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Optimization of Si solar cells with full band optical absorption increased in all polarizations using plasmonic backcontact grating

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ABSTRACT

We present a numerical study on the optimization of plasmonic thin-film solar cells with full band optical absorption increased in all polarization using plasmonic backcontact gratings. Particle swarm optimization (PSO) and the finite-difference time domain (FDTD) are combined to achieve the maximum absorption enhancement. Through optimization, we obtained approximately a 288% average absorption enhancement, 304% and 273% absorption enhancement for TE- and TM-polarized illumination as compared to a bare cell. The corresponding optimal design parameters of plasmonic solar cell are $P = 442$ nm, $h_4 = 283$ nm, $h_5 = 191$ nm and $w = 238$ nm. The full band absorption enhancement arises from the waveguide-plasmon-polariton, Fabry–Pérot (FP) cavity mode and multiresonant guided modes. The average absorption enhancement under an unpolarized illumination is almost immune to the incident angle ranging from -40° to 40°. If the thickness of the light absorbing layer is increased, the absorption enhancement could be reduced significantly. And the average absorption enhancement is maximum (2.88) when the thickness of Si layer is 100 nm.

1. Introduction

Reducing the cost and increasing the conversion efficiency is a major objective of research and development on solar cells. The thin film silicon cells need much less silicon materials, and therefore offer a possible solution for low-cost solar energy conversion. However, thin film silicon solar cells suffer from a low light absorption because of the weak-absorbing nature of silicon. There has been an increased interest, in recent years, in wavelength-scale light trapping techniques for application to ultra thin film solar cells. The improved absorption of light in a silicon thin film solar cell by utilizing plasmonic effects has received a lot of attention in recent years [1–4]. As a consequence the absorption of the solar cell is increased, which results in an increased short circuit current and conversion efficiency. Single layer of metallic nanogratings or nanoparticles placed at the top [5–8], bottom [9–11] or within [12–14] the active layer have been extensively studied for improving the performance of thin film solar cells. Despite the broadband absorption enhancement could be realized through placing one-dimensional periodic metallic nanostructures on the top of the thin film solar cell [15], but that will of course block a fairly large amount of total incident solar power because of the excitation of surface plasmon polaritons is normally polarization sensitive [16]. From Pala's studies [7], they found that putting metallic particles in direct contact with an absorbing semiconductor material induces an undesired, strong damping of the surface plasmon resonance that is responsible for the enhanced light absorption.

Ferry et al. [17] demonstrated a hydrogenated amorphous Si (with 160 nm and 340 nm a-Si:H thickness) solar cell with plasmonic light trapping structures built into the metallic back contact. The nanopatterns allow ultrathin a-Si:H cells with short circuit current densities exceeding that of similar cells with randomly textured back contacts due to near-field coupling to guided modes supported by the multi-layer solar cell structure. Xiao et al. [16] devised an ultra-thin-film silicon solar cell configuration assisted by plasmonic nanostructures. By placing a one-dimensional plasmonic nanograting on the bottom of the solar cell, the generated photocurrent for a fixed 200 nm-thickness crystalline silicon solar cell can be enhanced by 90% in the considered wavelength range.

In this paper, we present a numerical study on the optimization of conformal thin film solar cell with or without metallic back contact layer. The finite-difference time domain (FDTD) method is used here to analyze the integrated quantum efficiency of the cell, and particle swarm optimization (PSO) technique is used to optimize the cell structure. We systematically study the optimization of plasmonic thin-film solar cells with full band optical absorption increased in all polarization using plasmonic backcontact gratings.

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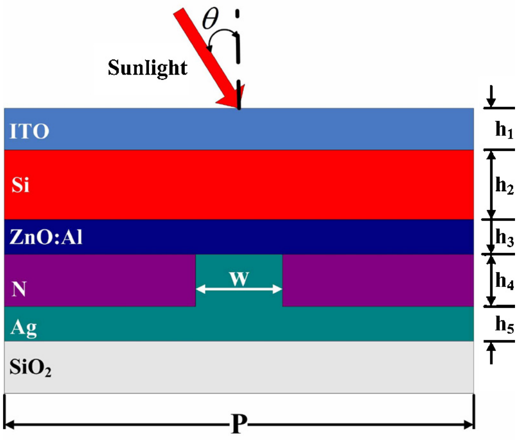

Fig. 1. Cross-sectional view of the thin film solar cell structure (one period) under study. The top electrode (ITO) thickness is h_1, the active layer (Si) thickness is h_2, the bottom electrode (ZnO:Al) thickness is h_3, the height and width of metal grating are h_4 and w, N is filled media with refractive index from 1 to 4, the metallic back contact layer (Ag) thickness is h_5, the period is P.

We further study the effects of incident angle of illumination and the thickness of Si active layer on overall optical absorptivity.

2. Model and numerical method

2.1. Model

Fig. 1 shows the cross-sectional view of the solar cell structure under study. This structure represents the one-period element of a 1D plasmonic backcontact grating solar cell. As shown in Fig. 1, the designed solar cell has an Ag back-reflector of h_5 in thickness on SiO_2 substrate. In the calculations, we assume that the thickness of substrate is infinity. The structure shown in Fig. 1 has a width of P, which corresponds to the period of 1D Ag grating. At the center, there is an Ag grating of w and h_4 in width and height, respectively. The insulator N with index refractive n_d from 1 to 4 and height h_4 were filled between Ag grating. The insulator can be chosen with suitable dielectric materials, which could provide an additional ability to fine-tune the dielectric environment of the nanowaveguide [18]. We choose the insulator N as ZnO:Al when the cell structure was optimized. But at last, the effect of n_d on performance of the solar cell will be studied. An transparent 10 nm thick Al doped ZnO (ZnO:Al) film is followed on top of the Ag grating (with insulator filled) layer for providing an cathode layer. The thin silicon layer acts as the device layer, where the absorption of the light is enhanced by plasmonic nanostructures. The thickness of Si layer is h_2, here h_2 is equal to 50, 100, 150, 200 and 250 nm to investigate the differences in the enhancement performance and differences in the dimensions of the optimized structures. A transparent 10 nm thick ITO (indium-tin-oxide) anode layer is followed on top of the Si layer for providing an electrical contact from the solar cell. The sunlight incident angle is defined as θ.

2.2. Numerical methods

FDTD was used to analyze and optimize the performance of the ultra thin-film solar cell. To model the material dispersion of Ag, ITO, silica and silicon, the multi-coefficient model (MCM) is used [19]. The perfectly matched layer (PML) boundary conditions are used for upper and lower boundary and periodic boundary conditions are used for the side boundaries to model the periodic nature of the nanoparticles. Symmetric and anti-symmetric boundary conditions are used to reduce the required memory size and computation time. To model the sunlight, a normally incident plane wave with a wavelength range from 400 nm to 1100 nm was used. To calculate the absorption in the Si slab for a normally incident 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, respectively, at a wavelength λ. Using the quantum efficiency, integrated quantum efficiency, IQE, is defined as

$$IQE = \frac{\int(\lambda/(hc))QE(\lambda)I_{AM1.5}(\lambda)d\lambda}{\int(\lambda/(hc))I_{AM1.5}(\lambda)d\lambda} \tag{3}$$

where h is Plank's constant, c is the speed of light in the free space and $I_{AM1.5}$ is AM1.5 solar spectrum. In Eq. (2), numerator and denominator means the number of photons absorbed by the solar cell and that falling onto the solar cell.

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

$$g(\lambda) = \frac{QE_{nanoparticle}(\lambda)}{QE_{bare}(\lambda)} \tag{4}$$

and

$$G = \frac{IQE_{nanoparticle}}{IQE_{bare}} \tag{5}$$

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

$$J_{sc} = e\int \frac{\lambda}{hc} QE(\lambda)I_{AM1.5}(\lambda)d\lambda \tag{6}$$

where e is the charge on an electron.

Optimization of structural parameters is a very important part of practical solar cell design. The particle swarm optimization (PSO) [20] has been shown to be effective in optimizing difficult multidimensional discontinuous problems in a variety of fields. The initial PSO concept was developed in 1995 [21] as a novel evolutionary optimization (EO) methodology over a complex solution space. PSO starts by designating each position in the solution space as potential design. A fitness function is then defined to quantify the performance of each candidate design. All the encountered positions are evaluated by this fitness function to represent how well the design criterion is satisfied. Finally, toward the end of the optimization, most particles converge to the global optimum, which expectedly results into the best design.

A PSO optimization is initiated by randomly allocating particle positions in the solution space and then searches for optima by updating generations. Particles profit from the discoveries and previous experience of other particles during the exploration and search for better objective function values. Let i indicate a particle's index in the swarm. Each particle flies through the D-dimensional search space with a velocity V_i, which is dynamically adjusted