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Absorption enhancement in thin-film solar cells based on periodically chirped structure

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ABSTRACT

Light trapping by a periodically chirped grating structure in thin-film amorphous silicon solar cells is investigated. A thin-film solar cell based on a periodically chirped grating structure is designed. The optical performance of the solar cells is evaluated by examining the integrated absorption, the short-circuit current density, and their angular independence. Further, enhanced absorption compared with a planar reference structure is also demonstrated. A qualitative physical explanation of this broadband absorption enhancement, which results from the leaky waveguide modes resonance, is presented. It is believed that the conclusions can provide a useful guide for the design of thin-film solar cells based on a dielectric subwavelength structure.

1. Introduction

The use of thin-film solar cells can dramatically reduce the cost of photovoltaic cells, which has made them a hot research topic in recent years (Atwater and Polman, 2010; Green and Pillai, 2012; Gu et al., 2017). However, the thin semiconductor layers generally suffer from poor absorption. Thus, advanced light trapping strategies should be employed to solve this problem. To date, many efforts have been made to enhance the absorption in thin-film solar cells by using nanostructures (Abass et al., 2011; Pala et al., 2009; Liu et al., 2013; Wang et al., 2018; Khan et al., 2014; Chen et al., 2009; Mokkapati et al., 2009; Bai et al., 2017), such as periodic gratings (Abass et al., 2011; Pala et al., 2009; Liu et al., 2013), metamaterials (Wang et al., 2018; Khan et al., 2014), and metallic nanoparticles (Chen et al., 2009; Mokkapati et al., 2009; Bai et al., 2017). Most of these light trapping technologies can be divided into two types. In one type, the incident light is coupled into the quasiguided modes of the thin film, usually by employing the dielectric nanostructures (Park et al., 2009; Wu and Magnusson, 2012; Martins et al., 2012; Bozzola et al., 2014). In the other type, a large local electric field enhancement is applied by using the resonance of metallic nanostructures (Atwater and Polman, 2010; Green and Pillai, 2012; Abass et al., 2011; Pala et al., 2009; Chen et al., 2009; Mokkapati et al., 2009; Bai et al., 2017).

Solar cells based on a wide variety of nanostructures including one-dimensional and two-dimensional nanostructures and ordered and disordered structures (Pala et al., 2009; Park et al., 2009; Wu and Magnusson, 2012; Martins et al., 2012; Bozzola et al., 2014; Wen et al., 2014; Pala and et al., 2013), have been investigated. However, the cost of design and fabrication increase with the complexity of the structure. Among these methods, one-dimensional ordered or disordered gratings can also effectively trap light in solar cells when an appropriate design is used. Their main advantage over two-dimensional nanostructures is that they are easier to fabricate by lithography. This is because less structure parameters need to be controlled and the lithography mobile platforms shift only in one-dimensional.

The first solar cells based on a one-dimensional ordered grating used a single-groove grating. Park et al. proposed the concept of patterning the absorbing layer with a one-dimensional grating (Park et al., 2009), and Wu and Magnusson reported solar cells based on the leaky-mode resonance (Wu and Magnusson, 2012); in both case, the solar cells are based on dielectric nanostructures. Pala et al. developed design rules to realize broadband absorption enhancements in Si films by depositing Ag strips on a silica-coated Si film backed with a silica substrate (Pala et al., 2009). Soon after, the use of a single-groove grating in solar cells was expanded to the use of double-groove and multi-groove gratings. Martins et al. proposed a basic design approach for solar cells with a supercell grating, which is achieved by patterning a multi-groove grating on a silicon-on-insulator wafer (Martins et al., 2012). Wen et al. introduced the concept of incorporating cascaded metallic gratings on top of the absorption layer to achieve broadband absorption enhancement, which is realized by simultaneous excitation of multiple localized surface plasmon resonances (Wen et al., 2014). Solar cells with a one-dimensional disordered grating were also proposed recently. Bozzola et al. investigated light trapping by Guussian disordered one-dimensional photonic structures in crystalline silicon solar cells (Bozzola et al., 2014). Pala et al. developed a semi-analytical light-trapping

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model and used it to demonstrate that arrays of nanometallic stripes featuring a limited amount of disorder can substantially enhance the solar absorption over that of conventional periodic and random arrays (Pala and et al., 2013).

To improve the light absorption in solar cells, using a combination of ordered and disordered subwavelength structure is found to be an effective and simple method (Bozzola et al., 2014; Pala and et al., 2013). However, there is little research on this approach, and further study is needed. In this paper, we theoretically investigate the light trapping effect of thin-film amorphous silicon (a-Si) solar cells with a periodically chirped grating structure. We first employ rigorous coupled-wave analysis (RCWA) Moharam et al., 1995; Lalanne and Morris, 1996 and the simulated annealing algorithm (Goffe et al., 1994; Shiozaki and Shigehara, 2005) to design thin-film solar cells based on a periodically chirped grating structure. Then the optical properties of the designed solar cells are studied by examining the integrated absorption, the short-circuit current density, and their angular independence. The results are compared with those of an optimized planar reference structure. Furthermore, a physical explanation of this broadband enhanced absorption effect, which results from the leaky waveguide mode resonance, is presented.

2. Design and simulation of solar cells

The unit structure of the proposed thin-film solar cells with periodically chirped structure is shown in Fig. 1(a). The structure is composed of an antireflective coating, an active layer patterned with the periodically chirped structure, an active film layer, and a metallic back reflector. The antireflective structure is made of indium tin oxide (ITO) with a refractive index of 2. The metallic back reflector is made of Ag, and the active layer is made of a-Si. The refractive indices of a-Si and Ag in the visible regime are obtained from http://refractiveindex.info/?group=CRYSTALS&material=a-Si.

The width of the grating ridge is linearly chirped along the x direction. The ridge width can be expressed as

$$w_n = w_1(1 + (n-1)\alpha) \quad n = 1,2,3,...$$

where, w_1 is the width of first ridge, w_n is that of the nth ridge, and α is the chirping coefficient. In Fig. 1, d_{n-1} is the distance between the (n-1) th and the nth ridges, d is the grating period, h_a is the thickness of the antireflective coating, h_1 is the dielectric grating depth, and h_2 is the thickness of the a-Si film. The thickness of the a-Si active layers is 150 nm; i.e., $h_1 + h_2 = 150$ nm. A thickness of 200 nm is chosen for the Ag to prevent light transmission of. Transverse magnetic (TM, with the magnetic field along the y axis) and transverse magnetic (TE, with the electric field along the y axis) polarized plane waves are incident from the air at an incident angle θ.

For comparison, a reference thin-film planar solar cell is also proposed, which is shown in Fig. 1(b). It consists of an a-Si slab with a thickness h_1 of 150 nm sandwiched between an optimized antireflection coating (ITO) with a thickness h_a of 60 nm and a Ag back reflector.

To evaluate the optical performance of the solar cells, we employed the integrated absorption as a figure of merit. The integrated absorption values for of TM- and TE-polarized light are defined as (Wu et al., 2012; Min et al., 2010):

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

where $S(\lambda)$ is the solar irradiance spectrum (here, the AM1.5 g solar spectral intensity distribution is selected); $\alpha_{TM}(\lambda)$ [$\alpha_{TE}(\lambda)$] is the absorption spectrum for TM- (TE-) polarized light, which are calculated by RCWA. For the solar cells in Fig. 1, the wavelength-dependent absorption spectrum can be obtained using (Chern and Hong, 2011; Hao et al., 2011):

$$\alpha(\lambda) = \frac{1}{2}\varepsilon_0\omega(\mathrm{Im}\varepsilon(\omega)) \int_V |E|^2 dv, \tag{2}$$

where ε_0 is the permittivity of vacuum, ε denotes the relative dielectric permittivity of the material, ω is the angular frequency, and E denotes the electric field. The integral is over a unit.

To determine the potential for solar cell application, the short-circuit current density is employed. When the internal quantum efficiency is assumed to be 1, the short-circuit current density J_{sc} (mA/cm^2) can be defined as follows (Massiot et al., 2014; Massa et al., 2014):

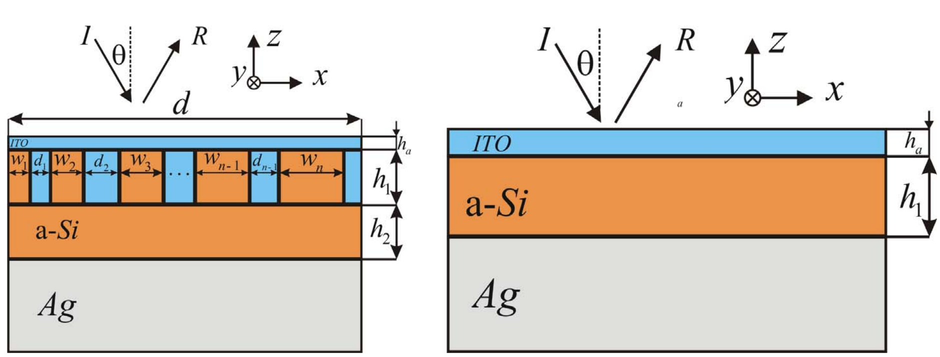
$$J_{sc} = \frac{q}{hc}\int_{\lambda_{min}}^{\lambda_{max}} \lambda\alpha(\lambda)S(\lambda)d\lambda, \tag{3}$$

where q is the elementary charge, λ is the wavelength, h is the Planck constant, and c is the speed of light; the integration is from $\lambda_{min} = 300$ nm to $\lambda_{max} = 800$ nm,

3. Analysis and discussion

We consider a periodically chirped structure with $n = 4$. After optimization, we obtain the following structural parameters of the proposed solar cells: $w_1 = 132$ nm, $d_1 = 131$ nm, $d_2 = 81$ nm, $d_3 = 172$ nm, $d_4 = 149$ nm, $h_a = 60$ nm, $h_1 = 70$ nm, and $\alpha = 0.349$.

The absorption spectra of the active layer of the solar cells in Fig. 1 under normal incidence are shown in Fig. 2(a). The absorption of the reference planar structure is greater than 60% at wavelengths of 344–671 nm, whereas it is low in the short and long wavebands. However, when the active layer is patterned with the periodically chirped structure, the absorption is enhanced in both the short and long wavebands, which results in broadband absorption for both TE- and TM-polarized light. The absorption of the solar cells with the periodically chirped structure is higher than that of the reference planar structure in nearly the entire waveband range. At long wavelengths, where the extinction coefficient of the a-Si is very small, there are four resonant absorption peaks for TE-polarized light and two resonant



(a) periodically chirped structure (b) reference planar structure

Fig. 1. Schematic of the thin-film solar cells: (a) periodically chirped structure and (b) reference planar structure.