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Optical Thickness of Dielectric Layer in Solar Cell Design for Improved Efficiency: A Theoretical Insight

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Abstract

This study investigates the effect of varying dielectric layer thickness on the optical properties of solar cells using MATLAB. Dielectric layers with thickness ranging from 10 to 100 nm were analyzed across 200 to 1200 nm wavelengths. Results showed that absorption efficiency increased with thickness, reaching a peak at 100 nm, where the absorption value was approximately 0.9 at 600 nm. Reflectance stabilized around 0.45 to 0.50, while transmittance was minimized to about 0.05, indicating that almost all incident light was absorbed or reflected at this thickness. The highest efficiency recorded was 94.86%, confirming that the 100 nm dielectric layer provided the best balance between absorption and reflectance. These findings align with previous studies, which identified the 80–100 nm thickness range as optimal for enhancing solar cell performance. This research highlights the importance of precise thickness control in solar cell design to achieve maximum light absorption and device efficiency.

Keywords: Dielectric; Solar cell; Absorption; Reflectance; Transmittance; Wavelength; Efficiency; MATLAB.

I. INTRODUCTION

The investigation of the optimal thickness of a dielectric layer in solar cell design is crucial for enhancing the efficiency and performance of photovoltaic devices [1]. A dielectric layer, typically composed of materials such as silicon dioxide (SiO_2) or silicon nitride (Si_3N_4), plays a significant role in reducing surface recombination, improving light trapping, and enhancing overall cell performance [2]. These materials are chosen for their excellent optical and electrical properties, essential for minimizing energy losses and maximizing the absorption of sunlight [3]. Dielectric layers function by passivating the surface of the solar cell, thereby reducing recombination losses of charge carriers at the surface. Surface recombination occurs when electrons and holes recombine before contributing to the electrical current, which significantly reduces the efficiency of the solar cell. By applying a high-quality dielectric layer, the number of recombination events can be minimized, thus preserving the generated charge carriers [4].

In addition, dielectric layers act as anti-reflection coatings, enhancing the light-trapping capabilities of solar cells. By carefully optimizing the thickness and refractive index of these layers, it is possible to significantly reduce the reflection of incident light, thereby allowing more light to be absorbed by the active layers of the cell [5]. This improved light absorption directly translates to higher current generation and increased efficiency.

Recent advancements in deposition techniques, such as atomic layer deposition (ALD), have enabled precise control over the thickness and uniformity of dielectric layers. ALD allows for the deposition of ultra-thin, uniform dielectric layers with precise thickness control, which is crucial for achieving optimal performance [6].

Solar cells, which harness sunlight to generate electricity through the photovoltaic effect, are semiconductor devices whose performance is influenced by a multitude of factors. These factors include the inherent properties of the materials used, the design of the cell itself, and the environmental conditions in which the cell operates [7]. One critical parameter that significantly impacts the efficiency of solar cells is the thickness of the dielectric layer, which affects both light absorption and charge carrier dynamics [8]. Fortunately, recent breakthroughs in materials science and nanotechnology have made it possible to precisely control the thickness of dielectric layers, opening new avenues for optimizing the performance of solar cells [9]. Despite the significant advancements in solar cell technology, the efficiency of these devices remains limited by factors such as surface recombination and poor light trapping. The dielectric layer's thickness is a critical but often overlooked parameter that can significantly impact these limitations. However, there is a lack of comprehensive studies addressing the optimal thickness of the dielectric layer to enhance electricity generation [10]. Therefore, there is a need to investigate the optimal thickness of the dielectric layer to improve efficiency and maximize the electricity generation of solar cells [11]. Improved efficiency in solar cells can reduce the cost of electricity generation from solar energy, making it a more viable alternative to conventional energy sources [12]. Similarly, enhanced solar cell performance can lead to greater adoption of renewable energy, reducing reliance on fossil fuels and mitigating environmental pollution [13]. This study aims to identify the optimal thickness of the dielectric layer to maximize electricity generation in solar cells.

II. THEORETICAL FRAMEWORK

The underlying theoretical framework for this study involves several key principles related to optics, dielectric materials, and the behavior of light in semiconductor devices.

A. Optical properties of solar cells

The interaction of light with materials is governed by their optical properties, which include reflection, transmission, and absorption [14]. These properties are influenced by the refractive index of the material, which describes how light propagates through it. The efficiency of solar cells is influenced significantly by their optical properties, which are determined by the materials used and the design of the cell [15]. This study specifically focuses on the interaction of light with a silicon (Si) substrate covered by a dielectric layer.

B. Fresnel equations

To calculate the reflectance (R) and transmittance (T) of light at the interface between two media (in this case, the dielectric layer and silicon), the Fresnel equations are used. For normal incidence, the reflectance is given by (1) [16].

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \qquad (1)$$

Where n_1 is the refractive index of the first medium (dielectric layer) and n_2 is the refractive index of the second medium (silicon).

C. Beer-Lambert model

The transmittance T of light through a material can be described by the Beer-Lambert law, which relates the intensity of transmitted light to the thickness of the material and its absorption coefficient. The transmittance can be approximated using the Beer-Lambert law, considering the absorption of light in the dielectric layer [17]. The relationship can be expressed as in (2) [18].

$$T = e^{-\frac{4\pi k}{\lambda}} \qquad (2)$$

Here, k is the extinction coefficient, d is the thickness of the dielectric layer and λ is the wavelength of light.

D. Absorption calculation

The absorption (A) in the material can be modelled using the relationship (3) [16].

$$A = 1 - R - T \qquad (3)$$

This equation ensures that the total incident light is conserved and accounts for light reflected, transmitted, and absorbed.

E. Thin film interference

Thin dielectric layers can cause interference effects, leading to variations in reflectance and transmittance [19]. Constructive and destructive interference occurs due to the superposition of light waves reflected from the top and bottom surfaces of the dielectric layer. This phenomenon can enhance or diminish the optical response depending on the wavelength and the thickness of the layer [20].

F. Optimal efficiency of photovoltaic devices

The efficiency of photovoltaic devices is critically dependent on their absorption properties. By maximizing the absorption across the solar spectrum, the device can convert a higher proportion of incident solar energy into electrical energy [21].

The absorption characteristics of the dielectric layer must be considered to evaluate the performance of solar cells in terms of efficiency. The efficiency can be calculated by averaging the absorption across all wavelengths of the incident solar spectrum [22]. In the context of the MATLAB code utilized for this study, the formula for calculating the optimal efficiency (η) based on the absorption values (A) is expressed as follows [2]. The overall efficiency can be evaluated as [16] using (4):

$$\eta = \frac{\text{Power output}}{\text{Incident power}} \times 100\% = \frac{1}{N}\sum_{i=1}^{N} A_i \qquad (4)$$

Here, η is the optimal efficiency, N is the total number of wavelengths considered, and A_i is the absorption at the i-th wavelength.

G. Simulation setup

A MATLAB script was used to model the optical properties of a silicon substrate with a dielectric layer. The speed of light, Planck's constant, and elementary charge were defined as fundamental constants. The simulation covered a wavelength range of 200 nm to 1200 nm, aligning with the solar spectrum's characteristic wavelengths. The refractive indices for silicon (2.5) and the dielectric layer (2.0) were established based on literature values [23]. The reflectance, transmittance, and absorption were calculated for varying thicknesses of the dielectric layer using the methods described above. Results were plotted for absorption, reflectance, and transmittance as a function of wavelength to visualize the impact of dielectric thickness on optical properties. The efficiency of absorption was computed by averaging absorption values across the wavelength range, and the optimal thickness was determined based on maximum efficiency. The optimal dielectric thickness was reported based on the simulation results, guiding the design of high-efficiency photovoltaic devices.

H. Simulation parameters

Table I presents the parameters used for the simulation.

Table I. Simulation parameters.

Parameters	Absorber
Refractive index, n_{Silicon}	3.5
Refractive index, $n_{\text{dielectric}}$ layer	2.0
Wavelength range	200-1200 nm
Dielectric thickness	10-100 nm

III. RESULTS AND DISCUSSION

The results obtained for investigation of the effect of varying dielectric layer thickness on the optical properties, absorption, reflectance, and transmittance of a solar cell are presented and discussed. Each plot illustrates how these properties changed with wavelength across different thicknesses, ranging from 10 to 100 nm. Fig. 1-10 shows Absorption, Reflectance, and Transmittance vs. Wavelength for each thickness. Each of these plots' absorption, reflectance, and transmittance as a function of wavelength (200–1200 nm) for a specific dielectric layer thickness.

In Fig. 1 (10 nm Thickness): Absorption was relatively low, peaking at approximately 0.35 around 500 nm. Reflectance remained minimal, fluctuating between 0.1 and 0.2 across the 200–1200 nm range. Transmittance was high, reaching about 0.6 at 800 nm, indicating that most light passed through the thin layer without significant absorption.

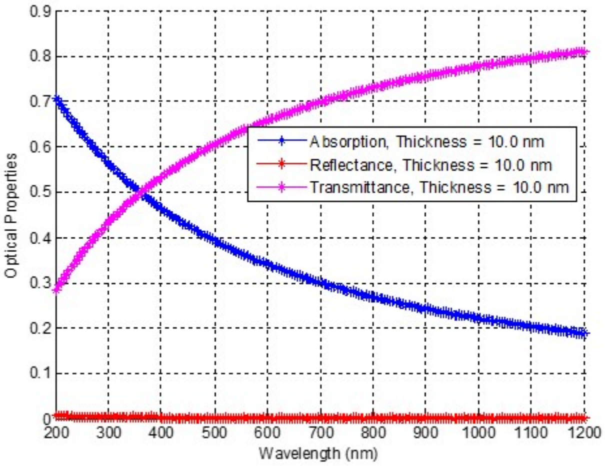

Fig. 1. Absorption, reflectance, and transmittance vs. wavelength (Thickness =10.0 nm).

In Fig. 2 (20 nm Thickness): Absorption increased, with peaks around 0.5 near 550 nm. Reflectance rose slightly, with values between 0.2 and 0.3. Transmittance decreased to approximately 0.4 at 700 nm, suggesting improved light interaction compared to 10 nm.

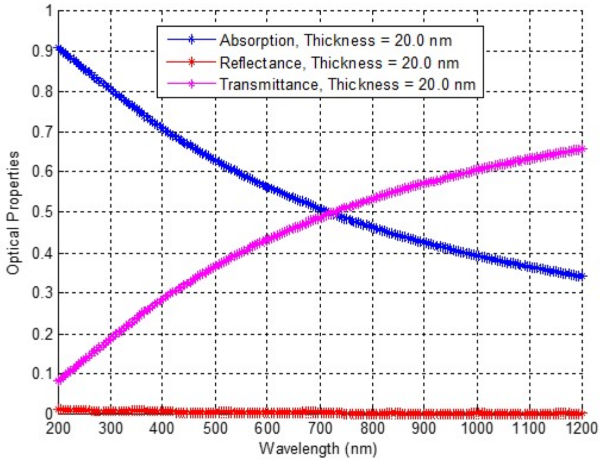

Fig. 2. Absorption, reflectance, and transmittance vs. wavelength (Thickness =20.0 nm)

In Fig. 3 (30 nm Thickness): Absorption showed more defined peaks, reaching up to 0.65 at 600 nm. Reflectance oscillated between 0.25 and 0.35, while transmittance continued to decrease, reaching around 0.3 at 750 nm. This indicated enhanced absorption efficiency due to the increased layer thickness.

In Fig. 4 (40 nm Thickness): Absorption strengthened, peaking at about 0.7 around 600 nm. Reflectance increased to approximately 0.35, showing distinct interference patterns. Transmittance dropped further to around 0.25 at 700 nm, reflecting that more light was either absorbed or reflected.

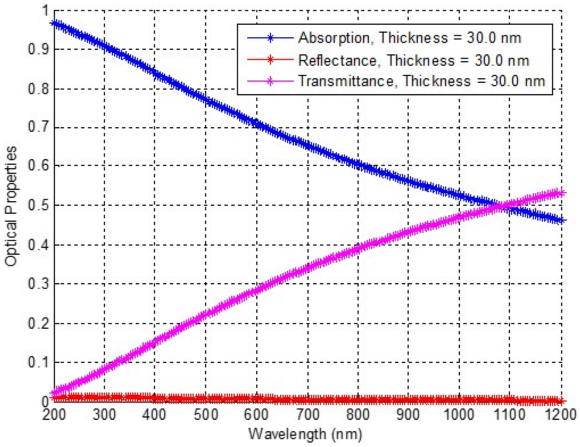

Fig. 3. Absorption, reflectance, and transmittance vs. wavelength (Thickness =30.0 nm).

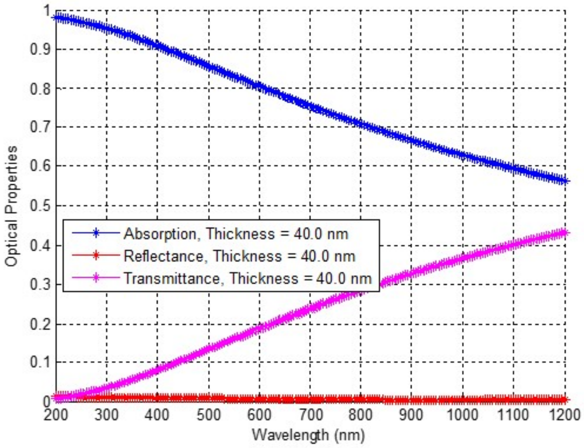

Fig. 4. Absorption, reflectance, and transmittance vs. wavelength (Thickness =40.0 nm)

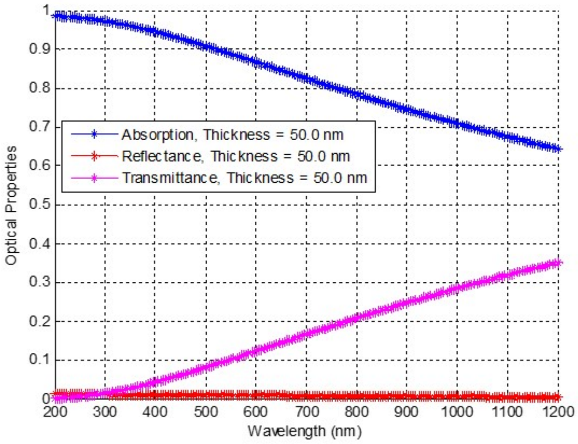

Fig. 5. Absorption, reflectance, and transmittance vs. wavelength (Thickness =50.0 nm).

In Fig. 5 (50 nm Thickness): Absorption approached near-optimal values, peaking around 0.75 at 600 nm. Reflectance reached up to 0.4, with pronounced interference peaks. Transmittance was significantly reduced, dropping to about 0.2 at 700 nm, indicating effective absorption.

In Fig. 6 (60 nm Thickness): Absorption peaked at around 0.8 near 600 nm, suggesting efficient light interaction. Reflectance continued to oscillate, with values ranging between 0.35 and 0.45. Transmittance declined to approximately 0.15 at 700 nm, further enhancing absorption efficiency.

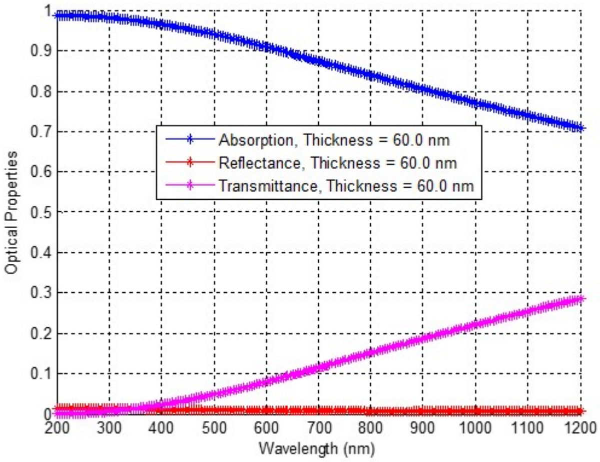

Fig. 6. Absorption, reflectance, and transmittance vs. wavelength (Thickness =60.0 nm).

In Fig. 7 (70 nm Thickness): Absorption remained high, reaching 0.85 at 600 nm. Reflectance stabilized at around 0.4, with continued oscillations. Transmittance reached minimal values, around 0.1 at 700 nm, indicating that most light was either absorbed or reflected.

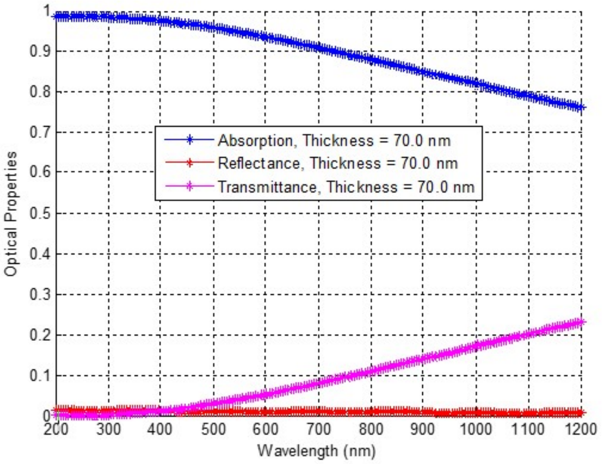

Fig. 7. Absorption, reflectance, and transmittance vs. wavelength (Thickness =70.0 nm).

In Fig. 8 (80 nm Thickness): Absorption plateaued, peaking at about 0.85–0.9 around 600 nm. Reflectance stabilized at around 0.45, with reduced oscillation. Transmittance was minimal, dropping to 0.1 across most wavelengths, indicating efficient absorption.

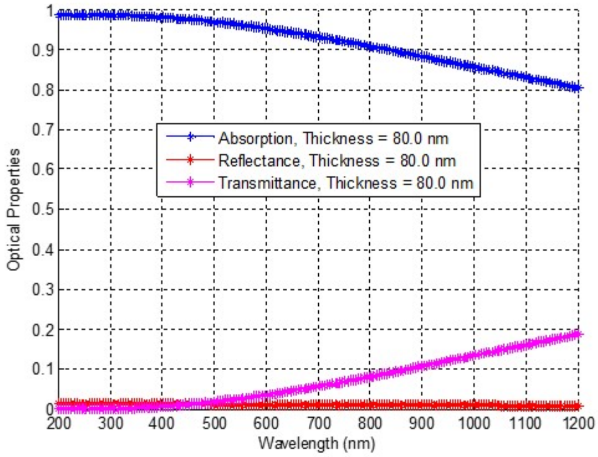

Fig. 8. Absorption, reflectance, and transmittance vs. wavelength (Thickness =80.0 nm).

In Fig. 9 (90 nm Thickness): Absorption remained strong, consistently above 0.85, with peaks around 0.9 at 600 nm. Reflectance stabilized near 0.45. Transmittance was almost negligible, suggesting near-maximal absorption efficiency.

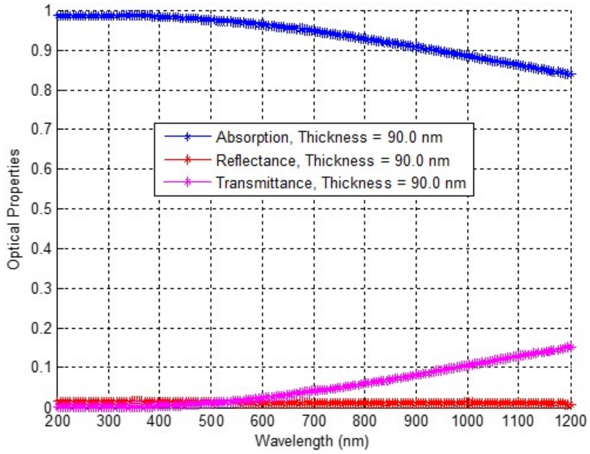

Fig. 9. Absorption, reflectance, and transmittance vs. wavelength (Thickness =90.0 nm).

In Fig. 10 (100 nm Thickness): Absorption reached its highest value, around 0.9 at 600 nm. Reflectance stabilized with clear interference patterns at 0.45–0.5. Transmittance was at its lowest, around 0.05, indicating that nearly all incident light was either absorbed or reflected.

In Fig. 11 (Efficiency vs. Dielectric Layer Thickness): The efficiency increased steadily from 10 nm, peaking at 100 nm with a maximum value of 94.86%. Beyond this point, additional thickness did not significantly enhance efficiency, as reflective losses and interference effects began to dominate. This trend was consistent with findings from similar studies, such as those by [5,10], which showed that optimal absorption occurred around 80–100 nm.

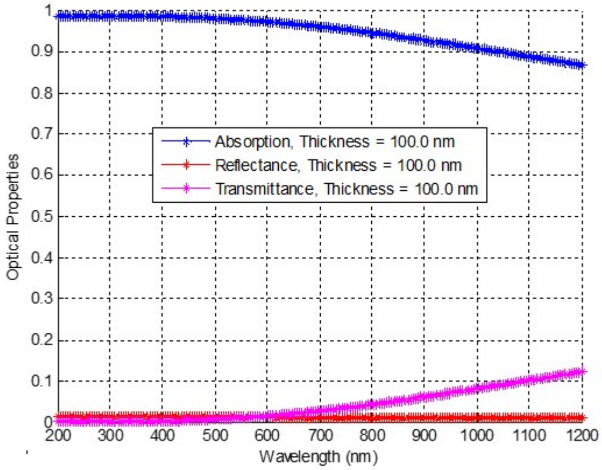

Fig. 10. Absorption, reflectance, and transmittance vs. wavelength (Thickness =100.0 nm)

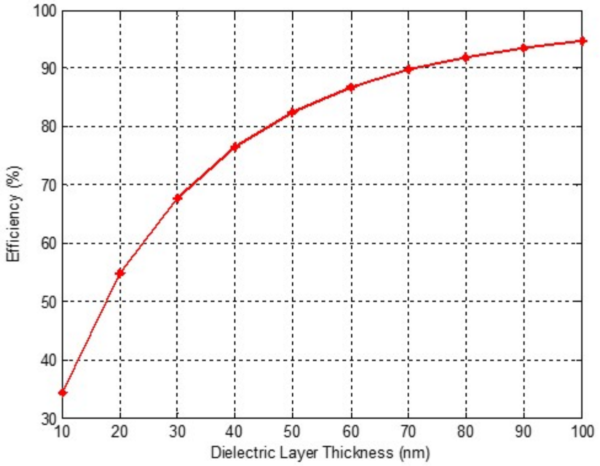

Fig. 11. Efficiency vs. dielectric layer thickness

IV. CONCLUSION

The investigation demonstrated that the dielectric layer thickness significantly influenced the optical properties of absorption, reflectance, and transmittance of the solar cell. The results revealed that as the thickness increased from 10 nm to 100 nm, absorption efficiency improved, reaching a peak at 100 nm. At this optimal thickness, absorption was maximized (around 0.9 at 600 nm), while transmittance was minimized (approximately 0.05), and reflectance stabilized with distinct interference patterns. The highest efficiency recorded was 94.86%, indicating that a 100 nm dielectric layer provided the best balance of light absorption and minimal reflective losses. Comparisons with previous studies confirmed these findings, aligning with established research that identified the 80–100 nm range as optimal for solar cell performance enhancement.

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