Use of Hybrid Bow-Tie Based Plasmonic Nanostructures to Enhance the Opto-Electronic Efficiency of Thin-Film Solar Cells

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***Abstract*— This study involves the response of thin-film silicon solar cells to the use of hybrid bow-tie based plasmonic metal nanostructures that modifies its corresponding opto-electronic behavior. A single set of bow-tie, one vertex of each of the two triangular (pyramidal) silver nanoparticles facing each other with a spherical nanoparticle in the middle, were placed on top of a thin film silicon substrate. Analysis of the absorption of incident sunlight within solar cell with a spherical particle and a bow-tie based nanostructure was completed and the short circuit current density, open circuit voltage and the output power generated from the solar cell structure due to the effect of both spherical and the spherical-pyramidal hybrid plasmonic nanoparticles were compared. It has been observed that the spherical-pyramidal hybrid bow-tie based plasmonic nanostructure shows larger values than spherical nanoparticles alone in terms of the short circuit current generated, the fill-factor, open circuit voltage and the output power generated. These results show that the effect of plasmonic metal nanoparticles to increase the opto-electronic efficiency of thin-film solar cells is not limited to only spherical nanoparticles alone but extends to other rarely used plasmonic nanostructures. Furthermore, these results indicate that an appropriately designed multi-particle hybrid plasmonic nanostructures can significantly enhance the opto-electronic performance of plasmonic solar cells when compared to the enhancements generated by single type of nanoparticle-based plasmonic solar cells.**

***Index Terms*—** *nanostructure; bow-tie; triangular; pyramidal; spherical; plasmon resonance; plasmonics; opto-electronic; silver nanoparticles; photovoltaic; thin-film solar cell.*

I. INTRODUCTION

From the time of dawn of modern technological evolution, solar energy has always been considered as the most viable source of renewable energy [1], [5]-[6]. Undoubtedly, the seemingly never ending supply of photons from the Sun has made it a promising candidate for meeting the ongoing energy demand. Hence, intensive research is ongoing worldwide to increase the efficiency of current photovoltaic cells, which operate to convert the solar energy into electrical energy by generating the electron-hole pairs with the help of the energy provided by the photons [1]-[4].

As it is found in previous studies that the overall efficiency of thin film amorphous Si solar cells is much lower than the commercially used thick-film crystalline PV cells [4], because, the reduced absorbing material lowers the number of minority carriers released [9]. Hence, it is very important to trap greater amount of photons within the PV cell structure to enhance optical absorption [12].

Authors from the same group have reported in previous studies that plasmonic solar cells designed with spherical silver nanoparticles show enhanced yields in short circuit current density, open circuit voltage and the output power compared to bare silicon solar cell substrates [5]-[11]. Therefore, the objective of this study was to determine if a single spherical-triangular (pyramidal) hybrid bow-tie based plasmonic nanostructure yields better efficiencies than a single spherical particle alone within the same simulation conditions.

The plasmon resonance of triangular (pyramidal) shaped nanoparticles (equilateral triangle in x-y plane) of three different sizes has been observed with different pitch sizes (inter-particle distances). Then the investigation was continued to observe the enhancement of light coupling and improved electrical activity of the PV cell by varying the physical parameters i.e. the side lengths of the triangular (pyramidal) particles, the pitch sizes, while keeping the height of the triangular (pyramidal) particles and diameter of the sphere constant.

II. MATERIALS AND METHODS

A. Simulation Setup

The simulations performed were carried out by using the FDTD Solution solver [16], a commercial-grade simulator that uses the finite-difference time-domain (FDTD) method to perform the calculations, for the optical enhancement analysis and the CHARGE (DEVICE) solver [17] was used for the electrical analysis portion, i.e. calculation of short circuit current density (J_{SC}), open-circuit voltage (V_{OC}), Fill Factor (FF) and output power for all configurations. The

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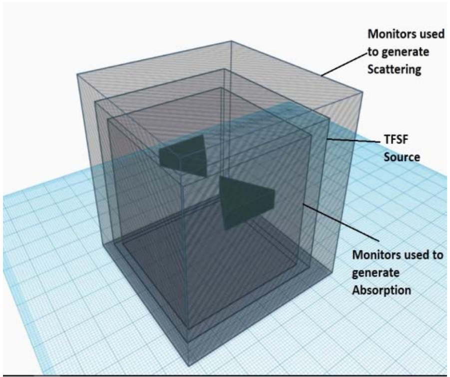
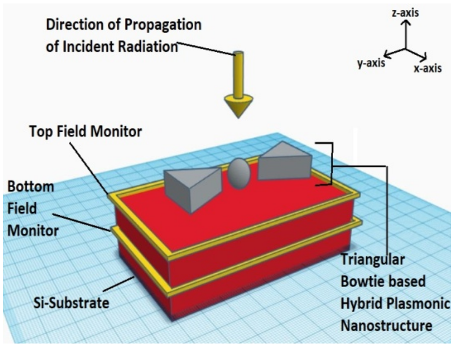
developer of these solvers is Lumerical Solutions, Inc. The physical conditions that were maintained while performing the simulations are: temperature of 25°C, incident radiation intensity of 1000 W/m^2, and a solar spectral irradiance of AM1.5G [14].

B. Procedure

To study the influence of this hybrid nanostructure on the efficiency of thin film solar cells, FDTD simulations were performed with different side lengths of triangular (pyramidal) nanoparticles, and keeping their heights and the diameter of the spherical particle constant. The silicon substrate used for the simulation was 2μm thick to get optimum results. Silver (Ag) was the only material used in this study as previous studies by the authors have revealed that among the different plasmonic metals, Ag nanoparticles showed the most significant enhancement. [5-11].



(a)



(b)

Fig. 1. Simulation setup for the analysis of (a) plasmon resonance of triangular (pyramidal) nanoparticles and (b) the optical absorption enhancement of hybrid bow-tie based plasmonic nanostructure

In the simulations presented, the diameter (*d*) of the Ag spherical nanoparticle was kept constant at 100 nm and the height (*h*) of the triangular (pyramidal) nanoparticles was also kept constant at 100 nm. However, the side lengths of both silver (Ag) triangular (equilateral triangle in x-y plane) nanoparticles considered were varied to 100 nm, 150 nm and 200 nm. Moreover, the distance (pitch size) between the apex points (vertices) of the neighboring triangular (pyramidal) nanoparticles in the hybrid structure was varied from p = 106 nm to p = 140 nm with the 100 nm spherical particle placed in the middle. Fig. 1 (b) shows the hybrid bow-tie based plasmonic nanostructure placed on top of the silicon substrate. To make the observation easier, the entire analysis has been divided into seven major sections: (i) plasmon resonance analysis, (ii) optical absorption enhancement analysis, (iii) short circuit current density analysis (J_{SC}), (iv) open circuit voltage (V_{OC}), (v) Power analysis (P), (vi) Fill Factor (FF) and (vii) Near-field optical enhancement analysis.

To begin with, the plasmon resonance of the hybrid bow-tie based plasmonic nanostructure was analyzed, shown in Fig. 1 (a). The range of wavelength within which the plasmon resonance occurred was observed and selected. The triangular (pyramidal) nanoparticles were surrounded by two sets of monitors with a total-field scattered-field light (TFSF) broadband light source placed between the two monitors. The source called total-field scattered-field (TFSF) was used to do the set of calculations as discussed in the earlier studies [5-11].

The next set of simulations performed allowed the optical absorption enhancement analysis. The optical absorption enhancement studies were then performed by placing the bow-tie nanostructure of different side lengths over the Si substrate along with a monitor placed immediately below the nanoparticle structure and another monitor 0.5μm below from the surface of the Si substrate, both in horizontal cross-section (x-y plane) of the model. Then, by subtracting the power values of the upper monitors from the lower monitors, the optical absorption within the solar cell was calculated. Figure 1 (b) shows the setup for the optical absorption enhancement analysis. A quantity *g* was defined in order to analyze the optical absorption enhancement. The formula for the optical absorption enhancement factor (*g*) is as follows:

$$g = \frac{Absorption\ across\ silicon\ substrate\ with\ hybrid\ bowtie\ structure}{Absorption\ across\ the\ bare\ silicon\ substrate} \quad (1)$$

Later, short circuit current density (J_{SC}) was calculated to analyze the electrical enhancement for the different set of side lengths of the bow-tie nanostructure. The same calculations were also repeated for the bare silicon substrate and a spherical particle alone on the silicon substrate, respectively, to compare the results.

Furthers analysis was to find the open circuit voltage (V_{OC}), which was calculated by creating the same model of the bow-tie nanostructure on top of the silicon (Si) substrate in a solver called CHARGE (DEVICE). It was done by calculating the solar generation rate in the FDTD solver using an analyzing unit. Then these data were fed to the CHARGE (DEVICE) solver. A script file was written and used to calculate the open circuit voltage (V_{OC}).

The maximum power absorbed by the solar cell was calculated by using the formula:

$$P = Jsc\ \times Total\ surface\ area\ \times Voc \quad (2)$$

The Fill Factor or more commonly known as "FF" is a parameter which, in conjunction with V_{OC} and J_{SC}, determines the maximum power generated from a solar cell [18]. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{OC} and I_{SC} [18]. For this study, the fill factor was calculated by the given formula:

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

Here, V_{OC} (n) is the normalized open circuit voltage [18]. This voltage is calculated by the given formula:

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

Where ‘q’ is the charge of an electron, ‘n’ is the ideality factor ‘T’ is the temperature in Kelvin [18] and ‘k’ is the Boltzmann constant = 1.38064852 × 10^{-23} m^2 kg s^{-2} K^{-1} [13].

The last analysis deals with the interaction of incident electromagnetic field with the plasmonic nanostructure and the surface of the silicon substrate. The images were generated by placing an electric field monitor both on the horizontal cross-section (x-y plane) and vertical cross-section (x-z plane) of the model. Previous studies discussed the near-field enhancements analysis methods [5-11].

III. Results and Discussions

The results and discussions have been divided into separate sections for each analysis.

A. Plasmon Resonance Analysis

To start with the procedure, initially, it was essential to determine the resonance wavelength of the triangular (pyramidal) nanoparticles of the bow-tie structure for different side lengths at different pitch sizes. This analysis showed the absorption, scattering and extinction spectra within the wavelength region of 200 - 1100 nm. Fig. 2 (a-c) shows the results for the absorption, scattering and extinction spectra of these pyramidal nanostructures. The different side lengths of the triangular (pyramidal) nanoparticles in the bow-tie structure

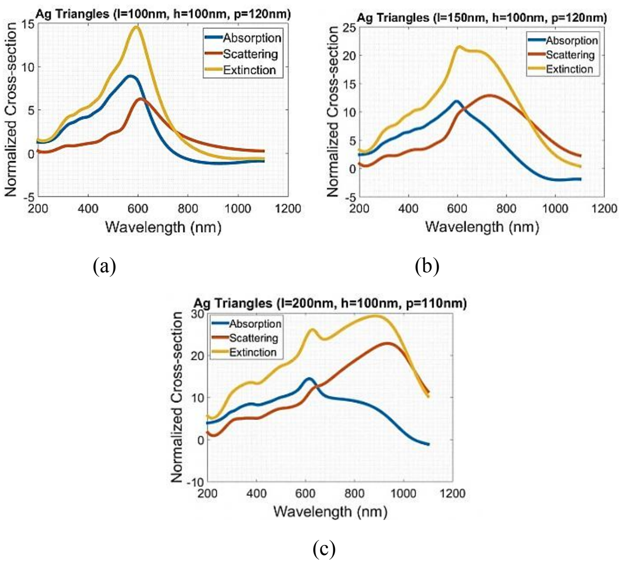


Fig. 2. Absorption. scattering and extinction spectra for triangular (pyramidal) nanoparticles with different side lengths (l) and pitch sizes (p); and constant height (h) of 100nm (a) l = 100 nm, p = 120 nm; (b) l = 150 nm, p = 120 nm and (c) l = 200 nm, p = 110 nm

showed individual resonant responses, which is represented by maximum amplitude for a specific wavelength in the figures. It was found out that the resonant wavelengths for the hybrid nanostructures with side lengths of 100 nm at 120 nm pitch size, 150 nm at 120 nm pitch size and 200 nm at 110 nm pitch size are at λ ~ 610 nm, λ ~ 730 nm and λ ~ 940 nm, respectively (Fig. 2 (a-c)).

B. Optical Absorption Enhancement Analysis

Since, the primary objective was to consider the maximum scattering spectra of the triangular (pyramidal) nanoparticles, hence, the optical absorption enhancement factor (*g*) was calculated, using formula (1) stated in the ‘procedure’ section, within the radiation spectra of 600 -1000 nm; displayed in Table I. The graphs of the optical absorption enhancement factor (*g*) as a function of the wavelength, varying the side lengths of both of the triangular (pyramidal) nanoparticles, of the hybrid bow-tie based plasmonic nanostructure on Si substrate are shown in the Fig. 3 (a-c).

TABLE I. Total Optical Absorption Enhancement

Pitch (di-stance between triangle vertices)	**Si Substrate with Ag bow-tie structure; λ=600-1000 nm [Sphere (d=100 nm), Triangles (l=100, 150, 200 nm)]**					
	Absorption Enhancement Factor (*g*)			**% change compared to sphere**		
	l=100	**l=150**	**l=200**	**l=100**	**l=150**	**l=200**
Sphere Only	153.622	153.622	153.622	0	0	0
106 nm	167.077	160.968	171.666	8.75	4.78	11.74
110 nm	170.629	165.468	180.980	11.07	7.71	17.81
120 nm	175.329	171.549	171.375	14.13	11.67	11.57
130 nm	167.874	165.307	176.712	9.28	7.61	15.03
140 nm	169.996	164.356	177.628	10.66	6.99	15.63

The initial analysis was that the *g* value is higher for smaller pitch sizes and the larger the pitch size, the lower the *g* value. Further analysis showed that for the triangular (pyramidal) nanoparticles of Ag hybrid nanostructures with side lengths of 200 nm at 110 nm pitch has the highest g value (*g* =180.980), which is approximately 18% more than a single spherical Ag nanoparticle placed on top of the Si substrate and so does the same structure with side lengths of 100 nm and 150 nm at 120 nm pitch size; which have second (*g*=175.329) and third highest (*g*=171.549) *g* values respectively; and are around 14% and 12% higher than the single spherical particle.

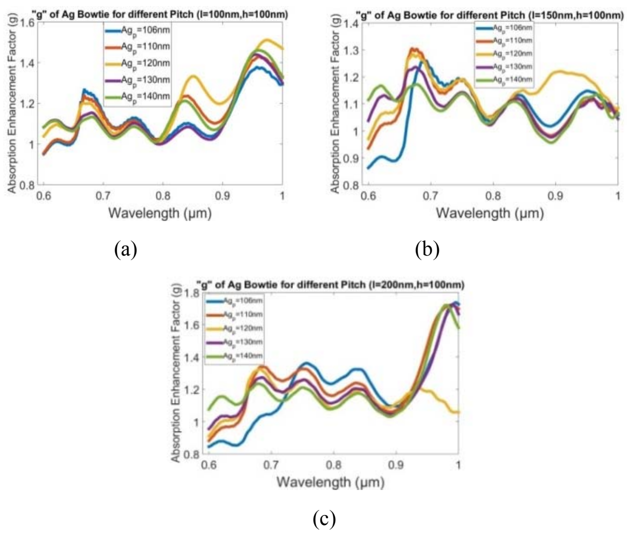


Fig. 3. Optical absorption enhancements for hybrid bow-tie based plasmonic nanostructures with different side lengths (l) and pitch sizes (p); and constant height (h) of 100nm (a) l = 100 nm, (b) l = 150 nm and (c) l = 200 nm

Apparently, all three of these optical enhancement factors (*g*) in case of all combinations of the bow-tie based hybrid plasmonic nanostructure yields higher value compared to the *g* value of the spherical particle alone. This is an important result because it shows that the triangular (pyramidal) Ag nanoparticles help enhance the ability of the spherical Ag nanoparticle (placed between the pyramidal particles) to help the Si substrate absorb more of the incident optical radiation. In fact, every other combinations of this hybrid nanostructure shows better optical absorption enhancement compared to a single Ag spherical particle on the same silicon substrate.

C. Short Circuit Current Density Analysis

It is expected that the short circuit current density (J_{SC}) will be maximum, when the optical absorption enhancement is maximum [6], [8]-[10], [15]; but in reality, there are few more factors at play [7] and evidently, it has been proven accurate for the triangular bow-tie based hybrid plasmonic nanostructure in this study. The values exhibited in the Table II shows the calculation of the average electricity generation inside the Si substrate. It is clear that the spherical particle alone shows only around 2% increase in J_{SC} value compared to bare surface of Si substrate. On the other hand, all combinations of the hybrid nanostructures in terms of pitch sizes and side lengths of the triangular (pyramidal) nanoparticles show significantly higher J_{SC} values. More importantly, just like the optical absorption enhancement factor, discussed in previous section, the hybrid nanostructure with side length of 200 nm with 110 nm pitch size yield approximately 17% increase in J_{SC}, but the same increase is evident for the 140 nm pitch size too, which are the highest. The triangular (pyramidal) particles of the same nanostructure with side lengths of 100 nm and 150 nm with 120 nm pitch size show around 13% and 14% enhancement in J_{SC} values compared to bare Si substrate respectively.

TABLE II. J_{SC} FOR DIFFERENT PITCH SIZES AND SIDE LENGTHS

Pitch (distance between triangle vertices)	Si Substrate with Ag bow-tie structure; λ=600-1000 nm [Sphere (d=100 nm), Triangles (l=100, 150, 200 nm)]					
	J_{SC} (mA/cm^2)			% change compared to bare Si substrate		
	l=100	l=150	l=200	l=100	l=150	l=200
No Particles	25.531	25.531	25.531	0	0	0
Sphere Only	26.163	26.163	26.163	2.48	2.48	2.48
106 nm	27.747	27.614	27.533	8.68	8.16	7.84
110 nm	28.271	28.479	29.763	10.73	11.55	16.58
120 nm	28.890	29.195	29.410	13.16	14.35	15.19
130 nm	27.864	28.675	29.379	9.14	12.31	15.07
140 nm	28.205	28.441	29.771	10.47	11.39	16.61

D. Open Circuit Voltage Analysis

When there is zero current flow, the open circuit voltage (V_{OC}) shows maximum available voltage for the solar cells [19]. The observed V_{OC} outcomes are demonstrated in the Table III.

As shown in Table III, compared to the triangular (pyramidal) hybrid nanostructures with 200 nm side lengths at 110 nm pitch size (0.41141 mV), the 120 nm pitch size for the same particle size shows a bit higher V_{OC} value; both yields approximately 3% higher value compared to bare Si surface. The other triangular (pyramidal) particle sizes, 100 nm and 150 nm, at 120 nm pitch have also shown significant values of V_{OC}. The calculation in Table III also shows the spherical particle alone only creates a negligible enhancement of around 0.15% compared to the bare Si substrate. Additionally, this hybrid nanostructure with side lengths of 100 nm and 150 nm show approximately 6% and 5% increase in V_{OC} for the pitch size of 120 nm. Hence, the highest V_{OC} obtained was for the hybrid nanostructure with side length of 100 nm with 120 nm pitch size.

TABLE III. OPEN CIRCUIT VOLTAGE (Voc)

Pitch (distance between triangle vertices)	Si Substrate with Ag bow-tie structure; λ=600-1000 nm [Sphere (d=100 nm), Triangles (l=100, 150, 200 nm)]					
	V_{OC} (mV)			% change compared to bare Si substrate		
	l=100	l=150	l=200	l=100	l=150	l=200
No Particles	0.40120	0.40120	0.40120	0	0	0
Sphere Only	0.40180	0.40180	0.40180	0.15	0.15	0.15
106 nm	0.40721	0.40601	0.40661	1.50	1.20	1.35
110 nm	0.42282	0.40781	0.41141	5.29	1.65	2.55
120 nm	0.42463	0.42042	0.41502	5.84	4.79	3.44
130 nm	0.40661	0.40721	0.40788	1.35	1.50	1.66
140 nm	0.42282	0.40661	0.40901	5.39	1.35	1.95

E. Power Analysis

When it comes to the use of these models in practical applications, the output power analysis plays a major role [11]. In this case, it is important to know that which configurations of this hybrid nanostructure will yield maximum output power. It can be seen in Table IV that the output power calculated using a formula (2) stated in the 'procedure' section for side lengths of 100 nm, 150 nm and 200 nm at the pitch sizes of 120 nm, 120 nm and 110 nm, respectively, follow the similar trend as *g* and J_{SC}, is approximately 20%, except, the nanostructure with 200 nm side lengths for both 120 nm and 140 nm pitch sizes show comparable increase in output power.

TABLE IV. OUTPUT POWER

Pitch (distance between triangle vertices)	Si Substrate with Ag bow-tie structure; λ=600-1000 nm [Sphere (d=100 nm), Triangles (l=100, 150, 200 nm)]					
	Power (10^{-11})			% change compared to bare Si substrate		
	l=100	l=150	l=200	l=100	l=150	l=200
No Particles	4.1	4.1	4.1	0	0	0
Sphere Only	4.2	4.2	4.2	2.44	2.44	2.44
106 nm	4.5	4.48	4.48	9.76	9.27	9.27
110 nm	4.8	4.6	4.9	17.07	12.20	19.51
120 nm	4.9	4.9	4.88	19.51	19.51	19.02
130 nm	4.5	4.7	4.8	9.76	14.63	17.07
140 nm	4.8	4.6	4.88	17.07	12.20	19.02

F. Fill Factor Analysis

The Fill Factor (FF) is a ratio calculation which measures the quality of a solar cell [18] and of course, for this study, it was dependent on the configurations of the hybrid bow-tie based plasmonic nanostructure and was calculated using formula (3) & (4) stated in the 'procedure' section [18] and is presented in Table V. It was being observed that the FF follows the similar trend as V_{OC} and that means, the hybrid nanostructure with side length of 100 nm with 120 nm pitch size have yielded maximum FF value. Hence, the simulations indicate that higher fill factor results from higher open circuit voltage [11].

TABLE V. FILL FACTOR (FF)

Pitch (between triangle vertices)	Si Substrate with Ag bow-tie structure; λ=600-1000 nm [Sphere (d=100 nm), Triangles (l=100, 150, 200 nm)]					
	Fill Factor			% change compared to bare Si substrate		
	l=100	l=150	l=200	l=100	l=150	l=200
No Particles	0.7706	0.7706	0.7706	0	0	0
Sphere Only	0.7708	0.7708	0.7708	0.03	0.03	0.03
106 nm	0.7729	0.7725	0.7727	0.30	0.25	0.27
110 nm	0.7787	0.7731	0.7745	1.05	0.32	0.51
120 nm	0.7794	0.7779	0.7759	1.14	0.94	0.69
130 nm	0.7727	0.7729	0.7732	0.27	0.30	0.34
140 nm	0.7787	0.7727	0.7736	1.05	0.27	0.40

G. Optical Near-Field Enhancement Analysis

It was observed in the previous studies that at the resonant wavelength of the nanoparticles, the generated optical

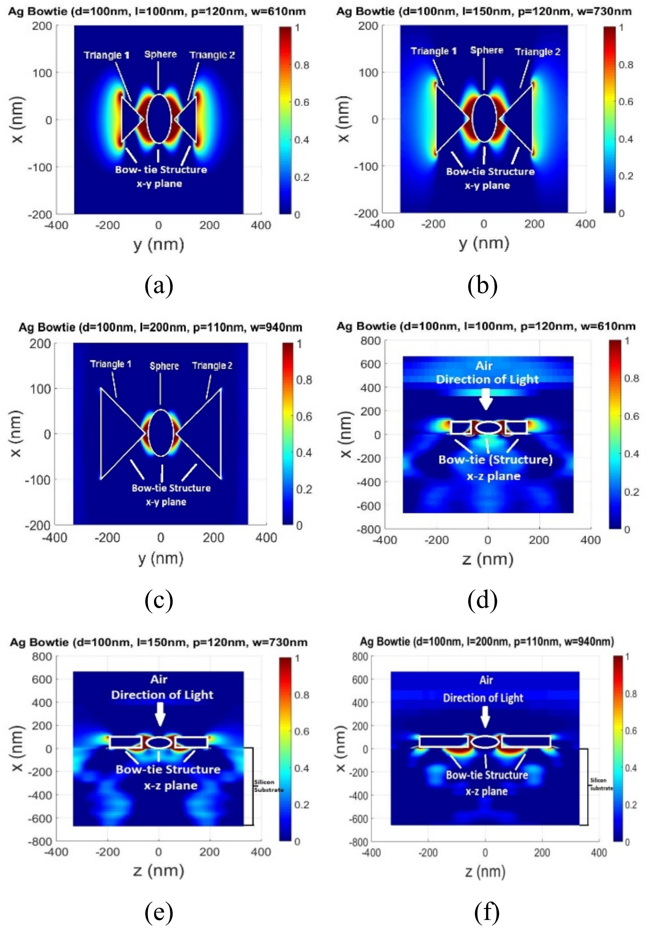


Fig. 4. Optical near-field enhancement images for the hybrid bow-tie based plasmonic nanostructures with different side lengths l, pitch sizes p, constant height h of 100nm, incident radiation wavelength w, and diameter of the spherical nanoparticle d; (a) (along x-y plane) l = 100 nm, p = 120 nm, w = 610 nm ; (b) (along x-y plane) l = 150 nm, p = 120 nm, w = 730 nm; and (c) (along x-y plane) l = 200 nm, p = 110 nm, w = 940 nm; (d) (along x-z plane) l = 100 nm, p = 120 nm, w = 610 nm ; (e) (along x-z plane) l = 150 nm, p = 120 nm, w = 730 nm; and (f) (along x-z plane) l = 200 nm, p = 110 nm, w = 940 nm.

near-field images help to understand the relationship between the distribution of the electric field within the immediate vicinity of the nanoparticles and around or within the semiconductor substrates [5]-[11]. Therefore, the optical near-field images for three different side lengths of the hybrid bow-tie based plasmonic nanostructure at three respective resonance wavelengths were being generated.

As it is mentioned earlier, the resonance wavelengths used in this study were associated to the triangular (pyramidal) nanoparticles of different side lengths at different pitch sizes. Three near-field images in the x-y plane and three near-field images in the x-z plane were obtained and are shown in Fig. 4 (a-f). It should be noted that these optical near-field enhancement images were generated in logarithmic scale (base 10). Thus, the dark red areas in the images correspond to an enhancement value of ‘1’ or greater in the log scale, which corresponds to near field enhancement of 10-fold or more [5]-[11].

It is clear from the images that the presence of this hybrid nanostructure at different pitch sizes with different side lengths yields changes in intensity of the electromagnetic radiation that is passing into the Si substrate due to the interactions between the nanoparticles and incident electromagnetic radiation. The optical near-filed enhancement images clearly show the hybrid bow-tie nanostructure (with the spherical silver nanoparticle in the middle) interacts with the incident radiation in a manner such that more of the incident light is passing through into the Si substrate (clearly seen in the images taken along the x-z plane). Additionally, this interaction also leads to significantly enhanced optical fields in the area between the vertices of the two triangular (pyramidal) nanoparticle where the spherical nanoparticle is placed (clearly seen in the images taken along the x-y plane) and appreciably enhanced optical fields in other areas around the hybrid nanostructure.

IV. CONCLUSION

This study explored the relationship between the energy conversion efficiency in amorphous thin film solar cells and the hybrid bow-tie based plasmonic nanostructure for different side lengths and pitch sizes. The diameter (d=100 nm) of the spherical particle and height (h=100 nm) of the triangular particle were held constant. The side lengths of the triangular particles considered were l = 100 nm, l = 150 nm and l = 200 nm with pitch sizes (distances between the vertices of two triangular particles) were varied from p = 106 to 140 nm.

It was seen that the triangular particles show more scattering than absorption within the wavelength from 600 to 1000 nm. The goal was to maximize the scattering of the triangular particles, so that the scattered radiation from the vertices of the triangular particles get scattered on the surface of the spherical particle placed in between the vertices of the two triangular (pyramidal) nanoparticles and then absorbed by the Si substrate. Even though the resonant wavelength of the spherical particle is approximately ƛ ~ 450 nm [5]-[11], the bow-tie nanostructure shows significant enhancement in near-field images within ƛ = 600 to 1000 nm.

It was also observed that these hybrid nanostructures, with the side lengths of 100 nm, 150 nm and 200 nm at the pitch sizes of 120 nm, 120 nm and 110 nm respectively, show higher absorption enhancement and electrical current generation for the Si substrate. Moreover, it is evident that the hybrid nanostructure with side length of 200 nm at 110 nm pitch size yields the maximum *g* and J_{SC} values.

The main goal of this study was to design triangular (pyramidal) nanoparticles that can concentrate and scatter incident radiation between their vertices so that a spherical silver nanoparticle placed in that region can experience an intense incident electromagnetic field. The Ag spherical nanoparticle can then be in resonance with this intense concentrated field and scatter/redirect the field inside the Si substrate thus increasing the optical absorption capability of the Si substrate. The triangular pyramidal nanoparticles basically act as electromagnetic field concentrators; much like a magnifying glass can be used to concentrate sunlight into a paper and burn the paper. It should, however, be noted that this study did not use the triangular (pyramidal) nanoparticles to scatter incident light at the resonance wavelength of the spherical silver particle (at approx. ƛ ~ 450 nm) [5]-[11]. Therefore, future work will be focused on designing more efficient triangular pyramidal Ag nanoparticles that can have scattering resonances that match the plasmon resonance of the spherical Ag nanoparticle placed in between the two vertices of the triangular nanoparticles. In such a case, the resonance wavelengths of both particles types shall be as close as possible to maximize the expected optical and electrical current generation enhancements from the thin-film solar cells. Additionally, future work will also be focused on the use of arrays of this hybrid nanostructure and other possible arrangements will also be investigated.

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