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# Increased Absorption with Al Nanoparticle at Front Surface of Thin Film Silicon Solar Cell

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**Abstract:** This article presents an effective structural design arrangement for light trapping in the front surface of a thin film silicon solar cell (TFSC). Front surface light trapping rate is significantly enhanced here by incorporating the Aluminium (Al) nanoparticle arrays into silicon nitride anti-reflection layer. The light trapping capability of these arrays is extensively analyzed via Finite Difference Time Domain (FDTD) method considering the wavelength ranging from 400 to 1100 nm. The outcome indicates that the structural parameters associated with the aluminium nanoparticle arrays like particle radii and separations between adjacent particles, play vital roles in designing the solar cell to achieve better light trapping efficiency. A detailed comparative analysis has justified the effectiveness of this approach while contrasting the results found with commonly used silver nanoparticle arrays at the front surface of the cell. Because of the surface plasmon excitation, lower light reflectance, and significant near field enhancement, aluminium nanoparticle arrays offer broadband light absorption by the cell.

**Keywords:** thin-film silicon solar cell; light trapping; metal nanoparticle; absorption enhancement; surface plasmon

## 1. Introduction

High conversion efficiency with reduced manufacturing cost is the prime developmental goal while designing a thin film silicon solar cell. It requires less manufacturing materials which makes it a promising candidate. However, to achieve high conversion efficiency for the thinner absorber layer is the main challenging task. Recent achievements are remarkable in the field of thin film solar cell technology as the conversion efficiency variation between individual cells and modules is lower compared to all other photo-voltaic technologies [1]. A substantial transmission variation can be achieved with different substrate materials such as glass or silicon substrate [2–4]. However, the main limitation of TFSC is that solar irradiation absorption becomes poor along with the decreasing thickness of silicon absorber layer.

Efficient light trapping structure is needed to trap the immense amount of sunlight within the cell. For enhanced electrical and optical performance, different shaped solar cell modules such as triangular [5], prism structured dielectric light trapping structure [6], nanocone shaped grating structures [7,8], dielectric moth-eye layer [9], etc. are employed lately with reduced wafer thickness. To surmount the effects of broadband green absorption limit, thin-film hydrogenated nano-crystalline silicon solar cell enhanced with decoupled front and back textures is designed in [10] maintaining a very large photocurrent density of >36 $mA/cm^2$. Among all the concurrent light trapping technologies, the plasmonic light trapping method is the most alluring and cost-effective one.

Plasmonic light trapping with metal nanowires are drawing much attention from researchers. Silver and gold nanowires along with silicon nitride layer, optimized with nanowire density and nanowire shape can bring an increased optical transmission. However, Metallic nanoparticle supports surface plasmons and they interact with the solar irradiance so as to bring about an expanded optical path-length by folding the light within the silicon absorber layer [11–15]. Front surface deposition of these metallic nanoparticles significantly reduces the light reflection and enhances conversion efficiency by coupling light into wave-guide modes. Position, size, and shape of metallic nanoparticle greatly influence the performance of thin film solar cell. These nanoparticles can be deposited at the front and/or rear surfaces of a solar cell to minimize front surface reflection and confine the light within the active layer by total internal reflection. Nanoparticle deposition can also be possible inside the active layer to increase light absorption. Titanium oxide coated coupled nanoparticles inside the active layer increases absorption inside the absorber layer as the surface plasmon excitation creates a strong electric field around and between the nanoparticles [16].

For enhanced light trapping, thin-film hydrogenated amorphous silicon (a-Si:H) solar cell is designed in [17] with silver nanoparticle where it shows that highest conversion efficiency can be achieved with both surface nanoparticle deposition. Choice of nanoparticle material and structural parameters plays a crucial rule in the photon absorption enhancement. Different nanoparticle shape including spherical and flattened hemispherical [18], nanopyramidal structures [19] for increasing the absorption and photocurrent density are drawing great attention. Plasmonic nanostructures should be optimized perfectly for different wafer thickness. Almost 97% material saving can be achieved with minimized efficiency loss by choosing the perfect nanostructural parameters [20]. Gold nanoparticles are also widely used as noble metal nanoparticle because surface plasmons interact strongly with solar spectrum at their resonance peak. Front surface integration of size tailored gold nanoparticles via dip coating process is an efficient way to increase the short circuit current by 0.93% at the wavelength range of 800–1200 nm. Light absorption, external quantum efficiency and conversion efficiency can also be harnessed by implementing gold nanoparticles [21]. Hybrid plasmonic anti-reflection coatings for multi-crystalline Si solar cell combining with gold nanoparticle and silicon nitride results in a significant photocurrent enhancement [22]. In spite of the fact that these silver and gold nanoparticles offer several advantages, they are more costly in contrast to other photovoltaic methods. Therefore, we need a metal nanoparticle that is both cost-effective and gives efficient light trapping. Aluminium is an abundant material in the earth crest and it provides strong light trapping at shorter wavelength range which cannot be achieved with silver or gold nanoparticles. Large parasitic absorption is unavoidable at silver and gold nanoparticle structures which is very little at aluminium nanoparticle over a broadband spectral range. Al nanoparticles with silicon nitride anti-reflection coating provides significantly enhanced absorption and a broadband external quantum efficiency enhancement due to the surface plasmon resonance supported by Al nanoparticles [23].

In this work, we have designed the front surface of silicon thin film solar cell with Al nanoparticles. It has shown that light transmittance increases effectively when a silicon nitride layer is placed between silicon and metal nanoparticle. Performance of Al nanoparticles is compared with Ag nanoparticles while deposited separately in the front side along with silicon nitride anti-reflection layer. We found significant absorption enhancement with Al nanoparticles because of its strong scattering effect. As the size and inter-particle spacing of nanoparticles significantly influences the front surface transmission, optimization has been done for proposed nanoparticle array structure considering these parameters.

## 2. Design Methodology

This article presents a structural design of thin film solar cell with aluminium nanoparticle arrays at front surface. Figure 1 depicts the construction where the metal nanoparticle array is implanted on a $Si_3N_4$ anti-reflection (AR) layer. To attain a high conversion efficiency of crystalline, thin film Si solar cell is the prominent strategy to place an AR layer over Si which lessens the surface recombination impact. Front surface light transmittance of the solar cell is greatly enhanced with this design arrangement.

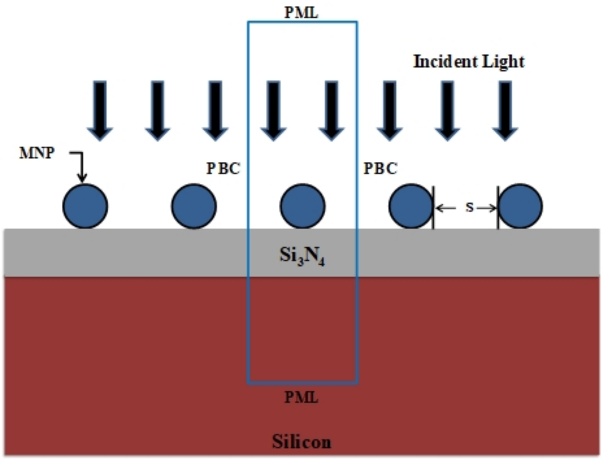



**Figure 1.** Structural design of thin film Si solar cell with an array of MNP located at the front surface of the cell.

To analyze the overall performance, Finite Difference Time Domain (FDTD) numerical simulation method is performed using Lumerical's FDTD Solutions [24]. A normally incident plane wave source with wavelength range of 400–1100 nm is used in our simulation. An array of spherical metal nanoparticles is placed over the top surface of Si layer with a $Si_3N_4$ anti-reflection coating. To maintain the uniform periodicity of the nanoparticle, array periodic boundary conditions (PBC) are applied at lateral boundaries. Perfectly matched layer (PML) boundary conditions are applied at the top and bottom boundaries of the simulation region. The thickness of $Si_3N_4$ AR layer used in our methodology is 50 nm which has also been considered in [25] after rigorous analysis of the effect of different AR layer thickness at the front surface of plasmonic solar cell.

The schematic drawing of 3D simulation setup is presented in Figure 1. To design the simulation objects, the dielectric constants of metal nanoparticles and Si is followed from the ref [26]. A conformal meshing algorithm is applied throughout the simulation region, except in the metal nanoparticles region. As the nano sized metal nanoparticles are very sensitive to field change, we have used an overriding mesh region around the metal nanoparticles to overcome this problem. We have placed a surface transmission monitor at the front surface of Si to record the top surface transmission of the cell.

## 3. Results

In this analysis, two types of metal nanoparticles: Ag and Al, are selected for front surface design. A rigorous investigation was done to evaluate the performance of this solar cell in terms of number of photon absorbed (NPA) in Si, absorption Enhancement, integrated absorption factor and the variations in the size and inter-particles spacing of metal nanoparticles.

### 3.1. NPA Enhancement

To assess the performance of these two nanoparticles we have calculated number of photon absorbed in Si with these two sorts of nanoparticles. The number of photon absorbed within the Si absorber layer is calculated with the following equation [27]:

$$\text{NPA} = \frac{\int \frac{\lambda}{hc}\ T(\lambda)\ I_{AM1.5}(\lambda)\ d\lambda}{\int \frac{\lambda}{hc}\ I_{AM1.5}(\lambda)\ d\lambda} \tag{1}$$

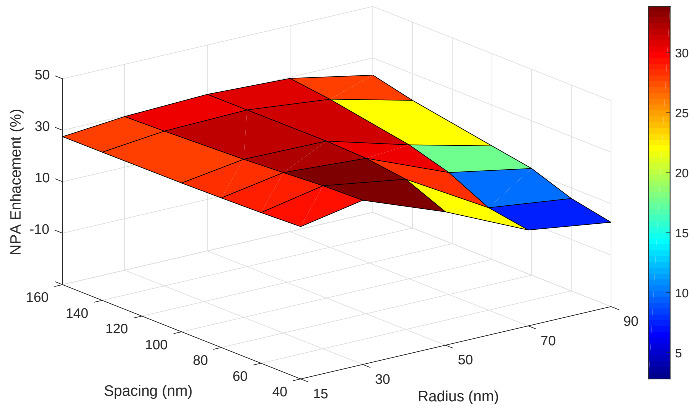
where, $\lambda$ is the wavelength of incident light, $h$ is Plank's constant, $c$ is the speed of light in free space, $T(\lambda)$ is the transmittance of light in Si measured from the front surface transmission monitor, $I_{AM1.5}$ is the air mass 1.5 solar spectrum.

NPA enhancement as a function of particle radius (r) and inter particle spacing (s) is plotted in Figure 2a,b for Ag and Al respectively. From the figures we noticed that Ag nanoparticle offers highest NPA enhancement of 33.8% for r = 30 nm and s = 40 nm while it is 35.9% for Al nanoparticle with the same parameters. That is, it is apparent that Al nanoparticles cause more photon absorption than Ag nanoparticles for our proposed front surface design parameters.

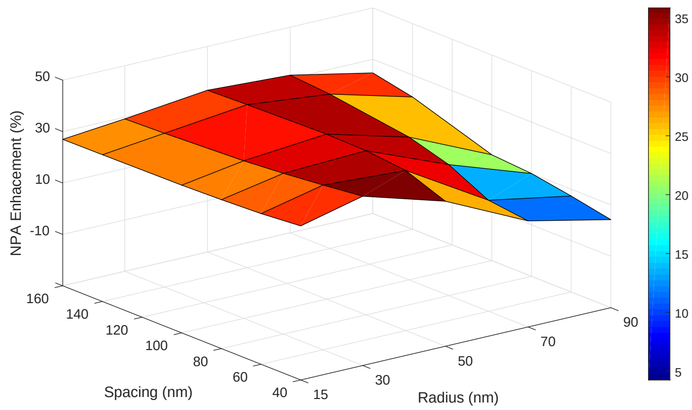
From further observations of Figure 2 we see that for both of Ag and Al nanoparticle, NPA enhancement is low for small nanoparticles (less than 15 nm) and for large nanoparticles (r = 70 nm and r = 90 nm). Whereas it is highest for particle radius r = 30 nm and r = 50 nm. Considering the effect of inter particle spacing we see that for radius r = 30 nm and r = 50 nm, inter particle spacing effectuates less impact compared to the larger nanoparticles. For radius r = 70 nm and r = 90 nm, NPA increases with the increase of the inter particle distance. This position sensitivity of the metal nanoparticles can be clarified by strong parasitic absorption by small metal nanoparticles and significant field enhancement at reduced inter-particle spacing. When light incident on metal nanoparticles, surface plasmon excitation causes light scattering from individual particles. In [28], it has been shown that the scattering cross-section of particles in the order of wavelength increases when the particle size is increased. Scattering cross section increases to a very large extent when incident wavelength nearly matches with the surface plasmon resonance.

### 3.2. Absorption Enhancement

To advance describe the functioning of Ag and Al nanoparticle, we have calculated the absorption enhancement, $g(\lambda)$ which is the ratio of quantum efficiency of the cell with metal nanoparticle to the quantum efficiency of the cell without metal nanoparticle. Figure 3 shows the resultant absorption enhancement spectrum for Ag and Al as a function of wavelength. It is apparent from this figure that, Al nanoparticle results in a significant enhancement at the wavelength range of 400–700 nm, whereas it slightly degrades at the longer wavelength range (700–1100 nm) and in this region Ag outperforms Al. While we watch the execution of Ag nanoparticle we see that it results very poor absorption enhancement at shorter wavelength range. At the wavelength range of 460–510 nm, it causes no enhancement compared to the bare cell as the value of $g(\lambda)$ is below 1. This low absorption within Si is due to a large light absorption of Ag nanoparticle at short wavelength range. On the other hand, Al nanoparticle causes a large amount of light absorption within Si as Al at front surface results in very reduced light reflectance at short wavelength range [27]. High absorption peak occurs around 400–550 nm wavelength range as the wavelength peak of $g(\lambda)$ for Al matches with the peak of solar spectrum at the same wavelength range. Therefore, it is clear that Al nanoparticle gives a broadband absorption enhancement compared with the Ag nanoparticle.




(**a**)




(**b**)

**Figure 2.** NPA Enhancement (%) in silicon as a function of radius and inter particle spacing of (**a**) Ag Nanoparticle (**b**) Al Nanoparticle.

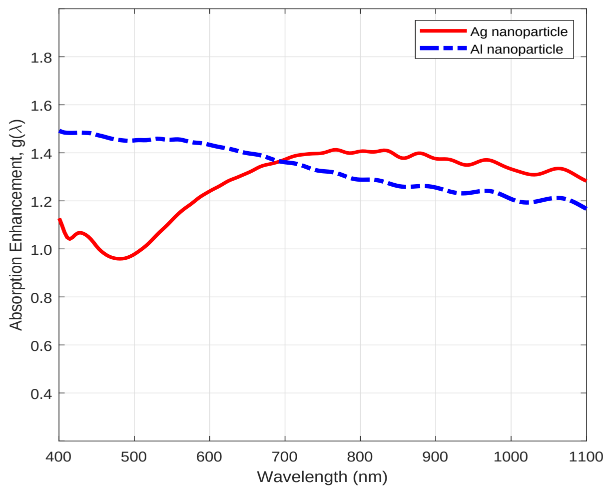
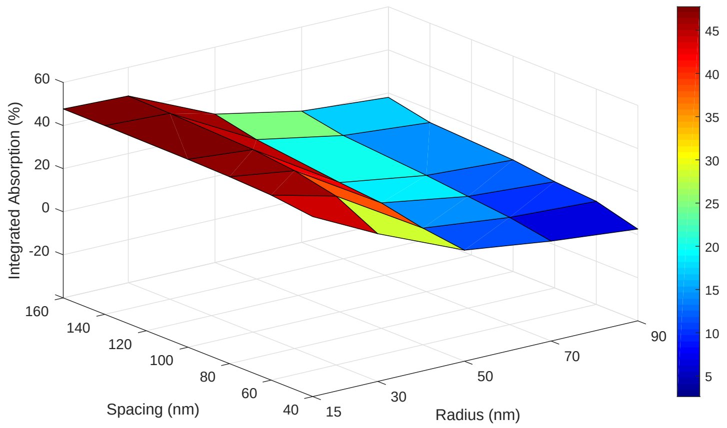



**Figure 3.** Absorption Enhancement $g(\lambda)$ of silicon as a function of wavelength for Ag and Al nanoparticle.

### 3.3. Integrated Absorption Factor

Figure 4 shows the calculated integrated absorption factor (G) as a function of radius and inter particle spacing for Ag and Al nanoparticle. G is calculated by integrating the light absorption within the incident wavelength range and weighting it by the $AM_{1.5}$ standard solar spectrum [20]. We have already shown that Al is the suitable nanoparticle for front surface light trapping in terms of absorption enhancement. Same observation persists when we compare Al and Ag in terms of integrated absorption factor. Al results in a highest integrated absorption of 50.3% for r = 30 nm and s = 100 nm while for the same radius and inter particle spacing Ag results in 44.7% integrated absorption. NP radius and spacing greatly influence the absorption of incident light into the cell. NP spacing and size dependent characteristics of absorption are also observed in [19] for pyramidal nanoparticle structure. Smaller NPs result in lower reflectance and higher absorption of incident light as the light scatters numerous time at the surface of the microstructure.

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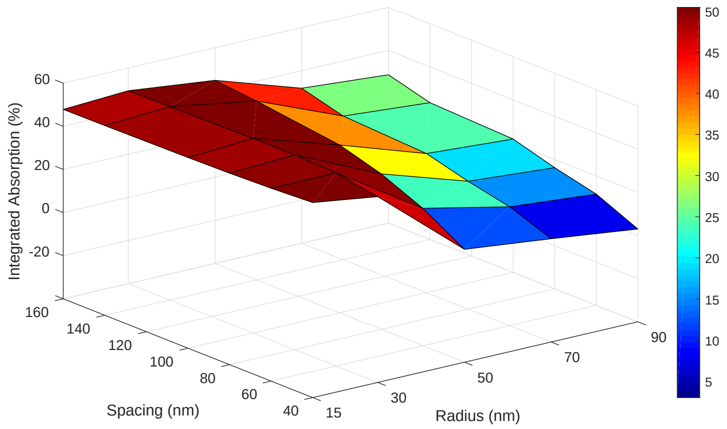



(**b**)

**Figure 4.** Integrated absorption factor G (%) in silicon as a function of radius and inter particle spacing of (**a**) Ag Nanoparticle (**b**) Al Nanoparticle.

### 3.4. Front Surface Transmission

The top surface transmissions are measured for the bare cell (without any AR layer and metal nanoparticle), cell with metal nanoparticles directly placed over Si and the cell with combined metal nanoparticles and AR coating over the top of Si layer. The resultant transmissions for these three configurations are shown in Figure 5. It reveals that surface transmissions for metallic nanoparticles (with and without AR layer) configurations are higher than bare cell. It also indicates that a significant transmission is achieved when the nanoparticle array is placed with the $Si_3N_4$ AR layer which is consistent with the findings of [29]. This improved performance is achieved due to the fact that coupling between metal nanoparticle and Si layer is influenced by the $Si_3N_4$ AR layer and it ensures that most of the scattered light is trapped within the Si absorber layer by the total internal reflection phenomenon.

To achieve a strong scattering effect, scattering cross section of the particle must be larger than the geometrical cross section where scattering cross section is greatly influenced by the size of the nanoparticle and also the strength of near-field effect as it is inversely proportional to particle size. Smaller nanoparticle results in higher parasitic absorption but gives a large peak at shorter wavelength and significant near-field enhancement. On the other hand, with larger nanoparticle high peak cannot be achieved compared to the smaller one but it provides a broad range stable scattering peak [30]. Therefore, to enhance the absorption within the Si absorber layer it is very crucial to choose the optimum size of nanoparticle and a reasonable trade-off is required for these two contradicting effects.

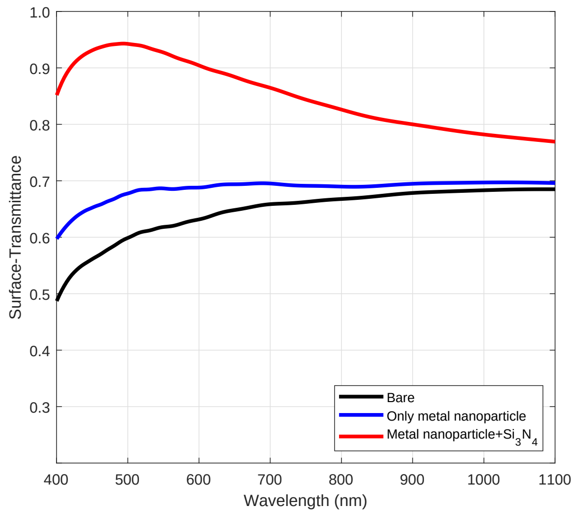
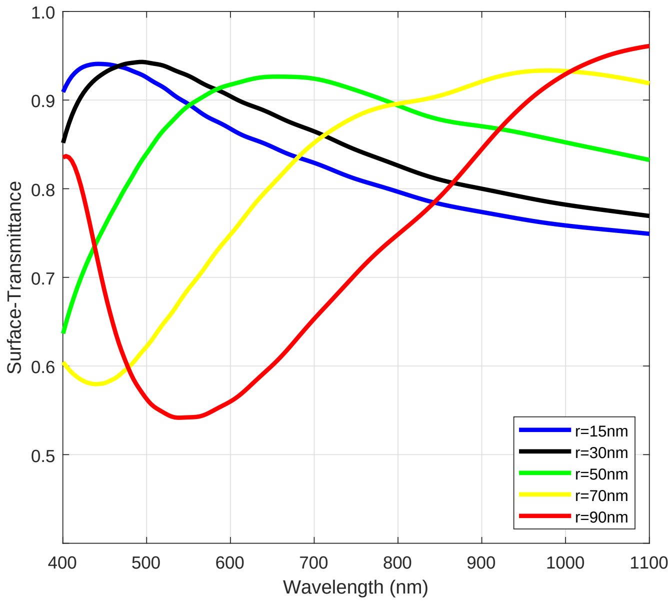



**Figure 5.** Front surface transmission of bare Si solar cell, cell with MNP directly placed over Si and cell with MNP+$Si_3N_4$ layer.

To optimize the size and spacing between adjacent Al nanoparticles we have simulated the transmittance of light into Si absorber layer for different radii and spacing as shown in Figure 6. In the Figure 6a, Al particle radius is varied from 15 nm to 90 nm with a fixed spacing of 100 nm. Furthermore, in the Figure 6b, spacing between adjacent Al nanoaprticle is varied from 40 nm to 160 nm for a fixed radius r = 30 nm. It is important to note here that we have picked these two fixed parameters (s = 100 nm and r = 30 nm) as it is verified from Figure 4b that for s = 100 nm and r = 30 nm we achieve highest value of G.

Figure 6a describes that dependence of light transmittance on particle size at constant spacing of 100 nm. From the figure we see that for r = 15 nm and r = 30 nm, we accomplish a bigger and stable transmittance over a broad wavelength range compared to the others. Furthermore, from the resultant transmittance we see that r = 50 nm radius gives a significant transmittance over the wavelength range of 600–1100 nm. However, when we look at the shorter wavelength the transmittance is not comparable to the radius r = 15 nm and r = 30 nm. Between these two cases r = 15 nm slightly outperforms r = 30 nm over a small wavelength range 400–470 nm. From Figure 6b, we observed the important light transmission behavior at the front surface for different inter particle spacing with a fixed radius of 30 nm. At the short wavelength range (400–470 nm), s = 140 nm and s = 160 nm provides large transmission compared to the other spacing and these two spacings almost overlap each other. However, at the remaining wavelength, range transmission is not at the satisfactory level. A significant transmission is achieved for s = 40 nm at the wavelength range of 560–1100 nm but at the short wavelength it shows poor light transmission. The other values of inter particle spacing also show the same systematic light transmission. This size and spacing dependence characteristics of Al nanoparticle shows a good agreement as explained for Figure 2.

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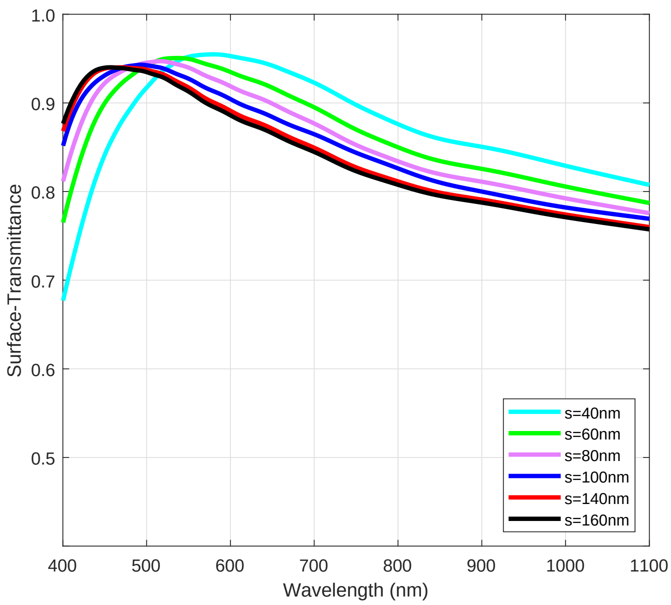


(**b**)

**Figure 6.** Front surface transmission with Al nanoparticle for (**a**) fixed spacing s = 100 nm (**b**) fixed radius r = 30 nm.

## 4. Conclusions

We have proposed a design configuration of a thin film silicon solar cell to enhance light trapping in the front surface of the cell with $Si_3N_4$ AR layer and spherical metal nanoparticle. It has shown that, Al nanoparticle provides best light trapping compared with the Ag nanoparticle. Observations reveal that Al nanoparticle results in the highest NPA enhancement and 50.3% integrated absorption for optimized geometrical parameters. From the wavelength dependent characteristics of light absorption we see that Ag nanoparticle results in very poor absorption enhancement due to its strong parasitic absorption at the shorter wavelength range. A broadband light absorption is achieved with Al nanoparticle which is dominated by reduced light reflectance by Al, significant scattering effect and near-field enhancement. Simulation results also show that, to achieve efficient front surface light transmission it is very crucial to optimize the nanoparticle size and inter particle spacing between the adjacent particles. This implies that researchers should meticulously investigate the performance of TFSC for different structural parameters to design an optimized structure in practical experiments. Our research outcome reveals that, with the optimized structural parameters, integration of Al nanoparticle with AR layer at front surface may provide efficient light trapping for all other thin film silicon solar cell structures. We hope this work will provide effective guidance in designing the TFSC practically and that it may facilitate future research regarding the next generation ultrathin solar cell technology.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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