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Broadband absorption enhancement in periodic structure plasmonic solar cell

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Abstract In this paper, a novel design of plasmonic solar cell is investigated and analysed using 3D finite difference time domain method. The suggested design has a cylindrical metallic nanoparticles with hydrogenated amorphous silicon (a-Si:H) as an active material. The aim of our work is to get maximum absorption of thin film solar cell by scattering the light from metal nanoparticles. Therefore, the effects of the structure geometrical parameters on the absorption are investigated. The numerical results show that 35 % absorption improvement is achieved over the conventional thin film solar cell without metallic nanoparticles.

Keywords Photovoltaic · Plasmonic · Absorption enhancement · Finite difference time domain

1 Introduction

In the last few years, the development of low cost, and environmentally friendly energy sources has attracted the attention of many researchers all over the world. In addition, the search for clean sources of energy that can face the population and economic growth becomes mandatory. The photovoltaic solar cell (SC) can be considered as a clean energy source instead of fossils fuel. However bringing photovoltaic solar cell to the market is limited due to its high cost. The bulk material cost of photovoltaic devices can be reduced by using thin film solar cell technology which paves the road to a new generation of solar cells. However, the absorption of thin film solar cells is quite weak. In addition, thin film materials have much short diffusion paths. Therefore, the losses from minority carrier recombination have been reduced (Müller

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et al. 2009). So we should find promising alternatives to improve the absorption in optically thin semiconducting films by using surface texturing, etched diffracting grating or distributed Bragg reflector (Green 1998; Müller et al. 2009). These alternatives can be used to improve the absorption of light in the active layer by scattering the light from the surface or the bottom boundaries of the solar cell. However, these strategies are incompatible well with thin film solar cell due to the high minority carrier recombination texture. In addition, the necessary texture dimension is nearly equal to 1.0 μm that can easily exceed the film thickness. Recent studies on both organic (Westphalen et al. 2000; Tong et al. 2008) and inorganic (Stuart and Hall 1998; Pillai et al. 2007) solar cells have shown that improving the thin-film solar cells performance can be significantly achieved by metallic nanoparticles deposited on top of the photo-active layer.

The metallic nanoparticles (NPs) can improve the absorption of the active region of thin film solar cells. Moreover, the NPs have special optical properties that are different than those of bulk materials. The incident light very effectively interacts with the metal nanoparticles over cross-sections much larger than the geometrical cross-sections of these nanoparticles (Akimov et al. 2009). In other words, the excitation of multiple surface plasmons leads to the extraordinary scattering (Luk'yanchuk et al. 2007; Hussein et al. 2014) and strong electromagnetic field enhancement in the vicinity of nanoparticle surfaces (Kottmann et al. 2000; Ewe et al. 2007). Due to enhanced near-fields, the scattered light can very efficiently couple into waveguide modes of the active layer (Soller and Hall 2002; Catchpole and Pillai 2006). In this regard, strong optical scattering and strongly enhanced optical near-field occur around the NPs due to their localized surface plasmon resonance (Akimov et al. 2004). This makes the nanoparticles a very efficient and flexible tool for solar cell applications, which can be used to manipulate the light trapping and energy conversion efficiency. The metallic nanoparticles have been used to enhance the absorption of thin film solar cell without increasing the thickness of the active layer which decreases the overall cost. The solar cell performance can be enhanced by using very different nanoparticle materials, shapes, sizes, and surface coverage. In addition, many researchers have studied the influence of the nanoparticle shapes (Catchpole and Polman 2008; Hägglund et al. 2008) on the localized field enhancement and light trapping. The absorption enhancement in thin-film silicon solar cells with two dimensional spherical nanoparticles arranged in square lattice is about 20 % (Akimov et al. 2009; Wu et al. 2010).

In this paper, a novel design of thin film plasmonic solar cell is reported and analyzed by 3D Finite Difference Time Domain (FDTD) Lumerical software package to simulate the light absorption in the reported structure. The suggested solar cell has cylindrical metallic NPs arranged in a periodic array. The effects of the structure geometrical parameters such as cylinders diameter and height on the performance of the proposed solar cell are investigated. The numerical results reveal that the proposed metallic NPs improve the absorption of the conventional thin film solar cell by 35 %.

2 Design and numerical method

Figure 1 shows cross section of the suggested cylindrical plasmonic solar cell (C-PSC). Our proposed structure is based on hydrogenated amorphous silicon (a-Si:H) as an active material of thickness T. The active material is placed over Al layer and is coated by ITO layer. The top surface of the ITO coating is uniformly covered by two rings of cylindrical aluminum NPs arranged in a periodic array. The central cylinder has a radius R_c. However, the cylinders of the 1st and 2nd rings have radii R_1 and R_2, respectively. The NPs of the first ring are arranged

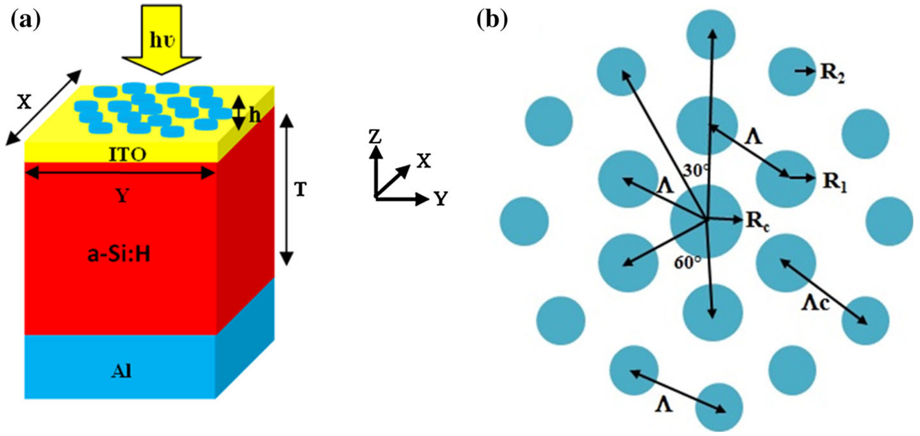

Fig. 1 **a** 3D diagram of the proposed cylindrical plasmonic solar cell. **b** 2D top view of arrangement of Al nano-particles unit cell

in hexagonal shape with hole pitch Λ. Additionally, the distance between two adjacent NPs in the 1st and 2nd ring is equal to Λ_c. Moreover the NPs of the 2nd ring are arranged in dodecagon shape with hole pitch Λ. Furthermore, X and Y are the length and width of the structure, respectively as shown in Fig. 1a.

In this study, the suggested design is illuminated from the top by plane wave normal to x-y plane with an electric field linearly polarized along the x-axis. Then, the 3D-FDTD method is employed for investigating the optical properties of the cylindrical plasmonic solar cell (C-PSC). In this regard, the FDTD (Obayya 2011; Pinto 2007) is applied to simulate the light absorption in the reported structure. The simulation results are obtained with periodic boundary condition in x and y directions and perfect matching layer in z-direction. In order to obtain accurate results, non-uniform meshing capabilities are used. The boundary conditions are employed to account the multiple scattering caused by nanoparticle-nanoparticle, nanoparticle substrate, and nanoparticle-substrate-nanoparticle interactions. Moreover the incident light shape is a plane wave shape. All the major effects of the metallic nanoparticles deposited on top of the cell are taken into account through the performed simulations.

3 Numerical results

In the proposed structure, firstly the second ring of the NPs has been removed. In addition, all the cylindrical NPs of the structure of height h = 80 nm have the same distance from the central cylinder centre $\Lambda = 100$ nm. Moreover, the distance between two adjacent NPs in the first and second ring is equal $\Lambda_c = 180$ nm. The photoactive layer thickness is T = 600 nm while the thickness of ITO and Al layers are taken as 20, 80 nm, respectively. Furthermore the length and width of the structure are equal to X = Y = 140 nm. Figure 2 shows the wavelength dependent absorption percentage of the photoactive layer a-Si:H at different cylinders radii with height h = 80 nm. In this study, the central cylinder radius R_c is equal to the radius of cladding cylinders. In addition, the absorption percentage variation for conventional thin film solar cell without NPs is also shown in Fig. 2. It is revealed from this figure that the absorption increases by increasing the central cylinder and cladding cylinders radii. However, this will be on expense of decreasing the absorption bandwidth. As the cylinder radius increases, the

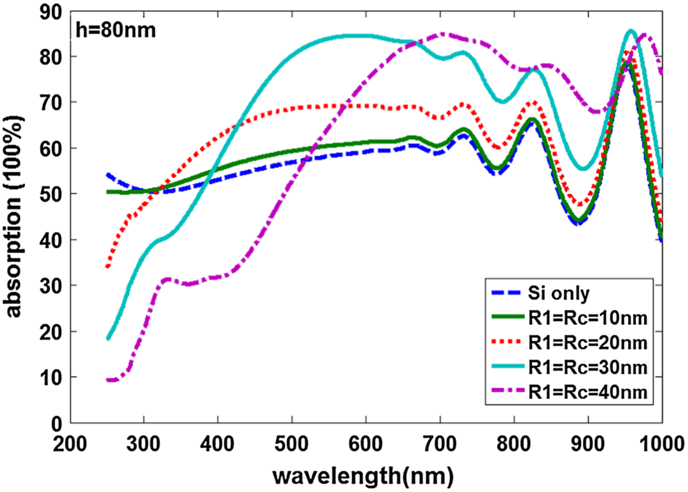

Fig. 2 Spectral absorption of the a-Si:H photo-active layer as a function of wavelength at different cylinders radii $R = R_c = 10, 20, 30$ and 40 nm

metal surface area and its absorption will be increased. Therefore, the active layer absorption bandwidth decreases as shown in Fig. 2. It should be noted that metallic nano structures are able to scatter the incident light with larger scattering cross-section than their own size through the excitation of the SP. In addition, an extraordinary optical absorption can be obtained by the metallic nanostructure through the enhanced near field associated with SP resonance. Therefore, the absorption in the active layer of the suggested design is enhanced compared to the conventional thin film solar cell as shown in Fig. 2. However, there is an optical absorption due to the metallic NPs around SP resonance wavelength. Therefore, the absorption in active layer is not 100 %. It is also evident from Fig. 2 that there is a peak and valley around $\lambda = 990$ nm and $\lambda = 870$ nm, respectively for all cases which are beyond the bandgap of the active layer. This is due to the Fabry Perot cavity resonance within the a-Si:H active layer. The constructive and destructive interference will also result in other peaks and valleys in the absorption of the SP resonance as shown in Figs. 2 and 3.

Figure 3 shows the variation of the absorption % of the photoactive layer at different central cylinder radii $R_c = 0, 10, 20, 30$ and 40 nm while the radius of the cladding cylinders is fixed to $R_1 = 30$ nm and the height is taken as h = 80 nm. It is revealed from Fig. 3 that the absorption increases by increasing the radius of the central cylinder. This is due to the good confinement of the field around the central cylinder as shown in Fig. 4a. Figure 4 a and b show the absorbed electric field distribution of the surface plasmon TE mode along x-y plane at the top surface of the active layer with $R_c = 40$ nm and $R_c = 0$, respectively. Additionally, the absorbed electric field in the conventional solar cell without NPs is shown in Fig. 4c. It is revealed from Figs. 3, and 4 that the absorption of the active layer of the proposal design is greater than that of the conventional solar cell and the suggested design without central cylinder ($R_c = 0$).

Next, the effect of the cylinders height is investigated. Figure 5 shows the variation of the absorption % of the photoactive layer of the proposed C-PSC at different cylinders height h=40, 60, 80, 100 and 120 nm with $R_c = 40$ nm and $R_1 = 30$ nm. It is revealed from Fig. 5 that as the height of the cylinders increases, the bandwidth of the absorption decreases due to the increase of the metal surface area and its absorption. Therefore, the absorption of the

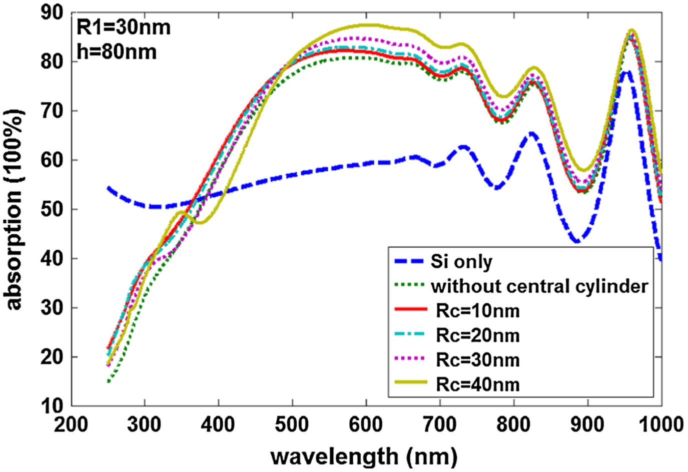

Fig. 3 Spectral absorption of the a-Si:H photo-active layer as a function of wavelength at different central cylinder radius $R_c = 10, 20, 30$ and 40 nm

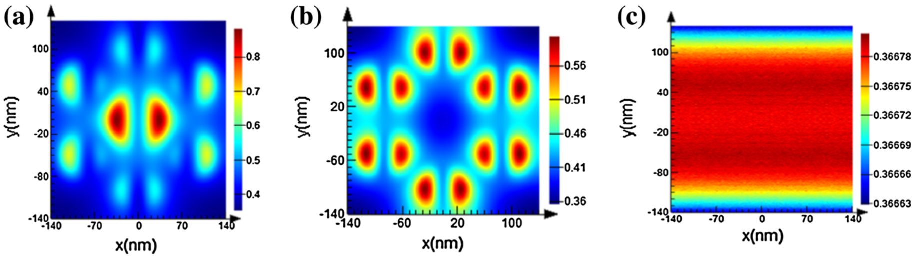

Fig. 4 Absorbed electric field distribution of TE mode along x- y plane on the top surface of the active layer in **a** C-PSC with $R_c = 40$ nm, **b** C-PSC without central cylinder $R_c = 0$ and **c** conventional solar cell without NPs

metallic nanoparticle increases. As a result, the absorption through the active layer decreases and hence the bandwidth decreases. This is similar to the behavior of increasing the radius of spherical nanoparticle reported in (Müller et al. 2009).

The impact of adding a second ring of NPs to the proposed structure is next studied. In this investigation, the 1st ring cylinders have the same distance from the central cylinder centre $\Lambda = 100$ nm. Furthermore, the distance between the 1st and 2nd ring cylinders is equal to $\Lambda_c = 80$ nm. The photoactive layer thickness T is equal to 600 nm while the thickness of ITO and Al layers is taken as 20, 80 nm, respectively. Moreover, the length and width of the structure are equal to $X = Y = 217$ nm. It should be noted that the use of different cylinders heights can suppress the incident solar spectrum reflection as well as increase the light trapping through the active layer. Therefore, the different heights of the cylinders in different rings can be optimized to improve the total absorption. Figures 6 and 7 illustrates the variation of the absorption % of the photoactive layer and absorption enhancement of the proposed C-PSC at different cylinders materials Ag, Au and Al with $R_2 = 30$ nm, $R_c = 40$ nm and $R_1 = 35$ nm. In this study, the central cylinder has height of 85 nm while the heights of the cylinders of first and second ring are taken as 80 and 60 nm, respectively. The absorption % of the photoactive layer and absorption enhancement using Al NPs with

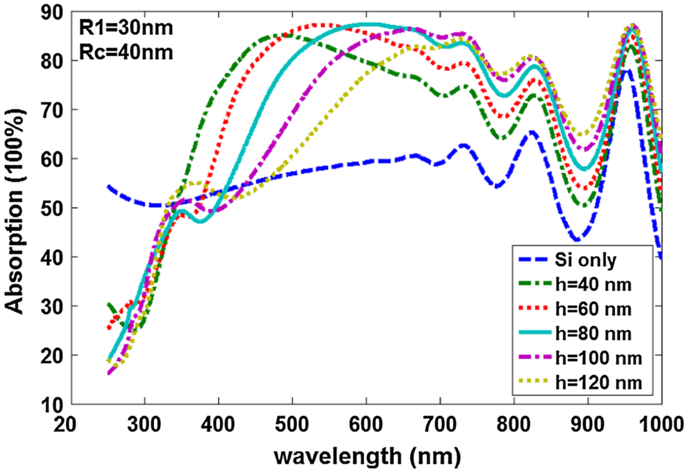

Fig. 5 Spectral absorption of the a-Si:H photo-active layer as a function of wavelength at different cylinders height h = 40, 60, 80, 100 and 120 nm

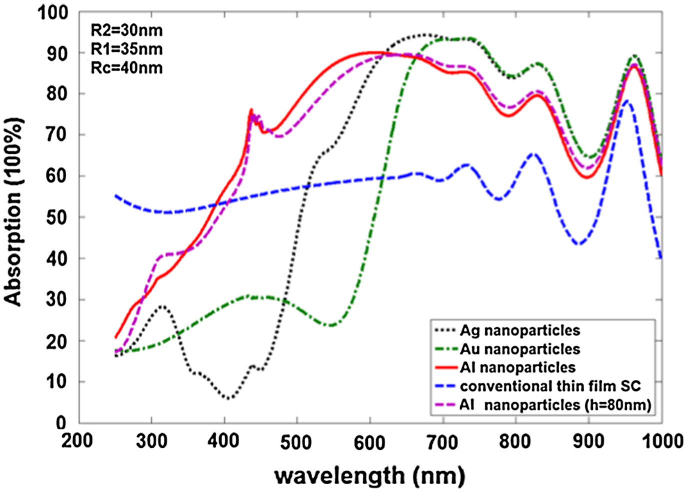

Fig. 6 Spectral absorption of the a-Si:H photo-active layer as a function of wavelength at different nanoparticles material Au, Al and Ag

the same height of 80 nm are also shown in Figs. 6 and 7, respectively. It is found that the absorption % of the photoactive layer and absorption enhancement using Al NPs of different heights are better than those with the same height as shown in Figs. 6 and 7. This is due to the multiple scattering of the electromagnetic wave and good confinement of the mode around the central cylinder. On the contrary, the same height of all cylinders increases the probability of the reflection of incident solar spectrum (Müller et al. 2009).

It's also evident from Fig. 7 that the best absorption enhancement in the active layer is achieved by Al NPs. Additionally, Figs. 6 and 7 show that the different heights of the cylinders increase the absorption inside the active layer. The SP resonance of Ag and Au NPs lie in the visible light region. Therefore, the absorption bandwidth appears to be narrow. In contrast,

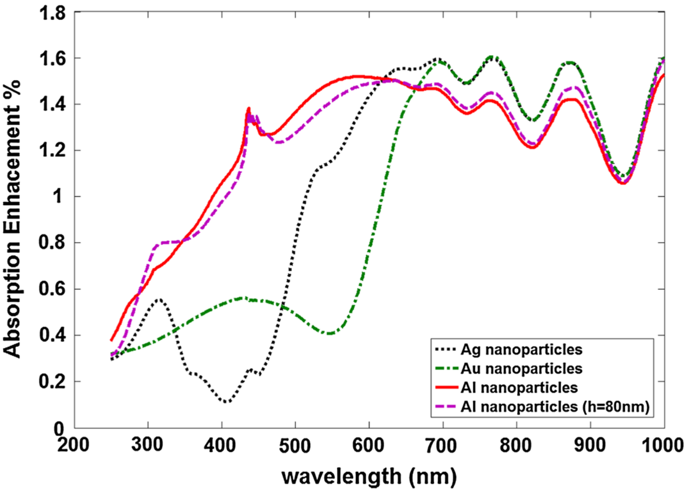

Fig. 7 Spectral absorption enhancement of the a-Si:H photoactive layer as a function of wavelength at different nanoparticles materials Au, Al and Ag

Al particles have a much wider absorption range, because their resonant wavelengths are in the ultraviolet region (Hägglund et al. 2008). Figs. 6 and 7 also reveal that there is a valley at $\lambda = 450$nm for Al NPs. This is due to the destructive interference between NPs scattered light through the a-Si:H active layer.

To calculate the total enhancement for optical power absorption, the total absorbed power, P_{tot}, has been calculated by integration of the absorption rate of the photoactive layer over the AM1.5 global spectrum for a wide range of the array parameters R, R_c and h. Then the required dependence of the plasmon enhancement on R, R_c and h are calculated from:

$$F(R,Rc,h) = \frac{P_{tot}(R,Rc,h)}{P_{tot}(0,0,0)} - 1 \tag{1}$$

where $P_{tot}(0, 0, 0)$ is the total absorbed power by the plain cell without NPs. It is found that an optimum absorption enhancement of 35 % over the conventional thin film solar cell can be obtained using two rings of Al NPs with different heights which is more than the enhancement absorption of one ring only by 2.75 %. Additionally, an absorption enhancement of 32 % is achieved using AL NPs with the same height of 80 nm. Moreover, the suggested design has an enhancement of 20 % over the spherical NPs plasmonic solar cells (Akimov et al. 2009).

4 Conclusion

Absorption enhancement in thin film hydrogenated amorphous silicon by using two dimensional metallic cylindrical nanoparticles array is studied using 3D FDTD method. We identify the mechanism used to calculate the enhancement absorption and consider the influence of nanoparticles size, height, and material in order to optimize the NPs for maximum absorption enhancement of solar cell. The Al nanoparticles array offers considerable increase in the absorption of photoactive layer. However, Au and Ag don't provide a good absorption enhancement to the solar cells due to their high energy dissipation in the visible region. The numerical results show around 35 % absorption improvement compared to the conventional thin film solar cell without metallic nanoparticles.

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