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Efficiency enhancement in ultrathin crystalline silicon solar cells with composite surface gratings

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A B S T R A C T

We investigate the light absorption in an ultrathin crystalline silicon solar cell with composite grating structures using three dimensional rigorous coupled wave analysis. Comparing with conventional surface gratings, the composite grating which is a superposition of two subgratings with different length scales demonstrates efficient light trapping in thin film solar cells in a broad spectral range. The light absorption is found to be close to the Yablonovitch limit in both visual and infrared regions. The optimized structure yields an ideal photocurrent density of 33.9 mA/cm^2 at an equivalent thickness of 2 µm. This is comparable to the performance of the recently proposed double-sided grating design (Wang et al., 2012 [19]). These results suggest that the composite grating structures promise efficiency enhancement in ultrathin solar cells with improved technology compatibility.

1. Introduction

Solar cells can convert sunlight into clean electric power and provide virtually unlimited energy to the world. Along with the development of crystalline silicon solar cells, reducing the silicon wafer thickness has become an important factor in reducing its costs [1]. As the thickness of state-of-the-art silicon solar cells is more than 150 µm, an ultra-thin solar cell can reduce its consumption of purified crystalline silicon by decreasing its thickness to less than 10 µm. Other than this improvement of cost efficiency, an ultra-thin solar cell benefits from several advantages such as the efficient carrier collection and high flexibility.

The performance of solar cells has its root in the optical design. An ultrathin solar cell suffers from poor light absorption due to its short optical path length, especially for photons at long wavelengths. In conventional thick solar cells, strategies such as anti-reflecting coating, random or periodic textures, have been widely applied in the solar cell industry to improve its light trapping and absorption. However, these measures can not be directly applied for ultra-thin devices due to its small length scale. It is thus of great significance for achieving enhanced light trapping for optical absorption over a broadband for ultrathin solar cells [2,3].

The designs for that goal include diffraction gratings, photonic crystals and surface plasmonics of metallic gratings [4–9]. Various nanostructures made of silicon, such as nanosphere, nanowire, nanopillar, nanocone and nanopyramid are considered as promising building blocks to improve the light absorption [10–16]. The geometry of the nanostructures was optimized for lower reflectivity and enhanced absorption in the active layer. Most studies so far have focused on surface grating structures with periodic arrangement of the building blocks. However, for a given nanostructure, the enhancement of optical absorption varies drastically in a wide wavelength range over the usable solar spectrum. Recent experiments show that an inverted pyramid grating can lead to an enhanced short-circuit current density of 25.3 mA/cm^2 for silicon solar cells with an equivalent thickness of 3 µm, while the short-circuit current is 18.3 mA/cm^2 for the planar counterparts without the gratings [17]. However, the light absorption of thin film crystalline silicon solar cells remains much lower than the conventional solar cells. For reference, the best reported silicon solar cell of arbitrary thickness has a short-circuit current of 42.7 mA/cm^2 [18].

Other than the conventional front nanostructures, recent optical simulations of thin-film solar cells show that the addition of nanostructures at the back side can play an important role in improving its broadband absorption [19–23]. Wang et al. [19] proposed a double-sided grating design where the front and back surface gratings are optimized, respectively, for the goals of antireflection and light trapping. By separately adjusting the geometry parameters of the two gratings, the absorptance curve is close to the Yablonovitch limit for wavelengths from 300 nm to 1100 nm. For realistic material para-

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meters, the authors reported an ideal photocurrent of 33.86 mA/cm^2 (Fig. 4 in Ref. [19]) for a solar cell with an equivalent thickness of 2 µm. Analysis shows that it is important that the two gratings on the front and back sides have different periods to achieve an improved absorption over a broadband. Alshal et al. [20] simulated an asymmetric double-sided pyramid grating design on 2 µm thick silicon. As the periods of the two gratings are identical, the optimized photocurrent density is estimated to be 27.73 mA/cm^2, less efficient than the design proposed in Ref. [19]. To date, experiments of double-side grating structures are mostly reported for solar cells of relative large thickness. For example, Zhou et al. [24] fabricated inverted nanopyramids on the two sides of a silicon film with the thickness of 20 µm. The photocurrent density is estimated to be 76% higher than that of a planar silicon film. Although the double-sided grating design can improve the performance of solar cells [23], it brings about technique challenges for ultra-thin film devices in practical applications. In addition, the patterned back surface may bring parasitic effect which may cause enhanced surface recombination rates [21]. To reduce these difficulties, it would be desirable to achieve high absorption over the broadband without a back grating in ultrathin solar cells.

The motivation of the present study is thus to achieve an enhanced optical absorption over a wide wavelength range with one top surface grating. For that purpose, we propose a composite grating structure which is a superposition of two subgratings with different length scales to improve the performance of an ultrathin solar cell. Comparing to the double-sided grating design, this composite grating structure is more technology-friendly from the practical point of view. The optical response of the device is investigated by the three-dimensional rigorous coupled wave analysis (RCWA) [25,26] with realistic material parameters. Our numerical results demonstrate efficient light trapping in ultrathin film solar cells over a broad spectral range. The light absorption curve is close to the Yablonovitch limit in the visual and infrared regions. Our optimized structure yields an ideal photocurrent density of 33.9 mA/cm^2 at an equivalent thickness of 2 µm. These results show that the composite grating structure is an efficient yet feasible design for high performance ultrathin solar cells.

The paper is organized as following. In Section 2, we briefly introduce the model device and the simulation method. Then, the device parameters are optimized and the corresponding numerical results are presented in Section 3. Discussions on the main findings are also included. Finally, a brief summary is given in Section 4.

2. Model and method

We use silicon nanopyramids as the basic building blocks for the surface grating due to its unique light trapping ability and compatibility with silicon processing technologies [27,28]. Different from previous studies where identical pyramids are periodically arranged in forming the grating, we propose a composite grating structure where the building block is a superposition of two nanopyramids with different length scales. The composite grating is on the top of an ultrathin crystal silicon film. A silver mirror is deposited on the back surface to reduce the transmission losses. A schematic plot of the device is presented in Fig. 1. Following Ref. [19], we define the equivalent thickness of the device as the thickness of featureless thin film which has the same amount of silicon with the device. For the sake of better comparison, without other statement, we vary the geometry parameters of device while keeping the equivalent thickness of the solar cell at a fixed value of 2 µm in optimizing the structure. As we will show in the following, this composite grating structure can enhance the light absorption of the ultrathin solar cell in a wide wavelength range.

From the perspective of numerical simulation, the periodic nature of gratings can be well captured by the RCWA method. In RCWA, the electromagnetic wave is decomposed into spatial harmonics with the help of Fourier expansion. The optical eigenmodes can then be obtained by solving a matrix eigenvalue problem where a truncation of the order of Fourier modes is needed. Due to the discontinuity of optical parameters in the structure, a proper Fourier factorization [29,30] is need to ensure the convergence of the numerical solution. Accordingly, we have developed an in-house numerical tool based on the RCWA method to analysis the transmittance $T(\lambda)$ and the reflectance $R(\lambda)$ of periodic three dimensional nanostructures. The absorptance $A(\lambda)$ can then be evaluated via

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

With the RCWA method, the spectral response of our model device is then obtained by solving the Maxwell equations at each wavelength where the optical parameters of the grating materials are given by the experimental data [31].

As the absorptance $A(\lambda)$ may display an oscillatory behavior over the spectrum, it is more appropriate to introduce the spectrally averaged absorptance $\mathrm{Abs}_{\mathrm{ave}}$ to quantify the light trapping efficiency. The averaged absorptance in a given spectrum range from λ_1 to λ_2 is defined as

$$\mathrm{Abs}_{\mathrm{ave}} = \frac{\int_{\lambda_1}^{\lambda_2} A(\lambda) d\lambda}{\lambda_2 - \lambda_1}. \tag{2}$$

The absorbed photo-current density J_{ph} is used as another important figure of merit in characterizing the nanostructure light trapping efficiency. J_{ph} is obtained by summing up the charge carriers which is generated by the absorbed photons in the silicon over the global tilt solar spectrum (AM1.5G) [32] with the light intensity 1000 W/m^2. In this estimation, the carrier collection efficiency is assumed perfect where electrical loss mechanisms such as various recombination processes are ignored for ultrathin solar cells [33]. Obviously, J_{ph} corresponds to the maximum potential short-circuit current density in ideal situation. The resulting photocurrent density J_{ph} is given by:

$$J_{ph} = e \int_{\lambda_{\min}}^{\lambda_{\max}} A(\lambda) S(\lambda) d\lambda, \tag{3}$$

where e is the charge unit and $S(\lambda)$ is the incident photon flux under the condition of AM1.5G. The integration is performed over the range of $\lambda_{\min} = 300$ nm and $\lambda_{\max} = 1100$ nm where the majority of usable solar energy for silicon cells is covered. The theoretical limit of J_{ph} is estimated to be 43.4 mA/cm^2 provided all incident photons are absorbed in the silicon layer to generate electron-hole pairs.

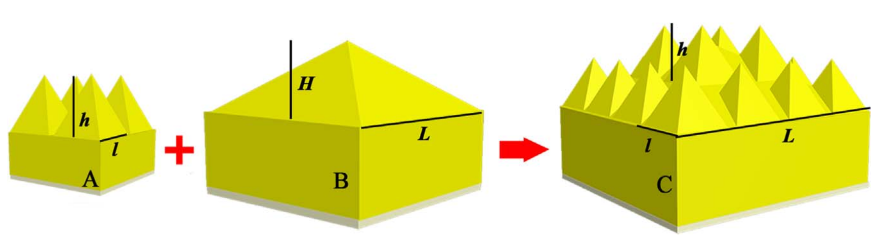

Fig. 1. Schematic plot the formation of composite grating as the superposition of two nanopyramids with different length scales. Superimposing subgrating A to subgrating B results in the composite grating C. The nanostructure can be characterized by their geometry parameters such as the period (l and L) and the height (h and H) of the respective pyramid. The equivalent thickness of the solar cell is fixed at 2 µm.