Optimized design of silicon thin film solar cells with silicon nanogratings

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ABSTRACT

To increase the performances of thin film solar cells, we show how nanophotonics concepts can be used to silicon nanogratings into effective photon management layers for solar cells. This is accomplished by patterning the silicon nanogratings present on thin film solar cell that support optical resonances. These resonances can be exploited to concentrate randomly polarized sunlight or to effectively couple it to guided and diffracted modes. Our optimization reveals that light absorption of thin film solar cell with silicon nanogratings is enhanced in randomly polarized sunlight. The simulated short-circuit current density (J_{sc}) over the solar spectrum shows an up to 127% enhancement when comparing with bare thin film cell. The average J_{sc} enhancement under an unpolarized illumination is almost immune to the incident angle ranging from $-40°$ to $40°$. It is interesting that J_{sc} enhancement of normal incident is not the maximum. The advantages of film solar cell with silicon nanogratings over plasmonic solar cell will be discussed.

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1. Introduction

There are many avenues being explored to improve the efficiencies and reduce the costs of solar cells. One of the candidates in this endeavor has been thin film solar cells, which offer solutions in terms of cost reduction [1–4]. In this vein, researchers have proposed and demonstrated a variety of approaches to improve the absorption efficiency of ultra-thin solar cells with active layer thicknesses less than one micron. A particularly promising approach involve the use of optically resonance metallic (i.e., plasmonic) and dielectric nanostructures [5–9].

More than a decade ago, it was first proposed to use the unique optical properties of metallic (i.e., plasmonic) structures to boost the efficiency of PV cells; those metallic nanostructures exhibit easily accessible collective electron oscillations known as surface plasmons. Surface plasmon excitations enable unparalleled light concentration and trapping. However, the absorption enhancement around the plasmon resonances is balanced by light absorption in the metallic nanostructures, and the surface plasmon resonance can only occur in the state of TM polarization [10]. Compared with the cell without metal silver grid, the J_{sc} of the solar cell model established by Pala et al raised 43% [11]. Within the

diversified class of sub-wavelength photonic crystals, planar gratings with high index contrasts can exhibit unexpected behaviors for light management [12].

Because silicon is a weak absorber, we established a solar cell with silicon nanogratings in this paper. We get the suitable silicon naongratings parameters of the solar cell model, using the finite difference time domain method and particle swarm optimization algorithm. This approach has lead to an increase in J_{sc} across the solar spectrum of over 127%, when comparing with bare thin film cell. Here we propose such a methodology and discuss some of the possible advantage of solar cell with silicon nanogratings. We further study the effects of incident angle of illumination on overall optical absorptivity.

2. Model and numerical method

2.1. Model

As shown in Fig. 1, we use a simple model system consisting of a periodic array of silicon nanogratings on a silica-coated, Si thin film supported by a silica substrate to illustrate these concepts. In the calculations, we assume that the thickness of substrate is infinity. The silicon nanogratings geometry was chosen because of its simple cross-sectional shape, which is described by just two parameters (thickness H and width W). The period of silicon nanogratings is named P. The sunlight incident angle is defined as θ.

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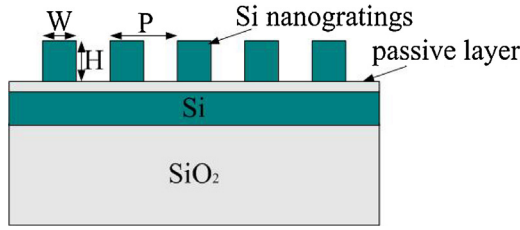*E-mail address:* yishui8524@163.com (Z. Zhou).

Fig. 1. Structure schematic a cross-sectional view. The top layer is Si nanogratings, the height is H, the width is W, the period is P; the passive layer is SiO_2, the thickness is 10 nm; the active layer (Si) thickness is 50 nm, the bottom layer is SiO_2.

2.2. Numerical methods

FDTD simulations enable the use of tabulated materials parameters and adaptive grid spacing. For the periodic arrays under study, we implemented periodic boundary conditions and perfectly matched layer (PML) boundary conditions were used at the top and bottom of the simulation volume. To model the sunlight, a plane wave with a wavelength range from 400 nm to 1100 nm was used. To calculate the absorption in the Si slab for a plane wave as a function of space and frequency, the following formula is used,

$$P_{abs} = -0.5\omega|E|^2 imag(\varepsilon) \tag{1}$$

where ω is the frequency of the incident plane wave, E is the local, simulated electric field, and $imag(\varepsilon)$ is the imaginary part of the permittivity.

The quantum efficiency of a solar cell, $QE(\lambda)$, is defined by

$$QE(\lambda) = \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} \tag{2}$$

where $P_{in}(\lambda)$ and $P_{abs}(\lambda)$ is the power of the incident light and absorbed light within the Si solar cell at a wavelength λ, respectively.

To see how the efficiency of solar cell with silicon nanogratings is improved compare with a bare solar cell, we define the following quantities, absorption enhancement $g(\lambda)$,

$$g(\lambda) = \frac{QE_{nanogratings}(\lambda)}{QE_{bare}(\lambda)} \tag{3}$$

The overall absorption enhancement is given by the average of enhancement under both TE- and TM-polarized illumination, i.e., $g_{Ave} = (g_{TE} + g_{TM})/2$.

If we assume that all electron-hole pair contributes to photocurrent, the short-circuit current density J_{sc} is given by

$$J_{sc} = e \int \frac{\lambda}{hc} QE(\lambda) I_{AM1.5}(\lambda) d\lambda \tag{4}$$

where e is the charge on an electron.

3. Results and discussion

To investigate the reasons for the absorption enhancement of the silicon nanogratings solar cell, absorption and absorption enhancement were calculated at optimized parameters. Fig. 2(a)–(d) shows the absorption and absorption enhancement for TE- and TM-polarized illumination as a function of the wavelength. In addition, data for the bare thin film solar cell is included for reference. Many sharp peaks and broader features can be observed in the enhancement spectrum for nanogratings structure. In contrast to an analogous plasmonic particle array, the absorption enhancement here is different for either illumination polarization [11]. By integrating the product of the spectral response, the quantum efficiency, and the AM 1.5 solar irradiance over the wavelength, we can
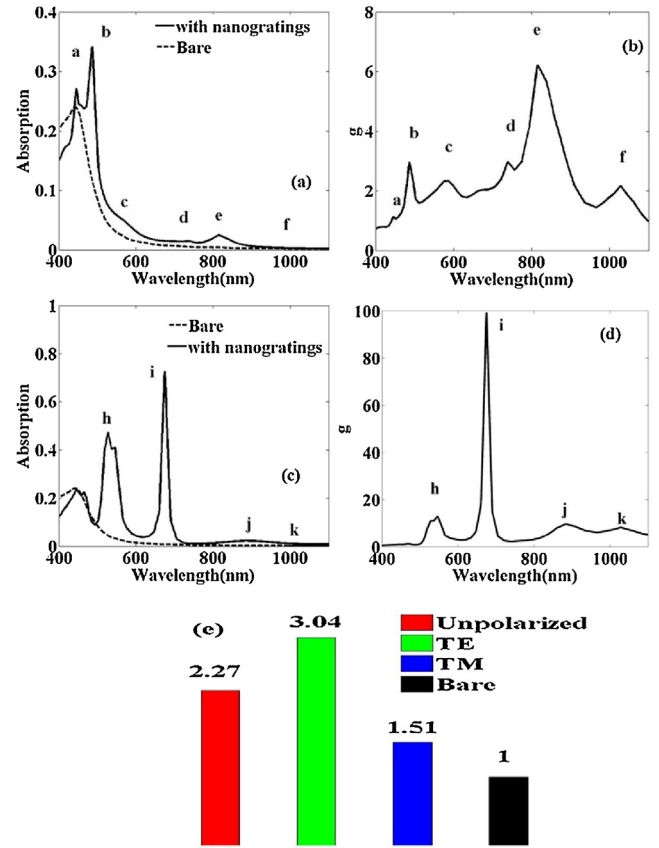

Fig. 2. (a) Absorption for the solar cell for TM-polarized illumination (b) $g(\lambda)$ for TM-polarized illumination. *a* at 445 nm, *b* at 487 nm, *c* 582 nm, *d* at 738 nm, *e* at 815 nm, *f* at 1028 nm. (c) Absorption for the solar cell TE-polarized illumination (d) $g(\lambda)$ for TE-polarized illumination. *h* at 546 nm, *i* at 675 nm, *j* at 884 nm, *k* at 1028 nm. (e) Normalized short-circuit current density.

compute the short-circuit current density (assuming a unity internal quantum efficiency). It is found that the nanogratings improve the J_{sc} of the bare structure by 127% for unpolarized light. The unpolarized J_{sc} is found by averaging the TE and TM enhancements, 204% and 51% respectively (Fig. 2(e)). The corresponding optimal design parameters of solar cell are $P = 509$ nm, $H = 97$ nm and $W = 162$ nm.

In order to further identify and study the optical phenomena that lead to the absorption enhancements. We start by generating maps of the absorption enhancement versus photon energy and reciprocal lattice constant, $G = 2\pi/P$. In these maps, the two key enhancement processes can conveniently be separated and studied. Fig. 3 shows such maps of the absorption enhancement on a natural
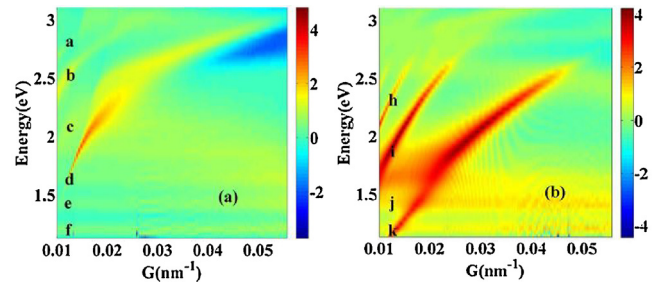

Fig. 3. Map of the absorption versus the incident photon energy and reciprocal lattice constant, (a) for TM-polarized illumination and (b) for TE-polarized illumination. (For interpretation of the references to color in text, the reader is referred to the web version of this article.)