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Study on the photoelectric conversion efficiency of solar cells with light trapping arrays

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ABSTRACT

In this paper, we have analyzed the antireflection, diffraction order, distribution of light field energy density and the photoelectric conversion efficiency of thin film solar cell with the silicon square nanoconical hole (SiSNH) decorated on its surface under different polarization modes and different top diameters (D_{top}). The results show that when the incident azimuthal angle (φ) of the transverse electric (TE) polarization takes the value of 30°, an ultimate efficiency of thin film solar cells with optimized SiSNH array is up to 42.83%, which is 3.09 times of the 2.33 μm thick film solar cell. The results also show that the enhanced ultimate efficiency of the thin film solar cell with SiSNH array is insensitive to D_{top} and incident light zenith (θ) angle.

1. Introduction

With regard to the design and the optical trapping performance of the light trapping structure, there are a lot of reports about light trapping array based on nanowire and nanohole [1–5]. In 2007, Chen et al. [6] analyzed the optical absorption performance of light trapping array influenced by the length, diameter and the filling factor of the silicon nanowire structure, and compared with the silicon thin film by means of the transfer matrix method (TMM). Studies indicate that compared to reflection value of silicon thin films, the periodic silicon nanowire light trapping arrays with the suitable filling rate have lower reflection value. In the high energy region, compared with the absorption of the silicon thin film with the corresponding thickness, the periodic silicon nanowire light trapping arrays have higher absorption value. But in the low energy region, the periodic silicon nanowire light trapping arrays have lower absorption value, however, the absorption value of it could be close to that of the silicon thin film by adjusting the filling rate. In 2009, Lin and Povinelli further studied the optical properties of silicon nanowire light trapping arrays by using TMM [7]. The results show that in the low energy region, compared with the absorption spectra of silicon nanowire light trapping arrays with a period of 100 nm, the enhanced absorption peak of silicon nanowire light trapping arrays with a period of 500 nm is derived from the guided wave resonance mode. In the high

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energy region, compared with the absorption value of 2.33 μm thick silicon film, the absorption enhancement of the silicon nanowires optical trapping array is due to the effective combination between the low reflection of the optical trapping array and the higher absorption value of the silicon material. The highest photoelectric conversion efficiency of 2.33 m thick silicon thin film is 13.83%. With the increase of the period, the maximum conversion efficiency of silicon nanowires optical trapping array is increase constantly. In addition, Under appropriate filling ratio and periodic condition, the highest conversion efficiency of silicon thin film cell decorated with silicon nanowires optical trapping array is higher than the highest conversion efficiency of silicon thin film cell with antireflective layer. Later, Yu and his colleagues [8] found that the optical trapping performance of silicon nanohole arrays with the same thickness and the optimized structure parameters is better than that of the silicon nanowire arrays, and have a higher conversion efficiency.

The above-mentioned research results indicated that silicon nanowire and nanohole arrays have better optical trapping properties compared with the optical properties of silicon thin films, so it has great potential application value in silicon solar cells.

Based on the above research background, we have studied the antireflection, diffraction order, distribution of optical field energy density and the photoelectric conversion efficiency of thin film solar cell decorated with the silicon square nanoconical hole (SiSNH) array under different polarization modes and different top diameters (D_{top}).

2. Method and modeling

The Rigorous Coupled Wave Analysis (RCWA) based on Modal Transmission Line (MTL) theory and Finite Difference Time Domain (FDTD) method are employed to analyze the coupling effect and distribution of light field energy density between incident light and the antireflection optical trapping structure (shown in Fig. 1). Our previous study based on RCWA and FDTD has been reported [9–11]. In order to let reflected light escape from interaction zone, the periodic boundary conditions were adopted in x and y direction, a perfectly matched layer boundary condition was used in the z direction. We first calculated the reflection and transmission coefficient, and then calculated the absorption coefficient according to $A = 1 - R - T$. The direction of the incident light is determined by the azimuthal (φ) and zenith (θ) angles. In the following calculation, both φ and θ angle are set to be zero unless otherwise stated, the polarization direction parallels to the x axis (wave of TE polarization mode, that is to say p wave). Therefore, the incident light is perpendicularly projected onto the silicon thin film surface with the photon energy varied from 1.1 to 4.0 eV, covering the major solar spectrum in interest.

3. Results and discussion

The schematic drawing of the silicon-based thin film solar cell textured by SiSNH array, and the parameters of the array structure, such as period P, D_{top}, bottom diameter (D_{bot}), the hole depth of SiSNH array (L) and the film thickness of SiSNH array (T), are shown in Fig. 1(a)–(c). T, L, D_{bot} and D_{top} (equal to P) are set to be 800 nm, 3000 nm, 200 nm and 700 nm respectively in the z direction. The refractive coefficient (n) and the absorption coefficient (k) used in the calculation refer to the crystalline silicon [12]. According to Fresnel theory, the continuous change of the effective refractive index between air and the underlying silicon thin film is essential for optical antireflection. Thus the study is performed under the condition that D_{bot} of SiSNH arrays is set to be the array period, i.e., $D_{bot} = P$. In order to understand the absorption trend of SiSNH arrays on the surface of the silicon thin film solar cells, Fig. 2 displays the absorption, reflection, transmission spectra and the distribution of diffraction order of three above-mentioned structures, with different $D_{top} = P$ (300, 700 and 1000 nm), respectively, under the normal incidence condition of TE light wave.

Note that the absorption spectra of the researched structure with D_{bot} (200 nm) owns Fabry–Perot-type resonances as that of the 2.33 μm thick silicon thin film in the low energy region of 1.5–2.4 eV, while in the high energy region the absorption is significantly enhanced. This is attributed to the enhancement peak of irregular cavity resonance and the guided mode resonance [13].

For periodic structures, the enhancement peak of cavity-resonances and guided resonances stem from the coupling of incident light to a superposition of modes propagating in the plane of the arrays and strong Fabry–Perot resonances between the top and bottom interfaces [13]. For $D_{bot} = 200$ nm, antireflection on the front surface of array dominates the absorption enhancement behavior in the high energy region due to the stronger absorption coefficients of the array and the graded refractive index between air and silicon thin film. In the low energy region, the absorption peaks degrade due to the high reflection loss and mode leakage, and thus lead to high-order diffraction cut-off, which are the main reason of its lower absorption enhancement and the lower ultimate conversion efficiency. Due to the good antireflection performance, cavity-resonances and guide-resonances excitation in the absorption spectra over broadband and broad height range, higher ultimate efficiency with 41.61% is achieved in $D_{top} = P = 700$ nm [9].

SiSNH arrays as a typical diffraction grating, it should satisfy two-dimensional diffraction equations, as shown in Eqs. (1) and (2). Moreover, according to the Snell refraction law, the total internal reflection will happen if the incident angle of light from silicon incident at the silicon-air boundary is larger than the critical angle. The critical angle should satisfy Eq. (3) as shown in the following expression:

$$n_i \sin\theta_{mn} \cos\varphi_{mn} = n_0 \sin\theta \cos\varphi + m\lambda/P_x \quad (1)$$