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Progressing Highlights Towards Efficient Plasmonic Solar Cells

Gurjit Singh[α] & SS Verma[σ]

Abstract- Solar cells as a light-electricity conversion device, light absorption plays crucial role towards their high performance conversion. Incorporation of plasmonic nanostructures with semiconductor materials offer great potential to improve the conversion efficiency of solar cells with much reduced material usage. So, developing low-cost and large-scale plasmonic nanostructures integratable with solar cells promises new solutions for high efficiency and low cost solar energy. Metal nanoparticles can improve the performance of solar cells by plasmonic scattering enhancement and plasmonic near field enhancement. Further, the localized absorption of metal nanoparticles via surface plasmon resonance has attracted great attention because of large electromagnetic field enhancement, the wavelength selective photon absorption and the adjustable resonance wavelength with the changing material, size, period and dielectric environment of metallic nanoparticles. This work highlight the progress made towards efficient plasmionic solar cells.

Keywords: plasmonic solar cells, absorption, conversion efficiency enhancement.

I. Introduction

Global climate change and rising prices of fossil fuels have derived us to use clean and environment friendly solar energy. Solar cell is most important renewable energy source which can convert incoming sunlight directly into usable electrical energy (Green, 1998). But cost always remains an important factor in the success of solar cells. So, the key aim of photovoltaics in the manufacturing of solar cells is to reduce production costs in order to compete with other fossil fuel technologies. With solar cell thickness of several micron or less (Luque and Hegedus, 2011), we can significantly decrease the amount of semiconductor material used and thus, production costs are reduced (Green, 2003). Hence, thin film solar cells promise a viable solution to these challenges (Chu and Majumdar, 2012). But thin film solar cells have limitation of poor absorption of sunlight as compared to wafer based solar cells. So, efficient light absorption mechanisms should be adopted for better performance of thin film solar cells. The surface texturing mechanism used in wafer based solar cells for light trapping (Green, 1998; Mullar et.al., 2004) cannot apply to thin film cells because of the surface recombination losses. To date, various light absorption mechanisms have been examined but promising mechanism for the light absorption enhancement was developed by the metal nanoparticle plasmons ([a]Cathpole and Polman, 2008). The metal nanoparticle plasmons are the collective oscillations of the free electrons in response to the irradiated light (Maier, 2007). The basic mechanism behind the functioning of plasmonic solar cells is the scattering and absorption of solar light by depositing metal nanoparticles across the surface of solar cell. As thin sheet of substrate does not absorb much light coming from sun, for this reason, more light needs to be scattered across the surface in order to increase the absorption of solar cell and convert it into the useful electricity. It has been found that metal nanoparticles help to scatter the incoming light across the surface of the substrate at resonance wavelengths. The scattering and absorption cross-sections are given by ([a]Bohren et. al., 1983):

$$C_{scat} = \frac{1}{6\pi}\left(\frac{2\pi}{\lambda}\right)^4 |\alpha|^2 \quad ; \quad C_{abs} = \frac{2\pi}{\lambda} Im|\alpha| \qquad (1)$$

Where $$\alpha = 3V\frac{\omega_p^2}{\omega_p^2 - 3\omega^2 - \imath\omega\gamma} = 3V\left[\frac{\epsilon_p/\epsilon_m - 1}{\epsilon_p/\epsilon_m + 2}\right] \qquad (2)$$

Where α is the polarizability of the particle, V is the particle volume, ϵ_p is the dielectric function of the particle and ϵ_m is the dielectric function of the embedding medium. If $\epsilon_p = -2\epsilon_m$, the particle polarizability will become very large. This occurs when the frequency is close to the surface plasmon resonance ω_{sp}, allowing the light to interact over an area larger than the geometric cross section of the particle ([b]Bohren et. al., 1983). In the case of a spherical structure the surface plasmon resonance occurs at $\omega_{sp} = \sqrt{3}\,\omega_p$.

The metal nanoparticles can enhance the performance of solar cells by: (a) plasmonic scattering enhancement and (b) plasmonic near field enhancement. In plasmonic scattering enhancement, when sun light hits the solar cell a surface plasmon is excited on the metal nanoparticle, which then re-radiates most of its energy into the semiconductor material so that the light is trapped inside the cell. In the plasmonic near field enhancement, the electric field around the particles is enhanced due to strong interaction between sun light and metal nanoparticles. The particles concentrate the light into small regions more effectively. If these particles are placed across the semiconductor then more light will be absorbed by the semiconductor in that region.

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As metal nanoparticles support localized surface plasmons in both visible and near-infrared regions, can be used to enhance the optical path length inside the solar cell (Sun et.al., 2012) which strongly increases the light absorption inside the thin film solar cell. The plasmonic resonance peak can be easily tuned by particle size, shape, material and dielectric environment (Sekhon and Verma, 2012; Muhammad et.al., 2015; Noguez, 2007; Akimov, et.al. 2010). Metal nanoparticles used at the front side as scatterers in solar cells can be used to qualitatively reduce the reflection and increase the short circuit current density (Schaadt et.al., 2005; Nakayama et.al., 2008; Sharma et.al., 2014, Pudasaini and Ayon, 2012).

II. Methodology

Numerical electromagnetic models for the scattering analysis of general structures have been developed using differential, integral, variational, and hybrid-based approaches. Differential-based approaches include the finite-difference frequency-domain (FD) and finite-difference time-domain (FDTD) methods. Integral-based approaches include both volume integral methods (VIMs) and boundary integral methods (BIMs). A variational-based approach is the finite element method (FEM). Hybrid-based approaches are models that incorporate combinations of the above methods. Because numerical techniques must be used in the application of these techniques they may be broadly referred to as computational electromagnetic methods (CEM). FDTD is most widely used among the available techniques. FDTD formulations find a number of applications in the area of electromagnetic radiation, scattering, and coupling as they provide for simulating the behavior of electromagnetic fields (John and Daniel, 1973). Further, FDTD method gives the direct solution to Maxwell's equations without converting the problem into another form. FDTD approach uses the formulation which was initially purposed by Kane S. Yee (Yee, 1966). Many researchers have contributed immensely to extend the method to many areas of science and engineering (Sadiku, 1992; Kunz and Lubbers, 1993; Taflove, 1998). The Finite-Difference Time-Domain (FDTD) method (www.lumerical.com, Sullivan 2000; Taflove 2005; Stephen, 2011) is a state-of-the-art method for solving Maxwell's curl equations in non-magnetic materials:

$$\frac{\partial \vec{D}}{\partial t} = \vec{\nabla} \times \vec{H} \tag{3}$$

$$\vec{D}(\omega) = \varepsilon_0 \varepsilon_r(\omega) \vec{E}(\omega) \tag{4}$$

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu_0} \vec{\nabla} \times \vec{H} \tag{5}$$

where $\vec{H}$, $\vec{E}$ and $\vec{D}$ are the magnetic, electric and displacement fields respectively, while $\varepsilon_r(\omega)$ is the complex relative dielectric constant. In three dimensions, Maxwell equations have six electromagnetic field components. The components in TE (Transverse electric) are E_x, E_y, E_z and in TM (Transverse Magnetic) are H_x, H_y, H_z.

Further, Maxwell's equations reduce to (in TM mode):

$$\frac{\partial D_Z}{\partial t} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \tag{6}$$

$$\vec{D}_z(\omega) = \varepsilon_0 \varepsilon_r(\omega) \vec{E}_z(\omega) \tag{7}$$

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu_0}\frac{\partial E_z}{\partial y} \tag{8}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu_o}\frac{\partial E_z}{\partial x} \tag{9}$$

The solar surface was illuminated under a plane wave source of wavelength ranging from 400-1100nm weighted against the 1.5AM solar spectrum (http://rredc.nrel.gov/solar/spectra/am1.5/). To account for multiple scattering caused by nanoparticle-nanoparticle, nanoparticle – substrate and nanoparticle-substrate - nanoparticle interactions, perfect matched layers (PML) are put on the top and bottom boundaries of computation area and periodic boundary conditions (PBC) are set along the periodic direction. Thus, the performed simulations will take into account all major effects of metal nanoparticles decorated on the top of photoactive layer.

The absorption per unit volume can be calculated from the divergence of the Poynting vector

$$P_{abs} = -0.5\, Re\left(\vec{\nabla}.\vec{S}\right) = -0.5\omega |E(\omega)|^2 Im\left(\varepsilon(\omega)\right), \tag{10}$$

Where $|E(\omega)|^2$ is electric field intensity squared and ε(ω) the corresponding material dielectric function.

To see how the efficiency of solar cell with metallic nanoparticles is improved comparing with bare solar cell, we define the following quantities, absorption enhancement g(λ) and conversion efficiency enhancement (G),

$$g(\lambda) = \frac{QE_{particle}(\lambda)}{QE_{bare}(\lambda)} \tag{11}$$

and

$$G = \frac{IQE_{particle}}{IQE_{bare}} \tag{12}$$

where QE(λ) and IQE are quantum efficiency and integrated quantum efficiency respectively.

P_{abs_t} basically evaluates what fraction of input optical power gets absorbed by the solar cell at each wavelength. Mathematically, it is given by

$$P_{abs\_t} = \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} \tag{13}$$

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Finally, in order to quantify the absorption enhancements of nanoparticle deposited thin film solar cell across the solar spectrum, the short circuit current density (J_{sc}) is calculated by

$$J_{sc} = e\int \frac{\lambda}{hc} QE(\lambda) I_{AM1.5}(\lambda) d\lambda \qquad (14)$$

where e is charge on electron, λ is wavelength, h is Planck's constant, c is speed of light in the free space and $I_{AM1.5}$ (λ) is spectral irradiance(power density) of the ASTM AM 1.5G solar spectrum.

The strengths of FDTD modeling can be summarized as:

- FDTD is a versatile modeling technique used to solve Maxwell's equations.
- FDTD is a time-domain technique, and when a broadband pulse (such as a Gaussian pulse) is used as the source, then the response of the system over a wide range of frequencies can be obtained with a single simulation. This is useful in applications where resonant frequencies are not exactly known, or anytime that a broadband result is desired.
- Since FDTD calculates the E and H fields everywhere in the computational domain as they evolve in time, it lends itself to providing animated displays of the electromagnetic field movement through the model. This type of display is useful in understanding what is going on in the model, and to help ensure that the model is working correctly.
- The FDTD technique allows the user to specify the material at all points within the computational domain. A wide variety of linear and nonlinear dielectric and magnetic materials can be naturally and easily modeled.
- FDTD uses the E and H fields directly. Since most EMI/EMC modeling applications are interested in the E and H fields, it is convenient that no conversions must be made after the simulation has run to get these values.

III. Progress Made so Far

Incorporation of plasmonic nanostructures into thin-film solar cells has been extensively discussed in recent years. Pillai *et.al* (2007) investigated that absorption of thin film c-Si solar cells can be enhanced by silver nanoparticles of small diameters less than 30 nm. They showed smaller silver metal nanoparticles can provide the maximum overall enhancement in visible and the near- infrared region and larger metal nanoparticles can be used for light emission from both thin and thick silicon light emitting diodes. The scattering of light from a single silver or gold nanoparticle with different material of nanoparticles, shape, size, and dielectric environment was theoretically studied ([b]Catchpole and polman, 2008) and showed that path length enhancements in cylindrical and hemispherical nanoparticles is higher than spherical nanoparticles. Further, path length enhancements for silver nanoparticles are much higher than gold nanoparticles. For absorption enhancement the distance of nanoparticles from the substrate is an important factor which is related to the excitation of gap modes ([a]Akimov et.al., 2009, Sreekanth et.al., 2011, Xu, R. et.al., 2012).

To study the effect of higher-order modes on plasmonic enhancement of thin film amorphous silicon solar cell, 3D modeling was used ([b]Akimov et. al., 2009). They used silver nanoparticles for both size and coverage optimization and given two optimal configurations of silver nanoparticles with diameters of 30 nm and 80 nm and showed that optimal coverage was 33% for 30nm and 11% for 80nm for silver nanoparticles respectively. Ferry et.al. (2010) report on the design, fabrication, and measurement of ultrathin film a-Si:H solar cell with nanostructured plasmonic back contacts, which demonstrate enhanced short circuit current densities compared to cells having flat or randomly textured back contacts. The primary photocurrent enhancement occurs in the spectral range from 550 nm to 800 nm. They use angle-resolved photocurrent spectroscopy to confirm that the enhanced absorption is due to coupling to guided modes supported by the cell.

Spinelli *et al.* (2011) used silver nanoparticle array geometries to study the coupling of light into a crystalline silicon substrate by scattering light. After simulation and optimization, the best impedance matching for a spectral distribution was observed with spheroidal silver nanoparticles 200 nm wide and 125 nm high in a square array with 450 nm pitch on top of a 50-nm-thick Si_3N_4 layer corresponding to the A. M. 1.5 solar spectrum. Byun *et al.* (2014) used silver nanoparticles of parabolic antenna-type and showed that the field intensity of the absorbing layer in a visible wavelength range(over 650 nm) is enhanced due to its simplified shape. Marco Notarianni et.al. (2014) showed that power conversion efficiency of a bulk heterojunction solar cell can be increased up to 10% by embedded gold nanoparticles by depositing and annealing a gold film on transparent electrode which can generate a plasmonic effect.

Mohammad Sabaeian et.al. (2015) investigated by putting the nano-strips of different cross sections (triangle, rectangular and trapezoidal) as a grating structure on the top of the solar cells. The waveguide, surface plasmon polariton (SPP), and localized surface plasmon (LSP) modes were evaluated in Transverse Electric (TE) and Transverse Magnetic (TM) polarizations by exciting them with the help of nano-strips. TM modes are more effective than TE modes in optical and electrical properties enhancement of solar cell. The optical absorption, generation rate and short-circuit

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current density enhancement for trapezoidal nano-strips showed noticeable impact than triangle and rectangular ones. Keya Zhou et.al. (2015) used different kinds of solar cells, such as amorphous silicon (a-Si) thin film solar cells, crystalline silicon (c-Si), organic solar cells, single nanowire solar cells and nanowire array solar cells and reviewed various current approaches. An experimental work by Varlamov et.al (2012) and Park *et al.* (2013) used optimized plasmonic silver nanoparticles and polycrystalline silicon thin film solar cells showed increased photocurrent of ~45%. Without a back reflector their absolute efficiency was 5.32% and with the back reflector was 5.95%.

Besides metallic nanoparticles, two-dimensional metallic nanostructures have also been used. Ferry *et al.* (2008) used thin film Si and GaAs solar cells using a back interface coated with a corrugated metal film and reported their findings that sub-wavelength scatterers can couple sunlight into guided modes. Pala *et al.* (2009) optimized the Ag strip geometries and reported that they could simultaneously take advantage of both effective coupling to waveguide modes of the semiconductors and high near-field concentration close to their SPs resonance frequency. Munday *et al.* (2011) showed that optimized integrated structure can result in a 1.8-fold total integrated current improvement by combining plasmonic gratings with traditional antireflection coatings together under AM 1.5G solar illumination.

Muhammad et. al. (2015) studies the effects of the structure geometrical parameters on the absorption and showed that 35% absorption improvement is achieved over the conventional thin film solar cell without metallic nanoparticles. Zhang et.al. (2012) simulated aluminium (Al) nanoparticles and shows 28.7% photon absorption enhancement as compared to noble metals. Further, combining with SiN_x ARC , particles can produce 42.5% enhancement which is 4.3% more than Standard SiN_x ARC in both blue and near-infrared region. Hong et.al. (2012) and Hylton et.al. (2013) simulated Al nanoparticles over GaAs solar cell and showed enhanced photocurrent and integrated efficiency at optimal structural parameters. Li et.al. (2015) purposed a plasmon enhanced solar cell structure based on GaAs nanowire array decorated with metal nanoparticles. The results show a large absorption enhancement of 50% at 760nm and a high conversion efficiency of 14.5% can be obtained at D/P ratio of 0.3.

Tanabe (2016) developed a simple model for photocurrent enhancement by plasmonic metal nanoparticles atop solar cell which can be used as powerful tool for investigations of surface plasmon enhanced thin film solar cells to provide design principle for improvement of device performance. Liu et.al. (2011) performed a systematic study of SPR on GaAs thin film solar cell with different sizes of Ag nanoparticles on the surface and found that SPR wavelength does not undergo red shift with increasing metal thickness but depends upon shape of nanoparticles and period. Further, observed that the short circuit current density of solar cell with 6nm Ag film after annealing was increased by 14.2% over that of untreated solar cell. Singh et.al (2013) study the absorption enhancement using a periodic array of cylindrical silver nanowire placed on thin silicon substrate. Studies show an absorption enhancement of 1.32 for nanoparticles of diameter of 140nm and period of 360nm.

IV. Future Scope of Work

For large scale implementation of solar light conversion to electricity through solar cells, the cost of manufacturing of solar cells needs to be reduced. Thin film solar cells reduce the materials consumption but have poor light absorption as compared to conventional solar cells. The localized absorption of metal nanoparticles via surface plasmon resonance has attracted attention because of large electromagnetic field enhancement, the wavelength selective photon absorption and the adjustable resonance wavelength by changing material, size, period and dielectric environment of metallic nanoparticles (Catchpole et.al. 2008). Hence, plasmonic nanostructures can enhance light trapping in solar cells which can be used in various photo detectors (Stuart et.al. 1996), photodiodes (Sachaadt et.al. 2005) and solar cell applications (Mullar et.al. 2004, Byun et.al. 2011).

There is no systematic study had been reported on GaAs thin film solar cells using plasmon enhanced light absorption. Hence, a systematic study on the optimization of the various parameters (like material, size and period) of metal nanoparticles for various optical properties is critically required for efficiency enhancement of GaAs thin film solar cells. The objective is to enhance the efficiency of solar cells by using different plasmonic nanostructures by optimizing the different materials as well as size and period for their use towards solar cell efficiency enhancement.

Study of various optical properties given below for plasmonic nanostructures by using FDTD simulations over the solar spectrum would be useful for strengthening the existing data base towards making efficient plasmonic solar cells.

- To investigate the absorption of solar cell for different materials, size and period of nanoparticles
- To investigate absorption enhancement for different material and size
- To investigate total power absorbed for different material and size
- To investigate enhanced conversion efficiency

a) With period of nanoparticles at different sizes
b) With different sizes at fixed period

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- To investigate current density for different sizes at fixed period
- To investigate integrated current density for various sizes at fixed period

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