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Study and Optimization of Metal Nanoparticles for the Enhanced Efficiency Thin Film Solar Cells

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Abstract. Thin film silicon solar cells have the potential to considerably decrease the cost of photovoltaic. To increase the conversion efficiency of thin film solar cells, nano-sized structures, such as nanoparticle deposition at the front end, were proposed. In the present study, spherical metal nanoparticles such as gold (Au) and silver (Ag) were deployed at the front of the silicon solar cell. The effect of metal nanoparticles on the absorption enhancement factor of the thin film solar cells was investigated using Lumerical Finite Difference Time Domain (FDTD) solutions. Also the influence of geometrical parameters of spherical nanoparticles on absorption enhancement factor was examined. The maximum absorption enhancement factor was achieved by optimizing the geometrical parameters of nanoparticles. The structure with Ag nanoparticles at the front end of the silicon solar cell exhibits higher absorption enhancement factor than the structure with Au nanoparticles.

1. Introduction

The development of solar cell is progressing with rapid speed. Solar cell is the device which can effectively convert sun light into electric power and also have the potential to replace fossil fuels as our main means of power generation [1]. Thin film solar cells have the potential to considerably reduce the cost of photovoltaics. It, however, becomes a critical problem to trap the light in the solar cell to increase light absorption, i.e. to increase the conversion efficiency. To increase the conversion efficiency, nano-sized structures, such as textured surface and nano–particle deposition on the surface, have been proposed [2]. In recent studies, a great number of studies on enhancing optical absorption and device efficiency have been carried out. Various methods for enhancing the absorption of the thin film solar cell have been proposed [3]. Silicon nanowire arrays are set as an antireflection film to decrease the surface reflection and then increase the light absorption [4]. A nanostructure which is deposited on the front surface of a solar cell is a best method [4]. The use of metal nanostructures could cause the excitation of Localized Surface Plasmon (LSP). When the surface plasmon resonance occurs, the light absorption in the solar cell significantly improved [5]. It has been demonstrated that the use of metal nanostructures in solar cells could produce stronger field and greater absorption enhancement [6]. Only light absorbed by the absorption layer can contribute to the external electricity, thus it is essential to analyze the absorption enhancement in the absorption layer of the thin film solar cell [8].

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In the present study, the absorption enhancement of silicon solar cell with spherical metal (Ag and Au) nanoparticles has been performed using Lumerical FDTD Solutions. Also the analysis, interpretation and comparison of absorption enhancement of solar cell with Ag and solar cell with Au nanoparticles have been made in detail.

2. Material and Methods

A Lumerical FDTD solution is used for the numerical simulations. FDTD Solution is used to simulate the interaction of light with a wide variety of solar cell designs. The solar cell designs vary from simple planar geometries to very complex patterns, and include a wide type of materials (organics and metals). The optical simulations of plasmonic solar cell in FDTD Solutions explain the workflow of solar cell.

The structure of solar cell with nano-particles used for the simulation study is shown in Figure 1. The spherical metal (gold and silver) nanoparticles are deposited on the silicon substrate. In the following studies h represents the height of the nano particle, P represents period of the nano particle array, D represents radius of the nano particle and t is the thickness of the silicon substrate. Silicon is selected as the absorbing layer because of its wide application in monocrystalline silicon solar cell.

The incident source is a uniform plane wave with a wavelength range from 400 to 1100 nm. Perfectly Matched Layer (PML) absorbing boundary conditions are used on the top and bottom boundaries of the computational domain that absorb the reflected and transmitted fields. The power absorbed in the silicon is calculated using two power monitors and one is located at the top of the silicon surface and another at the bottom. Difference between these two gives the absorbed power within the solar cell.

The quantum efficiency of a solar cell, $QE(\lambda)$, is defined as [7]:

$$QE(\lambda) = \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} \quad (1)$$

Where, $P_{in}(\lambda)$ and $P_{abs}(\lambda)$ is the incident light power and absorbed light power within the solar cell respectively at a wavelength of λ. The integrated quantum efficiency, IQE is defined as [7]

$$IQE(\lambda) = \frac{\int \frac{\lambda}{hc} QE(\lambda) I(\lambda) d\lambda}{\int \frac{\lambda}{hc} I(\lambda) d\lambda} \quad (2)$$

Where, c is the speed of light in air, h is the Plank's constant and AM1.5 solar spectrum is used. In equation (2) numerator corresponds to number of photons absorbed by the solar cell while denominator corresponds to number of photons falling onto the solar cell. The enhancement of light absorption efficiency of the solar cell with metal particles compared to bare solar cell is determined by absorption enhancement spectrum g(λ) and absorption enhancement factor g and are defined as:

$$g(\lambda) = \frac{QE_{particle}(\lambda)}{QE_{bare}(\lambda)} = \frac{P_{nanoparticle}(\lambda)}{P_{bare}(\lambda)} \quad (3)$$

and

$$g = \frac{IQE_{particle}}{IQE_{bare}} = \frac{\int \lambda P_{nanoparticle}(\lambda) I(\lambda) d\lambda}{\int \lambda P_{bare}(\lambda) I(\lambda) d\lambda} \quad (4)$$

Where, $IQE_{particle}$ and IQE_{bare} represents the integrated quantum efficiency of the solar cell with metal nano particle and without nano particle respectively. $P_{nanoparticle}(\lambda)$ and $P_{bare}(\lambda)$ corresponds to light absorption of silicon layer with and without metal nanoparticles at a wavelength λ respectively.

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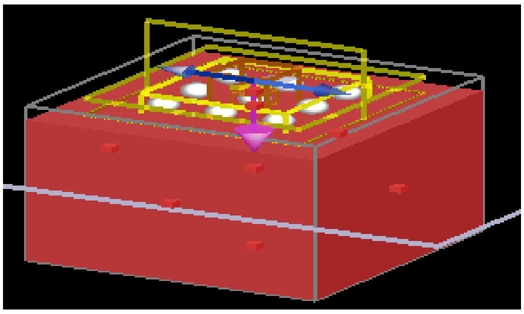

Figure 1. Solar cell structure with spherical nanoparticles

3. Results and Discussions

The optimization process of the nanostructures is studied systematically by varying the geometrical parameters of the metal nanoparticles. The absorption enhancement factor is determined by equation 4.

3.1. The effect of radius of the metal particle on the absorption

The absorption enhancement curves for gold and silver nanoparticles with different radius D, when P=400nm, S=2nm, t=500 nm are shown in Figure 2. It is observed that silver nanoparticles give better absorption enhancement factor compared to gold nanoparticles. Figure 3 shows the relation of g with the radius of nano spheres. For the structure with silver nanoparticles the g value increases with increase in radius of nano spheres and reaches the maximum value of 1.3355 (P = 400 nm, h = 2 nm, t = 500 nm) then gradually decreases. Gold nanoparticles exhibits maximum g value of 0.974 at P = 400 nm, h = 2 nm, t = 500 nm, D = 100 nm, further increase in radius causes rapid decrease in the value of g.

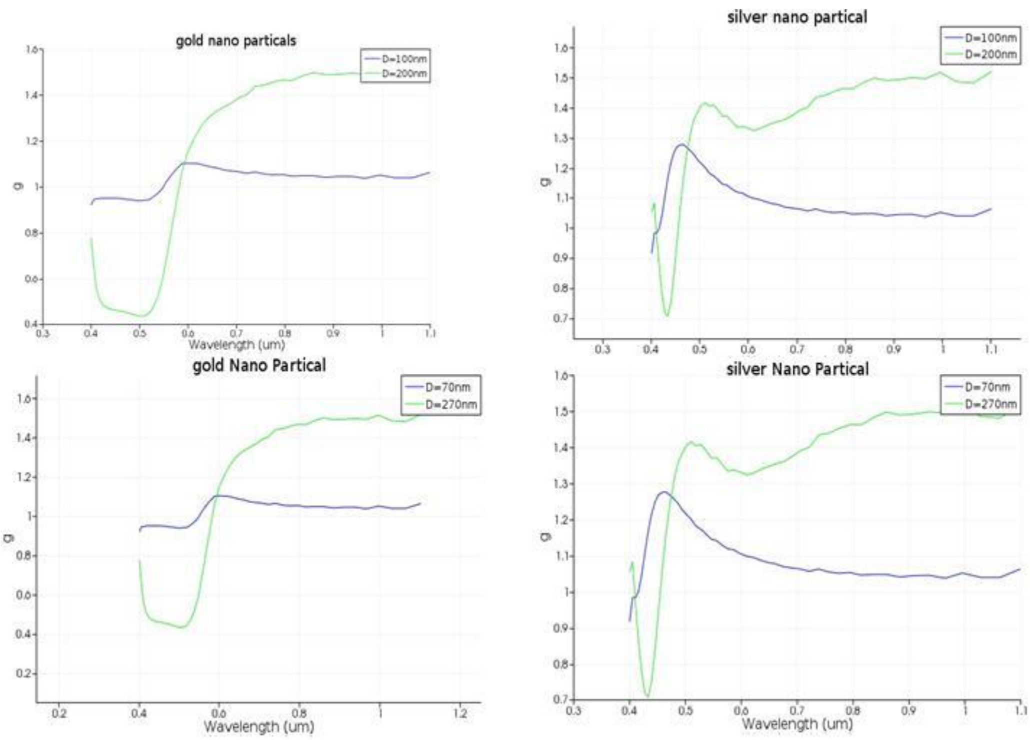

Figure 2. Absorption spectrum of silicon with Diameter of the spherical Au and Ag nanoparticles, at P = 400 nm, h = 2 nm, t = 500 nm

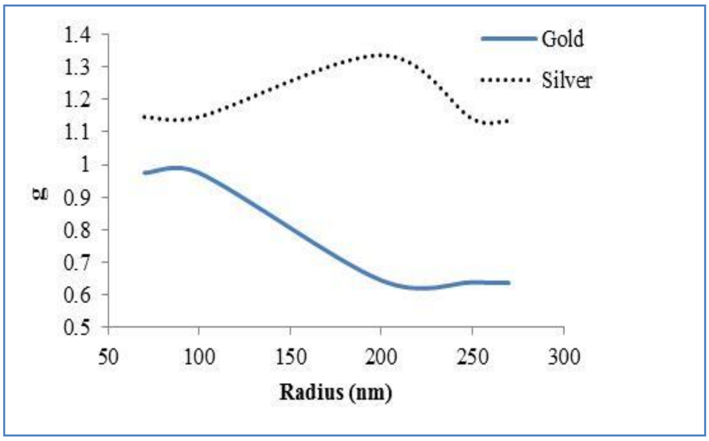

Figure 3. Relation of the absorption enhancement factor g with the radius of Au and Ag nanoparticles at P = 400 nm, h = 2 nm, t = 500 nm

3.2. The effect of period of the nano metal particles on the absorption
Relationship between absorption enhancement factor and periodicity of nanoparticles is as shown in Figure 4. The value of g increases with increase in period of nanoparticles from 200 nm to 300 nm and then remain constant, by maintaining other parameters such as h = 2 nm, t = 500 nm, D = 100 nm for Au constant. But for silver nanoparticles increase of radius of nano particle results in increase in the absorption enhancement factor g to a maximum value of 1.335 at h = 2 nm, t = 500 nm, D = 200 nm and P = 400 nm, beyond the period of 400 nm decrease in the value of g.

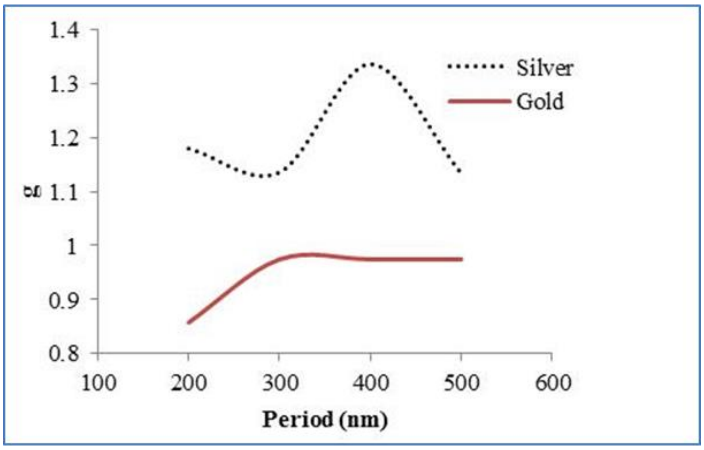

Figure 4. Relation of the absorption enhancement factor g with the period of Au and Ag nanoparticles at h = 2 nm, t = 500 nm, D = 100 nm for Au and D = 200 nm for Ag

3.3. The effect of height of the nano metal particles on the absorption
The graph, Figure 5, showing the relation of the absorption enhancement factor g with the height of Au and Ag nanoparticles ensures that Height of spherical nano particle does not much influences the absorption enhancement factor.

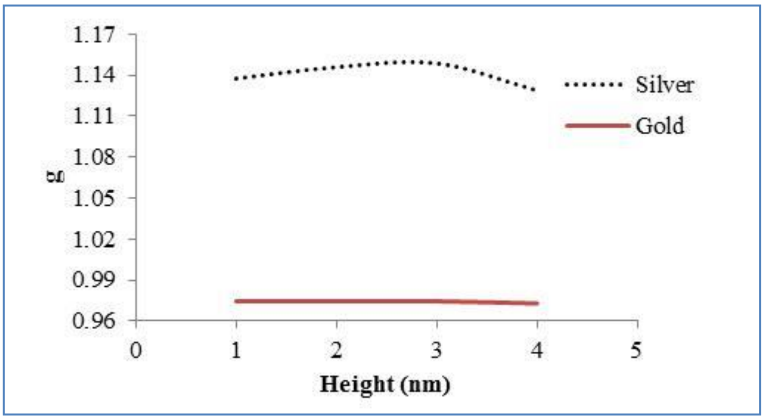

Figure 5. Relation of the absorption enhancement factor g with the height of Au and Ag nanoparticles at p = 400 nm, t = 500 nm, D = 100 nm for Au and D = 200 nm for Ag

Comparison between gold and silver nano particle is made in the Table 1. Table 1 also gives the optimized geometrical parameters of nanoparticles. Solar cell with Ag metal nanoparticles at the front end gives higher value of absorption enhancement factor, g, compared to Au nanoparticles. The Figure 6 shows the profile of the relative absorption distribution of solar cell solar cell with Ag metal nanoparticles. The solar cell without metal nanostructure exhibits parallel absorption distribution in the Si film because part of the incident light is reflected from the back contact in a direction opposite to that of the incident light, which shows that the light propagates in the Si film through the shortest path [8]. For the solar cell with the optimized silver nanoparticles at the front end, the effective absorption is enhanced reason behind this is the distance between the nanoparticles and Si is relatively small, coupling of surface plasmon resonance near-field into the lower part of Si film is possible, as shown in Figure 6.

Table 1. Optimized geometrical parameters of metal (Au and Ag) nanoparticles and corresponding maximum absorption enhancement factor g_{max} at t = 500nm

Nanoparticle Type	Radius (nm)	Height (nm)	Period (nm)	g_{max}
Au	100	2	300	0.97456
Ag	200	2	400	1.3355

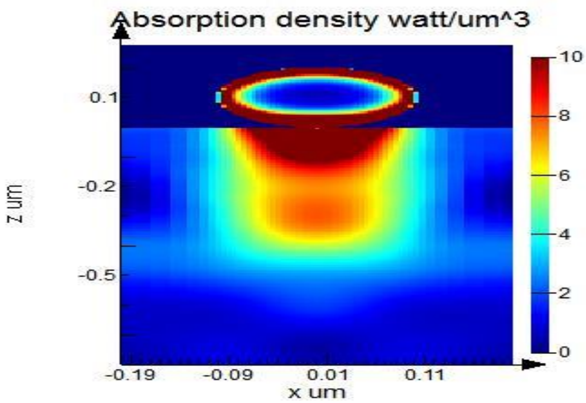

Figure 6. The relative absorption distribution per unit volume for a solar cell with optimized Ag nanoparticles

4. Conclusions

The influence of type of metal nanoparticles and geometrical parameters of spherical nanoparticles on the absorption enhancement factor of the thin film solar cells have been investigated using Lumerical Finite Difference Time Domain (FDTD) solutions. The fashion of absorption enhancement factor with different radius, periodicity and height of spherical nanoparticles has been studied. As a outcome g has the maximum value of 1.3355 at P = 400 nm, h = 2 nm, t = 500 nm for Ag nanoparticles; 0.974 at P = 400 nm, h = 2 nm, t = 500 nm, D = 100 nm for Au nanoparticles. The structure with Ag nanoparticles gives better absorption compared to Au nanoparticles. This simulation work is useful in fabrication of enhanced efficiency thin film solar cell.

5. References

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