



Photonic Light-Trapping Effects in Amorphous Silicon Thin-film Solar Cells with Top and Bottom Nanogratings

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ABSTRACT

Among four different generations of solar cells, thin-film amorphous silicon (a-Si) solar cells are extensively used and garnering great interest in photovoltaic (PV) applications due to their cost-effectiveness, environmental friendly and versatility. In this study, we investigated the light-harvesting mechanism in a-Si solar cells by integrating nanostructures such as anti-reflection coatings (ARC), top and bottom nanogratings, and a distributed Bragg reflector (DBR). The layer thicknesses of indium tin-oxide (ITO, ARC), silicon (Si), and silicon dioxide were optimized using the quarter-wavelength formula. Electromagnetic simulations were also performed using the rigorous coupled wave analysis (RCWA) method under transverse electric (TE) and transverse magnetic (TM) polarization modes. This simulation works including four different cell structures were analyzed: a reference cell (Cell A), a top-grating-enhanced cell (Cell B), a bottom-grating-enhanced cell (Cell C), and a dual-grating cell (Cell D). Among these four cell structures, the nanogratings and DBR integration significantly improved light absorption (harvesting) by increasing optical path length, multiple scattering, and reducing reflection effects of the light particles (photons). The highest thin film a-Si solar cell performance yielded by Cell D which was 16.5% (TE) and 15.18% (TM), corresponding to enhancements of 357.7% and 343.5% current densities. These findings highlight the crucial role of nanostructures and DBR layers in enhancing photon collection in thin-film a-Si solar cells, providing a promising approach for high-efficiency photovoltaic devices.

Keywords: Solar cells; Amorphous silicon; Nanogratings; Distributed Bragg reflector; Transverse electric polarization; Transverse magnetic polarization.

1. INTRODUCTION

Increasing energy demand and environmental pollution from fossil fuels have intensified the need for renewable energy sources. Particularly, solar energy is widely available and environmentally sustainable. Silicon-based solar cells, including crystalline, amorphous, and polycrystalline forms, play a vital role in the photovoltaic (PV) market (Sivanandan *et al.* 2025). Among these, amorphous silicon (a-Si) has become a well-established solar thin-film material in PV technology. (Saravanan and Dubey, 2022) theoretically analyzed an optimized distributed Bragg reflector (DBR)-integrated a-Si thin-film solar cell, resulting in increased light-harvesting efficiency. The optimized DBR (one-dimensional (1D) photonic crystal) was further analyzed using the rigorous coupled wave analysis (RCWA) method. Similarly, (Sigamani *et al.* 2023) investigated DBR layers in thin-film a-Si solar cells and examined the photonic band gap using the plane

wave expansion method. Their findings showed that the incorporation of DBR layers as back reflectors remarkably improves the light-harvesting efficiency of a-Si solar cells. (Chintala *et al.* 2025) investigated the light-harvesting mechanism in thin-film a-Si solar cells using the RCWA method. Their study reported increased light absorption and reduced recombination losses, resulting in a maximum current density (J_{sc}) of 25.16 mA/cm². (Hossain *et al.* 2017) highlighted the effect of back-side reflector absorption in a-Si thin film solar cells using the finite difference time-domain (FDTD) method. Two types of backside reflectors, a smooth surface and a pyramidal textured surface, were evaluated; however, the latter exhibited the highest current density from 13.27 to 16.36 mA/cm². In the present work, we investigate the interaction of electromagnetic waves with a-Si solar cells using the RCWA method. Further, nanostructured and periodic patterns were integrated, and various parameters were optimized. The optical performance of four distinct cell structures was analyzed under both transverse

electric (TE) and transverse magnetic (TM) field polarization modes.

2. METHODOLOGY

The rigorous coupled wave analysis (RCWA) method (RSoft synopsis tool) used for this theoretical (or) simulation work. Fig. 1 shows the schematic diagram of the proposed amorphous silicon (a-Si) thin film solar cell including anti-reflection coating (ARC), nanogratings (top and bottom) and distributed Bragg's reflector as back reflector. The thickness (d) of the indium tin-oxide (ITO), silicon (Si), and silicon dioxide (SiO_2) layers were calculated using the quarter wavelength formula ($d = \lambda_c/4n$) (Afsharipour *et al.* 2017). The center wavelength was fixed at 800 nm, and the refractive indices (n) were 1.8 (ITO), 3.42 (Si), and 1.45 (SiO_2). Based on the above formula, we calculated layers thicknesses are as 111 nm for ITO, 59 nm for Si, and 138 nm for SiO_2 . The active layer of a-Si has a 50 nm thickness, while the bottom triangular gratings (GRA_{BOT}) were composed of silver (Ag) with a thickness of 20 nm and grating period considered as 500 nm. The bottom gratings are considered as Ag/a-Si, as the silver nanogratings were embedded within the a-Si absorber layer. The top dielectric gratings are a combination of ITO/a-Si, with the ITO (GRA_{TOP}) layer of 20 nm thickness. These gratings supporting for the enhancement of life time of the light particles (photon) by prolonging path using various optical properties such as reflection, scattering and diffraction mechanisms.

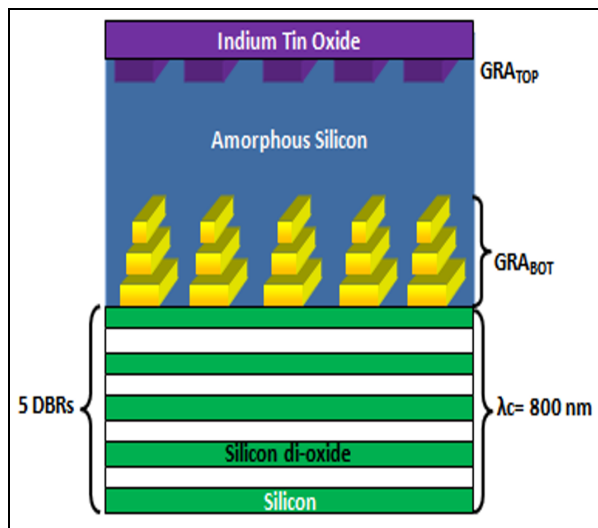


Fig. 1: The schematic diagram of an amorphous silicon thin-film solar cell

During the simulation, periodic boundary conditions (PBC) and perfectly matched layers (PML) were applied with Cartesian coordinate axes (X, Y, and Z). Further, DBR acts as an efficient back reflector to minimize the transmission of light particles from forth to back. The DBR layers were considered as an alternative

layer of Si and SiO_2 thin film materials (Shaaban *et al.* 2022; Hasbun and Desilva, 2020).

3. RESULTS AND DISCUSSION

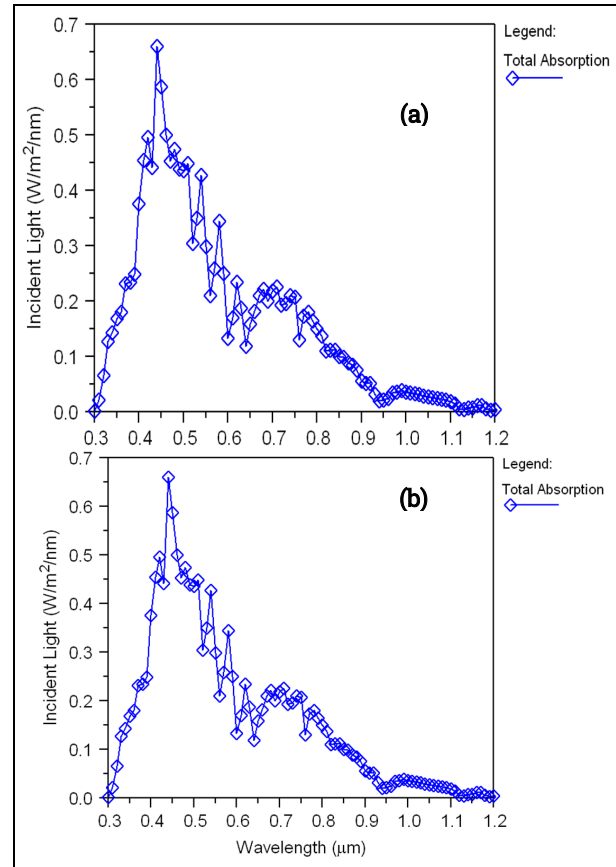


Fig. 2: The absorption spectra of 'Cell A' under TM (a) and TE (b) polarization modes

In 19th century, James Clerk Maxwell theoretically proposed and showed the nature of light as electromagnetic (EM) waves. Later, Heinrich Hertz experimentally demonstrated about the EM waves. These EM waves travelling in space at the speed of light (2.99×10^8 m/s). Electromagnetic waves can be described as a combination of transverse electric (TE) and transverse magnetic (TM) polarization conditions (or) modes. The performance of various thin-film a-Si solar cells is discussed below. First, the ARC + Tc + 5DBR structure, named 'Cell A', and the corresponding collection of light particles (photons) are illustrated in Fig. 2. This thin-film solar cell is considered a reference cell for comparison with other cell structures. Under TE and TM polarization conditions, the light absorption is noticeably higher in the TE mode compared to the TM modes. In this case, the incident light is efficiently trapped within the amorphous silicon active layer.

In TE mode, photonic effects such as Fabry-Pérot resonance are enhanced, resulting in a cell efficiency of 4.61% and a current density of 7.02

mA/cm^2 . However, light absorption is reduced in the TM mode, which results in a cell efficiency of 4.42% and a current density of $6.72 \text{ mA}/\text{cm}^2$. Overall, light harvesting is enhanced via a two-way process. The reflection of incident light is notably reduced due to the ITO – ARC with increased light transmission. This requires the incorporation of nanogratings within the active region.

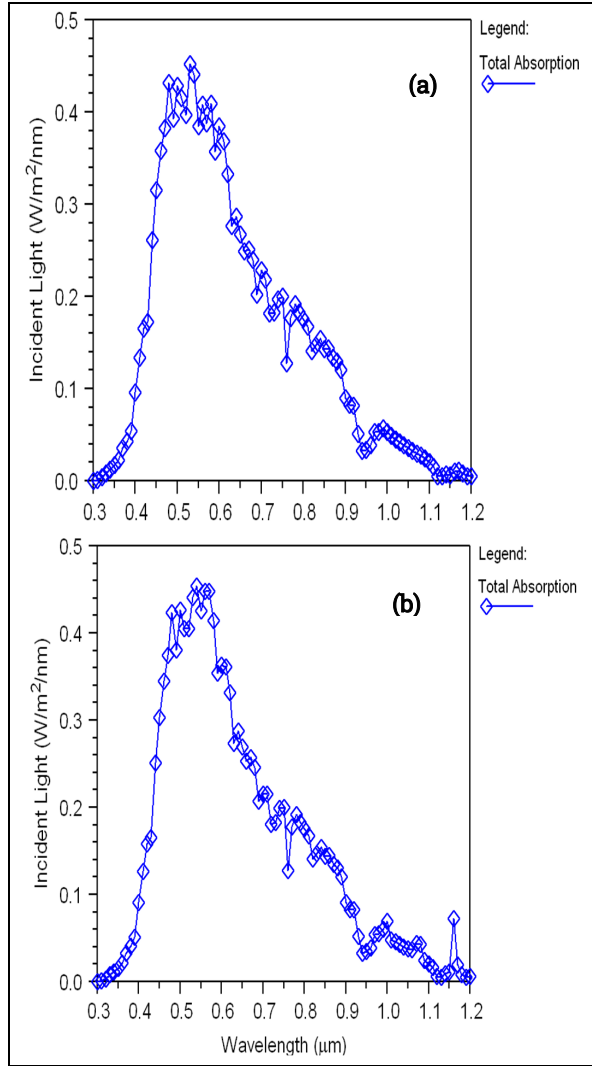


Fig. 3: Absorption spectra of 'Cell B' under TM (a) and TE (b) polarization modes

In this cell structure, we used the ARC + GRA (TOP) + Tc + 5DBR configuration, named 'Cell B'. Fig. 3(a)-(b) shows the photon absorption of Cell B under TE and TM polarization conditions. In comparison with Cell A (reference cell), Cell B exhibits strong light absorption by reduced transmission from the back reflector of the cell. Also, significantly decreased the reflectance on the ARC layer with the assistance of top ITO nanogratings the incoming light may not reflect back. The incoming light particle is staying longer time within the active layer by enhancing the life time of the photon and absorbed. This solar cell achieved the maximum of cell efficiencies

of 4.88% (TE) and 4.78% (TM) with current densities of $7.42 \text{ mA}/\text{cm}^2$ (TE) and $7.27 \text{ mA}/\text{cm}^2$ (TM).

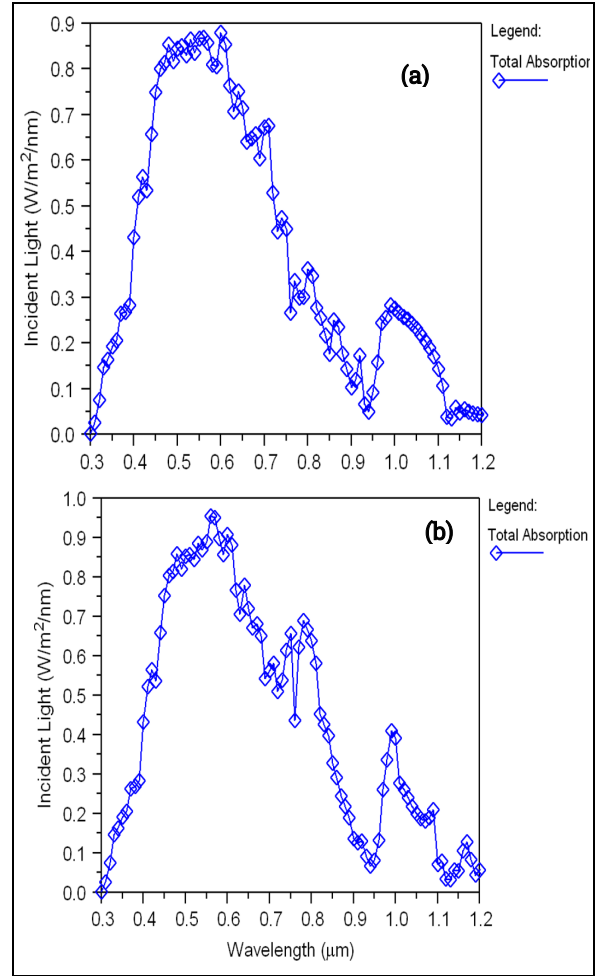


Fig. 4: The absorption spectra of 'Cell C' under TM (a) and TE (b) polarization modes

Fig. 4 shows the ARC + Tc + GRA_{BOT} + 5DBR solar cell structure, named 'Cell C'. Under TE mode, Cell C shows an enhanced cell efficiency of 13.62% with a current density of $20.71 \text{ mA}/\text{cm}^2$. Under TM mode, a similar cell structure exhibits a cell efficiency of 12.08% and a current density of $18.37 \text{ mA}/\text{cm}^2$. In this case, the bottom gratings increase the path length of the photons. As a result, light absorption is improved in both the visible and infrared regions, as shown in Fig. 4(a) and (b). These improved light photons due to multiple and strong scattering and reflection in between the amorphous silicon active region. For those distinct photonic effects in TE polarization modes and plasmonics affects in TM polarization conditions. However, the strong light absorption occurred due to photonics effects such as Fabry-Perot, surface guided modes etc.

Fig. 5(a) and (b) show the light absorption of Cell D under TE and TM polarization conditions. We considered a solar cell comprising dual gratings (top and

bottom), an ARC layer, an active layer (Tc), and 5DBR layers referred to as Cell D (ARC + Tc + Dual GRA + 5DBR). The solar Cell D structure exhibits the highest light-harvesting mechanisms under both polarization conditions, and the respective cell efficiency and current density are listed in Table 1.

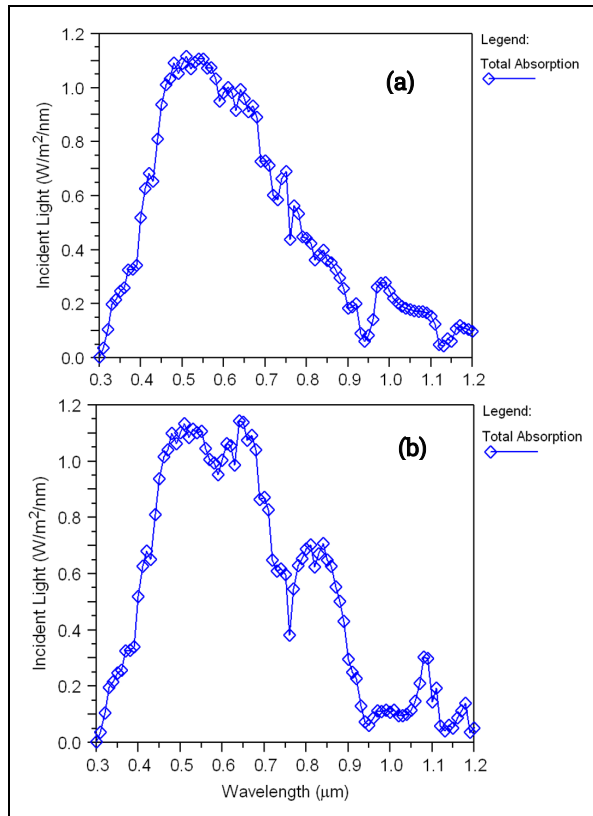


Fig.5: The absorption spectra of 'Cell D' under TM (a) and TE (b) polarization modes

The cell efficiency, current density and the relative enhancement of thin film solar cell structures are listed in Table 1. Initially, the reference solar cell structure shows a cell efficiency of 4.61% and a current density of 7.02 mA/cm². Compared to the reference cell (Cell A), the nanogratings improved the light absorption due to multiple scattering and reflection effects. In particular, the bottom triangular grating plays a crucial role by enhancing light absorption. With anti-reflection coatings, dual gratings, and an optimized DBR, solar cell D exhibits the highest cell efficiencies of 16.5% (TE) and 15.18% (TM). Overall, the enhancements of 357.69% (TE) and 343.45% (TM) are observed compared to the reference cell. These improvements observed due to photonic (interaction between dielectrics) and plasmonic (interaction between metallic structure) effects. As compare to plasmonic, the photonic effects are dominating the light harvesting mechanism by reducing the diffusion and increasing the collection of the charge carriers. The photonic effects are Fabry-perot resonance, surface guided mode resonance, surface excitation. These photonic effects are improving the optical properties

which helped to improve the thin film solar cell performance.

Table 1. Comparison of current density and cell efficiency for different solar cell structures

	Structure	η (%)	J_{sc} (mA/cm ²)	Relative Enhancement
Cell A	ARC + Tc + 5DBR	TE	4.61	Reference cell
		TM	4.42	
Cell B	ARC + Tc + GRA _{TOP} + 5DBR	TE	4.88	105.69
		TM	4.78	
Cell C	ARC + Tc + GRA _{BOT} + 5DBR	TE	13.62	295.01
		TM	12.08	
Cell D	ARC + Tc + Dual GRA + 5DBR	TE	16.5	357.69
		TM	15.18	

4. CONCLUSIONS

In this study, four different light-harvesting mechanisms were examined in thin-film a-Si solar cells by using rigorous coupled wave analysis method. These solar cell structures are including silver metallic nanogratings (bottom) and ITO-dielectric nanogratings (top) of the active layers were integrated as reflectors. In addition, a 5DBR structure (a combination of Si and SiO₂) acts as a back reflector. Therefore, these nanostructures enhanced photon collection under TE and TM polarization conditions. Among the four different cell structures studied, ARC + Tc + Dual GRA + 5DBR structure (Cell D) showed the highest optical performance of light absorption due to enhancement of light trapping schemes by prolonging the path length of the photon. These key findings demonstrate that optimized nanostructures and DBR layers can markedly improve photon absorption, laying the foundation for achieving better thin-film a-Si solar cell performance.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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