

The Use of Plasmonic Metal Nanoparticles to Enhance the Efficiency of Thin-Film Silicon (Si) and Gallium Arsenide (GaAs) Solar Cells – A Comparative Study

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Abstract— This study compares the response of thin-film silicon and gallium arsenide solar cells to the use of plasmonic metal nanoparticles for modifying their respective opto-electronic behavior. Square arrays of silver nanoparticles were placed at different inter-particle distances on top of a thin film of Silicon and gallium-arsenide substrate, respectively. The absorption of incident sunlight within each solar cell type is analyzed, and compared to the short circuit current density, open circuit voltage and the output power generated from each solar cell type due to the effect of the plasmonic nanoparticles. It is found that gallium-arsenide shows larger values than Silicon of the short circuit current generated, open circuit voltage, the fill-factor and the output power generated. These results show the effect of plasmonic metal nanoparticles to increase the opto-electronic efficiency of thin-film solar cells is not limited to only Silicon substrates but extends to other commonly used semiconductor substrates.

Index Terms— nanostructure; opto-electronic; plasmon; plasmonics; thin-film solar cell.

I. INTRODUCTION

The use of fossil fuels is at its peak due to the increase in the global population. As these finite energy sources are constantly being depleted, the adverse effects toward climate change is significant by virtue of temperature change (global warming), ice caps melting, violent tornadoes of sizes and strengths not seen in the past, and the systematic degradation of the different ecosystem of the world; it is high time that alternative energy resources be found to replace fossil fuels. The need for a sustainable and renewable “green” energy source which is economically feasible to replace fossil fuels have never been greater. Having said that, the most feasible alternative to non-renewable energy sources is provided by solar energy that can be harnessed via photovoltaic devices [1]. To harness the abundant solar energy the technology used is solar cells or photovoltaic (PV) cells [1]-[3]. This should mean that there is an abundant clean and sustainable electrical energy

converted from the sunlight. However, the low efficiency of the solar cells is the limiting factor which prevents the use of solar cells to be commercially implemented at an industrial scale as an economically viable alternative to fossil fuels, particularly in developing countries in Asia, Africa and Latin America. Si based PV cells have a record highest efficiency of 25% and for GaAs it is 41% and the cost-to-efficiency ratio is too large [4]. Because of its wide availability and economic feasibility,

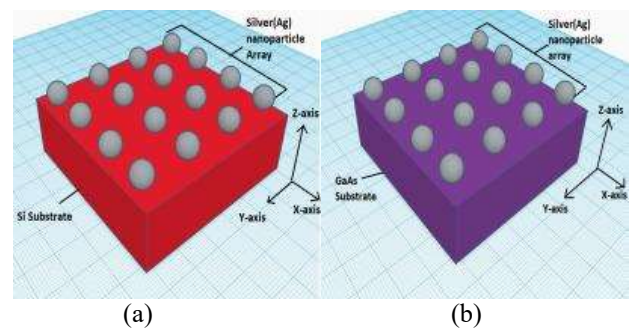


Figure 1. Model of metal nanoparticles on top of (a) silicon (Si) substrate and (b) gallium arsenide (GaAs) substrate.

Silicon is considered to be preferred material for manufacturing solar cells. There are several techniques to enhance the efficiency of PV cells using nanostructures. These techniques include mesoscopic solar cells [10]-[11], quantum dot solar cells [6]-[7] and plasmonic solar cells [12]. In the past, research has revealed that plasmonic solar cells show significant progress in enhancing the efficiency [8]-[9]. It is also important to note that, to enhance the absorption in thin-film solar cells, plasmonic nanoparticles have been utilized that are closely coupled to absorbing semiconductors [1]-[5].

Plasmon resonance is a phenomenon of plasmonic metals which is used by the plasmonic solar cells to increase the optical absorption of thin-film solar cells. Among the plasmonic metals studied frequently (e.g., silver, gold and aluminum), it has been found that silver particle showed the maximum enhancement in the visible region of the solar spectrum [17]. The plasmonic property of the metals showed enhanced optical absorption and scattering at particular wavelengths which is known as their respective resonance wavelengths. Previously the authors of this study have analyzed the shapes, the pitch (inter-particle distance), the size, and orientation of the nanoparticles placed on top and as well as embedded within the silicon substrate and how these particles can enhance the optical absorption as well as the electrical current generation of the solar cells. However, these studies were limited to using silicon as the substrate in the thin-film solar cells [12]-[17]. It is therefore possible that other photovoltaic substrates like GaAs, which is typically more efficient than Si, can also be influenced by plasmonic nanoparticles. Past research has revealed that one way to increase the efficiency of solar cells is to modify or alter the photovoltaic cell substrate at the nanoscale level to increase its opto-electronic performance. The use of plasmonic metals (e.g., silver, gold, aluminum) on the semiconductor substrate is one such alteration. This study compares the improvements in the opto-electronic performance of thin film silicon (Si) and gallium arsenide (GaAs) solar cells due to the effect of placing plasmonic metal nanoparticles on the respective semiconductor substrates. Through this study, the relationship between the physical parameters of the plasmonic metal nanoparticles and the opto-electronic performance of the two photovoltaic substrates were compared. One goal of this study was to investigate whether silicon is the only semiconductor substrate that is affected by the plasmonic metal nanoparticles or whether this effect can be replicated in other commonly used semiconductor substrates such as GaAs. The analysis were done primarily using finite-difference time domain (FDTD) simulations. For the nanostructures, silver (Ag) spheres of 100 nm diameter were used throughout the analysis with the spacing between the particles, known as pitch, as the changing parameter for the analysis. Ag was used as the only type of plasmonic metal, as it was found previously that for thin-film solar cells, Ag showed the best results in terms of optical absorption enhancement and electrical current generation enhancement by the early researchers as well the authors of this study [12]-[18], [19]-[21].

The comparison of the effect of plasmonic nanoparticles on the two types of thin-film solar cells were done by systematically analyzing the optical absorption, short circuit current density, open circuit voltage, output power generated, fill-factor and near-field energy enhancement.

II. MATERIALS AND METHODS

A. Simulation Setup

The simulations performed were done using the solvers – (i) FDTD Solutions [24], a commercial-grade simulator that uses the finite-difference time-domain method to perform the calculations, for the optical enhancement analysis and calculation of short circuit current density (J_{sc}), while (ii) CHARGE (DEVICE) [22], a commercial-grade simulator Eigen mode solver and propagator, was used for the electrical

analysis portion, i.e. calculation of open circuit Voltage (V_{oc}) and fill-factor for all configurations. The solvers were developed by Lumerical Solutions, Inc. All of the simulations were performed under the following conditions: temperature of 25°C, incident radiation intensity of 1000 W/m², and a solar spectral irradiance of AM1.5G [23].

B. Procedure

To improve the efficiency of thin-film silicon and gallium arsenide solar cells, the essential physical parameters were taken into account. Throughout the simulation, 100 nm diameter nanospheres were chosen to be placed on both the silicon and gallium arsenide substrates. Silver (Ag) was used as the plasmonic metal which was found to be the most effective plasmonic metal by the authors of this study [12]-[17]. For a sufficient amount of data and to infer an acceptable conclusion, eight different pitches (side-side inter-particle distance between

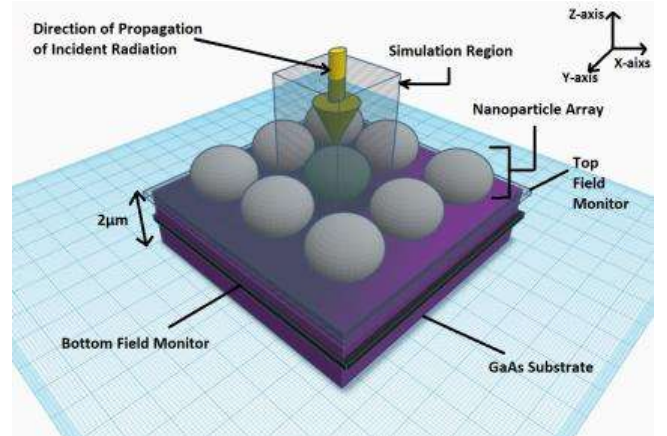


Figure 2. Simulation Setup for the optical absorption enhancement analysis

neighboring nanospheres) of 10 nm, 20 nm, 50 nm, 80 nm, 100 nm, 150 nm and 200 nm, respectively, were chosen for each of the substrate. The nanoparticles were placed on top of the solar cells in a periodic array as illustrated in Figure 1. Both the substrates were made to have a thickness of 2 μm to get the best results. The detailed analyses performed has been broken down and presented in seven major sections: (a) plasmonic resonance analysis of silver (Ag) nanoparticle cell, (b) optical absorption enhancement analysis of the PV cell, (c) short circuit current density (J_{sc}) analysis, (d) open circuit voltage (V_{oc}), (e) power (P), (f) Fill Factor (F) and (g) Near-field enhancement analysis.

As an initial step, it is important to analyze the plasmon resonance properties of the metal nanoparticle used. In this case, the range of the wavelengths at which the plasmon resonance of Ag nanoparticle occurs was calculated. This analysis includes calculating the extinction, scattering and absorption spectra for the 100 nm diameter Ag nanoparticle. The metal nanoparticle was placed in the simulation region and a total-field scattered-field (TFSF) source was directed towards it from all directions. In order to achieve the results, field monitors were placed on all six sides of the Ag nanosphere, a total field scattered field (TFSF) source was placed after that, and finally a second set of monitors were placed beyond the source. The first set of field monitors were used to calculate the

absorption spectra and the second set of field monitors were used to calculate the scattering spectra. The data from these two monitors were used to calculate the extinction spectra [13]. Using the data from the plasmon resonance calculations, a conclusion was made for the range of the wavelengths which would be used for the subsequent set of analyses.

The next analysis which comes into play is the optical absorption enhancement analysis. This study was performed by placing a square array of 100 nm diameter silver(Ag) nanoparticles periodically on top of both the silicon (Si) and gallium arsenide (GaAs) substrate, respectively, and then a plane wave was directed perpendicularly towards the PV cell. The incident plane wave had the electric field oriented along the x-axis and the propagation vector was along the z-axis. The monitors were placed immediately over the metal nanosphere substrate, and 0.5 μm below the nanosphere- Si interface, respectively. By subtracting the power values of the upper monitors from the lower monitors, the absorption within the solar cell was calculated. For each of the substrate, the optical enhancement within the cell was analysed. The diagram for the setup has been shown in Figure 2. To analyze the optical enhancement, a quantity (g) was defined that is the absorption enhancement factor. The formula for the absorption enhancement factor is as follows:

$$g = \frac{\text{Absorption across Si or GaAs with metal nanoparticles}}{\text{Absorption across the bare Si or GaAs}} \quad (1)$$

The diameter of the silver (Ag) nanosphere were kept constant at 100 nm while the inter-particle distance or pitch (side-side) was varied (pitch = 10 nm, 20 nm, 50 nm, 80 nm, 100 nm, 120 nm, 150 nm and 200 nm) to generate the absorption enhancement graphs of the Si and GaAs solar cell. The wavelength range was set to 400 nm to 1100 nm for the simulation.

For each configuration of silver (Ag) nanoparticle array on both the silicon(Si) and gallium arsenide (GaAs) substrates, the electrical enhancement- which is one of the analysis to be made- was then calculated by the short circuit current density (J) and compared with the J_{sc} of the bare substrate, respectively.

The open circuit voltage (V_{oc}) was calculated by creating the exact models of the Ag nanoparticles on top of both Silicon (Si) and gallium arsenide(GaAs) in the solver CHARGE(DEVICE). It is done by calculating the solar generation rate in the FDTD solver using an analysing unit. Then this data was fed to the solver CHARGE (DEVICE). A script file was then run which calculates the open circuit voltage (V_{oc}). After J_{sc} and V_{oc} , the maximum power absorbed by the PV cell was calculated. The formula for power (p) is:

$$p = J_{sc} \times \text{total surface area(substrate)} \times V_{oc} \quad (2)$$

It is a very well-known fact that the open circuit voltage and the short circuit current are considered to be the maximum voltage and current from a solar cell. However at these

maximum points the power of the solar cell is zero. Fill Factor or more commonly known as “FF” is a parameter which, in conjunction with V_{oc} and short-circuit current (I_{sc}), determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc} . For this study the fill factor is calculated by the given formula:

$$ff = \frac{V_{oc}(n) - \ln(V_{oc}(n) + 0.72)}{V_{oc}(n) + 1} \quad (3)$$

Where $V_{oc}(n)$ is the normalized open circuit voltage. This voltage is calculated by the given formula:

$$V_{oc}(n) = \frac{q}{nkT} V_{oc} \quad (4)$$

Where “q” is the charge of an electron, “n” is the ideality factor and “kT” is the temperature in Kelvin. This is how the ratio of the maximum obtainable power “FF” is calculated [25].

Finally, the near field images of each set up was generated to examine the interaction of incident electromagnetic field with the plasmonic nanoparticles and the surface of the PV cell. This result was obtained by placing an electric field monitor on the vertical cross-section of the model. The near field images allows a correlation to be made of the optical and electrical enhancements with the enhancement in electromagnetic fields in the immediate vicinity of the plasmonic nanoparticles and the PV substrate. The interaction between the plasmonic metal nanoparticles and both silicon (Si) and gallium arsenide (GaAs) substrates can also be seen.

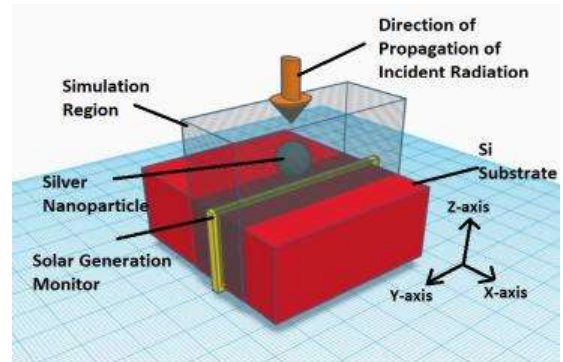


Figure 3(a): Setup for J_{sc} calculation (in silicon substrate)

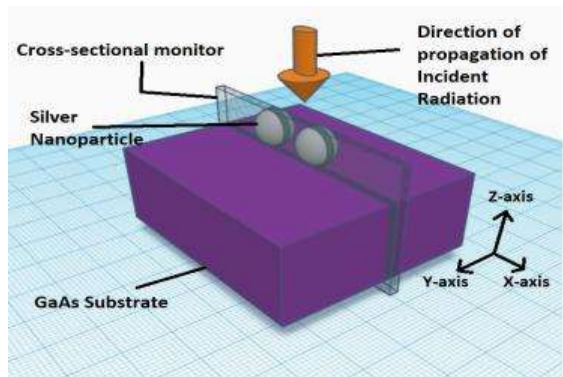


Figure 3(b): Setup for near-field enhancement analysis (in gallium arsenide substrate).

III. RESULTS AND DISCUSSION

This section has been divided into several different parts for each set of the analysis.

A. Plasmon Resonance Analysis

To begin this study, it is important to determine the plasmon resonance wavelength region for the Ag nanoparticle used in the research. For the silver (Ag) nanosphere the peak resonance occurs between 400nm and 500 nm which [15]. From the previous studies it has been found that for 100 nm diameter silver (Ag) nanosphere the peak was located at approximately 450 nm [16].

B. Optical Absorption Enhancement Analysis

TABLE I. TOTAL OPTICAL ABSORPTION ENHANCEMENTS

Pitch	Silicon Substrate Absorption Enhancement	Gallium Arsenide Absorption Enhancement
10nm	100.9128	99.0292
20nm	147.3605	144.8332
50nm	187.4488	184.5362
80nm	192.6916	190.4752
100nm	191.7667	190.1738
120nm	189.7904	188.7961
150nm	186.3288	186.0876
200nm	180.9012	181.4903

The optical absorption enhancement analysis setup used is shown in the simulation setup in Fig 2. For the analysis, the metal (Ag) as well as the diameter (100 nm) of the nanosphere is kept constant while the pitch (end-end) was varied to 10 nm, 20 nm, 50 nm, 80 nm, 100 nm, 150 nm and 200 nm, respectively. The absorption enhancement factor (g) for each configuration is calculated in the wide radiation spectra (400 nm - 1100 nm). The graphs for the wavelength-resolved absorption enhancement for both silicon and gallium arsenide substrates are shown in Figure 4 (a) and (b), respectively, and the total absorption enhancement factor (sum of the individual g values at each wavelength sampled from 400-1100nm) are shown in Table I. In the case of silicon, it can be seen that there is an increasing trend in the absorption enhancement factor (g) from 10 nm pitch to 80 nm pitch, which has the peak total g value of approximately 192.7 at 80 nm pitch. After 80 nm pitch, the g values decrease for the silicon substrate as seen in Table I. The peak value of the absorption is approximately 193-fold over bare Si wafer (80 nm pitch). For 200 nm pitch the absorption enhancement value is approximately 180-fold over bare Si wafer.

The same analysis has been repeated for the GaAs substrate. The graphs obtained are shown in Figure 4 (b). Interestingly, the results from GaAs substrate follow the same trend as that of silicon. The peak value for g is also at 80 nm pitch size and decreased for larger pitch size similar to that of silicon. In the case of the GaAs substrate, the total peak

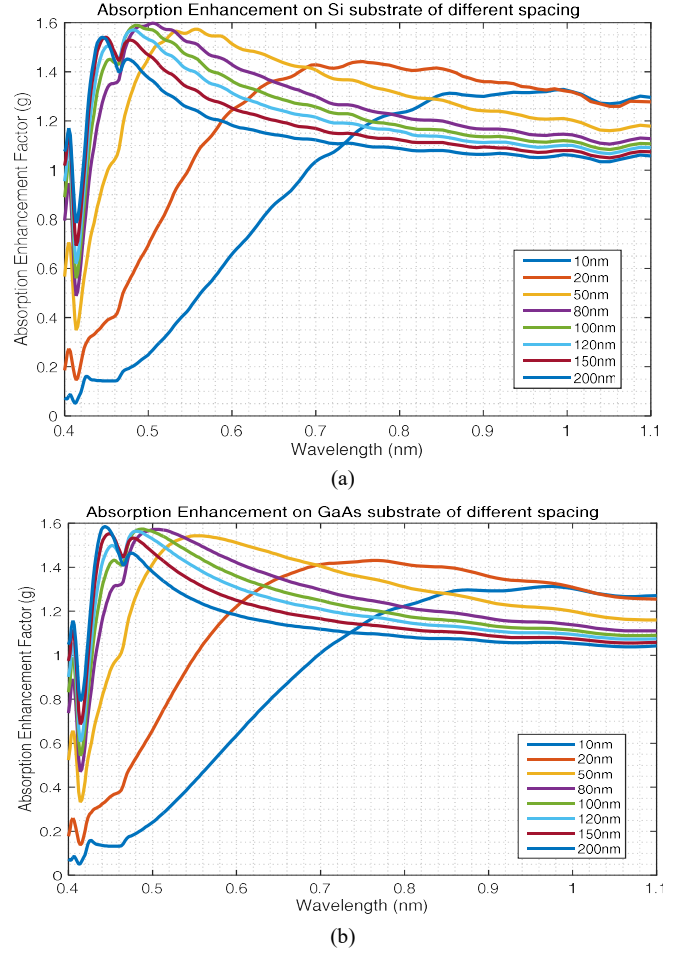


Figure 4. Wavelength-resolved optical absorption enhancement for (a) Silicon and (b) Gallium Arsenide, plasmonic solar cells.

absorption value (total g) was approximately 191-fold at 80 nm pitch while for 10 nm pitch the total g was 100-fold and for 200 nm pitch the total g was approximately 182-fold.

A general trend for all the pitches arises from the graph- the 10 nm pitch shows the least enhancement (lowest total g value), and then the total g value increases from 20 nm pitch until 80 nm pitch, which shows the highest optical absorption, then the values keeps declining from 100 nm pitch towards the larger progressively larger pitch sizes. From the data of both the substrates, the highest optical absorption enhancement occurs at 80 nm pitch and as the pitch increases the light coupling between the metal nanoparticle progressively decreases. The reason for the decrease of the optical absorption enhancement values can be due to distance which affects the efficiency of the plasmonic coupling between the neighboring particles.

It is quite evident that for both substrates, placing the plasmonic metal nanoparticles on top of the semiconductor substrate increases the absorption of the incident radiation into the thin-film solar cells. Previous studies showed that using glass particles (non-plasmon supporting dielectric) were not very effective for increasing the optical absorption enhancement [16].

The above results provide insight into how the silver (Ag) nanosphere can influence its plasmonic property to allow more incident radiation to be scattered/absorbed not only into the silicon (Si) substrate but also other common solar cells like - gallium arsenide (GaAs).

C. Short Circuit Current Density Analysis

TABLE II. J_{sc} FOR DIFFERENT PITCHES

Pitch	Ag($\lambda=400\text{nm}-1100\text{nm}$)			
	Silicon Substrate		Gallium Arsenide	
	J_{sc} (mA/cm ²)	% change	J_{sc} (mA/cm ²)	% change
No Particle	76.4627	0	198.54	0
10nm	40.9776	-53.59	162.502	-18.15
20nm	69.8807	-8.61	228.309	14.99
50nm	98.5355	28.87	263.827	32.88
80nm	102.694	34.31	259.067	30.49
100nm	102.182	33.64	253.631	27.75
120nm	100.899	31.96	248.41	25.12
150nm	98.6153	28.97	241.607	21.7
200nm	95.0331	24.29	232.882	17.3

It is expected that as the optical absorption within the solar-cell substrates increases, the electrical activity will also proportionally be increased [14]-[18]. However, this is not true in actual cases as electricity generation depends on a number of factors [12]. Hence to identify the extent to which the optical absorption enhancement of the substrates in the presence of silver (Ag) nanoparticles increases the electricity generation of the cells, the short circuit current density (J_{sc}) of the cell for each configuration was calculated

The results have been tabulated in Table II. The results for the Si substrate shows a direct connection with the absorption enhancement analysis shown previously, with the pitch of 80nm giving the highest J_{sc} value and decreasing as the pitch progressively increases above 80nm. The increase in J_{sc} is almost 34% when compared to that of the bare Si substrate. This set of analyses was repeated for the GaAs substrate. For the GaAs case, it is seen that the pitch of 50nm gives the highest J_{sc} value with approximately 33% increase compared to the bare GaAs case as shown in Table II. Although this does not exactly follow the pattern of the optical absorption enhancement analysis for GaAs substrate, the result of the J_{sc} calculations for the pitch size of 50nm and 80nm are comparable (33% and 30.5%, respectively). This could be due to the internal properties of GaAs. Hence, the trend observed in optical absorption enhancement can also be seen in the electrical current density (J_{sc}) analysis for Si substrate but the correlation is not as strong for the GaAs substrate.

D. Open Circuit Voltage(V_{oc}) Analysis

TABLE III. OPEN CIRCUIT VOLTAGE

Pitch	Ag($\lambda=400\text{nm}-1100\text{nm}$)			
	Silicon Substrate		Gallium Arsenide	
	V_{oc} (mV)	% change	V_{oc} (mV)	% change
No Particle	400	0	815.616	0
10nm	400	0	800.610	-1.8398
20nm	401.818	0.4545	804.204	-1.3992
50nm	401.818	0.4545	809.61	-0.7364
80nm	407.273	1.8183	813.213	-0.2946
100nm	410.909	2.7273	815.616	0
120nm	414.545	3.6363	818.018	0.2945
150nm	420	5	821.622	0.7364
200nm	423.636	5.909	827.628	1.473

Open circuit voltage would demonstrate the maximum voltage available for the solar cells when the current is zero [25]. The open circuit voltage (V_{oc}) for all the different configurations studied is calculated and shown in tabular form in Table III.

For Si substrates, the largest increase in V_{oc} can be seen for a pitch of 200nm which is a 5.909% increase. As the pitch is being reduced below 200nm, the V_{oc} values reduces proportionally until it reaches the pitch of 50nm then for the pitch of 20nm and 10nm it stays constant and starts falling down again till 400mV for the bare substrate. Additionally, for the GaAs substrate, the largest increase in V_{oc} is again found to be for the pitch of 200nm with a 1.473% increase. Then the calculated V_{oc} values starts falling till the pitch of 10nm. It can be observed that the V_{oc} values for the GaAs substrate are significantly higher than that of the V_{oc} values of Si Substrate.

E. Power Analysis

TABLE IV. OUTPUT POWER

Pitch	Silicon Substrate		Gallium Arsenide	
	Power (mW)	% change	Power (mW)	% change
No Particle	1.223	0	6.48	0
10nm	0.6556	-46.39	5.21	-19.60
20nm	1.123	-8.18	7.34	13.27
50nm	1.584	29.52	8.54	31.79
80nm	1.673	36.79	8.43	30.09
100nm	1.679	37.29	8.27	27.62
120nm	1.673	36.79	8.13	25.46
150nm	1.656	35.40	7.94	22.53
200nm	1.61	31.64	7.71	18.98

Analyzing the power for both the substrates of different configurations studied can help shed some light as to which configuration is better suited for practical usage. To this end, the output power of each configuration of different pitches of silver nanoparticles on both the Si and GaAs substrates were calculated by using the formula previously stated and results are shown in Table IV. For the Si substrate, the highest increase in power is seen for the pitch of 100nm which is almost 32% increase compared to the power of the bare Si substrate.

As for the GaAs substrate, the power table shows that the highest power generated is for a pitch of 50nm which is approximately 32% increase compared to the bare GaAs substrate. This observation suggests that even though for Si substrate the highest optical enhancement and the electrical current is found to peak at the pitch of 80nm, the highest power generated is for the pitch of 100nm and for the GaAs substrate the highest power generated is for the pitch of 50nm.

F. Fill Factor Analysis

TABLE V. FILL FACTOR

Silicon Substrate			Gallium Arsenide	
Pitch	Fill Factor	% change	Fill Factor	% change
No Particle	0.7701	0	0.8625	0
10nm	0.7701	0	0.8605	-0.232
20nm	0.7708	0.091	0.861	-0.174
50nm	0.7708	0.091	0.8617	-0.093
80nm	0.7729	0.364	0.8621	-0.046
100nm	0.7743	0.545	0.8625	0
120nm	0.7757	0.727	0.8628	0.034
150nm	0.7777	0.987	0.8632	0.081
200nm	0.779	1.156	0.864	0.174

The significance of Fill Factor is that it is a unit less ratio that measures the quality of the solar cell. So to determine the quality of both the substrates of different configurations studied, the fill factor is calculated using the formula previously stated and the results are presented in Table V. For both the substrates, the highest Fill Factor value is for the pitch of 200nm and shows a similar pattern with the V_{oc} calculations of both the substrate. This indicates that the higher the open circuit voltage, the higher the fill factor of the solar cell.

G. Near-Field Enhancement Analysis

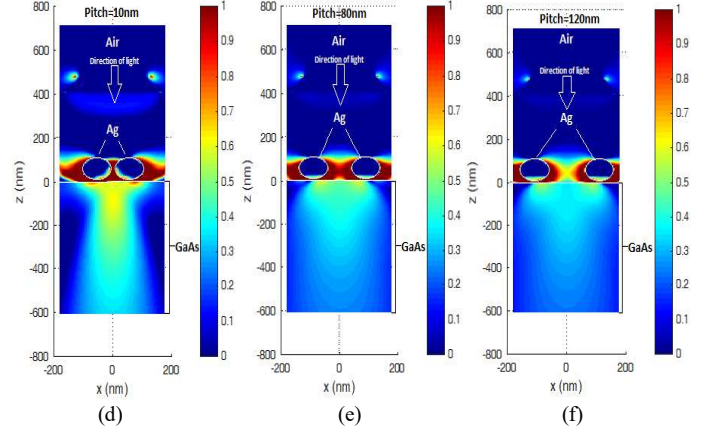
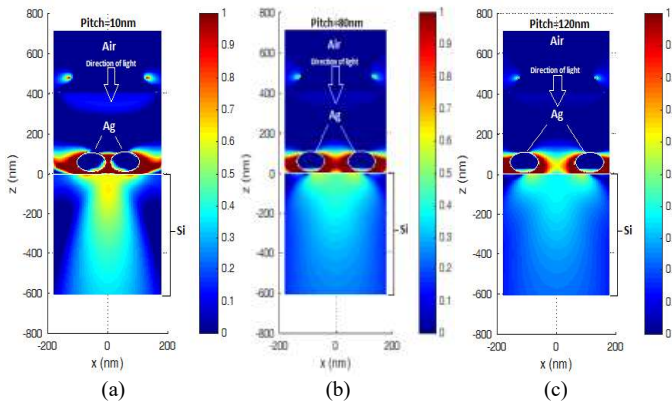


Figure 5: Near-field enhancement images of Ag nanoparticles on top of Si substrate (a-c) and GaAs substrate (d-f)

The near field images are generated help understand the relationship between the distribution of the electric field within/around the nanoparticles and around/within the semiconductor substrates at the resonant wavelength of the nanoparticle [12]-[17].

These images were generated to understand the electromagnetic interaction of the nanoparticles and the semiconductor substrates. This allows the creation of a plausible connection between the physical parameters of the Ag nanoparticles and the improvement in electrical activity of the plasmonic solar cells [12]. The near-field images also show the amount of plasmonic coupling that occurs between neighboring metal nanoparticles.

First, the wavelength at which Ag nanoparticle displays plasmon resonance is found and it is approximately $\lambda \sim 450$ nm. Six near field images were generated with different configurations for both the Si and GaAs substrates-(a) near-field enhancement image of Ag nanoparticles placed on top of Si substrate with a pitch of 10nm; (b) near-field enhancement image of Ag nanoparticles placed on top of Si substrate with a pitch of 80nm; (c) near-field enhancement image of Ag nanoparticles placed on top of Si substrate with a pitch of 120nm; (d) near-field enhancement image of Ag nanoparticles placed on top of GaAs substrate with a pitch of 10nm; (e) near-field enhancement image of Ag nanoparticles placed on top of GaAs substrate with a pitch of 80nm; (f) near-field enhancement image of Ag nanoparticles placed on top of GaAs substrate with a pitch of 120nm.

The near field images were generated at the respective resonance wavelength for each configuration as described previously [12]-[17]. It should be noted that the near-field enhancement images shown in Figure 5(a-f) are presented in the base 10 logarithmic scale. As a result, areas in the image which are dark red in color and correspond to an enhancement value of "1" or greater corresponds to enhancement values of 10-fold or greater, which is quite significant.

From the near-field images it can be clearly seen that there is a variation in the interaction of the substrates due to the presence of Ag nanoparticles compared to the bare substrate. The significant enhancement in the near-fields occur in the

region surrounding the metal nanoparticles due to the interaction with the incident electromagnetic radiation. These regions are shown in dark red in the near-field enhancement images. More importantly, it can be clearly seen that the enhanced electromagnetic fields penetrate quite significantly within the respective Si and GaAs substrates. Moreover, the enhancement images indicate a notable amount of the resonance scattering of the radiation caused by the nanoparticles is directed toward both inside the semiconductor substrates and also on top of the substrates.

The near-field images indicate a relationship between the interaction of the plasmonic nanoparticle with the incident light and the semiconductor substrate. Thus, the near-field images show that the use of plasmonic metal nanoparticles has an impact on the optical and electrical performance of thin-film solar cells (in this case Si and GaAs). It is difficult to make a direct correlation between the near-field enhancement images and that of the optical absorption enhancements and electrical activity of the plasmonic solar cells (J_{sc} , V_{oc} , power) because the near-field images are obtained from only a plane that slices through the metal nanoparticles and the semiconductor substrate underneath (x-z plane). This is however, not the complete picture as the plasmonic interaction of the metal nanoparticles with each other, the semiconductor substrate and the incident light occurs in three dimensions (3D). Hence, the 2-D planar near-field images shown in Figure 5 can only provide a qualitative understanding and appreciation of such a complex optical interaction.

IV. CONCLUSION

This comparative study investigates the effect of plasmonic metal nanoparticles to enhance the efficiency of two commonly used thin-film solar cells - silicon (Si) and gallium arsenide (GaAs). Plasmonic metal nanoparticles were deposited on the semiconductor substrates in a periodic array keeping the diameter of the nanoparticles fixed at 100 nm and the type of the material used was silver (Ag). By setting the pitch (end to end distance between the neighboring metallic nanoparticles) as the variable, the optical absorption enhancement and electrical activity enhancement were investigated for the thin-film solar cells. The different values of the pitch of the metallic nanoparticles studied were: 10 nm, 20 nm, 50 nm, 80 nm, 100 nm, 120 nm, 150 nm and 200 nm. Through extensive analysis it was found that both the silicon (Si) and the gallium arsenide (GaAs) substrate have the highest optical absorption enhancement (g) at 80 nm pitch and maintain a reverse parabolic (increasing up to a peak value from 0-80 nm pitch and then decreasing in value from 80-200nm pitch) trend for the different pitch values ranging from 10 nm to 200 nm. One reason behind this trend can be due to shading effect, where the closer the nanoparticles are, the more the incident light is prevented from reaching the semiconductor substrate underneath as it is being absorbed/scattered by the metal nanoparticles. For lower pitch values, the shading effect (a potential future scope for study) is more significant as more of the light incidents on the particles rather than the substrate itself. Also for lower pitch values, the neighboring nanoparticles are closer to one another and thus shades the semiconductor substrate underneath from the incident light. Additionally, for the higher pitch values the distance between

the particles is not close enough to have significant plasmonic coupling between neighboring nanoparticles (which could then increase the light absorption into the substrate). It was also observed that the corresponding values of the absorption enhancement were similar for both the substrates. This indicates that the effect of plasmonic nanoparticles is not only valid for silicon solar cells but also for other common semiconductor substrates that are widely in use such as - gallium arsenide (GaAs). Also, the distance between the neighboring metal nanoparticles- pitch- has a significant effect on the contribution as well.

To determine the degree to which the optical absorption enhancement affects the electrical generation, the short circuit current density (J_{sc}) analysis along with three other electrical parameters- open circuit voltage (V_{oc}), fill factor (FF) and power (P) - were studied. Similar to the optical absorption enhancement result, a significant rise (~35% increase for Si and ~33% increase for GaAs) in the J_{sc} was seen for Si and GaAs at 80nm pitch and 50 nm pitch, respectively. It is likely that increased number of electron-hole pairs are produced as more photons are absorbed by the substrate and /or scattered into the substrates (Si and GaAs), which leads to the generation of more short circuit current. However, as mentioned earlier, the shading effect can potentially cause less absorption of light into the substrate when the particles have a lower pitch (closer together); which in turn can cause the J_{sc} values to be smaller. For higher pitch values (larger inter-particle spacing), one reason why the J_{sc} values keeps declining can be due to the lower absorption enhancement. Furthermore, to further clarify the results, the near-field enhancement images were analyzed which demonstrates the enhancement in the electromagnetic intensity due to the presence of plasmonic metal nanoparticles. The near-field images showed that a large amount of enhancement occurs in the presence of the nanoparticles when compared to the bare substrates. It can be inferred that- although the degree of optical enhancement of the silicon (Si) based solar cells is larger compared to gallium arsenide (GaAs) substrate, the electrical activity (which includes the J_{sc} , V_{oc} and power analysis) of the GaAs substrate is higher owing to its internal property (inherent physical nature). Moreover, this study shows the effect of plasmonic metal nanoparticles to increase the optical and electrical performance of thin-film solar cells is not limited to Si substrates but also can be extended to other commonly used semiconductor substrates (in this case gallium arsenide - GaAs).

To conclude, it must be noted that, further analysis of the electrical activity such as the electrical efficiency needs to be done as well as the effect of shading (as mentioned earlier) of the plasmonic metal nanoparticles on the optical and electrical enhancement of the Si and GaAs performance needs to be thoroughly studied. Adding to that, the use of different types of nanostructures like - a bowtie structure can also be used for further analysis in this field in order to establish a more robust understanding of these relationships. Future work shall include the modeling, calculations and analysis of these additional parameters mentioned to get a clearer understanding on how the various properties of the plasmonic metal nanoparticles can

have an impact in improving the efficiency of thin-film solar cells.

These results indicate that for certain high-end applications where the initial costs of installation of the solar cells is not a limiting factor, plasmonic thin-film GaAs solar cells can be effective platforms to give high-quality performance. In other regular applications, plasmonic thin-film Si solar cells can be used as a suitable alternative to generate the required output electrical power at economically feasible costs.

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