Characteristics of Plasmonic Solar Cell Embedded by Silver Nanoparticles

Anjna Chetan, Rajeev Kumar, Kh.S. Singh and Sandeep Kumar*,
Department of Physics, D. J. College, Baraut, Baghpat, Uttar Pradesh, India-250611.
Corresponding author - *sandeep12kumar@gmail.com

Characteristics of plasmonic solar cells are studied. In particular, amorphous silicon thin films dispersed with Ag nanoparticles are studied theoretically using effective medium theory. The dependence of electron generation rate and the current density on the thickness of the film is investigated. The effect of dispersion of Ag nanoparticles on the absorption coefficient of nanocomposite is also investigated. The dependence of external quantum efficiency (EQE) on wavelength is estimated. There is almost no change in the open circuit voltage of the film with the introduction of Ag nanoparticle but there is an appreciable enhancement of closed circuit current density with Ag nanoparticles dispersed.

Keywords: Plasmonic solar cells, nanoparticles, effective-medium theory, external quantum efficiency.

1. INTRODUCTION

Solar energy is an endless and abundant energy resource on Earth. Solar cells which convert solar energy to electricity become one of the alternative sources of renewable energy to supplement global energy shortages. It is a great challenge for researchers to enhance the efficiency of solar cells using low-price materials. Solar cells based on thin film technology led to a reduction in material cost. However, such solar cells have efficiencies much lower than single crystal solar cells. When the thickness of the absorbing semiconductor layer is decreased, this also leads to a decrease in the absorption of solar energy [1]. There are different techniques to increase the absorption of solar radiation in thin film semiconductor solar cells. The efficiencies of thin film based solar cells can be enhanced when the absorbance of the device is increased [2]. For example, back reflectors and diffraction gratings are used in the planar structure for the better absorption of light. Another novel technique is based on the plasmonic effect [2, 3]. The interaction between the incident light and free electrons in metals leads to plasmonic effect. Later, metallic nanostructures which assist surface Plasmon (SP) generation have been considered an effective way for increasing light absorption in thin films dispersed with such nanoparticles. Thus, various designs of solar cells based on plasmonin effect, namely plasmonic solar cells (PSCs) have been proposed. The absorption of light in PSCs is enhanced by the scattering of light by excitation of surface Plasmon polariton (SPP) at metal-dielectric interface of the system. Due to SPP, the incident electromagnetic field remains confined at the metal-semiconductor or metal-dielectric interface resulting to enhanced absorption. There are three main Plasmonic nanostructures are available in solar cell devices [4].

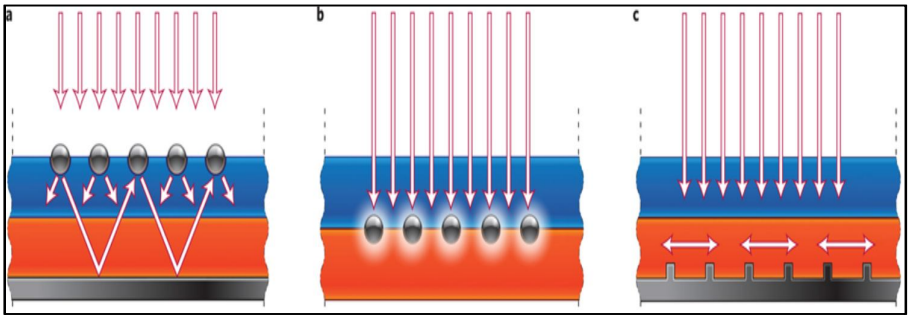

Fig.1: Geometries for light trapping in thin film plasmonic solar cells. Light trapping due to
(a) scattering of light on metal-nanoparticle interface.
(b) localized surface plasmon excitation in metal-nanoparticles interface embedded in semiconductors.
(c) excitation of SPP at the metal-semiconductor interface.

In the first structure shown in Figure 1, scattering of light from metal-nanoparticles, distributed on the top surface of the solar cell, leads to enhanced absorption. Symmetric scattering in the forward and backward direction is achieved by metal nanoparticles. When the nanoparticles are distributed on the interface between two semiconductor layers, the layer with large permittivity will receive more scattered light and it will result to an angular spread in that layer and an increase in the effective optical path length. In the second structure, metal nanoparticles are uniformly distributed in the solar cell's active layer. They behave as sub-wavelength lenses and light are trapped by the improved near field of the nanoparticles. In the third structure, light is trapped by surface plasmon polariton (SPP) resulting to the excitation of SPPs at the metal-semiconductor interface and effectively trapping and guiding light in a semiconductor layer. The SPP fields (evanescent waves) are more or less confined near the metal-semicondictor interface when the frequency of light is at plasmon resonance frequency when the dimensions of nanoparticles are much smaller than the wavelength of light. Out of the various structures for the enhancement of absorption due to the plasmonic effect in metal nano-particles dispersed thin film solar cells, we consider a thin film solar cell system based on amorphous silicon as the active layer, in which Ag nanoparticles are randomly dispersed rather than a distribution of metal nanoparticles on one of the interfaces/surfaces as in Figure 2.

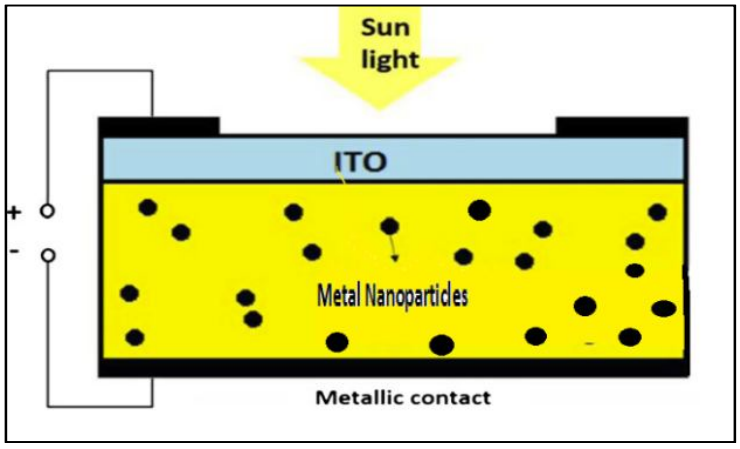

Fig. 2: Schematic structure of plasmonic solar cell.

2. METHODOLOGY AND INPUTS

The absorption coefficient of any material is a measure of qualitatively, how far into a material light of a particular wavelength can penetrate effectively before a definite fraction of the energy of incident light is absorbed. Different materials have different values of the absorption coefficient. Materials having higher absorption coefficient can absorb more energy and such material may be useful in solar cell applications. For comparison of the efficiency of our proposed nano-composite material solar cell with traditional silicon based bare thin film solar cells, we calculate the absorption coefficient of silicon and that of a Ag-nanoparticle dispersed silicon thin film. We can calculate the absorption coefficient of bare silicon using proper k-selection rule in the matrix element, which is given below [1]

$$\alpha(\ \mathrm{m})^{-1} = \begin{Bmatrix} -0.425\left(\hbar\omega - \mathrm{E_g}\right)^3 + 0.757(\hbar\omega - \mathrm{E_g})^2 \\ -0.0224\left(\hbar\omega - \mathrm{E_g}\right) + 10^{-4}, \\ \text{when } (1.1\mathrm{eV} < \ \hbar\omega < 1.5\mathrm{eV}\ ) \\ \text{or} \\ 0.0287\exp\left[2.72\left(\hbar\omega - \mathrm{E_g}\right)\right] \\ \text{when } (\hbar\omega > 1.5\mathrm{eV}) \end{Bmatrix} \quad \ldots\ldots(1)$$

Using the Maxwell-Garnett (MG) effective medium theory, we can express the effective dielectric function (EDF) of nanocomposite, which is given by [1,5,6,7]:

$$\varepsilon_{\mathrm{eff}} = \varepsilon \begin{bmatrix} \left(\frac{1+\frac{2\mathrm{f_S}(\varepsilon_S-\varepsilon)}{\varepsilon_S+2\varepsilon}}{1-\frac{\mathrm{f_S}(\varepsilon_S-\varepsilon)}{\varepsilon_S+2\varepsilon}}\right) \\ + 2\mathrm{if_s}\mathrm{k}^3\mathrm{a}^3\left|\frac{\frac{\varepsilon_S-\varepsilon}{\varepsilon_S+2\varepsilon}}{1-\frac{\mathrm{f_S}(\varepsilon_S-\varepsilon)}{\varepsilon_S+2\varepsilon}}\right|\left\{1+\frac{\mathrm{L}}{\mathrm{N}}\right\} \end{bmatrix} \quad \ldots\ldots(2)$$

where k is the wave vector of E.M. wave, ε_{eff} is the EDF, ε is the embedding medium dielectric function and ε_s is the metal nanoparticle dielectric function [8,9,10,11]. Also, f_s is the volume filling fraction of the metal nano-particles in the film and N is the number of nano-particles dispersed. The quantity L is given by

$$L = \frac{N^2}{V} Re\left\{\int drg(r)e^{ikr}\right\} \quad \text{... ...(3)}$$

Here, *g*(r) is the pair distribution function at the position 'r' and *V* is the volume containing the scatterers. In the Percus-Yevick approximation [7], *L* is given by:

$$L = N\left[\frac{(1-f)^4}{(1+2f)^2} - 1\right] \quad \text{.....(4)}$$

The refractive index n_{eff} and extinction coefficient n'_{eff} for nanocomposite (Si-Ag) can be calculated using the effective dielectric function of nano-composite (ε_{eff}). we calculate the absorption coefficient of nanocomposite with the help of the extinction coefficient using the expression [12]:

$$\alpha = \frac{2n'_{eff}\omega}{c} \quad \text{... ...(5)}$$

The coefficient is calculated using generation rate G. The expression of the generation rate is given by [13]:

$$G(z,\lambda) = \phi(\lambda)(1 - R_{ITO})\alpha(\lambda)e^{-\alpha(\lambda)z} \quad \text{.....(6)}$$

$\phi(\lambda)$, R_{ITO} and $\alpha(\lambda)$ are the density of photon flux, the reflectance of the ITO layer and the absorption coefficient of the relevant layers (one with silicon thin film and another Ag-nanoparticle dispersed silicon thin film) respectively [14,15]. Here, two types of the absorption coefficients are calculated for the relevant layers under consideration. The short circuit current density, J_{sc}, can be calculated with the help of generation rate and collection probability and is given by [16]:

$$J_{sc} = q\int_0^\infty d\lambda \int_0^z dx\, G(\lambda, x)\eta_c(x) \quad \text{... ...(7)}$$

η_c is collection probability which is defined as "collection probability is that probability which describes carrier created by light absorption in a particular region of the device".

$$\eta_c(x) = \cosh\frac{x}{L} - \frac{L}{Leff}\sinh\frac{x}{L} \quad \text{... ...(8)}$$

Where L_{eff} is given by

$$L_{eff} = L\frac{LS\sinh\frac{z}{L} + D\cosh\frac{z}{L}}{LS\cosh\frac{z}{L} + D\sinh\frac{z}{L}} \quad \text{... ...(9)}$$

Where L is diffusion length, D is diffusion constant, S is recombination velocity and *z* is the thickness of the solar cell.

Equation 7 can be written as

$$J_{sc} = q\int_{300}^{1200} d\lambda\phi(\lambda)\int_0^z dx\, g(\lambda,x)\eta_c(x) \qquad \ldots\ldots(10)$$

Where g(λ,x) is the normalized generation rate.

$$g(\lambda,x) = \frac{G(\lambda,x)}{\phi(\lambda)} \qquad \ldots\ldots(11)$$

with the help of these equations, we can calculate External quantum efficiency [17]

$$EQE(\lambda) = \int_0^z dx g(\lambda,x)\eta_c(x) \qquad \ldots\ldots(12)$$

3. RESULTS AND DISCUSSION

Figure 2 shows the schematic diagram of the solar cell structure we considered here. It has a silicon thin film with Ag-nanoparticles randomly distributed. An ITO layer is deposited on it. We have studied the effect Ag-nanoparticles, being randomly distributed in the silicon layer, on the effective absorption coefficient, generation rate, J_{sc} and the EQE of the system. Using the effective dielectric function for nanocomposite, the absorption coefficient has been calculated with the help of equation (5). The dependence of the absorption coefficient of silicon thin film on the wavelength(λ) of incident light is shown in Figure 3 and that of Ag-nanoparticles dispersed silicon thin film is shown in Figure 4. The absorption coefficient for bare silicon is calculated with the help of equation (1). From Figure 3 it is clear that the absorption coefficient of bare silicon has very small values above 400nm.

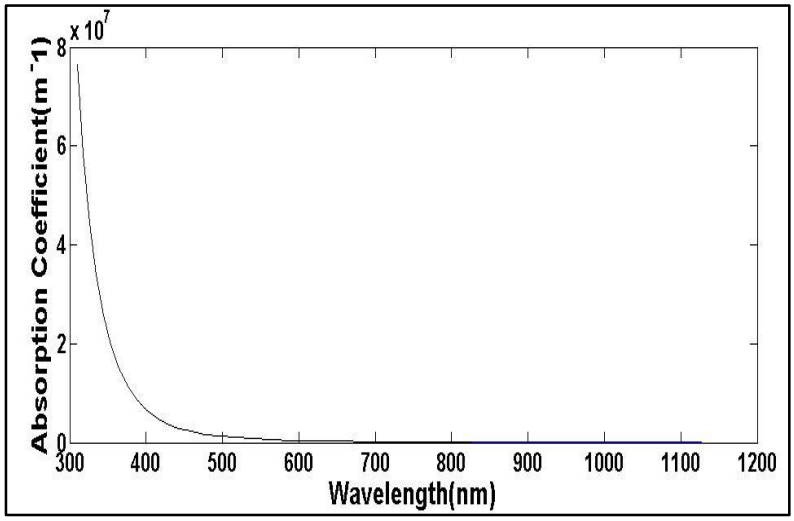

Fig. 3: Absorption coefficient of silicon layer without Ag nanoparticles.

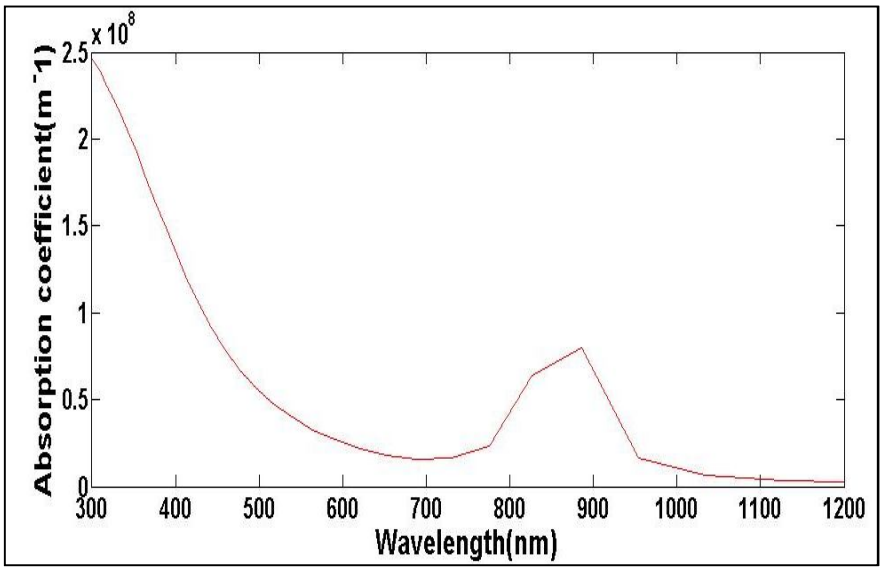

Fig. 4: Absorption coefficient of nanocomposite.

It is also clear from these Figures 3 and 4 that the value of the absorption coefficient for nanocomposite is higher than for bare silicon. The effect of filling fraction (f_s) and radius of nanoparticles on the absorption coefficient of nanocomposite is shown in Figure 5 and Figure 6. From Figure 5, we observe that there is a wide-band wavelength response for PSCs for f_s = .05 for nanoparticle filling fraction. From Figure 6 we can see that there is no significant change in the absorption coefficient when we change the radius of the nanoparticle. Thus, the filling fraction is an important parameter in the solar cell. The change in filling fraction leads to a change in absorption coefficient which further leads to a change in generation rate and hence resulting in a change in current density.

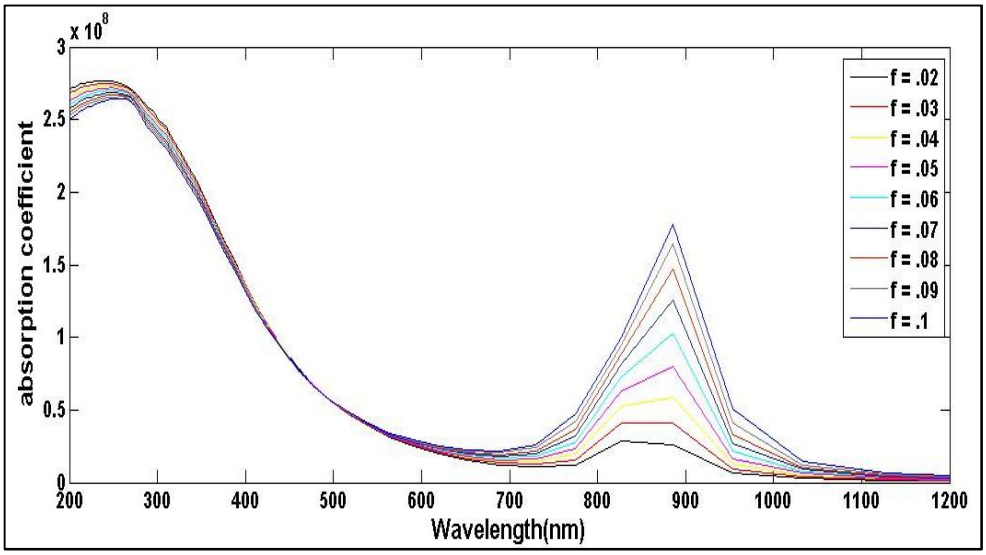

Fig. 5: Absorption coefficient for the different filling fractions.

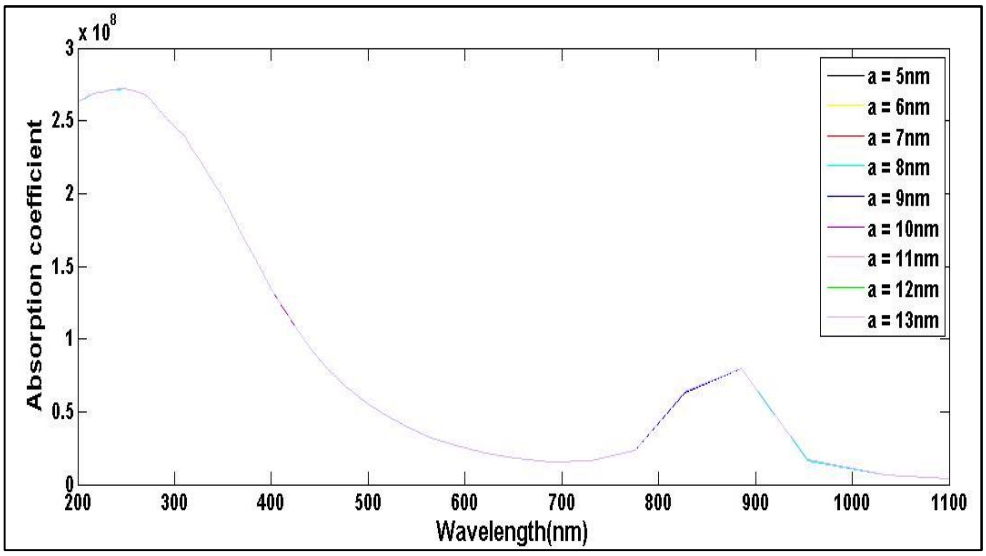

Fig. 6: Absorption coefficient for different radius.

After this comparison we have calculated the generation rate of these structures.

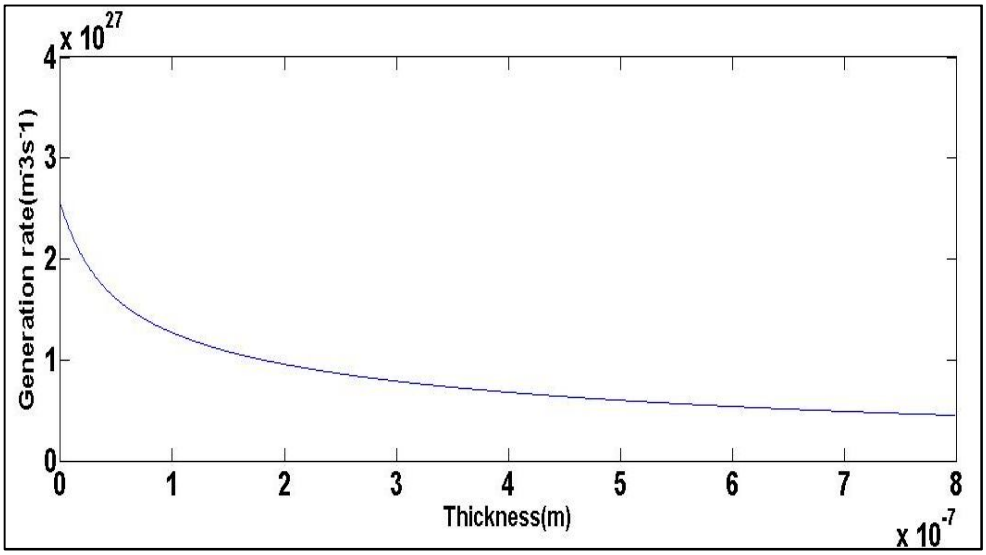

Fig. 7: Generation rate for bare silicon layer.

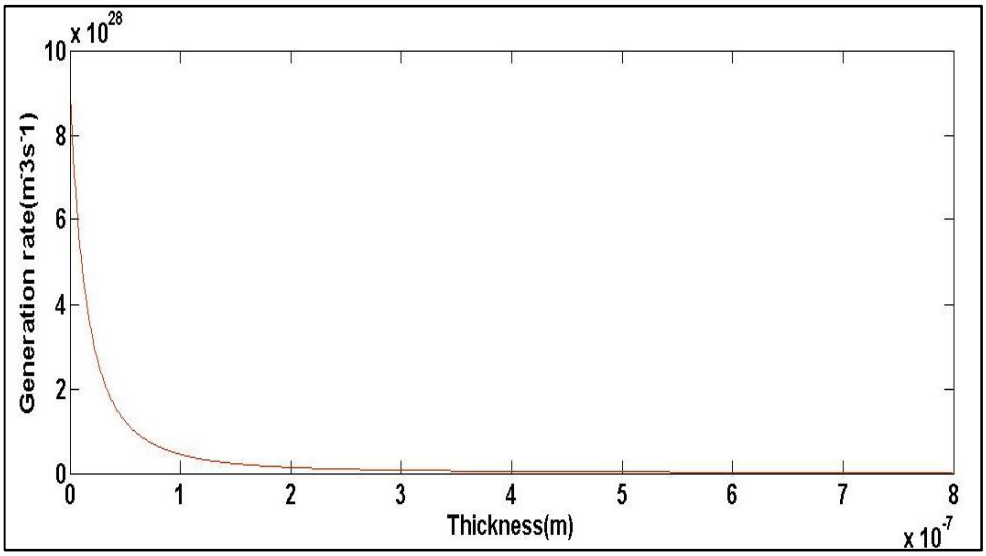

Fig. 8: Generation rate for nanocomposite.

The variation of Generation rate (integrated over wavelength), with thickness for bare silicon is shown in Figure 7, and the generation rate variation with thickness for nanocomposite is shown in Figure 8. Generation rate is increased for nanocomposite structure. Generation rate is an important parameter for solar cells, using this short circuit current density Jsc can be evaluated.

After calculating the generation rate, we drew Jsc - V characteristic for these two structures. In our study, we have chosen the thickness of the active layer as 800nm with a filling fraction of 0.05 and the radius of the Ag nanoparticle as 7.5nm.

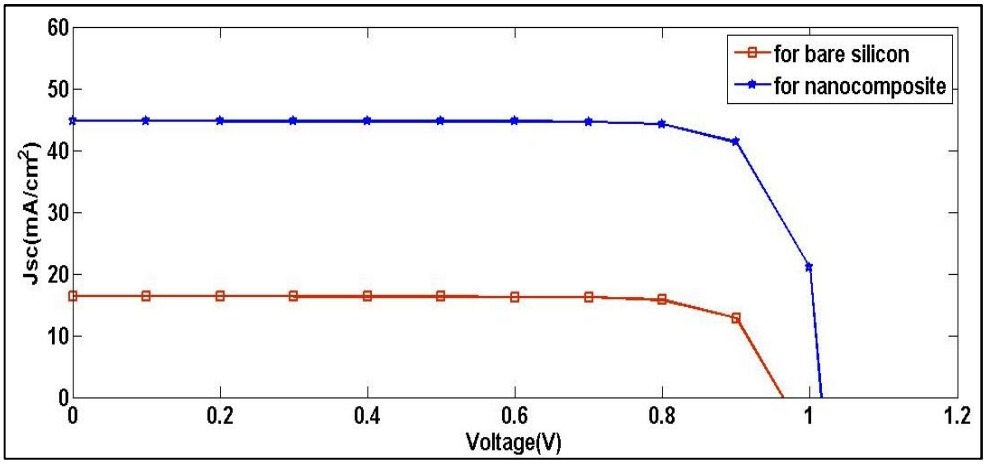

Fig. 9: J_{sc} variation with voltage for both structures.

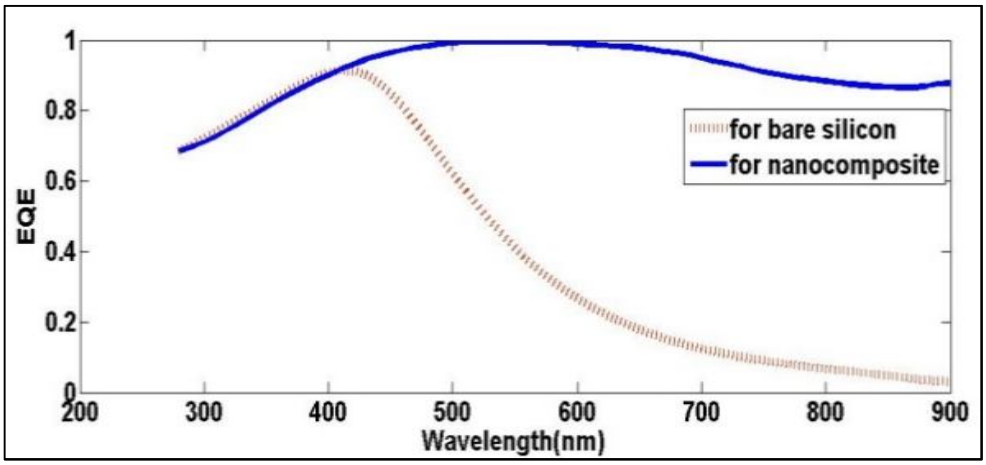

Fig. 10: EQE variation with wavelength for both structures.

With random dispersion of Ag nanoparticles in the active layer, it is observed that J_{sc} is increased and the open circuit voltage (V_{oc}) is also slightly increased. We also compare external quantum efficiency (EQE) for these two structures, which is shown in Figure 10.

It is clear from the graph for the EQE of the bare thin film silicon solar cell is decreased rapidly for the shorter wavelength region of radiation. EQE has comparatively higher values in the nanocomposite than the bare silicon. We have also studied the effect the thickness (x) of the film on J_{sc} (Figure 11). It can be concluded that the values of J_{sc} are

higher in nanocomposite as compared to the values for bare silicon. The effect on J_{sc} due to the increase in the thickness of the film is only marginal from 200nm to 800nm.

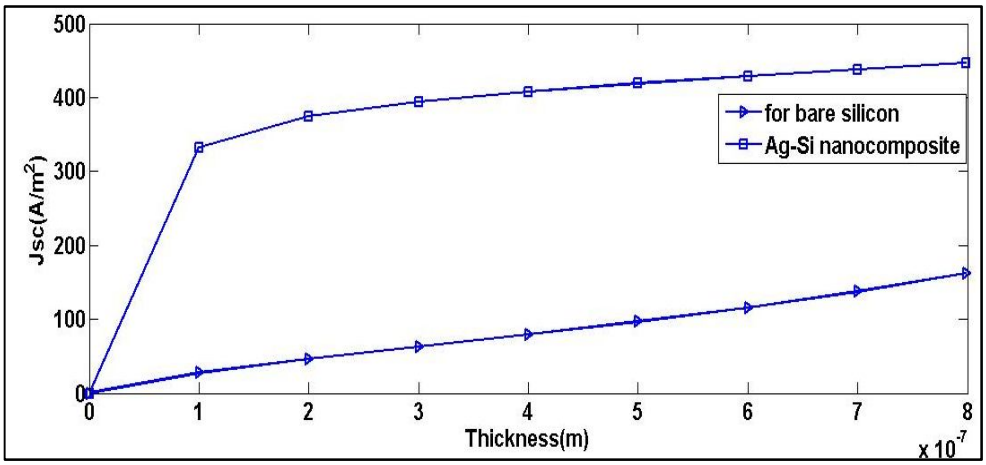

Fig. 11: J_{sc} variation with thickness for both structures.

For a typical thickness of active layer taken to be 800nm, Jsc is 162.5A/m^2 for bare silicon solar cell and Ag distributed silicon film, it is 447.07A/m^2.

4. CONCLUSION

With the help of Maxwell-Garnett's effective medium theory, the EDF of Si thin film dispersed with Ag nanoparticles has been computed. Using this calculated EDF (ε_{eff}), the absorption coefficient, generation rate, J_{sc} and the EQE are computed. Our results show that nanocomposite material has a broad range enhancement in the absorption coefficient of structure. The generation rate depends on the absorption coefficient of the solar cell structure. This leads to an increase in the Generation rate. An increase in generation rate further leads to an increase in J_{sc} and EQE for a wide range of the solar spectrum. Thus, the plasmonic solar cell structures when Ag-nanoparticles are dispersed in amorphous Si-thin films can be considered a promising candidate for the design of low-cost novel solar cells. Relevant solar cell parameters are estimated for the solar cell structures considered here.

REFERENCES

[1] M. Piralaee, A. Asgari and V. Siahpoush; "Modeling and optimizing the performance of plasmonic solar cells using effective medium theory", Physics Letters A, Vol. 381(5), pp. 489-493, 2017. http://doi.org/10.1016/j.physleta.2016.11.029

[2] M. Piralaee and A. Asgari; "Modeling of optimum light absorption in the random plasmonic solar cell using effective medium theory", Opt. Mater., Vol. 62, pp. 399–402, 2016. http://doi.org/10.1016/j.optmat.2016.10.021

[3] H.A. Atwater and A. Polman; “Plasmonics for improved photovoltaic devices”, Nat. Mater., Vol. 9(3), pp. 205-213, 2010.

[4] K. Nakayama, K.Tanabe and H.A. Atwater; “Plasmonic nanoparticle enhanced light absorption in GaAs solar cells”, Appl. Phys. Lett., Vol. 93(12), pp. 3-5, 2008. http://doi.org/10.1063/1.2988288

[5] J.C.M. Garnett; “Colours in metal glasses, in metallic films, and in metallic solutions-II”, Phil. Trans. R. Soc. A, Vol. 205, pp. 237–288, 1906.

[6] J.C.M. Garnett; “Colours in metal glasses and in metallic films”, Phil. Trans. R. Soc. A, Vol. 203, pp. 385-420, 1904. http://doi.org/10.1098/rsta.1904.0024

[7] D.S. Mclachlan, A. Priou. I. Chenerie, E. Issac and F. Henry; “Modelling the permittivity of composite materials with a general effective medium equation”, J. Electromag. Waves & Appl., Vol. 6(9), pp. 1099-1131, 1992.

[8] S.A. Maier; “Plasmonics: Fundamentals and Applications”, Springer Science, United Kingdom, 2007.

[9] A.D. Rakic, A.B. Djuristic, J.M. Elazar and M.L. Majewski; “Optical properties of metallic films for vertical-cavity optoelectronic devices”, Appl. Opt., Vol. 37(22), pp. 5271-5283, 1998. http://doi.org/10.1364/AO.37.005271

[10] E.D. Palik; “Handbook of Optical Constants of Solids”, first ed., Academic, Orlando, Fla.,1985.

[11] H.R. Philipp and H. Ehrenreich; “Optical properties of semiconductors”, Phys. Rev., Vol. 129 (4), 1963. http://doi.org/10.1103/PhysRev.129.1550

[12] J. Sancho-Parramon, V. Janicki and H. Zorc; “On the dielectric function tunning of random metal-dielectric nanocomposite for metamaterial application”, Opt. Express., Vol. 18(26), pp. 26915-26928, 2010. http://doi.org/10.1364/OE.18.026915

[13] Z. Arefinia and A. Asgari; “An analytical model for optimizing the performance of grapheme based silicon Schottky barrier solar cell”, Mater. Sci. Semicond. Process., Vol. 35, pp. 181-188, 2015. http://doi.org/10.1016/j.mssp.2015.02.030

[14] Z. Arefinia and A. Asgari; “A new modelling approach for grapheme based silicon nanowire Schottky junction solar cells”, J. Renew. Sustain. Energy, Vol. 6, pp. 043132, 2014. http://doi.org/10.1063/1.4893433

[15] H. Zhao; “Light Trapping for silicon Solar cells: Theory and Experiment”, Syracuse University, 2013.

[16] W.-J. Ho, Y.-Y. Lee and S.-Y. Su; “External quantum efficiency response of thin silicon solar cell based on plasmonic scattering of indium and silver nanoparticles”,

Nanoscale Res. Lett., Vol. 9(1), pp. 483, 2014. http://doi.org/ 10.1186/1556-276X-9-483

[17] A. Bozzola, P. Kowalczewski and L.C. Andreani; “Towards high efficiency thin-film crystalline silicon solar cells: the role of light trapping and non-radiative recombinations”, J. App. Phy., Vol. 115, pp. 094501, 2014. http://doi.org/10.1063/1.4867008