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Plasmon coupled 2D random medium For Enhanced absorption in solar cells

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ABSTRACT

Random textures are proved to be better for energy harvesting in solar cells. In this research, we have studied the absorption properties of a random dielectric medium with plasmonic nanostructures in it. This structure has shown significant enhancement in broad band absorption of light spectrum and higher extinction of near infrared wavelengths. We also discuss several strategies to improve the solar cell efficiency based on dielectric and plasmonic random media. Finally, a comparative study of solar cell efficiencies with flat, periodic and random structures as active medium and back reflectors is carried out with a proposal for possible potential solar cell configurations.

1. Introduction

Nano photonic structures have become one of the significant elements of light harvesting devices such as thin film solar cells, which are expected to offer better absorption enhancement and hence conversion efficiency [1]. The efficiency of the solar cell is affected by absorption of the material, photon flux, broadness of the light spectrum and the surface volume recombination in the material. The usage of photonic structures in the solar cells is to enhance the path length by trapping the light, whereas the surface and volume recombinations are controlled by thickness. The short circuit current in the solar cell is determined by [2]

$$j_{sc} = e \int_0^\infty A(E) \frac{dN}{dE} dE = \int_0^\infty \frac{dj_{sc}}{dE} dE \quad (1)$$

Where j_{sc} , $A(E)$, $\frac{dN}{dE}$ and $\frac{dj_{sc}}{dE}$ are short circuit current, absorption, photon flux and spectral broadness respectively. The statistical ray trapping absorption limit or the *Lambertian* limit is given by [3]

$$A = 1 - \frac{1}{4L\alpha n^2} \quad (2)$$

Where $\alpha = \frac{2\pi k}{\lambda}$ the absorption coefficient, n and k are the real and imaginary part of refractive index of the material, and L is the material thickness. A structure which gives the absorption near to the Lambertian limit can enhance the solar cell efficiency. Hence it is inferred that a photonic structure that can provide the necessary broad band absorption through light trapping with less recombination losses is desired for efficient solar cell fabrication.

Research and development of thin film solar cells has recently emerged again due to their low cost and less volume recombination, and their potential to offer better efficiencies [4]. Various photonic structures such as regular [5], random [6], quasi random [7] and plasmonic structures [8-10] are investigated theoretically and experimentally for solar cells applications. Still the quest continues for better configuration of solar cell for improving efficiencies. The random structures are reported as good for broad band light trapping and antireflection in solar cells. Particularly the Gaussian random structures are shown to enhance the performance of the device [11]. Further, the photonic crystals are used as back reflectors and the surface anti reflectors [12]. The plasmonic periodic structures are used in solar cells to concentrate the EM radiation into the solar cell [13].

In this paper, we present an ultrathin and highly absorbing structure by combining concepts associated with periodic, random and plasmonic structures. Firstly, the absorption properties of Si random texture with different back

reflectors are presented. Further, based on the reflection properties, a random structure with a nano-pillar back reflector is analyzed in terms of light propagation, plasmon coupling and overall absorption. This structure is shown to be an ultra-thin broad band absorber with high absorption, and expected to be good for high efficiency solar cell fabrication.

2. Absorption of a random medium structure with different back reflectors

The simulations are performed using FDTD (*Lumerical*) with PML boundary conditions. The broad band source (0.2 μm -1.5 μm) is applied on to the structure through a 2D field monitor (for reflection and incident field measurement) and the transmitted field is measured by another 2D field monitor at the back reflector. The total thickness of the structure is 0.6 μm . In order to observe the light transport scenario inside the structure, the 2D cross sectional field monitors are kept at 0.1 μm , 0.2 μm , 0.3 μm , 0.4 μm , and 0.5 μm propagation distances from plane of incidence. The random 2D surface texture with specific features is chosen using the inbuilt structures from the software.

The absorption of a random structure with different back reflectors is measured by simulation approach. A typical structure consist of a block of Si with randomly textured surface and a Ag back reflector as shown in Figure 1. The spike amplitude in the surface random texture is 250 nm. The shape and geometry of Ag back reflectors used in this study are planar (S1), saw tooth (S2), sinusoidal wavy (S3) and nano-pillar (S4). Figure 1 shows the structure, its absorption spectra and the field enhancements in the structure (from left to right). The absorption is normalized with respect to the effective radiation incident on it, excluding the reflection. So here absorption curve shows the effective amount of absorbed intensity out of total light intensity traversing through the structure.

The structure with planar back reflector (S1) (Figure 1a) shows the least absorption (Figure 1e) whereas the structures with saw tooth (S2), sinusoidal wave (S3) and nano-pillar (S4) back reflectors (Figure 1b,c and d respectively) are showing the pronounced absorption enhancement in visible and infrared regions (Figure 1f, g and h). Among these, S2 structure shows above 95% absorption in visible region where as it reduced to 85% in IR region (Figure 1f). The S3 structure showing the consistent 95% absorption over the visible and IR regions (Figure 1g). Interestingly the IR absorption is dominant in S4 structure (Figure 1h). In all structures, the field accumulation or enhancement is observed. In random media it is due to multiple scattering, and near the back reflector it is due to the diffraction and interference of a randomized light. The effect of planar back reflector is nominal, which is evident by low enhancement factor of the field. In other structures (S2, S3 and S4) the plasmon effect from back reflector contributes to the enhancement along with increased the path length of the travelling wave. Plasmon assisted field enhancements are observed near the surfaces of back reflectors.

Figure 1: The silicon random structures with different back reflectors *a*) Planar, *b*) saw tooth, *c*) Sinusoidal wavy, *d*) nano pillar. (*e*, *f*, *g*, *h*) and (*i*, *j*, *k*, *l*) are the respective absorptions and field enhancements of structures (*a*), (*b*), (*c*), (*d*).

However, the reflection spectra from these structures (S1, S2, S3 and S4) shown in figure 2, suggest that there is high broad band reflection in structures S1, S2 and S3 whereas it is comparatively less in S4. Hence there is a back reflector dependent reflection in these structures as expected due to their $0.6 \mu\text{m}$ thin structure. Based on this analysis, the S4 structure (with less broad band reflection comparative to other structures) is chosen for further studies.

Figure 2: The reflection spectra of S1, S2, S3 and S4 (from bottom to top respectively) structures.

3. Si random structure with nano pillar back reflector for high absorption and light localization

Figure 3 shows a Si random structure with Ag back reflector with increased nano pillar height from 40 nm to 250 nm. A significant reduction in broad band reflection is observed, upon increasing the nano pillar height (Figure 3b). This feature has advantage in solar cell configuration as it avoids the need for separate anti reflection coatings. This structure is a perfect combination of random and regular structures with plasmon effects. The field enhancement in this structure is shown in Figure 3c, from which it is clear that the light trapping conditions are existing on top and middle of the nano pillars with significant enhancement. Expectedly, the absorption by the structure is above 90% over the broad wavelength range of visible to IR regions. Furthermore, the absorption curve got smoothened, which is generally observed in pure random structures. It is inferred from the reduced reflection and improved absorption that the extended path length contributed to the observed performance.

The broad band light propagation through the structure is observed after certain propagation distances, 0.1 μm , 0.2 μm , 0.3 μm , 0.4 μm , and 0.5 μm from the plane of incidence. Figure 3 *e, f, g, h and i* are the field distributions at the propagation distances of 0.1 μm , 0.2 μm , 0.3 μm , 0.4 μm , and 0.5 μm respectively. At 0.1 μm distance field is getting randomized by the random structure and accumulating at certain spots. Field channelization is observed at 0.2 μm distance, where light is prompted to travel in channels due to randomly varying refractive index and multiple scattering. The randomized field found to be affected by the surface plasmon at 0.3 μm which is attributed to nano-pillars. From Figure 3 *h, i* the randomized field is strongly localized among the periodically arranged nano pillars. This analysis is further supported by the absorption percentage calculated for the respective propagation distances of 0.1 μm , 0.2 μm , 0.3 μm , 0.4 μm , and 0.5 μm . Figure 4 indicates that the absorption increases with the propagation distance. Due to the randomization there is nearly 20% absorption whereas after entering the periodic nano pillar zone there is a drastic variation in absorption (up to 80%). This significant enhancement in absorption from 0.3 μm to 0.5 μm propagation distances is the evidence of plasmon induced localization of randomized light.

Figure 3: *a*) The random structure with nano pillar back reflector, *b*) The reflection spectra of the structures with 40 nm (Red curve) and 250 nm (Black curve) nanopyler height, *c*) The vertical cross sectional field profile, *d*) The absorption spectrum of the structure, the field distributions at *e*) 0.1 μm , *f*) 0.2 μm , *g*) 0.3 μm , *h*) 0.4 μm and *i*) 0.5 μm propagation distances from incident plane.

Figure 4: The absorption curves at different propagation distances 0.1 μm (Red), 0.2 μm (Blue), 0.3 μm (Green), 0.4 μm (Mejenta) and 0.5 μm (Pale green).

Conclusion

In conclusion, an ultra-thin (0.6 μm) Si random structures with different back reflectors are analyzed through FDTD simulation. Among all the different structures considered in the analysis, the nano pillar structure found to offer low reflection structure with high broad band absorption $> 90\%$. In the same structure, the dependence of reflection on nano pillar height is demonstrated. Further, plasmon affected localization in the proposed structures with chosen features are observed. Hence the structure with random, periodic and plasmonic features, if integrated, expected to offer significant broadband absorption and in turn improved conversion efficiency in thin film solar cell structures.

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REFERENCES

- [1] Sang, E. H., and Gang, C. "Toward the Lambertian Limit of Light Trapping in Thin Nanostructured Silicon Solar Cells", *Nano Lett.*, 10, 4692–4696 (2010).
- [2] Whittaker and Culshaw, "Absorption by Rigorous Coupled Wave Analysis", *Phys. Rev B*, 60, 2610 (1999).
- [3] Sergey, E., Alexei, D. and Sajeev, J., "Near perfect solar absorption in ultra-thin-film GaAs photonic crystals", *J. Mater. Chem. A*, 2, 761–769(2014).
- [4] Makoto, K., "Present Status and Future Prospects of Silicon Thin-Film Solar Cells", *Japanese Journal of Applied Physics* 50, 030001 (2011).
- [5] Guillaume, G., Xianqin, M., Emmanuel, D., Khalil, E. H., Emmanuel, G., Romain, P., Alain, F., Regis, O., Mustapha, L., and Christian, S., "Light harvesting by planar photonic crystals in solar cells: the case of amorphous silicon", *J. Opt.* 14 024011 (2012).
- [6] Filippo, P., Matteo, B., Francesco, R., Kevin, V., and. Wiersma, D. S., "Disordered photonic structures for light harvesting in solar cells", *Optics Express*, 21, A461(2013).
- [7] Emiliano, R. M., Juntao, L., YiKun, L., Valérie, D., Zhanxu, C., Jianying, Z., and Thomas, F. K. "Deterministic quasi random structures for photon control", *Nature Commun.* 4, 2665 (2013).
- [8] Spinelli, P., Ferry, V. E., J van de, G., van Lare, M., Verschuuren, M. A., Schropp, R. E. I., Atwater, H. A., and Polman, A., "Plasmonic light trapping in thin-film Si solar cells", *J. Opt.* 14 024002(2012).
- [9] Sidharthan, R., and Matham, M. V. "Improved light absorption in thin film solar cell using combination of gap modes and grating back reflector," *Thin Solid Films* 548, 581-584 (2013).
- [10] Sreekanth, K.V., Sidharthan, R., Murukeshan, V.M., "Gap modes assisted enhanced broadband light absorption in plasmonic thin film solar cell," *Journal of Applied Physics* 110(3), 033107 (2011).
- [11] Piotr K., Marco L., and Lucio, C. A., "Engineering Gaussian disorder at rough interfaces for light trapping in thin-film solar cells", *Optics Letters*, 37, 4868 (2012).
- [12] Curtin, B., Biswas, R., and Dalal V. "Photonic crystal based back reflectors for light management and enhanced absorption in amorphous silicon solar cells" *Applied Physics Letters*, 95, 231102 (2009).
- [13]. Schuller, J.A., Barnard, E. S., Cai, W., Jun, Y. C., White, J.S. and Brongersma, M.I, "Plasmonic for extreme light concentration and manipulation" *Nature Materials*, 9, 193–204 (2010)