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Broadband absorption enhancement in plasmonic thin-film solar cells with grating surface

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ABSTRACT

The plasmonic thin-film solar cells with grating surface is structured and simulated by Comsol Multiphysics software using finite element method. The absorption efficiency of solar cells has been systemically studied by considering structure characteristic parameters. The absorption of grating surface cell is much broader and stronger than that of smooth surface on a-Si at the wavelength from 400 to 700 nm. The value of total absorption efficiency (*TAE*) increases from 47% to 69.3%. The embedded Ag nanoparticle array contributes to the improvement of the absorption of a-Si at longer wavelength range. The localized surface plasmon resonance is induced by Ag nanoparticles, and so that the *TAE* is increased to 75.1% when the radius of nanoparticle is 60 nm at the bottom of a-Si with periodic width 200 nm. The grating surface always plays a role to suppress light scattering from the active region, so more light can be absorbed again by a-Si in the infrared-region. Therefore, the results have significance in providing a theoretical foundation for the applications of thin-film solar cell.

1. Introduction

In recent decades, photovoltaic solar cells have been extensively studied because it can convert effectively sunlight into clean electrical power. However, the conventional thick Si solar cells have relatively high cost of manufacture and low absorption of sunlight. For this reason, there is a great interest in second-generation Si solar cells: thin-film solar cells (TFSCs) based on amorphous silicon/hydrogen alloys or polycrystalline compound semiconductors. TFSCs are deposited on cheap foreign substrates such as glass, ceramics, plastic or stainless steel. They are made from variety of semiconductors. But in all TFSC technologies, there is poor absorption efficiency around bandgap light, especially for the indirect bandgap semiconductor Si [1]. Therefore, for the purpose of increasing the light absorption, it is very important to structure the TFSC so that light is trapped inside.

Recent researches into the field of plasmonic show that the use of metal nanostructures is an effective method for increasing the light absorption of TFSCs [2–8]. When a monolayer of Ag nano particles was deposited onto the 165 nm thick silicon-on-insulator (SOI) photodetectors [4], a nearly factor-of-20 photocurrent enhancement was observed for light of wavelength 800 nm. Similarly, depositing Au nanoparticles above the amorphous silicon (a-Si) film [5], Derkac et al. observed an 8.1% increase in short-circuit current density and an 8.3% increase in energy conversion efficiency. Subsequently Pillai et al. deposited Ag nanoparticles on 1250 nm SOI cells [6], obtaining an absorption enhancement of close

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to 16-fold at a wavelength near 1050 nm and the overall photocurrent improvement of 33%. Adjusting the wavelengths of the localized surface plasmon resonances (LSPR) of Ag strips to match the spectral sensitivity of the solar cell, Hallermann et al. found that more than 50% photons can be absorbed in a-Si layer under TM-polarized illumination [7]. These results show that the metal nanostructures make great contribution to the enhancement of absorption. When illuminated with light of suitable frequency, metal nanoparticles exhibit the phenomenon of LSPR and are strong scatters of incident light at wavelengths near the plasmon resonance [8]. Due to the LSPR, light absorption of the active region can be effectively enhanced by light scattering and light localization [9–13]. The location of the resonances depends strongly on the metal nanoparticles characteristic parameters such as shape, size, material, and dielectric environment [14–16].

Researchers have explored the various structural thin film solar cells in order to enhance the absorption efficiency [3,6,17–21]. Among these structures, periodic grating array is an important and simple way for effective enhancement of absorption in TFSCs [11,16,20,21]. So in this paper, we design a grating structure thin film a-Si solar cells with Ag nanoparticles array to save raw materials of a-Si, and more importantly, to get a broad and strong absorption at visible light. By adjusting the structure parameters of a-Si solar cells such as the radius of Ag nanoparticles, the width of grating surface, the periodic width of grating and the distance from the bottom of nanoparticles to bottom of a-Si, we demonstrate the grating surface achieves broadband absorption enhancement in the visible region. The Ag nanoparticle array structure improves the absorption efficiency of the cell in the longer wavelength.

2. Structural model and simulation method

The 3-D periodic model for thin-film a-Si solar cells here proposed is depicted in Fig. 1. As a front contact, the upper part of the cell is a 20 nm high ITO [22]. The active region is a 300 nm high a-Si with grating surface, and the width of grating surface and its height are defined as *a* and 100 nm, respectively. The Ag nanoparticles array is embedded in the active region, and the radius of the nanoparticle is defined as *r*. The *d* means the distance from bottom of a-Si to the bottom of Ag nanoparticle. A 200 nm high Al layer is considered as the back contact at the bottom of the thin film solar cells. The *w* is the periodic width. All these simulation optical data such as the refractive (*n*, *k*) of a-Si, Ag, Al, and ITO are taken from the SOPRA database [23].

This model for plasmonic solar cell is simulated by Comsol Multiphysics software [24]. The software solves the 3-D Maxwell's equations by finite element method [3]. The incident light is a TM plane wave of unit amplitude with wavelengths from 400 to 950 nm, and the plane wave is placed above the grating surface. The model is periodically distributed along the *x* and *y* axis [25]. The perfectly matched layer (PML) boundary condition are used for upper and lower boundary conditions to approximate the infinite space and infinite bottom contact respectively. The periodic conditions are used for the front, the back, the right and the left of the cell. It is easy to create the grating surface on the a-Si by the imprinting method [26].

The absorption efficiency $AE(\lambda)$ of solar cells, as shown by Eq. (1), which is defined as the ratio of the power of the absorbed light $P_{abs}(\lambda)$ to that of the incident light $P_{in}(\lambda)$ within the a-Si substrate. For the broad spectrum of incident electromagnetic radiation, the total absorption efficiency *TAE*, which takes the solar spectral irradiance into account, determines the overall absorption efficiency of the solar cell [24]. The *TAE* is calculated using Eq. (2).

$$AE(\lambda) = P_{abs}(\lambda)/P_{in}(\lambda) \tag{1}$$

$$TAE = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \frac{\lambda}{hc} AE(\lambda) I_{AM1.5G}(\lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} \frac{\lambda}{hc} I_{AM1.5G}(\lambda) d\lambda} \tag{2}$$

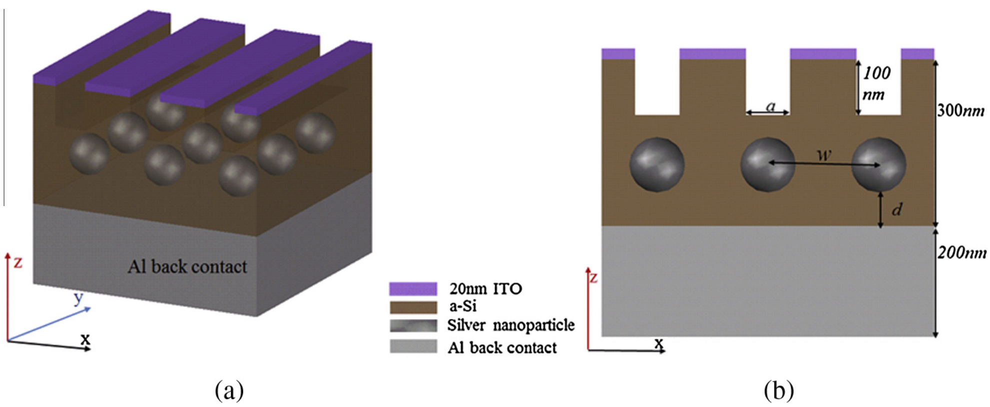

Fig. 1. Structure of TFSCs with Ag nanoparticles array, (a) view of the 3-D model, and (b) the cross-section view with parameters.