Research Article

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RCWA-based Investigation of Incident Wavelength Effects on Amorphous Silicon Thin-film Solar Cell

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ABSTRACT

In the study, the effect of the incident wavelength of 600 nm on the performance of a thin-film amorphous silicon solar cell was determined. The Rigorous Coupled-wave Analysis (RCWA) method was used to investigate the interaction of electromagnetic waves in transverse electric (TE) and transverse magnetic (TM) polarizations with an amorphous silicon solar cell. At the nanoscale level, nanostructures were integrated to improve the light-harvesting mechanism. Initially, the distributed Bragg reflector (1 DBR to 5 DBR) was optimized for the center wavelength (λ_c = 600 nm) based on reflectivity and integrated as a backside reflector. The optimized 5 DBR (Si/SiO_2), triangular bottom gratings (silver), and rectangular top gratings (indium tin oxide) played a significant role. Light harvesting improved within a 50 nm thick amorphous silicon absorber region, resulting in a conversion efficiency of up to 15.75% and a current density of 23.9 mA/cm^2, through the photonic modes under TE polarization. In the future, these design and structural parameters could be applied to miniaturized photovoltaic devices.

Keywords: Solar cell; Thin film; Cell efficiency; Light harvesting; DBR.

1. INTRODUCTION

In the last few decades, the photovoltaic industry has grown by leaps and bounds. It is becoming one of the major energy sources, and solar expansion is facing new challenges, which research communities are actively addressing. In theory, thin-film simulation or modeling employs various methods, such as the Finite Element Method (FEM), the Finite-difference Time-domain (FDTD) Method, Rigorous Coupled-wave Analysis (RCWA), and the Finite-difference Frequency Method (FDFM). These methods are fundamentally dependent on the Maxwell equations, including Faraday's law, Ampere's law, and Gauss's laws. They explain the interaction of light with complex structures and electromagnetic waves. Sigamani *et al.* (2023) proposed an optimized distributed Bragg reflector (DBR)-integrated amorphous silicon thin-film solar cell. The DBR composed of alternating Si/SiO_2 layers was investigated and integrated as a back reflector, enhancing optical performance. Similarly, the photonic and plasmonic nanostructures significantly improved the light-harvesting mechanisms, and a remarkable current density of 33.53 mA/cm² was reported (Saravanan *et al.*2022). Dewan *et al.* (2014) investigated the quantum efficiency and current density of a silicon thin-film solar cell prepared with random and periodic textured nanostructures using the RCWA method. Sarma *et al.* (2025) reported that top and bottom gratings remarkably enhanced the photon collection, which was converted into electricity. They demonstrated improved light harvesting within a 50 nm-thick amorphous silicon absorber region. Silicon-derived materials, such as monocrystalline silicon, polycrystalline silicon, and amorphous silicon, play an important role in photovoltaic technology due to their natural abundance and potential to address the upcoming energy crisis. The researchers are working towards the poor light absorption from the visible (λ = 400-700 nm) and infrared (λ = 700-1200 nm) spectral regions. However, light harvesting significantly improved in the ultraviolet region (Sigamani *et al*. 2022). Sayed *et al*. (2025) employed theoretical modeling with 1D photonic crystal as anti-reflection coating (ARC) and 1D binary photonic crystal as back reflector for amorphous silicon solar cells by FEM method. They examined and optimized various parameters due to enhance the light absorbance and conversion cell efficiency. Erman, et al. (2024) explored the design, fabrication and characterization of semi-transparent organic solar cells with the assistance of 1D photonic crystal. These solar cells achieved the highest cell efficiency of 5.08%. Overall, 1D photonic crystals were significantly enhances optical and photovoltaic properties.

In this work, the performance of an amorphous silicon thin-film solar cell was theoretically demonstrated by integrating DBR layers using the RCWA method. The

various designing parameters, including Si/SiO_2 DBR layers thickness, refractive index of each layer, and the choice of materials were explored. Furthermore, the electromagnetic waves (TE/TM) interaction with semiconductor and metallic nanostructures was discussed in relation to the incidence spectrum and quantum efficiency.

2. DESIGN

The RSoft synopsis tool was used for this design and simulation of an amorphous silicon solar cell (Fig.1). In photovoltaic (PV) market, amorphous silicon solar cells are playing pivotal role due to larger band gap as compared silicon derived materials. The selected materials include indium tin oxide (ITO), which acts as a transparent anti-reflection coating (ARC) layer, and amorphous silicon (a-Si) as the thin-film absorber or active layer (50 nm). The DBR consists of alternating layers of silicon (Si) and silicon dioxide (SiO_2). This proposed amorphous silicon solar cells used the quarter-wavelength condition for calculating each layer thickness (d) is given by:

$$d = \frac{\lambda_c}{4n} \quad \ldots (1)$$

where, 'λ_c' is the incident center wavelength and 'n' is the refractive index. The center wavelength is maintained at 600 nm, and the refractive indices are 1.8 (ITO), 3.4 (Si), and 1.45 (SiO_2), with the corresponding thicknesses being 84, 45, and 103 nm. The period distance between the nanogratings is 500 nm, while the top grating thickness (G_T) and the bottom grating thickness (G_B) are 20 nm. The top gratings are the integration of ITO and a-Si. The bottom grating thickness is varied and designed as triangular gratings by reducing the grating width. These bottom gratings are the combination of a-Si and Ag. The integration of nanogratings at the top and bottom of the absorber region is feasible through various fabrication methods with advanced technologies. Periodic boundary conditions (PBC, along the X- and Y-axes) and the perfectly matched layer (PML, along the Z-axis) are applied around the designed thin-film solar cell. These PBC and PML conditions are ensuring the smooth transition of electromagnetic (EM) waves. The PML is useful to prevent artificial reflections and enabling the accurate energy dissipation. In PV technology, silicon derived materials are dominating due to direct band gap, economical, high efficiency, stability and non-toxic in environment. The researchers are continuously working on economies of manufacturing scale by reducing the cost and making available and accessible in residential and industrial usages.

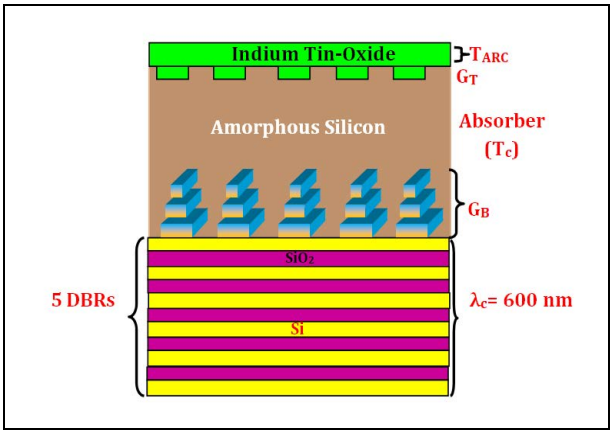


Fig. 1: Schematic diagram of an amorphous silicon thin-film solar cell

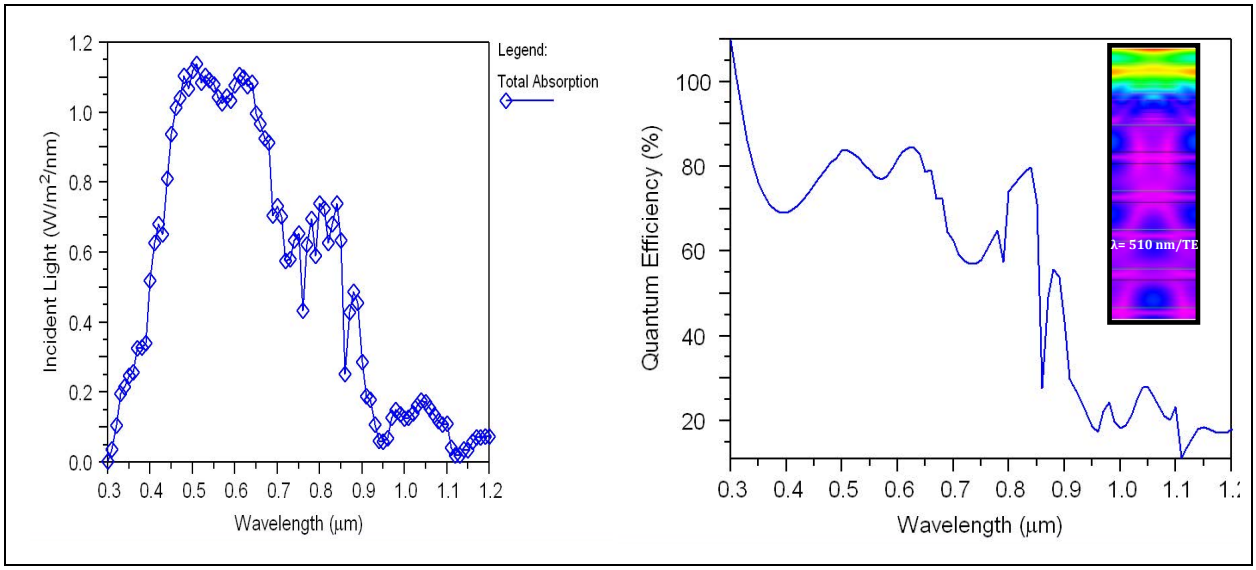


Fig. 2: (a) Absorption and (b) quantum efficiency of the amorphous silicon thin-film solar cell under TE mode

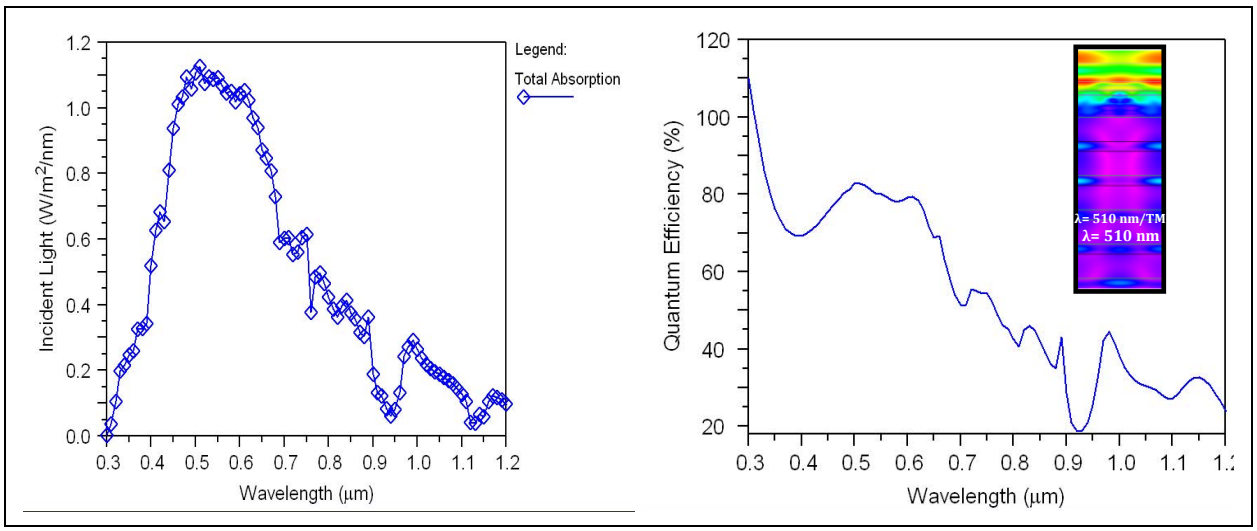


Fig. 3:(a) Absorption and (b) quantum efficiency of the thin-film solar cell under TM mode

3. RESULTS AND DISCUSSION

The incident electromagnetic waves are the combination of transverse electric field polarization and transverse magnetic field polarization. Accordingly, the simulation results are discussed. Initially, Fig. 2 depicts the absorption of photons from the solar spectrum and the conversion of photons to electrons. Fig. 2(a) depicts the light absorption spectrum in the range of 0.3 μm to 1.2 μm. The collection of the photons is enhanced within the ultraviolet region (0.3 to 0.7 μm) due to the selected materials' photonic band gap (Bernardes *et al.* 2020). It increases or guides the highest collection of photons with more energy.

As reported by various researchers, ultraviolet photons carry more energy compared to photons in the visible and infrared regions. Here, when light particles or photons are absorbed by atoms or molecules in the ground state, electrons can jump to an excited or higher energy level. It generates the photocurrent, which is evidenced in Fig. 2(b). The inset diagram of Fig. 2(a) illustrates the light interaction with the nanostructures. The light harvesting is enhanced by various photonic effects, such as surface guided modes and Fabry-Perot resonance. However, the optical properties, such as reflection and transmission, increase in the visible spectral region (0.7 to 0.9 μm). As a result, photon absorption is considerably reduced at lower energies. Furthermore, infrared photon absorption is significantly reduced due to surface excitation of electrons. These light-harvesting mechanisms depend on photonic effects, specifically the interaction of light with the semiconductor and transverse electric (TE) field polarization modes (Raghvendra *et al*. 2022; Dubey *et al.* 2025; Alireza *et al.* 2020). Fig. 2(b) explores the quantum efficiency, also known as the conversion of photonsinto electrical current (J_{sc}, mA/cm^2). The proposed amorphous silicon thin-film solar cells yielded a conversion cell efficiency of 15.75% and a short-circuit current density of 23.9 mA/cm^2.

Fig. 3 shows the absorbance spectrum and quantum efficiency of amorphous silicon thin-film solar cells under transverse magnetic (TM) polarization. The light harvesting or trapping of light particles improved with respect to sub-wavelength structures and plasmonics modes such as light localization field, excitation, surface plasmon polariton, and surface guided modes (shown in the inset diagram). Hence, these plasmonic effects increase the optical path length, as Plasmon trapping considerably enhances absorption (Shaghouli *et al.* 2023; Ali *et al*. 2022; Zahra *et al.* 2020). Here, plasmonics is acts as a leverage mechanism between the incident TM field and metallic surfaces. These are the key factors to increase the conversion cell efficiency to 14.77% with 22.46 mA/cm^2 of short-circuit current. The conversion of photons into electricity decreases across certain regions of the solar spectrum. In particular, the visible spectral region shows the lowest absorption, while the near-infrared region exhibits a slight increase in conversion. Overall, the conversion cell efficiency increased under TE modes due to the integration of DBR nanostructure. Here, photon manipulation enhances the capture and utilization of solar light, which is subsequently converted into electricity. The various optical or simulation parameters optimization will be the responsible to the better conversion cell efficiency as reported in literature survey (Sayed et al. 2025, Saravanan and Dubey, 2022).

4. CONCLUSION

This design and simulation work focused on the investigation of an amorphous silicon thin-film solar cell using the RCWA method. The enhancement of electromagnetic properties with nanostructured materials constitutes an extended research field in photonics and plasmonics. At the top of the cell, ITO thin film is placed

as an ARC layer, and a quarter-wavelength-based DBR serves as a better back reflector. Under TE and TM polarization modes, the light harvesting increased considerably due to the photonic and plasmonic effects. In contrast, plasmonic effects yielded up to 14.77% efficiency and a short-circuit current of 22.46 mA/cm^2. In the future, these design parameters will plays a key role in miniaturized and flexible photovoltaic devices.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

Ali, A., Fedwa, E. M., Anirban, M. and Brahim, A., Research progress of plasmonic nanostructure-enhanced photovoltaic solar cells, *Nanomater.*, 12(5),788(2022). https://doi.org/10.3390/nano12050788

Alireza, T., Fathi, D. and Mehdi, E.,High-performance perovskites solar cell using photonic nanostructure, *Sci. Rep.*, 10(1), 1-13(2020). https://doi.org/10.1038/s41598-020-67741-9

Shaghouli, E., Nosrat, G. and Negin, M., Plasmonic enhanced ultra-thin solar cell: A combined approach fractal and nano-antenna structure to maximize absorption, *Res. Phy.*, 50, 106600(2023). https://doi.org/10.1016/j.rinp.2023.106600

Bernardes, S., Ricardo, A. M. L., Joao, P. N. T. and Carlos, A. F. F., Characterization and design of photovoltaic solar cells that absorb ultraviolet, visible and infrared light, *Nanomater.*, 11(1), 78 (2020). https://doi.org/10.3390/nano11010078

Dewan, R., Jovanov, V., Hamraz, S. and Knipp, D., Analyzing periodic and random textured silicon thin film solar cells by rigorous coupled wave analysis, *Sci. rep.*, 49(1), 1-7(2014). https://doi.org/10.1038/srep06029

Dubey, R.S., Rajyalakshmi, C., Naga, R.J.M., Saravanan, S. and Padma, P.K., Front nanogratings decorated ultrathin film amorphous Si solar cell performances, *J. Environ. Nanotechnol.*, 13(4), 108-113 (2025). https://doi.org/10.13074/jent.2024.12.244985

Erman, C., Caglar, C., Serkan, E., and Baris, K., Tunable optical and photovoltaic performance in PTB7-based colored semi-transparent organic solar cells integrated MgF_2/WO_3 1D-photonic crystals via advanced light management, Sci. Rep., 14, 23430 (2024). https://doi.org/10.1038/s41598-024-75119-4

Raghvendra, S. D. and Sigamani, S., Ultrathin film amorphous silicon solar cell performance using Rigorous coupled wave analysis, *Int. J. Renew. Energy Develop.*, 11(3), 782-788 (2022). https://doi.org/10.14710/ijred.2022.46009

Saravanan, S. and Dubey, R. S. Study of ultrathin-film amorphous silicon solar cell performance using photonic and plasmonic nanostructures, *Int. J. Energy Res.*, 46(3), 2558-2566 (2022). https://doi.org/10.1002/er.7328

Sarma, G. V. S. S., Sreenivasa, R. P., Dubey, R. S., Saravanan, S. and Ananda, K. B., Improvement of quantum efficiency and photon absorption from electromagnetic waves: Amorphous silicon thin film solar cell, *J. Environ. Nanotechnol.*, 14(2), 178-181 (2025). https://doi.org/10.13074/jent.2025.06.2521477

Sayed, H., Ahmed, A. M., Ali, H., Abdelkawy, M. A., and Aly, A. H., Optimization of amorphous silicon solar cells through photonic crystals for enhanced optical properties, Sci. Rep., 15, 16529 (2025). https://doi.org/10.1038/s41598-025-00443-2

Sigamani, S. and Dubey, R. S., Performance of ultrathin amorphous silicon solar cells: An influence of plasmonic effect, *Progres Electromag. Res.*, 112, 29-39, (2022). https://doi.org/10.2528/PIERM22020901

Sigamani, S., Dubey, R. S. and Kalainathan S., Optimization of distributed Bragg's reflectors in thin film solar cells, *Mater. Today Proce.*, 89, 8-13 (2023). https://doi.org/10.1016/j.matpr.2023.05.540

Zahra, K., Fatemeh, F. M. and Arash, M., Performance improvement of thin-film silicon solar cells using transverse and longitudinal titanium nitride plasmonic nanogratings, *Optical Mater.*, 99, 109532 (2020). https://doi.org/10.1016/j.optmat.2019.109532