Research Article

Journal of Environmental Nanotechnology

Influence of Distributed Bragg Reflectors for Enhanced Light Trapping in Amorphous Silicon Thin-film Solar Cells Using RCWA Method

T. Sivanandan[1], P. Srinivasa Rao[2], R. S. Dubey[3] and S. Saravanan[4*]

[1]Department of Physics, Indian Arts College, Tiruvannamalai, TN, India
[2]Department of Science and Humanity, Mallineni Lakshmaiah Women's Engineering College, AP, India
[3]School of Computer Science & Artificial Intelligence, SR University, Warangal, TS, India
[4]Department of Physics (S&H), Swarnandhra College of Engineering & Technology, Narsapur, West Godavari, AP, India
Received: 26.06.2025 Accepted: 08.08.2025 Published: 30.09.2025
*shasa86@gmail.com

ABSTRACT

This study presents a comprehensive analysis of reflectance properties by varying the number of distributed Bragg reflectors (DBRs) in amorphous silicon thin-film solar cells using the Rigorous Coupled Wave Analysis (RCWA) method. This amorphous silicon is emerging as a promising thin-film technology for harvesting solar energy due to its natural abundance and flexibility. The optimized reflectance was observed when varying the number of DBR layers from 1 to 10, enabling the improved and promising light-harvesting schemes in amorphous silicon thin-film solar cells. The optimized 5DBR configuration integrated as back reflector in amorphous silicon thin-film solar cells which is substantially enhances the light-trapping mechanism. The property of photonic crystals depends on various parameters, such as the refractive index, thickness, center wavelength (λc), and material selection. Here, focusing the optimized reflectivity of the 1D photonic crystal structure (Si/SiO_2) determined by the center (incident) wavelength, such as 400 nm, with the highest reflectance (~100%) achieved using 5 DBR layers/stacks. In addition, the optimized 5DBR configuration was integrated as a backside reflector in amorphous silicon thin-film solar cells. The structure includes an anti-reflection coating (ARC) of Indium Tin Oxide (ITO), a top grating (ITO), and an absorber layer. The proposed thin-film solar cell achieved a maximum conversion efficiency of 18.0% (J_{sc} = 27.49 mA/cm^2) and 17.65% (J_{sc} = 26.83 mA/cm^2) under transverse electric and transverse magnetic field polarizations, respectively. The thickness of the amorphous silicon absorber region is only 40 nm.

Keywords: Light harvesting; Amorphous silicon; Reflectance; Thin-film solar cell.

1. INTRODUCTION

The major photovoltaic (PV) modules are silicon-derived devices. Globally, the energy crisis is escalating, and renewable energy sources are widely regarded as the most viable alternative, as reported by many scientific communities. Specifically, amorphous silicon (a-Si) has garnered great interest in the PV market due to improved optical performance because of better light absorption as compared to others (Sayed *et al.*2025). Experimentally, the amorphous silicon solar cells could be fabricated by various techniques such as plasma enhanced chemical vapor deposition (PECVD), atmospheric pressure chemical vapor deposition (APCVD), and magnetron sputtering techniques. Nowadays, thin-film solar cell thicknesses vary from several micrometers to the nanometer scale. The research communities are increasingly interested on nanomaterials of various sizes and shapes due to their unique properties, which is significantly enhance collection of the photon and greatly improve light harvesting within the active layer region. Furthermore, the researchers are continuously working on nano-scale structures to achieve better absorption within a few nanometers-thick active region by prolonging photon lifetime—for example, nanoparticles (dielectric/metal), nanogratings, distributed Bragg reflectors (or 1D photonic crystals), nanopillars, and porous nanorods (Lin *et al.* 2016). The properly selected, designed, and fabricated photonic (dielectric) nanostructured layers could prohibit light propagation or allow it along the desired directions and localize light in specified areas. Raghvendra *et al.* (2022) presented an ultra-thin amorphous silicon solar cell optical performances using the RCWA method. The optical properties such as scattering, low reflection, diffraction, and field distributions are significantly enhanced due to photonic effects, resulting in short-circuit current densities of 23.82 and 22.75 mA/cm^2 under transverse electric (TE) and magnetic (TM) field polarizations, respectively. Similarly, Dubey *et al.* (2024) designed and simulated a nanograting-decorated ultrathin amorphous silicon thin-film solar cell, which revealed the major contributions from photonic effects such as Fabry–Pérot resonance and

surface-guided modes. They obtained the highest short-circuit current of 16.02 mA/cm^2 within a 30 nm-thick amorphous silicon active region. Chintala *et al.* (2025) investigated the significance of distributed Bragg reflectors (DBRs) integrated as backside reflectors in amorphous silicon thin-film solar cells. The integration of photonic and plasmonic nanostructures are highlighted a remarkable contribution to enhancing the light-harvesting mechanism. These cell structures are contributed to the highest short-circuit current (25.16 mA/cm^2) under the transverse electric (TE) modes due to the dominance of photonic effects. Recently, various design and simulation tools have become available to enhance light-harvesting schemes. In solar cell design and simulation, methods such as the Plane Wave Expansion (PWE) method, Rigorous Coupled-Wave Analysis (RCWA), Transfer Matrix Method (TMM), Finite Element Method (FEM), Finite Difference Frequency Domain (FDFD) method, and Finite Difference Time Domain (FDTD) method play a crucial role.

In this paper, the focus is on the optimized DBR under 400 nm center wavelengths, which is act as back reflector with an amorphous silicon thin-film solar cell. This proposed solar cell structure has two-way light propagation, which enhances the collection of the light particles (photons) and improved the optical performances. The light particle collections are within the absorber region (photon energy), which converts into electricity (quantum efficiency) as discussed in results section. Finally, concluding the work in conclusion section. The findings of Kissinger (2023) on tunable optical properties through controlled Na incorporation into the CIGS solar cells are in line with the present work on RCWA analysis of DBR-modulated reflectance in a-Si solar cells.

2. DESIGN APPROACH

This section explores the design and simulation parameters for the optimized DBR, or 1D photonic crystals used as a backside reflector in an amorphous silicon solar cell. Initially, silicon (Si) and silicon dioxide (SiO_2) thin films are considered as DBR layers with refractive indices of 3.6(n_1), 1.45 (n_2), respectively. Based on the quarter-wavelength conditions ($d = \frac{\lambda c}{4}$), the layer thicknesses are calculated as 28 nm for Si, 68 nm for SiO_2, and 90 nm for the ITO anti-reflection coating layer. Additionally, ITO rectangular gratings are placed at the top of the absorber layer, and triangular silver nanogratings are placed at the bottom, to prolong the incidence photon path length through a scattering mechanism at maximum angles. During the simulation process, the periodic boundary conditions (PBC) and perfectly matched layers (PML) are applied along the X, Y, and Z Cartesian coordinate axes (Alexander and Loringm, 2024). These PBC and PML boundary layers could protect from the unwanted radiation from the surrounding environment. The design and simulation process were carried out by using the RCWA method, known for its simplicity and computational efficiency. Thorough out this simulation process was carried out by RSoft synopsis tool.

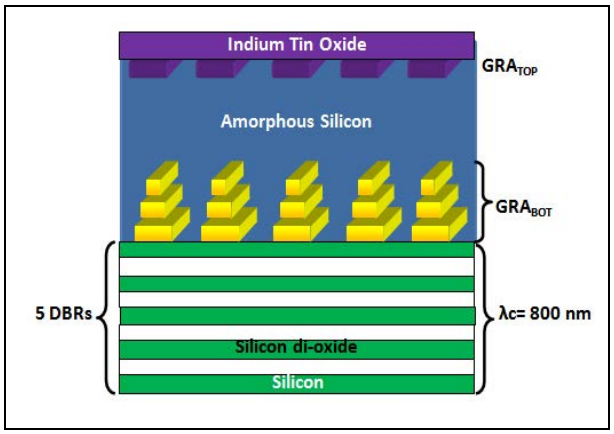


Fig. 1: Schematic diagram of an amorphous silicon thin-film solar cell

3. RESULTS AND DISCUSSION

The bio-inspired Bragg's reflector is also known as a one-dimensional photonic crystal (1DPC) or distributed Bragg reflector (DBR). The DBRs or 1DPCs consists of alternatives to simple dielectric layer pairs with differing refractive indices (n1 and n2). Here, the interaction between incident electromagnetic waves from sunlight and the artificial nanostructures is influenced by the refractive indices of the constituent materials, leading to enhanced light propagation. Fig. 2 (a–e) depicts the reflectance (R) of 1DBR (2 layers), 2DBR (4 layers), 3DBR (6 layers), 4DBR (8 layers), and 5DBR (10 layers). These DBR layers are the combination of Si and SiO_2 materials with corresponding refractive indices are 3.6 (n_1) and 1.5(n_2). The addition of bio-inspired DBR layers creates a refractive index contrast that reduces surface reflectance and facilitates the propagation of more incident light into the absorber region (Shen *et al.* 2021). Fig. 2(a) shows the reflectance (around 68%) of 1DBR, which is combination of alternating layers of Si/SiO_2 nanostructures. With an effective 400 nm center wavelength (or incident light), the layer thicknesses are 28 nm for Si and 67 nm for SiO_2. These DBRs are designed to reflect incident light within specific wavelength ranges and this phenomenon known as the photonic band gap (PBG). This effect arises from constructive interference of light waves reflecting between alternating Si and SiO_2 layers. Fig. 2(b) shows the rising the photonic band gap (PBG) in between 0.3 µm and ~0.75µm. Again, incorporated DBR layers (or 3DBR), the reflectivity enhanced and optimized among 0. 3 to 0.65 µm is as shown in Fig. 2(c). Next, 4DBRs enhanced the reflectivity with clear PBGs from 0.3 to 0.6

µm as shown in Fig. 2(d). Finally, the Fig. 2(e) shows the reflectance spectra of 5 DBR layers configurations, and demonstrating enhanced reflectance (up to ~99.98%) due to increasing number of layers. The reflectivity corresponding to Si/SiO_2 DBR layer schematic diagram is shown in Fig. 2(f). Overall, the reflectivity (or) diffraction efficiency (or) the collection of the light particles is enhancing with respect to increment of no. of DBR layers. These optimized 5DBR layers could serve as better back reflector in thin film solar cells.

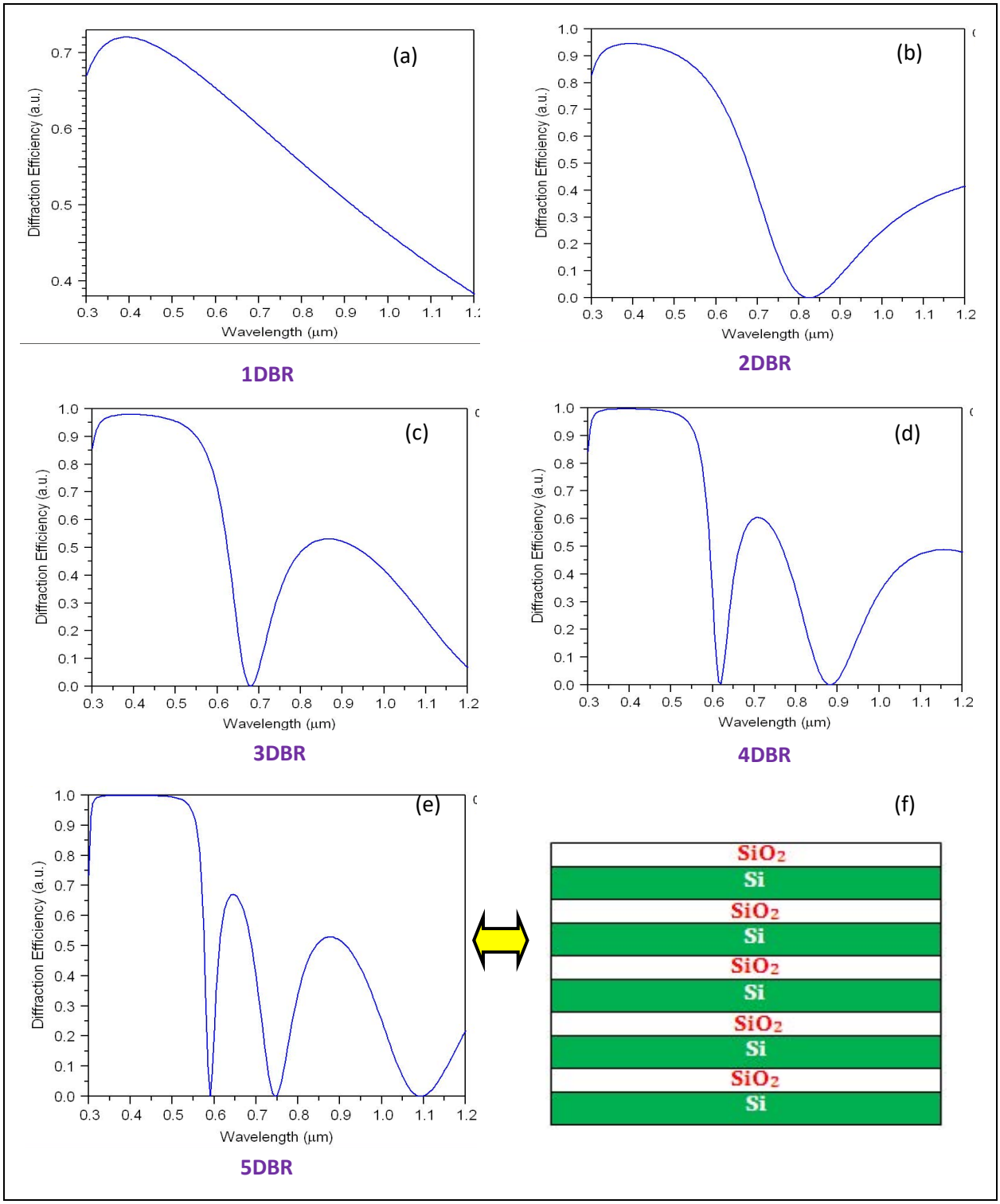


Fig. 2(a-e): Reflectance (R) spectra of structures (a) 1DBR, (b) 2DBR, (c) 3DBR, (d) 4DBR, (e) 5DBR, and (f) schematic diagram of DBR

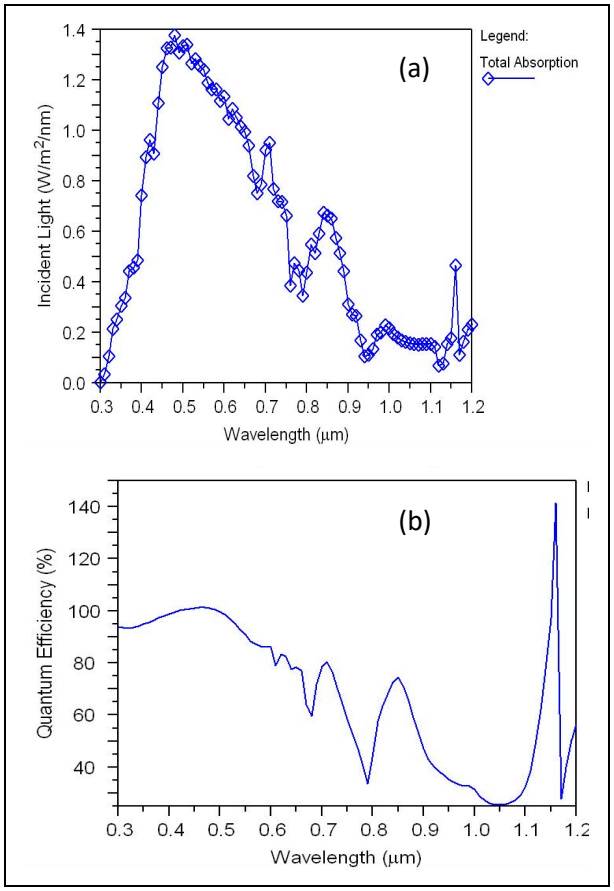


Fig. 3:(a) Absorption spectrum, and (b) Quantum efficiency of an amorphous silicon thin-film solar cell under the influence of TE polarization modes

The proposed solar cell consists of ITO anti-reflection coating, top ITO gratings, amorphous silicon absorber/active layer, bottom Ag gratings and optimized 5DBR integrated as back reflector. Fig. 3(a) shows the absorption or collection of the photons from the incident spectrum under AM 1.5G illumination. The photonic mode plays a significant role to traps the incident light. These modes arise from the interaction of light (electromagnetic waves) with the semiconductor or dielectric material layers. This phenomenon is also known as photonic effect. The light interaction is bidirectional, occurring both when light enters the cell and when it is reflected towards the active (absorber) layer. In this cell structure, the amorphous silicon layer serves as the absorber/active layer. On the top of the absorber layer, ITO nanostructures are integrated, which act as anti-reflection coating (ARC) materials, along with that nanograting are positioned below the ARC layer. At the bottom of the absorber, triangular Ag nanogratings and optimized 5DBR (Si/SiO_2) are incorporated. The combination of backside reflectors and nanogratings effectively enhances light trapping by increasing the optical path length of incoming photons within the amorphous silicon absorber region. The collection of photons is significantly enhanced in the ultraviolet and near-visible spectral regions due to photonic effects, such as Fabry-Pérot resonance and surface-guided resonance modes.

The collection of photons is converted into electricity, as shown in Fig. 3(b). Hence, the quantum efficiency spectrum differs from the corresponding absorption spectrum. This is because not all incident photons, or light particles, are converted into electricity (Mahmoud *et al.* 2016). This limitation could be addressed by selecting novel photonic nanostructure shapes and sizes. The amorphous silicon solar cell achieved a conversion efficiency of 18% and a short-circuit current density of 27.49 mA/cm².

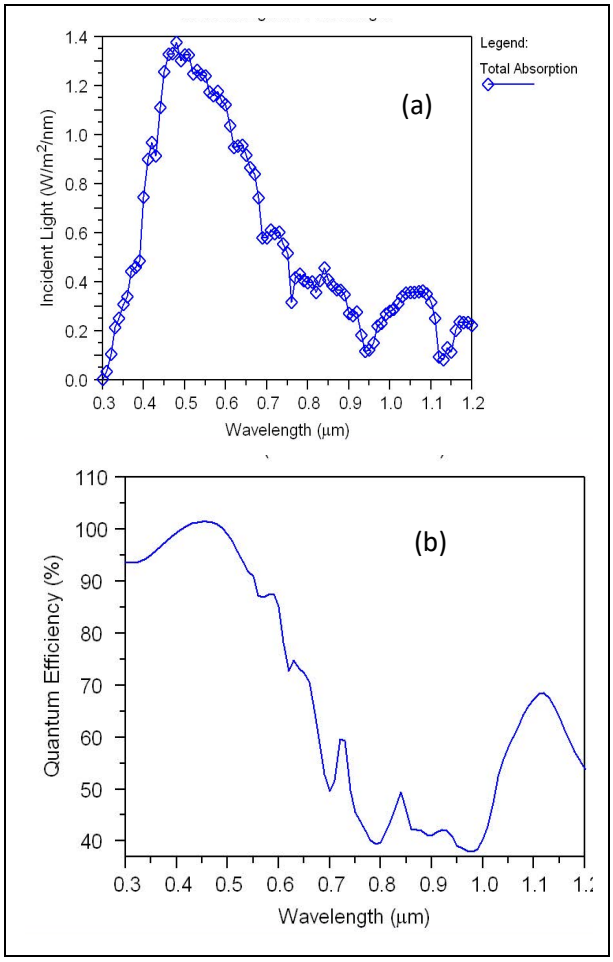


Fig. 4: Absorption spectrum, and (b) Quantum efficiency of an amorphous silicon thin-film solar cell under the influence of TM polarization modes

Fig. 4(a)-(b) depicts the absorption spectrum and quantum efficiency under the influence of transverse magnetic (TM) field polarization, also known as plasmonic effects. The absorption spectrum, shown in Fig. 4(a), indicates the enhanced photon collection in the near-infrared region due to plasmonic effects such as localized surface plasmons, Floquet modes, surface excitations at the semiconductor–metal interface, and

surface-guided modes within the amorphous silicon absorber region (Sha *et al.* 2010). The skin effect depends on the magnetic field (TM) and frequency (ω) of the conducting layer. Due to the plasmonic effect, the field propagation was enhanced considerably in the IR spectral (870nm) region. At wavelength ranges of 1050nm, the collection of the photons is substantially enhanced by surface plasmon resonance. This enhancement is primarily due to the crucial role played by silver nanogratings with a triangular structure (Saravanan *et al.* 2022).

It works as a better back reflector with optimized 5DBR layers, resulting in an enhanced photon path length by exciting optical (photonic or plasmonic) modes. According to the electromagnetic theory, the constructive light interactions could occur in between the metal nanostructures or nanogratings. This phenomenon is known as plasmonic effects. Fig. 4(b) evidences the collection of the light particles (photons) converted into electron charge carriers (quantum efficiency). The absorbed photons are not fully converted into electricity due to the need for a novel light-harvesting mechanism involving suitable materials, shapes, or sizes that could enhance photon collection. This optimized cell structure enhances the light path length through various optical properties such as reflection, scattering, and transmission. Finally, the integrated and optimized amorphous silicon solar cells achieved a conversion efficiency of approximately 17.65% and a short-circuit current density of 26.83 mA/cm^2.

Researchers have been focusing on flexible thin-film amorphous silicon solar cells by integrating nanopillars and dual-layered thin film, resulting in a remarkably improved light-harvesting mechanism. These flexible devices yielded approximately a 43% conversion efficiency enhancement (Lin *et al.* 2016). Hence, the design and simulation of thin-film solar cells pave a promising pathway towards the fabrication of flexible photovoltaic devices at the nanoscale level.

4. CONCLUSION

In this work, an amorphous silicon thin-film solar cell was successfully designed and simulated using the RCWA method. The proposed cell structures including the top of the ITO layer functions as the anti-reflection coating, followed by the amorphous silicon absorber, and an optimized five-layered DBR structure is integrated as the backside reflector for the proposed solar cell. These cell structures demonstrate the highest optical efficiency or reflectivity across the varying number of DBR layers. DBR or 1D photonic crystals were employed based on the step-index criterion, and reflectivity was effectively reduced in the solar cell structure. Additionally, the photonic band gap was confined with an optimization, enhancing its performance as a backside reflector in amorphous silicon thin-film solar cells. Overall, the conversion cell efficiency reached 18% and 17.65% under TE and TM polarization modes, respectively. It was evident that photonic modes play a crucial role as both reflected and transmitted photons were considerably reduced. These key research findings highlight the potential for further enhancement of the optical performance of thin-film solar cells in future studies.

FUNDING

The financial support provided by Defence Research and Development Organization (DRDO), New Delhi, INDIA is highly acknowledged.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).



REFERENCES

Alexander, C. and Loring, T. A., Classifying photonic topology using the spectral localizer and numerical K-theory, *APL Photonics., 9*, 111102 (2024). https://doi.org/10.1063/5.0239018

Chintala, J. N. P., Arumugam, S., Dubey, R. S., Saravanan, S. and Kotari, S., Empowerment of photonics in thin film amorphous silicon solar cells, *Eng. Sci*., 33, 1-9 (2025). https://dx.doi.org/10.30919/es1370

Dubey, R. S., Rajyalakshmi, J. M. N., Ramya, J. M. N., Saravanan, S., Padma, K. P. and Sarma, G. V. S. S., Front nanogratings decorated ultrathin film amorphous silicon solar cell performance, *J. Environ. Nanotechnol.*, 13(4), 108-113 (2024). https://doi.org/10.13074/jent.2024.12.244985

Kissinger, N. J. S., The Effect of Sodium on a Molybdenum Layer by Varying the Growth Pressure on CIGS Solar Absorp-tion Layer, *J. Environ. Nanotechnol.,* 12(4), 35-42(2023). https://doi.org/10.13074/jent.2023.12.234481

Lin, Y., Xu, Z., Yu, D., Lu, L., Yin, M., Mahdi, T. M., Chen, X., Hao, Y., Fan, Z., Cui, Y. and Li, D., Dual-layer nanostructured flexible thin-film amorphous silicon solar cells with enhanced light harvesting and photoelectric conversion efficiency, *ACS Appl. Mater. Interf.*, 8(17), 10929-10936 (2016). https://doi.org/10.1021/acsami.6b02194

Mahmoud, A. M. A., Mohamad, A. B., Ludin, N. A., Kadhum, A. A. H. and Sopian, K., Dye-sensitized solar cells: Development, structure, operation principles, electron kinetics, characterization, synthesis materials and natural photosensitisers, *Renew. Sustain. Energy Rev*., 65, 183-213(2016). https://doi.org/10.1016/j.rser.2016.06.045

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

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

Sayed, H., Ahmed, A. M., Hajjiah, A., 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

Sha, W. E. I., Wallace, C. H. and Chew, W. C., A comprehensive study for the plasmonic thin-film solar cell with periodic structure, *Opt. Express*, 18(6), 5993 (2010). https://doi.org/10.1364/OE.18.005993

Shen, X., Wang, S., Zhou, H., Kamale, T., Chen, Y., Improving thin-film solarcells' performance via designing moth-eye-like nanostructure arrays, *Res. Phy*., 20, 103713 (2021). https://doi.org/10.1016/j.rinp.2020.103713