Optics Communications 399 (2017) 62–67

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dual interface gratings design for absorption enhancement in thin crystalline silicon solar cells

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ARTICLE INFO

Keywords:
Solar energy
Subwavelength structures
Gratings
Plasmonics

ABSTRACT

We numerically study and analyze the light absorption enhancement in thin crystalline silicon solar cell with dual interface gratings. The structure combines the front dielectric nanowalls and the sinusoidal plasmonic grating at back reflector. We show that having specific interfaces with well-chosen period, fill factor and height can allow more efficient dielectric and plasmonic modes coupling into active layer and can improve the solar cell performance. For 1 μm active layer case, the optimal result for the proposed structure achieves short-circuit current of ~23.6 mA/cm^2, which performs over 50% better than flat solar cell structure, the short-circuit current of which is ~15.5 mA/cm^2. In addition, the active layer thickness and angular analysis show that the proposed structure maintains its advantage over flat structure.

1. Introduction

Solar energy is known as a renewable and alternative energy source which has called for large amount resources to develop. Photovoltaic devices give a way to produce electricity using sunlight and have attracted much attention in solar energy applications, representing the trend of energy utilization technology in the 21st century [1]. Among the photovoltaic applications, crystalline silicon(*c*-Si) solar cells are currently enjoying worldwide investment because of the natural abundance of *c*-Si and its mature fabrication method. However, the cost over watt remains high since *c*-Si with thickness of 100–300 μm is required in the conventional *c*-Si solar cells. This is due to indirect electronic bandgap of *c*-Si and its low absorption efficiency near the bandgap. The wafer thickness limitation imposes restrictions on the scale of structures as well. In this way, thin film solar cell is a promising candidate to reduce material consumption and then significantly lower manufacturing costs, whereas the reduced thickness leads to a decreased solar cell efficiency. Therefore, many advanced light trapping schemes have been investigated to balance the thickness and efficiency, which include introducing nanophotonic surfaces or multilayer material distribution to enhance anti-reflection effect, adopting photonic crystal structures to improve light confinement, using nanoparticals to lengthen light path via light scattering effect and plasmonic structures to increase energy conversion.

Generally, nanotexturing on top end of thin film solar cell is regarded as a mandatory design for anti-reflection effect enhancement. Different dimensions of textures have been proposed, among which two-dimensional designs are still a large fraction of nanostructure researches, such as hexagonal gratings [2], nanostructure arrays [3–9], and nanosphere coatings [11–13]. All one, two and three-dimensional designs focus on tuning more guided modes to promote penetration of incident light into active layer of thin film solar cell. In practical terms, however, high-dimensional approaches would create more processes during manufacturing. That is, the irregular surfaces [2–6,10] or the introductions of additional materials [11–14], to some extends, make the fabrication procedure not convenient and not applicable to other patterns.

On the other hand, structures involving surface plasmon polaritons(SPPs) have drawn lots of attention and made notable progresses in recent years [15]. SPPs are known as the waves that are coupled to oscillations of collective electrons and propagate along the metal/insulator interface. The strong near-field intensity distribution of electromagnetic field, which is caused by SPPs, will result in large energy absorption of SPP modes in active layer of thin film solar cell. Therefore, tremendous amounts of work have been carried out with enhanced light absorption performance, on account of the incorporation of metallic nanoparticles [16–21], strips [22], and nanogratings [23–29]. Whereas, in the works introduced metallic nanoparticles, the enhancements only appear when the resonant wavelength matches. Besides, utilization of metal strips and nanogratings on front side of solar cell [22,23] leads to poor solar photon absorptivity due to the reflection and ohmic loss of metal.

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http://dx.doi.org/10.1016/j.optcom.2017.04.062
Received 23 February 2017; Received in revised form 19 April 2017; Accepted 24 April 2017
0030-4018/

In this paper, a novel light trapping scheme used in thin *c*-Si solar cell is proposed. The structure consists both front anti-reflection grating structure and periodic sinusoidal metallic grating back reflector, the kind of which has not been systematically investigated before. We first investigate the effect of the front grating by varying its period and fill factor. Then the sinusoidal surface design of back reflector is applied to the optimum front grating structure. The results for different sinusoidal gratings, whose textures are defined by scaling the sinusoidal surface horizontally and vertically, are discussed. The demonstrated numerical simulations of this type of hybrid structure show that significant short-circuit current enhancement is achieved compared to the referenced flat structure. Particularly, the Finite Element Method(FEM) software COMSOL Multiphysics are implemented to calculated optical property of the solar cell within spectral range of 300 nm to 1100 nm under solar radiation(AM1.5). Both transverse electric(TE) and transverse magnetic(TM) polarizations are considered to simulate incident light of the sun.

2. Model and method

The cross-section view of proposed thin *c*-Si solar cell structure with dual interface gratings in one period is shown in Fig. 1(a). As we mainly focus on presenting performance on absorption enhancement of hybrid gratings, one-dimensional grating structure is considered in this study and is schematically shown in Fig. 1(b). The design is defined by following parameters: period P of the unit solar cell, height H and filling factor FF of front anti-reflection grating, total thickness T_1 of *c*-Si active layer and thickness T_2 of silver(Ag) back reflector with a sinusoidal grating described by function $f(x) = Y \times \cos(2n\pi x/P+\varphi)$. A commonly used transparent electrode indium tin oxide(ITO) layer with a thickness of T_{ITO} and refractive index of 1.7 is coated on top of active layer. The optical constants of *c*-Si and Ag are taken from [30]. A referenced flat solar cell structure(not shown) is used in this work to compare with proposed structure, which consists of a T_{ITO} thick ITO layer on top, a flat *c*-Si active layer with thickness of T_1 and a flat Ag back reflector with thickness of T_2. Linearly polarized plane wave with incident angle θ is illuminated from the top of unit cell. Periodic boundary conditions are applied along x-axis to simulate an infinite-extended array. Perfectly matched layer(PML) absorbing boundary conditions are used on top and bottom of unit cell to simulate infinite-extended air and Ag layers along y-axis.

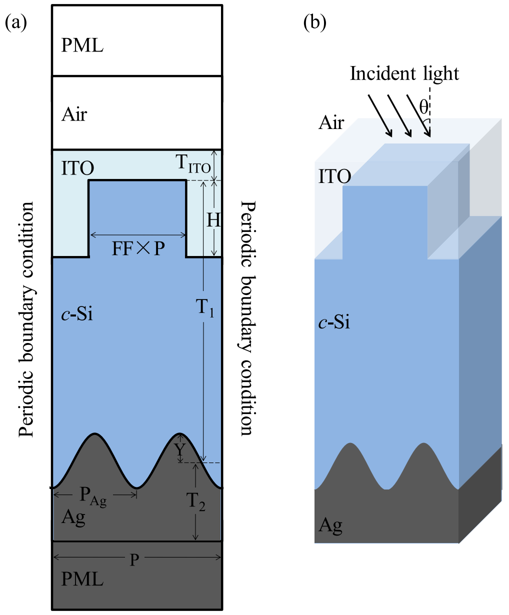

Fig. 1. The proposed thin *c*-Si solar cell structure. (a) Cross-sectional view outlining the simulated structure. (b) A three-dimensional conceptual schematic.

To investigate the light trapping capability of thin *c*-Si solar cell, normalized absorption efficiency(also known as absorptance) A(λ) in active layer(2D volume S) is calculated:

$$A(\lambda) = \frac{1}{P_{in}} \int \frac{1}{2}(\omega\cdot\mathrm{Im}(\varepsilon)\cdot|E(x,\ y,\ \lambda)|^2)dS, \tag{1}$$

where P_{in} is the power of incident light, λ is the incident light wavelength in vacuum, ω is the angular frequency, Im(ε) is imaginary part of permittivity of *c*-Si, $|E(x,y,\lambda)|^2$ is the squared magnitude of electric field obtained from solving Maxwell equations. TE and TM-polarizations contribute to absorptance equally in this calculation. Note that, when calculating energy absorbed in active layer, the integration should only cover the *c*-Si area. Then the absorptance enhanced in a structure comparing to a reference can be defined as $AE(\lambda) = A(\lambda)/A_{referenced}(\lambda)$ where $A_{referenced}(\lambda)$ is the absorptance of referenced solar cell structure. With the derived absorptance, ultimate efficiency η which is regarded as a figure of merit of solar cell is calculated as following:

$$\eta = \frac{\int_{300nm}^{\lambda_g} A(\lambda)I(\lambda)\frac{\lambda}{\lambda_g}d\lambda}{\int_0^\infty I(\lambda)d\lambda}, \tag{2}$$

where λ_g =1100 nm is the wavelength corresponding to *c*-Si band gap, I(λ) is the spectral intensity of the incident AM 1.5 sunlight. By the assumption of each photon generating one electron-hole pair, the short-circuit current J_{sc} relating to ultimate efficiency is defined as:

$$\begin{aligned} J_{sc} &= \frac{e}{hc}\int_{300nm}^{\lambda_g} A(\lambda)I(\lambda)\lambda d\lambda \\ &= \eta\frac{e\lambda_g}{hc}\int_0^\infty I(\lambda)d\lambda = 81.83\eta\,(\mathrm{mA/cm^2}), \end{aligned} \tag{3}$$

where e is the electron charge, h is Planck constant and c is the light velocity in vacuum. Similarly, short-circuit current enhancement in a structure comparing to a reference can be calculated using $E_{Jsc}=100\% \times(J_{sc} - J_{sc\text{-}ref})/J_{sc\text{-}ref}$ where $J_{sc\text{-}ref}$ is the short-circuit current of referenced solar cell structure.

3. Design and analysis

In this section, to ensure as much energy entering the active layer as possible, we first investigate the short-circuit current enhancement by the grating at front side of solar cell. We fix the thickness parameters of solar cell structure at T_{ITO} =100 nm, H =300 nm, T_1 =1 μm and T_2 =200 nm. Here, 100 nm thickness of ITO is enough for having a low sheet resistance. The height of front grating is chosen in a dimension of sub-wavelength. As demonstrated in Fig. 2, the work is carried out by varying the period P and fill factor FF of grating to identify the possible maximum short-circuit current enhancement. The scanning is con-

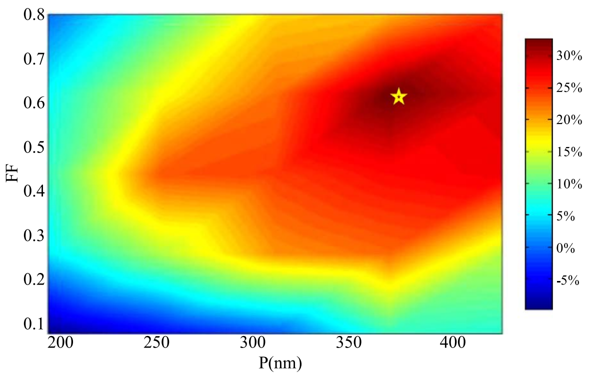

Fig. 2. Short-circuit current enhancement versus solar cell period P and antireflection grating's fill factor FF. The incidence is assumed to be at normal.