Universiti Teknologi MARA

I-URIID 2025

INTERNATIONAL UNDERGRADUATE RESEARCH INNOVATION, INVENTION AND DESIGN

UNDERGRADUATES PIONEERING TOMORROW'S BREAKTHROUGH

E-BOOK OF EXTENDED ABSTRACTS

INFLUENCE OF DIFFERENT ANTI-REFLECTIVE COATING ON SILICON SOLAR CELLS IN PVLIGHT HOUSE

Nur A'inul Mardhiah Kamal*, and Siti Hajar Mohmad Salleh

Faculty of Applied Sciences, Universiti Teknologi MARA (UiTM) Cawangan Perlis, Kampus Arau, 02600 Arau, Perlis, Malaysia

*ainul.mardhiah4221@gmail.com

ABSTRACT

Crystalline silicon (c-Si) is the most commonly used material in solar photovoltaics (PV) due to its stability and availability. However, its high surface reflectivity causes significant optical losses, reducing overall solar cell efficiency. This study evaluates the effectiveness of five single-layer anti-reflective coating (ARC) materials (Silicon nitride, Silicon dioxide, Titanium dioxide, Aluminium oxide, and Zinc oxide) applied on planar c-Si surfaces with thickness of 200 µm. Using the Wafer Ray Tracer by PV Lighthouse, optical behavior was simulated, and the maximum photocurrent density (J_{max}) was calculated. Among all tested materials, ZnO achieved the lowest reflection and highest J_{max} of 35.84 mA/cm², representing a 40.05% enhancement from the reference c-Si. The results show that ZnO is the most effective ARC in improving light trapping and enhancing solar cell performance.

Keywords: Crystalline silicon, anti-reflective coating, ray tracing, simulation, solar cell efficiency

INTRODUCTION

The need of clean and renewable energy has become an urgent matter as climate change is become worse and potential limitation of fossil fuels. Solar energy has become an alternative because it is widely available, low environmental impact, and rapid technological improvement (Vadiyala, 2020; Behrani, 2023). Among various solar technologies, crystalline silicon (c-Si) remains the most commonly used material due to its abundance, maturity, and stability in photovoltaic (PV) applications (Wang, 2022). According to the International Energy Agency (IEA, 2024), solar PV are predicted to provide 80% to dominate renewable energy expansion, generating nearly 80% of all renewable energy generation capacity by 2030. This shows the importance in improving solar cell performance in order to meet future energy demands. However, silicon surface actually suffers high reflectivity due to its nature of silicon causing up to 30% of sunlight to be reflected instead of absorbed (Kumaragurubaran & Anandhi, 2014). This optical loss, limit the power output of solar cells. Anti-reflective coatings (ARC) are widely used to tackle optical problem, minimise reflection and improve light trapping. Choosing the best ARC material and configuration is still difficult, despite the fact of numerous materials and coating methods have been researched.

This study uses Wafer Ray Tracer, an advanced ray-tracing modelling tool made by PV Lighthouse, to describe light interacts with c-Si solar cells. Ray-tracing simulations provide a lot of data on light behaves optically, allowing to accurately measure reflection, absorption, and transmission without having to do physical experiments. A few researchers have used ray tracing for evaluation of ARC, which making it a reliable and widely accepted approach. The wafer ray tracer simulator uses a thickness of 200 μm c-Si in order to perform the task of ray tracing in silicon solar cells. Five ARC materials such as Silicon nitride (SiN_4), Silicon dioxide (SiO_2), Titanium dioxide (TiO_2), Aluminium oxide (Al_2O_3) and Zinc oxide (ZnO), each with a thickness of 75 µm, applied on a planar surface of c-Si. This analysis of the optical properties of solar cells will involve using the wavelength range that runs between 300 and 1200 nm and the AM1.5G solar spectrum at zero incidence angle.

To determine the optical performance of each ARC, the maximum photocurrent density (J_{max}) is calculated using Equation (1):

$$J_{max} = q \int \quad EQE(\lambda).S(\lambda)\ d\lambda \tag{1}$$

where q = 1.6 x10^{-19} is the electron charge, EQE is the external quantum efficiency and S(λ) is the standard spectral irradiance of sunlight for AM1.5 G spectrum. The carrier collection is assumed to be one (i.e. internal quantum, IQE = 1).

The J_{max} enhancement (%) is calculated using Equation (2):

$$J_{max}\ \ enhancement\,(\%) = \frac{(J_{max}\,scheme - J_{max}\,ref)}{J_{max}\,ref} \times 100\% \tag{2}$$

where J_{max} scheme represents the maximum potential of photocurrent density of the light trapping scheme which has to be added to the c-Si substrate while J_{max} ref is refers to photocurrent density of the standard silicon wafer without enhancements.

The simulated values of reflection, photocurrent density (J_{max}), and J_{max} enhancement are analysed to find the most effective ARC material to improve the optical performance of c-Si solar cells.

RESULTS AND DISCUSSION

This part highlights the results obtained from the simulation and numerical analysis of anti-reflective coatings (ARC) for silicon solar cells using Wafer Ray Tracer by PV Lighthouse simulation. The materials ARC used are SiN_4, SiO_2, TiO_2, Al_2O_3, and ZnO, which each Each parameter is written as Scheme I to Scheme V in the graph. A reference c-Si without ARC and planar surface is also presented for comparison. Based on Figure 1 shows among all ARC materials, Scheme V (ZnO) and Scheme I (SiN_4) demonstrated the lowest reflection in the visible range (400–700 nm). ZnO achieved nearly 0% reflectance at 580 nm, while Si_3N_4 reached as low as 0.0028 at 560 nm. This significant reduction is attributed to their optimal refractive index of ZnO (~2.0) and SiN_4 (~2.0)—which act as effective cushion between air (n ≈ 1.0) and silicon (n ≈ 3.5), minimising front-surface light loss (Muhi, 2018; Lai et al., 2020). In contrast, Scheme II (SiO_2) exhibited the highest reflection across the spectrum, with reflection exceeding 30% at many wavelengths due to its lower refractive index (~1.45), resulting in poor optical matching and increased surface reflection (Zahid et al., 2020).

Although absorption and transmission graphs are not shown, the simulation trends indicate that schemes with lower reflection such as ZnO and Si_3N_4 which related with stronger photon absorption in the active solar spectrum (visible range), while higher transmission beyond 960 nm suggests optical losses in the infrared region, where silicon's ability to absorb photons declines (Zambree et al., 2023). These optical behaviours are supported by the calculated photocurrent density (J_{max}) values in Table 1. Scheme V (ZnO) achieves the highest J_{max} of 35.84 mA/cm², representing a 40.05% improvement compared to reference scheme (25.59 mA/cm²). Scheme I (Si_3N_4) follow closely with 39.58% enhancement, while Scheme III (TiO_2) achieves 37.71%. Meanwhile, Scheme II (SiO_2) produces the lowest J_{max} of 20.02 mA/cm², which confirming its inefficiency due to high reflection. Another study by Jamaluddin et al. (2024) also investigates the efficiency of silicon solar cells using various ARC materials and demonstrates a similar trend, where ZnO and SiN_4 show the highest overall performance, with values that are very close to each other. These results confirm the exceptional performance of ZnO as the ideal ARC material, making it the preferred choice for optimizing solar cell efficiency.

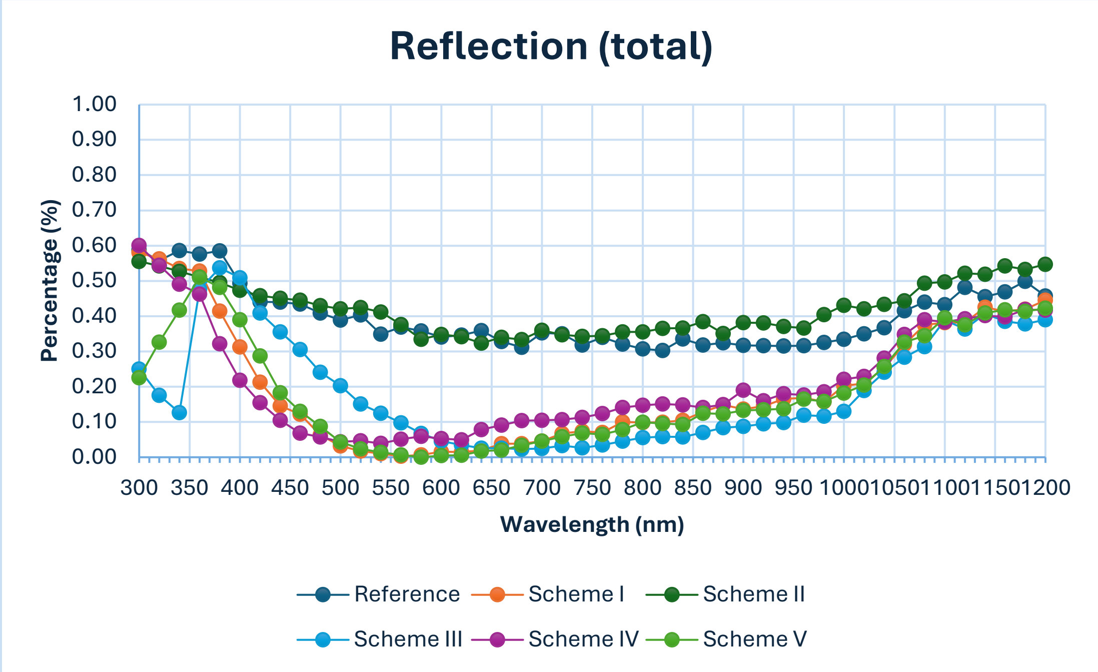

Figure 1: Reflection curve for c-Si with different ARC material on the c-Si solar cell

Table 1: The simulation data of LT Schemes with the J_{max} enhancements

LT Scheme	$\boldsymbol{J_{max}}$ (mA/$\boldsymbol{cm^2}$)	$\boldsymbol{J_{max}}$ enhancement (%)
Reference c-Si scheme with thickness 200µm	25.59	-
Scheme I: Planar surface Silicon Nitride ARC with thickness of 75 µm	35.72	39.58
Scheme II: Planar surface Silicon Dioxide ARC with thickness of 75 µm	20.02	21.76
Scheme III: Planar surface Titanium Dioxide ARC with thickness of 75 µm	35.24	37.71
Scheme IV: Planar surface Aluminium Oxide ARC with thickness of 75 µm	35.05	36.98
Scheme V: Planar surface Zinc Oxide ARC with thickness of 75 µm	35.84	40.05

CONCLUSION

This study demonstrates that the choice of anti-reflective coating (ARC) material significantly affects the optical performance and photocurrent generation of crystalline silicon (c-Si) solar cells. Among the five materials tested, Zinc Oxide (ZnO) exhibits the best overall performance, achieving the highest J_{max} (35.84 mA/cm²) and lowest reflection in the visible spectrum. Its refractive index provides excellent matching between air and silicon, leading to 40.05% enhancement in photocurrent compared to uncoated silicon. Silicon Nitride (Si_3N_4) closely follows with similarly low reflection and J_{max} enhancement (39.58%), making it another viable ARC option, especially due to its industrial compatibility. Meanwhile, Silicon

Dioxide (SiO_2) showed the poorest performance, highlighting the importance of selecting materials with appropriate optical properties. In conclusion, ZnO is identified as the most effective single-layer ARC material for enhancing light trapping and boosting silicon solar cell performance in this study. These findings can help guide the development of high-efficiency, low-cost photovoltaic devices using numerical ray tracing methods.

ACKNOWLEDGEMENT

Authors would like to thank Universiti Teknologi MARA (UiTM) for supporting this research.

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