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Novel Design of Optical Nano-Antennas to Enhanced Light-Absorption In Thin Film Solar Cell

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Abstract— We propose a novel design of enhanced light-absorption schemes for thin-film solar cells based on optical Nano-Antennas whose parameter governing the features of localized surface Plasmon's resonance and their effect on photosensitive possessions of the materials. The procedure of our design is based on excitation of collective modes of the optical Nano-Antennas whose electric field is localized between contiguous medium, collective modes is very productive to harness the long range of energy from solar spectrum with different and emerging material used in thin-film solar cells. We demonstrated theoretically substantial enhancement of solar-cell absorption spectral density in the whole spectrum range of the solar-cell operation equated to conventional structures commissioning anti-reflecting coating. We have been used COMSOL Multiphysics environment which is based on numerical finite element method (FEM). This approach is paramount substitute of anti-reflection coating and texturing in thin-film solar cells. Owing to less material usage along with efficient novel broad band light-harvesting structures, thin-film solar cells technically well-suited for large area fabrication techniques.

Keywords— Localized Surface Plasmon Resonance, Nano-Antenna, Ligth Management Scheme, Thin Film Photovoltaics

I. Introduction

The modern world going towards advancement in the arena of thin film solar cells (TFSC) technology for large-area panel production to harvest the solar energy, further efficiency enhancement and reduction in cost. The cost of thin film solar cell as compared to other solar cells is quite less due to fewer materials' usage, as the material cost is around 40% of the total solar panel module, rapid payback and minor extent of toxic waste [18-20].

The thin film photovoltaics technology is the promising green energy technology which is the remedy of energy shortage and environmental delinquent. TFSC energy generation deals declining greenhouse gas releases and improve ecological co-benefits in the protracted term. In the first-generation solar cell, the bulk silicon material used which purification around 99.99% owing to these processing complexities cost of the solar cell technology is comparatively higher than fossil fuel technology. The thin-film technology is very promising technology to contribute in the energy mix of the globe to achieve the energy demand in a clean and green manner [28, 30, 35].

In TFSC the depth of the active layer is shortened, though the absorption is not taken place effectively at low energy photon in visible and infrared spectrum which is quite optimum energies near to the bandgap energy of the photovoltaics. To produce efficient thin film solar cells of a very small thickness around 120-150 nm, conventional texturing technique is quite unmanageable to employee upon the expose active surface of photovoltaic. However, for sake of more thin structure the anti-reflecting coating (ARC) would also be replaced by a novel design of light-harvesting structures which have the broad band spectrum and material independence properties [2-11]. Since anti-reflecting coatings has uni-spectral property and cannot prevent the transmission and refection of light through at very thin photovoltaic layer.

The operation band of TFSC according to their band gap energy can be tuned for localized surface Plasmon resonance (LSPR) upon changing the following parameter of the Nano-Antennas used in the novel design of light-trapping structure for TFSC [22-24]:

- Size of the Nano-Antenna
- Shape of the Nano-Antenna
- Local dielectric medium or environment or background medium
- Polarization of incident wave

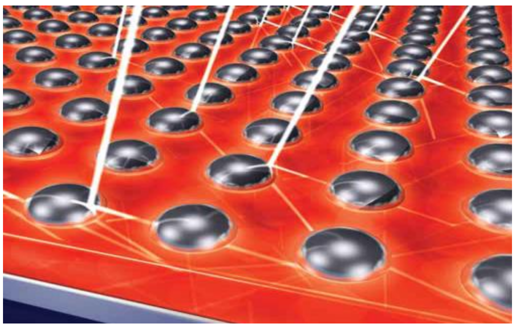

Figure 1. Optical Nano-Antenna Array [54]

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In this work we demonstrated the various conceivable mechanism of absorption enhamcment of thin film GaAs solar cell by using a Nano-Antenna of different materials i.e gold (Au) and silver (Ag) and deployment methods, such as single and dimer optimized configurations to excite higher order plasmonic modes for better abosption efficiency in TFSC.

II. LITERATURE REVIEW

The thin-film photovoltaics to become an effective solution to the manufacturing and processing cost of first-generation photovoltaics a novel and alternate technique of improving the efficiency by increasing the absorption in active region of thin-film photovoltaics is desirable. The utmost encouraging technique is to achieve the plasmonic miracle of metallic nanostructures for improve performance, such as silver aluminum, copper and gold. The implementation of subwavelength metallic nanostructures which localized the electromagnetic radiation incident to very small region of plasmonic Nano structure. Furthermore, the other means of energy carried in the absorbing layer is scattering, the light is efficiently catch by activating into lateral waveguide modes [4, 8]. Together, these significantly improve the light absorption in active material and enhance the power conversion efficiency (PCE) of thin film solar cell.

A. Physics of Photonics

The photonics field is deal with interaction of light with matter, matter may be semiconductor, conductor and insulator. The field of plasmonic deal only interaction of light with metal. The interaction of light with Nano-Metal particle whose size is very less than size of wavelength of operational band then collective oscillation of electron taken place at the surface of these Nano-Particle called surface plasmon resonance. These surface plasmon is further categorized in to two category (i) Polariton moving surface plasmon resonance (ii) LSPR. In this work we will be observed the phenomena of LSPR to enhance the near-field of Nano-Antenna which intensity will be more than the incoming light intensity and yield to light-absorption in TFSC which results in photo-current and efficiency enhancement.

There are four noble metal gold (Au), silver (Ag,), copper (Cu) and aluminum (Al) [37] used to which exhibits a property of absorption and scattering due to collective oscillation of free electron which also form of LSPR. The LSPR or dipole modes depends on the following parameters such as (i) size of a Nano-particle, (ii) shape of Nano-particle, (iii) local dielectric medium and (iv) polarization of incident wave. LSPR is also highly depends upon the density of free electron in the Nano antenna or particle, these electronic densities for different noble metallic materials displays the sort of optics, which resembles to the resonance, Aluminum particle suitable for ultra-violet spectrum, gold visible, silver ultra-violet, copper visible range [3]. However, the operational spectrum is altering from blue-shift to the red-shift and vice versa by varying the embedded medium, shape and scope. In most of the previous work we observed that by employing silver Nano-particle directly on to a high index substrate such as transparent conductive oxide (TCO) and silicon dioxide SiO2 coating the LSPR is red-shifted in the direction of the near-IR region, growing light harvesting at those specific frequencies. To broaden the operational spectrum of solar cell high index medium or high size particle is used. In TFSC concentrated solely to grab the more energy content of solar spectrum which is long wavelength as, where all noticed a significant drop in photocurrent and light as compared to short wavelength, whose photo absorption and current below the LSPR for gold (Au) and silver (Ag) noble metal Nano-particles [33, 42, 48].

Previous work [49] display that if the LSPR is blue-shifted extreme enough, the improvement in photo absorption leads over the greater part of the operational sun spectrum, instead of show decreases at shorter wavelengths. The trade-off is condensed enhancements at longer wavelengths, but however, this method allows for an overall improvement in solar cell light absorption. The short-circuit current and external quantum efficiency (EQE) is highly improved by utilizing the red-shift response Nano-particle with high index medium to broaden the operational spectrum. The material selection for Nano-particle keep the cost and desired operational spectrum is very challenging. The cheap material is silver, but it is likely unstable and get oxidize quickly and narrower peak of absorption than gold is exceptionally steady and demonstrates the reverberation crest more extensive than silver. Conversely, copper is less expensive than silver, and more absorbing than gold but high losses occur as compare to other metal. Aluminum shows LSPR response in the UV range and having very weak oxidation than other plasmonic metal.

B. Higher-Order Modes Excitation for Enhanced Absorption

Confinement of photon energy in photovoltaic layer can also achieve effectively by excite higher order modes in Nano-antenna structure using two kind of excitation techniques for higher order modes.

i) Use cluster of Nano-Antennas
ii) Symmetry breaking

As there is two kind of modes bright mode and dark mode and overlapping of these modes enhance near field energy [51, 53] which improve the efficiency of TFSC. Array or cluster or structure of Nano-antennas is used to excite higher order modes which yield surface enhance ramen scattering (SERS) [33, 34, 36]. The various structure for higher order modes excitation includes such as Nano-particle dimmer [38], dolmen Nano-structure [40], metal Nano-shell [41], coupled Nano-rods [42], the stoutest structures nanoparticle oligomers [44].

The Pentamer and heptamer structure which is special types of oligomers structure is very efficient structure for SERS. In these different metal and high index dielectric core-shell structure the distance between two Nano-particle in the array is play a vital role in the excitation of higher order modes. As the gap between two Nano-particle increases they become independent and less chances of higher order modes excitation. The radius and index of dielectric is taking part in modes excitation where the process of hybridization of the Plasmon's of inward center and external shell decides the operational full frequencies of the complex nanostructure [46]. The interaction of hybridize dipole mode with stray modes can be achieved.

These hot-spot and field generated by the Nano-antennas will be much stronger than the incoming field due to LSPR and SERS which improve further the generation of photocurrent and increase sensitivity to the operational band [50].

Symmetry breaking in metal-dielectric (core-shell) Nano-particle properties is significantly change with the geometry due to dependence of fundamental dipole mode with surface of Nano-particle [32, 53]. Symmetry breaking alter the connections between plasmon modes which is hybridized dipole mode and stray modes and provide growth to SERS, and completely novel plasmonic feature is achieved. There are three alternates of a core–shell nanoparticle which near field strength is different from each other that is Nano-shells, Nano-eggs and Nano-cups. Nano-shells, comprising of a round high file dielectric center covered with a thin metal shell, change to Nano-egg by balancing the center inside the shell. Balances of the center more than the profundity of the shell layer, where the center cuts the shell, result in Nano-cups. Due to symmetry breaking, the modes are highly mix and results in quadrupole mode (Dipole active quadrupole mode), octupole (Dipole active octupole mode) and other higher order modes. In TFSC technology the TCO, ARC and Nano-antenna are used as core-shell structure and employee the symmetry breaking and cluster of Nano-antenna for short-circuit current density and efficiency improvement by increase absorption enhancement [53].

III. SIMULATION MODEL

We have been investigated the various mechanism of plasmoic Nano-structure encompassed of Au and Ag nanospheres on top of GaAs solar cell for absorption enhamcement with presence of embedded medium SiO2. The various size and cluster of nanpsphere are chosen such that the most absorbing one has easily found out among the optimized scenario's. The improved absorption, well-defined as :

$$\bar{A}\,(\lambda) = P_{ABS\text{-}GaAs}(\lambda) \,/\, P_{Source}(\lambda) \qquad (1)$$

Where as the PSource(λ) is the incident power from the sun source of photon flux of AM1.5G, PABS-GaAs(λ) is the power absorbed in the GaAs solar cell while λ is the wavelength around the air and GaAs. The power defined in (1) is tells us how much power is scattered out of plasmonic layer and absorbed in active layer. However, in order to find the absorbed power in the active bulk of photovoltaic layer with better matching between air and thin photovoltaic layer the equation will be turned out to the following equation:

$$\bar{A}_{GaAs}(\lambda) = P_{Trans\text{-}GaAs}(\lambda) \,/\, P_{Source}(\lambda) \qquad (2)$$

Where $P_{Trans\text{-}GaAs}(\lambda)$ is the power which transpassing the Nano-partical laid on front-surface and captivated in GaAs layer. There are two principal loss mechanism which reduce the absorption in the active bulk layer that's power absorbed in the plasmonic layer and scattered out power. In order to get more power absorbed in the GaAs layer local field in active layer vicinity and path length enhamcement is best approach to reduce the effects of loss mechanism. The model we propose included back reflector of Au and Ag according to plasmonic partical selection, prevent the transmittance of light out of GaAs absorbing layer and enhances the path length.

$$\bar{A}_{eff}\,(\lambda) = P_{ABS\text{-}GaAs}(\lambda) \,/\, P_{Trans\text{-}GaAs} \qquad (3)$$

The enhanced absorption effeicincy of the model were measured using (3) and considerd various stratagem such as clustering and Nano-partical size optimization methods.

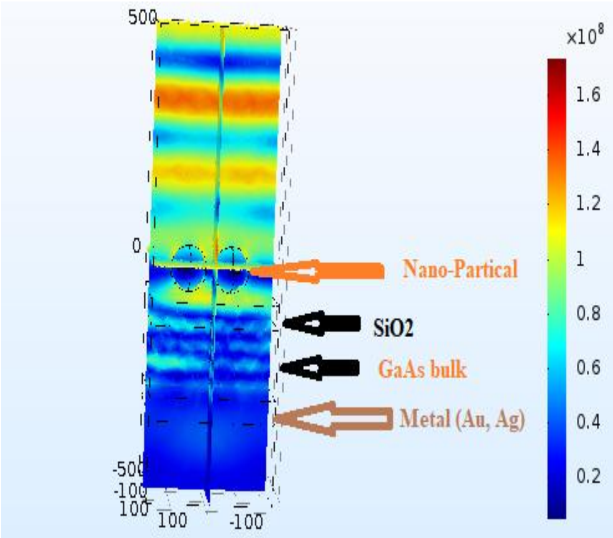

Figure 2. COMSOL simulation model ofpPlasmonic solar cell

Th simulation model developed in the COMSOL Multiphysics software which is very effective numerical simulation software built on finite element method (FEM), which precisely disentangles electromagnetics problem at very Nano-scale. The simulation in COMSOL Multiphysics will be carried out by the radio frequency (RF) module. Many Research group around the globe working on the Nano-device have been employed this software for design and simulation. The simulation in software accomplished usually by constructing a 3D simulation Planetary, which is consist of a perfectly matched layer (PML), boundaries were comsisted of perfectly electric conductor (PEC) and perflectly megnatic conductor (PMC) and oriented according to plane wave polarization, an embedding medium and spherical volume of far field layers. The two port network of simulation model were built for plane wave excitation injection and reception in order to get the absorption values for various model configuration for simulations.

We built and performed, plasmonic layer arrangement in single and array configuration using Au and Ag meta-material overhead of SiO2 , GaAs substrate and back reflector respectively in COMSOL environment as shown in fig.2. The dielectric function of Ag, Au and GaAs are based on already measured data from Nanohub [search]. The absorbed power in the different layer were monitored to get optimum novel shape for enhanced backscatterd light absorption in active photovoltaic layer.

IV. Results and Discussion

First, we investigated the absorption of our proposed model by plane wave excitation of wavelength range from 300-1100 nm on GaAs and SiO2 in absence of plasmonic Nano-antenna. The gold (Au) single Nano-partical was then laid on top of GaAs and SiO2 with 150 nm and 50 nm respectively, while varying the size of partical, we observed that partical size below 30nm were not so effective to enhance absotion in active bulk by back scattering power. However, Au Nano-antenna with size 50 nm and 70 were stood up finest in the wavelength rangle from 300-650 nm. The operational band of Au partical is widend and easily tunable for higher order plasmonic modes by varying size and shape, as we did by optimized size for more absoption .Owing to norrow band features of SiO2 ARC this Au plasmonic partical with size above 50 nm with enhaced surface plasmone resonace make absorption efficiency $\bar{A}eff$ (λ) high enough to substitute the ARC for thin film photovoltaics as can be readly seen in fig. 3. The Au partical size 15 nm and 70nm observed enhanced efficiency 15% and 33% accordingly compare to lone ARC layer.

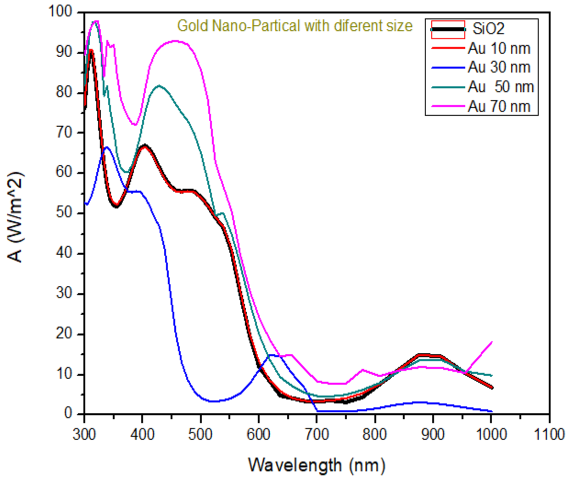

Figure 3. Different size gold Nano-antenna

The profound operational band of Au partical mostly lies in ultra-voilet wavelength range , hot spot and near field generation were achived by SERS and LSPR responses which improved further the absorption efficiency.

Fig. 4 shows the absorption efficiency $\bar{A}eff$ (λ) of Au partical with different cluster size such as, dimer, trimer, tetramer and pentamer. The higher absorption efficiency were achived at greater cluster size due to excitation of higher modes from individual partical LSPR and SERS distribution and field interferences. The spacing and size of partical in cluster decides the net absorption efficiency. In order to observed the effect of number of partical in cluster, we kept the size of partical 30 nm persistent and were varying the cluster size increased to get notice the effect. In the array configuration we noticed, it seems that the main machinery contributing to the heightened absorption is the growth in array size. As the Au partical is blue shifted, so the dipole, quadrapole and hexapole of absorption peak at wavelength 300 nm, 450 nm and 550 nm were observed respectively, in different cluster configuration. The 10% increase observed enhanced efficienced 10% from dimer to pentamer cluster configuration.

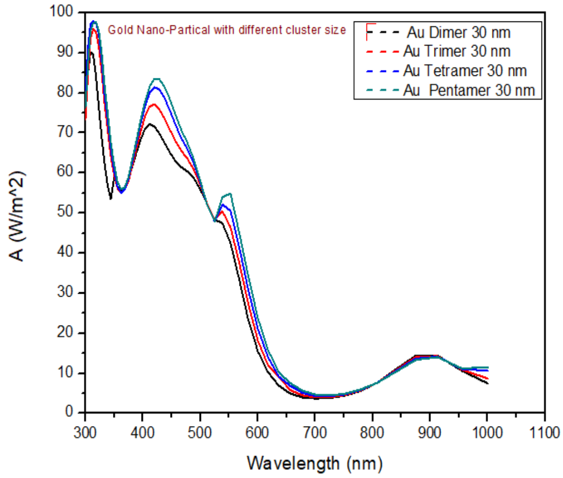

Figure 4. Gold Nano-antenna with different cluster size

The retort of absorption efficiency $\bar{A}_{eff}$ (λ) can also be shifted either red or blue by using different material. In fig. 5 the silver (Ag) Nano-partical have used to get red-shifted broad band region. The Ag partical is more broad capricious LSPR and SERS response compare to Au partical owing to the fact that Au is more stable partical. The red-shifted higher order LSPR modes makes Ag a very desirable plasmonic Nano-partical to harness the visible range of solar spectrum for GaAs. With increase in partical size the higher order excitation were detected and the most prominent size were again 50 and 70 nm.

The average 10% and 30% enhanced absorption efficiency above ARC layer were pragmatic in wavelength range 500-1100 nm of partical size 50 and 70 nm repectively.

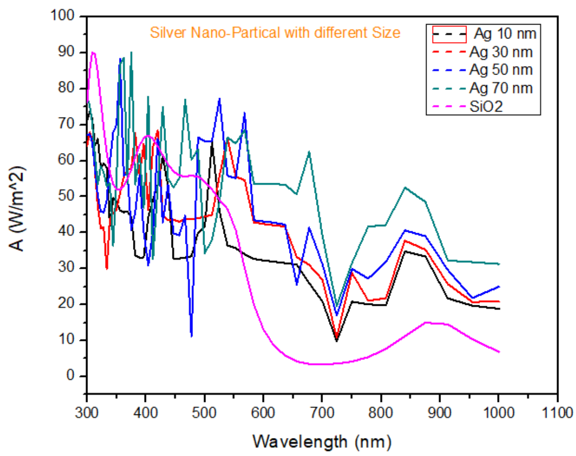

Figure 5. Different size silver Nano-antenna

Due to angular back scattered light of Ag partical in longer wavelength region enhanced the absorption efficiency and path length for higher short circuit current density.

Fig. 6 shows the absorption efficiency $\bar{A}_{eff}$ (λ) of Ag partical with different cluster size such as, dimer, trimer, tetramer and pentamer. In order to observed the effect of number of partical in cluster, we kept the size of partical 50 nm persistent and were varying the cluster size increased to get notice the effect of different array configuration. The shifting from dimer to pentamer in Ag array configuration the significant absorption efficiency difference among array configuration were not observed. However, the wavelength range from 500-1100 nm seems a very prominent absorption efficiency regime under each array configuration. In this long wavelength range around 30% increase observed from dimer to pentamer configuration.

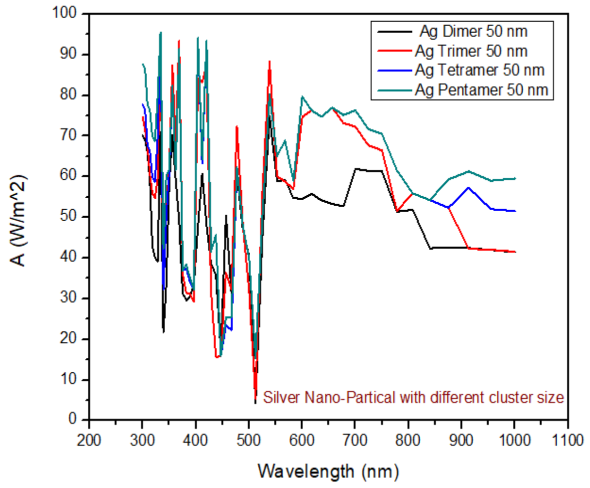

Figure 6. Silver Nano-Partical different with cluster size

The shift to longer wavelength of the absorption peak in case of Ag Nano-partical is associated with partical and cluster size. In order to get optimized broad band spectrum we used to keep the partical size 50 nm, instead of 30 nm as was in case of Au partical. The higher order modes were observed more in Ag as compare to Au due to material nature. The angular back scattering field modified a lot the absorption in GaAs layer. The excitation of higher order modes and peak shifting can also be done through embedded medium, in our case was SiO^2. In over-all comparison both plasmonic partical at different cluster configuration the Au and Ag gives us optimum absorption efficiency at shorter wavelength and longer wavelength respectively. Moreover, in single spherical consideration Au and Ag have given us blue-shifted and red-shifted responses respectively. However, these responses may pron to changes under different parameter variation which mentioned earlier.

CONCUSLION

In summary we have suggested and analyzed the different approaches of light-traping leading to improved absorption in thin film GaAs layer of 150 nm. Our novel model can be employed in a variety of thin film solar cell technologies in the ultra-voilet, visible and infrared band region. More significantly, the proposed light-traping structure is broad band and shows us the desired operational band material and cluster configuration. The presence of anti-reflection coating also effect the collective excitation modes of these Au and Ag Nano-antennas. We have demonstrated that our single and cluster Au and Ag nano plasmonic partical are noticbly better light absorption efficiency than sole anti-reflecting coatings in broad band operational region.

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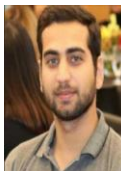
[54] Photo courtesy: www.ecn.nl, "Plasmonic solar cell".



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