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Design of plasmonic solar cells combining dual interface nanostructure for broadband absorption enhancement

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ABSTRACT

We propose an ultra-thin film solar cell structure combining front semicircular dielectric grooves and back trapezoidal metal reflector. The back trapezoidal metal structure traps light by the excitation of plasmonic modes and the outstanding scattering effect of our optimized shape to enhance the absorption at long wavelengths. The front groove structure boosts absorption at short wavelengths by the mechanisms of Fabry–Perot resonance, scattering and the interaction with back plasmonic structure. The total absorption efficiency over the entire spectrum in 100 nm thick active layer is as high as 78.4% under normal incident light and it can also be maintained in a high level even if the incident angle varies from -60° to 60°. Broadband absorption, efficiency enhancement and insensitivity to the angle indicate the dual interface nanostructure to be a practical reference.

1. Introduction

Solar cell technology has been the promising candidate to meet growing energy demands in a sustainable way, as it can convert sunlight into electrical power by the photovoltaic effect. However, due to the high materials and processing costs, the price of solar electrical energy generation has remained higher than fossil fuel for electrical power generation. Thin film solar cells offer the potential for a considerable cost reduction which benefits from the reduced material volume of thin film devices and much less energy wasted during the fabrication process [1].

Among the common thin film solar cell semiconductor materials, hydrogenated amorphous silicon (a-Si:H) is a suitable choice because of its advantages of non-toxicity, earth abundance, low cost and mature processing technology [2]. But the carrier transport property of a-Si is poor, in order to reduce carrier recombination in the semiconductor and improve carrier collection efficiency, a thinner active layer thickness is needed. Paradoxically, the performance of a-Si thin film solar cells is limited by the low light absorption due to the reduced active layer thickness. As a result, improving the light absorption in thin film solar cells by using advanced light trapping techniques has attracted more and more attention. And various structures with enhanced absorption have been proposed, such as surface texturing [3,4], antireflection coatings [5–7], back reflectors [8–10], photonic crystals [11,12], the top or bottom metallic nanoparticles based on surface plasmons [13–20].

Among these structures, the plasmonic nanostructures are found to perform an unparalleled light concentration and broadband absorption enhancement [1,21–27]. Surface plasmons are coherent electron oscillations at the interface between metal and dielectric. The charge motion and the electromagnetic field generated from it, which are known as surface plasmon polaritons (SPPs) and localized surface plasmon polaritons (LSPs), can capture and trap the sunlight into the active layer of solar cells.

However, many plasmonic nanostructures have not shown the good performance as we expect. For example, some designs which involve the use of surface metal nanostructures directly on the top layer of solar cells will block a large amount of incident solar photons. What is more, the size and shape of metal nanostructures can strongly influence the scattering or absorption through the excitation of localized surface plasmons [28]. Besides, SPPs and LSPs can only get a large absorption at a certain range of wavelength, so we should explore a better nanostructure to get the entire spectrum absorption.

In this paper, we propose an ultrathin a-Si thin film solar cell structure consisting of front semicircular dielectric grooves and back trapezoidal metal reflector. The finite element method (FEM) is used to simulate the electromagnetic field distribution. We analyze the influence of period, shape and size to the absorption performance and get the best back metal structure. Through the optimization of the front dielectric structure, we improve the overall absorption

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efficiency and get a balance between the absorption at long wavelengths caused by surface plasmon modes and the absorption at short wavelengths induced by scattering and Fabry–Perot resonance.

Section 2 describes the dual interface nanostructure we have designed and modelling method. Then we introduce the numerical methods which we use to analyze the performance of thin film solar cell. In Section 3 we get the optimal structure step by step and give the related discussions. Section 4 concludes the paper.

2. Model and method

Fig. 1(a) illustrates the schematic diagram of the proposed thin film solar cell with front semicircular dielectric grooves and back trapezoidal metal reflector. To achieve numerical accuracy at a small computational expense, we use a 2D physical model to represent the structure. The sketch of the reference structure is depicted in Fig. 1(b), which consists from the top to the bottom of a 60 nm thick layer of indium tin oxide (ITO), a 100 nm thick layer of a-Si and a 100 nm thick layer of silver.

The ITO deposited on the top of a-Si serves as transparent conducting oxide layer and antireflection coating. The thickness of antireflection coating is equal to $\lambda/4n$. The a-Si acts as active layer which contributes to the external electricity and the Ag is a back contact. The front semicircular grooves are filled with ITO and the back trapezoidal metal is silver. The refractive index of ITO is 1.7; the refractive index of a-Si and Ag is the experimental data in [29].

In our work, electromagnetic simulations are performed by the commercial finite element software of COMSOL Multiphysics. Periodic boundary conditions are set at the left and right boundaries to represent an infinite array along the x direction. The top and bottom use the perfectly matched layer (PML) absorbing boundary conditions. Due to SPPs can be excited only by TM polarization (the magnetic field has one component in the z direction), we mainly consider TM polarization in our study. TE polarization (the electric field has one component in the z direction) will serve as a contrast to TM polarization which enhances the absorption through SPPs and LSPs, and we will apply the data acquired under TE polarization to calculate the whole absorption under unpolarized light in the end. The structure is illuminated from the top surface by normal TM incident light with wavelengths of 300–900 nm.

The electromagnetic field is calculated by solving the Maxwell equations. Assuming every electron hole pair excited by incident photon is collected, the total absorbed power in active layer can be calculated by integrating the energy dissipation density within the 2D volume (excluding the metal in the active layer):

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

where λ is the wavelength of incident light, ε is the imaginary part of the permittivity in free space, ω is the angular frequency, and S is the area of the active layer. When we set the incident light power to 1 W, the numerical value of absorbed power is equivalent to the absorption efficiency. The absorption efficiency of the total illuminated energy is calculated by

$$A_{\mathrm{AM1.5\,G}}=\frac{\int[P_{\mathrm{AM1.5\,G}}(\lambda)\times A(\lambda)]d\lambda}{\int P_{\mathrm{AM1.5\,G}}(\lambda)d\lambda} \tag{2}$$

where $P_{\mathrm{AM1.5\,G}}(\lambda)$ is the photon flux of AM 1.5G.

3. Design and analysis

3.1. Design of the back metal structure

First we want to design an optimized metal nanostructure to gain broadband absorption enhancement utilizing a plasmonic effect. The position, shape and size of plasmonic nanostructure are all the key design points. Different locations of the metal structure in active layer all can excite surface plasmon modes. In consideration of the plasmonic nanostructure which is inside of or on the top of active layer will block a large number of solar photons, we choose the back reflector structure. An additional advantage of this structure is that silver back reflector can strongly scatter incident light and improve optical path length inside the a-Si layer. Through our research, we find trapezoidal metal reflector is a more optimized structure, which we will analyze based on the graph below.

To start our design, we set a trapezoidal silver structure at the interface of a-Si and silver which we introduce in Fig. 1(b) and explore the period dependence of back trapezoidal silver reflector. We use fixed values for the slope of lateral side and the height of isosceles trapezoid to start the optimization. The slope is set to 2.5 and the height is 50 nm.Through varying the period and the width of bottom base, we can acquire the optimal parameter which can gain the greatest absorption efficiency. As shown in Fig. 2, when the period is 350 nm and the widths of top base and bottom base are 40 nm and 80 nm, the absorption efficiency of active layer is as high as 71.5%. It shows an obvious improvement

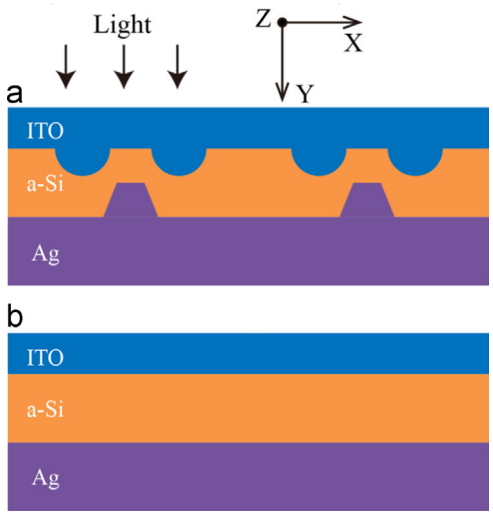

Fig. 1. (a) Schematic diagram of our proposed thin film solar cell structure. (b) The flat thin film solar cell structure.

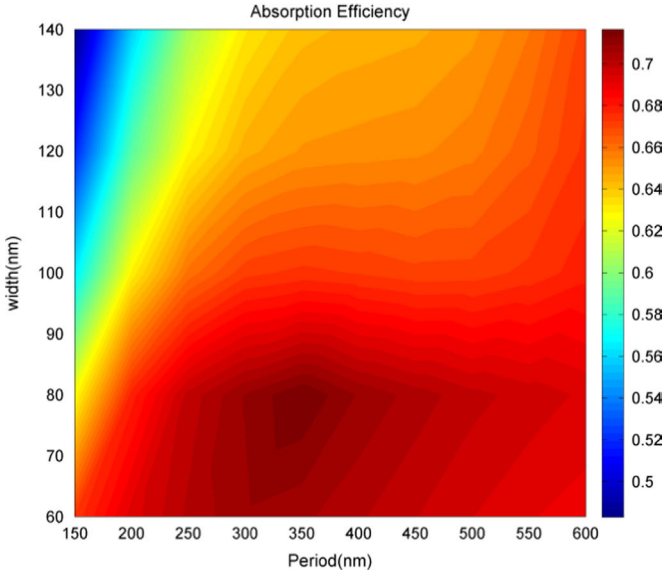

Fig. 2. Absorption efficiency of various solar cell structure is shown in the color graph, as a function of period and width of the back metal structure.