



# Design of Ag nanograting for broadband absorption enhancement in amorphous silicon thin film solar cells

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## ARTICLE INFO

### Article history:

Received 30 March 2015

Received in revised form

11 June 2015

Accepted 18 June 2015

### Keywords:

Amorphous silicon solar cell

Light-trapping

Ag nanograting

COMSOL

## ABSTRACT

Light trapping is one of the key issues to improve the light absorption and increase the efficiency of thin film solar cells. The effects of the triangular Ag nanograting on the absorption of amorphous silicon solar cells were investigated by a numerical simulation based on the finite element method. The light absorption under different angle and area of the grating has been calculated. Furthermore, the light absorption with different incident angle has been calculated. The optimization results show that the absorption of the solar cell with triangular Ag nanograting structure and anti-reflection film is enhanced up to 96% under AM1.5 illumination in the 300–800 nm wavelength range compared with the reference cell. The physical mechanisms of absorption enhancement in different wavelength range have been discussed. Furthermore, the solar cell with the Ag nanograting is much less sensitive to the angle of incident light. These results are promising for the design of amorphous silicon thin film solar cells with enhanced performance.

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## 1. Introduction

For the characteristic advantages of non-toxicity, abundance and mature processing technology, the amorphous silicon (a-Si) plays an important role in the second generation of solar cells [1]. However, photoelectric conversion efficiency of  $\alpha$ -Si thin film solar cells is still very low compared with the wafer-based solar cells [2]. In addition, carrier diffusion paths are much shorter in thin-film. In order to collect photocarriers adequately, the thickness of the active layer should be several times shorter than the diffusion length. However, the ultrathin active layer leads to a poor absorption. So effective light-trapping is essential in the incident light of wavelengths longer than 500 nm [3,4].

Sufficient researches have been explored recently to enhance the optical absorption of thin-film cells [5,6]. Most of these achievements are attributed to the introduction of certain nanostructures which including the dielectric nanopillars [7,8], metallic nanoparticles [9–12] and multilayer antireflection (AR) coatings [13,14]. However, single enhanced mechanism commonly only works in a narrow wavelength range. Recently, Metal nanograting cell structure has aroused extensive attention because of its good

performance in the light absorption for the solar cell [15–19]. Yang et al. numerically investigated the optical behaviors of the core-shell nanograting-based a-Si:H solar cell and gave an optimal design [20]. It's important to investigate the absorption influenced by the shape of the metal nanograting and the angle of incident light. What's more, a broadband absorption enhancement by the metal nanograting structure results from confused physical mechanisms. The mechanisms are not clear enough at present.

In this paper, a light trapping structure consisting of one dimensional metal nanograting and front conformal antireflective coating is proposed for  $\alpha$ -Si thin film solar cells. By the numerical simulation based on the finite element method, the effects of the light trapping structure on the light absorption of a-Si solar cells were investigated under different angle, area of the grating. Furthermore, the light absorption with different incident angle has been calculated. The physical mechanisms of absorption enhancement in different wavelength range have been discussed.

## 2. Solar cell structure and numerical method

Fig. 1 shows the cross-sectional view of the solar cell structure under study. This structure represents the one-period element of a 1-D grating solar cell. In this solar cell, the structure extends to infinity along the z axis and repeats to form a periodical pattern

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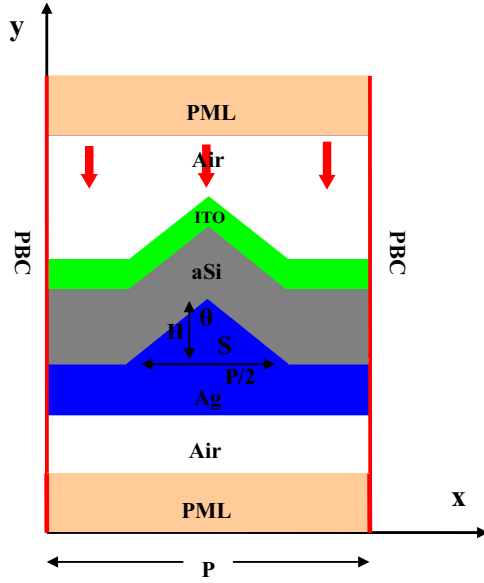


Fig. 1. Cross-sectional view of the solar cell structure with Ag nano-grating.

along the x axis. TM polarized plane wave and TE polarized plane wave within the range of 300–800 nm are used as the incident light, respectively. As shown in Fig. 1, the designed solar cell has an Ag back-reflector of 100 nm in thickness. The thickness of indium tin oxide (ITO) and a-Si layer are 60 nm, 150 nm, respectively. The structure shown in Fig. 1 has a width of  $P$ , which corresponds to the period of 1-D grating. The cross-section of the Ag grating is triangle. The bottom width of triangle is defined as  $P/2$ . At the center, there is an Ag nano-structure of  $S$  and  $\gamma$  in area and apex angle, respectively. This metal structure extends to infinity to form a nano-wall along the  $z$  axis.

In numerical computations, the commercial software COMSOL Multiphysics is used for evaluating the absorption of the a-Si layer. The numerical technique of this software is based on the finite element method. Because of the periodic structures of the solar cell, we use the periodic boundary condition along the  $x$  direction. On the top and bottom of the solar cell structure, we use the boundary condition of perfectly matched layers for simulating the infinitely extended layers of air along the  $y$  direction. In order to analyze and compare conveniently, the bare solar cell is investigated as reference cell 1 (Ref [1]) and the solar cell with 60 nm ITO anti-reflection film deposited on the front surface is marked as reference cell 2 (Ref [2]). The thickness of the Si layer of the reference samples are designed to make the total volume of Si about the same.

By solving Maxwell's equations, we can find the electric field distribution in the whole solar cell structure. The electric field distribution  $E$  in the absorption layer is used for evaluating the photon absorption  $A(\lambda)$ , defined as

$$A(\lambda) = \frac{\frac{\omega}{2} \epsilon_0 \int_V \text{Im}[\epsilon(\omega)] |E|^2 dV}{\frac{1}{2} S_1 |\text{Re}(\vec{E}_i \times \vec{H}_i)|} \quad (1)$$

Here,  $\omega$  is the angular frequency,  $\epsilon_0$  is the permittivity in free space,  $\text{Im}[\epsilon(\omega)]$  is the imaginary part of the dielectric constant of amorphous Si,  $V$  is the volume for the calculated region,  $S_1$  is the surface area of the integration region, and  $(1/2) |\text{Re}(\vec{E}_i \times \vec{H}_i)|$  is the average energy flux density of the incident wave.

The integrated photon absorption  $G_T$  contributed by the entire AM1.5 spectral range of a-Si absorption (300–800 nm) is then given by

$$G_T = \int_{AM1.5G} \varphi_0(\lambda) A(\lambda) d\lambda \quad (2)$$

Here  $\varphi_0(\lambda)$  is the photon flux density under AM1.5 solar spectra.

$G_{Ref}$  is defined as the total number of absorbed photons in the reference cell. The increased percentage of absorption  $E_{abs}$  can be calculated by Eq. (3)

$$E_{abs} = \frac{G_T - G_{Ref}}{G_{Ref}} \times 100\% \quad (3)$$

In numerical computations, the refractive indices of Ag and a-Si are obtained from literature [21]. The refractive index of ITO is defined as 1.9.

### 3. Light trapping structure optimization

Now, it needs to look for the optimal  $S$  and  $\gamma$  of the grating to ensure highest absorption enhancement. In our study, we vary  $S$  from 12,000 to 24,000 nm<sup>2</sup> and  $\gamma$  from 60° to 120°. TM and TE polarized light used in the light-trapping structure optimization are normally incident.

We calculated  $A(\lambda)$  and  $E_{abs}$  under AM1.5 illumination with different  $S$  and  $\gamma$ . Fig. 2 shows  $E_{abs}$  under AM1.5 illumination with different  $S$  and  $\gamma$ . Obviously, the impact of  $S$  on  $E_{abs}$  is relatively small, which implies the absorption of the light trapping structure is not sensitive for the change of the area  $S$ . It also provides a good compatibility for subsequent industrial production.  $E_{abs}$  reached its maximum of 96% when  $S = 18750$  nm<sup>2</sup>,  $\gamma = 80^\circ$ .

Fig. 3 shows the photon absorption rates of the solar cells with Ag nanograting as functions of wavelength when  $S = 18,750$  nm<sup>2</sup>,  $\gamma = 80^\circ$ . TE and TM polarized light are normally incident. The results of Refs. [1] and [2] are also shown in Fig. 3 for comparison. The hybrid polarized incident sunlight includes half-TE and half-TM polarizations in this paper. Obviously, the absorption of the solar cell with light trapping structure is higher than the reference cells in the incident light of wavelengths from 300 nm to 800 nm. The enhancement of photon absorption is believed to be due to the the front surface textured caused by Ag nanograting structure in the incident light of wavelengths shorter than 500 nm.

In the case of Ref [1], one can see a major peak around 620 nm and a broad hump around 500 nm. The peak around 620 nm and the broad hump around 500 nm originate from Fabry–Perot resonance in the planar structure. The Fabry–Perot resonance peak of Ref [2] slightly shifts in wavelength when the anti-reflection film is introduced. The new absorption peak appeared around 480 nm of the reference cell 2 is attributed to the contribution from ITO anti-reflection film.

The interactions between the incident sunlight and the solar

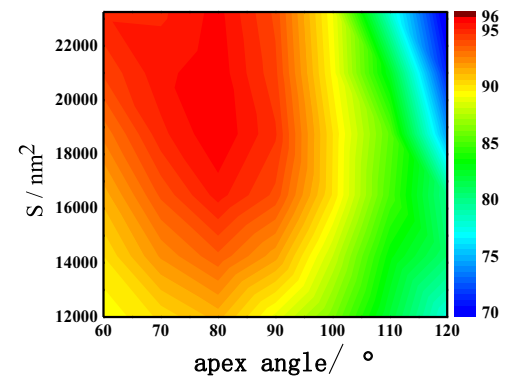


Fig. 2.  $E_{abs}$  under AM1.5 illumination with different  $S$  and  $\gamma$ .

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