time-domain method (FDTD) in the wavelength range from 300 nm to 1100 nm, covering the major solar spectrum of interest. The FDTD simulation region is shown by the dotted line in Fig. 1(a). Periodic boundary conditions were implemented in x, y directions and perfectly matched layer (PML) boundary conditions were imposed in the z direction. Spectral responses of absorption, reflection and transmission are calculated under normal incidence. The optical constants of Ag and Si are taken from experimental data in literature [21]. Since the optical constant of ZnO:Al varies little within the wavelength region we are interested [22], the real part of the refractive index is set to 1.4. The absorption in ZnO:Al is neglected by setting the imaginary part of the refractive index to zero.

The spectral responses of reflection (R) and transmission (T) of solar cell model can be obtained by solving the Maxwell equations. The total absorption is then be evaluated via:

$$A(\lambda) = 1 - R(\lambda) - T(\lambda), \tag{1}$$

$A(\lambda)$ consists of two parts: absorption in the active layer of silicon and the absorption in Ag. Only the former will conduct to the photocurrent , while the latter causes parasitic loss. Therefore, we need to calculate the light absorption in each layer, which can be obtained from the space electric-field distribution by:

$$A(\lambda) = \frac{1}{2P_{in}(\lambda)} \int_V \omega(\lambda) |E(\lambda)|^2 \varepsilon''(\lambda) dV, \tag{2}$$

where λ is wavelength, $\omega(\lambda)$ the angular frequency of incident light, $\varepsilon''(\lambda)$ the imaginary part of the permittivity, $E(\lambda)$ the electric-field and $P_{in}(\lambda)$ is the total incident power

3. Results and discussion

Fig. 2 shows the simulated absolute electric-field distribution of the geometry for incident light of 700 nm, 800 nm and 900 nm. For the model with Ag-NS (second row), enhanced electric-field in silicon is observed compared with the control planar solar cell (first row). Meanwhile, high electric-field occurs in the vicinity of the Ag nanostructures, indicating increased light absorption in Ag. As for the model with ZnO-NS (third row), enhanced electric-field is also observed near the Si–ZnO interface. Unlike Ag, the extinction coefficient of ZnO:Al is quite small. Hence, the parasitic loss in ZnO-NS is negligible, resulting in stronger electric-field in top silicon substrate.

Fig. 3(a)–(c) illustrate the simulated reflection, absorption in silicon and absorption loss in Ag of three models. In the wavelength range between 300 nm and 460 nm, incident photons are mainly absorbed in the top Si layer during a single path. The optical responses in this wavelength range rely on the light coupling at the front interface, which are identical for the three models. In longer wavelength region, absorption in Si is significantly increased for the model with Ag-NS and ZnO-NS, which is mainly attributed to scattering induced light trapping of the nanostructures. As depicted in Fig. 3(c), Ag-NS result in large parasitic absorption in the back reflector, which will not contribute to the photocurrent. This portion of absorbed photons is clearly decreased in the model of ZnO-NS.

To give a quantitative analysis of light absorption capability of each model, the short circuit current density (J_{SC}) is calculated under the standard solar spectrum AM 1.5G using Eq. (1) [23]:

$$Jsc = \frac{q}{hc} \int_0^{\lambda g} \lambda \times I(\lambda) \times A(\lambda) d\lambda, \tag{3}$$

where q is the electric charge carried by a single electron, h is the Planck constant, c is velocity of light in a vacuum, $I(\lambda)$ is the solar energy density spectrum at AM 1.5G, $A(\lambda)$ is the absorption spectrum in each layer, and λ_g is the wavelength corresponding to the band gap of silicon. Eq. (3) assumes that each absorbed photon with energy higher than the band gap of silicon will generate one electron–hole pair. All the photogenerated carriers will be collected and give a contribution to the photocurrent without considering the recombination process.

The calculated optical absorption in silicon along with the reflection loss and optical loss in Ag are shown in Fig. 3(d). Numerical simulations show that the models with nanostructured back reflectors (Ag-NS and ZnO-NS) have higher J_{SC} as compared to the planar control model. For the model with ZnO-NS, absorption loss in back reflector is greatly reduced. Despite increased light reflection loss, the model with ZnO-NS can achieve comparable photocurrent density as compared to the model with Ag-NS. It is expected that better enhancement behavior could be realized for the model with ZnO-NS if the reflection loss can be suppressed.