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Enhanced light trapping with double-groove grating in thin-film amorphous silicon solar cells

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ABSTRACT

A design to enhance light absorption in thin-film amorphous silicon (a-Si) solar cells is proposed. It is achieved by patterning a double-groove grating with waveguide layer as the absorbing layer and coating a double-groove grating anti-reflective layer in the front window of the cell. The broadband absorption under normal incidence can be achieved for both TE and TM polarizations. It is shown that the averaged integrated absorptions have very large angle independence for the optimized solar cell. An qualitative understanding of such broadband enhanced absorption effect, which is attributed to the guided mode resonance, is presented. The conclusions can be exploited to guide the design of solar cells based on a grating structure.

1. Introduction

In recent years, solar power harvesting with nanostructures in thin film solar cells has attracted a lot of attention [1,2]. Thin film solar cells can reduce the cost of photovoltaic cells and be deposited on flexible substrates [3,4], which make it one of the promising candidates for future development of photovoltaic devices. In order to improve the collection of current and obtain optimal electronic properties in the cell, the thickness of active layer should be reduced to less than 200 nm and even more [5,6]. However, the thin-film semiconductor materials with planar structure have poor absorption. Therefore, to improve the light absorption in ultra-thin film solar cells, advanced light trapping strategies should be employed. Up to now, various light trapping methods have been proposed, such as metallic nanoparticles [7–9], metamaterials [10,11], periodic gratings [12–14] and non-periodic structure [15] etc. Among these strategies, periodic grating, as an important and simple nanostructure, can effectively enhance the absorption in thin-film solar cells. The major advantages of grating structures is that they are easy to design and fabrication.

Park et al. proposed the concept of patterning an absorbing layer as a one-dimensional photonic crystal [16]. Wu et al. reported a leaky-mode resonant absorber with the thickness of absorbing layer around 360 nm, which exhibited integrated absorption of ~66% in the 300–750 nm wavelength bands [17]. Lee et al. proposed an approach of enhancing light-trapping based on a guided mode resonance effect in a thin-film silicon solar cell by adding a two-filling-factor asymmetric binary grating on it for the near-infrared wavelength range [18]. Massiot et al. investigated the multi-resonant absorption mechanism achieved in a-Si:H solar cells with a silver grating embedded in the front window of the cell, A short circuit density of 14.6 mA/cm^2 is predicted for a cell with a 90 nm-thick a-Si:H active layer [19]. Nguyen-Huu et al. proposed the concept of compound grating (consists of two simple grating) with an average absorbance of 0.92, which is about 1.5 larger than that of the Si plain and conventional grating structures [20]. Martins et al. proposed a generic design approach with a supercell geometry, which results in a integrated absorption enhancement of nearly 100% [21]. Wen et al. proposed a unique light trapping strategy incorporating cascaded metallic gratings on top of the absorption layer to obtain a broadband absorption enhancement, which gives rise to an enhancement of 60% in photocurrent for the TM-polarized illumination. [22].

In a previous paper [23], we have investigated the enhancement of absorption in a thin-film a-Si solar cell based on guided mode resonance, which is achieved by patterning a single-groove or a double-groove grating with waveguide layer as the absorbing layer. And the antireflective grating structure is also proposed and discussed for reducing reflection and enhancing absorption. It is found that the optimized solar cell with double-groove grating has better optical performance than single-groove grating structure and the solar cell with antireflective grating has much better performance than those without an antireflective grating. However, the antireflective structure is only discussed for the single-groove grating.

In this paper, the enhancement of absorption based on double-groove grating and antireflective structure is investigated. It is

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achieved by patterning a double-groove grating with waveguide layer as the absorbing layer and coating a double-groove grating anti-reflective layer in the front window of the cell. The optimized grating parameters are obtained by use of rigorous coupled-wave analysis (RCWA) [24,25] and the simulated annealing (SA) algorithm [26,27]. The broadband absorption under normal incidence can be achieved for both TE and TM polarizations. It is shown the averaged integrated absorptions have very large angle independence for the optimized solar cell. An qualitative understanding of such broadband enhanced absorption effect, which is attributed to the guided mode resonance, is presented. The conclusions can be exploited to guide the design of solar cells based on a grating structure.

2. Design and simulation of solar cells

The thin-film a-Si solar cell under investigation is shown in Fig. 1. It consists of a double-groove grating anti-reflective layer, a double-groove grating and a planar waveguide layer with the materials of a-Si backed with a silica substrate. The refractive indexes of a-Si are taken from Ref. [28]. The material of anti-reflective structure is indium tin oxide (ITO) with a refractive index of 2. The refractive index of SiO_2 is 1.46. Generally speaking, in practical application, the refractive indexes of these materials are usually frequency dependent. However, the conclusions obtained by the simplified model remain unchanged for real application though with a small change in absorption spectrum. The grating period is d; h_1 is the thickness of anti-reflective layer; h_3 is the thickness of grating layer; $h_2=h_3-h_1$; h_4 is the thickness of waveguide layer; f_1 and f_2 are duty cycles of the two ridges, d_1 is the separation of the two ridges.

A TM (with H-field pointed along the stripes) and a TE (with E-field pointed along the stripes) polarization plane wave are incident from the air with an incident angle θ. The absorbing layers (h_3+h_4) is selected as 150 nm.

To evaluate the total performance of the devices over a wide wavelength range, the integrated absorption is employed as a figure of merit. The integrated absorptions over all the interesting wavelengths range for TM and TE polarizations are [23,29]:

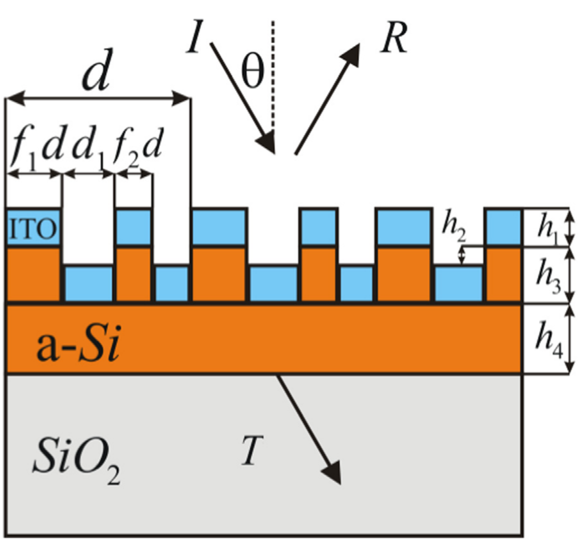

Fig. 1. Schematic of the solar cells based double-groove grating and anti-reflective grating structure.

$$A_{TM}=\frac{\int_{300}^{800}a_{TM}(\lambda)S(\lambda)d\lambda}{\int_{300}^{800}S(\lambda)d\lambda},\ A_{TE}=\frac{\int_{300}^{800}a_{TE}(\lambda)S(\lambda)d\lambda}{\int_{300}^{800}S(\lambda)d\lambda} \tag{1}$$

where $\alpha_{TM}(\lambda)$ ($\alpha_{TE}(\lambda)$) is the absorption spectrum of TM(TE) polarization in the active layer, which are obtained from RCWA by the reflection ($R(\lambda)$) and transmission spectrums ($T(\lambda)$): $\alpha_{TE}(\lambda)=1-R(\lambda)-T(\lambda)$, and $S(\lambda)$ is the solar irradiance spectrum, which is selected as AM1.5g solar spectral irradiance. The integration is done from 300 nm to 800 nm. The averaged integrated absorption is defined as the mean value of TE and TM polarizations.

To obtain the optimized structure parameters, we employ the simulated annealing (SA) algorithm. The cost function is [23]:

$$\phi=-1/2(A_{TM}+A_{TE}) \tag{2}$$

The objective is to minimize $\phi(d, h_1,h_3,h_4,f_1,d_1,f_2)$ by selecting suitable grating parameters. After optimization, we obtained the optimized structure parameters of the solar cells, which are shown as follows: $d=506$ nm, $h_1=58$ nm, $h_3=100$ nm, $h_4=50$ nm, $f_1=0.208$, $d_1=74$ nm, $f_2=0.341$. Though the optimized structure parameters are obtained with the device under normal incidence, the integrated absorption is still large when the incident angle is nonzero, which will be shown later.

The optical response of the solar cells under normal incidence is shown in Fig. 2. Broadband absorption is achieved for both TE and TM polarizations. At short wavelengths, the absorption for TM polarization is slightly higher than TE polarization. However, at long wavelengths, the situation is reversed due to the two large resonant absorption peaks for TE polarization. Therefore, the absorption spectrum presents a large polarization dependence, which is the inherent characteristic of one-dimensional grating. To solve this problem, the one-dimensional grating structure should be replaced by a two-dimensional grating structure. For a two-dimensional square lattice of nanocuboid, the spectral response is the same for TE and TM polarizations at normal incidence due to the symmetry of cuboids. Thus the polarization-independent absorption can be achieved by use of square lattice of nanocuboid.

At normal incidence, the averaged integrated absorption is about 73.18% for the structure proposed in this paper, which is much larger than the integrated absorption of the corresponding planar structure (about 38% for the unpatterned a-Si layer with thickness of 150 nm). Thus, the solar cells achieve about 92.6% increases. To obtain the potential for solar cell applications, a short-circuit current density is employed. When the internal quantum efficiency is selected as 1, the short-circuit current density J_{sc} (mA/cm^2) can be defined as follows [30,31]:

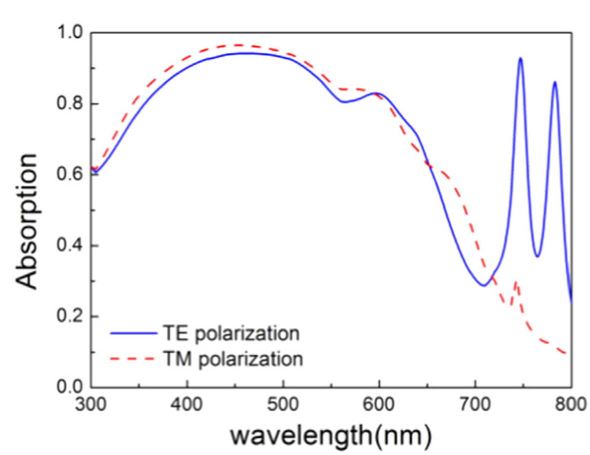

Fig. 2. Spectral absorptions in solar cells.