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Indium Nanoparticle Enhanced Light Trapping in Thin Film Silicon Solar Cells

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Plasmonic nanoparticles can be engineered to achieve light trapping and get the full potential of thin film solar cells. This paper presents indium (In) nanoparticle based plasmon enhanced light trapping mechanism for thin film silicon solar cells. With the light trapping at the front, at the rear or at both surfaces of the solar cell along with a thin silicon nitride (Si_3N_4) antireflection coating, surface transmittance, reflectance and absorption enhancement of incident light were studied. In all the cases indium nanoparticle based light trapping resulted in more light absorption implying more photocurrent generation but the geometry and position of the nanoparticles determine the scattering and coupling properties. Therefore, optimization of indium nanoparticle diameter and inter-particle spacing was performed. Compared to more commonly used (but highly expensive) gold nanoparticles, indium nanoparticles based light trapping performed well in every aspect. These demonstrate the suitability of indium nanoparticles for light trapping in the thin film silicon solar cells, particularly in deep ultraviolet (UV) and near visible regions.

Keywords: Thin film solar cell, Light trapping, Plasmonics, Antireflection coating, FDTD method.

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1. INTRODUCTION

Light absorption in thin film silicon solar cells is quite low, particularly at longer wavelengths because the thickness of Si absorber layer is very small [1-2]. To address this issue efficient light trapping arrangements can be used as they increase the optical path length of the incident light within the cell. However, conventional methods of light trapping by creating pyramids on the surface cannot be used because thin film silicon solar cells are only a few microns thick and the pyramids have larger dimensions. On the other hand, introduction of submicron-sized features by plasma etching techniques can damage the silicon. The other alternative of substrate-texturing also results in in-creased recombination losses because the incremented surface area increases minority carrier recombination in the surface and junction regions. Therefore, a well-designed light trapping mechanism which will aid to get the full potential of thin film solar cells is essential [3-5]. Different types of light trapping strategies have been suggested in the literature. These include reduction of reflectance of incident light and enhancement of absorption of the same by incorporating antireflection coatings (ARCs). In recent years use of metallic nano-structures supporting surface plasmons have been pro-posed by many researchers for achieving light trapping [6-8]. These metallic nanostructures demonstrate local surface plasmon resonance at which incident light strongly excites the collective oscillation of conduction electrons leading to either strong absorption or scattering of light. By proper engineering of the metallic nanostructures light can be concentrated and folded into the thin semiconductor absorber layer which increases the absorption [9]. In such light trapping strategy, the size and geometry of the metallic nanoparticles and the local dielectric environment determine the amount of light scattering and coupling efficiency [10]. Silver (Ag) and gold (Au) are the most commonly used nanoparticles for plasmonic light trapping. However, because of their scarcity in the earth crust and high cost, use of such noble metallic nanoparticles is not a practical option [11-12]. In this work we studied indium nanoparticle [13] based light trapping for thin film Si solar cells. Light trapping using indium nanoparticles was used at the front, at the rear or at both surfaces of the solar cell along with a thin silicon nitride (Si_3N_4) anti-reflection coating and performance was studied in terms of surface transmittance, reflectance and absorption enhancement of incident light. In all the cases the light trapping arrangement resulted in more light absorption implying more photocurrent generation but the geometry and position of the nanoparticles affected the performance. Therefore optimization of indium nanoparticle diameter and inter-particle spacing was performed. We compared the performance of light trapping based on indium nanoparticles against more commonly used gold nanoparticles.

2. INDIUM NANOPARTICLE ENHANCED THIN FILM SILICON SOLAR CELL

In thin film silicon solar cells incoming light is not completely absorbed in one single pass while to minimize the process time the absorber layer thickness should be as small as possible [2]. Therefore, the optical path length of the light inside the cell needs to be increased. To achieve this, we have designed a plasmon enhanced thin film silicon solar cell with Si_3N_4 antireflection coating (ARC) and an array of In nanoparticles, both placed on the Si absorber layer. The purpose of such arrangement is to reduce the reflection from the illuminating surface and enhance the absorption of incident light in the Si absorber layer. Schematic diagram of the designed thin film silicon solar cell having the front surface light trapping is shown in Fig. 1(a), where, t_1 and t_2 are, respectively, the thick-

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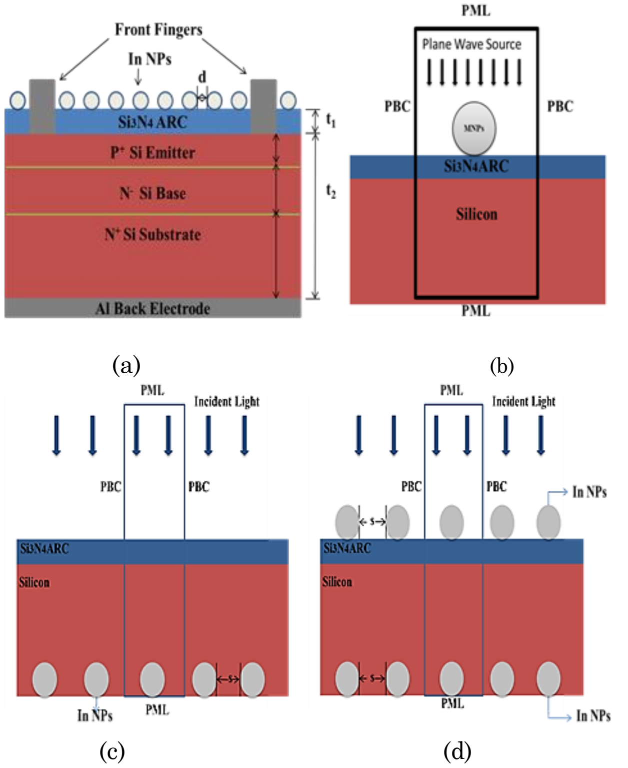
nesses of the Si_3N_4 ARC and the silicon absorbing layer and d is the distance between adjacent nanoparticles. In the arrangement of Fig. 1 (c) In nanoparticles are placed on the rear surface of the cell while in the configuration of Fig. 1 (d) both the front and rear surfaces of the cell have In nanoparticles placed on them. The thickness of the Si absorber layer was 1 μm. For a single layer ARC the reflectance of incident light significantly reduces when the refractive index of the ARC material is $n_1 = \sqrt{n_0 n_2}$ and $t_1 = \lambda / 4n_1$ is the thickness of the ARC [14]. Here, λ is the wavelength of the incident light, t_1 is the thickness of the ARC, n_0, n_1 and n_2 are, respectively, the refractive indices of air, ARC, and Si. Following this, Si_3N_4 having the refractive index of 2.05 was used as the ARC material while thickness of the ARC layer was 60 nm which is an optimized value for the wavelength range of 400 nm-1100 nm. The diameter of the indium nanoparticles and the distance between adjacent nanoparticles were optimized to obtain the highest possible light absorption.



(a) (b)

(c) (d)

Fig. 1 – (a) Structure of the proposed plasmon enhanced thin film silicon solar cell with front surface light trap-ping, (b) 2D representation of a unit cell of the 3D FDTD simulation, (c) rear surface light trapping (d) both surface light trapping

3. RESULTS AND DISCUSSION

The thin film solar cell with light trapping arrangement was studied using three-dimensional FDTD numerical simulations. Simplified two-dimensional diagram of the simulation setup for the front surface light trapping (Fig. 1(a)) is shown in Fig. 1 (b). It shows a unit cell which is periodically repeated along the lateral direction. In the FDTD simulation perfectly matched layer (PML) boundary condition was used in the solar irradiance direction whereas periodic boundary conditions (PBC) were used in the lateral directions. Incident radiation intensity of 1000 Wm^{-2}, temperature of 25 °C and solar spectral irradiance of AM1.5 [15] were used in this study. To observe the performance of the light trapping structures surface transmittance, reflectance and absorption of incident light within the silicon absorber layer and thereby the absorption enhancement were studied. First, the increase of surface transmittance due to the presence of antireflection coating was studied. Fig. 2 shows more light reaches the Si absorber layer because of the use of ARC compared to the case when no ARC is present. When plasmonic nanoparticles are used with the ARC for light trapping, surface transmittance is also increased but the geometry and position of the nanoparticles determine the scattering and coupling properties. Therefore, front surface light transmittance was studied for different diameters of the indium nanoparticles (50 nm, 100 nm, 150 nm, 200 nm) and for different separation distances between adjacent nanoparticles. The optimized distance was found to be 150 nm and with this distance front surface light transmittance for different nanoparticle diameters are shown in Fig. 3.

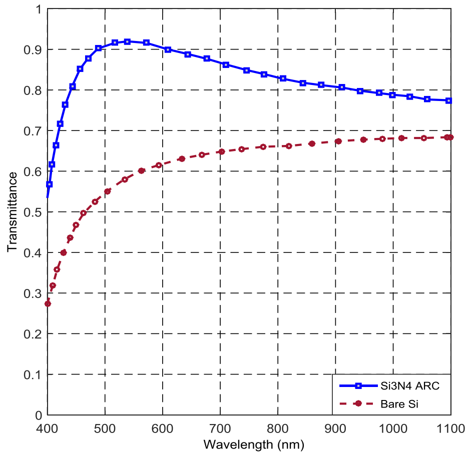


Fig. 2 – Surface transmittance with Si_3N_4 ARC placed on the front surface of the cell and without any ARC (i.e. bare Si cell)

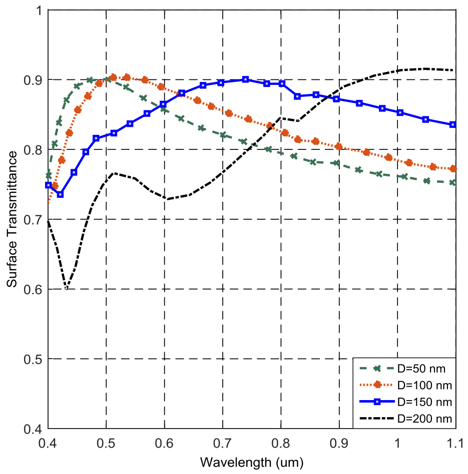


Fig. 3 – Surface transmittance for In nanoparticles of different diameters (D) having fixed inter-nanoparticle spacing of 150 nm

A diameter of 150 nm with a spacing of 150 nm gave the overall best surface transmittance over a wide frequency range. Performance of the indium nanoparticles based light trapping is compared with gold nanoparticles based light trapping in Fig. 4.

In the deep UV and near visible regions of the solar spectrum indium nanoparticles provide higher surface transmittance than the gold nanoparticles. Advantage of using indium nanoparticles over gold nanoparticles is further demonstrated by comparing the absorption of incident light in the Si absorber layer for both cases.

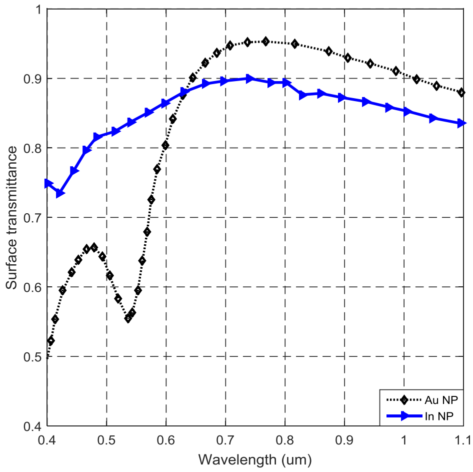


Fig. 4 – Comparison of performance between In and Au nanoparticles in terms of surface transmittance

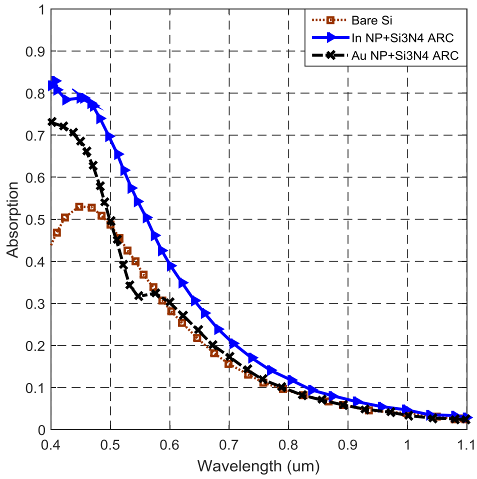


Fig. 5 – Absorption of incident light in Si absorber layer when In or Au nanoparticles based front surface light trapping is used along with Si_3N_4 ARC. Performance when neither light trapping nor ARC is used is also shown

Fig. 5 shows more light is absorbed in the Si absorber layer implying that more photocurrent is generated when In nanoparticles are used. The increment of absorption is quantified by the parameter *light absorption enhancement* $g(\lambda)$, defined as: $g(\lambda) = \frac{Absorption\,with\,light\,trapping\,structure}{Absorption\,in\,bare\,Si\,cell}$. If the value of g ($\lambda$) is larger than unity the light trapping structure enhances the absorption of incident light which possibly enhances the photocurrent generation. Between 800-1100 nm wavelength range gold nanoparticles provide almost no absorption enhancement over bare Si cell i.e. there is no benefit of light trapping structure in this case. However, in this wavelength range at least 22 % absorption enhancement is achieved by the indium nanoparticles based light trapping structure. On the other hand, within the wavelength range of 400-700 nm absorption enhancement by the indium nanoparticles based light trapping is significantly higher than that by the gold nanoparticles based light trapping. For example, at 500 nm absorption enhancement by indium nanoparticles based system is almost 41 % higher than the gold nanoparticles based system. Overall, indium nanoparticles provide an average absorption enhancement of 39.88 % over the wavelength range of 400-1100 nm except only at certain wavelengths where gold nanoparticles show higher parasitic absorption.

In the rear surface light trapping configuration a periodic array of In nanoparticles are placed on the rear surface of the cell while Si_3N_4 antireflection coating is used on the front surface. In this case the objective is to reduce the escaping of light from the rear surface of the cell so that more absorption of light and more photocurrent generation can be achieved. Therefore, unlike front surface light trapping, a small value of transmittance through the rear surface light trapping is desired. For the rear surface light trapping the optimum diameter and inter-particle spacing for indium nanoparticles were found to be 300 nm and 150 nm, respectively. Fig. 6 shows significant reduction of rear surface light transmittance due to the presence of rear surface light trapping structure. Compared to Au nanoparticles In nanoparticles show better performance in this case as well.

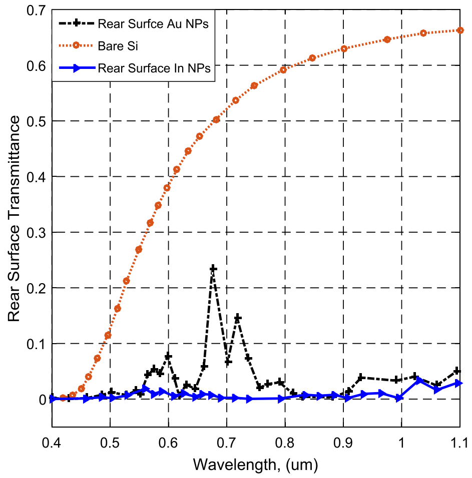


Fig. 6 – Rear surface light transmittance of the cells for rear surface light trapping using In nanoparticles in comparison with that of using Au nanoparticles. Performance when no light trapping is used is also shown. Geometric parameters of the nanoparticles are optimized properly

Next we studied the performance when the light trapping is used at both front and rear surfaces (Fig. 1(d)). Here optimized geometrical parameters of the nanoparticles for the individual front surface case and rear surface case were used together. Absorption of incident light in the Si layer in presence of light trapping structures at rear surface and at both surfaces are shown in Fig. 7 compared to the case when no such

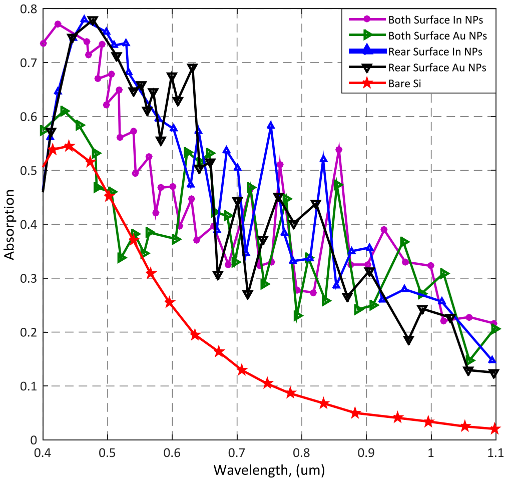


Fig. 7 – Absorption of light in Si with light trapping at rear surface and at both surfaces using indium and gold nanoparticles. Performance for the case when no light trapping is used (bare Si cell) is also shown

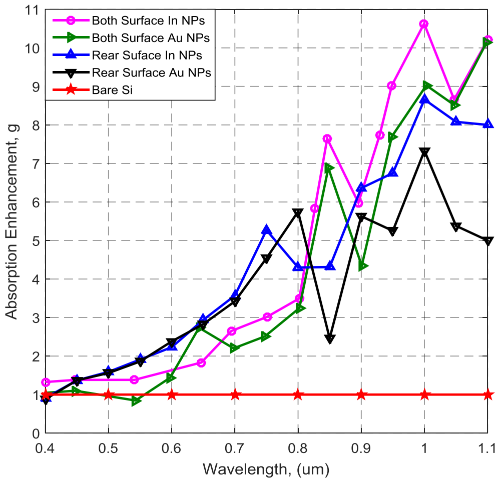


Fig. 8 – Light absorption enhancement in Si with light trapping at rear surface and at both surfaces using indium and gold nanoparticles and for bare Si cell

structure is used. Both indium and gold nanoparticles based light trapping structures were studied. The advantage of using the light trapping structure is obvious. Use of indium nanoparticles is advantageous over gold nanoparticles in this case as well. This is further quantified in terms of absorption enhancement in Fig. 8. From 400-815 nm wavelength range more absorption is caused by the light trapping at the rear surface than the light trapping at both surfaces. Above this wavelength light trapping at both surfaces causes more absorption. However, in all the cases indium nanoparticles based light trapping has overall better performance than the gold nanoparticles based light trapping.

4. CONCLUSION

Indium nanoparticle based efficient light trapping for thin film Si solar cells have been studied. Surface transmittance, reflectance and absorption enhancement of incident light were numerically studied when light trapping is used at the front, at the rear or at both surfaces of the solar cell along with a thin silicon nitride (Si_3N_4) antireflection coating. The light trapping arrangement offered improved surface transmittance and light absorption enhancement, particularly, in the deep UV and near visible regions of the solar spectrum. Geometry and position of the nanoparticles determine the scattering and coupling properties and therefore optimization of indium nanoparticle diameter and inter-particle spacing was performed. For front surface light trapping an optimized nanoparticle diameter of 150 nm with an inter-particle spacing of 150 nm provided the overall best performance over a wide frequency range. For the rear surface light trapping these values were 300 nm and 150 nm, respectively, and for the case of light trapping at both surfaces the optimized values for front and rear surface cases can be used together. When compared with more commonly used (but highly expensive) gold nanoparticles, indium nanoparticle based light trapping performed better in every aspect. Suitability of indium nanoparticles for light trapping in the thin film silicon solar cells is evident from this study.

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