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SIGNIFICANCE OF 1D PHOTONIC CRYSTALS AS BACK REFLECTORS (DBR) IN AMORPHOUS SILICON THIN FILM SOLAR CELLS

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ABSTRACT

The naturally abundant silicon-derived materials are significant in photovoltaic (PV) technology. In nanoscale engineering, the periodic 1D photonic crystals (Si/SiO_2) plays a crucial role in PV technology. This one-dimensional photonic crystal (1DPC) is also known as distributed Bragg's reflectors (DBRs), which are alternating high- and low refractive indexed materials. The photonic band gap of Si/SiO_2 multilayers was optimized using the plane wave expansion (PWE) and rigorous coupled wave analysis (RCWA) method. The optimized 10DBR multilayers were integrated as an effective back reflector with anti-reflection coating (ARC), amorphous silicon absorber, top-ITO and bottom (Ag) nanogratings. Using the RCWA method, amorphous silicon thin film solar cell structures were enhanced to improve the light harvesting mechanism and quantum efficiency. This RCWA method is also known as a simple method to solve electromagnetic wave-based problems using Maxwell's equations. The proposed cell structure, which considered as 50 nm amorphous silicon as the absorber region, achieved 15.75% and 14.71% conversion cell efficiencies under transverse electric and magnetic field polarization conditions. Finally, the light harvesting mechanism improved in the photonic effects (TE) as compared with the plasmonic effects (TM). In future, results could be appreciably enhanced by incorporation of nanorods and nanopillars within the absorber region.

Keywords: Photonic Crystal, Si/SiO_2, RCWA Method, Solar Cell, Thin Film, DBR.

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INTRODUCTION

Photonic crystals are highly ordered structures oriented in 1D, 2D and 3D which are available in nature. It recognized by their bright colors and beautiful shapes for example peacock feathers, tropical fish, butterflies, beetles, etc. These colors of structures occur due to the diffraction of light particles (photons) at distinct angles. The prolonged evaluation of natural creatures developed as perfect photonic crystal structures. The various pioneering works on the photonic crystals prompted an intensive studies and generated huge interest led by *Eli Yablonovitch* and *Sajeev John* in 1987.[1] Theoretically, the design and simulation of photonic crystals used various methods like FDTD, FDFD, FEM method, finite element method, plane wave expansion, RCWA method, etc.[2] Experimentally, bottom-up (or) top-down approaches are useful for the fabrication of 1D, 2D and 3D-photonic crystals. Here, distributed Bragg's reflector (or) DBR layers consists of two alternative layers with two distinct materials includes low and high refractive indices. The thickness of the each layer separated by a constant parameter, such as glancing angle (θ), incidence wavelength (λ), selection of the materials, etc. *Yue et al.* reported tunable one-dimensional photonic crystals from soft materials. They explored the polymer-integrated one-dimensional photonic crystals for sensors, optical switches, etc. The improvement of tandem microcrystalline solar cell performance observed due to the integration of anti-reflection coatings (SiO_2 and Si_3N_4), and a tunnel recombination junction including n- and p-type μc-Si: H. These tandem solar cells yielded the highest current density of 12.51 mA/cm^2, fill factor of 80.82%, and open-circuit voltage

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of 1.38 V. These solar cell structures were achieved the maximum conversion efficiency of 14%.[3] Using the transverse matrix method, a 1D photonic crystal consisting of alternating titanium dioxide and graphene oxide (TiO_2/GO) structures was used for the thermo-photovoltaic. These optical properties can be improved by optimizing various parameters such as incident angle and thickness of the each layer.[4] Further, the optimized thin film organic solar cell showed improved the conversion cell efficiency due to the incorporation of DBR pairs. Additionally, thermal stability analysis of the proposed design showed the decreased cell efficiency to 10.7% from 11.02%. These demonstrations could provide the photon pathway to enhance the harvesting mechanism[5]. Saravanan and Dubey experimentally prepared stacks of 5 (10 layers), 7 (14 layers), 9 (18 layers) and 11 (22 layers) using sol-gel synthesis and the spin-coating method. These stacks or DBR layers are considered an alternative to TiO_2 and SiO_2 thin films.[6] These literature reviews focused on the design, simulation and fabrication of thin film solar cells, which are also economical and clean energy devices. The research communities are continuously working on renewable energy sources such as solar energy. In this work, focusing on the design and simulation of a one-dimensional photonic crystal (SiO_2/TiO_2) and nanogratings (Ag) integrated as a backside reflector for amorphous silicon thin film solar cells using the RCWA method. The designing tool, distinct parameters and methods are discussed. The electric field, band gap, quantum efficiency and absorption spectrum are discussed in the results section and concluded in the results section.

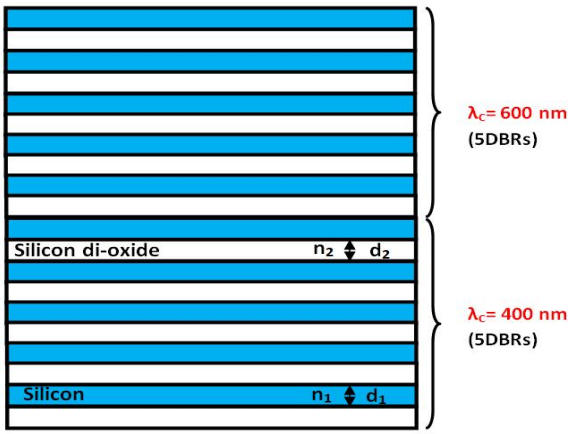


Fig.-1: The Schematic Diagram of 1D Photonic Crystal (10 DBR layers) of Si & SiO_2 Thin Films

EXPERIMENTAL

Back Reflector (or) 1D Photonic Crystals

RSoft synopsis tool is used for the design and simulation of 1DPCs or distributed Bragg's reflectors (DBR's). Initially, the plane wave expansion (PWE) method used for the band gap studies. Next, field analysis, optical absorption and quantum efficiency analysis were carried out by RCWA method. These PWE and RCWA methods are useful for the investigation of electromagnetic wave problems using *Maxwell's* equations[7]. Initially, the DBR layers are Si and SiO_2 thin film structures in the form of periodic refractive index along their surfaces. Initially, the refractive index of the Si thin film is 3.5 (n_1) and 1.5 (n_2) for SiO_2 thin films. Also, the thickness of each layer calculated by using quarter wave formula,

$$d = \frac{\lambda c}{4n} (1)$$

Where, d- thickness of the selected material layer, λc- center wavelength of the incidence and n is the refractive index. Initially, d_1= 29 nm and d_2=67 nm for the Si and SiO_2 thin films under the centre wavelength (λc) of 400 nm. Similarly, the thickness of the Si and SiO_2 thin films is 43 (d_1) and 100 nm (d_2). During the simulation work, followed two boundary conditions were used: periodic boundary conditions (PBCs) for the X and Y axes. Next, perfect matched layer (PML) conditions were used for the Z–axis. These conditions are useful to avoid noise and simulate infinite domains without any reflections.

Amorphous Si Thin Film Solar Cell

The anti-reflection coating (ARC) thickness is 111 nm with a refractive index of 1.8 and the amorphous silicon absorber layer thickness is maintained at 50 nm with a refractive index of 3.65. This absorber

incorporates top and bottom nanogratings with the thickness (heights) of 20 nm of ITO-top (GRA_{TOP}) and silver (GRA_{BOT}) has 20 nm (60 nm for 3 nanogratings). Further, the 10 DBR layers used as a back reflector include 5 DBR (Si/SiO_2) under a 400 nm centre wavelength, which has the following thickness of each layer: 29 and 67 nm.

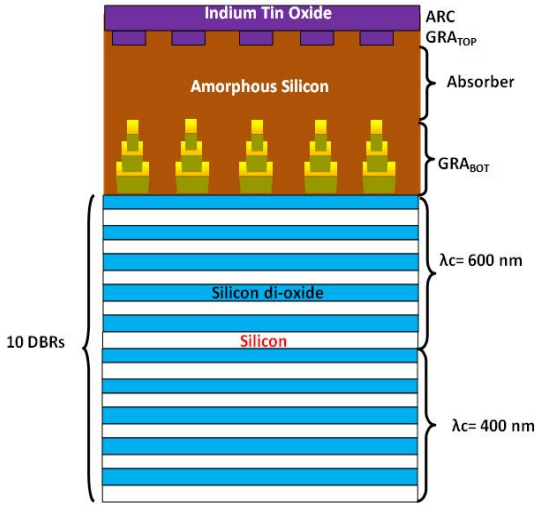


Fig.-2: The Schematic Diagram of Amorphous Silicon Thin Film Solar Cell

Next, the 5DBR layers consist of 43 nm and 100 nm under centre wavelengths of 600 nm. These gratings have a 500 nm period and a 400 nm duty cycle. Here, the bottom triangular gratings (GRA_{BOT}) are made up of silver (Ag), and the top gratings are ITO. The silver nanogratings between amorphous silicon also act as gratings due to the enhancement or employment of a light-harvesting mechanism in the bottom gratings, which are considered Ag/a-Si, because the Ag nanogratings are kept within the a-Si absorber layer. During the simulation process, PBC and PML boundary conditions were applied with Cartesian coordinate axes (X, Y and Z); periodic boundary conditions (PBC) and perfectly matched layers (PML) were applied.

RESULTS AND DISCUSSION

Figure-3 shows the transverse electric (TE) field polarization with a processing time of 60 mins. The field bar diagram shows the intensity of the electric field within the 1D photonic crystals. Initially, the strong field appeared as light red and yellow, shown as a stronger field, and gradually light transmission reduced due to reflection and absorption of Si/SiO_2 DBR layers. Using the plane wave expansion method, the photonic band gaps of Si/SiO_2 thin films for 5DBR structures are shown in Fig.-4. The multilayer band gaps are similar as compared to those of individual DBR layers like 1DBR, 2DBR, 3DBR, 4DBR, 5DBR & 6DBR stacks. The photonic bandgap of multilayers is shown in Fig.-4. These band gaps vary with the effect of the number of layers (DBR or stacks), the thickness of each layer, selection of the dielectric materials, etc.[8-10]

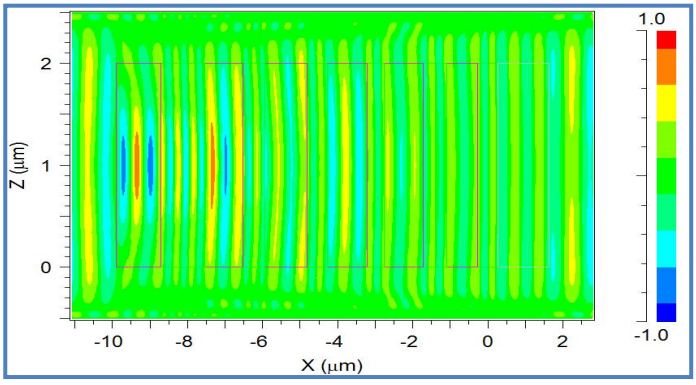


Fig.-3: The transverse electric (TE) field of 1D photonic crystal (Si/SiO_2)

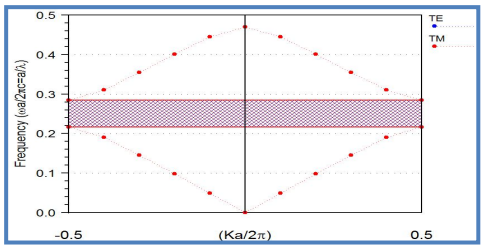
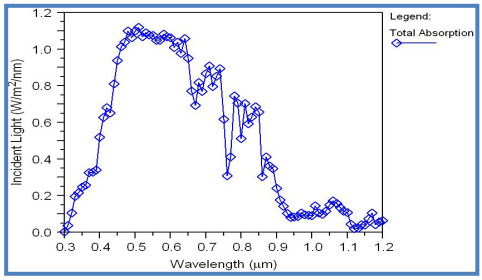


Fig.-4: The Photonic Band Gap of DBR Layers of Si/SiO_2 Thin Films

(a)



(b)

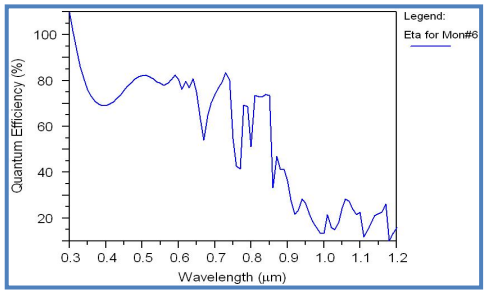


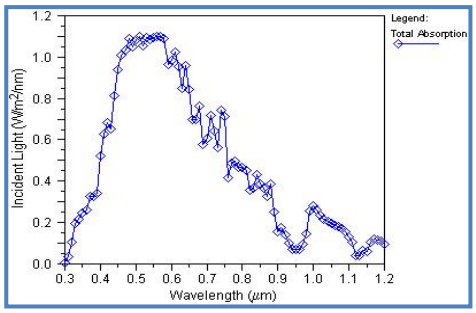
Fig.-5: Under TE Mode, the Absorption Spectrum (a) and Quantum Efficiency (b) of 10DBR Layers Integrated Amorphous Silicon Thin Film Solar Cells

The modifying the thickness of each layer and shifting the centre wavelength, broader band gap. These photonic band gaps in which the propagation of electromagnetic waves between the forbidden region and particular direction of irradiation.Fig.-5 shows the absorption spectrum and quantum efficiency of amorphous Si thin film solar cells by integration of 10DBR layers, top and bottom nanogratings. Here, the light harvesting mechanism increased between 400 and 820 nm. Figure-5(a) confirms the collection of the light particles (photons) under AM1.5 conditions in transverse electric (TE) modes. The employment of light harvesting and photonic crystal structures is remarkably increased by manipulating the interactions with electromagnetic waves. The various photonic effects plays are crucial role in the improvement of light harvesting and the lifetime of the light particles, such as Fabry-Perot resonance, surface guided modes, etc.[11-12]Figure-5(b) shows the collection of the photonic modes converted into electricity. It is also called the quantum efficiency, which means the ratio between the number of charge carriers collected and the number of photons given energy. These photonic effects between surface structures were engineered at the nanoscale level. Using the photonic materials and optical engineering mechanism of solar cells yielded the cell efficiency (η) and short-circuit current (Jsc) of 15.41% and 23.43 mA/cm^2. Fig.-6 depicts the absorption spectrum and quantum efficiency spectrum of amorphous silicon thin film solar cells under plasmonic effects (TM mode). These spectra show reduced the absorption and quantum efficiency as compared to Fig.-5. Particularly, the collection of the light particles or photons is enhanced from ~400 nm to ~700 nm. However, the other spectral region is reduced and needs more optimization to improve light trapping mechanisms. The maximum conversion cell efficiency and short-circuit current density reached up to 14.71% and 22.37 mA/cm^2.

The plasmonic effect plays a crucial role for the enhancement of light trapping particles (also known as photons) such as surface-guided resonance mode, localized surface modes, surface excitation, etc.[13-14]. These plasmonic effects and nanostructures remarkably boost the incident light absorption in visible and

infrared spectral region. These one-dimensional photonic crystals or distributed *Bragg* reflectors (TiO_2/SiO_2) are also employed in sensors and optical filters related to cavity mode spectral domain resonances. [15] The proposed design and simulation of a thin-film amorphous silicon solar cell could be fabricated by using advanced techniques like RF sputtering, lithography, CVD, PECVD, etc.

(a)



(b)

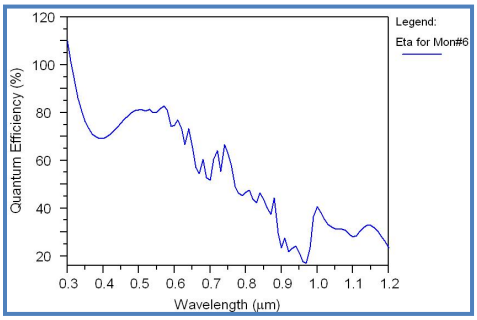


Fig.-6: Under TM Mode, the Absorption Spectrum (a) and Quantum Efficiency (b) of 10DBR Layers Integrated Amorphous Silicon Thin Film Solar Cells

CONCLUSION

In this paper, the design and simulation of optimized one-dimensional photonics crystals (Si/SiO_2) integrated as a back reflector in thin-film amorphous silicon solar cells using the PWE and RCWA methods. The Rsoft synopsis tool used for the design and simulation of amorphous silicon thin film solar cells which are based on *Maxwell's* equations. An ITO ARC layer (111 nm thick) incorporated with a 50 nm thin amorphous silicon absorber region to enhance light harvesting. Under TE and TM polarization conditions, the amorphous silicon thin film solar cell achieved the highest short-circuit current (Jsc) densities are 23.9 mA/cm^2 and 22.37 mA/cm^2. The assistance of photonic and plasmonic nanostructures was significant for the contribution of thin film photovoltaic technology. However, the obtained results are confirming the significance of nanomaterials for clean energy sources, which is also environmental friendly.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-7: Affordable and Clean Energy*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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