Study on surface plasmon-based improvement in absorption in plasmonic solar cell

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Abstract: Recently, plasmonics offers very high attention and greatly deals with various field includes the nanophotonics domain. In the plasmonic field, when the nanoparticle is much smaller than the wave length of light, coherent oscillation of the conduction band electrons induced by interaction with an electromagnetic field and conjointly improves absorption through scattering. In this paper, we studied the effectiveness of nanoparticle dimension to enhance extinction in terms of absorption and scattering for silver, gold, copper and aluminium nanoparticles. We also studied finite difference time domain-based solar cell model that improves various simulated plasmonic field components and observed that the high sensitivity of the surface plasmon resonance spectrum of noble metal nanoparticles to adsorbate induced changes in dimension and dielectric constant of the surrounding nanoenvironment. We also observed that noble metal specifically silver and gold nanoparticles significantly improve optical absorption than copper and aluminium nanoparticles.

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1 Introduction

According to our global demands, all natural energy sources like fossil fuel, oil, gases, etc., are firstly depleting and they are also the largest polluters of the environment and as a result of ecological damages. Thus, the recent trend is going towards renewable energy. The solar energy is most promising and also reliable among the renewable sources. The solar energy incident on the earth surface is about 1,650 TW/sec is much higher than the combined power consumption by our world is about 20TW using traditional energy sources. Thus the solar energy has the advantage to produce more electricity. For this purpose, a demand for large-scale production of solar cell has emerged commercially.

The solar cell is a device that converts solar energy into electricity by the photovoltaic effect. In 1954, the modern solar cell has been first demonstrated in Bell Laboratories with starting efficiency 6%. Since then there is several solar cell design proposal has been coming on the basis of used materials, technology to increase photovoltaic conversion efficiency. Today commercially available market-leading solar cell is a crystalline-silicon based solar cell with efficiency up to 14.7% (Marrero et al., 2007). Using improved design technique, like back surface field (BSF) gives further improvement at 15.5% (Limmanee et al., 2008) and rear local contact (RLC) enhance efficiency up to 20%. But the first generation silicon-based solar cell has several drawbacks and also to lower cost per watt demand, second and third generation solar cell has been coming that is based on thin-film technology.

From the starting of solar cell has efficiency 6% increases to the present scenario is 18% and remaining, i.e., more than 80% is a loss. In a solar PV cell, if the photon energy is greater than or equal to the bandgap energy, the photon energy is absorbed and generates an electron-hole pair. If photon energy is less than the bandgap and it passes occurs sub-band loss. Plasmonics can be considered as one of most modern promising techniques as it improves absorption through photon scattering using metallic nanoparticle excited at surface Plasmon resonance (Atwater, 2007). Using metal nanoparticle, the magnitude of Raman scattering is increased. This scattering offers more photons which will be available to excite surface plasmon and electrons will be excited and move through a solar cell to make a photocurrent.

2 Basic solar cell

Photovoltaic solar cell absorbs incident photonic energy converts to electrical energy and the operation is similar to PN junction diode. If the incident photon energy is greater than or equal to the bandgap energy, the photon energy is absorbed and generates an electron-hole pair. If photon energy is less than the bandgap and it passes occurs sub-band loss. Plasmonics can be considered as one of most modern promising techniques as it improves absorption through photon scattering using metallic nanoparticle excited at surface Plasmon resonance (Atwater, 2007). Using metal nanoparticle, the magnitude of Raman scattering is increased. This scattering offers more photons which will be available to excite surface plasmon and electrons will be excited and move through a solar cell to make a photocurrent.
solar cell is determined by the fraction of incident photon energy which is converted to electricity.

3 Plasmonics

Plasmon is a density wave in an electron gas which oscillates in sync. It is similar to acoustic wave, that’s a density wave in a gas of molecules. Plasmon exists especially in metals, where electrons are loosely bound to the atoms and free to move (Enoch and Bond, 2012). For the choice of metal, noble metals (gold, silver) are most effective for plasmonic resonance. Plasmons are two types-localised surface plasmons and propagating plasmon (surface plasmon polariton). Localised surface plasmon occurs dipole or multipole oscillation of electrons at locally whereas surface plasmon bounded at the metal-dielectric interface. A typical localised plasmon is shown in Figure1.

![Localised surface plasmon using nanosphere](image)

Figure 1  Localised surface plasmon using nanosphere

Plasmon phenomenon occurs mainly in metals where electrons are weakly bound, those free electron gas can be modelled by jellium model. According to this model, in presence of a uniform electric field, the electrons are displaced by \( x \) and when the field is turn off, the electrons will be accelerated by the electric field and want to return to their initial state. This manner might be repeated and could produce an oscillation using Newton’s law applied to single electron,

\[
m \frac{d^2 x}{dt^2} = -eE_x.
\]

Using Gauss’s theorem, it is considered that the field generated by a surface charge \( nex \) for a displacement \( x \) will be \( E_x = 2nex / 2\varepsilon_o \). So the plasma frequency \( \omega_p \) will be

\[
\omega_p = \sqrt{\frac{ne^2}{m\varepsilon_o}}.
\]
If we consider the radius of metallic nanosphere is much less than the incident wavelength. Then the field component due to uniform polarisation $P_z$ will be $E_z = -P_z / \varepsilon_0$. So, the resonance frequency due to collective oscillation of electrons is given by,

$$\omega_{sp} = \frac{\omega_p}{\sqrt{3}} = \sqrt{\frac{4\pi n e^2}{3m\varepsilon_0}}$$

The surface plasmon polariton is a class of surface waves which propagate at the interface between a metal and a dielectric. For surface plasmon, noble metals like Ag and Au are the best choice whose dielectric constant is defined by the Drude model and also the dielectric constant highly depends on incident frequency.

$$\varepsilon_i(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma(\omega)\omega}$$

The absorption improvement in metallic nanoparticle into solar cell occurs due to scattering and near-field concentration of light. Metal nanoparticles are strong scatterers of light at wavelengths near the plasmon resonance, which is due to a collective oscillation of the conduction electrons in the metal. In infrared to visible region, the refractive index will be purely imaginary and effective permittivity is negative which is highly depending upon frequencies also varies with materials. When light is incident on the metallic nanoparticle, there occurs two phenomenon-absorption and scattering. Scattering is two types front and backscattering. Backscattering is basically loss also termed as reflectance and front scattering sometimes additively depends on particle size, position, and local environments, etc. Also, the extinction is an addition to absorption and scattering taken as optical efficiency metric. So, according to Mie theory, the optical scattering and extinction are given by

$$\sigma_{sc} = \frac{\lambda^2}{2\pi} \sum_{n=0}^{\infty} (2n+1) \left( |a_n|^2 + |b_n|^2 \right)$$

$$\text{and } \sigma_{ext} = \frac{\lambda^2}{2\pi} \sum_{n=0}^{\infty} (2n+1) \text{Re}(a_n + b_n)$$

where $a_n$ and $b_n$ are denoted by Mie coefficients, defined by Ricatti-Bessel functions, with $n$ is the index ranging from 1 to $\infty$ and also the absorption cross sections are calculated by $\sigma_{abs} = \sigma_{ext} - \sigma_{sc}$. The extinction efficiency can be $Q_{ext} = \sigma_{ext} / \pi r^2$, where $r$ is the radius of the nanoparticle. For metallic nanosphere with a diameter ($d$) is much less than the 1/10th wavelength ($\lambda$) of incident light, the scattering and absorption of cross-sections are strongly depended on polarisability ($\alpha$) of the particle with radius $r$ is given by

$$\alpha = 4\pi r^3 \frac{\varepsilon_{sp}(\omega) - \varepsilon_{em}}{\varepsilon_{sp}(\omega) + 2\varepsilon_{em}}.$$
Here, $\varepsilon_{sp}(\omega)$ is a dielectric function of metal nanosphere and $\varepsilon_{em}$ is a dielectric function of embedding medium. Resonant enhancement occurs under the condition that $\varepsilon_{sp}(\omega) + 2\varepsilon_{em}$ is a minimum (Maier, 2007). The corresponding efficiency ($Q$) for scattering, absorption is given below.

$$Q_{sca} = \frac{128\pi^4 r^4}{3\lambda^2} \left| \frac{\varepsilon_{sp}(\omega) - \varepsilon_{em}}{\varepsilon_{sp}(\omega) + 2\varepsilon_{em}} \right|^2$$

and

$$Q_{abs} = \frac{8\pi r}{\lambda} \text{Im} \left\{ \frac{\varepsilon_{sp}(\omega) - \varepsilon_{em}}{\varepsilon_{sp}(\omega) + 2\varepsilon_{em}} \right\}$$

For a spherical metallic nanoparticle with volume $V = \frac{4}{3}\pi r^3$ and dielectric function $\varepsilon_{sp}(\omega) = \varepsilon_K + i\varepsilon_I$ (Maier, 2007). So the efficiency of extinction is given by

$$Q_{ext} = \frac{72\pi r^{3/2}}{3\lambda} \frac{\varepsilon_I}{(\varepsilon_K + 2\varepsilon_{em})^2 + \varepsilon_I^2}.$$

The absorption, scattering and extinction efficiency versus wavelength for Au, Ag, Cu and Al with various diameters are shown in following figures.

**Figure 2** Absorption, scattering and extinction vs. wavelength for Au nanoparticle with $D = 10$ nm, 30 nm, 50 nm and 80 nm (see online version for colours)
Figure 3  Absorption, scattering and extinction vs. wavelength for Ag nanoparticle with 
D = 10 nm, 30 nm, 50 nm and 80 nm (see online version for colours)

Figure 4  Absorption, scattering and extinction vs. wavelength for Cu nanoparticle with 
D = 10 nm, 30 nm, 50 nm and 80 nm (see online version for colours)
Figure 5  Absorption, scattering and extinction vs. wavelength for Al nanoparticle with
D = 10 nm, 30 nm, 50 nm and 80 nm (see online version for colours)

4 Plasmonic solar cell

We have studied plasmonic nanostructure of the solar cell to improvement in light
trapping. This mechanism depends on the local environment includes the particle
dimension, adsorbates and electrical structure of the solar cell. Here, we studied
finite-difference time domain (FDTD) based solar cell model that uses silicon substrate
and dielectric as a base material with metal nanoparticles on top of the dielectric surface.

Figure 6  FDTD model with Ag nanosphere diameter 30 nm (see online version for colours)
Figure 7  The simulated plot of fields of $E_x$, from observation plane 1 (see online version for colours)

Figure 8  The simulated plot of pointing vector $S_z$ from observation plane 1 (see online version for colours)
Figure 9  The simulated plot of fields of $H_y$, from observation plane 1 (see online version for colours)

Figure 10  The simulated plot of fields of $E_y$, from observation plane 1 (see online version for colours)
Figure 11  Extinction vs. wavelength for different radius of Au nanosphere (see online version for colours)

Figure 12  Extinction vs. wavelength for different radius of Ag nanosphere (see online version for colours)
Figure 13  Extinction vs. wavelength for different radius of Cu nanosphere (see online version for colours)

Figure 14  Extinction vs. wavelength for different radius of Al nanosphere (see online version for colours)
The FDTD-based proposed plasmonic solar cell with silver nanosphere at the top of dielectric is shown in Figure 6. Here, the modelled specimen dimension is length 1,000 nm, width 425 nm and height 600 nm with silver nanosphere diameter 30 nm and the incident light has been applied through an X–Y plane which is equivalent to light incident at the AM1.5 global standard solar spectrum.

In this simulation model, we use two observation planes and an observation point to explore the properties and behaviour of various plasmonic components based on the metal-dielectric-semiconductor configuration.

The various simulated fields components include Ex, Hy, Ez and pointing vector Sz form the observation plane 1 and observation plane 2 has studied. The field components Ex and Sz are observed from the observation plane 1 are shown in Figure 7 and Figure 8 respectively and the field component Hy and Ez are observed from observation plane 2 are shown in Figure 9 and Figure 10 respectively.

The simulated data for optical extinction efficiencies vs. different dimension are plotted for Au, Ag, and Cu and Al nanoparticles shown in respective figures.

**Figure 15** Extinction vs. wavelength for different radius of Au, Ag, Cu and Al nanosphere (see online version for colours)

From the extinction graph, we observed that initially there is a strong attenuation associated with the photonic band. The first transmission band is plasmon photonic band corresponds to Bragg condition and then the transmission spectrum bands are successively decreased with their respective contrasts. From our comparative study, the improvement in photonic absorption is calculated with peak extinction of silver, gold, copper and aluminium nanosphere with respect to photonic absorption of Si as given in (Johnson and Christy, 1972; Palik et al., 1985). Plasmon metallic nanoparticles like silver or gold, typically 20 nm to 100 nm in diameter, which scatters optical light elastically with remarkable efficiency because of a collective resonance of the conduction electrons in the metal. The magnitude, peak wavelength, and spectral bandwidth of the plasmon
resonance associated with a nanoparticle are dependent on the particle’s size, shape, and material composition also the local environment. For Au nanosphere, we consider radius 10 nm to 100 nm and get peak absorption is 16.89% at the approx 30 nm dimension. Similarly for Ag nanosphere with radius 10 nm to 100 nm and get peak absorption is 18.78% near 30 nm dimension. As both silver and gold are high-cost materials thus we go for low-cost materials like copper and aluminium. For Cu nanosphere, we consider same radius 10 nm to 100 nm and get peak absorption is 14% at the approx 30 nm dimension. Similarly for Al nanosphere with radius 10 nm to 100 nm and get peak absorption is 9.24% near 10 nm dimension. The comparative result is shown in Figure 15.

Also, we see that if the size of nanoparticle increase, the efficiency will be sharply decreased. So, according to Mie theory, the scattering will be greater than absorption as the size of nanoparticle increased and also we see that if the radius is less than 50 nm, absorption becomes much higher than scattering.

5 Conclusions

In this paper, finite difference time domain-based plasmonic solar cell model has been designed with silicon and metallic nanoparticles on the top of dielectric layer and applied AM1.5 global solar irradiance. We see that simulated observation is characterised due to plasmonic fields which propagate inside the solar cell. Also From the simulation result, our observation is when the dimension of silver and gold and copper nanoparticle radius near 30 nm, the optical efficiency in terms of extinction will reach up to 16.89% and 18.78% and 14% respectively and the dimension of aluminium nanoparticle near 10 nm get peak efficiency 9.24%. If the dimension is further increased, the backscattering will dominate absorption and hence decrease in efficiency. Among of them, silver nanoparticle has significantly improved the quantum efficiency than gold, copper and aluminium nanoparticles. From our comparative study, we see the low cost like copper performs better than aluminium. So, the use of plasmonic can be a very useful technique to the control of optical field at the nano dimension and scaled in incident wavelength. So, the surface Plasmon can be a promising technique to improve absorption in term of extinction to enhance in efficiency.

References

