

INCREASING THE EFFICIENCY OF SILICON SOLAR CELLS THROUGH ANTIREFLECTIVE TiO₂ WITH THE SPIN COATING METHOD

Alfiatul Ma'arifah¹, Markus Diatoro^{1,2}, Norazlin³, Herlin Pujiarti^{1,2*}

¹*Department of Physics, Faculty of Mathematics and Natural Sciences, State University of Malang, Indonesia*

²*Center of Advanced Materials and Renewable Energy, State University of Malang, Indonesia*

³*Center of Ionics University Malaya, Department of Physics University Malaya Kuala Lumpur, Malaysia*

Received: 11th February 2026; Revised: 30th April 2026; Accepted: 5th May 2026

ABSTRACT

In this study, the efficiency of silicon solar cells is enhanced by using a titanium dioxide (TiO₂) anti-reflective (AR) coating. The use of the TiO₂ AR coating aims to reduce recombination at the solar cell interface. Many researchers have developed TiO₂ AR coating using the spin coating method. However, research with variations in spin coating speed has not yet been studied. Based on the UV-DRS results, the minimum reflectance was obtained in the sample with the lowest spin coating speed. Low reflectance indicates that more photons reach and are absorbed by the silicon. These results were confirmed by the results of the I-V test that had been carried out at the lowest spin coating speed, resulting in the highest J_{sc} of 135.4 mA/cm² and a maximum efficiency of 20.7%. This high J_{sc} can be attributed to maximum photon absorption, thereby increasing efficiency. The EIS results also showed that the highest recombination resistance of 836.4 Ω was obtained for the lowest spin coating speed variation. Where recombination was successfully suppressed with the increase in R_{rec} obtained in this study.

Keywords: Antireflective; TiO₂; spin coating; silicon solar cell.

Introduction

Silicon solar cells were the first type of solar cells to be mass-produced.¹ However, the main obstacles to achieving high efficiency in these solar cells are losses due to electron-hole recombination, thermal losses, and unwanted reflections.² Pure silicon cells have a high refractive index of around 3.8, which causes silicon reflection losses to range from 31 to 51%.^{1,3} This causes approximately 30% of sunlight to be lost due to reflection, and only 70% can reach the solar cell.¹ This light loss due to reflection can be reduced by applying an antireflective (AR) coating.⁴ Coating solar cells with an AR coating can significantly increase the amount of sunlight absorbed by the cell surface, thereby reducing energy losses due to reflection and increasing conversion efficiency.^{5,6}

Several materials have been used extensively as AR layers, such as TiO₂, ZnO, SiO₂, and Al₂O₃.⁷ Among the various AR materials available, titanium dioxide (TiO₂) is widely used due to its good electrical and optical properties, high chemical resistance, and excellent stability at high temperatures.^{8,9} TiO₂ has the ability to absorb ultraviolet light and high transmittance throughout the visible region, which promotes more absorption of incident light in solar cells.^{10,11} In addition, TiO₂ has a high electrical resistivity (around 10¹⁴ Ω cm), which makes it a good passivation layer that ensures no recombination occurs on its surface, thus helping the efficiency of solar cells.¹¹ Research conducted by Jain et al., using TiO₂ as AR by the sputtering method, resulted in an efficiency of 12.58% with a reflectance of 12%.¹¹ Meanwhile, the research conducted by Anbupalani et al. with the same method achieved a maximum efficiency of 15.01% in

*Corresponding author.

E-Mail: herlin.pujiarti.fmipa@um.ac.id

an open-source environment with a reflectance of 14%.¹²

AR coatings can be prepared using several methods, such as electron beam evaporation (e-beam), chemical vapor deposition (CVD), and sol-gel. One of the sol-gel methods widely used for AR coatings is the spin coating method. The spin coating method has advantages such as the formation of a highly homogeneous film layer, coating on a wider surface area, and cost efficiency compared to other coating methods.¹³ In addition, the spin coating method allows high thickness control, so it can be used to coat nanolayers.¹⁴ Research conducted by Jung et al. using TiO₂ with the spin coating method obtained an efficiency of 13.08%.¹⁵ Meanwhile, research conducted by Azaiez et al., using TiO₂ with the same method, obtained a maximum efficiency of 15.8%.¹⁶ This shows that AR coating using the spin coating method can increase the efficiency of silicon solar cells by controlling the layer thickness and refractive index of the anti-reflective layer so that minimum reflectance can be achieved.³ Although the spin coating method has been widely used for the deposition of TiO₂ as an AR coating, the effect of varying spin coating speeds on the efficiency of silicon solar cells has not been systematically studied. Therefore, in this study, a study will be conducted on how the spin coating speed affects the reflectance and efficiency of the TiO₂ AR layer of silicon solar cells.

Materials and Methods

Materials

The materials used in this study include a silicon substrate, Ti-Nanoxide Blocking Layer (Greatcell Solar Materials), and alcohol (Merck, 96%).

Deposition AR TiO₂

The deposition process of the TiO₂ AR layer begins by washing the silicon substrate using alcohol. The next step is to prepare ready-to-use titanium nanoxide BL as a TiO₂ precursor. Then, the solution is deposited using a spin coating method at speeds of 3000, 5000, and 7000 rpm for 60 seconds onto the silicon substrate, which we then refer to as TiO₂-3k, TiO₂-5k, and TiO₂-7k, respectively. Variations in speed of 3000, 5000, and 7000 rpm are based on our previous study. Next, the samples are annealed using a hotplate at temperatures of 100, 300, and 500°C, as shown in Figure 1.

Result and Discussion

The optical properties of the TiO₂ AR layer were measured using ultraviolet diffuse reflectance spectroscopy (UV-DRS) to determine the reflectance of the TiO₂ AR layer deposited on a silicon substrate using the spin coating method at variations in spin coating speeds.

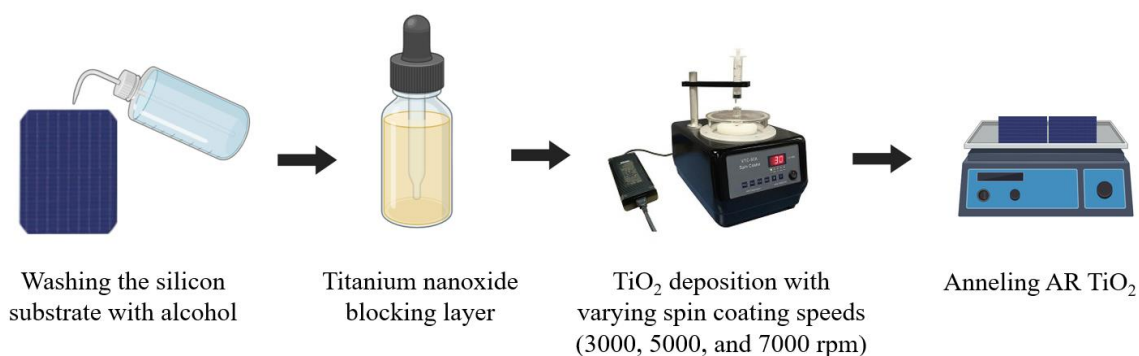


Figure 1. Deposition of AR TiO₂



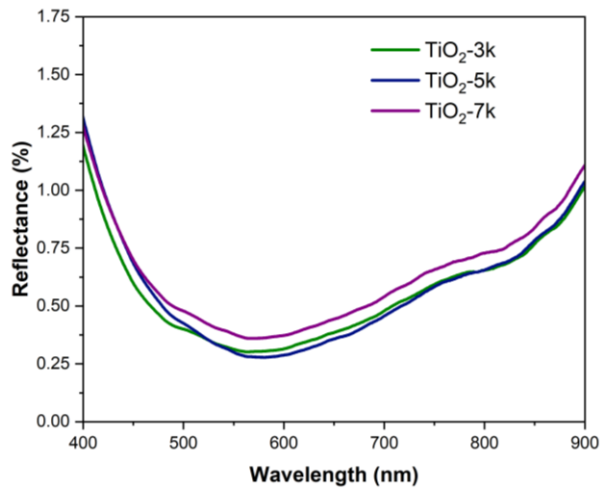


Figure 2. Reflectance spectra of AR TiO₂ with variations in spin coating speed

Figure 2 shows the reflectance spectrum of the AR TiO₂-coated surface in the visible region, which is in the spectral range of 400 nm to 900 nm. From the reflectance spectrum, the minimum photon reflection is obtained in the TiO₂-3k sample. From the reflectance spectrum, it can be understood that the reflectance decreases in the order from the lowest to the highest spin coating speed, as shown in Table 1. This reflectance is lower compared to the reflectance results obtained in the study conducted by Jung et al., which was around 5.42% in the wavelength range of 400–1000 nm.¹⁵

Table 1. Reflectance of AR TiO₂ with variations in spin coating speed

Samples	Reflectance (%)
TiO ₂ -3k	0.55
TiO ₂ -5k	0.56
TiO ₂ -7k	0.62

The reduction in reflection losses increases the photovoltaic cell's light capture capacity.¹² Additionally, low reflectance indicates that the absorption of incident photons is maximized, allowing more photons to reach silicon. This can lead to an increase in J_{sc}.¹⁷

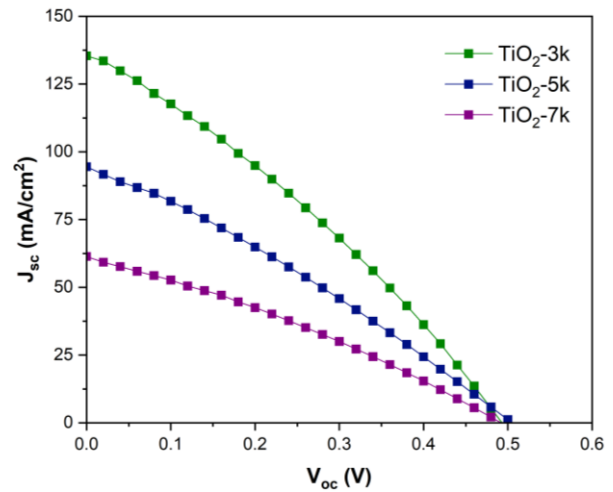


Figure 3. J-V curve of AR TiO₂ with variations in spin coating speed

Figure 3 shows the J-V curve of titanium nanoxide-based TiO₂ for TiO₂-3k, TiO₂-5k, and TiO₂-7k samples. Based on the analysis, it is known that the lower the spin coating speed, the higher the efficiency of the silicon solar cell. Silicon solar cells made with the lowest spin coating speed variation (TiO₂-3k) produced the highest J_{sc} of 135.4 mA/cm² and an efficiency of 20.7%. Meanwhile, the TiO₂-5k and TiO₂-7k samples showed a decrease in J_{sc} of 94.47 and 61.36 mA/cm², respectively, as in Table 2. This resulted in a decrease in the resulting efficiency of 13.9% and 9.13%. This shows that a sufficient thickness of the AR layer can significantly reduce the surface reflectance so that it can increase the photocurrent density from 61.36 mA/cm² to 135.4 mA/cm².³ Decreasing reflectance can increase sunlight absorption, leading to increased current and overall cell efficiency, with optimized cells achieving efficiencies of up to 20.7%.¹⁸ The efficiency results in this study are higher compared to the efficiency obtained in the research conducted by Jung et al. and Azaiez et al., with efficiencies of 13.08% and 15.8%, respectively.^{15,16}



Table 2. Parameters I-V of AR TiO₂ with variations in spin coating speed

Samples	J _{sc} (mA/cm ²)	V _{oc} (V)	FF (%)	η (%)
TiO ₂ -3k	135.4	0.49	31	20.7
TiO ₂ -5k	94.47	0.50	29	13.9
TiO ₂ -7k	61.36	0.49	30	9.13

Electrochemical Impedance Spectroscopy (EIS) is used to understand how electrochemical parameters vary with the spin coating speed on AR coatings, such as series resistance (R_s), recombination resistance (R_{rec}), and parallel or junction capacitance (C_j) on TiO₂-based silicon solar cells as an AR coating.¹⁹

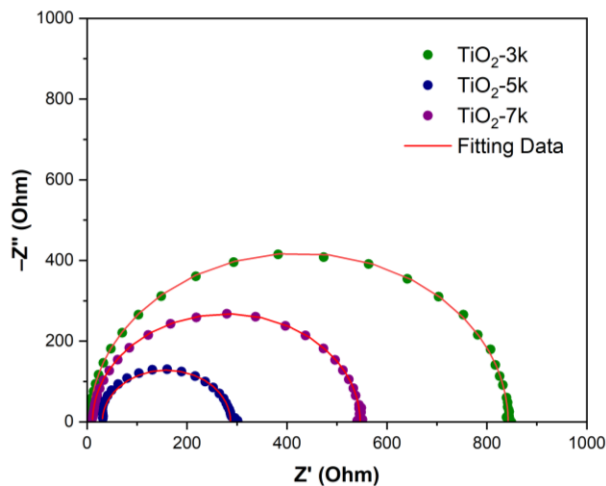


Figure 4. Nyquist plot of AR TiO₂ with variations in spin coating speed

Figure 4 shows the Nyquist plots of solar cells with various spin coating speeds for TiO₂-based AR coating. In this study, the smallest R_s of 5.975 Ω and the highest R_{rec} of 836.4 Ω were obtained for the TiO₂-3k sample, where the high R_{rec} indicates an increase in the AR layer and a reduction in leakage current. The increase in the AR layer is related to a decrease in defect states at the AR layer interface, thereby reducing recombination with holes at the interface. A low recombination in the material can increase the efficiency of the solar cell.²⁰

Table 3. Parameters EIS of AR TiO₂ with variations in spin coating speed

Samples	R _s (Ω)	R _{rec} (Ω)	C _j (Ω)
TiO ₂ -3k	5.975	836.4	0.165
TiO ₂ -5k	30.53	256.5	0.189
TiO ₂ -7k	10.96	535.3	0.285

A low R_s value can efficiently improve charge transport and result in higher J_{sc} and FF.²¹ Meanwhile, R_{rec} is a key parameter affecting cell performance, as a high R_{rec} can suppress charge carrier recombination and suppress leakage current at the junction. Thus, maintaining a higher FF improves overall efficiency.¹⁹

Conclusion

The performance improvement of silicon solar cells studied here was achieved by optimizing the structure of the TiO₂ antireflective layer with the spin coating method. The efficiency of silicon solar cells deposited with the lowest spin coating speed variation resulted in the highest J_{sc} and maximum efficiency. This is due to the minimum reflectance produced by the sample with the lowest spin coating speed. This is also supported by the maximum recombination resistance produced by the sample deposited with the lowest spin coating speed that can minimize recombination in silicon solar cells. Based on the results obtained, a decrease in reflectance can increase the absorption of sunlight, which leads to an increase in current and overall cell efficiency.

Acknowledgment

This research is supported and funded through the DPPM Grant PTM scheme in 2025.

References

1. Alkallas FH, Alghamdi SM, Velu Kaliyannan G, Gunasekaran R, Rathanasamy R, Gouider Trabelsi AB, et al. Enhanced efficiency of mono-crystalline Si solar cells utilizing RF sputtered TiO₂-Al₂O₃ blended anti-reflection coating for optimal sunlight



- transmission and energy conversion. *Ceramics International*. 2024;50:14865–77. doi:10.1016/j.ceramint.2024.01.402
2. Isoe WM, Mageto MJ, Maghanga CM, Mwamburi MM, Odari BV. Optical modelling of TCO based FTO/TiO₂ multilayer thin films and simulation in hydrogenated amorphous silicon solar cell. *Scientific African*. 2023;20:e01678. doi:10.1016/j.sciaf.2023.e01678
 3. Mohmad Salleh SH. Simulation of Anti-Reflective TiO₂/SiO₂ Coating for Silicon Photovoltaic Application by Ray Tracing. *SRJ*. 2023;20:1–11. doi:10.24191/srj.v20i1.19056
 4. Almuflih AS. High-efficiency polycrystalline solar cells via COC-SiO₂ anti-reflective coversheets: A study on power conversion and thermal impact. *Ceramics International*. 2025;51:2340–52. doi:10.1016/j.ceramint.2024.11.215
 5. He T, Qian Z, Wang Q, Zhang Y, Wang H, Zhang J, et al. One step coating anti-reflective SiO₂ film for silicon solar cells applications by atmospheric pressure plasma jet. *Materials Letters*. 2023;350:134915. doi:10.1016/j.matlet.2023.134915
 6. Oleksenko RI. Simulation Photoconverters of porous-Si/Si with Different Anti-Reflective Coatings. *ijmph*. 2023;14. doi:10.26577/ijmph.2023.v14.i2.010
 7. Almakayeel N, Velu Kaliyannan G, Gunasekaran R. Enhancing power conversion efficiency of polycrystalline silicon photovoltaic cells using yttrium oxide anti-reflective coating via electro-spraying method. *Ceramics International*. 2024;50:42392–403. doi:10.1016/j.ceramint.2024.08.084
 8. Sagar R, Rao A. Nanoscale TiO₂ and Ta₂O₅ as efficient antireflection coatings on commercial monocrystalline silicon solar cell. *Journal of Alloys and Compounds*. 2021;862:158464. doi:10.1016/j.jallcom.2020.158464
 9. Hocine D, Belkaid MS, Pasquinelli M, Escoubas L, Torchio P, Moreau A. Characterization of TiO₂ antireflection coatings elaborated by APCVD for monocrystalline silicon solar cells. *Phys Status Solidi C*. 2015;12:323–6. doi:10.1002/pssc.201400085
 10. Ramadhani DAK, Sholeha N, Khusna NN, Diantoro M, Afandi AN, Osman Z, et al. Ag-doped TiO₂ as photoanode for high performance dye sensitized solar cells. *Materials Science for Energy Technologies*. 2024;7:274–81. doi:10.1016/j.mset.2024.02.002
 11. Jain S, Paliwal A, Gupta V, Tomar M. Plasmon-Assisted Crystalline Silicon Solar Cell with TiO₂ as Anti-Reflective Coating. *Plasmonics*. 2020;15:1091–101. doi:10.1007/s11468-020-01127-5
 12. Anbupalani MS, Venkatachalam CD, Rathanasamy R, Sivaraj S. Utilisation of SiO₂/TiO₂/Al₂O₃ mechanical blends for enhancing the photovoltaic efficiency in polycrystalline silicon solar cells. *Surfaces and Interfaces*. 2025;65:106466. doi:10.1016/j.surfin.2025.106466
 13. Kanmaz İ, Tomakin M. Anti-reflective effect of CeO₂ thin films produced by sol-gel method on crystalline silicon solar cells. *J Sol-Gel Sci Technol*. 2023;108:361–7. doi:10.1007/s10971-023-06161-3
 14. Ragavendran A, Rajasekar R, Jaganathan S, Raj MKA. Anti-Reflection Coating. In: Rajasekar R, Moganapriya C, Mohankumar A, editors. *Materials for Solar Energy Conversion* [Internet]. 1st ed. Wiley; 2021 [cited 2025 Sep 26]. p. 323–52. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/9781119752202.ch12> doi:10.1002/9781119752202.ch12
 15. Jung J, Jannat A, Akhtar MS, Yang OB. Sol-Gel Deposited Double Layer TiO₂ and Al₂O₃ Anti-Reflection Coating for Silicon Solar Cell. *j nanosci nanotechnol*. 2018;18:1274–8. doi:10.1166/jnn.2018.14928
 16. Azaiez K, Benabderrahmane Zaghouni R, Amdouni R, Dimassi W. Investigation on TiO₂ spin-coated thin



- films effect on the optoelectronic properties of stain-etched porous silicon for solar cell applications. Phosphorus, Sulfur, and Silicon and the Related Elements. 2024;199:551–9. doi:10.1080/10426507.2024.2402712
17. Tuama SA, Abdulrazzaq OA, Nasir NA, Saloom AH, Mohammed M. Enhanced Photovoltaic Performance of Silicon Solar Cells via Plasma-Deposited Antireflective Titanium Dioxide Coatings. JASN. 2025;5:1–11. doi:10.53293/jasn.2025.7573.1334
18. Shivangi, Saxena AK, Shadab Siddiqui M. Effect of AR Coating Properties on Diffused Reflectance and Overall Efficiency of mc-Si Silicon Solar Cells. In: Kumar M, Pandey RK, Kumar V, editors. Advances in Interdisciplinary Engineering [Internet]. Singapore: Springer Singapore; 2019 [cited 2025 Sep 26]. p. 407–12. (Lecture Notes in Mechanical Engineering). Available from: http://link.springer.com/10.1007/978-981-13-6577-5_38 doi:10.1007/978-981-13-6577-5_38
19. Chen T, Guo H, Yu L, Sun T, Chen A, Wang J, et al. Antireflection Improvement and Junction Quality Optimization of Si/PEDOT:PSS Solar Cell with the Introduction of Dopamine@Graphene. Energies. 2020;13:5986. doi:10.3390/en13225986
20. Zala P, Tripathi B, Khemnani M, Hirpara D, Kapadia R, Gupta M, et al. Optimizing anti-reflection coating using electrochemical impedance spectroscopy to enhance electrical performance of solar cell. Opt Quant Electron. 2025;57:452. doi:10.1007/s11082-025-08371-1
21. Hu X, Zhao Y, Yang H, Hou P, Liu C, Chang J, et al. Interfacial Chemical Bridging Constructed by Multifunctional Lewis Acid for Carbon Nanotube/Silicon Heterojunction Solar Cells with an Efficiency Approaching 17.7%. Advanced Science. 2023;10:2206989. doi:10.1002/adv.202206989

