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Absorbance enhancement of thin film solar cells with front double dielectric and back metallic grating

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HIGHLIGHTS

- The combination of a subwavelength aperture and a double nano-structured dielectric grating with back triangle metallic grating will result in an enhancement in total optical absorption.
- 90.85% Average harvesting can be achieved by the optimized structure in the spectrum range from 300 to 1100 nm.
- The high integrated absorption and is weakly dependent on incident angle.

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ABSTRACT

We present finite difference time domain (FDTD) and rigorous coupled-wave analysis (RCWA) simulations to analyze the optical absorption enhancement of thin film solar cells (TFSCs) employing front double dielectric and back plasmonic grating structures. Simulation results show that the combination of a subwavelength aperture and a double nano-structured dielectric grating with back triangle metallic grating results in an enhancement in total optical absorption. The absorption of the planar structure is enhanced thanks to an increase of the optical path length of the red and near-infrared photons, causing a proportional enhancement of the absorption in this spectral range. 90.85% Average harvesting (on TE and TM) can be achieved by the optimized structure in the spectrum range from 300 to 1100 nm. The designed SC has high integrated absorption and is weakly dependent on incident angle, which should be useful for application in film photovoltaics, photodetectors and infrared imaging.

1. Introduction

There has been increased awareness of the negative impacts of fossil fuel consumption on the environment and economies of countries around the world. Photovoltaic devices have draw great interest when the oil price is raising, which is due to the fact that the sun light is the most pure and inexhaustible power in the world. The photovoltaic applications would be the most important issue for the power generation in the future. Till now, more than 90% of presently fabricated SCs are based on crystalline silicon [1]. A looming silicon shortage would therefore severely limit a future increase of cost efficiency, which is needed for a widespread clean and sustainable power supply [2,3]. TFSCs represent a very promising technology for low cost and high volume production of SCs. Nevertheless, too thin active layer also decrease the light absorbing ability and a majority of light escaped from TFSCs before being absorbed as a result of the low absorption coefficient of a-Si in the visible and infrared range [4]. Therefore, implementation of light-trapping mechanism is essential for high efficiency photovoltaic cells. Coherent light trapping schemes using periodic photonic structures, as opposed to geometrical optic schemes using random surface texturing have attracted a lot of attention with hope of achieving higher absorption enhancement at least over limited spectrum near the band-edge of active material.

The overall goal of such light trapping schemes usually contains two aspects, reduce the reflection on the surface and increase the path length of photons inside the light absorbing layer by any technical means to enhance the probability of photon absorption [5]. With this goal, various methods for light trapping have been explored recently [6–21]. Among these technologies, periodic grating structure is an important and simple way for effective enhancement of absorption in TFSCs. Since gratings could be put on both the front and back side, numerous theoretical and experimental

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studies have been reported [8,12]. The latest progress in the field of surface plasmon (SP) enhanced SCs opens a new path to realize ultrathin SCs with much higher solar conversion efficiency. However, many previous studies focused mainly on metal nanostructures at the top interface of the cells which often show a bit of decrease in light absorption at the shorter wavelengths [19,20].

In this paper, we discuss one more efficient approach to improve light trapping combining front dual-grating and back triangle metallic grating rather than the single grating structure. Finite difference time domain (FDTD) and rigorous coupled-wave analysis (RCWA) simulations are used to investigate the absorption enhancement of the double front grating combined plasmonic-based back grating SC structure and compare its performance to single metallic back grating structure. The role of front dielectric gratings is to reduce the reflection on ITO-a-Si interface and extend the optical path length inside the a-Si layer by changing the incident light into a lager propagating angle. The plasmonic gratings can both diffract photons within the absorber layer and concentrate light to high intensities in regions of the cell. SPs are excited at the dielectric–metal interface. The strong field associated with SPs is evanescent, that extends into dielectric much further than into metal. Hence, the use of the SP to improve absorption is suited for TFSC applications.

2. Design principles and simulation methods

2.1. Design principles

Our starting design with dual-interface gratings (Fig. 1) uses amorphous Si (a-Si) as the active layer material. This type of layer and grating structure provides a system where guided or Bloch mode engineering can play a significant role in the overall absorption enhancement, as will be discussed in the following sections.

The most important function of front dielectric gratings is to reduce the reflection on ITO-a-Si interface and extend the optical path length inside the a-Si layer by changing the incident light into a lager propagating angle because of the grating diffraction effect. The diffracted angles of the corresponding diffractive order are calculated by the grating equation followed:

$$n_o \sin\theta_m + n_i \sin\theta_i = m\lambda/d \quad (1)$$

where n_i and n_o are the refractive index of the incident and outgoing material respectively, λ is the wavelength in vacuum, d is the grating constant, m is the diffractive order (0, ±1, ±2,...), θ_i is the incident angle, and θ_m is the diffractive angle of the m_{th} order.

The back periodic metallic gratings apply are designed to avoid or minimize losses due to surface reflections and ohmic losses in a top metal surface. Triangular shape of the gratings is used to leverage strong enhancements in both TE and TM polarizations with the excitation of various optical as well as plasmonic modes and their coupling [22]. Triangular gratings buried into the active layers allow the exploitation of the near field by placing the absorbing layer in close proximity of the enhanced fields. Triangle gratings are proved to be an ideal reflector, light would be reflected completely and scattered in all directions to increase the optical path.

2.2. Numerical simulation

In this paper, RCWA and FDTD methods are used to calculate the diffraction efficiency and field intensity distribution in SCs respectively. RCWA method is based on rigorous coupled-wave theory to analyze and design diffractive structures. It is a rigorous solution of Maxwell's equations with corresponding boundary conditions for the electromagnetic diffraction properties by periodic grating structures [23,24]. With the consideration of sufficient high-order diffraction modes under solar incidence, the reflection (R) and transmission (T) for every wavelength can be calculated, enabling to obtain the device absorption ($A = 1 - R - T$ which is simplified here as $A = 1 - R$ since $T = 0$ with the presence of Ag back reflector). RCWA is especially helpful in quickly finding the optimal design by sweeping the device parameters in very broad ranges. To compensate the limitation of RCWA, we also perform the electromagnetic calculation for the nano-patterned device by using FDTD to verify the correctness of RCWA calculation [25]. The exact calculation of electric and magnetic field inside the device exports the detailed spatial information of field and power density, allowing to directly calculate absorption percentage in each layer.

The total field and scattered field of the model are calculated as a function of wavelength, respectively. The broadband illumination as an incident plane wave across a range from 300 nm to 1100 nm is selected to match the solar spectrum and the significant spectral response of α-Si. Necessarily, both transverse magnetic (TM, electric field perpendicular to the grating) and transverse electric (TE, electric field parallel to the grating) polarizations are considered to approximate un-polarized solar light irradiation. In our computations, we assumed experimentally obtained data for optical properties (refractive index, absorption) of Si, Ag [26,27] and ITO

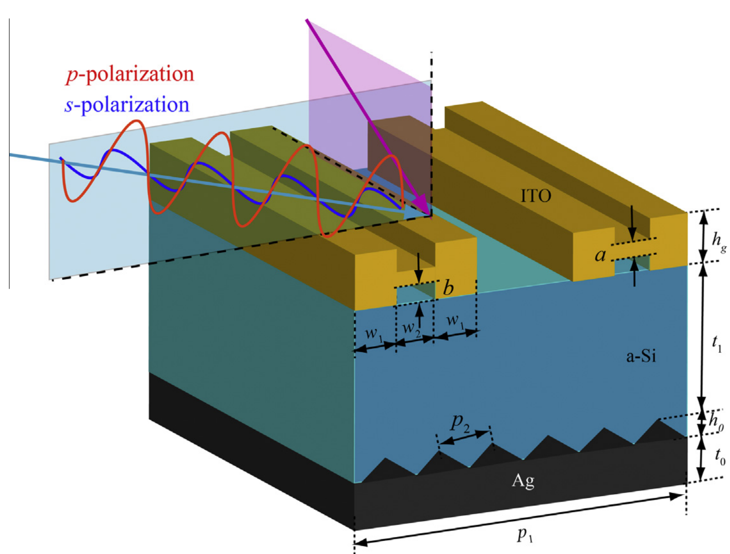

Fig. 1. Schematic nanostructure for improving the absorption of TFSCs. Top subwavelength hybrid dielectric gratings and back metallic triangle substrate are introduced.