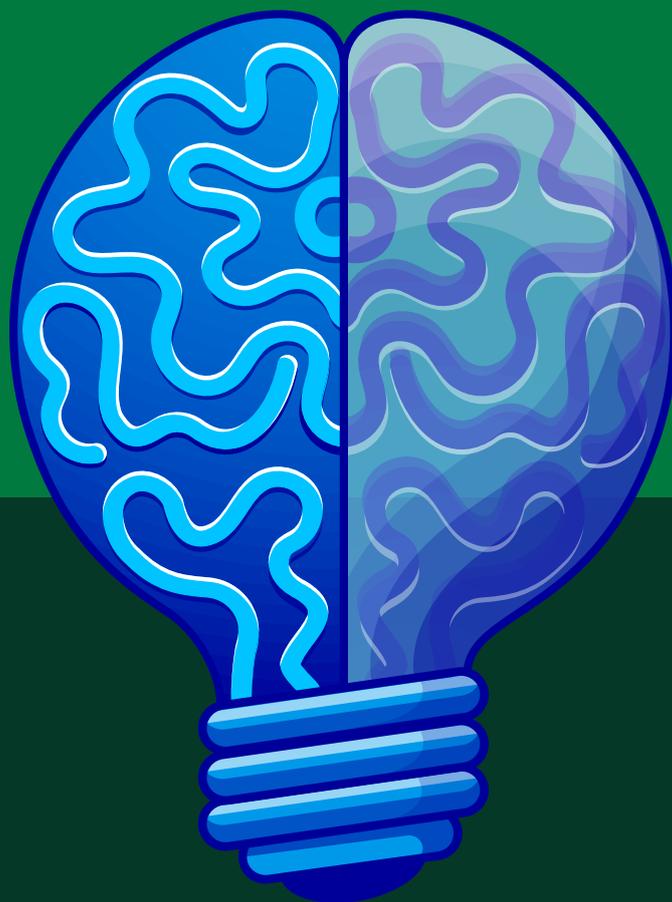


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PERAK BRANCH

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Preface

The Scientific Project Colloquium offers a platform for publishing Diploma Science final year projects (FYP). The objective is to effectively distribute research findings throughout all scientific disciplines. The primary objective of including final year projects into the course curriculum is to encourage students to put their theoretical knowledge into practical applications.

We would like to express our gratitude to our primary establishment, the Faculty of Applied Sciences and Universiti Teknologi MARA, Perak Branch, for their invaluable assistance.

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MODELING SILICON NITRIDE (SiNx) ANTI-REFLECTIVE COATINGS FOR SILICON SOLAR CELLS VIA RAY-TRACING SIMULATION

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Abstract: This research focuses on optimizing double-layer anti-reflective coatings (ARC) combined with front surface upright pyramid texturing to enhance the optical performance of silicon solar cells. Simulations were conducted using the PV Lighthouse wafer ray tracer software to evaluate a light trapping (LT) scheme applied to a 100 μm thin crystalline silicon (c-Si) base under the AM1.5G solar spectrum at normal incidence, to improve broadband absorption in the 300–1200 nm wavelength range. Double-layer ARC of Silicon Nitride (SiNx) and silicon dioxide (SiO₂) with varying thicknesses were examined. The findings demonstrate that the double-layer ARC with an upright pyramid front surface, consisting of 80 nm SiNx and 60 nm SiO₂, yielded the highest performance, achieving a photocurrent density of 40.82 mA/cm². This represents a J_{max} enhancement of 65.33%, indicating that the combination of optimized ARC thickness and front surface texturing provides the most effective light trapping and absorption enhancement.

Keywords: *Light trapping, Solar cell, Anti-reflective coating (ARC), Ray tracing, Photocurrent density*

INTRODUCTION

Most electricity in the world was taken by several forms such as nuclear resources, fossil fuels and renewable resources. Some examples of fossil fuels and nuclear resources are coal, oil, and natural gas while examples for renewable resources are solar, wind, geothermal and hydropower (Zambree et al., 2023). All these renewable resources have been thoroughly investigated and very useful in energy production. It is because renewable resources are widely available, free and are not harmful to the environment (Amalathas & Alkaisi, 2019). Among all these renewable resources, solar energy is recognized as the clean renewable energy source because it is gained from the sunlight. Solar cell or called a photovoltaic cell is a device that can generate electrical energy from the light energy through the photovoltaic effect (Zambree et al., 2023). Solar energy can replace fossil fuels to generate electricity because it requires low cost and more efficient in its production (Jamaluddin et al., 2022). Solar cells produce electricity without the need for any moving parts or electricity generators or chemical reactions such as batteries or fuel cells (Zambree et al., 2023).

Like other technologies, solar cells must overcome several obstacles and problems to provide consumers with reasonably priced electricity. One of the problems of solar cells is optical losses or reflection losses. When the light energy hits the surface of the solar cell, some part of the light will absorb into the cell while other parts will reflect. To overcome this problem, a light trapping (LT) scheme was applied to the solar cell which included the surface texturing and anti-reflective coating (ARC) to reduce the reflection of light and increase the performance of the solar cell. Anti-reflective coating (ARC) is one of the efficient ways to prevent the reflection of light from the surface of the cell exactly as its name suggests. ARC used to increase light absorption and performance of the solar cell. They are made up of two layers either single layer and double layer ARC of precisely selected thickness dielectric substance.

However, the number of anti-reflective coating compounds available is limited due to refractive index limits. For example, SiO₂, MgF₂, SiNx, Al₂O₃, TiO₂, and ZnS are the common materials that have been used for ARC (Salleh, 2022). Besides, one popular method to produce light trapping is to change the angle at which light travels in the solar cell by incidentally hitting an angled surface (Zambree et al., 2023). Planar and pyramid are the type of surface that is regularly used for the front surface of the solar cell. Pyramid surface which is textured surface is the best type of surface to reduce reflection which makes the optical path length increase (Zambree et al., 2023).

In this paper, ray tracing of LT schemes of double-layer ARC of Silicon Nitride (SiNx) and silicon dioxide (SiO₂) in thin c-Si solar cells (with 100 μm thickness) is investigated. Four LT schemes with difference thickness, each on random upright pyramid front surface are studied. Effects of these LT schemes towards reflection, transmission and absorption of the incident light in the thin c-Si absorber are analysed.

METHODOLOGY

In this work, wafer ray tracer software that is called PV Lighthouse is used to investigate ray tracing of LT schemes

in thin c-Si solar cells (with a thickness of 100 μm). This software has many functions which can determine the photogenerated current density in a solar cell or modelling the structure using a selected light source. In addition, it shows a generated curve of reflection, absorption and transmission which make it easier to plot a graph. By using this software, it produces more accurate and detailed results. The solar spectrum used is AM1.5G at zero incidence angle which is normal to the surface of the solar cell. For ray tracing, a maximum of 50,000 rays can be used where 5,000 rays are used per run. The range of wavelengths is from the minimum wavelength of 300 nm to the highest wavelength of 1200 nm with a wavelength interval of 20 nm is used (Jamaluddin et al., 2022).

In this research, the substrate of the solar cell is a thin crystalline silicon, c-Si with a random planar surface which is used as reference shown in Figure 1. Materials for anti-reflective coating (ARC) were used are SiN_x and SiO_2 where SiN_x is placed at the top layer while SiO_2 is placed at the bottom layer. Figure 2 indicated a double layer ARC of SiN_x and SiO_2 with thickness of SiN_x was fixed at 80 nm while SiO_2 with various thickness that starts at 40 nm, 60 nm, 80 nm, and 100 nm. Solar cells are improved by adding the upright pyramid front surface to observe the performance of light absorption. The angle of the pyramid is 54.74° , with height 3.536 μm and width 5 μm which was set in the software.

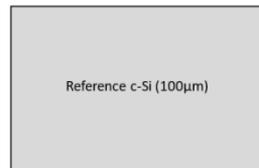


Figure 1 Schematic diagram of c-Si (with thickness 100 μm) without LT scheme as reference

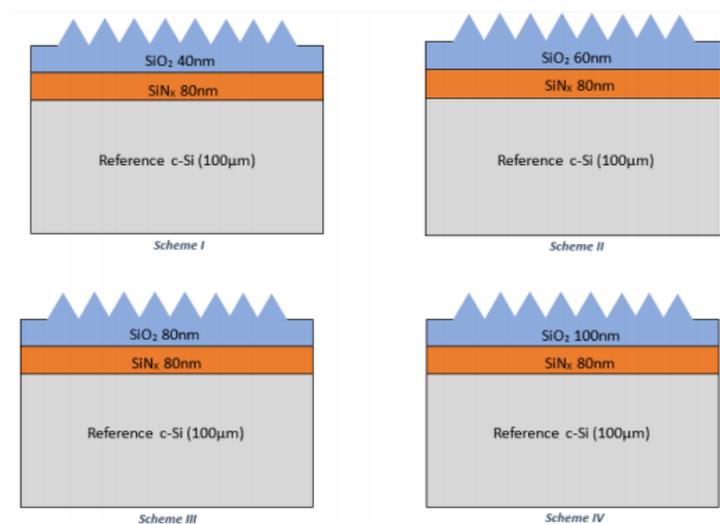


Figure 2 Schematic diagram of double layer ARC with upright pyramid front surface on substrate silicon

In the simulation, total reflection, absorption, transmission, and photocurrent density, J_{max} of double layer ARC in thin c-Si wafers were analysed. Besides, the value of J_{max} is used to observe the performance of solar cells. The percentage of J_{max} enhancement was calculated by using the formula as shown in Equation (1).

$$J_{\text{max}} \text{ enhancement} = [(J_{\text{max}} \text{ LT scheme} - J_{\text{max}} \text{ ref})/J_{\text{max}} \text{ ref}] \times 100 \dots(1)$$

FINDINGS

The curves for reflection, absorption and transmission of a thin crystalline silicon, c-Si solar cell are included in Figure 3(a)–(c). A reference graph is included in order to analyse and compare the differences between the four LT schemes. Reference solar cells show high broadband reflection throughout the 300–1200 nm the wavelength region. This is explained by the sudden shift in refractive index (n) that occurs when incident light moves from air ($n=1$) to c-Si ($n=3.5$). With LT Scheme (upright pyramid; height = 5mm, base angle = 54.74°) reflection from wavelength 300 nm to 950 nm is lower and reduces even more compared to LT schemes before because of increased light scattering at the interface between the air and the pyramid. High oblique angles cause the incident light to be scattered into the thin c-Si. A portion of the scattered light is eventually trapped in the c-Si absorber after passing through total internal reflection.

Due to the fact that it does not pair up with any type of LT scheme, the standard reference of c-Si in Figure 3b) has a very low broadband of absorption, increasing to only 40% at wavelength 420 nm to 860 nm. Broadband light absorption also increases significantly due to the increased light scattering from 300 to 600 nm compared to reference. From the optical results above, the device structure that gives the optimum result is the Scheme I. Figure 3(c). The transmission profile on an identical front surface remains constant regardless of thickness. However, it is clear that an upright pyramid front surface has a significant effect on lowering light transmission in solar cell schemes. The value of reduction of transmission is almost 25 % compared to reference. Transmission of the short wavelength reduces to 0 due to the presence of ARC. However, at long wavelengths (above 900 nm) the transmission for all LT schemes is increasing, reaching 28% and 10 % at 1,100 nm for front planar and upright pyramid front surfaces, respectively. This is due to indirect bandgap semiconductor in Si so there is a long tail in absorption out to long wavelength resulting in higher transmittance. (Zambree et al., 2023)

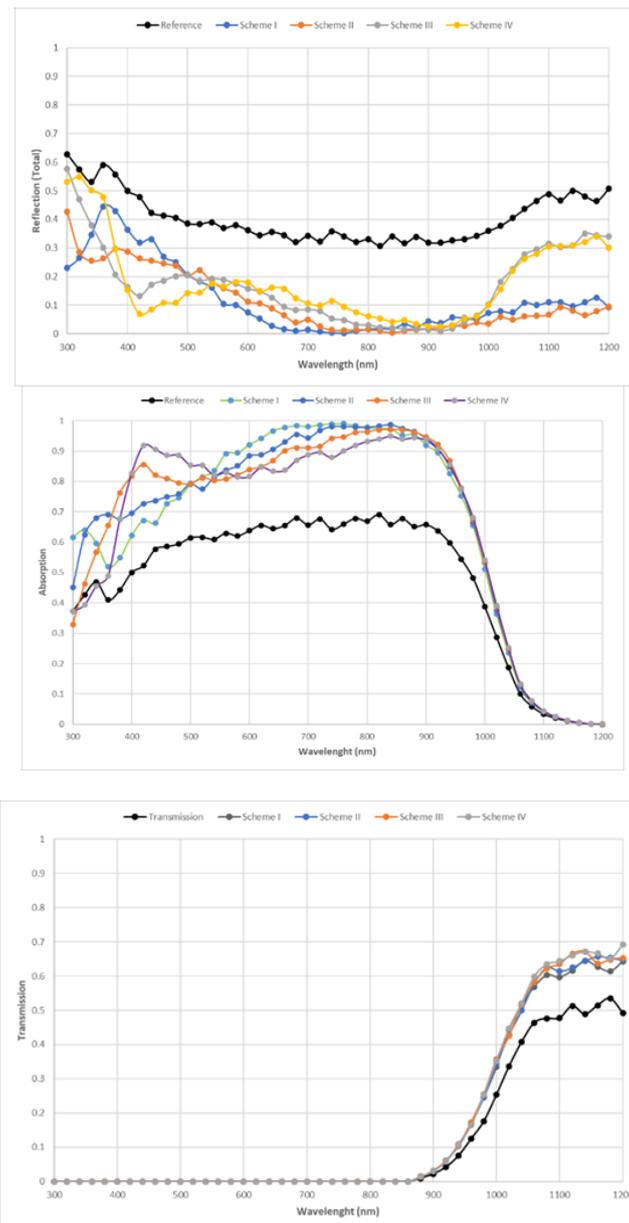


Figure 3 a) Reflection b) Absorption c) Transmission curves for silicon solar cells with SiN_x ARC and different thickness of 40 nm, 60 nm, 80 nm, 100 nm SiO₂ ARC. Reference curve of silicon solar cells (black curve) included for comparison.

Table 1 Summary of J_{\max} of thin c-Si (with 100 μm thickness) with incremental LT schemes. J_{\max} reference c-Si is included for comparison.

LT Scheme	J_{\max} (mA/cm ²)	Enhancement (%)
Reference c-Si (thickness = 100nm)	24.69	-
Scheme I: Upright Pyramid (height = 5mm, base angle = 54.74°) with SiO ₂ /SiN _x (SiO ₂ = 40nm, SiN _x = 80 nm)	40.76	65.08
Scheme II: Upright Pyramid (height = 5mm, base angle = 54.74°) with SiO ₂ /SiN _x (SiO ₂ = 60nm, SiN _x = 80 nm)	40.82	65.33
Scheme III: Upright Pyramid (height =5mm, base angle = 54.74°) with SiO ₂ /SiN _x (SiO ₂ = 80nm, SiN _x = 80 nm)	40.79	65.21
Scheme IV: Upright Pyramid (height =5mm, base angle = 54.74°) with SiO ₂ /SiN _x (SiO ₂ = 100 nm, SiN _x = 80nm)	40.77	65.12

Table 1 displays the J_{\max} measured value of the thin c-Si (100 μm thickness) using incremental LT schemes. Comparing Scheme I (40 nm) with the c-Si reference, where J_{\max} is equal to 24.69 mA/cm². J_{\max} increased to 40.76 mA/cm², indicating a 65.08% improvement. In addition, at some point in the wavelength range, light absorption within the thin c-Si begins to increase using Scheme II (60 nm) It is because the best achievement of highest absorption, lower reflection and transmission. This condition is known as the finest condition of the efficiency of solar cells. At 40.82 mA/cm², J_{\max} increased, indicating a 65.33% improvement. The thin c-Si's high optical light absorption increased after Scheme III (80 nm) was used. At 40.79 mA/cm², the J_{\max} tends to rise for an enhancement of approximately 65.21%. In the end, Scheme IV's high optical wavelength of 100 nm for light absorption gained roughly 40.77 mA/cm² with a 65.12% enhancement.

CONCLUSIONS

The ray tracing of LT schemes in 100 μm thick thin c-Si solar cells with SiN_x anti-reflective coating (ARC) has been studied in this work. Research has been done on the impact of surface texturing of the front layer of film on silicon solar cells' performance. For the double-layer anti-reflective coating (ARC), SiO₂/SiN_x was used. The study focused on four distinct light trapping techniques, derived from multiples of the SiO₂ thickness values of 40 nm, 60 nm, 80 nm, and 100 nm. This simulation demonstrates that among LT schemes, double-layer ARC with an upright pyramid front surface of 80 nm SiN_x and 60 nm SiO₂ thickness gave the best improvement in current density of 40.82 mA/cm². This showed the J_{\max} enhancement is 65.33%.

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Setuju.

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