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E-BOOK OF EXTENDED ABSTRACTS

BOOSTING SOLAR OUTPUT WITH INNOVATIVE ANTI-REFLECTIVE LAYER DESIGN

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ABSTRACT

This research aims to improve the performance of silicon solar cells by using double-layer anti-reflective coatings (DLARCs). The goal of this research is to investigate how DLARCs minimize the reflection of light and maximize energy output. The DLARCs are simulated, using software known as PC1D, by creating three DLARC configurations: MgF_2/TiO_2, SiO_2/TiO_2, and Al_2O_3/TiO_2. The performance of all the configurations was found to be higher than that of the reference cell. The MgF_2/TiO_2 coating had the best efficiency of 23.10%, while the reference cell had an efficiency of 15.70%. The comparable performance of MgF_2/TiO_2 and SiO_2/TiO_2 can be attributed to their proximity in refractive indices, as well as to the limitations of the used material database in the simulation.

Keywords: Anti-reflective coatings, silicon, solar cell, PC1D, photovoltaic

INTRODUCTION

With the global shift toward cleaner and renewable sources of energy, solar has emerged as one of the best solutions. Particularly, silicon-based PV cells are still the most common and popular technology because of their availability, stability, and price (Andreani et al., 2018). However, high surface reflectivity of silicon is one of the limitations that can impair its performance as it reflects over 30% of the incoming sunlight (Sharma, 2019). This reflected loss decreases the quantity of the incident photons being absorbed by the active layer and suppresses the generation of charge carriers, thus leading to reduced power conversion efficiency (PCE) of the solar cell. To overcome this issue, anti-reflective coatings (ARCs) are applied to the front surface of solar cells. These coatings present greater light absorption that reaches the active region of the cell and lead to increased efficiency (Adwan et al., 2023). One potential resolution is a double-layer anti-reflective coating (DLARCs) for this issue. Through the different refractive indices of two materials, DLARCs can efficiently form a smoother transition area for the incident light from air to the silicon substrate. Such structures assist in achieving lower reflectance across a wider wavelength range than single-layer coatings, while maintaining reasonable fabrication complexity (Ji et al., 2022; Salleh, 2023).

In this study, the electrical performance of silicon solar cells with different DLARC configurations was simulated using PC1D. This step was done in the form of a one-dimensional device simulation, which is common practice in photovoltaic research. The simulation also included setting key parameters such as layer thicknesses, material properties, doping concentrations, and operating conditions under standard illumination (AM 1.5G) to examine the effects of the DLARCs on cell efficiency. The simulation results showed that every configuration of DLARC provided marked improvement when compared to an uncoated reference cell. More specifically, improvements were observed in the short-circuit current and open-circuit voltage alongside other metrics measured across all power conversion efficiency (PCE). With regards to these changes, the most effective DLARC design's PCE reached 23.10%, considerably exceeding bare silicon cells' 15.70%. This signifies more than 47.13% of the relative gain in efficiency post-implementation of DLARCs on silicon solar cells. Therefore, confirming that DLARCs can effectively increase energy output from silicon solar cells, thus justifying the continued development to advance the utilisation of solar power technology systems within renewable energy frameworks (Law et al., 2023).

METHODOLOGY

This study focuses on evaluating the effect of double-layer anti-reflective coatings (DLARCs) on the electrical performance of silicon solar cells through simulation. The research explores how the addition of two anti-reflective layers can reduce reflection losses and improve power conversion efficiency (PCE), which is relevant for optimising photovoltaic design and improving the output of commercial solar modules. PC1D allows researchers to model a solar cell and observe its electrical behavior by setting key devices and environmental parameters. It is suitable for this study because it provides detailed insight into how changes in front-layer coatings impact important electrical characteristics, such as short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum power (P_{max}). In this simulation, DLARCs were represented as two thin film layers on top of a crystalline silicon (c-Si) substrate, as illustrated in Figure 1. The materials listed in Table 1 were selected due to their compatibility with silicon and because their refractive indices can help in forming destructive interference that leads to lower reflectance.

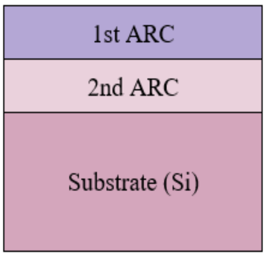

Figure 1: Schematic diagram of DLARCs configuration.

Table 1 Refractive index and thickness of ARC materials.

Materials	**Refractive Index (n)**	**Thickness (nm)**
MgF_2	1.36	110.3
SiO_2	1.46	102.7
Al_2O_3	1.62	92.6
TiO_2	2.30	65.2
c-Si (Substrate)	3.94	1 x 10^5

RESULTS AND DISCUSSION

The simulation using PC1D showed that applying double-layer anti-reflective coatings (DLARCs) to silicon solar cells significantly improved their electrical performance compared to an uncoated reference cell. The results obtained from the simulation mentioned in Table 3, with the baseline uncoated silicon cell to serve as a reference for comparison and followed by three different configurations. All three configurations recorded higher I_{sc}, V_{oc}, P_{max}, and PCE than the uncoated silicon cell. Among them, the MgF_2/TiO_2 configuration achieved the best performance, with an I_{sc} of 3.684 A, a V_{oc} of 0.7394 V, and a P_{max} of 2.310 W, resulting in a PCE of 23.10%. Meanwhile, SiO_2/TiO_2 and Al_2O_3/TiO_2 show slightly lower efficiencies of 23.01% and 22.55%, with respective readings of I_{sc} = 3.670 A, P_{max} = 2.301 W, V_{oc} = 0.7394 V, and I_{sc} = 3.594 A, P_{max} = 2.255 W, V_{oc} = 0.7388 V. In comparison, the uncoated reference cell recorded an efficiency of 15.70%, highlighting a relative efficiency improvement of over 47.13% for the best-performing DLARC.

Table 2 PC1D simulation results of the Reference and DLARCs scheme.

Scheme	Material	I_{sc} (A)	P_{max} (W)	V_{oc} (V)	Efficiency, μ (%)	Efficiency Enhancement (%)
Substrate (reference)	Silicon	2.542	1.570	0.7302	15.70	-
DLARC	MgF_2 / TiO_2	3.684	2.310	0.7394	23.10	47.13
	SiO_2 / TiO_2	3.670	2.301	0.7394	23.01	46.56
	Al_2O_3 / TiO_2	3.594	2.255	0.7388	22.55	43.63

The improvement observed is closely related to the optical behavior of the coating materials. Materials with appropriate refractive indices were selected to create a gradient between air and the silicon surface, which reduced reflection through destructive interference (Ji et al., 2022). The combination of a low-index top layer and a high-index bottom layer allowed better light transmission and minimised losses due to reflection (Salleh, 2023; Mousa et al., 2020). However, the differences in individual parameters for MgF_2/TiO_2 and SiO_2/TiO_2 remain below 1%, which indicates similar performance trends. This similarity aligns with previous studies that both MgF_2/TiO_2 and SiO_2/TiO_2 DLARCs exhibit low reflectance and efficient light trapping across the visible spectrum, resulting in comparable optical performance despite material differences (Ali et al., 2014; Mercy et al., 2020). These similarities can also be observed in the shape and slope of their I-V curves, as in Figure 2.

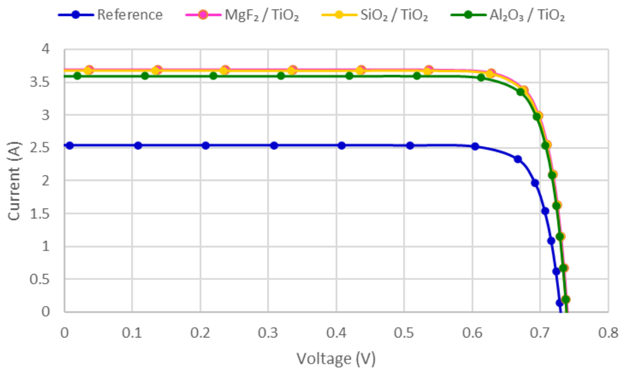

Figure 2: I-V curve for DLARC configuration.

CONCLUSION

This research demonstrates that the use of double-layer anti-reflective coatings (DLARCs) enhances the electrical characteristics of silicon solar cells while reducing reflection losses and enhancing absorption. All three DLARC configurations performed better than the uncoated cell, with MgF_2/TiO_2 being the most efficient. The similar performances of MgF_2/TiO_2 and SiO_2/TiO_2 may be owed to the similar refractive indices and the limitation of the material library used in the simulation. Overall, DLARCs improve solar cell energy output efficiently and need further validation in real-world settings as an area for future work, predicting performance under various conditions, while using different material combinations would be especially relevant.

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