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NOVEL TECHNIQUES TO IMPROVE THE LIGHT HARVESTING OF THIN FILM SOLAR CELLS

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ABSTRACT

Thin film solar cells are novel technologies receiving particular attention for their potentials to produce less expensive and more environmentally friendly renewable electricity from the sun light. This paper reports on different techniques that have been considered to improve the light harvesting, from the plasmonic resonance of noble metal nanoparticles, to the nanoparticles of a different semiconductor with different refractive index and band gap, to the anti-reflection surface textures as moth-eye-like shapes. Results of novel simulations solving the Maxwell's equations are compared to previous simulations.

Keywords: solar cells, nanoparticles, nanostructures, moth eye

1. INTRODUCTION

Solar has the potential to become the primary source of power generation if the economic and efficiency drawbacks could be eliminated. The aim is to utilize the maximum possible incident solar radiation in the cheapest possible way. Nanostructures can increase the efficiency of single-crystalline silicon solar cells (SC) over a wide range of wavelengths. The solution of the Maxwell's equations permits the design of novel SC performing much more efficiently than today's thin film silicon SC. Numerical simulations are performed to study the effect of nanoparticles of different materials as well as the texture of the surface with nanostructures. Submerged noble metal nanoparticles show the opportunity to achieve significant increases in the collection efficiency versus the bare solar cell due to better light trapping and plasmonic resonance effects. Significant advantages are also possible when the noble metal nanoparticles are replaced by nanoparticles made by a different semiconductor because of enhanced light trapping and conversion effects. Advantages are also found with a surface texture that also increases the light trapping effects. The method and the specific results are presented for all these novel designs, all permitting enhanced collection efficiencies than the bare silicon solar cell as well as the silicon solar cell with noble metal nanoparticles deposited on the surface.

This paper analyses different methods to improve the light harvesting, specifically plasmonic resonance of noble metal nanoparticles, scattering effects of nanoparticles of a different semiconductor with high refractive index and different band gap, anti-reflection surface textures as moth-eye-like shapes (schematic is shown in Figure 1). The use of spherical nanoparticles made of noble metals, Ag or Au, placed on top of a thin film silicon substrate produces a theoretical improvement of the light trapping efficiency of the solar cell of about 20%. These improvements have been confirmed by experiments.

Further significant improvements of the theoretical light trapping efficiency are obtained by embedding the spherical nanoparticles within the silicon substrate. Even by considering the parasitic losses in the metal, this technique still permits to double the collection efficiency of the bare solar cell, pending the experimental evaluation of the recombination effects at the solid-silicon surface not accounted for in the Maxwell's equations solver. Much larger theoretical enhancements up to 300% are obtained by embedding in the silicon substrate spherical nanoparticles made of a different semiconductor, such as GaAs or InAS. These particles do not introduce parasitic losses and do not exhibit plasmonic effects. The possible recombination effects at the boundaries of the spherical nanoparticles still need experimental evaluation. Finally, improvements of the light trapping efficiency of the SC of more than 50% are obtained by using moth-eye-like surface textures. Different structures prove theoretically to reduce the light reflection considerably. The significant improvements have been confirmed by experiments with some of the textures.

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The use of nanostructures reducing the reflection and increasing the light trapping within the semiconductor is the next step considered here to design more efficient SC.

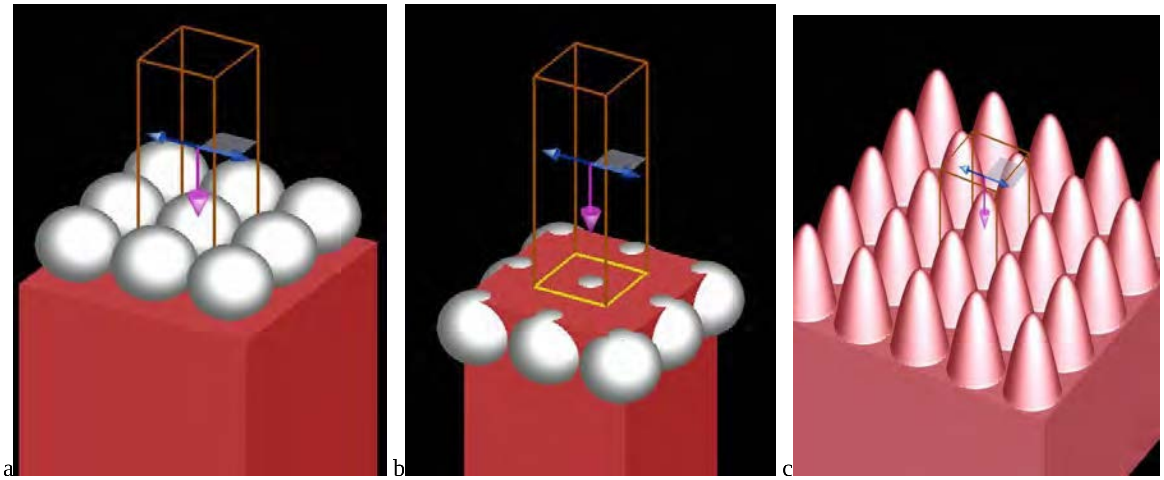

Figure 1 – Schematic of typical plasmonic thin film solar cell with suspended Ag nanoparticles (left) and here proposed thin film solar cell with submerged nanoparticles made by Ag or InAs/GaAs semiconductors (middle) and thin film solar cells with moth eye like texture (right).

2. METHOD

The quantum efficiency of a solar cell, *QE (λ)*, is defined by:

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

where P_{in} (λ) and P_{abs} (λ) is the power of the incident light and absorbed light within the Silicon SC, respectively, at a wavelength λ. The integrated quantum efficiency, IQE, is defined as:

$$IQE = \frac{\int \frac{\lambda}{h \cdot c} \cdot QE(\lambda) \cdot I_{AM\,1.5}(\lambda) \cdot d\lambda}{\int \frac{\lambda}{h \cdot c} \cdot I_{AM\,1.5}(\lambda) \cdot d\lambda} \quad (2)$$

where ***h*** is Plank’s constant, ***c*** is the speed of light in the free space and $I_{AM1.5}$ is the AM 1.5 solar spectrum. In the equation above, numerator and denominator means the number of photons absorbed by the SC and that falling onto the solar cell. The reference sun spectrum $I_{AM1.5}$ is taken from [15]. To see how the efficiency of SC with nano-particles or surface texture is improved compared with a bare SC, we define the following quantities, absorption enhancement g (λ) and G:

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

$$G = \frac{IQE_{particle}}{IQE_{bare}} \quad (4)$$

If we assume that all electron-hole pair contributes to photocurrent, the short circuit current density J_{sc} is given by:

$$J_{sc} = e \cdot \int \frac{\lambda}{h \cdot c} \cdot QE(\lambda) \cdot I_{AM\,1.5}(\lambda) \cdot d\lambda \qquad (5)$$

where ***e*** is the charge on an electron. The optical absorption *L(x,λ)* is finally calculated by the formula:

$$L(\bar{x}, \lambda) = \nabla \cdot \left(\frac{1}{2} \cdot real(\overline{E}(x, \lambda) \times \overline{H}(x, \lambda))\right) = \frac{1}{2} \cdot \quad \cdot \left|\overline{E}(\bar{x}, \lambda)\right|^2 \cdot \mathrm{Im}(\ _{Si}(\lambda)) \quad (6)$$

The useful optical absorption is obviously only the one in the semiconductor, being the one in the metal a parasitic loss. The quantum efficiencies above are actually light harvesting efficiencies. Simulations are performed with high resolution conformal meshes as needed for the proper treatment of the particles-silicon interface. The latest conformal mesh technique of [14] permits reduced computational and memory requirements while providing more accurate results than the traditional staircase mesh adopted in other solvers of the Maxwell's equations.

3. SILVER NANO SPHERES

In thin film SC it is critical problem to trap the light in the SC to increase the light absorption and therefore to increase the conversion efficiency. Noble metal nanoparticles deposition on the surface has been proposed in [1-13]. A thin film plasmonic SC simulation is set up using FDTD Solutions [14]. This n/p crystalline silicon thin film SC has distributed nano-sized silver spherical particles. We assume that the particles are of the same size and regularly located. Only one period of the periodic structure is modeled using periodic boundary conditions. The thickness of silicon is set to 0.5 µm and the diameter of the spherical nanoparticle and the period of particles are denoted as D and P respectively. The Perfectly Matched Layer (PML) boundary conditions are used for upper and lower boundary. To model the sunlight, a normally incident plane wave with a wavelength range from 400 nm to 1100 nm is used. To calculate the power absorbed in the Si, two power monitors are adopted. One is located at the surface of the silicon and the other is located at 0.5 µm below the surface. The absorbed power $P_{abs}(\lambda)$ can then be calculated by the difference in between the two outputs. A power monitor and an index monitor named in the x-z plane are also used to record the field and index profile to calculate the absorption profile.

For simulations as in [8, 9], the particles are located above the silicon surface. Results of $g(\lambda)$ for SC with spherical silver nanoparticles calculated with FDTD Solutions agree well with predictions proposed in [8]. The light absorption is enhanced and suppressed, respectively, above and below the surface plasmon resonance frequency. The absorption enhancement G takes minimum values when the period is equal the diameter of spherical nanoparticles and strongly increases with the period [9]. For long wavelengths, no enhancement is found (G tends to 1) because the surface of the silicon is strongly diluted and the nanoparticle enhancement effect disappears. These results agree with other predictions proposed in [9]. As expected, we get more than 20% absorption enhancement compared with the bare SC if we use silver spherical nanoparticles on top of the silicon surface.

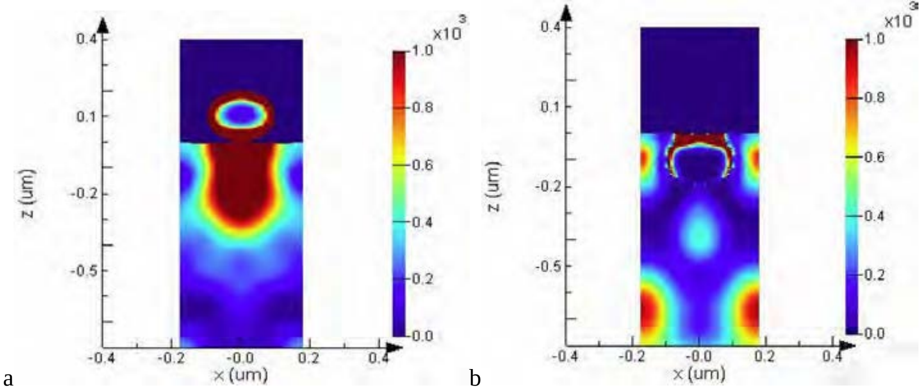

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Figure 2 - Absorption per unit volume $L(x, \lambda)$ for wavelength 621.5 nm, D 200 nm and P 350 nm with: (a) Ag nanoparticles suspended on top of the silicon; (b) Ag nanoparticles submerged in the silicon.

Figure 2 shows the absorption per unit volume $L(x, \lambda)$ for wavelength 621.5 nm, D 200 nm and P 350 nm with: (a) Ag nanoparticles suspended on top of the silicon; (b) Ag nanoparticles submerged in the silicon. The suspended silver particle increase the absorption in the Si by the enhanced forward scattering due to the surface plasmon resonance [9]. The enhancement as a function of particle diameter and period for silver spherical nanoparticles on top of the silicon substrate shows an area with more than 20% absorption enhancement compared with the bare SC if we use silver spherical nanoparticles on top of the silicon surface. With fully submerged spherical silver particles, G values are much higher. However, these G values are obtained considering the power absorbed in both the silicon substrate and in the noble metal nanoparticles. These values therefore also include the parasitic losses in the noble metal nanoparticles and overestimate the actual G that can be achieved submerging the noble metal nanoparticles. When the noble metal nanoparticles are submerged inside the silicon, a different method (Pabs) has been developed to properly compute $g(\lambda)$ and *G*. In this case, the absorption at each mesh cell rather than in a volume is considered and a selective integration has to be performed to get the total power absorbed within the semiconductor only.

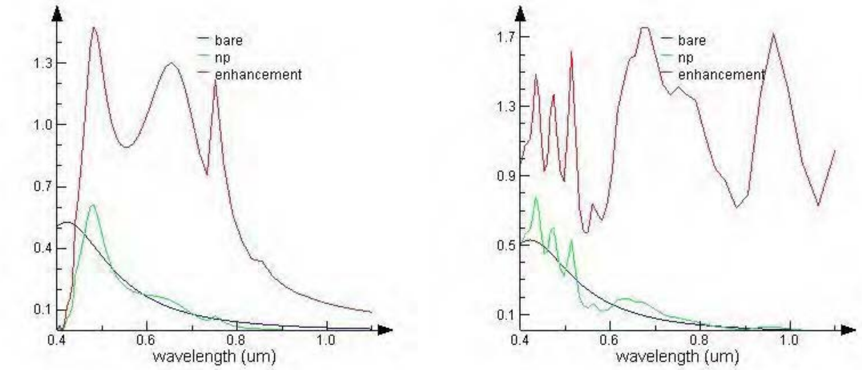

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Figure 3 – Quantum efficiency, *QE(λ),* with and without nanoparticles and their ratio *g(λ)* (spectral enhancement) for a given diameter and period (D=200 nm, P=200 nm) with: (a) Ag nanoparticles suspended on top of the silicon; (b) Ag nanoparticles submerged in the silicon.

Figure 3 shows the spectral quantum efficiency, QE(λ), with and without nanoparticles and their ratio g(λ) ((spectral enhancement) for a given diameter and period (D=200 nm, P=200 nm) with: (a) Ag nanoparticles suspended on top of the silicon; (b) Ag nanoparticles submerged in the silicon. The silicon substrate of reduced volume of the case with embedded nanoparticles collects more light than the larger volume of silicon of the bare SC over some of the wavelengths of interests. Enhancements of up to 2 times the bare silicon solar cell may be obtained optimizing the technique working further on the shape of the nanoparticles and the location relative to the surface. Further details are available in [33].

4. INAS/GAAS NANO SPHERES

The previous simulations show the opportunity to further improve the light harvesting efficiency of thin film solar cells with noble metal nanoparticles embedding the nanoparticles rather than using the nanoparticles on the surface. This is obviously a theoretical improvement because the possible recombination effects at the interface between nanoparticles and silicon are not accounted for in a solution of the Maxwell's equations. The major issue of the technique are the large parasitic losses in the nanoparticles. To address this downfall, nanoparticles made by another semiconductor have been considered. Simulations have been performed by considering nanoparticles made up by another semiconductor. Gallium Arsenide (GaAs) multi-junction cells were originally developed for special applications such as satellites and space exploration. A triple-junction cell consists of three semiconductors, for example GaAs, Ge, and GaInP2, with each type of semiconductor having characteristic band gap energy. Selection of the semiconductors is made to absorb nearly all the solar spectrum. GaAs multi-junction cells are the most efficient solar cells to date. Recent uses of GaAs and InAs in solar cells are reported in [16-25].

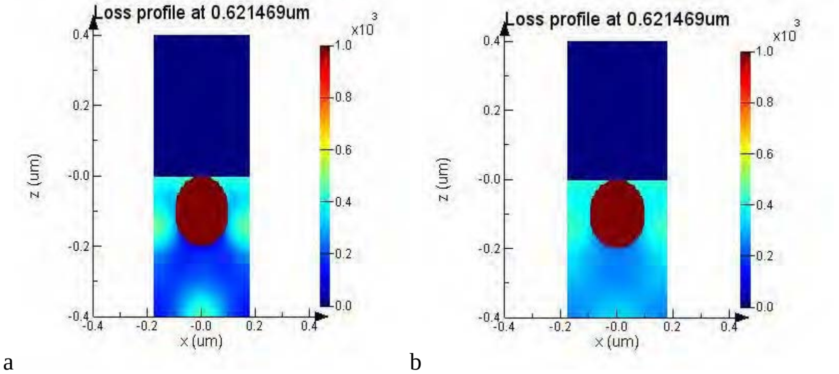

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Figure 4 - Absorption per unit volume *L(x, λ)* for wavelength 621.5 nm, D 200 nm and P 350 nm with: (a) InAs nanoparticles submerged in the silicon; (b) GaAs nanoparticles submerged in the silicon.

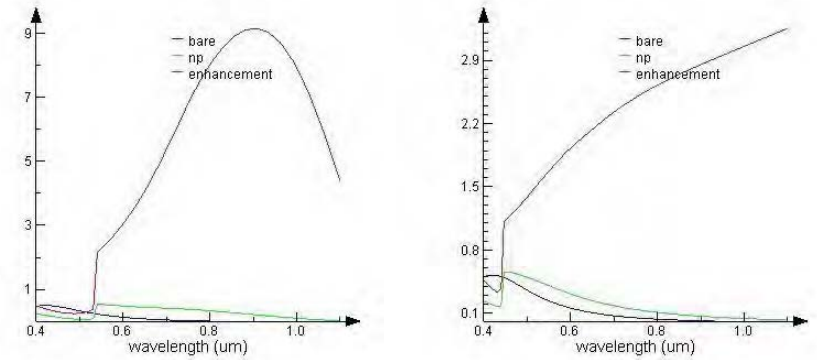

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Figure 5 – Spectral quantum efficiency, QE(λ), with and without nanoparticles and their ratio g(λ) (spectral enhancement) for a given diameter and period (D=200 nm, P=200 nm) with: (a) InAs nanoparticles submerged in the silicon; (b) GaAs nanoparticles submerged in the silicon.

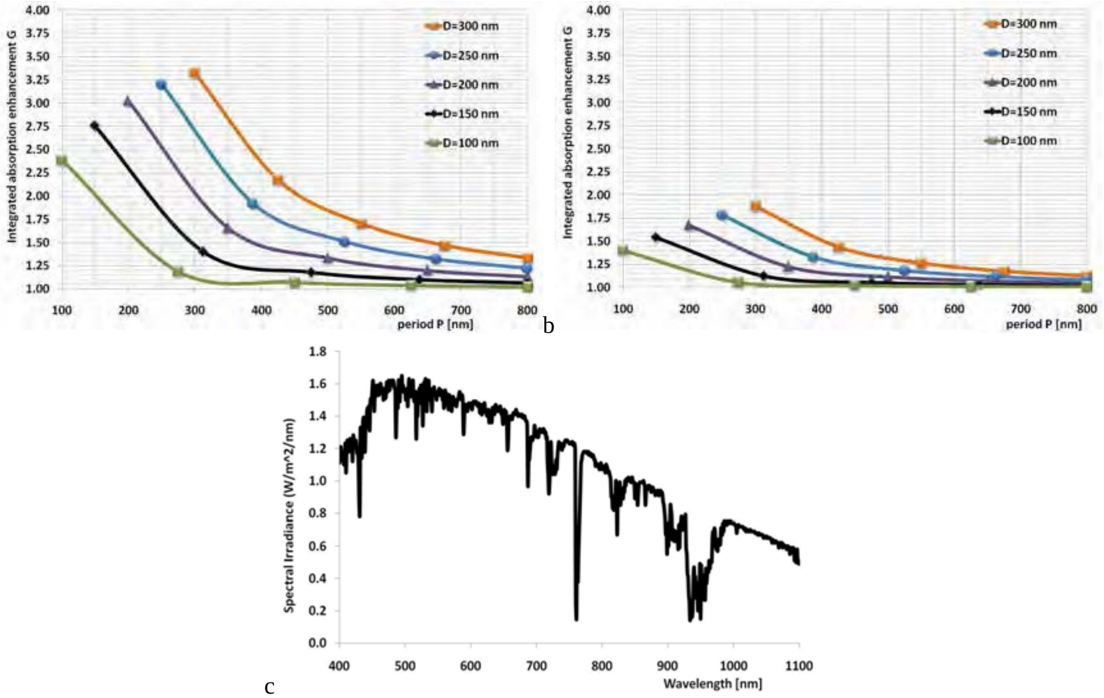

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Figure 6 - Integrated absorption enhancement G for various diameters and periods with: (a) InAs nanoparticles submerged in the silicon; (b) GaAs nanoparticles submerged in the silicon for the sun spectra in (c) taken from [15].

The metal nanoparticles made by noble materials (gold, silver) increase the absorption within the silicon substrate due to the plasmonic and other light trapping effects. With reference to the deposition of metal nanoparticles on the surface of the silicon, this technique increase the absorption per unit volume of the silicon substrate, however parasitic losses in the metal are present. The submerged noble metal nanoparticles are replaced by other semiconductors more precious than silicon. While the absorption within the metal nanoparticles is a parasitic loss that do not contribute to the SC collection efficiency, the nanoparticles made by semiconductors as InAs or GaAs would absorb even better than silicon, but will lose the plasmonic resonance effect. The method is exactly the same described in the above paragraph.

Figure 4 presents the absorption per unit volume $L(x, \lambda)$ for wavelength 621.5 nm, D 200 nm and P 350 nm with: (a) InAs nanoparticles submerged in the silicon; (b) GaAs nanoparticles submerged in the silicon. Figure 5 presents the

QE(λ) with and without nanoparticles and their ratio *g(λ)* for a given diameter and period (D=200 nm, P=200 nm) with: (a) InAs nanoparticles submerged in the silicon; (b) GaAs nanoparticles submerged in the silicon.

Figure 6 show the integrated absorption enhancement G for various diameters and periods with: (a) InAs nanoparticles submerged in the silicon; (b) GaAs nanoparticles submerged in the silicon for the sun spectra in (c) taken from [15]. The enhancement is up to 3 times the bare silicon SC with InAs nanoparticles submerged, and up to 2 times with GaAs nanoparticles submerged. This is due to the increased absorption in the second semiconductor (especially InAs is a direct band gap semiconductor) and the light trapping effects increasing the absorption within the silicon. These theoretical improvements are much more relevant than those found using metal nanoparticles. The recombination effects at the nanoparticles-silicon interface are still not accounted for, but the efficiency improvement in the light harvesting process is significant. Further details of the simulations are available in [33].

5. MOTH EYE ANTIREFLECTION LAYER

This layer – Figure 7 - takes inspiration from the texture of moth eye. The eye of a moth comprises of microscopic nipples that successfully trap most of the incident light. The nipples are nanostructures that are smaller in size then the wavelength of light. The light sees the surface as having a continuous refractive index gradient between the air and the medium, which decreases reflection by effectively removing the air-cell interface. The antireflection layer is made by the same silicon of the substrate. A slightly different method is used to study the moth eye anti-reflection layer with FDTD [14]. The moth eye anti-reflection layer is modelled as a square lattice of parabolic structures with a period of 500nm and a height of 500nm. This layer is placed on top of a silicon substrate 4□m x 4□m of thickness 2□m. The radius of curvature is 50nm. Only the region around one conic shape is simulated since the structure exhibits both symmetry and periodicity. To model the sunlight, a plane wave with a wavelength range from 350nm to 850nm is used.

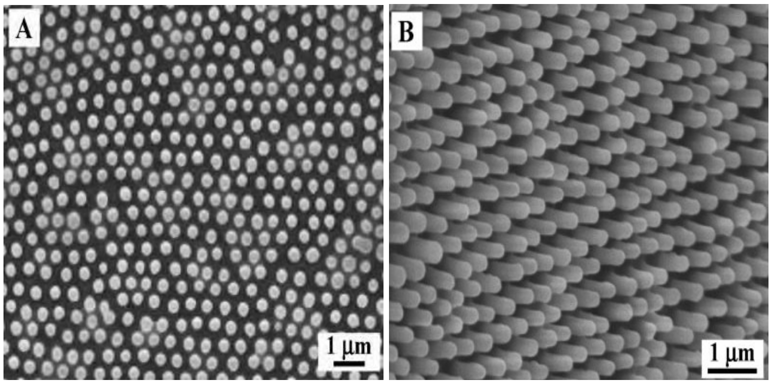

Figure 7 – Top and tilted view SEM images of sol–gel glass pillar array template from a silicon pillar array (taken from [34]).

Figure 8 presents the reflection, transmission and loss in structures with and without the moth eye antireflection coating, moth eye and flat absorption profile and $|E|^2$ profile at the minimum and maximum wavelengths as well as the centre wavelength with moth eye antireflection. The moth eye like texture results are compared with the results without the conic structures of the bare SC. The waves < 500nm are mostly absorbed by the cones, and the waves > 500nm are mostly absorbed by the substrate. The broadband reflectivity overall is quite low. The $|E|^2$ profile at the minimum and maximum wavelengths as well as the centre wavelength is also presented. In the plot at 350nm, since the conic has high absorption, the $|E|^2$ field is very close to 0 at the conic-substrate interface. With the flat silicon substrate, anything that is not reflected is absorbed, and then the following image shows the simulated absorption enhancement possible by using moth-eye structures.

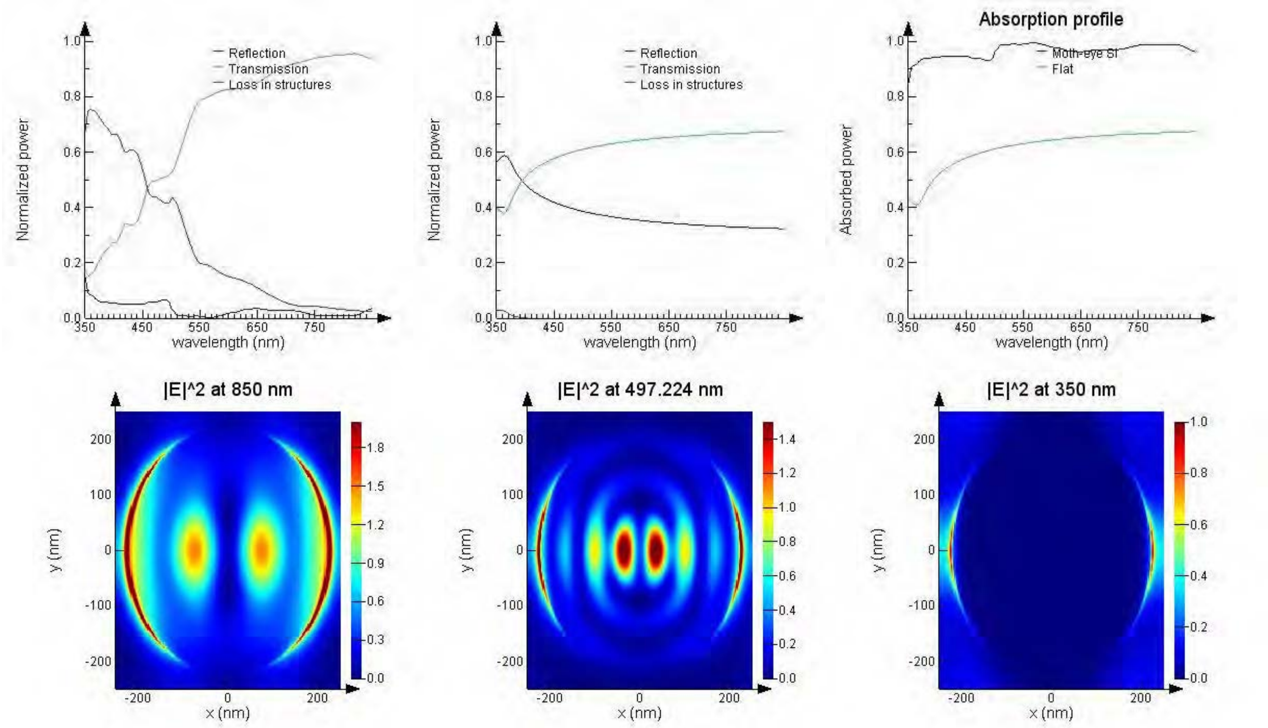

Figure 8 – Reflection, transmission and loss in structures with and without the moth eye antireflection coating (top). The absorption (1-reflection) profile is also shown, as it is conventionally defined as the light not reflected. $|E|^2$ profile at the minimum and maximum wavelengths as well as the center wavelength with moth eye antireflection (bottom).

6. COMPLEX INAS NANOSTRUCTURES

The use of nanostructures reducing the reflection and increasing the light trapping within the semiconductor is the next step to consider for more efficient SC. Due to symmetry, only one nanoparticle / nanostructure is considered. The use of symmetry boundary conditions reduces considerably the computational time and memory requirement for a fine grid solution. The quality of simulations is particularly high due to the use of the conformal mesh technique of Lumerical FDTD. From suspended Ag nano spheres to submerged Ag nano-spheres to submerged InAs nano spheres there is a clear trend of improvements in the light harvesting of the SC further enhanced with partially submerged tapered cylinders with sharp or round tips. These results are not those of a numerically optimised configuration being the solution of the Maxwell's equation just a small, introductory activity to foster the development of novel SC.

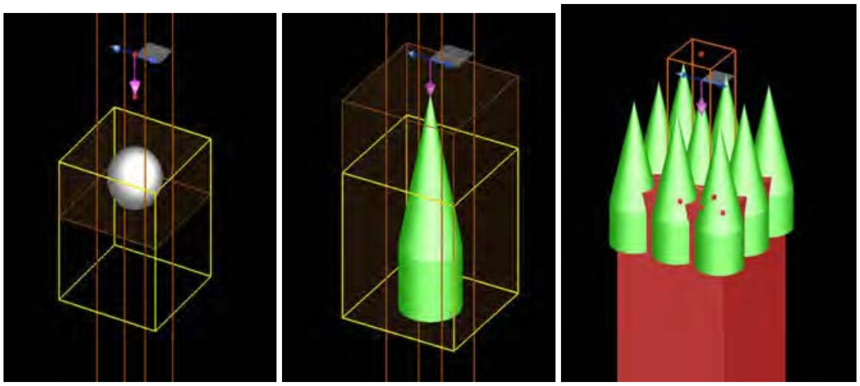

Figure 9 – Submerged Nanospheres (left) and partially submerged tapered cylinders with round or sharp tips (middle) and array of partially submerged tapered cylinders with round or sharp tips (right).

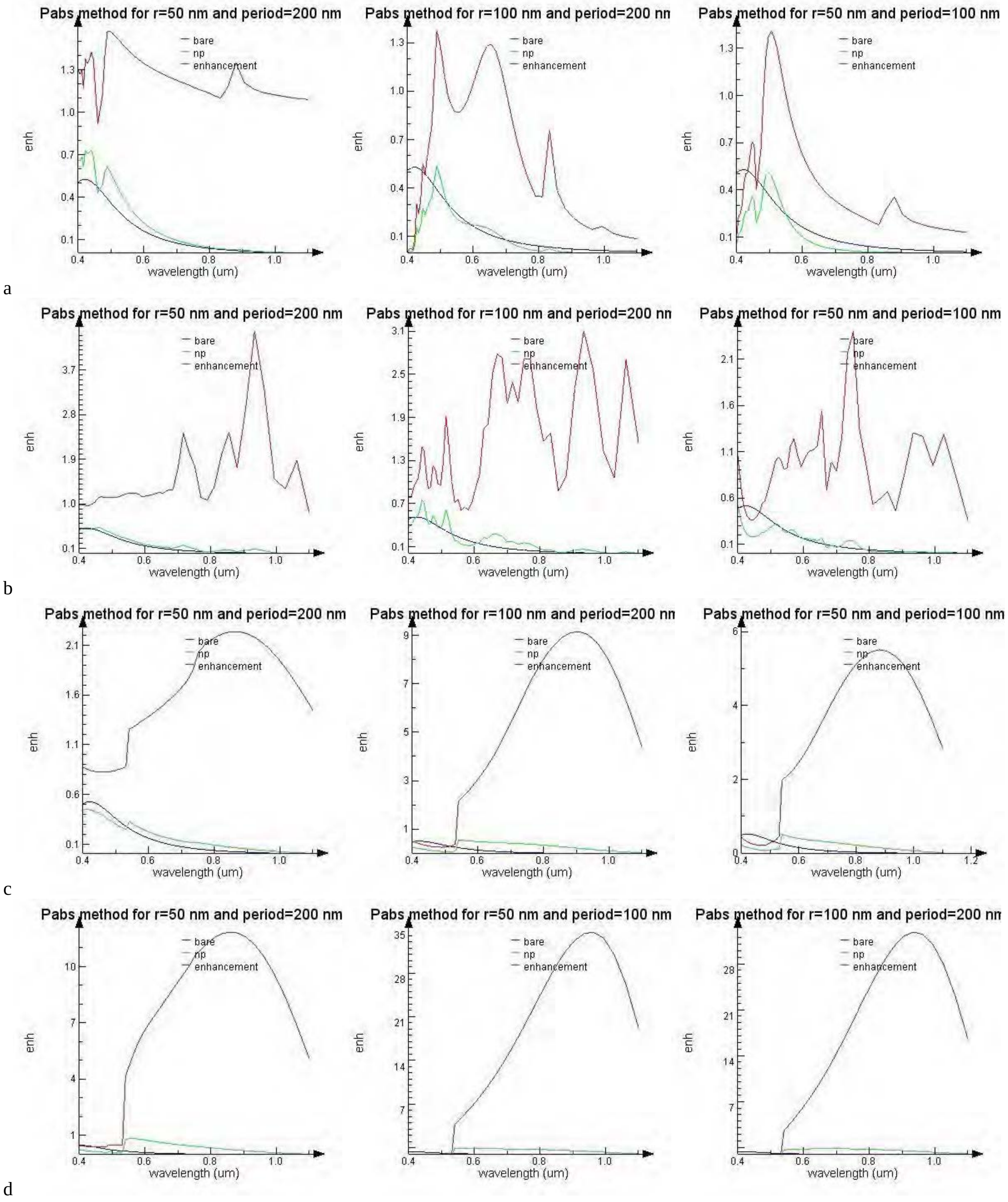

Figure 10 - *QE(λ)* with and without nanoparticles and their ratio *g(λ)* (enhancement) for the given radius (r) and period with: (a) Ag nanoparticles on top of the silicon; (b) Ag nanoparticles embedded in the silicon; (c) InAs nanoparticles embedded in the silicon; (d) InAs partially submerged tapered cylinders with round tip (preliminary results, configuration not optimised).

Figure 9 presents the submerged nanospheres and the partially submerged tapered cylinders with sharp or round tips (right). Figure 10 presents *QE(λ)* with and without nanoparticles and their ratio *g(λ)* for the given radius and period with:

(a) Ag nanoparticles on top of the silicon; (b) Ag nanoparticles embedded in the silicon; (b) InAs nanoparticles embedded in the silicon; (d) InAs partially submerged tapered cylinders with round tip. These latter results are only preliminary, and the configuration is therefore not optimised. The substrate thickness is 2000 nm and the structure height is 800 nm. The part submerged in the silicon is mostly cylindrical, while the part outside the silicon is mostly conical. The conical portion is rounded on the tip.

7. CONCLUSIONS

Simulations performed in thin film solar cells with spherical silver nanoparticles show the opportunity to achieve increments in the collection efficiency compared to the bare SC, improving the light trapping in the thin silicon film submerging the noble metal nanoparticles. The submersion of the nanoparticles changes the collection efficiency. Once the parasitic losses in the metal are considered, the improvement of efficiency versus the bare SC is still up to 100% better.

Simulations performed in thin film silicon solar cells with spherical nanoparticles made by a second, more precious and efficient semiconductor, show the opportunity to achieve still large increments in the collection efficiency versus the bare silicon SC because of the improved light trapping in the silicon and because of the better semiconductor properties of the nanoparticles material. The InAs nanoparticles perform better than the GaAs nanoparticles for the selected sun energy spectrum. With the InAs nanoparticles, the efficiency of the SC may increase up to more than 300% compared to the bare silicon solar cell.

Both these results are theoretical improvements of the light harvesting of the solar cell. Other effects, in particular the recombination effect at the interface between the nanoparticles and the silicon may affect this result. The more efficient semiconductor may however also further improve the number of electrons finally collected at the electrodes that is actually the only result of interest. Further experimental activities are certainly needed to further refine this technique.

Simulations performed with a moth eye texture of the surface of the silicon SC finally show enhancement of more than 50% of the light collected in the SC for selected wave lengths. This solution has the advantage of the much simpler production versus the two prior designs that however have better efficiency. The efficiency is better than with the nanoparticles of noble metal suspended on the silicon substrate.

The use of nanostructures located on top of and within the silicon substrate to reduce reflection and increase light trapping is the most promising opportunity shown by the simulations. Only initial simulations have been made so far, and the configurations computed are therefore very far from the optimal design. In addition to further explore the numerical solution of the Maxwell's equation, an experimental campaign is now planned to prove the concept and provide guidance for further model development and optimization.

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Introduction

The fourth Thin Film Solar Technology conference was held this year at the SPIE Solar Energy + Technology symposium. The program was strong with stimulating talks from various areas in the field, ensuring a well-attended and successful event. The conference included speakers from leading international academic institutions, government laboratories, and industry.

This volume features contributions from scientists and engineers in the general area of Thin Film Solar Technology, with special emphasis on Thin Film Photovoltaics (TF PV). Thin film solar technologies are a compelling alternative to conventional crystalline silicon solar technologies because they offer a cost reduction potential, driven mainly by the need for a lower amount of material, as well as the possibility of monolithic integration. It is important to note, however, that silicon pricing has continued to drop dramatically this year, challenging TF PV manufacturers to further improve the efficiency and reduce the cost of their modules. As a result, this year has seen continued shake-out in the TF PV space, leaving fewer companies in each technology area standing, as well as significant consolidation activity through mergers and acquisitions. The PV industry came out of this period of change stronger.

To illustrate the breadth of topics covered in this conference, we mention just a few of the papers presented in each session. The first session dealt with nanostructured thin film PV. Jeehwan Kim et al. from the IBM Thomas J. Watson Research Center presented a talk on the progress and challenges in three-dimensional thin film silicon PV, with a focus on nanocone-based solar cells. Ulrich Paetzold et al. from Forschungszentrum Jülich, Germany, proposed plasmonic reflection grating back contacts for thin film silicon solar cells. Vivek Shah and his colleagues from the group of Prof. Pratim Biswas at Washington University in St. Louis tackled nature-inspired nanostructures for enhanced performance using a single-step process to synthesize bio-hybrid and bio-mimetic solar PV devices. The second session focused on advances in thin film silicon PV. Jeremy Fields and coworkers from the Colorado School of Mines and MVSystems proposed synthesizing hydrogenated nanocrystalline silicon thin films using a double-pulsed PECVD process. Tanzina Khaleque from Prof. Robert Magnusson's group at the University of Texas at Arlington described experiments with resonant thin film hydrogenated amorphous silicon solar cells. Barbara Leszczynska and coworkers from the Technische Universität Dresden and the Forschungs- und Applikationslabor Plasmatechnik, Germany, described the high-rate deposition of silicon thin film layers using linear plasma sources operated at very high excitation frequencies (80-140 MHz). Chang Su Kim et al. from the Korea Institute of Materials Science described innovative amorphous silicon and organic hybrid tandem thin film solar cells.

The third session dealt with advances in crystalline silicon PV. Romain Cariou and his colleagues from the Ecole Polytechnique, France, and their collaborators from Università degli Studi di Messina, Italy, and the Indian Association for the cultivation of Science, described a novel process for the epitaxy of silicon below 200°C. Louay Eldada from Amprius described hybrid PV systems that integrated high-efficiency crystalline silicon panels, long-lifetime energy storage solutions, and back-up generators; these systems were deployed globally for rural electrification, mine exploration, irrigation, and desalination. The fourth session covered novel PV materials and characterization methods and the emerging field of CZTS (copper zinc tin sulfide/selenide) solar cells. Wei Wang et al. from the Hong Kong Polytechnic University described SnS van der Waals epitaxies on graphene buffer layer. Volker Buschmann and his colleagues from PicoQuant, Germany, and their coworkers from the Ferdinand Braun Institut and the Helmholtz Institut für Materialien und Energie, Germany, discussed the characterization and quality control of semiconductor wafers using time-correlated single photon counting. Akram Aqili from the Hashemite University, Jordan, and his collaborators from the Optics Laboratories, Pakistan and the Lawrence Berkeley National Laboratory, described the optical and structural properties of silver doped ZnSe thin films prepared by CSS and ion exchange process. Kaushik Choudhury and his colleagues from DuPont covered the topic of CZTS solar cells from inks in their talk on solution chemical routes to high efficiency Cu2ZnSn(S,Se) thin-film solar cells.

The fifth session focused on CIGS (copper indium gallium selenide) PV modeling, fabrication, and characterization. Mustafa Pinarbasi of SoloPower gave an invited talk on the processing and performance of low weight flexible CIGS cells and modules. Antonin Moreau and coworkers from the Institut Matériaux Microélectronique Nanosciences de Provence and NEXCIS, France, and the Technical University of Madrid, Spain, discussed characterizing CIGS devices using photoreflectance spectroscopy. Yu-Ting Hsu and coworkers from the National Chiao Tung University, the National University of Kaohsiung, the National Cheng Kung University and the Institute of Science and Technology, Taiwan, presented their results on studies of CIGS thin films with different pairs of CuGa/In sputtered layers. Finally, the last session of the conference, the sixth session, dealt with transparent conducting oxides. Maxwell Mageto and coworkers from Uppsala University, Sweden, and Kenya's University of Science and Technology and Moi University, discussed the electrical and optical properties of TiO2:Nb thin films prepared by the spray pyrolysis technique, and Thomas Gennett and colleagues from David Ginley's group at the National Renewable Energy Laboratory (NREL) presented an invited talk on innovative amorphous InZnO transparent conductors that improve the Epi-Si heterojunction PV performance.

Although this volume cannot include all the recent important work in the vast field of thin film solar technologies, it does cover a significant cross section of the advances happening globally, and it provides a roadmap for this fast-growing and exciting field by presenting the cutting-edge work and the visions of leading experts who are actively inventing the future.

Louay A. Eldada