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Ultrathin solar cells with Ag meta-material nanostructure for light absorption enhancement

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ABSTRACT

The two major problems of conventional photovoltaic devices are their low conversion efficiencies and relatively high production cost. Lately, ultrathin film photovoltaics have been proposed to overcome the mentioned issues. However, the thin film solar cells have some weaknesses, and the main deficiency is their low light absorption, which is related to the reduced absorber thickness. Therefore, light management plans are needed for ultrathin solar cells to enhance their light absorption. Using plasmonic and more specifically the meta-material structures is one of the efficient techniques to manage and trap the incident light inside the active region of photovoltaics. Here, we have proposed an ultrathin Si solar cell with embedded meta-material nanostripes in which their positions were swept in x and z directions to acquire the optimum performance. The results show that the designed structure gives rise to 154.8% light absorption enhancement and 189.5% short-circuit current density enhancement over the solar spectrum compared to the reference conventional structure.

1. Introduction

Recently, ultrathin films have attracted lots of attention for solar cell application, due to their low production cost, reduced carrier recombination rate, and high open-circuit voltage. Besides those mentioned merits, their main drawback is low light absorption at the wavelengths around their electronic bandgap due to the decreased optical traveling path length. Accordingly, applying light trapping schemes for obtaining high-efficiency thin film solar cells (TFSCs) is undoubtedly vital. In the past years, many light trapping techniques have been proposed, but applying plasmonic and more specifically the meta-material structures, engineered within the solar cell geometry, is one of the most efficient methods to manage and trap the incident light inside the active region of the photovoltaic cells (Tan et al., 2012; Farangi et al., 2012; Poursafar et al., 2016; Bashirpour et al., 2016; Brongersma et al., 2014; Sun et al., 2014). The meta-material nanostructures make the incident light scatter and thereby couple into different modes like light scattering, localized surface plasmons, and surface plasmon polaritons within the active layer. This process results in light absorption enhancement in different wavelength ranges (Brongersma et al., 2014; Fei Guo et al., 2014; Yang et al., 2014; Lee et al., 2015).

There have been a large number of reports demonstrating the TFSCs' efficiency enhancement using the plasmonic nanostructures. A GaAs-based solar cell with the plasmonic structures has been reported experimentally, which showed high absorption peaks' enhancement and 8% overall efficiency improvement (Nakayama et al., 2008). Recently, a polymer photovoltaic structure containing Au nanoparticles demonstrated power conversion efficiency enhancement from 3.57% to 4.24% (Wu et al., 2011). An ultrathin a-Si:H solar cell with a cell thickness of 60 nm was also investigated and demonstrated that by adding Ag nanoparticles to the cell structure the overall performance was increased. This group confirmed that the short circuit current density and efficiency were improved more for thinner cells with an increase in overall efficiency of 50% for the 60 nm cell (Winans et al., 2015). Another group proposed a crystalline gallium arsenide plasmonic metamaterial photovoltaic structure for enhancing the light absorption. Their structure contained a bottom metallic film and a top subwavelength concave grating which effectively trapped light with aim of wave interference and magnetic resonance effects which gave rise to significant short circuit current density enhancement by three times (Wang and Wang, 2015). However, the reported improvement of the TFSCs performance was very limited and the proposed structures have had complex

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Table 1
Finite-difference time-domain method parameters.

Min mesh step (nm)	0.25
Time step d_t (fs)	0.075822
Stability factor	0.99
Simulation time (fs)	1000
Min sampling per cycle	2
Spatial cell size d_x (nm)	5
Spatial cell size d_y (nm)	5
Spatial cell size d_z (nm)	3
Frequency point	177

designs, fabrication difficulties, and high costs (Awal et al., 2015). In this study, a simple meta-material nanostructure design to obtain a significant light absorption enhancement was suggested. For this reason, the back reflector of the TFSC was grated and Ag nanostripes' positions were swept inside the absorption layer of the TFSC in z- and x-direction. The effect of the Ag nanostripe position on the short circuit current density was considered with respect to the grated back reflector to achieve the optimum cell performance.

2. Structure design and simulation method

The finite-difference-time-domain (FDTD) method for solving Maxwell's wave equations was used to analyze the proposed structure. The design is a 2-D structure. Thereby, both transverse electric (TE) and transverse magnetic (TM) plane polarized light were used to obtain more accurate results. The perfectly matched layers' (PMLs) boundary conditions were used in the propagation direction. The main FDTD simulation parameters are presented in Table 1 (Awal et al., 2015; Shaban et al., 2017; Bashirpour et al., 2017).

The complex Poynting vector is given by:

$$\overrightarrow{P} = \overrightarrow{E}(w) \times \overrightarrow{H}^*(w) \tag{1}$$

where $\overrightarrow{E}(w)$ and $\overrightarrow{H}^*(w)$ are the electric and the magnetic fields. Eq. (1) can be used to obtain the power flow in a particular direction. Clearly, the power of the propagating wave is just proportional to the real part of the Poynting vector, which is associated with the conservation of energy for the time-averaged quantities (Awal et al., 2015; Zhu et al., 2013; Pala et al., 2009; Ahmadivand et al., 2012). Thus, the total time-averaged power flowing across a surface should be:

$$Power(w) = \frac{1}{2}\int_s real(\overrightarrow{P})\cdot\overrightarrow{d_s} \tag{2}$$

The 1/2 factor in Eq. (2) is related to the time-averaging of the clockwise fields. The imaginary part of the Poynting vector can be ignored for obtaining the transmitted power (T(w)), due to its relation to the non-propagating reactive or stored energy. As a result, the transmitted power (T(w)) can be computed as follows by considering the real time-averaged power variations along the x and y axes for monitor and electric field source, respectively:

$$T(w) = \frac{\frac{1}{2}\int real(P_y^{Monitor}(w))\cdot d_x}{\frac{1}{2}\int real(P_x^{Source}(w))\cdot d_x} \tag{3}$$

In this way, all associated quantities such as absorption, reflection, etc. were calculated from the transmitted power plane (Ahmadivand et al., 2012)

For ultrathin Si solar cells where the Si layer thickness is remarkably smaller than the diffusion length (100 nm), it is reasonable to suppose that, all photo-generated carriers can be collected at the electrodes. If every absorbed photon generates an electron-hole pair, J_{sc} (the short-circuit current density) becomes:

$$J_{sc} = q\int_0^\infty I(\lambda)R(\lambda)d\lambda \tag{4}$$

where q is the charge of an electron, $I(\lambda)$ is the solar irradiance, and $R(\lambda)$ is the spectral response of the cell. The AM 1.5 solar spectrum was taken into account to calculate the short circuit current densities (Awal et al., 2015; Ahmadivand and Pala, 2015). To obtain promising results from the simulation, the materials' (silver, silicon dioxide, and crystalline silicon) parameters have been extracted from the previously published experimental data (Humlíček et al., 1998; Schinke et al., 2015; Lynch and Hunter, 1997).

The schematic diagram of reference structure and the designed structure with their geometrical parameters are illustrated in Fig. 1(a)–(c). For the sake of comparison, a reference structure was also taken into account and considered as a crystalline silicon layer deposited on an Ag substrate (Fig. 1(a)). Considering the mentioned reference structure, one can suppose that the proposed structure is the reference structure in a way that the metal stripes were cut from the back reflector and their positions changed inside the absorbing layer to see the phenomena and finally, to confirm the meaning of the meta-materials.

As shown in this figure, the Ag back contact layer was grated and the Ag nanostripes were moved, first in the z-direction and then, in the x-direction. The geometrical dimensions are a = 10, b = 100, c = 40 and d = 150 nm. The structure is periodic in the x-direction.

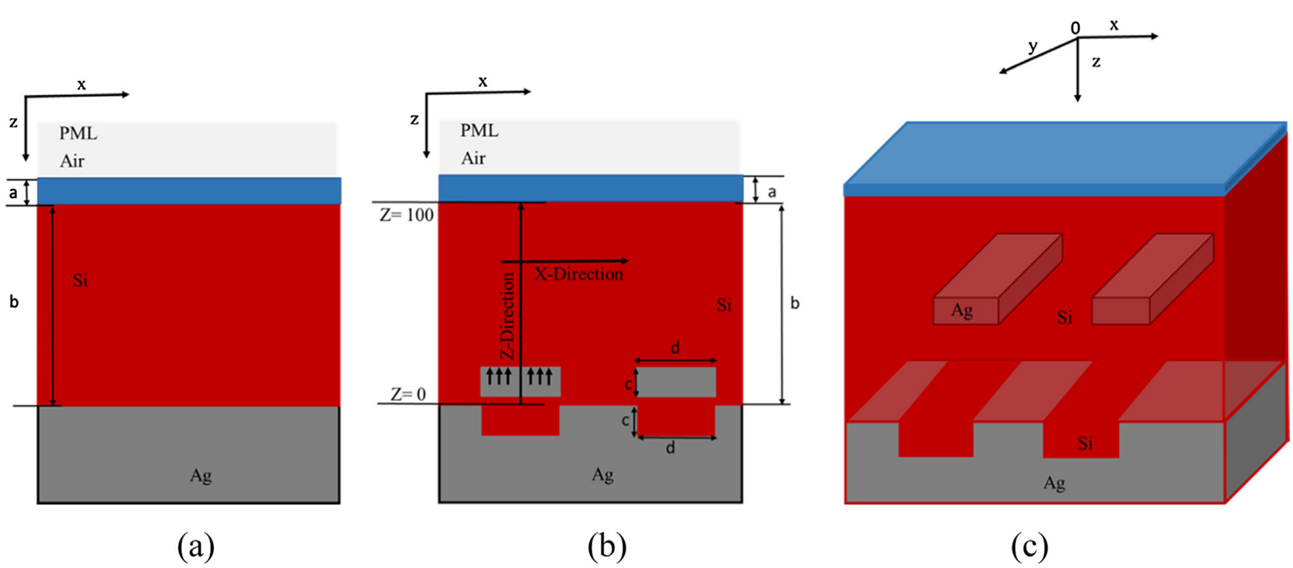

Fig. 1. (a) Side view of the reference structure. (b) Side view of the structure. (c) Schematic diagram of the proposed double layer plasmonic solar cell structure.