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Full-spectrum photon management of solar cell structures for photovoltaic–thermoelectric hybrid systems

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ABSTRACT

In this paper, a novel ultra-broadband photon management structure is proposed for crystalline silicon thin-film solar cells used in the photovoltaic–thermoelectric hybrid system. Nanostructures are employed on both front and back side. Optical behavior of the structure in ultra-broadband (300–2500 nm) are investigated through the Finite Difference Time Domain method. By combing moth-eye and inverted-parabolic surface, a new composite surface structure is proposed for anti-reflection in the ultra-broadband wavelengths. Front metallic nanoparticles, plasmonic back reflector and metallic gratings are studied for light-trapping and the effect of plasmonic back reflector is validated by the experimental data of the external quantum efficiency. The effects of incident angle are discussed for metallic gratings. Numerical computation shows that the incorporation of anti-reflection and light-trapping can obtain high absorption in the solar cell and ensure the rest incident light transmits to the thermoelectric generator efficiently. This work shows potential full-spectrum utilization of solar energy for various photovoltaic devices related with hybrid photovoltaic–thermoelectric systems.

1. Introduction

Crystalline silicon (c-Si) thin-film solar cells have been widely studied because of their lost cost in materials. However, as the band gap of the thin-film silicon limit the incident light absorbed in PV cells, the typical c-Si thin film solar cells only absorb incident light in 300–1100 nm. Lots of incident solar energy (1100–2500 nm) is wasted. Hence, photovoltaic (PV)–thermoelectric (TE) system was proposed [1], which combines a c-Si thin film solar cells and a TE generator into a hybrid device [2]. The hybrid device has potential to utilize solar energy in the full spectrum of AM1.5G. Recently the proposed novel system is to set the TE generator on the back side of silicon. Therefore, a remarkable low reflection must be obtained in the full spectrum [3]. This indicates the absorption in solar cell must be high enough in the solar usable range. In the meantime the TE generator converts solar cell heat and the residual sunlight transmitted through the solar cell into electricity. In this way, photon management of a wide wavelength range (300–2500 nm) is required for the solar cell to lead to a higher energy conversion efficiency.

Over recent years, two promising concepts, anti-reflection and light-trapping, have been proposed in various thin-film PV devices according to light management concept. Coatings are commonly used for anti-reflection. Zhou et al. [4] demonstrated a hemi-spherical structure as an antireflection coating with almost zero omnidirectional reflection. De Vos et al. [5] advised that the use of anti-reflection coatings should take consideration of the emission loss. Textured surfaces, such as nanowires, nanopillars, nanocones, and bioinspired structures, are also widely applied to solar cells. Basically, these textured surfaces could provide a smoothed refractive index matching in order to suppress reflection [6]. Al-Douri et al. [7] found that the transmittance of nanostructured CdS deposited on a quartz substrate was higher than that of the layer deposited on the glass substrate. Besides antireflection, scattering effects of nanowire and nanopillar arrays could result in enhanced absorption in the substrate [8]. Spinelli and Polman [9] studied patterned nanocylinder gratings on the top side and found that the light absorption was enhanced over a broadband wavelength range due to the Mie resonances among the nanocylinders [9]. Being apart from nanostructures on the front surface of the active layer, Wang et al. [10] introduced a double-side nanocone structure for antireflection and light trapping. Textured transparent conductive oxide also resulted in significant efficiency enhancement [11].

Metallic nanostructures, which are known to support localized surface plasmons (SPPs), are employed as plasmonic light-trapping in solar cells. This effect results in an enhanced

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Nomenclature

n_{air}	refractive index of air	P_{abs}	energy absorbed in silicon
n_{Si}	refractive index of c-Si	R	radius of the front metallic nanoparticles, nm
h	height of the nanostructures, μm	A	frequency of incident waves
n_e	effective refractive index of the nanostructures	E	electric field, V/m
n_c	refractive index of the active layer	H	magnetic field, A/m
e	electron charge, 1.62×10^{-19} C	ε''	imaginary part of the permittivity, F/m
f	ratio of silicon in one period	μ''	imaginary part of the permeability, F/m
R_1	bottom radius of the moth-eye, μm	D	bottom diameter of the hemi-ellipsoid back reflector, nm
R_2	top radius of the inverted parabolic, μm	Λ	grating period, nm
J_{sc}	short circuit current, mA/cm^2	λ_{lmn}	absorption peak wavelength of microcavities, nm
λ_0	wavelength corresponding to the band gap of silicon, nm	l, m, n	integers
α	absorption	L_x, L_y, L_z	length, width, height of the metallic gratings, nm
F	spectral energy density at AM 1.5G incident light, W/m^2		

electric field around and inside the metallic structures [12]. The metallic nanoparticles are the most common tricks for plasmonic light-trapping. The intensity of the near-filed around these nanoparticles is highly sensitive to the particle size [13]. The wavelength range in which nanoparticles will be useful can be tuned by selecting different materials of nanoparticles [14]. Other metallic structures, such as bottom metallic gratings, can lead to SPP resonances and waveguide coupling to enhance absorption [15]. However, most studies only consider optical properties only in 300–1100 nm. As part of the hybrid system, high absorption in silicon in the range of 300–1100 nm must be obtained and, in the meantime, the rest incident light in 1100–2500 nm must transmit to TE through photon management.

Herein, in this research, the combination of anti-reflection and light-trapping is proposed for photon management in full spectrum (300–2500 nm) for the application in PV–TE system. The spectral characteristics are calculated by the Finite Difference Time Domain method. Composite surface structure consisted of moth-eye and inverted-parabolic is studied for ultra-broadband anti-reflection. Multilayer films on the bottom of silicon is to obtain high transmission in 1100–2500 nm. Front metallic nanoparticles, plasmonic back reflector and metallic gratings are used for light-trapping. From the numerical results, excellent photon management is obtained in the ultra-broadband wavelengths omni-directionally with nanostructures on both front and back side of silicon.

2. Simulation model and method

2.1. Simulation model

By following the biomimetic principle, the moth-eye morphology is used as the basic building element because it bears some unique broadband optical properties. Thus moth-eye and inverted-parabolic arrays are employed on the top surface for anti-reflection. Fig. 1 illustrates the basic schematic of the cell structure. The top textured surface consists of moth-eye of height 0.5 μm and inverted-parabolic of height 0.5 μm. Their base radiuses are tangent on the interface between air and silicon. A significant increase in Fresnel reflection caused by the large refractive index difference from air to silicon can be suppressed. The period is set as 0.5 μm and the thickness of silicon is fixed as 2 μm. In order to achieve high transmittance in near-infrared range, patterned anti-reflection coatings consisted of ITO (indium tin oxide)/ZrO_2 /MgO /SiO_2 are incorporated onto the bottom side, as shown in Fig. 1(c). The thickness of each film is 10 nm, 100 nm, 100 nm, 50 nm respectively. The patterned surface can eliminate part of the total reflection on plan surface to enhance transmission in 1100–2500 nm further.

2.2. Simulation method

Fig. 2(a) gives the top view of the structure. A simplified structure is given along the view of the blue arrow as shown in Fig. 2(b). Here the period is set to be equal to 0.5 μm. Height $h = 0$ corresponds to the interface of the maximum radius of moth-eye and inverted-parabolic. R_1 and R_2 represent the maximum radius of inverted-parabolic and moth-eye respectively. According to effective medium theory, the composite surface structure can be regarded as thin films with graded effective index, and the effective refractive $n_e(f)$ is calculated from the following simplified formula [16]

$$n_e(f) = fn_c + (1 - f) \quad (1)$$

where n_c is the refractive index of the calculated material, f is the ratio of the material in one period.

Fig. 2(c) illustrates the effective refractive index of composite surface with the change of height from Eq. (1). The black solid line indicates an ideal linear profile of refractive index. Radius R_1 varies from 0.125 μm to 0.2 μm. There is a step change of graded effective refractive index when $H = 0$. Here $R_1 = 0.1785$ μm and $R_2 = 0.175$ μm are chosen for the numerical simulation. In the parameters, the profile is the closest to the linear profile.

The Finite Difference Time Domain method is employed by solving a full set of 3D Maxwell equations for the incident plane waves to calculate the optical properties. The wavelength range of the normal incident light investigated varies in the ultra-broadband range 300–2500 nm. The refractive index for metallic nanostructures are obtained from the literature [17], and crystalline silicon from the literature [18]. Simulations are performed by using periodic boundary conditions for the square arrays. The mesh grid is set at 5 nm in the entire simulation volume. The reflectivity and transmissivity spectra are calculated with two frequency-domain transmission monitors above plane wave source and beneath the SiO_2 layer respectively [19].

2.3. Simulation validation

The RCWA-simulated results [4] and the experimental data [20] respectively are used to validate the FDTD-based numerical