

UNIVERSITI TEKNOLOGI MARA

**NUMERICAL MODELLING OF THE
EFFICIENCY OF ZNO/GAAS AND
ZNO/ALGAAS/SI SOLAR CELLS
USING VARIOUS TYPES OF ANTI-
REFLECTIVE COATING (ARC)**

FATINAH NAJWA BINTI ROSLAN

MSc

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FATINAH NAJWA BINTI ROSLAN

Thesis submitted in fulfilment of the requirements for
the degree of
**Master of Science
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I certify that a Panel of Examiners has met on 27th January 2026 to conduct the final examination of Fatinah Najwa Binti Roslan on Master of Science thesis entitled “Numerical Modelling of the Efficiency of ZnO/GaAs and ZnO/AlGaAs/Si Solar Cells Using Various Types of Anti-Reflective Coating (ARC)” in accordance with Universiti Teknologi MARA Act 1976 (Akta 173). The Panel of Examiners recommends that the student be awarded the relevant degree. The Panel of Examiners was as follows:

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ABSTRACT

A solar cell is an electronic device that can convert sunlight to electricity through the photovoltaic effect. However, most light will be bounced back into the air when it strikes the top of the solar device, which indirectly reduces light absorption. Numerous researchers investigated the solar cell to find the best materials and parameters to generate the highest efficiency. Various methods were introduced to enhance the work function of the solar cell. Applying an anti-reflective coating (ARC) on the top of the solar cell will play a big role in reducing the reflection of light. In order to identify the most effective layer for increasing efficiency, this study has employed a number of layers, including single-layer anti-reflective coating (SLARC), double-layer anti-reflective coating (DLARC), and triple-layer anti-reflective coating (TLARC). Some studies found that because the triple layer offers a wider spectrum response, it will yield high efficiency. Every material has its own characteristics that will contribute to the efficiency of the results, such as refractive index and thickness at a specified wavelength. For the purpose of absorbing light in a solar cell with destructive interference, these materials were stacked from low to high refractive index. The single, double, and triple layers were applied on top of both ZnO/GaAs and ZnO/AlGaAs/Si solar cells. Although crystalline silicon and ZnO/Si are both utilized extensively in the photovoltaic industry due to their high efficiency, many researchers discovered that n-ZnO/p-GaAs also showed promise for high efficiency and had additional benefits over other solar cells. Also, designing the cell device in a triple-heterojunction was approved by many researchers as it can improve the performance. In this study, a personal computer 1-dimensional (PC1D) simulation have been used to simulate the efficiency of a solar cell at specified wavelengths between 250nm – 1200nm under AM1.5G condition. The PC1D simulation provides maximum power output (P_{max}), open-circuit voltage (V_{OC}), and short-circuit current (I_{SC}) as a result that were used to calculate the efficiency of the solar cell. Based on the PC1D simulation, the uncoated ZnO/GaAs solar cell resulted 17.76% of the efficiency. The ZnO/GaAs solar cell was improved by implementing the single-, double- , and triple-layer on top of it. The SiO₂ as a single-layer ARC successfully achieved the efficiency of 19.62%. Meanwhile, for double-layer ARC, among six pairs, SiO₂/ZnO was observed to have the highest efficiency with 19.64%. Moreover, SiO₂/ZnO/Si₃N₄ as a triple-layer ARC was achieved the best efficiency, out of nine schemes with 19.65%. For the new designs of a triple-heterojunction, the uncoated ZnO/AlGaAs/Si solar cell, was gained 21.98% of the efficiency. The applicant of ARC also be made on the ZnO/AlGaAs/Si solar cell to reduce the light reflectance. The results showed the highest efficiency for a single-layer ARC by using SiO₂ with 24.08%, SiO₂/ZnO as a double-layer ARC with 24.15%, and SiO₂/ZnO/Si₃N₄ as a triple-layer ARC with 24.16%. These results could show the different material with various types of ARCs could produce different output across the wavelength. Based on the simulations that were carried out, there are numerous methods that can be used to improve the solar cell for further enhancement.

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LIST OF SYMBOLS

Symbols

η	The Efficiency of Solar Cell
I_{light}	Light Intensity
P_{input}	Power Input
n_{ARC}	Refractive Index of ARC
n_{air}	Refractive Index of Air
λ_0	Specified Wavelength
c	Speed of Light
E	Energy
h	Planck's Constant
n	Refractive Index
q	Electronic Charge
A	Device Surface Area
d	Thickness
α	Alpha
β	Beta
λ	Wavelength
ν	Frequency of Light

LIST OF ABBREVIATIONS

Abbreviations

AlGaAs	Aluminum Gallium Arsenide
ARC	Anti-Reflective Coating
BSF	Back Surface Field
DLARC	Double-Layer Anti-Reflective Coating
E_f	Fermi Level
EQE	External Quantum Efficiency
FF	Fill Factor
GaAs	Gallium Arsenide
GaInP	Gallium Indium Phosphide
Ge	Germanium
HfO ₂	Hafnium (IV) Oxide
HJ	Heterojunction
HJSC	Heterojunction Solar Cell
InP	Indium Phosphide
I_{sc}	Short-Circuit Current
I-V curve	Current-Voltage Curve
J_{sc}	Short-Circuit Density
MgF ₂	Magnesium Fluoride
PC1D	Personal Computer 1-Dimensional
P_{max}	Maximum Power Output
PV	Photovoltaic
QE	Quantum Efficiency
RI	Refractive Index
Si	Silicon
Si ₃ N ₄	Silicon Nitride
SiO ₂	Silicon Dioxide
SLARC	Single-Layer Anti-Reflective Coating
SR	Spectrum Response

TiO ₂	Titanium Dioxide
TLARC	Triple-Layer Anti-Reflective Coating
UV	Ultraviolet
V_{oc}	Open-Circuit Voltage
ZnO	Zinc Oxide
ZnS	Zinc Sulphide

CHAPTER 1

INTRODUCTION

1.1 Research Background

Considering that the proportion of fossil fuel-based energy sources in the production of electricity has decreased recently, renewable energy sources now account for a larger portion (Ekren, 2018). Renewable energy is energy obtained from natural sources that are renewed more rapidly than they are utilized. Instances of such continuously replenishing sources are sunlight and wind. Compared to other renewable energy sources, solar energy has had a greater influence on resolving the energy issue in recent years due to its maximum power conversion efficiency, endless energy, and environmental friendliness (Prashanth et al., 2021).

Numerous technologies, including photovoltaic (PV) cells and solar cells, which are now in use worldwide, may harness solar energy. A solar cell is a mechanical device that can convert sunlight directly to electricity. Sunlight enters the solar cell and produces charge carriers, which are electron-hole pairs. The charge carriers produced by the light are subsequently separated. The p-region of an external solar circuit allows the holes to move away from the junction, whereas the n-region allows the electrons to move out and travel across the circuit before recombining with the holes (Al-Ezzi & Ansari, 2022). The electric current has produced by the charge flow through metal wires, and the electrons will pass through the metal wires, which will recombine with the holes. However, photons with energies lower than the material's band gap energy are unable to produce photo carriers (Nayak et al., 2024).

The efficiency of the solar cell may be reduced as a result of some photons reflecting into the air when sunlight strikes the top of the cell. There are a few ways that have been studied to optimize the function of solar cells, which are the materials of solar cells, texturing the surface, usage of anti-reflective coating (ARC) on the top of solar cells, and many more. Adding an ARC on top of the solar cell can help to reduce the reflectance of light. There are a few parameters in ARC that need to be adjusted to increase the efficiency of the solar cell, which are the number of layers of ARC, the

thickness, the material of ARC, and the texturing surface on top of the ARC. There are a few types of ARCs, which are Single-Layer Anti-Reflective Coating (SLARC), Double-Layer Anti-Reflective Coating (DLARC), and Triple-Layer Anti-Reflective Coating (TLARC). The reflection of photons can also be minimised as the number of layers increases. However, triple-layer coatings are more stable and long-lasting than other multi-layer coatings, and they also provide outcomes that are appropriate for each form of solar cell (Ekren, 2018).

The first development of a high efficiency solar cell was successfully made by crystalline silicon. As the days pass by, many researchers study the best material of substrate that can be used for solar cells, such as zinc oxide (ZnO), which is widely used in the photovoltaic industry after silicon due to its characteristics. ZnO can be paired with other p-types such as gallium arsenide (GaAs). Numerous studies on ZnO/Si heterojunction solar cells have already been published, but only a few experiments have demonstrated that ZnO/GaAs exhibits greater electrical quality and efficiency when properly optimized and constructed (Derbali, 2022). Besides that, ZnO also be studied as a triple heterojunction combined with aluminum gallium arsenide (AlGaAs) and silicon (Si).

In this study, different materials were used for each type of ARC layer to determine the highest efficiency for ZnO/GaAs and ZnO/AlGaAs/Si solar cells using Personal Computer 1-Dimensional (PC1D) software in a specified wavelength range between 250nm – 1200nm. Also, the results were generated by PC1D simulation, such as the maximum power output (P_{max}), open-circuit voltage (V_{oc}), and short-circuit current (I_{sc}) have calculated and analyzed to determine the best material that can be used as an ARC on the top of the solar cell. This study provides the findings of both solar cells with coated and uncoated, allowing local researchers to improve their new invention of cell device structure.

1.2 Motivation for This Work

The ever-increasing demand for energy worldwide, coupled with increasing issues on the environment, has increased the desire to use high-efficiency photovoltaic technologies. Within this number of choices of solar cell materials, GaAs-based and III-V/Si hybrid cells have received a substantial amount of scholarly interest due to their

excellent optical absorption properties, high carrier mobilities, as well as the potential of achieving efficiencies that outperform conventional silicon solar cells. However, a major drawback of these devices is the optical loss caused by surface reflections, especially the large refractive index difference between the ambient air and the high-index semiconductor substrates.

In order to improve light absorption into the absorber layers and minimise reflection losses, the ARCs are essential. Single-layer ARCs are relatively easy to produce, but generally can only offer efficient anti-reflections in a small spectral range. Multilayer ARC designs, such as double-layer and triple-layer designs, in contrast, provide wider spectral coverage and better optical performance. Although they are very important, the optimal arrangement, choice of material, and sequence of layers of ARCs optimized to ZnO/GaAs and ZnO/AlGaAs/Si solar cells have not been explored extensively, particularly with systematic numerical modelling.

The relationship between reflectance behavior, external quantum efficiency (EQE), and overall device efficiency is rarely discussed in previous research since it frequently concentrates on optical or electrical performance independently. This lack of knowledge creates a dilemma as to the reason as to why some ARC schemes can provide greater overall efficiencies despite the fact that their reflectance does not necessarily have to be the lowest. The issue of these gaps needs to be resolved to allow the rational design of high-performance and practical solar cells. Driven by these limitations, the current study aims to use the numerical simulation tools to analyze how various configurations of ARC affect the optical and electrical performance of ZnO/GaAs and ZnO/AlGaAs/Si solar cells. Through a rigorous interpretation of reflectance spectra, EQE features, and important photovoltaic parameters, it is hoped that the study will produce more in-depth information regarding the ARC engineering and also suggest the best design of coating structures that will not only increase the efficiency of the device but also simultaneously lessen the experimental cost and complexity of the work.

1.3 Problem Statement

A solar cell has to absorb the maximum number of photons to produce a good amount of electricity. Nevertheless, this solar cell has a few issues that may occur, including exciton production, inadequate light absorption, and, more specifically,

reflection loss. When the rays of light hit the surface, they were reflected into the air, which causes the light transmission to be low. This can occur because of the difference in refractive index between air and substrates (Shen et al., 2023). There are some methods that can be used to reduce the reflectance, such as applying an ARC and texturing the surface. The use of ARC on a solar panel is a common technique to reduce the reflectance in the photovoltaic industry. Various types of ARCs have been examined in this study to identify the best types with the highest efficiency, such as a single-layer ARC, a double-layer ARC, and a triple-layer ARC. However, the amount of comparative data for each type of ARCs in ZnO/GaAs solar cells is insufficient. Consequently, comprehensive data collection, analysis, and calculation using appropriate equations are required to achieve precise parameters, a suitable ARC design, and a material combination to minimize the reflectance and enhance the optical response to the device. Therefore, the use of the materials for each ARC have been studied as each material has a unique refractive index, bandgap, and other characteristics. The results of this study will differ because the combinations of materials for ARC layers are different. The refractive index and thickness for each material of the ARC were calculated by using the equation to achieve the optimal value for each wavelength between 250nm – 1200nm. The sun spectrum spans this range, which is why these wavelengths are used (Haug et al., 2013).

Moreover, the combination of ZnO and GaAs to form a heterojunction solar cell began because it can promise a good efficiency. However, the optimal parameters for this configuration have not been optimized and studied (Jin & Tang, 2021). It shows that the efficiency of the ZnO/GaAs solar cell was still not maximized. To boost the efficiency of solar cells, the triple heterojunction solar cell (HJSC) was developed, as it is reported to have a great efficiency by stacking multiple materials with various band gaps. Hence, Si has been added as the absorber; concurrently, the GaAs was replaced with AlGaAs in the configuration to match the graded bandgap to form a ZnO/AlGaAs/Si solar cell. Despite that, the ZnO/AlGaAs/Si solar cell still reflects the sunlight to the air, which causes the efficiency is not be maximized. Therefore, this approach aims to achieve better lattice matching and higher absorption of the photons with the coated and uncoated solar cell devices. Other than that, due to the large number of parameters and material alternatives, developing ARC is a challenging undertaking. It is also difficult and expensive to produce an ARC experimentally with the solar cell. Therefore, there are a few simulations that were invented to help researchers study their

cell design before working in a real experiment. A PC1D simulation was chosen to be used as the simulator to study the photovoltaic properties for both devices with ARCs. Ultimately, this study aims to enhance the absorption and optimize the ARCs design with appropriate layers and materials for ZnO/GaAs and ZnO/AlGaAs/Si solar cells using PC1D simulation.

1.4 Research Questions

1. How can ARC materials be selected to yield the highest efficiency when applied to ZnO/GaAs and ZnO/AlGaAs/Si as a triple heterojunction solar cell?
2. How does the number of ARC layers (single, double, and triple) influence light absorption and solar cell efficiency?
3. How do different ARC materials and configurations influence the photovoltaic properties of planar solar cells?
4. How effective is the ZnO/GaAs and ZnO/AlGaAs/Si heterojunction structure compared to conventional solar cell configurations in terms of simulated performance?

1.5 Research Objectives

Main objectives are;

1. To investigate the effect of different ARC materials on the efficiency of ZnO/GaAs and ZnO/AlGaAs/Si solar cells using PC1D simulation.
2. To compare the performance of single-layer, double-layer, and triple-layer ARC configurations in enhancing light absorption and minimizing reflection on a planar surface of ZnO/GaAs and ZnO/AlGaAs/Si solar cells.
3. To identify the optimal combination of ARC materials and layer configuration by evaluating key photovoltaic parameters, including, short-circuit current, open-circuit voltage, maximum power output, fill factor, power conversion efficiency of ZnO/GaAs and ZnO/AlGaAs/Si solar cells.

1.6 Significance of Study

The study is significant because it represents detailed numerical research on the optical and electrical performance of the ZnO/GaAs and the ZnO/AlGaAs/Si solar cells with different kinds of ARCs. Through a systematic study of the ARC set ups of single-layers, double-layers, and triple-layers, this research explains how refractive index matching, sequence of layers, and thickness optimization can be used to reduce the optical losses and maximize the photon absorption in a wide range of wavelengths. Scientifically, the work brings in a better knowledge on the interaction between multilayer ARC structures and high refractive index semiconductor substrates. The fact that reflectance spectra, as well as the EQE, and the overall device efficiency are correlated, can give useful understanding of the reason for some ARC schemes can perform better despite not necessarily having the lowest minimum reflectance. This facilitates the elimination of discrepancies between optical and electrical performance that are usually witnessed in photovoltaic devices.

Besides that, technologically, the results provide realistic design principles in streamlining the ARC configurations in high efficiency III-V and hybrid III-V/Si solar cells. The numerical modelling method saves cost and time of experiment and provides the ability to control material parameters accurately such that the results are extremely relevant to device engineers as well as researchers who seek to enhance the solar cell efficiency by means of optical management. Moreover, this study promotes the design of cost-efficient and performance photovoltaic devices by determining ARC structures that can maximize the light absorption without affecting material incompatibility and fabrication capabilities. The results are especially applicable in the advanced photovoltaic applications, such as high-efficiency terrestrial and optoelectronic-integrated solar systems. In general, this study promotes the optimization of photovoltaic devices to show that designing the ARC is highly vital in enhancing the performance of ZnO-based GaAs and AlGaAs/Si solar cells.

Furthermore, one of the significances in this study is to identify the appropriate materials of the ARCs to optimize the performance of the solar cell. Every material has its own characteristics that could give advantages to the solar cell for optimizing the performance. Therefore, there are five materials that were used as the ARCs, which consisting SiO₂, Si₃N₄, ZnO, ZnS, and TiO₂. Besides its physical and chemical

properties, the refractive index and thickness also were calculated for each of the materials along the wavelengths at 250nm – 1200nm. The optimal refractive index and thickness were used to maximize the performance and controlling the destructive interference. The materials for the double- and triple-layer were combined to form an appropriate layer of the ARCs which would give a different result of the efficiency. The data and findings in this study could help the further studies to analyse and enhance the solar cell with suitable ARCs types.

1.7 Limitation

Despite the fact that the current investigation has produced valuable results, there are some limitations that should be mentioned. First of all, the relative lack of literature dedicated to ZnO/GaAs and ZnO/AlGaAs/Si photovoltaic cells with multilayer anti-reflection coatings does not allow making a direct comparison and confirming the existing experimental and theoretical results. Based on this, parts of the discourse are based on general optical coating theory and related photovoltaic structures instead of literature related to devices.

Moreover, the calculations involved the use of PC1D simulation which was mainly optimized to the silicon-based photovoltaics. Although the program provides material parameters, on a detailed scale, of silicon, other semiconductor compounds such as GaAs, AlGaAs, and ZnO are either not well-documented. Therefore, particular material properties were estimated, guessed, or found in secondary sources, which may create differences between the results of simulations and the actual device behavior. Furthermore, complex phenomena including interface states, lattice mismatch, strain-driven defects, and intricate recombination pathways that are pertinent to III-V and heterostructure photovoltaics are not represented by PC1D simulation. The effects of this nature that can significantly change electrical and optical characteristics of real devices are not explained within the existing paradigm of simulation.

1.8 Thesis Scope

The scope of this study is to identify the material of ARC to achieve the maximum of absorption of photons by using various materials for single, double, and triple layer. For SLARC, there are three materials that has been used to investigate the best material for SLARC which are silicon dioxide (SiO_2), silicon nitride (Si_3N_4) and zinc oxide (ZnO), $\text{SiO}_2/\text{Si}_3\text{N}_4$, $\text{SiO}_2/\text{TiO}_2$, SiO_2/ZnO , SiO_2/ZnS , ZnO/TiO_2 and ZnO/ZnS for ZnO/GaAs solar cell and $\text{ZnO}/\text{AlGaAs}/\text{Si}$ were examined by DLARC's pair same as ZnO/GaAs but with additional three pairs with $\text{ZnO}/\text{Si}_3\text{N}_4$, $\text{Si}_3\text{N}_4/\text{TiO}_2$ and $\text{Si}_3\text{N}_4/\text{ZnS}$ as DLARC, meanwhile TLARC will consist of $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnO}$, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnS}$, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{TiO}_2$, $\text{SiO}_2/\text{ZnO}/\text{ZnS}$, $\text{SiO}_2/\text{ZnO}/\text{TiO}_2$, $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$, $\text{ZnO}/\text{Si}_3\text{N}_4/\text{TiO}_2$, $\text{ZnO}/\text{Si}_3\text{N}_4/\text{ZnS}$ and $\text{ZnO}/\text{TiO}_2/\text{ZnS}$ for both solar cell. Applying the ARC on the top of solar cell will help to minimize the reflection of light which can lead to increment of efficiency of the solar cell. Furthermore, this study is carrying out to determine the best material and type of ARC that can be used for solar cell to achieve the maximization of efficiency. Numerous researchers before were studied the solar cell using silicon, Si as p-type and zinc oxide, ZnO or gallium arsenide, GaAs as n-type. Thus, in this study is to examine the efficiency of zinc oxide, ZnO as n-type and gallium arsenide, GaAs as p-type and for other device, ZnO and AlGaAs as n-type and Si as the p-type in solar cell. Besides that, the photovoltaic properties for every material for ARC can be identify for every scheme. The PC1D simulation has been carried out to determine the open circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum power output (P_{max}) which can be used to calculate efficiency (η) and fill factor (FF). Hence, this study investigates the ARC in single, double, and triple layers with various materials on the ZnO/GaAs and $\text{ZnO}/\text{AlGaAs}/\text{Si}$ solar cell.

1.9 Thesis Outline

A clear and well-structured thesis outline is essential for guiding the flow of the research and ensuring that each chapter develops logically from the previous one. Hence, this thesis consists of six chapters. Chapter 1 consists of the research background, the motivation for this work, the problem statement, the research objectives, the research questions, the significance of the study, limitations, thesis

scope, and thesis outline. This chapter provides a clear detail of the study for better understanding and shape the development of the thesis. Chapter 2 provides a comprehensive review of the literature related to the principal selection. The theoretical background, fundamental ideas, and prior research findings that underpin the current work's development are presented in this chapter. This chapter sets the scientific framework and highlights gaps that need additional research by looking at relevant papers, material properties, device structures, and analytical techniques. Furthermore, the flow work of this study was explained scientifically and structured in Chapter 3, methodology. This chapter describes the general research framework, which includes the material combinations, simulation settings, and design parameters used to assess the solar cell structures' performance.

All the data that was collected using the simulation were recorded in the table for each type of ARC. These findings of the simulations are presented in Chapter 4 and Chapter 5, for ZnO/GaAs and ZnO/AlGaAs/Si solar cells, respectively, along with a thorough analysis of their relevance to the study's goals. The performance of the solar cell under several ARC methods is examined in this chapter, with particular attention paid to metrics like reflectance, EQE, and total device efficiency. Lastly, Chapter 6 provides the conclusion of this study by summarizing key findings and their relation to the objectives of the study. Besides, the recommendation is also presented in this chapter for further enhancement to guide further researchers by enhancing the simulation accuracy, and exploring alternative materials and methods to improve the solar cell.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

All types of energy that exist in this world are very important and useful to all living things to continue their daily life. Day by day, usage of energy is increasing, which can lead to running out of the source. This can happen to non-renewable energy like petroleum, coal, and natural gas. Also, long-term usage of these fuels has resulted in several environmental risks, including air and water pollution and dangers to animal species (Dambhare et al., 2021). To overcome these problems, researchers came out with a lot of solutions by using renewable energy in our daily lives. Renewable energy is energy that can be produced again as needed and comes from natural sources such as the sun, wind, rain, and tides (Swami R, 2012). Since society is becoming more conscious of the need for a clean environment, renewable energy sources (RE) are gaining popularity owing to their ecologically benign qualities and capacity to provide electricity with virtually no emissions of air pollutants (Ang et al., 2022).

Solar energy is a limitless source that will always be available for the whole world. The sun's emission is around $6.4 \times 10^7 \text{ W/m}^2$. Of this, assuming no solar absorption occurs in space, around 1370 W/m^2 is incident on Earth's atmosphere, and roughly 980 W/m^2 of power density reaches the Earth's surface (Dambhare et al., 2021). There are two methods for using solar energy, which are photovoltaic and photothermal (Deshpande, 2021). In this study, sun energy was used in photovoltaics which it can convert the photon energy to electricity using solar cell device. First observer of photovoltaic effect by Edmond Becquerel in 1839 which he discovered that when exposed to sunlight, two separate brass plates submerged in a liquid generated a constant current (Fraas & Partain, 2010). After 100 years passed, Russel Ohl introduced first modern solar cell in 1946 and Daryl Chapin, Calvin Fuller and Gerald Pearson developed the first practical at 1954 at Bell Labs (Sankalpa et al., 2010). Solar energy's primary advantage over other traditional power sources is its ability to directly capture sunlight via the use of minuscule photovoltaic (PV) solar cells (Sharma et al., 2015).

However, there are major problems that can be detected for using sunlight as main source energy for this technology. It's not always consistent, and it's not accessible at night (Dambhare et al., 2021). Thus, enormous researcher came out the solution to overcome every problem that arise for this technology.

2.2 Solar Cell

2.2.1 Basic Structure of Solar Cell

In a solar cell, the main structure in the solar cell is the n-type (emitter), which has more electrons than the p-type (base), which has more positively charged holes. This solar device is called a p-n junction device. The thickness of the n-type must be thinner than the p-type to ensure the electrons can pass through in a short time and produce current before recombining with holes (Al-Ezzi & Ansari, 2022). The semiconductor is divided into two types, which are homojunction and heterojunction. A heterojunction is a junction made of separate materials for each p-n type, whereas a homojunction is a junction made of the same material for both p-n types but with a different doping level. Based on Figure 2.1, on the top and bottom of the device, there are front and rear contacts. The entire performance of the solar cell can be significantly impacted by the contact between the front and rear. A solar cell's P_{CE} and V_{OC} are improved via a low-resistance ohmic interface (Babu et al., 2016). Both contacts are additional electrical contact layers to carry the electric current out to an external load and back into the cell. Reflection of light will happen when the sunlight strikes the top of the solar cell, which can lead to lower efficiency. Applying the ARC on top of the solar cell can help to reduce the reflection.

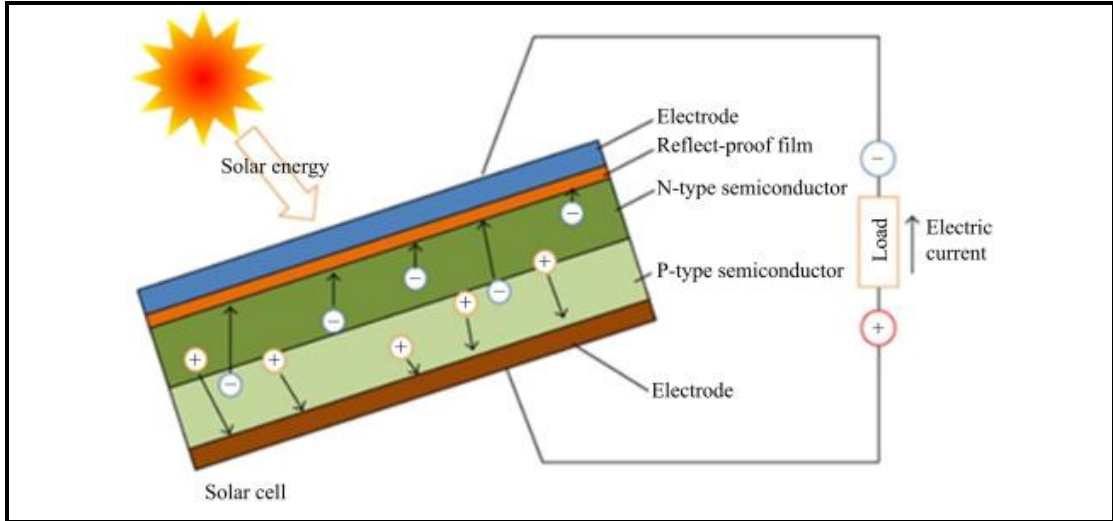


Figure 2.1 Structure of Solar Cell (Alazrag et al., 2023)

2.2.2 Operation of Solar Cell

Fundamentally, a solar cell produces two different types of semiconductors, which are p-type and n-type, that can be combined to become a p-n junction. In this operation, the electron in the n-region will move to the positive side of p-type, meanwhile, the holes in the p-region will move to the negative side of n-type. An electrical voltage is created by this field when negatively charged particles travel in one direction and positively charged particles move in the other (Guerra et al., 2018). The working principle of the solar cell was discovered by Alexander Becquerel. However, this photovoltaic effect is closely related to the photoelectric effect, which was explained by Albert Einstein in 1905 (Guerra et al., 2018). He assumed that photons in sunlight are quantum energy, which can form a formula as;

$$E = h\nu \quad (2.1)$$

which E is the energy, h is Planck's constant and ν is the frequency of light. The amount of $h\nu$ must be higher than the energy gap to excite the electron from the valence band to the conduction band, and indirectly will leave a hole in the valence band (Al-Ezzi & Ansari, 2022).

The working principle for this solar cell is based on the photovoltaic effect. It happens when the light strikes the top of the device, and some of it is transmitted and

absorbed into the cell, which will produce a photon-generated electron-hole pair, while the rest will reflect. Before recombining, the electron-hole pair is separated by the p-n junction's internal built-in electric field (Guerra et al., 2018). The charge carrier will be extracted from the solar cell with electrical contacts (rear and front contacts). It will contribute to the output current in the external circuit. Electrons can move out over the n-region and cross the circuit before recombining with the holes in an external solar circuit, whereas the holes can move away from the junction through the p-region (Al-Ezzi & Ansari, 2022). Ultimately, electric energy is produced from the charge carriers' chemical energy (Guerra et al., 2018).

2.2.3 ZnO/GaAs Dual Heterojunction Solar Cell

The choice of ZnO/GaAs solar cells is supported by several researchers. Zinc oxide (ZnO)-based materials exhibit potential for use in photovoltaic, thermal, and piezoelectric energy harvesting applications (Zhou et al., 2017). In the photovoltaic industry, ZnO has been widely used due to its characteristics that can make a significant contribution to promising good efficiency. It has emerged as a potential functional semiconductor material with a wide variety of innovative uses because of its enormous free exciton binding energy and direct and wide band gap in the near-UV spectral region (MD T., 2019). However, ZnO coating may be paired with different p-type absorber materials to function as an active layer for single heterojunction solar cells in addition to being an antireflective layer (Manoua et al., 2023), such as Si and GaAs. An enormous researcher has studied and carried out an experiment to increase the efficiency of ZnO/Si solar cells, as silicon can promise high efficiency.

Similar to ZnO, gallium arsenide finds extensive application in semiconductors because of its appealing characteristics. High optical absorption coefficients, direct energy band gaps, and advantageous minority carrier lifetime and mobility values are among the characteristics of III-IV compounds, such as GaAs, that make it possible to create extremely effective solar cells (Dhamija et al., 2014). The GaAs has a direct bandgap of 1.42 eV, which will allow the material to withstand exposure to high temperatures. Although pairing ZnO and GaAs with silicon will give high efficiency, researchers found that ZnO/GaAs promising efficiency more than ZnO/Si and GaAs/Si. However, researchers are still studying the optimization value of ZnO/GaAs by using a

lot of methods, such as studying the ZnO's thickness, affinity and carrier concentration, investigating with various thicknesses and carrier concentrations of ZnO/GaAs (Manoua et al., 2023), and Derbali (2022) improved the structure by using a few methods in experimental way. In this study, ZnO/GaAs solar cells have been investigated by applying various ARC on top of the device. Table 2.1 shows the comparison of reported solar cell design and optimization with previous study.

Table 2.1
Comparison of Reported Solar Cell Design and Optimization for ZnO/GaAs Solar Cells

Structure	ARC used	Methods	Optimization parameters	References
ZnO/GaAs	Yes (ZnO nanorods as DLARC)	Experimental	Gettering process, ZnO emitter thickness, interface microgrooves, ZnO nanorods, and carrier lifetime	Derbali (2022)
ZnO/GaAs	No	Atlas Silvaco Simulation	Thickness and Doping Concentration for both substrates	Manoua et al. (2023)
ZnO/GaAs	No	Silvaco TCAD	ZnO's thickness, affinity, and carrier concentration	Jin and Tang (2021)
ZnO/GaAs	Yes (SLARC, DLARC, TLARC)	PC1D Simulation	ARC thickness and Refractive Index	This study

2.2.4 ZnO/AlGaAs/Si Triple Heterojunction Solar Cell

Multijunction solar cells were meant to improve the performance of solar cells by using appropriate materials, such as a triple heterojunction (HJ) solar cell. Researchers before started to study new devices of solar cells by combining three materials such as AlGaAs/GaAs/Si (Sathya & Supriya, 2017), GaInP/AlGaAs/Si tandem cell (Dimroth et al., 2020), and many more. They used various methods, including experimental and simulation, to find optimization parameters and good

efficiency. Table 2.2 shows the comparison and summarization for solar cells design and optimization by previous study. The ZnO/GaAs solar cell was approved by researchers before due to its characteristics. Thus, aluminum gallium arsenide (AlGaAs) and silicon (Si) will combine with ZnO to form a triple HJ solar cell for studying its performance. AlGaAs's significant band gap energy functions as a Back Surface Field (BSF), and its performance is enhanced by the addition of a window layer (Kc et al., 2020). Its broad bandgap (1.817eV) further makes it an n-type substrate. It has been found that AlGaAs for the top layer and silicon for the substrate might be the best choice for a multijunction solar cell (Sathya & Supriya, 2017).

Table 2.2
Comparison for Various Related Solar Cell Design and Optimization Parameters by Previous Study

Structure	ARC used	Methods	Optimization parameters	References
AlGaAs/Si	No	Experimental	Fabrication technique and heterojunction integration	Xiong et al. (2018)
AlGaAs/c-Si	No	PC1D simulation	Thickness and Doping Concentration of the different layers in device	Roy et al. (2023)
ZnO/Si	Yes (SLARC, DLARC, and TLARC)	PC1D simulation	ARC thickness and Refractive Index	Jamaluddin et al. (2024)
GaInP/AlGaAs/Si	Yes (DLARC)	Experimental	Design of device and subcells	Dimroth et al. (2020)
AlGaAs/GaAs/Si	Yes (DLARC with textured surface)	PC1D simulation	Bandgap alignment, subcell thickness, doping	Sathya and Supriya (2017)
ZnO/AlGaAs/Si	Yes (SLARC, DLARC,	PC1D Simulation	ARC thickness and Refractive Index	This study

and
TLARC)

Multiple materials can be stacked together in this multijunction solar cell, and they are ordered according to their bandgap by placing the widest bandgap on top of the layer and in descending order. Based on the band gap of each material, ZnO with 3.37eV as the top layer and followed by AlGaAs and Si with 1.817eV and 1.124eV, accordingly. The design of the solar cell for ZnO/AlGaAs/Si is shown in Figure 2.2.

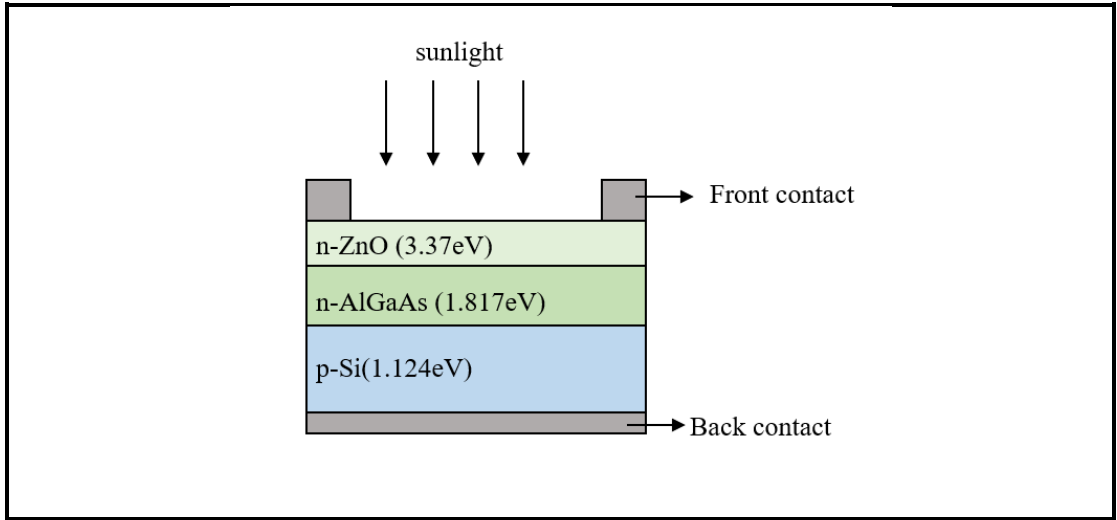


Figure 2.2 The Schematic Diagram of the ZnO/AlGaAs/Si Solar Cell

2.3 Anti-Reflective Coating (ARC)

For the solar cell to operate as efficiently as possible, it must absorb as much light or photons as feasible. There are a few factors that can cause loss of efficiency, one of which is material used in the solar cell is not suitable for high temperatures. Module efficiency decreases when the operation temperature rises because of the absorber material's temperature coefficient (Law et al., 2023). This aspect needs to be emphasized as the device has exposed to the sun directly to capture the photons to convert them to electricity. Besides that, accumulation of dirt on the top of the device will prevent the light transmission to absorb fully in into the cell. Ibrahim (2011) found that dust collection caused a daily drop of 2.78% in I_{SC} and a daily decrease of 0.863% in V_{OC} (Appels et al., 2013). Furthermore, the light that strikes the top of the solar cell

has the potential to be reflected to the air. The usage of ARC at the top of the solar cell will help to reduce the reflection of light.

ARCs have been used extensively on optical surfaces to boost transmittance and decrease reflectance losses (Zahid et al., 2023). It has been applied as a layer on top of the solar cell with a lower refractive index than the base solar cell. The arrangement of layers is important to ensure the destructive interference occurs by placing them according to a graded refractive index will help to smooth the transition. This method can avoid abrupt changes of refractive index from one medium to another medium which can lead to reflection of light. Numerous factors, including the material selection, number of layers, layer thickness, incidence angle of light, and wavelength band where reflectance must be minimised, affect how effective ARC thin film is (Adwan et al., 2023).

Anti-reflective coatings (ARCs) need to have their thickness calibrated to minimize reflection; otherwise, they won't work as well. A wider range of wavelengths can be achieved with minimal reflection when two materials of different thicknesses are tuned (Al-Turk, 2011). By finding the optimization of thickness, the ARC can work in a destructive interference phenomenon, where all the waves that reflect will cancel out by each other, resulting in the reduction of reflection and an increase in the absorption of light. The optimized thickness is one-quarter of the wavelength and can be calculated by using this equation:

$$d = \frac{\lambda_0}{4n_{ARC}} \quad (2.2)$$

where d is the thickness of ARC, λ_0 is the specified wavelength and n_{ARC} is the refractive index of the ARC. Moreover, the refractive index of ARC also plays a vital role in reducing the reflection and obtaining high efficiency. The optimization of refractive index can be determined as follows;

$$n_{ARC} = \sqrt{n_{air} \times n_{ARC}(\lambda_0)} \quad (2.3)$$

where n_{air} is the refractive index in air (1.00). By finding the optimization of the refractive index, it will work in destructive interference, which can help to reduce the reflection. The optimal arrangement is achieved by selecting a material whose thickness and refractive index (the square root of the substrate's refractive index) are such that reflectance is reduced at a specific wavelength (Al-Turk, 2011).

2.3.1 Types of Layers Anti-Reflective Coating (ARC)

2.3.1.1 Single-Layer Anti-Reflective Coating (SLARC)

The function of applying the ARC is to reduce the reflectance of light and increase the transmission. More than 30% of incident light is reflected from the surface of a crystalline silicon solar cell without ARC, causing a large reduction in total efficiency because of the lower generation rate (Uzum et al., 2017). The best way to overcome this problem is by placing the single-layer anti-reflective coating on the top of the solar cell. On a particular wavelength, SLARC offers almost zero reflectance (Mandong, 2019). Additionally, the optimal thickness of the ARC plays a crucial part in order to achieve maximum reduction of reflectance. Figure 2.3 shows the incoming and outgoing waves into the solar cell, where the black indicates transmitted waves while the red represents reflectance waves.

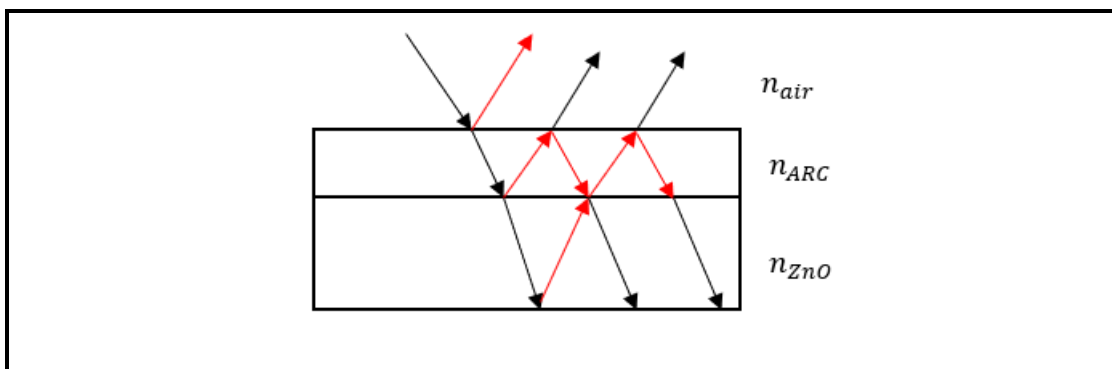


Figure 2.3 Schematic Diagram of Single-Layer Anti-Reflective Coating (SLARC)

ARCs primarily limit the Fresnel reflection loss brought on by light propagating through various media by using the destructive interference principle (Ji et al., 2022). The destructive interference phenomenon occurs when the reflected waves with 180

degrees are cancelled with each other. This phenomenon will contribute to reducing the reflection of light by applying the optimal thickness and refractive index of ARC. SLARC could lower the reflectivity in a broad spectral range of 450–1100 nm to about 2.5% (Ji et al., 2022).

2.3.1.2 Double-Layer Anti-Reflective Coating (DLARC)

A single layer can effectively trap a large number of photons, but it can only minimize reflectance at a single wavelength. Thus, adding the number of layers will help to improve the minimization of reflectance in a wide range of wavelengths. In contrast to the SLARC, which approaches zero at the center wavelength and greatly increases when it deviates from it, the effective reflectivity dramatically drops when the conventional DLARC is utilized (Ji et al., 2022). In the design of DLARC, the layers have been arranged according to their refractive index by placing the lowest refractive index at the first layer and followed by the highest refractive index at the second layer, as shown in Figure 2.4.

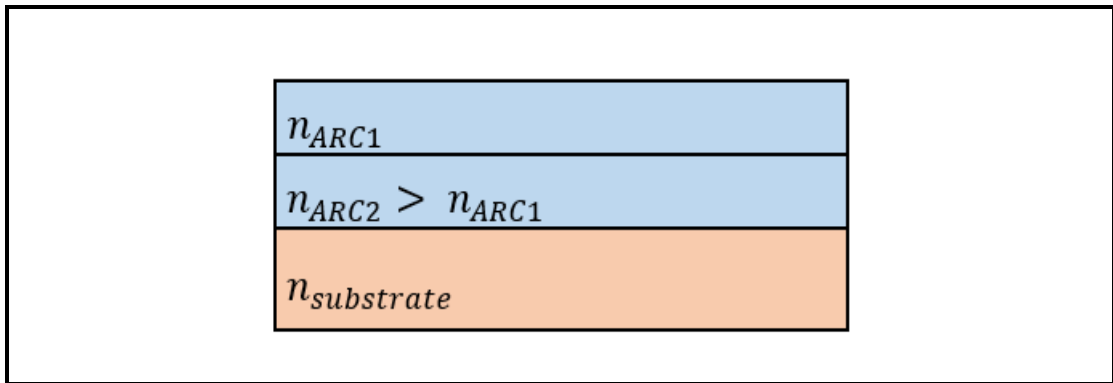


Figure 2.4 Schematic Diagram of Double-Layer Anti-Reflective Coating (DLARC)

In order to successfully remove the active back waves from the material surface, the double-layer ARCs must meet the interference requirements (Assadi & Moayedfer, 2018). Nevertheless, compared to a single layer, the design and computation were more complicated to determine the ideal thickness for utilizing the sun's energy. The more complicated reflections in DLARC can obstruct other reflected waves, lowering the total reflectance (Mandong, 2019).

2.3.1.3 Triple-Layer Anti-Reflective Coating (TLARC)

The performance of DLARC outperforms that single layer; however, by applying an additional layer of ARC, a further reduction can be accomplished in a wide range of wavelengths. To achieve the minimization of reflectance, however, the design and calculation will become more complex as the number of layers increases. A triple-layer AR coating is considered to be an advancement over the already employed double-layer coating technique (Aiken, 2000). Figure 2.5 shows the design of a solar cell with a triple-layer anti-reflective coating on the top.

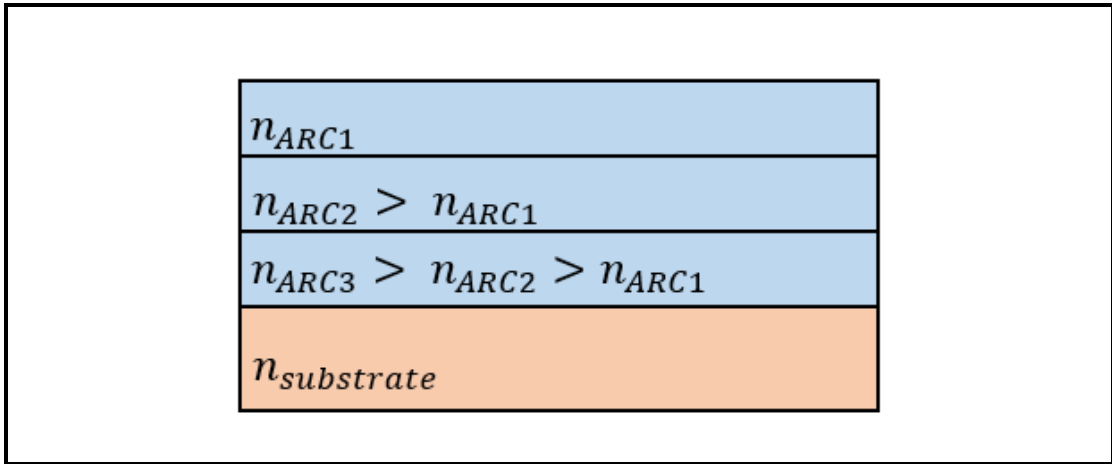


Figure 2.5 Schematic Diagram of Triple-Layer Anti-Reflective Coating (TLARC)

2.3.2 Material of Anti-Reflective Coating (ARC)

Varied materials will produce varied results when used for ARCs because of variations in thickness and refractive index (RI). This can help to determine the optimization value for refractive index and thickness for each material of ARCs. Furthermore, all the materials that exist have their own characteristics that can improve the efficiency of a solar cell. Finding suitable materials to be used as ARC will help and ease other future researcher to explore their study. However, some of the material is expensive due to its availability and their process requirement. Finding an affordable material might be aided by researching other materials. In this paper, the ARCs were studied in a specified wavelength which is 250nm - 1200nm that covering the range of the solar spectrum.

2.3.2.1 Silicon Dioxide (SiO_2)

Silicon dioxide, or known as silica, consists of silicon and two atoms of oxygen. The material silicon dioxide (SiO_2) is a pleasant substance that has several uses in semiconductor devices. SiO_2 is chemically stable at high temperatures and has strong passivation and scratch resistance qualities (Ali et al., 2014, Rathanasamy et al., 2022). Refractive index for SiO_2 is 1.457 at wavelength 632.8 nm (Hashmi et al., 2018). However, in this study refractive index of SiO_2 has been various at specific wavelengths between 250nm – 1200nm. Silicon dioxide is an excellent insulator due to its high electrical resistivity, which is $10^{16} \Omega\text{cm}$. Silicon dioxide (SiO_2) was used by many researchers in their study as ARC in either a single layer (SL) or in pairing with other materials. Rathanasamy et al. (Rathanasamy et al., 2022) studied silicon dioxide (SiO_2) ARC experimentally in two conditions, which are under direct sunlight and under a controlled source of environment, exhibited an efficiency of 15.81% and 17.17% respectively. Additionally, Hashmi et al. (Hashmi et al., 2018) used SiO_2 for SLARC on a silicon solar cell, resulting in 18.99% at 600nm wavelength for the efficiency.

2.3.2.2 Silicon Nitride (Si_3N_4)

Silicon nitride is a chemical compound that consists of silicon and nitrogen, with the chemical formula Si_3N_4 . In photoelectric and microelectronic applications, Si_3N_4 film has been widely employed as an insulating film, passivation layer, or dielectric coating due to its exceptional photoelectric and passivation capabilities (Feng et al., 2022). Si_3N_4 has been utilized as an ARC material due to its exceptional surface passivation quality for refractive indices above 2.3 and its ability to vary its refractive index from 1.8 to 3.0 by adjusting the deposition settings (Sharma, 2018). Furthermore, long-term durability is enhanced by silicon nitride's ability to retain its structure at high temperatures and its resistance to moisture and most chemicals. Sharma (2018) carried out a simulation using PC1D simulation on a silicon cell exhibited an efficiency of 19.60% when Si_3N_4 was used as SLARC.

2.3.2.3 Zinc Oxide (ZnO)

An oxidic mixture known as zinc oxide is present in the mineral zincite, which crystallizes as wurtzite P63mc, a hexagonal shape (Szindler & Szindler, 2023) as shown in the figure below. Zinc oxide was widely used and known in the photovoltaic industry. Considering ZnO has a refractive index of roughly 2, a broad optical bandgap in the 3.3–3.7 eV range, transparency in the visible spectrum, good adhesive qualities, and hardness, it has great promise for coating silicon solar cells to prevent reflections (Suhandi et al., 2017). Thus, ZnO becomes one of the ARC materials that researchers are interested in because of its characteristics that promise a good contribution to solar cells. Also, there are a lot of methods that have been used by researchers to study ZnO as an ARC. Makableh et al. (2021) found that ZnO nanoparticle size can reduce optical reflection near zero. Also, Heeravathi et al. (2023) determined that absorption in the cell is enhanced when the cell is coated with ZnO, and increased the efficiency by 4% from a bare silicon cell.

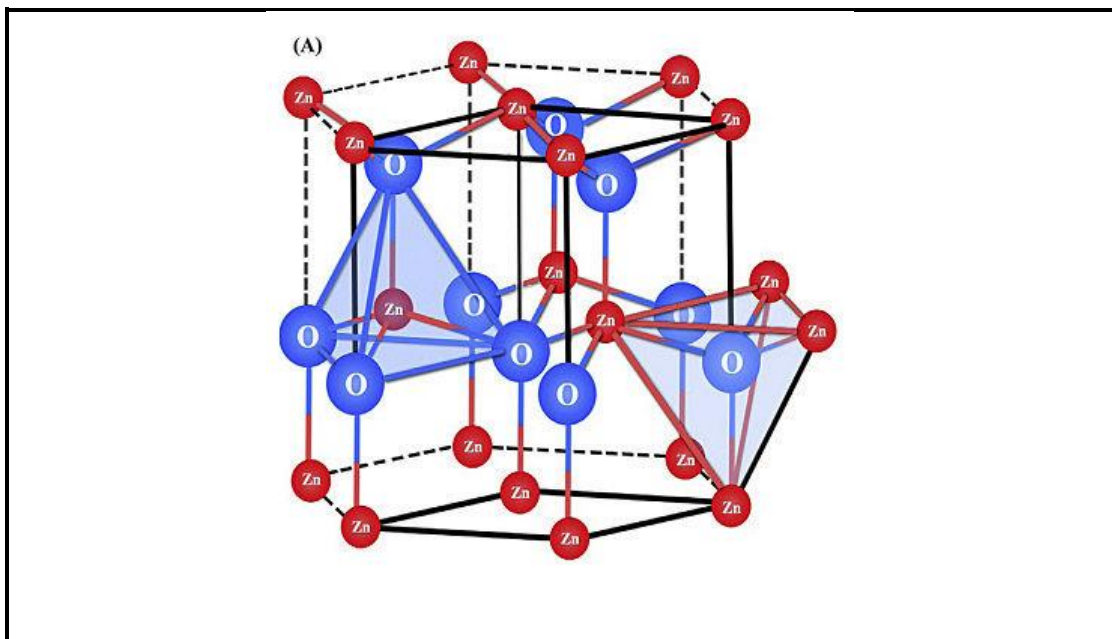


Figure 2.6 Hexagonal Wurtzite Crystal Structure of ZnO (Adegoke et al., 2018)

2.3.2.4 Titanium Dioxide (TiO_2)

Titanium dioxide (TiO_2) is an inorganic substance that is stable and non-toxic, and has been used in many applications for decades, especially in the photovoltaic industry. Different materials have been explored to develop as ARCs; however, many researchers agree that TiO_2 can promise good efficiency for solar cells. Due to its high refractive index of 2.7, nontoxic nature, abundance, affordability, low absorption in the visible area, and self-cleaning qualities, the TiO_2 was more acceptable than other materials (Muhammad & Ali, 2025) and also can absorb light in a wide spectral range from 320nm to 6000nm, promising good transparency (Sivakumar et al., 2023). Many researchers used TiO_2 in various types of ARC and methods. Parajuli et al. (2023) studied the optimal thickness of TiO_2 as SLARC gives the highest conversion efficiency of 24.75% at a thickness of 62nm. Zhang et al. (Zhang et al., 2021) pairing TiO_2 with other materials to build double layer (DL) and triple layer (TL) which exhibited 21.29% and 29.44% for $\text{TiO}_2/\text{Al}_2\text{O}_3$ and $\text{TiO}_2/\text{Al}_2\text{O}_3/\text{MgF}_2$ respectively by using Essential Macleod Program software and Crosslight Apsys software.

2.3.2.5 Zinc Sulphide (ZnS)

Zinc sulphide is an inorganic compound from the II-VI group semiconductor with the chemical formula ZnS . Figure 2.7 shows two structures of ZnS , which are α -phase (hexagonal wurtzite structure) and β -phase (cubic sphalerite structure). ZnS can be used as a transparent material in the visible spectrum due to its broad band gap of roughly 3.67 eV and exhibits a high refractive index at 632 nm (2.35) (Salih et al., 2017). Therefore, ZnS is solely sensitive to the absorption of UV light ($\lambda < 340$ nm) for electron-hole separation when illuminated (Lee & Wu, 2017). ZnS , which has a melting temperature of about 1850°C, has the potential to be transparent and is utilized as an optical and infrared optic window. ZnS is often used as a DLARC because it exhibits a high refractive index, making it effective to reduce the reflectance over a wide range of wavelengths. Many researchers found that ZnS makes a good pair with magnesium fluoride (MgF_2) which have a lower refractive index than ZnS . Liu & Zhang (2013)

studied the optimum thickness for finding the best design of MgF_2/ZnS on GaAs solar cell exhibits a total reflectance of only 1.49%.

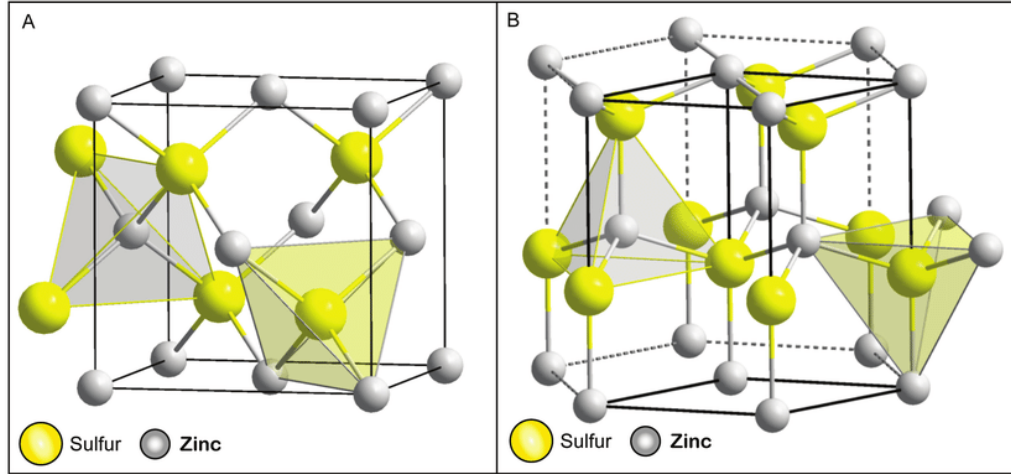


Figure 2.7 Crystal Structure of ZnS in (a) β -phase (Cubic Sphalerite Structure) and (b) α -phase (Hexagonal Wurtzite Structure) (Archibald & Piercey, 2015)

2.4 P-N Junction

A P-N junction is created by combining a p-type and an n-type material to create a semiconductor diode (Elfiky et al., 2023). In the n-type region, electrons will be filled in the area, while the holes will be filled in the p-type region. When these two materials are combined, n-type electrons move into the p-type side and recombine with holes. This movement will cause a depletion region at the junction, and the electric field is established as shown in the figure below. Both the n- and p-semiconductors' bands bend at the interface when the junction forms because the Fermi levels (E_f) of the two sides match, causing the conduction and valence bands to bend upward on the n-type side and downward on the p-type side (Yoon et al., 2010). The photon from sunlight will strike the top of the solar cell and excite the electron in the cell, creating electron-hole pairs. At the P-N junction, the electrons are driven toward the n-type side and the holes toward the p-type side by the electric field. By connecting both semiconductors by using a metal contact, which is a cathode with n-type and an anode with p-type, electrons will flow through the wire and generate a current.

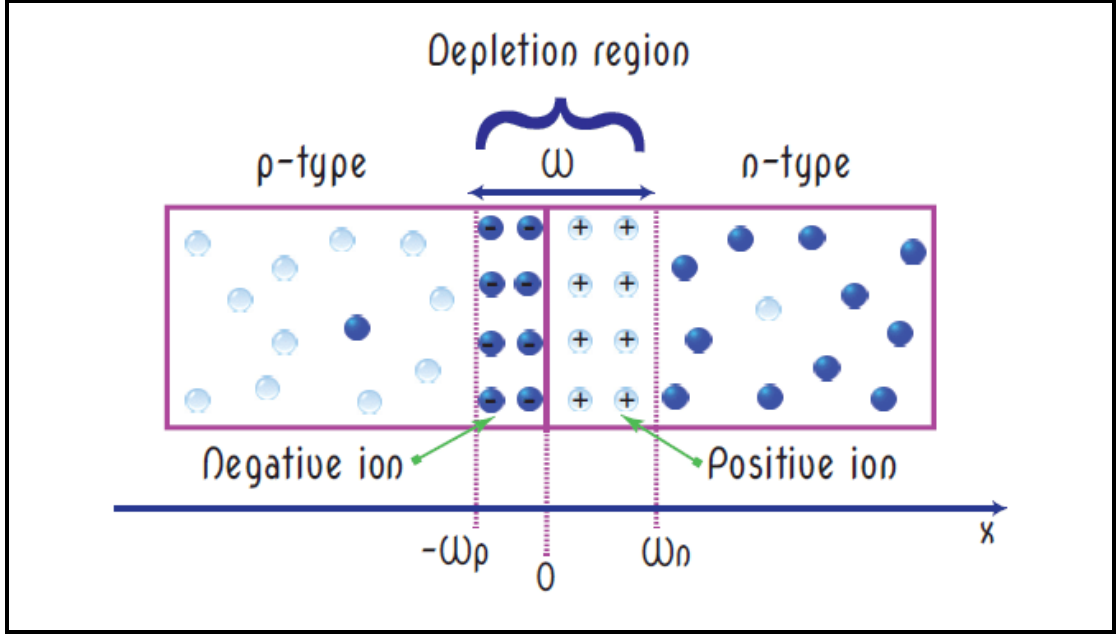


Figure 2.8 Illustration of P-N Junction (Alazrag et al., 2023)

2.5 Fill Factor (FF) and Efficiency

Researchers in the photovoltaic industry are primarily focused on enhancing solar cell performance to guarantee optimum functionality. The simulation's results were used to determine the fill factor and efficiency of the solar cell. Fill factor (FF) is the ability of solar cells to store the energy they receive from the sun (Toifur, 2019). Fill factor is the ratio of maximum power (P_{max}) of the solar cell to the product of short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}) which can be mathematically represented as;

$$FF = \frac{P_{max}}{V_{OC} \times I_{SC}} \quad (2.4)$$

Furthermore, the solar cell's efficiency is the most crucial factor in assessing how effective the device is in comparison to others. A solar cell's power conversion efficiency is directly correlated with its FF; a greater fill factor corresponds to a higher efficiency (Javier et al., 2023). Efficiency is defined as the percentage of the electric energy produced by solar cells of the energy received from solar radiation (Toifur, 2019). The efficiency can be calculated by using the equation below;

$$\eta = \frac{V_{OC} \times I_{SC} \times FF}{P_{input}} \times 100\% \quad (2.5)$$

where I_{SC} is short-circuit current, V_{OC} is the open-circuit voltage, FF is the fill factor of the solar cell, and P_{input} is a power input received from solar light. The simulation was simulated under spectrum intensity light, which can be calculated by using;

$$P_{input} = I_{light} \times A \quad (2.6)$$

where I_{light} is light intensity, which is 0.1 Wcm^{-2} for AM 1.5G spectrum, and A is the device surface area of the solar cell.

2.6 External Quantum Efficiency (EQE)

External quantum efficiency (EQE) is the term used to describe the difference between the number of charge carriers produced by the solar cell and the number of incident photons of the specified energy that are irradiated inward onto the solar cell (Javier et al., 2023). Before obtaining the EQE result, the spectral response (SR) measurement must be completed (Karmalawi et al., 2020). The EQE can be calculated by using the equation below;

$$EQE(\lambda) = \frac{hc}{q\lambda} \times SR \quad (2.7)$$

where h is referring to Planck's constant (6.63×10^{-34}), c is the speed of light (3×10^8), q is the electronic charge and λ is the wavelength. The solar cell's ability to efficiently convert incident light into electrical power is demonstrated by its EQE. It will also account for transmission and reflection.

2.7 Summary

This chapter discussed zinc oxide (ZnO) and gallium arsenide (GaAs) as n-type and p-type, respectively, in a solar cell. Anti-reflective coatings (ARC) are available in three distinct types: single layer (SL), double layer (DL), and triple layer (TL). These coatings are applied to the top of solar cells to enhance their performance by lowering reflection and increasing transmission. Furthermore, a variety of ARC's materials were selected in order to identify the most effective that could reach high efficiency.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Numerous techniques are available for accurately examining the efficiency of solar cells, such as using simulation. There are a lot of simulations that have been developed to make research easier, including Silvaco Atlas, SCAPS-1D, PC1D, and many more. In this study, PC1D simulation was used to simulate the solar cell. This simulation software was developed by the Photovoltaic Special Research Centre of the University of New South Wales, Australia. Before undertaking experiments, several researchers used PC1D to simulate different kinds of solar cells to confirm the viability of their ideas (Mandong & Uzum, 2019). PC1D has become one of the most used software in the photovoltaic research area due to its benefits to users. PC1D's primary benefits are quick computation times, an easy-to-use interface, and a comprehensive collection of material and physical properties (Haug et al., 2013). Furthermore, due to its free availability and proven reliability also become a reason for PC1D simulation, it's useful for researchers. Additionally, they use both mathematical and experimental data to predict how a solar cell would behave in terms of output (Mandong & Uzum, 2019).

3.2 Personal Computer 1-Dimensional (PC1D)

In this study, PC1D simulation was used to simulate both ZnO/GaAs and ZnO/AlGaAs/Si solar cells to achieve the best possible conversion for ARC on the solar cell. PC1D enables one-dimensional (axial symmetry) simulation of the behavior of semiconductor-based photovoltaic systems (Belarbi et al., 2014). It finds the related nonlinear equations for carrier production, recombination, and transport in semiconductor devices using a finite-element numerical approach (Belarbi et al., 2014, Mandong & Uzum, 2019). A PC1D simulation is widely used in the photovoltaic

industry due to its advantages, such as open-source, easy to use, quick calculation, and more.

A PC1D simulation includes library files for the crystalline semiconductors GaAs, a-Si, AlGaAs, Si, InP, and Ge that are utilized in PV technology (Shah et al., 2022). Although PC1D simulation offers material files with optimization parameter values, the user is still free to alter the parameters as they discover desirable. Furthermore, the user can also create their own material file in PC1D for free by setting the parameters needed in the software. Besides that, PC1D also provides “SCAN-QE” and “ONE-SUN” for solar spectrum files. The PC1D displays the performance of the solar cell device in a graphical style, including the current-voltage (I-V) curve, open circuit voltage (V_{OC}), short circuit density (J_{SC}), external and internal quantum efficacy (Roshi et al., 2022). This is one of the reasons PC1D is preferred to be used by many researchers.

3.3 Parameters in PC1D Simulation

In this work, the device area has been set up to 110cm^2 , which provides a standard and convenient size for studying solar cells using simulation, and the exterior front reflectance is 10%. Figure 3.1 is a diagram of the solar cell in PC1D simulation that shows a different region for different material with different extrinsic concentration. In REGION 1, n-type, ZnO was set up with an intrinsic concentration of 1.1×10^{-9} and n-type background doping of $1 \times 10^{18} \text{ cm}^{-3}$. Meanwhile, the p-type of GaAs form was established in REGION 2. Intrinsic concentration and p-type background doping have respective values of 1×10^9 and $5 \times 10^{15} \text{ cm}^{-3}$. The thickness of the substrate also plays a vital role in avoiding the recombination bulk happening. Manoua et al. (2023) simulated to determine the optimization value of thickness for n-zinc oxide (n-ZnO) and p-gallium arsenide (p-GaAs), which is $0.2\mu\text{m}$ and $100\mu\text{m}$ respectively. Other parameters in both regions were set up by default in PC1D’s material files, as shown in Table 3.1.

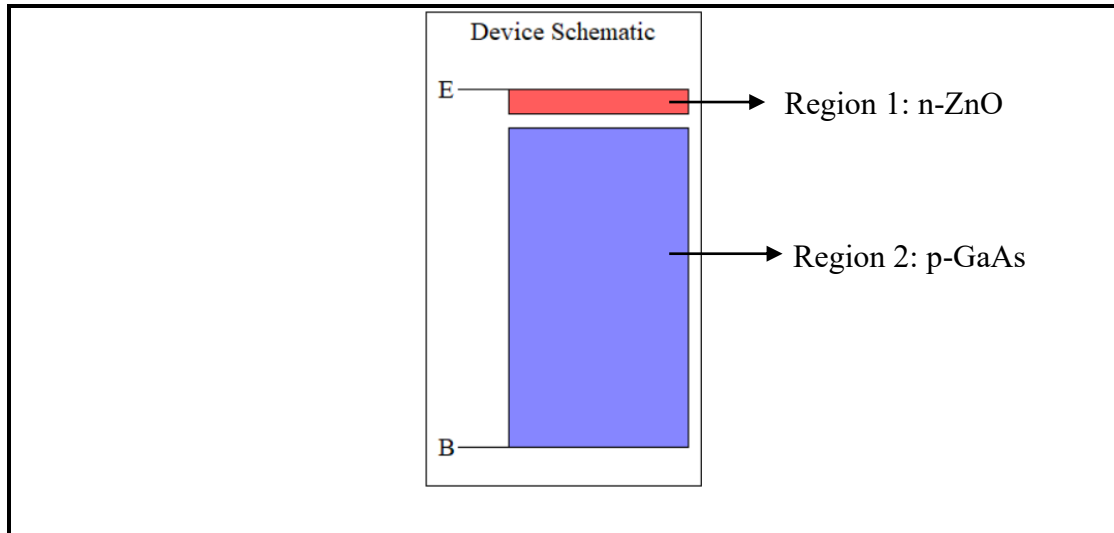


Figure 3.1 Schematic Diagram of ZnO/GaAs Solar Cell in PC1D Simulation

Table 3.1
The Parameters of ZnO/GaAs Solar Cell Using PC1D Simulation

Parameter	Value	References
DEVICE		
Device area	110 cm ²	(Jamaluddin et al., 2024)
Surface texturing	None	
Surface charge	None	
Exterior front reflectance	10%	(Jamaluddin et al., 2024)
Exterior rear reflectance	None	
Internal optical reflectance	None	
REGION 1		
Thickness	0.2μm	(Manoua et al., 2023)
Material	ZnO	
Dielectric constant	7.9	
Band gap	3.289 eV	
Intrinsic concentration at 300K	1.1x10 ⁻⁹	
Refractive index	2.00	
N-type background doping	1x10 ¹⁸ cm ⁻³	
Bulk recombination, $\tau_n = \tau_p$	1000μm	
REGION 2		

Thickness	100 μ m	(Manoua et al., 2023)
Material	GaAs	
Dielectric constant	13.18	
Band gap	1.424 eV	
Intrinsic concentration at 300K	1x10 ⁹	
Refractive index	3.66	
P-type background doping	5x10 ¹⁵ cm ⁻³	(Jin & Tang, 2021, Kao et al., 2019)
Bulk recombination, $\tau_n = \tau_p$	1000 μ m	

EXCITATION

Excitation from	one-sun
Excitation mode	Transient, 16 timesteps
Temperature	25°C
Base circuit	-0.8 to 0.8 V
Collector circuit	Zero
Primary light source	Enabled
Constant intensity	0.1 W cm ⁻²
Spectrum	AM1.5G
Secondary light source	Disabled
Other parameters are default by PC1D	

For the ZnO/AlGaAs/Si solar cell, the parameters under the “DEVICE” section will remain as in Table 3.1. For the substrates, one region has been added as three materials were used for the substrate, as shown in Figure 3.2. Thus, “REGION 1”, “REGION 2”, and “REGION 3” were set up as ZnO, AlGaAs, and Si, respectively, as shown in Table 3.2. The thickness of the first layer, which ZnO needs to be thinner than other layers, because the electrons can quickly move through the circuit and produce current before joining the holes again (Al-Ezzi & Ansari, 2022). Thus, the thickness of ZnO has been deposited as 0.1 μ m while AlGaAs and Si were 0.6 μ m and 300 μ m accordingly. For the doping concentration, ZnO has been highly doped with 1x10¹⁹ cm⁻³, while other materials have the same value of doping with 1x10¹⁷ cm⁻³.

In the “EXCITATION” area, PC1D provides two files of excitation, and “ONE-SUN” were chosen because it will provide short-circuit current (I_{SC}), maximum power

output (P_{max}) and open-circuit voltage (V_{OC}) as a result (Belarbi et al., 2014). The results were used in calculation to calculate the FF and the efficiency of the solar cell. This excitation file will change the excitation mode to transient with 16 timesteps. The simulation for both device solar cells under illumination of standard global spectrum signifies AM1.5G, which corresponds to 0.1 W cm^{-2} . Figure 3.3 and 3.4 shows the completed settings parameters of the ZnO/GaAs and ZnO/AlGaAs/Si solar cell, respectively, in PC1D simulation. The excitation has been changed to “SCAN-QE” to execute EQE and reflectance curves.

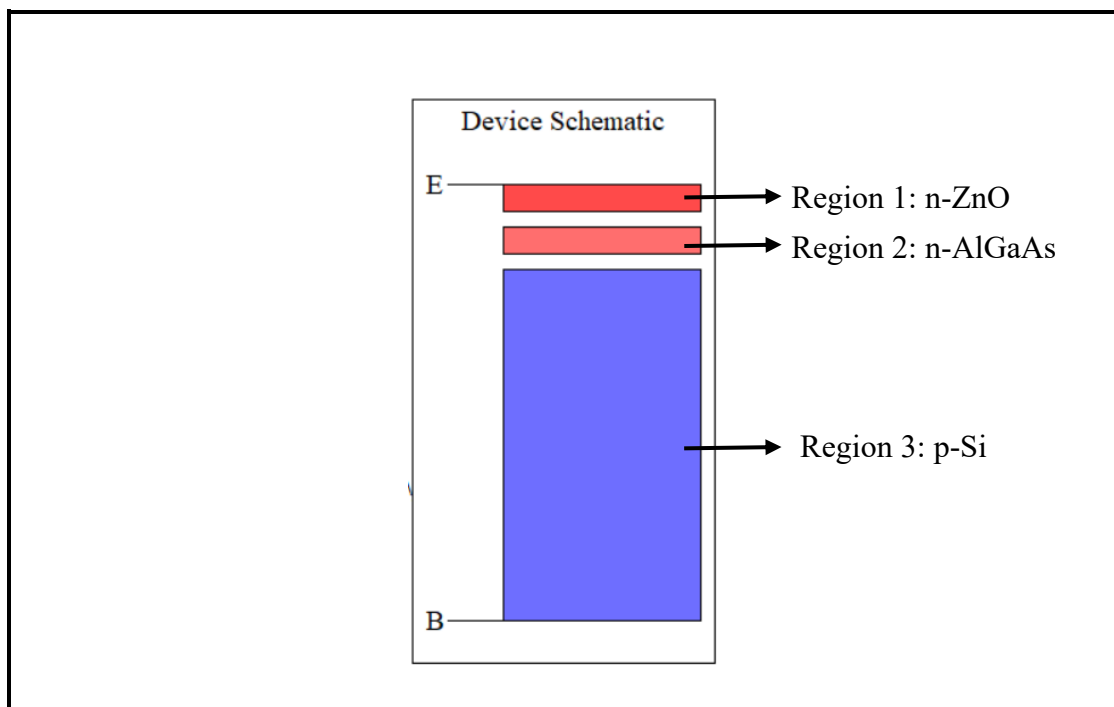


Figure 3.2 Schematic Diagram of ZnO/AlGaAs/Si Solar Cell in PC1D Simulation

Table 3.2
The Parameters of ZnO/AlGaAs/Si Solar Cell Using PC1D Simulation

Parameter	Value	References
DEVICE		
Device area	110 cm^2	(Jamaluddin et al., 2024)
Surface texturing	None	
Surface charge	None	
Exterior front reflectance	10%	(Jamaluddin et al., 2024)
Exterior rear reflectance	None	

REGION 1

Thickness	0.1 μm	(Chandran et al., 2023)
Material	ZnO	
Fixed electron mobility	20 cm^2/Vs	(Chandran et al., 2023)
Fixed hole mobility	10 cm^2/Vs	(Chandran et al., 2023)
Dielectric constant	86	(Chandran et al., 2023)
Band gap	3.37 eV	(Chandran et al., 2023)
Intrinsic concentration at 300K	1.1 $\times 10^{-9}$	
Refractive index	2.00	
N-type background doping	1 $\times 10^{19} \text{ cm}^{-3}$	(Chandran et al., 2023)
Bulk recombination, $\tau_n = \tau_p$	1000 μs	
Front-surface recombination, $S_n = S_p$	Enable	

REGION 2

Thickness	0.6 μm	
Material	AlGaAs	
Dielectric constant	12.24	
Band gap	1.817eV	
Intrinsic concentration at 300K	1754	
Refractive index	3.81	
N-type background doping	1 $\times 10^{17} \text{ cm}^{-3}$	(Naim et al., 2022)
Bulk recombination, $\tau_n = \tau_p$	1000 μs	
Front-surface recombination, $S_n = S_p$	70000	

REGION 3

Thickness	300 μm	
Material	Si	
Dielectric constant	11.9	
Band gap	1.124eV	
Intrinsic concentration at 300K	1 $\times 10^{10}$	
Refractive index	3.48	
P-type background doping	1.1 $\times 10^{17} \text{ cm}^{-3}$	
Bulk recombination, $\tau_n = \tau_p$	1000 μs	
Front-surface recombination, $S_n = S_p$	Enable	

EXCITATION

Excitation from	one-sun	
Excitation mode	Transient, 16 timesteps	
Temperature	25°C	
Base circuit	-0.8 to 0.8 V	

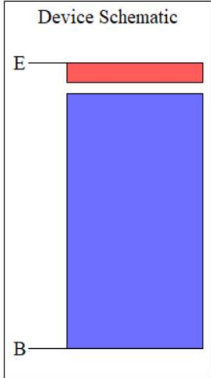
Collector circuit	Zero
Primary light source	Enabled
Constant intensity	0.1 W cm^{-2}
Spectrum	AM1.5G
Secondary light source	Disabled
Other parameters are default by PC1D	

DEVICE

Device area: 110 cm^2
No surface texturing
No surface charge
 Exterior Front Reflectance: 10%
No Exterior Rear Reflectance
No internal optical reflectance
 Emitter contact enabled
 Base contact enabled
No internal shunt elements

REGION 1

Thickness: $0.2 \text{ }\mu\text{m}$
 Material modified from zno.mat
 Fixed electron mobility: $205 \text{ cm}^2/\text{Vs}$
 Fixed hole mobility: $50 \text{ cm}^2/\text{Vs}$
 Dielectric constant: 7.9
 Band gap: 3.289 eV
 Intrinsic conc. at 300 K: $1.1 \times 10^{-9} \text{ cm}^{-3}$
 Refractive index: 2
 Absorption coeff. from zno2.abs
 Free carrier absorption enabled
 N-type background doping: $1 \times 10^{18} \text{ cm}^{-3}$
No front diffusion
No rear diffusion
 Bulk recombination: $\tau_n = \tau_p = 1000 \text{ }\mu\text{s}$
No Front-surface recombination
No Rear-surface recombination



Device Schematic

REGION 2

Thickness: $100 \text{ }\mu\text{m}$
 Material modified from gaas.mat
 Carrier mobilities from internal model
 Dielectric constant: 13.18
 Band gap: 1.424 eV
 Intrinsic conc. at 300 K: $1 \times 10^9 \text{ cm}^{-3}$
 Refractive index: 3.66
 Absorption coeff. from gaas300.abs
No free carrier absorption
 P-type background doping: $5 \times 10^{15} \text{ cm}^{-3}$
No front diffusion
No rear diffusion
 Bulk recombination: $\tau_n = \tau_p = 1000 \text{ }\mu\text{s}$
No Front-surface recombination
No Rear-surface recombination

EXCITATION

Excitation from one-sun.exc
 Excitation mode: Transient, 16 timesteps
 Temperature: 25°C
 Base circuit: Sweep from -0.8 to 0.8 V
 Collector circuit: Zero
 Primary light source enabled
 Constant intensity: 0.1 W cm^{-2}
 Spectrum from am15g.spc
 Secondary light source disabled

(a)
(b)

Figure 3.3 The Settings Parameter of “DEVICE” and “REGION 1” (a) and “REGION 2” and “EXCITATION” (b) for ZnO/GaAs Solar Cell in PC1D Simulation

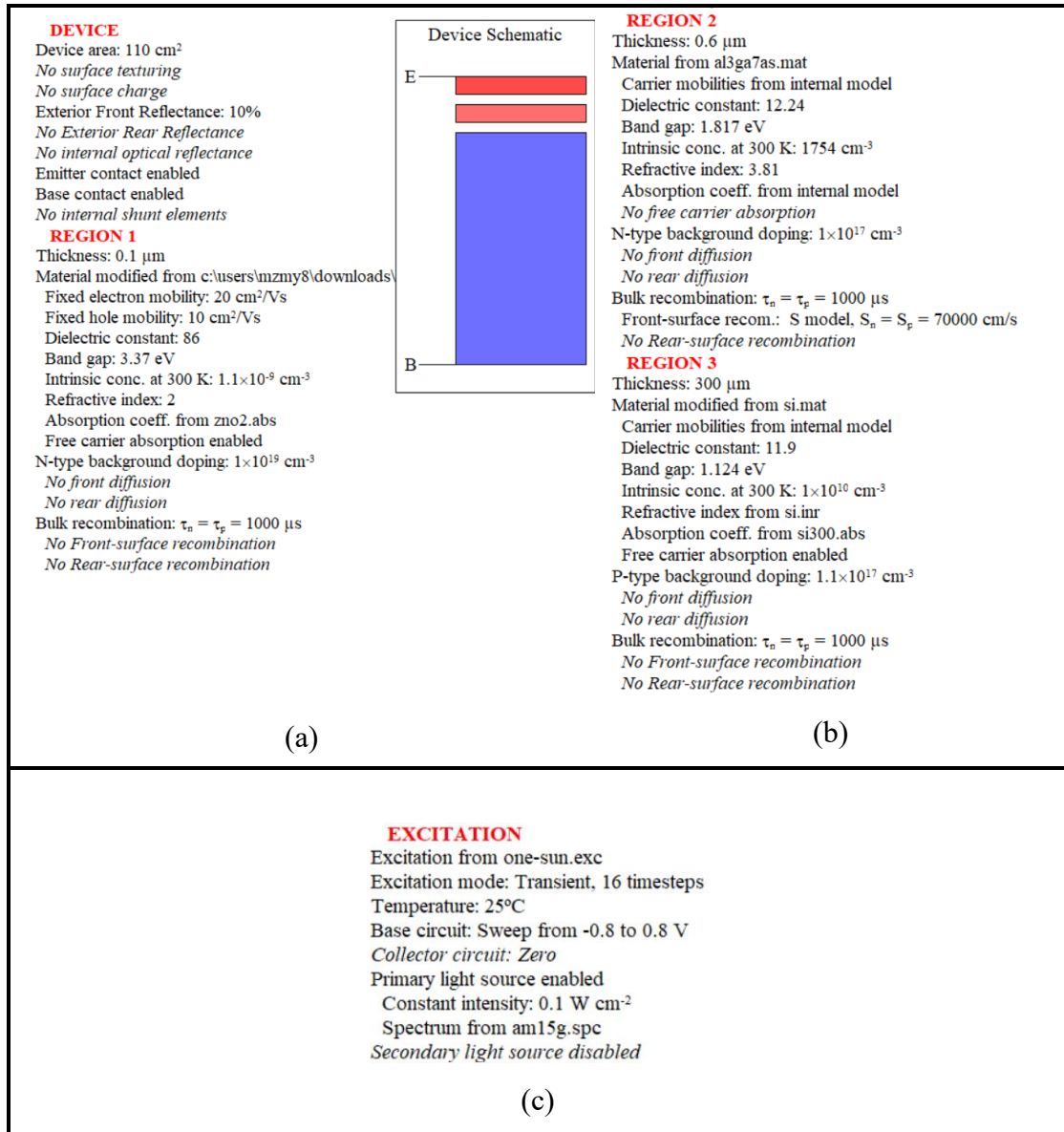


Figure 3.4 The Settings Parameter of “DEVICE” and “REGION 1” (a), “REGION 2” and “REGION 3” (b) and “EXCITATION” for ZnO/AlGaAs/Si Solar Cell in PC1D Simulation

The ARC has been set up in “Exterior Front Reflectance” in the “DEVICE” area, as shown in Figure 3.5. For SLARC, the refractive index and thickness at the specified wavelength of the material, which are silicon dioxide (SiO₂), zinc oxide (ZnO), and silicon nitride (Si₃N₄), were put in the “Inner Layer”. While other parts will remain as default with zero thickness and a refractive index of one. Furthermore, the DLARC with SiO₂/Si₃N₄, SiO₂/TiO₂, SiO₂/ZnO, SiO₂/ZnS, ZnO/TiO₂, and ZnO/ZnS have been set up with the right arrangement in order to reduce the reflection of light. A material having a lower refractive index was placed in the "Middle Layer," while a material with a higher index was placed in the "Inner Layer". The method will apply

for $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnO}$, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnS}$, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{TiO}_2$, $\text{SiO}_2/\text{ZnO}/\text{ZnS}$, $\text{SiO}_2/\text{ZnO}/\text{TiO}_2$, $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$, $\text{ZnO}/\text{Si}_3\text{N}_4/\text{TiO}_2$, $\text{ZnO}/\text{Si}_3\text{N}_4/\text{ZnS}$ and $\text{ZnO}/\text{TiO}_2/\text{ZnS}$ as TLARC also, the material with most low refractive index was set in “Outer Layer”, followed by second material as a “Middle Layer” and last material with high refractive index in “Inner Layer”.

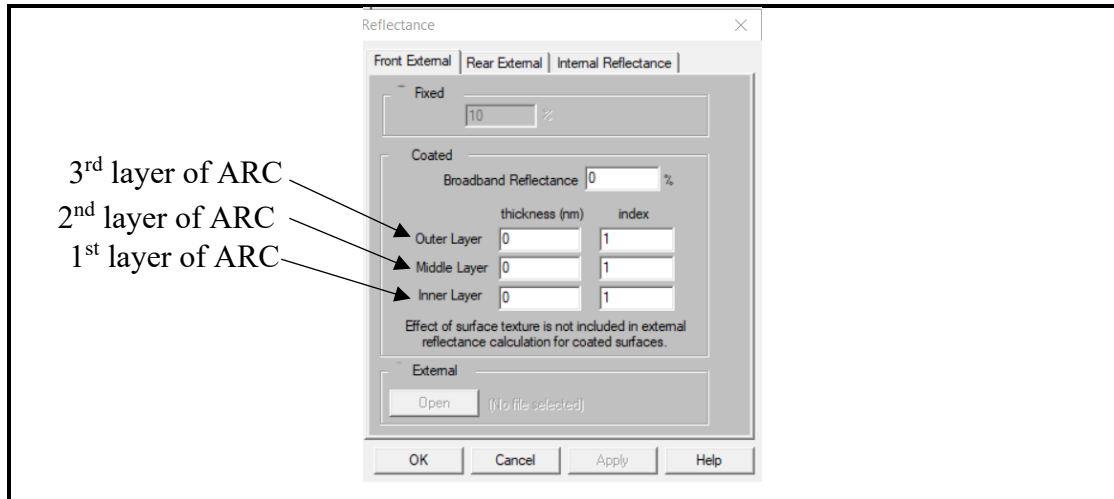
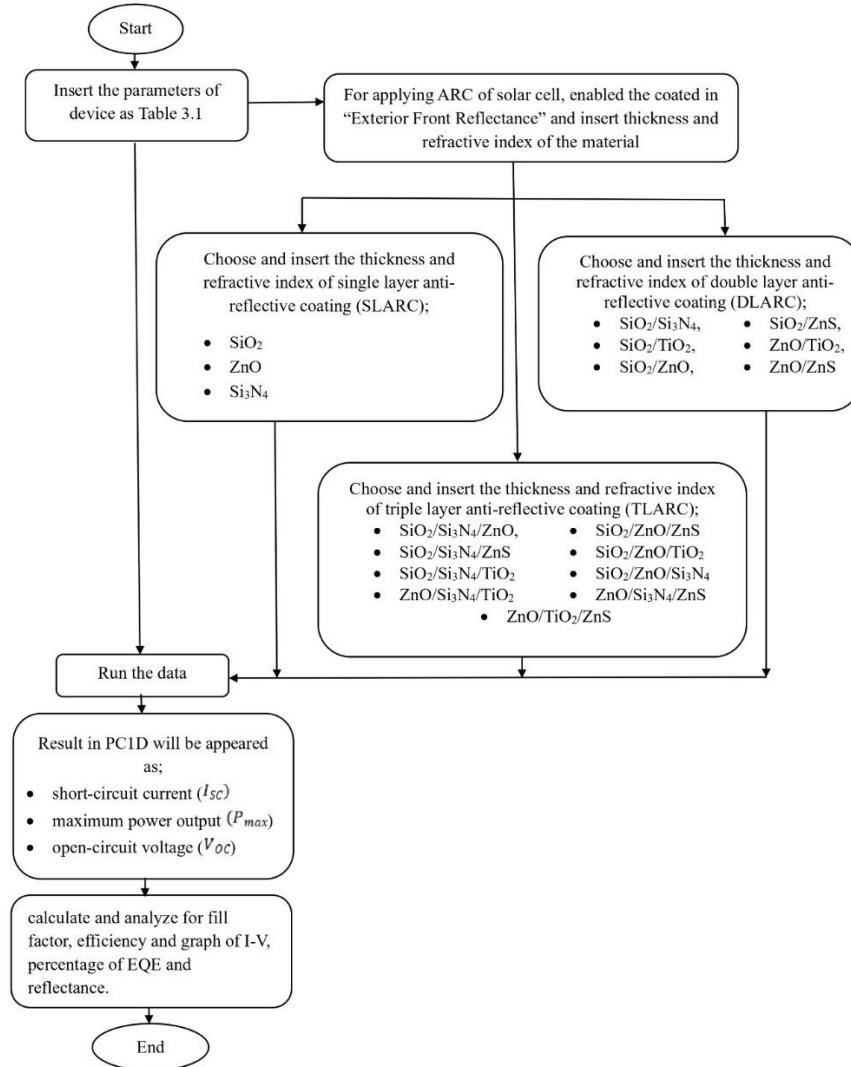


Figure 3.5 Setting of ARCS in PC1D Simulation

3.4 Flowchart

There are a few stages that must be followed to obtain the desired outcome while using the PC1D simulation software. Figures 3.6(a) and 3.6(b) show the work process of simulation for single, double, and triple layers of ARC on the top of ZnO/GaAs and $\text{ZnO}/\text{AlGaAs}/\text{Si}$ solar cells by using PC1D simulation software. Based on the figures, all the parameters for the cell device were set up and run by PC1D simulation to analyze the uncoated cell before implementing the ARC on the solar cell. Next, the exterior front reflectance was changed to the required thickness and refractive index of the ARC's material. The simulation was run as the input were completed set up correctly to find and analyze the performance and efficiency of the coated solar cell. The steps were repeated for other schemes in each type of the ARC for both solar cells.



(a)

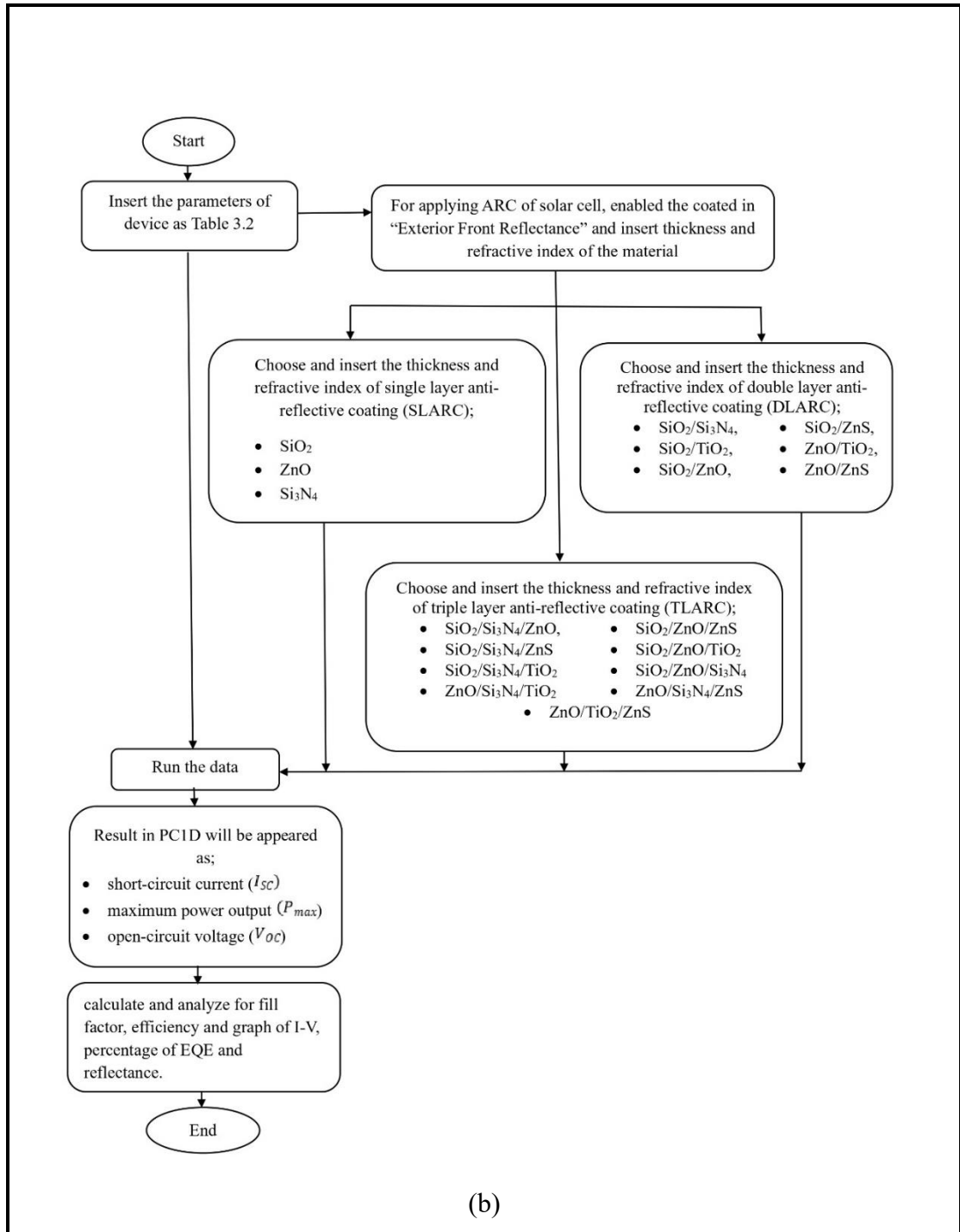


Figure 3.6 Flowchart of The Simulation of ZnO/GaAs (a) and ZnO/AlGaAs/Si (b) Solar Cell Using PC1D Simulation

3.5 Summary

In the final analysis, Personal Computer 1-Dimensional (PC1D) simulation is a good choice to be used as a simulation software to study the solar cell due to its user-friendly and free availability. By using a simulation to identify the best one before the real product is released, this strategy can also help lower the cost of research. Furthermore, short-circuit current (I_{SC}), maximum power output (P_{max}) and open-circuit voltage (V_{OC}) as parameters in the PC1D simulation will help to analyze the efficacy of solar cells, which play a crucial part. This study is expected to identify the optimal material and type of ARCs for enhancing light trapping and absorption, notably in the sun spectrum's visible and near-infrared regions.

CHAPTER 4

THE ZNO/GAAS SOLAR CELL USING VARIOUS ANTI-REFLECTIVE COATINGS (ARC)

4.1 Introduction

The uncoated and coated ZnO/GaAs solar cell was studied to observe the performance in various ways. Different materials were used as an ARC, such as SiO₂, Si₃N₄, ZnO, TiO₂, and ZnS, to analyze the performance of the cell by using the PC1D simulation, as it will generate, I_{SC} , P_{max} and V_{OC} for the results which can be used to calculate the fill factor (FF) and efficiency (η) by using (2.4) and (2.5) respectively. Each material has a different value of thickness and refractive index across the wavelength range of 250nm – 1200nm, as it will cover the entire spectrum. Hence, the chosen value for refractive index and thickness for each material in this study is based on the findings of Hashmi et al. (2018) that were studied the solar cell with the required thickness and refractive index in the range of 250nm – 1200nm using the simulation.

4.2 The ZnO/GaAs Solar Cell without using Anti-Reflective Coating (ARC)

The bare device was simulated to study the performance of the cell, which consisted I_{SC} , P_{max} , V_{OC} , FF, and efficiency as shown in Table 4.1 and Figure 4.1 shows the schematic diagram of uncoated ZnO/GaAs solar cell. The ZnO/GaAs solar cell was produced with 3.253A, 1.954W, and 0.7130V for the I_{SC} , P_{max} and V_{OC} respectively. Based on the results, the FF and efficiency can be calculated, which obtained 17.76% with 0.8425 of the fill factors. According to a study by Derbali (2022), the efficiency of ZnO/GaAs solar cell was achieved 8.31% in experimental ways. Besides that, Manoua et al. (2023) achieved a high efficiency of 21.21% with a thickness of ZnO and GaAs with 0.2 μ m and 100 μ m, respectively, by using the Atlas Silvaco simulation. Jin and Tang (2021) also successfully achieved an efficiency of 22.48% by optimizing the thickness, electron affinity, and doping concentration under AM1.5. In contrast, this

finding shows that different values of the parameters, such as doping concentration and electron affinity, can affect the efficiency, either a small or a huge difference. Besides, in their explanation of the different software available for the solar cell simulation method, Raisa et al. (2025) highlighted how different simulators employ different modeling and computational approaches, which could lead to variations in the expected performance of solar cells.

Table 4.1
Data of PC1D Simulation for ZnO/GaAs Solar Cell Without ARC

I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
3.253	1.954	0.7130	0.8425	17.76

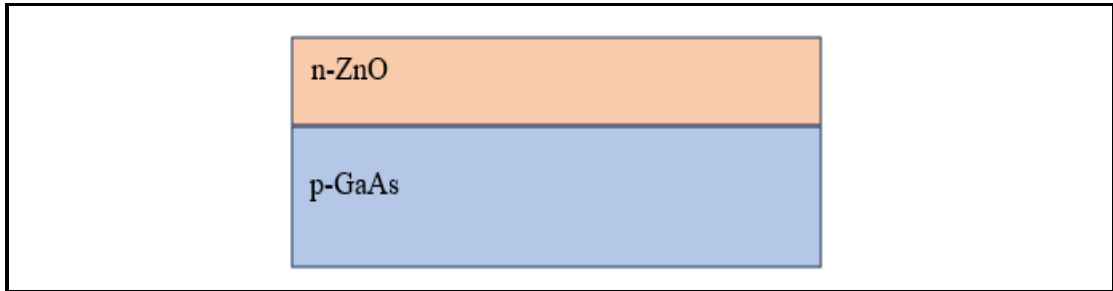


Figure 4.1 The Schematic Diagram of Uncoated ZnO/GaAs Solar Cell

Figure 4.2 shows the I-V curve of the bare device for the ZnO/GaAs solar cell, which can be drawn from the results generated in PC1D simulation. The I-V curve is important to determine the parameters, such as the short-circuit current (I_{SC}), maximum power output (P_{max}), open-circuit voltage (V_{OC}), current at maximum power (I_{MP}), and voltage at maximum power (V_{MP}) (Khunchan & Wiengmoon, 2018). The curve shows the current is at a constant value of approximately 3.25A between the voltage from 0V to 0.6V, and starts to drop to almost zero at 0.71V. Besides, the I_{SC} can be observed when the voltage is zero, which is 3.25A. The cell device can be improved by various methods, including implementing an ARC, a textured surface, and doping with other materials. Applying ARC on top of a cell device was chosen as a further enhancement method by using various materials. The materials were selected based on their properties and also approved by other researchers as it commonly used as ARC's

materials. The thickness and refractive index were calculated for each wavelength between 250nm – 1200nm to achieve high efficiency.

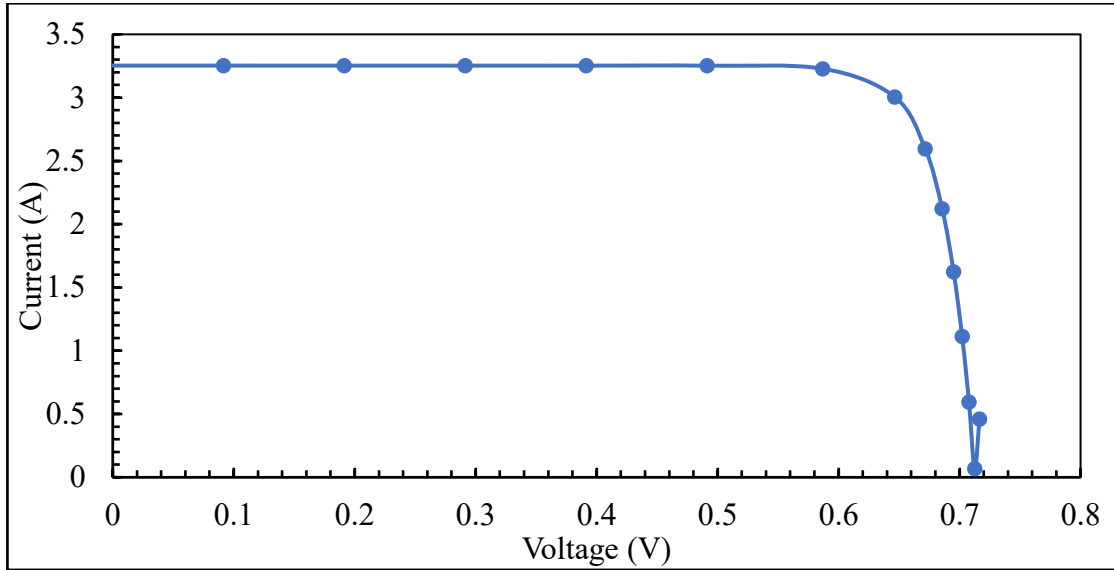


Figure 4.2 The I-V Curve of an Uncoated ZnO/GaAs Solar Cell

4.3 The ZnO/GaAs Solar Cell with Anti-Reflective Coating (ARC)

4.3.1 Single-Layer Anti-Reflective Coating (SLARC)

The different types of ARC layers with various materials were used to study the effectiveness of ARC in improving the performance of the solar cell. SiO₂, ZnO, and Si₃N₄ were the only materials selected as a single-layer ARC due to their refractive index being lower than n-ZnO as the first layer of the base cell, and was placed on top of the solar cell as shown in Figure 4.3. There are no studies that have found any suitable wavelength for designing the ARC. Thus, the refractive index and thickness of each material have been calculated for each wavelength to find the optimum value between 250nm – 1200nm. The only way to achieve optimal absorption and, thus, maximum V_{OC} , I_{SC} , and efficiency is to tune the film's thickness because the absorption coefficient, refractive index, and excitation coefficient are wavelength-dependent and difficult to modify (Manoua et al., 2023).

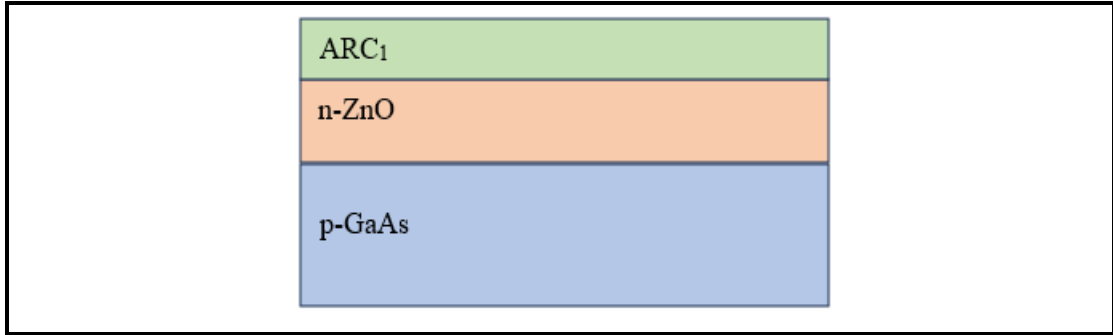


Figure 4.3 The Schematic Diagram of SLARC Configuration on ZnO/GaAs Solar Cell

The results of the ZnO/GaAs solar cell with a single-layer ARC on top of it were generated by using PC1D simulation, as shown in Table 4.2, along with the value of refractive index, thickness, fill factor, and efficiency that have been calculated. Based on the results, out of the three materials, SiO₂ recorded the highest efficiency, approximately 19.62% at a wavelength of 600nm. It resulting 3.551A, 2.158W and 0.7152V I_{SC} , P_{max} and, V_{OC} respectively. Hashmi et al. (2018) studied the improvement of the performance of a solar cell by using a single-layer ARC and achieved 18.99% for SiO₂. Furthermore, it's followed by ZnO, which recorded 18.08% as the second highest efficiency at 700nm with 3.311A, 1.989W, 0.7134V, and 0.8421 for I_{SC} , P_{max} , V_{OC} and fill factor accordingly. Lastly, Si₃N₄ achieved the lowest efficiency, and even lower than the uncoated solar cell with 17.59%, which means the reflectance is increasing. Mismatched parameters for thickness and refractive index will lead to an increase in reflectance (Khawaji et al., 2025).

The difference in the efficiency between the ARC's materials can be seen, caused by the different values of the refractive index. The refractive index of SiO₂ at wavelength 600nm, which was observed to achieve high efficiency, was graded to an appropriate value between the air and the substrate, which is 1.480. This can be considered as the optimal value of the refractive index for SiO₂ at a wavelength of 600nm. By looking at ZnO as a SLARC, it shows intermediate results compared to other materials. This happened due to refractive index value that were not graded properly from air ($n = 1.00$) to n-type substrate ($n_{ZnO} = 2.00$). The sudden increase from air to ZnO as SLARC made a huge effect to the efficiency of solar cell. Besides that, the thickness also plays a vital role in contributing to the efficiency value. As can see the data in the Table 4.2, at a wavelength of 1200nm, the value of refractive index is the lowest among other wavelengths which could result a good efficiency as it can graded

better than other wavelengths. However, the thickness is too thick compared to other wavelengths, which would affect the percentage of absorption and indirectly decreased the efficiency.

Furthermore, the Si_3N_4 acted differently under the same excitation, which causes the efficiency to be low. The error was occurred for Si_3N_4 which recorded 17.59% at four different wavelengths, which are 900, 1000, 1100, and 1200 nm. However, the last three values of wavelength produced the same value for I_{SC} , P_{max} and, V_{OC} . This happened because of its bandgap, meaning it can absorb the light with wavelengths below 1000 nm. The inability of photons with wavelengths longer than 1100 nm to drive electrons from the valence band to the conduction band is the reason why silicon is not an effective light absorber. Wavelengths over 1000 nm were excluded from consideration of reflection values since light reflected at the solar cell's back and not absorbed by the silicon dominates this region of the reflection spectrum (Sai et al., 2015).

Table 4.2
Data of PC1D Simulation of ZnO/GaAs Solar Cell with SLARC

Silicon dioxide (SiO_2)							
λ (nm)	Refractive index, n	Thickness, d (nm)	I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
250	1.520	41.12	3.344	2.017	0.7137	0.8451	18.34
300	1.510	49.67	3.390	2.050	0.7140	0.8469	18.64
400	1.500	66.67	3.476	2.109	0.7147	0.8489	19.17
500	1.482	84.35	3.536	2.148	0.7151	0.8495	19.52
600	1.480	101.35	3.551	2.158	0.7152	0.8497	19.62
700	1.474	118.72	3.531	2.145	0.7151	0.8495	19.50
800	1.473	135.78	3.488	2.117	0.7148	0.8491	19.25
900	1.472	152.85	3.440	2.085	0.7144	0.8484	18.95
1000	1.471	169.95	3.397	2.055	0.7141	0.8471	18.68
1100	1.470	187.07	3.366	2.033	0.7139	0.8460	18.48
1200	1.469	204.22	3.348	2.020	0.7137	0.8454	18.36
Silicon Nitride (Si_3N_4)							
λ (nm)	Refractive index, n	Thickness, d (nm)	I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
250	2.289	27.304	3.086	1.860	0.7116	0.8470	16.91
300	2.167	34.610	3.120	1.880	0.7119	0.8464	17.09
400	2.070	48.309	3.159	1.902	0.7122	0.8466	17.29
500	2.030	61.576	3.186	1.917	0.7125	0.8445	17.43
600	2.020	74.257	3.195	1.922	0.7125	0.8443	17.47

700	2.003	87.369	3.210	1.931	0.7127	0.8441	17.55
800	1.996	100.200	3.215	1.933	0.7127	0.8436	17.57
900	1.991	113.009	3.218	1.935	0.7127	0.8437	17.59
1000	1.985	138.539	3.219	1.935	0.7127	0.8434	17.59
1100	1.985	138.539	3.219	1.935	0.7127	0.8434	17.59
1200	1.983	151.286	3.219	1.935	0.7127	0.8434	17.59
Zinc Oxide (ZnO)							
λ (nm)	Refractive index, n	Thickness, d (nm)	I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
250	2.388	26.173	3.039	1.833	0.7113	0.8480	16.66
300	2.404	31.198	2.977	1.795	0.7107	0.8484	16.32
400	2.114	47.304	3.125	1.882	0.7120	0.8458	17.11
500	1.968	63.516	3.242	1.948	0.7129	0.8428	17.71
600	1.913	78.411	3.292	1.977	0.7133	0.8419	17.97
700	1.883	92.937	3.311	1.989	0.7134	0.8421	18.08
800	1.864	107.296	3.311	1.988	0.7134	0.8391	18.07
900	1.851	121.556	3.301	1.982	0.7134	0.8387	18.02
1000	1.841	135.800	3.289	1.975	0.7133	0.8420	17.95
1100	1.833	150.027	3.279	1.970	0.7132	0.8424	17.91
1200	1.826	164.294	3.274	1.967	0.7132	0.8424	17.88

Based on the results obtained in Table 4.2, a few curves can be drawn to observe and show the effectiveness of each material as SLARC. Figure 4.4(a) and (b) show the current and voltage against wavelengths, respectively, for each material of the single-layer. The curves could show the pattern of the exhibition of the current and voltage across the wavelength. As can be seen, SiO₂'s curve, represented by the orange curve, was the highest for both graphs compared to other materials. SiO₂'s curve increased maximally at a wavelength of 600nm for both graphs and slowly decreased because a single-layer will reduce the reflectance at the specified wavelength only. Next, ZnO, as represented by the yellow curve, has the same pattern with a sudden drop at a wavelength of 300nm for current and voltage graphs and an increase back at 400nm. The highest peak was achieved by ZnO for a current at a wavelength of 700nm with 3.311A; meanwhile, the voltage was observed at a wavelength of 800nm with 0.7134V. Lastly, the Si₃N₄ was indicated by the grey curve, which achieved a higher value of current than ZnO at wavelengths between 250nm – 400nm. However, ZnO was rapidly increasing, which made Si₃N₄ have the lowest production of the current and voltage.

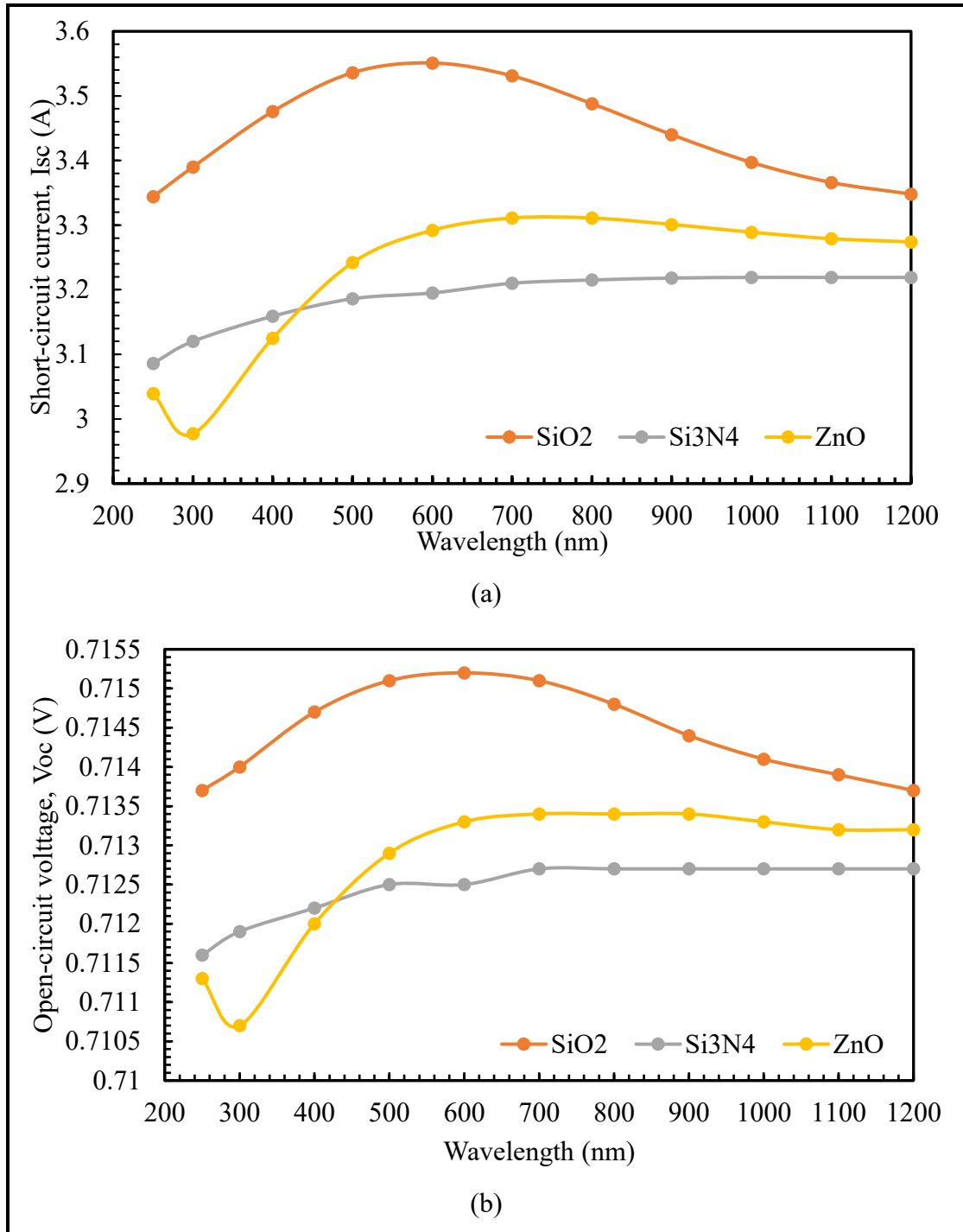


Figure 4.4 The Short-Circuit Current (a) and Open-Circuit Voltage (b) Against Wavelength for a ZnO/GaAs Solar Cell with a Single-Layer ARC

Figure 4.5 illustrates the percentage of reflectance for the uncoated and coated cell devices that were generated by PC1D simulation under “SCAN-QE” excitation mode. For the uncoated device, it is shown that a constant percentage along the wavelength with 10%. At short wavelengths, all three materials generated a higher percentage than the uncoated device, which means the photons reflected more to the air

at approximately between 300nm – 450nm. Furthermore, the lowest percentage was recorded by SiO₂ with approximately 0.21% at a wavelength of 600nm, followed by ZnO with 7.76% at a wavelength of 700nm. Both curves were slowly decreasing at short wavelengths until they reached the lowest percentage at the specified wavelength, then slowly increased as the wavelength increased. However, Si₃N₄'s curve consistently draws a higher percentage than the uncoated cell. Based on the findings in Table 4.2, the efficiency of Si₃N₄ as a single layer is also lower than the efficiency of a solar cell without ARC which it shows that Si₃N₄ cannot be a suitable material as SLARC on top of ZnO/GaAs solar cell. This could happen due to its abruptness of refractive index between the air and substrate.

The reason for SiO₂ being able to reduce the reflectance up to 0.21% that its refractive index along the wavelengths was suitable to be implemented on the solar cell. The gradual decrease from the substrates to the air that closely satisfies the optimal ARC. Therefore, for a limited wavelength band that only occurs around a design wavelength, the single-layer ARC satisfies the quarter-wave destructive interference criterion. The short and long wavelengths will increase the reflectance, producing a U-shaped curve. This observation of the reflectance curve was supported by Diaw et al. (2021), who studied the various single- and double-layer on silicon solar cells.

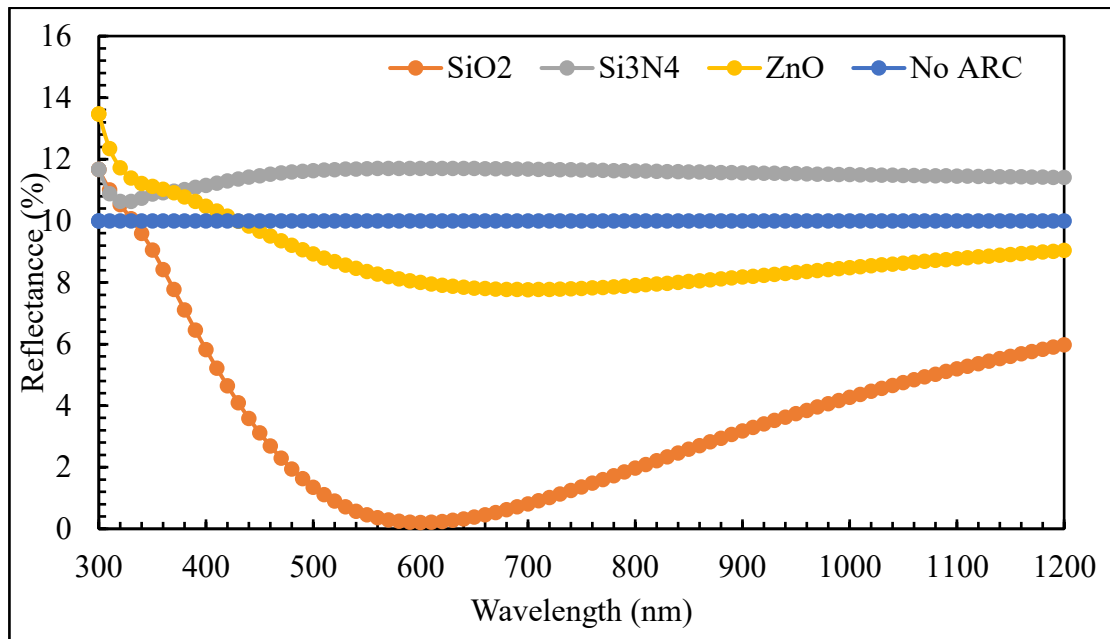


Figure 4.5 The Reflectance Curve for Coated ZnO/GaAs with SLARC

Moreover, external quantum efficiency (EQE) can be drawn to analyze the performance of the solar cell. The fraction of incident photons that the device converts into electrical current is measured by EQE (Parthiban et al., 2025). The EQE curve in Figure 4.6 demonstrates that the SLARC significantly enhance the quantum efficiency of the solar cell compared to uncoated device. Based on the curve, ZnO, Si₃N₄, and the bare cell, as represented by the yellow, grey, and blue curves, respectively, were closely followed by each other. The different percentages of EQE for each of them are slightly different, which causes them to be drawn closely. However, it can still be seen that Si₃N₄'s curve was observed as the lowest percentage, followed by the uncoated cell and ZnO. Meanwhile, the SiO₂, represented by the orange curve, showed a higher rate of EQE peak close to 100% than other schemes at a wavelength of 600nm. The cell's external quantum efficiency increases as a result of this decrease in reflection, which is equivalent to high transmission and absorption, producing a significant generation of charge carriers (Diaw et al., 2021). However, the device performs in accordance with the predicted absorption profile of GaAs, as evidenced by a dramatic fall in EQE about 870–900 nm, which corresponds to the GaAs bandgap cutoff.

As can be seen, it's noticed that the EQE of the configuration for the single-layer ARC is approaching approximately 85% - 90%, which was observed that have a strong absorption at short wavelengths. Besides that, the reason for the decrease in EQE percentage at long wavelengths because the absorption of photons is low as the energy also becomes low and has a longer penetration depth. This can cause the photons to be wasted, leading to a drop in the EQE percentage. The EQE curve was influenced by both thickness and refractive index of the ARC. The thickness of the ARC will determine the destructive interference to occur at specified wavelength, followed by quarter-wave conditions (Priyadarshini & Sharma, 2015), where the reflectance is minimizes and the percentage of the EQE was maximized. Meanwhile, the refractive index would control the reflectance reduction, which the material that has closer refractive index to the ideal value would reduce the reflectance efficiently.

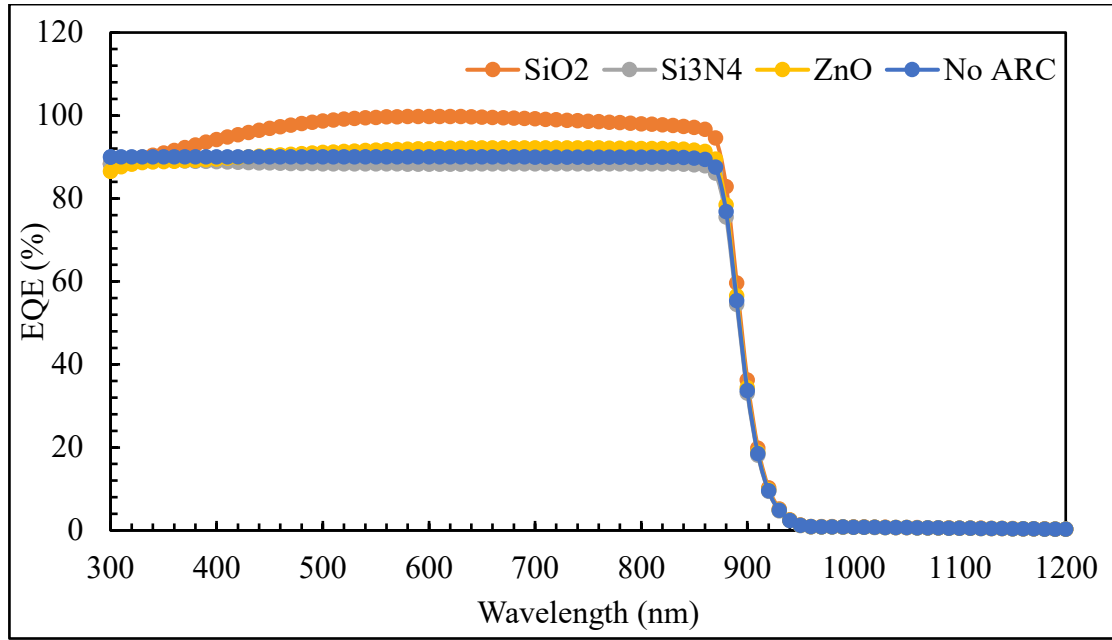


Figure 4.6 The EQE Curve for Coated ZnO/GaAs with SLARC

4.3.2 Double-Layer Anti-Reflective Coating (DLARC)

The layer of ARC was added to enhance the efficiency of the solar cell, becoming a double-layer ARC. The enhanced interference effects that further lower reflectivity beyond what single-layer coatings can achieve are the main cause of double-layer coatings' superior performance (Abdullah & Almushikya, 2025). $\text{SiO}_2/\text{Si}_3\text{N}_4$, $\text{SiO}_2/\text{TiO}_2$, SiO_2/ZnO , SiO_2/ZnS , ZnO/TiO_2 , and ZnO/ZnS are materials that have been used to examine the efficacy of a solar cell using double-layer ARC. Arrangement of layers will play a vital role in ensuring the effectiveness of ARC to function optimally. Thus, material that has a lower refractive index has been placed at the top layer (ARC_1) and followed by high refractive index (ARC_2), as shown in Figure 4.7, for the destructive interference phenomenon to happen.

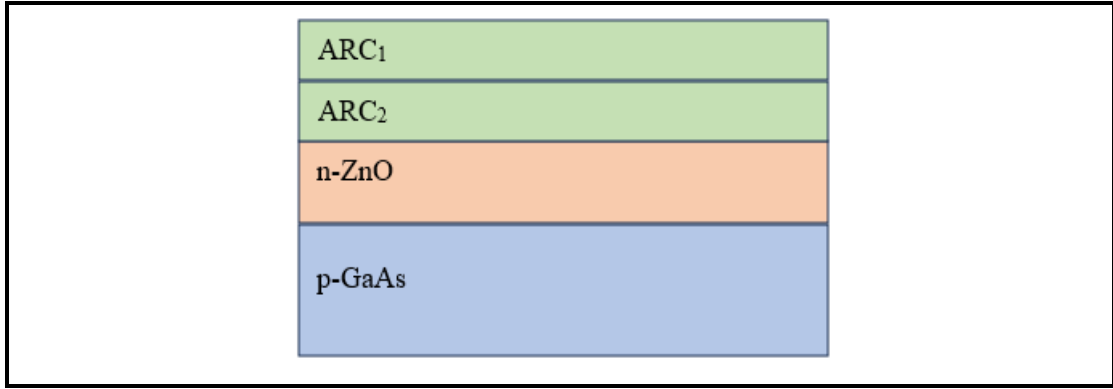


Figure 4.7 The Schematic Diagram of DLARC Configuration on ZnO/GaAs Solar Cell

Table 4.3 shows the complete results of the ZnO/GaAs solar cell using a double-layer ARC that was generated by PC1D simulation. Among these six pairs of materials of double-layer ARC, SiO₂/ZnO recorded the highest efficiency at a wavelength of 600nm, which is 19.64%. It produced 3.555A, 2.160W, and 0.7153V for I_{SC} , P_{max} , and V_{OC} respectively. A pair of SiO₂/ZnO increases 1.9% of the efficiency without using ARC. Placing SiO₂ for the first layer, as its refractive index is the lowest, followed by ZnO in the second layer, will help improve it a little. Furthermore, SiO₂/Si₃N₄ achieved 19.60% of the efficiency at 600nm, which gives a difference with SiO₂/ZnO of only 0.04%. It produced 3.549A, 2.156W, and 0.7152V for I_{SC} , P_{max} , and V_{OC} respectively. This slight difference can be due to different values of refractive index, which can also lead to changes value of thickness. The lowest efficiency at 600nm wavelength is 18.50% for ZnO/TiO₂ as a DLARC with 3.369A, 2.035W, and 0.7139V for I_{SC} , P_{max} and V_{OC} accordingly. These data can be used to compute the fill factor, which comes out to be 0.8461.

Table 4.3

Data of PC1D Simulation of ZnO/GaAs Solar Cell with DLARC

SiO ₂ /Si ₃ N ₄ ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	Si ₃ N ₄	SiO ₂	Si ₃ N ₄					
250	1.520	2.289	41.12	27.304	3.195	1.922	0.7125	0.8443	17.47
300	1.510	2.167	49.67	34.610	3.303	1.984	0.7134	0.8420	18.04
400	1.500	2.070	66.67	48.309	3.449	2.091	0.7145	0.8485	19.01
500	1.482	2.030	84.35	61.576	3.529	2.143	0.7151	0.8492	19.50

600	1.480	2.020	101.35	74.257	3.549	2.156	0.7152	0.8494	19.60
700	1.474	2.003	118.72	87.369	3.531	2.145	0.7151	0.8495	19.50
800	1.473	1.996	135.78	100.200	3.489	2.118	0.7148	0.8493	19.25
900	1.472	1.991	152.85	113.009	3.442	2.086	0.7144	0.8483	18.96
1000	1.471	1.985	169.95	138.539	3.401	2.058	0.7141	0.8474	18.71
1100	1.470	1.985	187.07	138.539	3.371	2.036	0.7139	0.8460	18.51
1200	1.469	1.983	204.22	151.286	3.353	2.024	0.7138	0.8457	18.40
SiO ₂ /TiO ₂ ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	TiO ₂	SiO ₂	TiO ₂					
250	1.520	2.46	41.12	25.407	3.102	1.869	0.7118	0.8465	16.99
300	1.510	3.326	49.67	22.550	2.595	1.548	0.7072	0.8435	14.07
400	1.500	2.680	66.67	37.313	3.091	1.863	0.7117	0.8469	16.94
500	1.482	2.480	84.35	50.403	3.322	1.995	0.7135	0.8417	18.14
600	1.480	2.404	101.35	62.396	3.410	2.064	0.7142	0.8475	18.76
700	1.474	2.364	118.72	74.027	3.415	2.068	0.7142	0.8479	18.80
800	1.473	2.341	135.78	85.434	3.378	2.042	0.7140	0.8466	18.56
900	1.472	2.325	152.85	96.774	3.325	1.997	0.7136	0.8417	18.15
1000	1.471	2.313	169.95	108.085	3.278	1.969	0.7132	0.8422	17.90
1100	1.470	2.305	187.07	119.306	3.246	1.950	0.7129	0.8427	17.73
1200	1.469	2.298	204.22	130.548	3.235	1.944	0.7129	0.8429	17.67
SiO ₂ /ZnO ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	ZnO	SiO ₂	ZnO					
250	1.520	2.388	41.12	26.173	3.141	1.892	0.7121	0.8459	17.20
300	1.510	2.404	49.67	31.198	3.164	1.905	0.7123	0.8453	17.32
400	1.500	2.114	66.67	47.304	3.430	2.078	0.7143	0.8481	18.89
500	1.482	1.968	84.35	63.516	3.541	2.151	0.7152	0.8494	19.55
600	1.480	1.913	101.35	78.411	3.555	2.160	0.7153	0.8494	19.64
700	1.474	1.883	118.72	92.937	3.535	2.147	0.7151	0.8493	19.52
800	1.473	1.864	135.78	107.296	3.499	2.124	0.7149	0.8491	19.31
900	1.472	1.851	152.85	121.556	3.464	2.101	0.7146	0.8488	19.10
1000	1.471	1.833	169.95	150.027	3.435	2.081	0.7144	0.8480	18.92
1100	1.470	1.862	187.07	161.117	3.405	2.060	0.7142	0.8471	18.73
1200	1.469	3.200	204.22	93.75	2.832	1.699	0.7095	0.8456	15.45
SiO ₂ /ZnS ARC									

λ (nm)	Refractive index		Thickness (nm)		I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	SiO ₂	ZnS	SiO ₂	ZnS					
250	1.520	2.600	41.12	24.038	3.024	1.824	0.7111	0.8482	16.58
300	1.510	2.570	49.67	29.183	3.062	1.846	0.7114	0.8474	16.78
400	1.50	2.560	66.67	39.063	3.172	1.909	0.7124	0.8448	17.35
500	1.482	2.421	84.35	51.632	3.358	2.027	0.7138	0.8457	18.43
600	1.48	2.363	101.35	63.479	3.431	2.079	0.7144	0.8482	18.90
700	1.474	2.332	118.72	75.043	3.431	2.078	0.7144	0.8478	18.89
800	1.473	2.324	135.78	86.059	3.386	2.047	0.7140	0.8467	18.61
900	1.472	2.310	152.85	97.403	3.332	2.001	0.7136	0.8416	18.19
1000	1.471	2.301	169.95	108.648	3.283	1.972	0.7132	0.8422	17.93
1100	1.470	2.296	187.07	119.774	3.250	1.953	0.7130	0.8428	17.75
1200	1.469	2.290	204.22	131.004	3.238	1.946	0.7129	0.8430	17.69
ZnO/TiO ₂ ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	ZnO	TiO ₂	ZnO	TiO ₂					
250	2.388	2.46	26.173	25.407	2.807	1.681	0.7092	0.8444	15.28
300	2.404	3.326	31.198	22.550	2.367	1.413	0.7049	0.8469	12.85
400	2.114	2.680	47.304	37.313	2.981	1.797	0.7108	0.8481	16.34
500	1.968	2.480	63.516	50.403	3.270	1.964	0.7131	0.8423	17.85
600	1.913	2.404	78.411	62.396	3.369	2.035	0.7139	0.8461	18.50
700	1.883	2.364	92.937	74.027	3.375	2.039	0.7139	0.8463	18.54
800	1.864	2.341	107.296	85.434	3.331	2.001	0.7136	0.8418	18.19
900	1.851	2.325	121.556	96.774	3.271	1.965	0.7131	0.8424	17.86
1000	1.833	2.313	150.027	108.085	3.178	1.912	0.7124	0.8445	17.38
1100	1.862	2.305	161.117	119.306	3.157	1.901	0.7122	0.8455	17.28
1200	3.200	2.298	93.75	130.548	2.632	1.569	0.7076	0.8425	14.26
ZnO/ZnS ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	ZnO	ZnS	ZnO	ZnS					
250	2.388	2.600	26.173	24.038	2.734	1.630	0.7086	0.8414	14.82
300	2.404	2.570	31.198	29.183	2.738	1.633	0.7086	0.8417	14.85
400	2.114	2.560	47.304	39.063	3.025	1.824	0.7111	0.8479	16.58
500	1.968	2.421	63.516	51.632	3.279	1.969	0.7132	0.8420	17.90
600	1.913	2.363	78.411	63.479	3.370	2.036	0.7139	0.8463	18.51
700	1.883	2.332	92.937	75.043	3.375	2.040	0.7139	0.8467	18.55

800	1.864	2.324	107.296	86.059	3.333	2.002	0.7136	0.8417	18.20
900	1.851	2.310	121.556	97.403	3.274	1.967	0.7132	0.8424	17.88
1000	1.833	2.301	150.027	108.648	3.183	1.915	0.7124	0.8445	17.41
1100	1.862	2.296	161.117	119.774	3.160	1.903	0.7123	0.8455	17.30
1200	3.200	2.290	93.75	131.004	2.634	1.570	0.7076	0.8424	14.27

Figure 4.8(a) shows the curve of I_{SC} against the wavelength for all the schemes of double-layer ARC. Based on Figure 4.8(a), all the curves had low current at short wavelengths and started to increase at a wavelength of 400nm. The primary difference among all the schemes lies in the current value generated by the simulation. As can be seen, SiO_2/ZnO and $\text{SiO}_2/\text{Si}_3\text{N}_4$ were closely followed by each other along the wavelength, except at wavelengths of 300nm and 1200nm. At short wavelengths, the surface recombination occurs, which causes the current produced to be low. Thus, in the visible region, the ARC works effectively as it reduces reflection and absorbs photons optimally, matching the optimal absorption depth in a semiconductor. This explains why the ideal current value was attained by all schemes at wavelengths between 600 and 700 nm. Furthermore, the open-circuit voltage against wavelength can also be plotted using the generated results, as shown in Figure 4.8(b). The pattern of the curves is the same as in Figure 4.8(a), which also leads to the production of high voltage in the visible region. As can be seen, the SiO_2/ZnO curve was producing optimal high voltage and was followed closely by the $\text{SiO}_2/\text{Si}_3\text{N}_4$, with slightly different values at the wavelength of 400nm – 1100nm. Meanwhile, at wavelengths of 300nm and 1200nm, there is a huge difference between the two schemes.

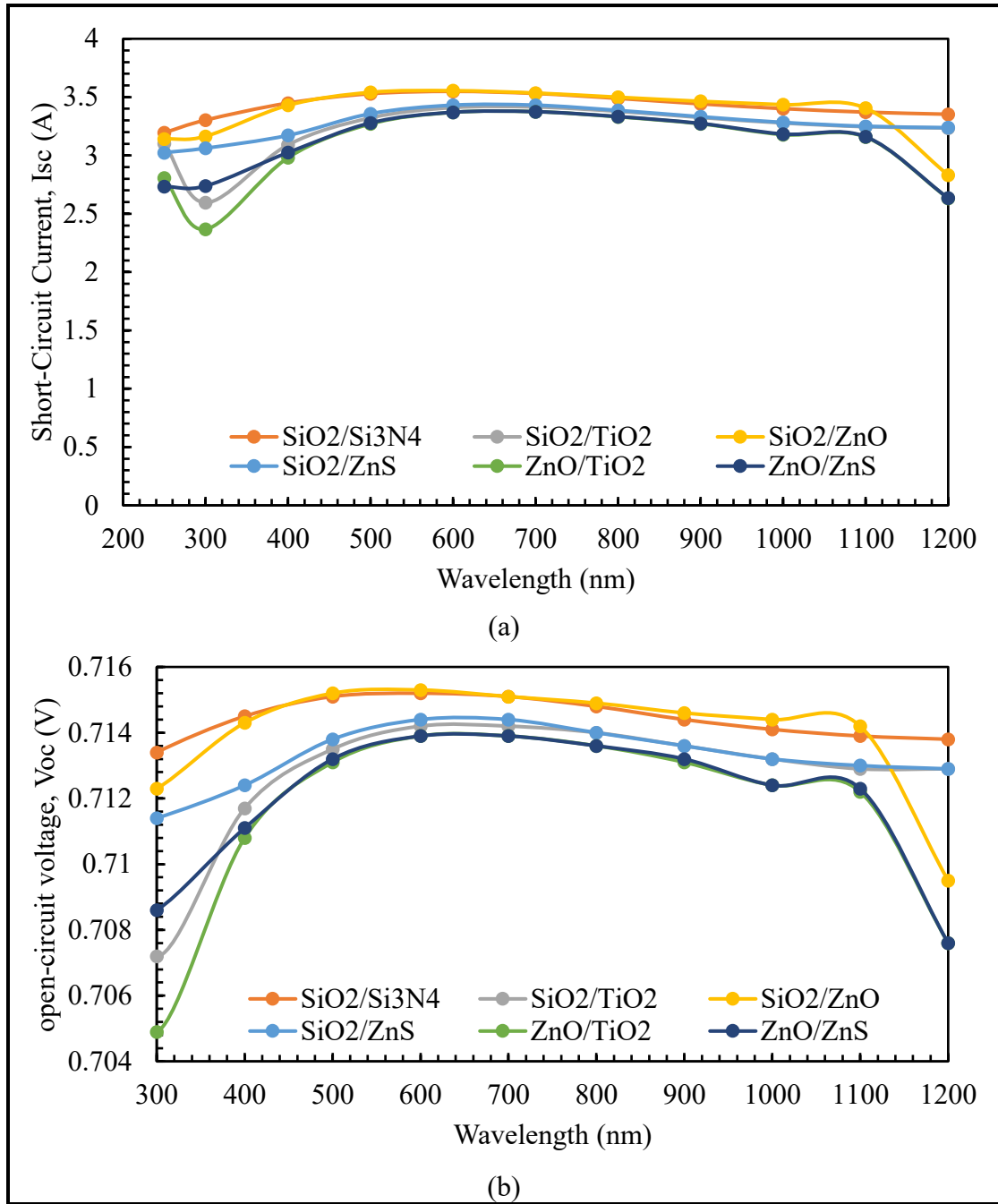


Figure 4.8 The Short-Circuit Current (a) and Open-Circuit Voltage (b) Against Wavelength for ZnO/GaAs with a Double-Layer ARC

The performance of the uncoated and coated solar cell can be observed by reflectance and EQE curve. Figure 4.9 shows the reflectance curve for each scheme, including an uncoated solar cell. It is essential to show the amount of light that is reflected to the air to monitor the work function of ARC for each scheme. Furthermore, SiO₂/ZnO, illustrated by the grey curve, was constantly produced a low percentage of reflectance which resulting in high efficiency and suitable to be use in a broad range of spectra. Among the six designs, SiO₂/ZnO attained the highest efficiency of 19.64%, as

shown in Table 4.3 with 0.805% of reflectance at a wavelength of 600nm. Mahnot et al. (2016) was studied the percentage of reflectance of SiO₂/ZnO as a double-layer ARC on crystalline silicon and achieved 6.5% under AM1.5G conditions. Besides that, SiO₂/Si₃N₄ achieved the lowest reflectance with 0.126% at a wavelength of 600nm.

However, there are an error might occur between SiO₂/ZnO and SiO₂/Si₃N₄ due to the difference between the analyzation in the curves and the results. As can be seen, the reflectance percentage that was observed for SiO₂/Si₃N₄ is the lowest which could lead to high efficiency, yet the efficiency is lower than SiO₂/ZnO due to the possibility that it might be lost in the device in heat the material. Efficiency could be determined by the conversion of optimal absorption energy rather than just the amount of light absorbed. Moreover, SiO₂/ZnO offers better refractive index gradient which will smooth the transition reduces Fresnel losses across a wider spectrum even if small peaks still appear at certain wavelengths with appropriate value of the thickness. The refractive index of SiO₂/Si₃N₄ becomes ideal as the wavelength increase which could produce the good efficiency, however, the thickness for both materials were increased that could lead the reflectance is increased. The phase shift of the reflected beams is determined by thickness. Antireflection performance is decreased by a thicker ARC because the reflected waves are no longer cancelled out.

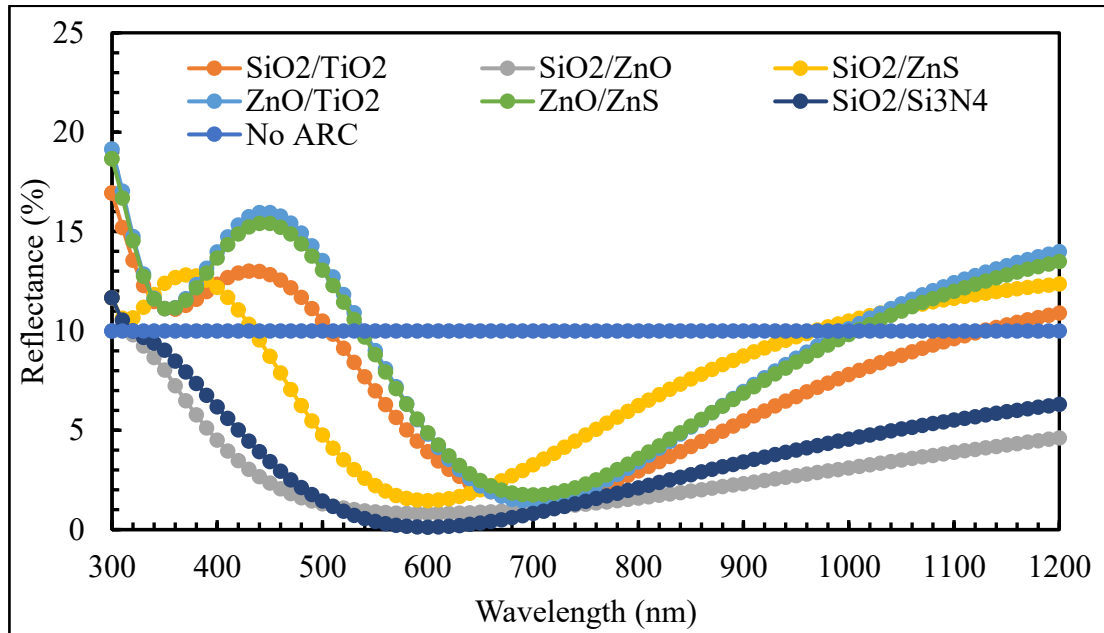


Figure 4.9 The Reflectance Percentage Curve on ZnO/GaAs with DLARC

On top of that, external quantum efficiency (EQE) also needed to observe the solar cell's behavior, as illustrated in Figure 4.10. A solar EQE is the difference between the number of charge carriers it produces and the number of incoming photons of the same energy that are irradiated onto it from the outside (James et al., 2024). Based on Figure 4.10, the SiO₂/ZnO curve, as represented by the yellow curve, shows a high percentage EQE with 99.19% at 600nm wavelength. The increment of percentage from the uncoated solar cell with 89.99% about 9.2%. Reduced reflectance is equivalent to strong transmission and strong absorption, which produce a significant production of charge carriers and raise the cell's external quantum efficiency (Diaw et al., 2021). However, as can be seen in the figure, the efficiency for all schemes suddenly drops due to photon lack of energy to overcome the bandgap at higher wavelengths.

Based on the figure, at short wavelength, between 300nm – 450nm, it's noticed that the EQE of the double-layer ARC configuration is approaching high percentage, approximately 80% - 90%, which was observed to has strong absorption. This proves that the configurations of two layers with appropriate gap could lead the high absorption of photons, which will directly increase the efficiency of solar cell.

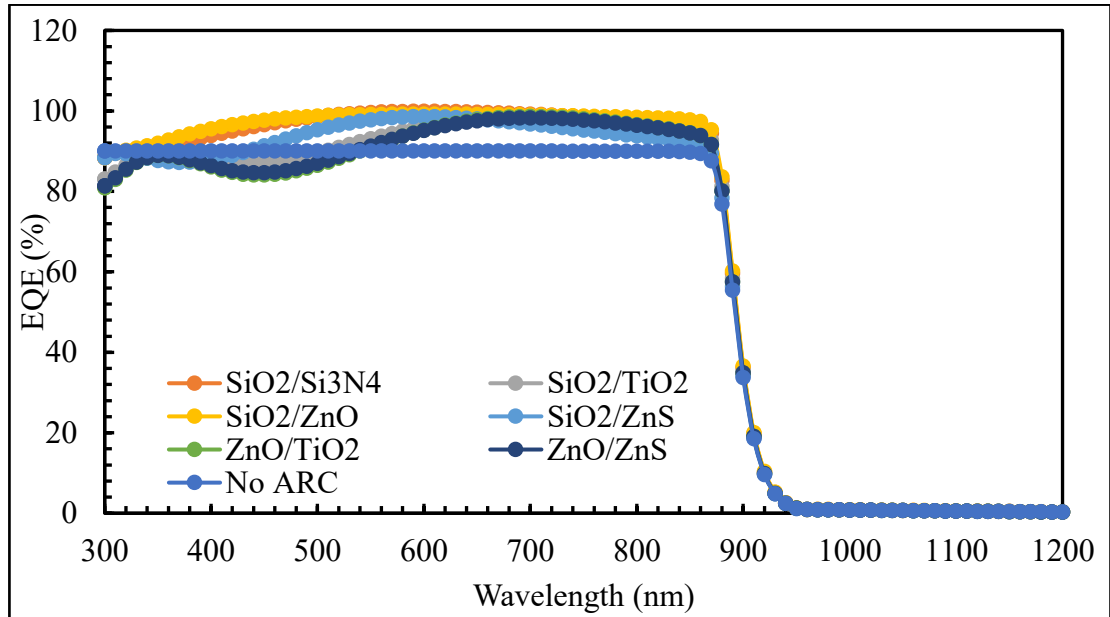


Figure 4.10 The EQE Curves of Different Types of Double-Layer ARC

4.3.3 Triple-Layer Anti-Reflective Coating (TLARC)

The efficiency of ZnO/GaAs solar cells can be improved by using a TLARC on the top of the solar cell. However, as the coating thickness increased when working with

four or more floors, the light transmittance dropped, resulting in a drop in efficiency and open-circuit voltage (Ekren, 2018). The most suitable structure for the visible and far-infrared areas is the quarter-half-quarter structure, which is a typical TLARC structure that can be created by putting a half-wavelength-thickness film into the center of the V-shaped film with an equal thickness (Ji et al., 2022, Cox et al., 1962). There are various trios of materials that have been chosen as TLARC to study on top of the ZnO/GaAs solar cell. $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnO}$, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnS}$, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{TiO}_2$, $\text{SiO}_2/\text{ZnO}/\text{ZnS}$, $\text{SiO}_2/\text{ZnO}/\text{TiO}_2$, $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$, $\text{ZnO}/\text{Si}_3\text{N}_4/\text{TiO}_2$, $\text{ZnO}/\text{Si}_3\text{N}_4/\text{ZnS}$, and $\text{ZnO}/\text{TiO}_2/\text{ZnS}$ are chosen to be used as TLARC from Hashmi et al. (2018). These materials have been arranged according to their refractive index from lowest to highest. Figure 4.11 shows the schematic diagram of the TLARC on the ZnO/GaAs solar cell structure. Only a restricted range of reflectivity is decreased by the single-layer and double-layer ARC. Triple-layer ARC is extensively used to increase silicon solar cells' current density and conversion efficiency (Kumaragurubaran B. & Anandhi S., 2014).

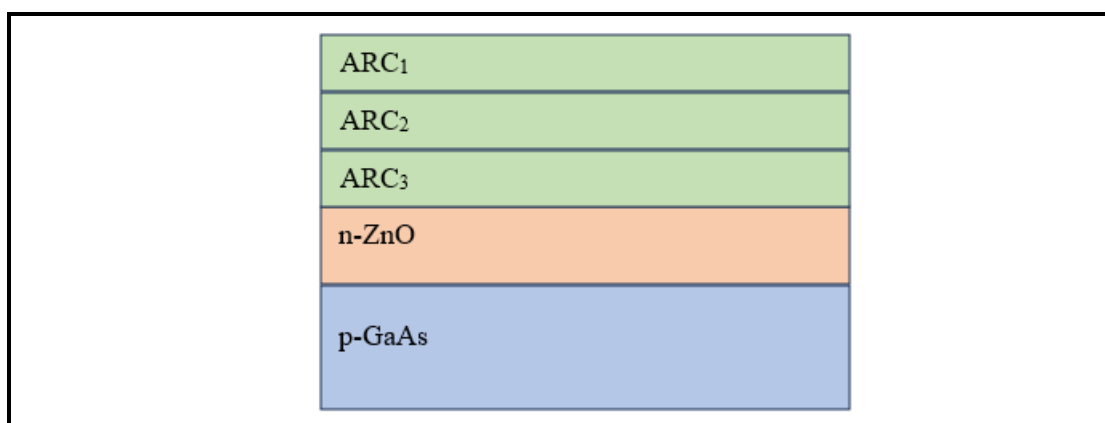


Figure 4.11 The Schematic Diagram of TLARC Configuration on ZnO/GaAs Solar Cell

Table 4.4 shows the full data of the ZnO/GaAs solar cell using a TLARC. Based on the results, $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ achieved the highest efficiency among the six schemes with 19.65%. PC1D simulated these materials and generated with 3.556A, 2.161W, and 0.7153V as I_{SC} , P_{max} , and V_{OC} accordingly. Furthermore, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnS}$ recorded the second-highest efficiency, which is 19.53% at 500nm and 600nm wavelengths. The I_{SC} values for these two wavelengths differ; for 500 nm and 600 nm, they are 3.536A and 2.535A, respectively. The fact that this difference exists because of their thickness, which is thicker at a 600nm wavelength. However, the value of P_{max} and V_{OC} were the

same for both wavelengths, which are 2.148W and 0.7151V, respectively. The lowest efficiency was recorded as 18.70% with 0.8472 as the fill factor for ZnO/TiO₂/ZnS as a triple-layer ARC. It generates 3.400A, 2.057W and 0.7141V for I_{SC} , P_{max} and V_{OC} respectively.

Table 4.4
Data of PC1D Simulation for ZnO/GaAs Solar Cell with TLARC
SiO₂/Si₃N₄/ZnO ARC

λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	Si ₃ N ₄	ZnO	SiO ₂	Si ₃ N ₄	ZnO					
250	1.520	2.289	2.388	41.12	27.304	26.173	3.099	1.868	0.7118	0.8468	16.98
300	1.510	2.167	2.404	49.67	34.610	31.198	3.259	1.958	0.7130	0.8426	17.80
400	1.50	2.070	2.114	66.67	48.309	47.304	3.472	2.107	0.7147	0.8491	19.15
500	1.482	2.030	1.968	84.35	61.576	63.516	3.518	2.137	0.7150	0.8496	19.43
600	1.48	2.020	1.913	101.35	74.257	78.411	3.523	2.140	0.7150	0.8496	19.45
700	1.474	2.003	1.883	118.72	87.369	92.937	3.509	2.131	0.7149	0.8495	19.37
800	1.473	1.996	1.864	135.78	100.200	107.296	3.472	2.107	0.7147	0.8491	19.15
900	1.472	1.991	1.851	152.85	113.009	121.556	3.423	2.073	0.7143	0.8478	18.85
1000	1.471	1.985	1.833	169.95	138.539	150.027	3.391	2.051	0.7141	0.8470	18.65
1100	1.470	1.985	1.862	187.07	138.539	161.117	3.366	2.033	0.7139	0.8460	18.48
1200	1.469	1.983	3.200	204.22	151.286	93.75	3.045	1.836	0.7113	0.8477	16.69

SiO ₂ /Si ₃ N ₄ /ZnS ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	SiO ₂	Si ₃ N ₄	ZnS	SiO ₂	Si ₃ N ₄	ZnS					
250	1.520	2.289	2.600	41.12	27.304	24.038	3.029	1.827	0.7112	0.8481	16.61
300	1.510	2.167	2.570	49.67	34.610	29.183	3.217	1.934	0.7127	0.8435	17.58
400	1.50	2.070	2.560	66.67	48.309	39.063	3.438	2.083	0.7144	0.8481	18.94
500	1.482	2.030	2.421	84.35	61.576	51.632	3.536	2.148	0.7151	0.8495	19.53
600	1.480	2.020	2.363	101.35	74.257	63.479	2.535	2.148	0.7151	1.1849	19.53
700	1.474	2.003	2.332	118.72	87.369	75.043	3.492	2.120	0.7148	0.8493	19.23
800	1.473	1.996	2.324	135.78	100.200	86.059	3.445	2.088	0.7145	0.8483	18.98
900	1.472	1.991	2.310	152.85	113.009	97.403	3.413	2.066	0.7142	0.8476	18.78
1000	1.471	1.985	2.301	169.95	138.539	108.648	3.372	2.037	0.7139	0.8462	18.52
1100	1.470	1.985	2.296	187.07	138.539	119.774	3.346	2.019	0.7137	0.8455	18.35
1200	1.469	1.983	2.290	204.22	151.286	131.004	3.315	1.991	0.7135	0.8418	18.10
SiO ₂ /Si ₃ N ₄ /TiO ₂ ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)

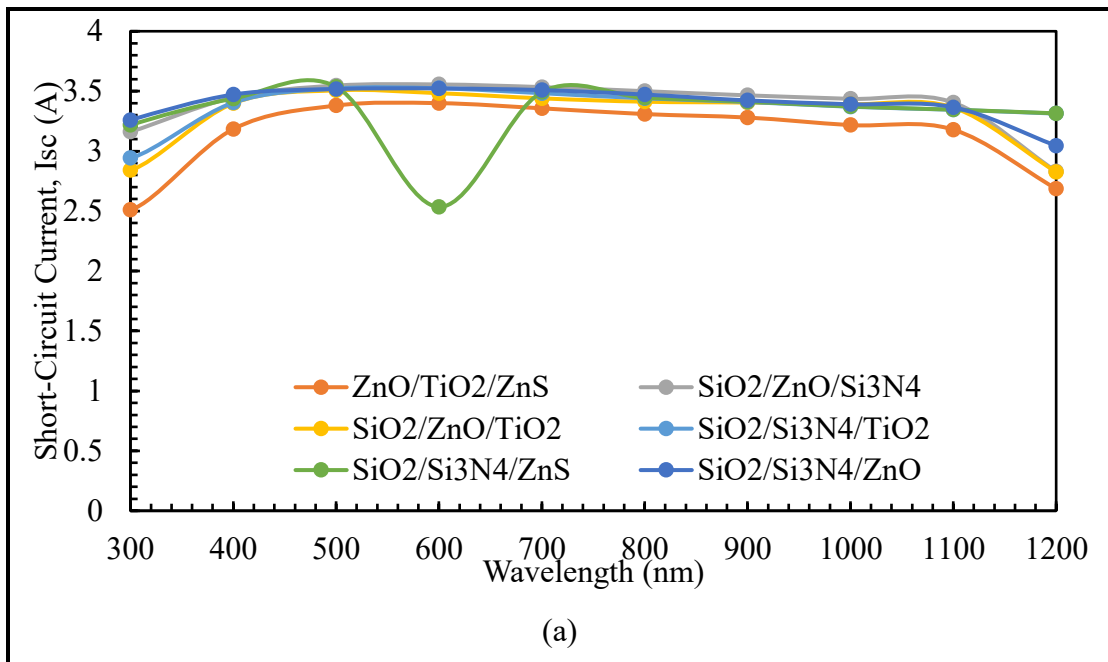
	SiO ₂	Si ₃ N ₄	TiO ₂	SiO ₂	Si ₃ N ₄	TiO ₂					
250	1.520	2.289	2.46	41.12	27.304	25.407	3.076	1.855	0.7116	0.8475	16.86
300	1.510	2.167	3.326	49.67	34.610	22.550	2.942	1.773	0.7104	0.8483	16.12
400	1.50	2.070	2.68	66.67	48.309	37.313	3.404	2.060	0.7142	0.8473	18.73
500	1.482	2.030	2.48	84.35	61.576	50.403	3.522	2.139	0.7150	0.8494	19.45
600	1.48	2.020	2.404	101.35	74.257	62.396	3.524	2.141	0.7150	0.8497	19.46
700	1.474	2.003	2.364	118.72	87.369	74.027	3.483	2.114	0.7147	0.8492	19.22
800	1.473	1.996	2.341	135.78	100.200	85.434	3.440	2.084	0.7144	0.8480	18.95
900	1.472	1.991	2.325	152.85	113.009	96.774	3.410	2.064	0.7142	0.8475	18.74
1000	1.471	1.985	2.313	169.95	138.539	108.085	3.370	2.036	0.7139	0.8463	18.51
1100	1.470	1.985	2.305	187.07	138.539	119.306	3.345	2.018	0.7137	0.8453	18.35
1200	1.469	1.983	2.298	204.22	151.286	130.548	3.313	1.990	0.7135	0.8419	18.09
SiO ₂ /ZnO/TiO ₂ ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	ZnO	TiO ₂	SiO ₂	ZnO	TiO ₂					
250	1.520	2.388	2.46	41.12	26.173	25.407	3.024	1.824	0.7111	0.8482	16.58
300	1.510	2.404	3.326	49.67	31.198	22.550	2.841	1.705	0.7095	0.8457	15.50

400	1.50	2.114	2.68	66.67	47.304	37.313	3.399	2.057	0.7141	0.8475	18.70
500	1.482	1.968	2.48	84.35	63.516	50.403	3.507	2.130	0.7149	0.8496	19.36
600	1.48	1.913	2.404	101.35	78.411	62.396	3.483	2.114	0.7147	0.8492	19.22
700	1.474	1.883	2.364	118.72	92.937	74.027	3.440	2.085	0.7144	0.8484	18.95
800	1.473	1.864	2.341	135.78	107.296	85.434	3.412	2.065	0.7142	0.8474	18.77
900	1.472	1.851	2.325	152.85	121.556	96.774	3.405	2.060	0.7142	0.8471	18.73
1000	1.471	1.833	2.313	169.95	150.027	108.085	3.391	2.050	0.7141	0.8466	18.64
1100	1.470	1.862	2.305	187.07	161.117	119.306	3.363	2.031	0.7138	0.8461	18.46
1200	1.469	3.200	2.298	204.22	93.75	130.548	2.826	1.695	0.7094	0.8455	15.41
SiO ₂ /ZnO/Si ₃ N ₄ ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	ZnO	Si ₃ N ₄	SiO ₂	ZnO	Si ₃ N ₄					
250	1.520	2.388	2.289	41.12	26.173	27.304	3.075	1.854	0.7116	0.8473	16.85
300	1.510	2.404	2.167	49.67	31.198	34.610	3.162	1.904	0.7123	0.8454	17.31
400	1.500	2.114	2.070	66.67	47.304	48.309	3.448	2.090	0.7145	0.8484	19.00
500	1.482	1.968	2.030	84.35	63.516	61.576	3.547	2.155	0.7152	0.8495	19.59
600	1.480	1.913	2.020	101.35	78.411	74.257	3.556	2.161	0.7153	0.8496	19.65
700	1.474	1.883	2.003	118.72	92.937	87.369	3.534	2.147	0.7151	0.8496	19.52

800	1.473	1.864	1.996	135.78	107.296	100.200	3.500	2.125	0.7149	0.8493	19.32
900	1.472	1.851	1.991	152.85	121.556	113.009	3.465	2.101	0.7146	0.8485	19.10
1000	1.471	1.833	1.985	169.95	150.027	138.539	3.436	2.082	0.7144	0.8482	18.93
1100	1.470	1.862	1.985	187.07	161.117	138.539	3.405	2.061	0.7142	0.8475	18.74
1200	1.469	3.200	1.983	204.22	93.75	151.286	2.831	1.698	0.7094	0.8455	15.44
ZnO/TiO ₂ /ZnS ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	ZnO	TiO ₂	ZnS	ZnO	TiO ₂	ZnS					
250	2.388	2.46	2.600	26.173	25.407	24.038	2.828	1.696	0.7094	0.8454	15.42
300	2.404	3.326	2.570	31.198	22.550	29.183	2.511	1.500	0.7064	0.8457	13.64
400	2.114	2.68	2.560	47.304	37.313	39.063	3.184	1.915	0.7124	0.8443	17.41
500	1.968	2.48	2.421	63.516	50.403	51.632	3.380	2.043	0.7140	0.8466	18.57
600	1.913	2.404	2.363	78.411	62.396	63.479	3.400	2.057	0.7141	0.8472	18.70
700	1.883	2.364	2.332	92.937	74.027	75.043	3.357	2.027	0.7138	0.8459	18.43
800	1.864	2.341	2.324	107.296	85.434	86.059	3.309	1.987	0.7134	0.8417	18.06
900	1.851	2.325	2.310	121.556	96.774	97.403	3.280	1.970	0.7132	0.8421	17.91
1000	1.833	2.313	2.301	150.027	108.085	108.648	3.217	1.934	0.7127	0.8435	17.58
1100	1.862	2.305	2.296	161.117	119.306	119.774	3.179	1.913	0.7124	0.8447	17.39

1200	3.200	2.298	2.290	93.75	130.548	131.004	2.686	1.599	0.7081	0.8407	14.54
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By using the result obtained in Table 4.4, a graph of short-circuit current vs wavelength and open-circuit voltage vs wavelength can be created for analyzing the efficacy of the solar cell. Based on Figure 4.12(a), all six triplet materials were achieving consistently high values of current. $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ started to increase at a wavelength of 400nm with 3.472A and consistently produced a high value with slightly higher than other materials. But it starts to drop at a wavelength of 1100nm with 3.366A. Also, at a wavelength of 600nm, the current of $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnS}$ was having a sudden drop, while other materials were having high current values. Additionally, in Figure 4.12(b), the open-circuit voltage was analyzed for all materials. The graph of $\text{ZnO}/\text{TiO}_2/\text{ZnS}$ shows the lowest value of voltage from 250nm – 1200nm wavelength, but the pattern of the graph is the same of other materials, which is the sudden drop at a wavelength of 300 nm and a slight increase between 1000nm – 1100nm. Meanwhile, $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ still achieved consistency of high voltage and drop at a wavelength of 1100nm with 0.7142V. While other materials were having a sudden drop at 1100nm, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnS}$ was having a consistent voltage value until 1200nm and achieved the highest value, which is 0.7135V at a wavelength of 1200nm.



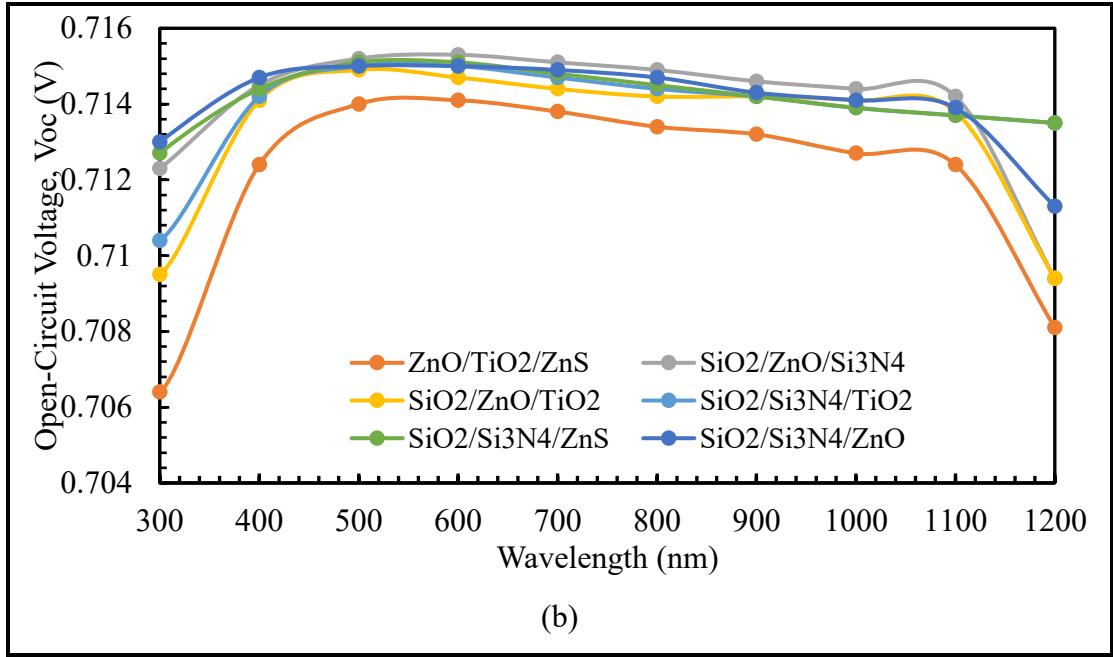


Figure 4.12 The Short-Circuit Current (a) and Open-Circuit Voltage (b) Against Wavelength for ZnO/GaAs with a Triple-Layer ARC

Besides calculating the efficiency of the solar cell, the efficacy of applying TLARC on the top of the solar cell can be seen through the reflectance curve graph, as illustrated in Figure 4.13. The $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$, as represented by the green curve, shows a constantly low percentage of reflectance and recorded 0.991% at a wavelength of 600nm. This behavior shows that $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ can work as a TLARC with efficiency in a broad-spectrum range. Moreover, Table 4.4 shows that out of the six schemes, $\text{ZnO}/\text{TiO}_2/\text{ZnS}$ had the lowest efficiency, indicating a high reflectance of the solar cell. The $\text{ZnO}/\text{TiO}_2/\text{ZnS}$, shown by the blue curve in Figure 4.13, proved to have the highest percentage of reflectance. However, some of the curves occurred lower than the uncoated solar cell, which indicates the TLARC gives a good change in reducing the reflectance.

The curve for few schemes can be seen for having two peaks across the wavelength. Feng et al. (2011) state that a multilayer ARC expands the range of relatively low reflectivity by having numerous reflectivity minima at different wavelengths. This double peak behaviour indicated poor impedance matching and wavelength-dependant cancellation that will lead to low EQE. This curve was drawn when the arrangement is not in gradual or not aligned that cause their destructive interference occur at different wavelength. In contrast, the curve with highest efficiency

shows only one broad reflectance minimum because the gradient refractive index and thickness are optimally tuned.

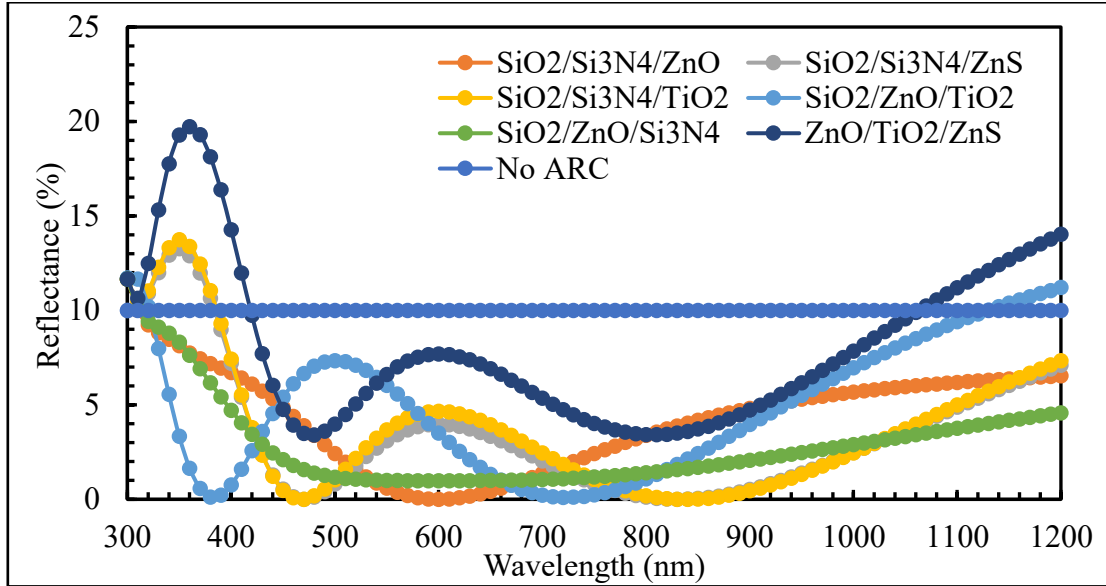


Figure 4.13 The Reflectance Curves of ZnO/GaAs of Triple-Layer ARC

Additionally, one crucial technique used to monitor how solar cells behave within a certain wavelength range is the measurement of EQE, as shown in Figure 4.14. EQE denotes the ability of a solar cell to convert all the incident photons to electrons that are transported to the external circuit. All schemes were drawn closely, but the $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$, represented by the green curve, with 19.65% efficiency was achieved 99.01% of EQE at a wavelength of 600nm. In addition, $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnO}$ recorded the highest percentage of EQE with 99.99% that represented by the orange curve, but the efficiency was slightly lower than $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$.

This apparent contradiction is explained by the fact that EQE at every wavelength is merely one of the measures of overall performance, the overall photocurrent multiplied by the AM1.5G spectrum and electrical factors define the ultimate power conversion efficiency. In addition to that, the triple-layer ARCs introduce multiple interference conditions due to the fact that each layer adds a different optical thickness. Unless the optical thicknesses are optimized together, the reflectance spectrum may be divided into more than one minimum and maximum; this phenomenon changes and draws the EQE curve. This stack of $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{ZnO}$ is expected to result in a sharper minimum in the destructive-interference at a certain a

wavelength, so that the observed peak EQE is nearly unity. In comparison, $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ seems to generate a more spectral and uniform antireflection.

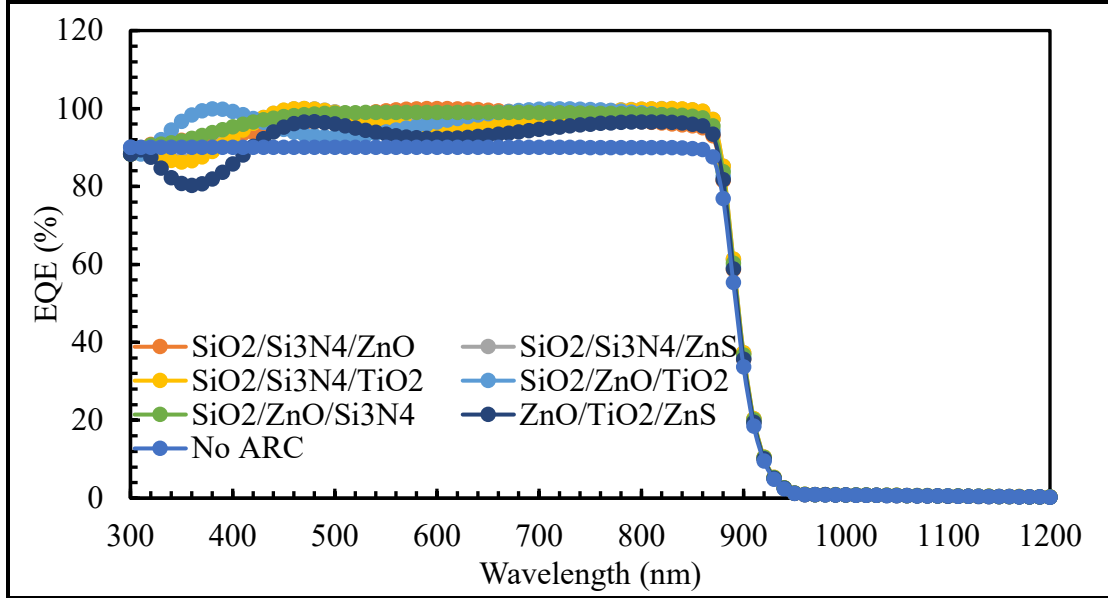


Figure 4.14 The EQE Curves of ZnO/GaAs of Triple-Layer ARC

Overall, the data indicates a different output for different material in different ARC configuration. The result was analyzed to determine the best material in ARC with maximum efficiency. Table 4.5 shows the comparison of the results in these findings with previous study for ZnO/GaAs solar cell. A few approaches and methods have been made by some researcher which could lead to a different result of the efficiency. Based on the table, the increment of the electrical parameters, I_{SC} , P_{max} , and V_{OC} , from uncoated were proved that ARC could reduce the reflectance due to refractive index grading and destructive interference effects which cause indirectly, high absorption and efficiency (Kim, 2015) in this study. Among all the schemes in this study, it shows that $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ as a TLARC has the highest efficiency among another configuration because the design can reduce reflections in the solar spectrum and broaden the anti-reflection bandwidth. The efficiency improvement, however, is minimal when the number of ARC layers is increased, indicating decreasing returns when more than two layers are coated.

Table 4.5

Comparison of Study Results with Findings from Similar Studies for ZnO/GaAs Solar Cell

ARC Structure	ARC Materials	I_{sc} (A)	P_{max} (W)	V_{oc} (V)	Efficiency (%)	References
DLARC	Nanorods ZnO	-	-	0.6830	19.70	Derbali (2022)
Uncoated	-	-	-	0.9770	21.21	Manoua et al. (2023)
Uncoated	-	-	-	0.9400	22.84	Jin and Tang (2021)
Uncoated	-	3.253	1.954	0.7130	17.76	
SLARC	SiO ₂	3.551	2.158	0.7152	19.62	
DLARC	SiO ₂ /ZnO	3.555	2.160	0.7153	19.64	This study
TLARC	SiO ₂ /ZnO/Si ₃ N ₄	3.556	2.161	0.7153	19.65	

4.4 Summary

ZnO/GaAs solar cell that was not loaded with ARC had an efficiency of 17.76%, which can be attributed primarily to optical loss due to front-surface reflection. Application of SLARC with a device made of SiO₂ was highly effective as it increased the efficiency to 19.62% by cutting the difference in the refractive index between air and ZnO, thus, improving the light penetration into the GaAs absorber. More efficiency enhancement was realized in the case of double and triple layer (SiO₂/ZnO and SiO₂/ZnO/Si₃N₄) ARC structure with an efficiency of 19.64% and 19.65% respectively. These multilayer designs have a smoother refractive index transition and wider anti-reflection properties, but the efficiencies have very small improvements over SLARC. This shows that the better the ARC is made, the less the optical benefits are gained, indicating that a single layer SiO₂ has already reached the point where all gains are limited by electrical losses and not optical considerations.

CHAPTER 5

THE ZNO/ALGAAS/SI SOLAR CELL USING VARIOUS ANTI-REFLECTIVE COATINGS (ARC)

5.1 Introduction

Enhancement of the efficiency can be made by adding the junction of the cell device. Multiple p-n junction semiconductor sub-layer solar cells can collect a wider spectrum of sun wavelengths because they will surpass the Shockley-Queisser photoconversion efficiency limit of conventional PV cells (Raisa et al., 2025). Unlike previous works that used different material systems for triple heterojunction solar cells, a ZnO/AlGaAs/Si structure was introduced for exploring new device designs to improve the performance. Hence, the base cell was examined under the same illumination with AM1.5G at one-sun mode to study its performance of the three-material combination as a triple-heterojunction solar cell. Furthermore, the ARCs were implemented on the cell device to reduce the reflectance and indirectly improve the efficiency until it is maximized.

5.2 The ZnO/AlGaAs/Si solar cell without Anti-Reflective Coating (ARC)

Figure 5.1 shows a schematic diagram for the uncoated ZnO/AlGaAs/Si solar cell. The efficiency of the uncoated solar cell was generated after simulating with parameters as shown in Table 3.2. The result of I_{SC} , P_{max} and V_{OC} were shown in Table 5.1, which are 3.870A, 2.418W, and 0.7417V, respectively. By using (2.4) and (2.5), the fill factor will result in approximately 0.8424, which can achieve 21.98% of the efficiency, respectively. The AlGaAs/Si solar cell was observed by Xiong et al. (2018) experimentally on how efficient of III-V/Si multijunction solar cell is and achieved 12.7% efficiency. Besides that, Roy et al. (2023) achieved 22.3% for an AlGaAs/Si dual junction solar cell using PC1D simulation with surface texture depth at 3 μ m. For the ZnO/Si solar cell, Jamaluddin et al. (2024) studied without applying

any ARC using PC1D simulation and gained 22.27% efficiency. Each dual heterojunction shows the best performance of a solar cell from previous researchers, which means the combination of the materials was approvable and can be used to improve the solar cell. However, there was a different percentage of efficiency due to the different values of parameters that are still being investigated to be used for this combination.

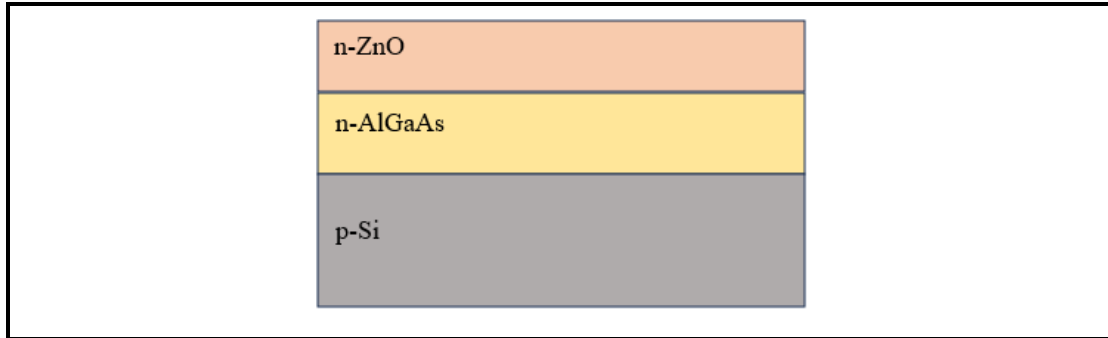


Figure 5.1 The Schematic Diagram of Uncoated ZnO/AlGaAs/Si Solar Cell

Table 5.1
Data of PC1D Simulation for ZnO/AlGaAs/Si Solar Cell without ARC

I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
3.870	2.418	0.7417	0.8424	21.98

Figure 5.2 shows the I-V curve of the uncoated device for the ZnO/AlGaAs/Si solar cell that can be drawn using the results obtained which represents the relationship between current and voltage output under a given condition. The curve is significant to the researcher as it can illustrate how a solar cell behaves electrically (Olayiwola et al., 2024). Based on the curve in Figure 5.1, the current has a constant value of approximately 3.870A as the voltage increases. Also, when the voltage is zero ($V=0$), the I_{SC} can be observed in the curve. Furthermore, the current remained constant as the voltage increased, and it started to drop drastically at a voltage of 0.6227V. Both values, current and voltage, were improved by implementing the ARC with various layers and materials.

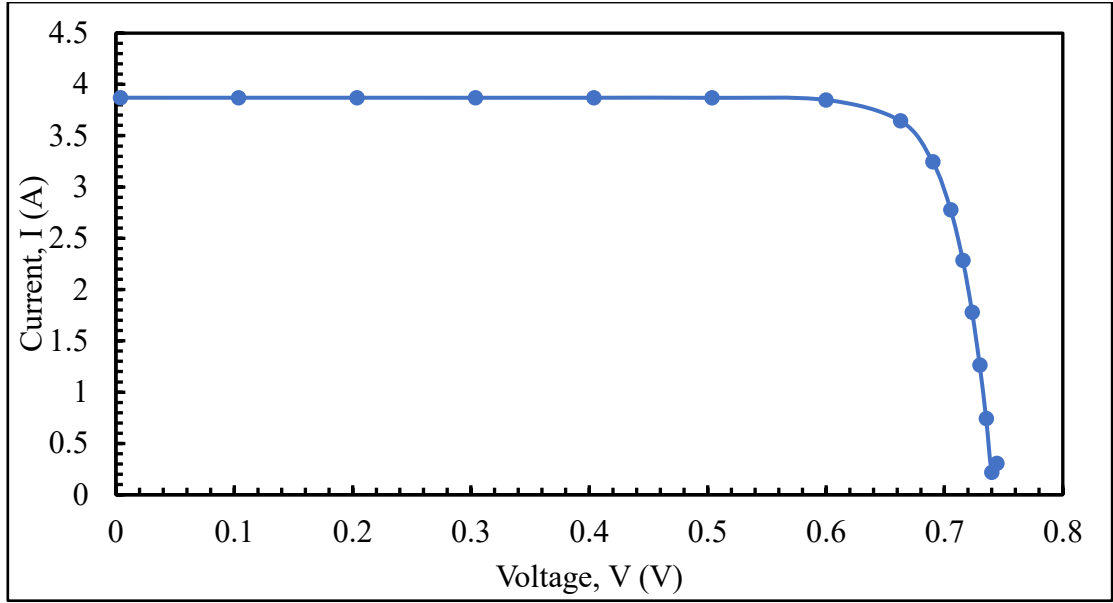


Figure 5.2 The I-V Curve of an Uncoated ZnO/AlGaAs/Si Solar Cell

5.3 The ZnO/AlGaAs/Si solar cell with Anti-Reflective Coating (ARC)

5.3.1 Single-Layer Anti-Reflective Coating (SLARC)

Although the uncoated ZnO/AlGaAs/Si solar cell shows promising performance, the main problem which that light reflectance still occurs, which will affect the efficiency. In consequence, further enhancement can be made by applying the ARC on the cell device by using appropriate materials. The single-layer, double-layer, and triple-layer ARCs were used to examine the solar cell to find the best type of ARCs for achieving the highest efficiency. The materials of the single-layer ARC were SiO₂, Si₃N₄, and ZnO to study the effectiveness of the ARC to reduce the reflectance and indirectly boost the efficiency. The material was placed on front surface of the solar cell, as shown in Figure 5.3.

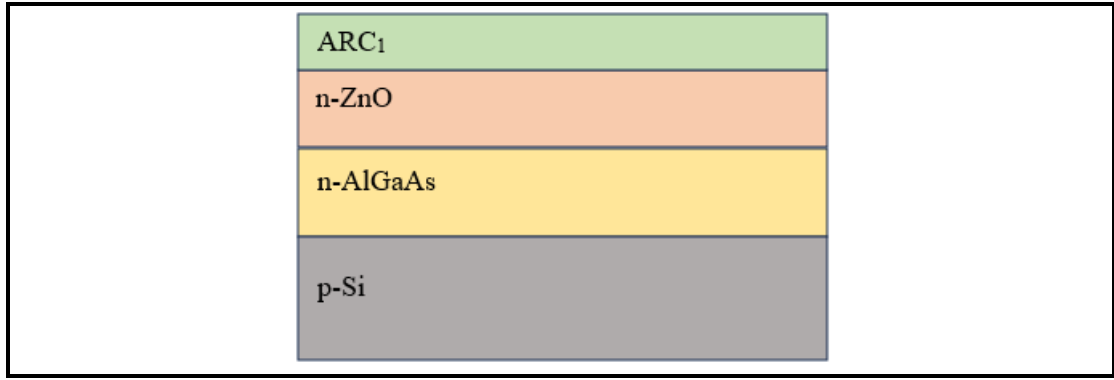


Figure 5.3 The Schematic Diagram of the SLARC Configuration on ZnO/AlGaAs/Si Solar Cell

Based on Table 5.2, the required value of refractive index and thickness were changing along the wavelength, which can produce different results of I_{SC} , P_{max} , V_{OC} and efficiency. Among the materials studied, SiO_2 as a layer ARC achieved the highest efficiency, with 24.08% and a fill factor of 0.8449 at a wavelength of 600nm under AM1.5G conditions. The value of I_{SC} , P_{max} and V_{OC} were generated with 4.215A, 2.649W, and 0.7438V, respectively. Also, the efficiency for SiO_2 at wavelengths between 250nm – 1200nm was recorded as higher than the efficacy of a bare solar cell. The main factor in this incident was that the value of the SiO_2 's refractive index is lower than that of n-ZnO's refractive index, which can act as an intermediate matching layer between air and substrate (Liu et al., 2024). The SiO_2 as single layer ARC resulted in 9.43% efficiency on a silicon solar cell by using Silvaco TCAD software (Abdullah et al., 2009). Besides that, Kanmaz (2024) successfully increased the efficiency from 14.63% to 18.95% after applying SiO_2 on top crystalline silicon cell with optimum thickness. Next, ZnO recorded 22.38% as the second-highest efficiency with I_{SC} , P_{max} and V_{OC} were 3.947A, 2.462W, and 0.7422V, respectively. The increment of the efficiency after applying ZnO as SLARC is 0.40% only. Lastly, Si_3N_4 produced the lowest efficiency among other materials and bare devices with 21.78% at 1200nm. The value of the I_{SC} , P_{max} and V_{OC} were 3.874A, 2.212W, and 0.7387V, respectively, resulting in a fill factor of 0.7730.

The error in the results of Si_3N_4 as SLARC is due to its refractive index value not being constant and gradually increasing from the air to the substrates. The suitable arrangement of the refractive index is $n_{air} (1.00) < n_{SLARC} < n_{ZnO} (2.00)$ to achieve the maximum percentage of the reduction of light. Based on the results, at wavelengths 250nm – 700nm, the value of the refractive index was larger than $n_{ZnO} (2.00)$, which

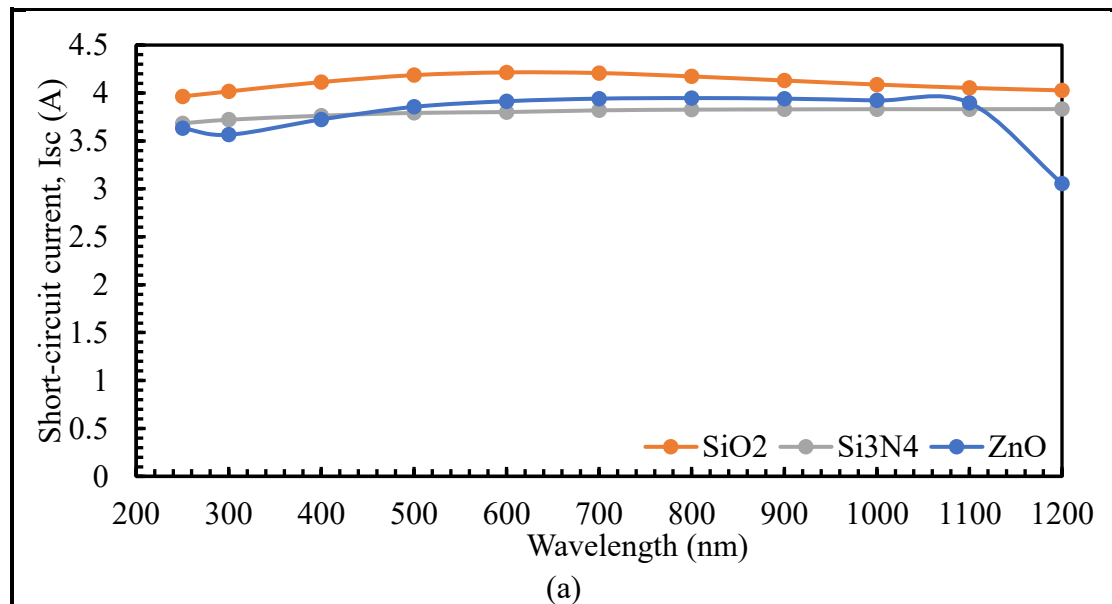
prevents the ARC from functioning. However, the value of the refractive index of Si_3N_4 at wavelengths 800nm – 1200nm was lower and closer to that of n-ZnO. The sudden sharp increase in the refractive index of Si_3N_4 from the air could affect the performance of the ARC.

Table 5.2
Data of PC1D Simulation for ZnO/AlGaAs/Si Solar Cell with SLARC

Silicon Dioxide (SiO_2)							
λ (nm)	Refractive index, n	Thickness, d (nm)	I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
250	1.520	41.12	3.964	2.472	0.7423	0.8401	22.47
300	1.510	49.67	4.016	2.499	0.7427	0.8378	22.72
400	1.500	66.67	4.114	2.581	0.7433	0.8440	23.46
500	1.482	84.35	4.186	2.630	0.7437	0.8448	23.91
600	1.480	101.35	4.215	2.649	0.7438	0.8449	24.08
700	1.474	118.72	4.208	2.644	0.7438	0.8448	24.04
800	1.473	135.78	4.173	2.625	0.7435	0.8461	23.86
900	1.472	152.85	4.130	2.596	0.7432	0.8458	23.60
1000	1.471	169.95	4.088	2.566	0.7430	0.8448	23.33
1100	1.470	187.07	4.053	2.541	0.7428	0.8440	23.10
1200	1.469	204.22	4.027	2.510	0.7427	0.8392	22.82
Silicon Nitride (Si_3N_4)							
λ (nm)	Refractive index, n	Thickness, d (nm)	I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
250	2.289	27.304	3.684	2.308	0.7404	0.8462	20.98
300	2.167	34.610	3.721	2.330	0.7407	0.8454	21.18
400	2.070	48.309	3.763	2.356	0.7410	0.8449	21.42
500	2.030	61.576	3.792	2.373	0.7412	0.8443	21.57
600	2.020	74.257	3.801	2.378	0.7412	0.8441	21.62
700	2.003	87.369	3.819	2.389	0.7414	0.8438	21.72
800	1.996	100.200	3.826	2.392	0.7414	0.8433	21.75
900	1.991	113.009	3.829	2.394	0.7414	0.8433	21.76
1000	1.985	138.539	3.831	2.395	0.7414	0.8432	21.77
1100	1.985	138.539	3.831	2.395	0.7414	0.8432	21.77
1200	1.983	151.286	3.832	2.396	0.7414	0.8434	21.78
Zinc Oxide (ZnO)							
λ (nm)	Refractive index, n	Thickness, d (nm)	I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
250	2.388	26.173	3.633	2.275	0.7401	0.8461	20.68
300	2.404	31.198	3.564	2.229	0.7396	0.8456	20.26
400	2.114	47.304	3.724	2.333	0.7407	0.8458	21.21
500	1.968	63.516	3.855	2.409	0.7416	0.8426	21.90
600	1.913	78.411	3.914	2.443	0.7420	0.8412	22.21

700	1.883	92.937	3.941	2.458	0.7421	0.8405	22.35
800	1.864	107.296	3.947	2.462	0.7422	0.8404	22.38
900	1.851	121.556	3.941	2.458	0.7421	0.8405	22.35
1000	1.841	135.800	3.922	2.447	0.7420	0.8409	22.25
1100	1.833	150.027	3.897	2.433	0.7418	0.8416	22.12
1200	1.826	164.294	3.056	1.902	0.7358	0.8459	17.29

From the results obtained by PC1D simulation, there are a few graphs that can be drawn to analyze the performance of the solar cell. Figure 5.4 (a) and (b) show the curve of short-circuit current and open-circuit voltage corresponding to wavelength. For both graphs, SiO₂, represented by the orange curve, shows a constantly high value of current and voltage as the wavelength increases. This curve proves the results of SiO₂ in Table 5.2, which yielded obtained good value percentage of the performance. Meanwhile, ZnO that represented by the blue curve, was observed to have low current and voltage at short wavelengths between 250nm – 400nm. However, it's slowly increasing from 500nm which resulting in good performance at a broad wavelength. Si₃N₄, represented by the grey curve, clearly shows that the curve was at the lowest among other materials except at short wavelength between 250nm – 400nm, it produces a higher value than ZnO.



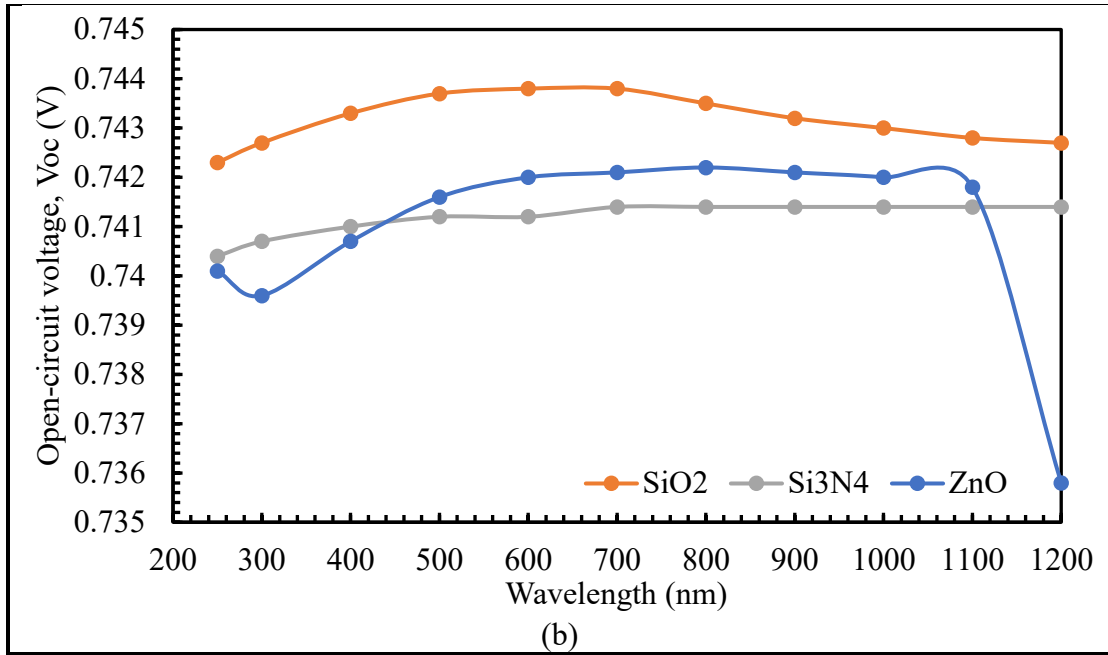


Figure 5.4 The Curve of Short-Circuit Current (a) and Open-Circuit Voltage (b) Against Wavelength for a ZnO/AlGaAs/Si Solar Cell with a Single-Layer ARC

Figure 5.5 shows the reflectance curve of the ZnO/AlGaAs/Si solar cell with and without using the SLARC. Applying ARC on top of the cell device could reduce the reflectance of light; however, it can increase the reflectance if the refractive index of the materials and the arrangement are inappropriate. Hence, the reflectance curve was constructed to observe the performance of the ARC along the wavelengths.

Based on the curve in Figure 5.5, the uncoated cell, represented by the blue curve, recorded 10% of the reflectance percentage at wavelengths 300nm – 1200nm. The SiO₂, indicated by the orange curve, successfully reduces the reflectance up to 0.21% at a wavelength of 600nm and indirectly records the lowest percentage among the other SLARCs. The ZnO curve, represented by the yellow line, reads slightly higher than the bare device but gradually decreases around 500nm. ZnO's lowest reflectance, at 7.25% occurs at 800nm. Finally, the Si₃N₄ curve, shown in the grey curve, is consistently higher than the bare device, as shown in Table 5.2, which recorded the lowest efficiency.

The SLARC's curves that were drawn under uncoated curves show that the ARC works efficiently; otherwise, it fails to reduce the reflectance. The Si₃N₄'s curve, as represented by gray curve, shows it cannot be a possible SLARC material for ZnO/AlGaAs/Si solar cell due to its high reflectance. The error might have happened due to the mismatch of the refractive index between Si₃N₄ as ARC layer and n-ZnO.

The refractive index of Si_3N_4 along the wavelengths was not suitable to be stacked with n-ZnO , as the gradient is abrupt. This will affect the performance of the cell device as it cannot reduce the reflectance that is reflected on the surface, and indirectly, the absorption fails miserably.

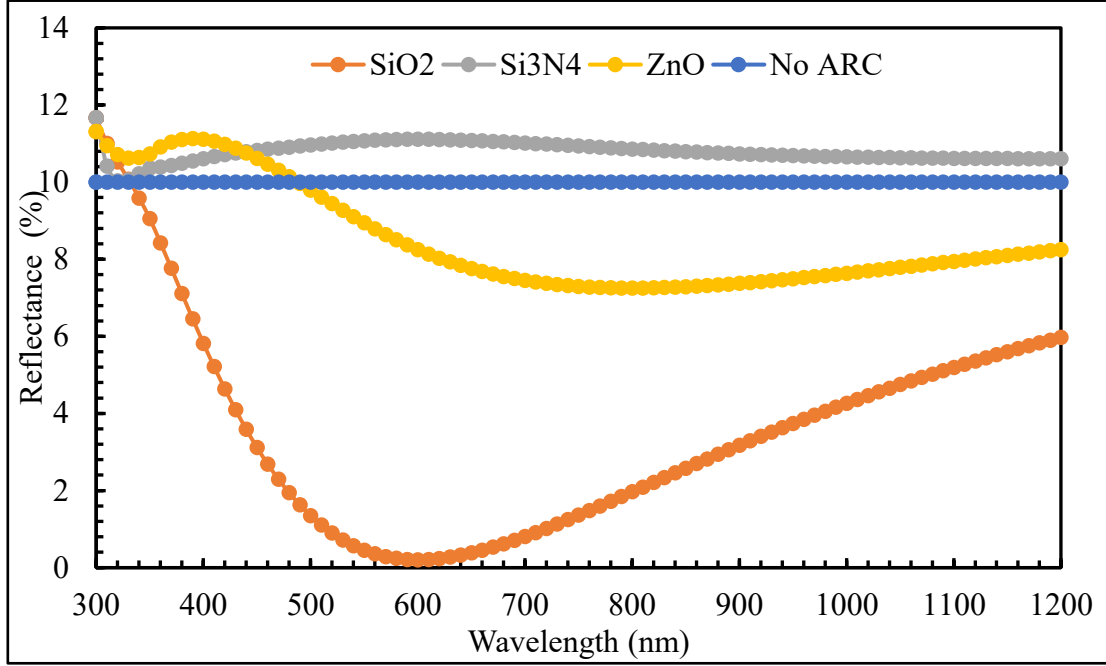


Figure 5.5 The Reflectance Curve for ZnO/AlGaAs/Si Solar Cell with and without SLARC

Besides that, the PC1D simulation also provides quantum efficiency (QE) curves for the analysis. It shows the proportion of incident photons for a specific wavelength to the number of collected carriers during short-circuit operating conditions (Slami & Benramdane, 2021). There are two types of QE, one of them is external quantum efficiency (EQE). EQE is the difference between the quantity of charge carriers produced by the solar cell and the quantity of incident photons of the specified energy that are irradiated onto the solar cell from the exterior (James et al., 2024).

Figure 5.6 shows the EQE curve plotted for both the coated and uncoated cell devices. All schemes followed the same pattern and were closely drawn together. They began at nearly 0% EQE between 300nm and 400nm and gradually increased. The bare device reached an EQE of 89.74%. The SiO_2 had the highest EQE at 99.01%, indicating nearly complete photon absorption; meanwhile, the ZnO and Si_3N_4 showed lower EQEs of 92.31% and 88.72%, respectively. The increment of the percentage from the

uncoated device was affected by a few factors, one of them is the value of the thickness of ARC. Applying an appropriate-thickness antireflection coating may improve the GaAs solar cell's performance by boosting the number of charge carriers (Asahi et al., 2017). At a wavelength of 1000nm, the percentage of EQE for all three materials decreased and converged to similar levels at higher wavelengths.

According to the quarter-wave thickness model, the EQE enhancement peak moves towards longer wavelengths when the material's thickness is increased up to 20nm at a wavelength of 400nm. The thickness of the ARC plays a significant role in improving the efficiency and performance. Shah et al. (2022) studied various thicknesses of HfO_2 as a single-layer ARC on a silicon solar cell and found that at a thickness of 70nm, HfO_2 successfully increased the power conversion efficiency from 12.27% to 21.15% with a percentage EQE of 98%. Besides that, Parajuli et al. (2025) also studied to find the optimum thickness for TiO_2 on GaAs solar cells, which would observe the EQE curves along the range of thickness and wavelengths. He successfully increased the efficiency of the solar cell and indirectly increased the EQE percentage after implementing the TiO_2 as a single-layer ARC from 60% to nearly 90%. Both studies prove that the thickness of the ARCs can affect the percentage of the EQE.

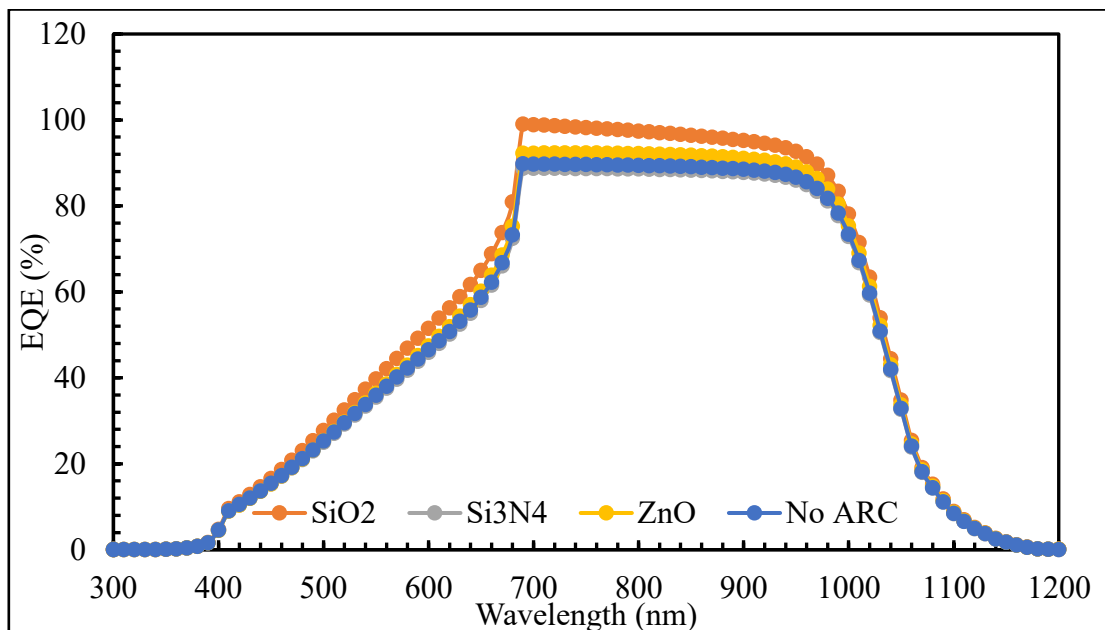


Figure 5.6 The External Quantum Efficiency (EQE) Curve for ZnO/AlGaAs/Si Solar Cell with and without SLARC

5.3.2 Double-Layer Anti-Reflective Coating (DLARC)

Adding more layers to the ARCs can be more complex, but it can help boost the solar cell's performance over a wide range of wavelengths. In contrast to the single-layer ARC, which approaches zero at the center wavelength and greatly increases when it deviates from it, the effective reflectivity dramatically drops when the conventional double-layer ARC is utilized (Ji et al., 2022). The double-layer ARC needs to be arranged, as shown in Figure 5.7, based on its refractive index by layering with ascending order of refractive index and starting with the lowest refractive index at the top. The principle behind the anti-reflective coating is the destructive interference phenomenon. It occurs when these two reflected wavefronts are totally out of phase, completely canceling out both beams and increasing the transmittance (Zahid et al., 2023). All the materials were paired based on their refractive index, with an appropriate arrangement. Nine pairs of double-layer ARCs were proposed to examine the ability to reduce reflectance, which are $\text{SiO}_2/\text{Si}_3\text{N}_4$, $\text{SiO}_2/\text{TiO}_2$, SiO_2/ZnO , SiO_2/ZnS , ZnO/TiO_2 , ZnO/ZnS , $\text{ZnO}/\text{Si}_3\text{N}_4$, $\text{Si}_3\text{N}_4/\text{TiO}_2$, and $\text{Si}_3\text{N}_4/\text{ZnS}$ by using PC1D simulation software.



Figure 5.7 The Schematic Diagram of DLARC Configuration on ZnO/AlGaAs/Si Solar Cell

Table 5.3 shows the complete data for the ZnO/AlGaAs/Si solar cell with a double-layer ARC on top of it. Nine pairs of double-layer ARCs were proposed to examine the ability to reduce reflectance. Out of nine pairs, SiO_2/ZnO recorded the highest efficiency of 24.15% at a wavelength of 600nm. The combination successfully produced 4.227A, 2.636W, and 0.7439V of I_{SC} , P_{max} and V_{OC} , respectively, resulting

in the fill factor of 0.8447. However, ZnO/TiO₂ will be a great pair compared to SiO₂/ZnO because TiO₂ has its exceptional resistance to weather and corrosion, high chemical and thermal stability, and harmless nature (Tang et al., 2024) as the ZnO may be etched under acidic rain. Nevertheless, other properties make SiO₂/ZnO become a strong pair as DLARC. The choice of ARC materials with a suitable RI and thickness is significant as it can help to reduce reflectance and increase transmission. Furthermore, the choice of cell device materials will affect the results, which can lead to various possible pairs of ARCs achieving high efficiency.

The second pair to achieve high efficiency was SiO₂/Si₃N₄, with 24.05%, producing 4.210A, 2.646W, and 0.7438V of I_{SC} , P_{max} and V_{OC} , respectively. Comparing both pairs, SiO₂/Si₃N₄ could be a great pair based on its properties and reactions to natural conditions. The ZnO in the ARC layer may be etched under acidic rain, as it has an amphoteric nature. However, many researchers have confirmed that ZnO is suitable for use as an ARC in various types and methods by studying its performance in solar cells (Rahimi et al., 2025, Suhandi et al., 2017, Atilgan A., 2025). Furthermore, the choice of cell device materials will affect the results, which can lead to various possible pairs of ARCs achieving high efficiency. The lowest efficiency was achieved by Si₃N₄/ZnS with 3.923A, 2.448W, and 0.7420V of I_{SC} , P_{max} and V_{OC} , respectively, resulting in an efficiency of 22.25%. Although the performance was higher than that of the base cell, Si₃N₄/ZnS is not a suitable pair for DLARC. Sathya and Supriya (2017) were successfully achieved 33.87% of the efficiency for AlGaAs/GaAs/Si solar cell with implementing DLARC and textured surface by using the PC1D simulation. Dimroth et al. (2020) study the optimization device and subcell matching and also successfully achieved 34.1% of the efficiency by experimental way. Each previous study has a different approaches and methods to produce high efficiency of the solar cell which could lead a different output.

Moreover, as can be seen, the material that is paired with TiO₂ exhibits low efficiency at a wavelength of 300nm. It is because the refractive index of TiO₂ is high that causes the refractive index to be non-constant and to vary gradually between the air and the substrate. The arrangement of the refractive index for ZnO/TiO₂ is n_{air} (1.00) < n_{ZnO} (2.404) < n_{TiO2} (3.326) > n_{n-ZnO} (2.00). The sudden increase in refractive index from air to ZnO, and the value of TiO₂ is much larger than n-ZnO, could cause the absorption of photons, and the efficiency is low. This proves that

appropriately optimizing the value of the refractive index is significant to reduce the reflectance in maximizing.

Table 5.3

Data of PC1D Simulation of ZnO/AlGaAs/Si Solar Cell with DLARC

SiO ₂ /Si ₃ N ₄ ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	Si ₃ N ₄	SiO ₂	Si ₃ N ₄					
250	1.520	2.289	41.12	27.304	3.797	2.376	0.7412	0.8442	21.60
300	1.510	2.167	49.67	34.610	3.914	2.443	0.7420	0.8412	22.21
400	1.500	2.070	66.67	48.309	4.079	2.556	0.7431	0.8433	23.24
500	1.482	2.030	84.35	61.576	4.175	2.623	0.7436	0.8449	23.85
600	1.480	2.020	101.35	74.257	4.210	2.646	0.7438	0.8450	24.05
700	1.474	2.003	118.72	87.369	4.207	2.643	0.7438	0.8446	24.03
800	1.473	1.996	135.78	100.200	4.174	2.626	0.7435	0.8462	23.87
900	1.472	1.991	152.85	113.009	4.132	2.597	0.7433	0.8456	23.61
1000	1.471	1.985	169.95	138.539	4.092	2.569	0.7430	0.8450	23.35
1100	1.470	1.985	187.07	138.539	4.058	2.545	0.7428	0.8443	23.14
1200	1.469	1.983	204.22	151.286	4.033	2.514	0.7427	0.8393	22.85
SiO ₂ /TiO ₂ ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	TiO ₂	SiO ₂	TiO ₂					
250	1.520	2.46	41.12	25.407	3.692	2.313	0.7405	0.8460	21.03
300	1.510	3.326	49.67	22.550	3.106	1.934	0.7361	0.8459	17.58
400	1.500	2.68	66.67	37.313	3.646	2.284	0.7403	0.8462	20.76
500	1.482	2.48	84.35	50.403	3.908	2.436	0.7420	0.8401	22.15
600	1.480	2.404	101.35	62.396	4.021	2.507	0.7427	0.8395	22.79
700	1.474	2.364	118.72	74.027	4.055	2.543	0.7428	0.8443	23.12
800	1.473	2.341	135.78	85.434	4.042	2.520	0.7427	0.8394	22.91
900	1.472	2.325	152.85	96.774	4.055	2.496	0.7425	0.8290	22.69
1000	1.471	2.313	169.95	108.085	3.960	2.470	0.7422	0.8404	22.45
1100	1.470	2.305	187.07	119.306	3.919	2.445	0.7420	0.8408	22.23
1200	1.469	2.298	204.22	130.548	3.899	2.434	0.7418	0.8416	22.13
SiO ₂ /ZnO ARC									
λ	Refractive index		Thickness (nm)		I_{SC}	P_{max}	V_{OC}	FF	η (%)

(nm)	SiO ₂	ZnO	SiO ₂	ZnO	(A)	(W)	(V)		
250	1.520	2.388	41.12	26.173	3.736	2.340	0.7408	0.8455	21.27
300	1.510	2.404	49.67	31.198	3.755	2.351	0.7410	0.8449	21.37
400	1.50	2.114	66.67	47.304	4.054	2.539	0.7429	0.8430	23.08
500	1.482	1.968	84.35	63.516	4.195	2.636	0.7437	0.8449	23.96
600	1.48	1.913	101.35	78.411	4.227	2.656	0.7439	0.8447	24.15
700	1.474	1.883	118.72	92.937	4.216	2.649	0.7438	0.8447	24.08
800	1.473	1.864	135.78	107.296	4.182	2.632	0.7436	0.8464	23.93
900	1.472	1.851	152.85	121.556	4.147	2.608	0.7434	0.8460	23.71
1000	1.471	1.833	169.95	150.027	4.117	2.587	0.7432	0.8455	23.52
1100	1.470	1.862	187.07	161.117	4.090	2.568	0.7430	0.8451	23.35
1200	1.469	3.200	204.22	93.75	3.355	2.082	0.7381	0.8408	18.93
SiO ₂ /ZnS ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	SiO ₂	ZnS	SiO ₂	ZnS					
250	1.520	2.600	41.12	24.038	3.605	2.257	0.7399	0.8462	20.52
300	1.510	2.570	49.67	29.183	3.638	2.279	0.7402	0.8463	20.72
400	1.50	2.560	66.67	39.063	3.742	2.344	0.7409	0.8455	21.31
500	1.482	2.421	84.35	51.632	3.952	2.461	0.7423	0.8389	22.37
600	1.48	2.363	101.35	63.479	4.050	2.535	0.7428	0.8427	23.05
700	1.474	2.332	118.72	75.043	4.074	2.557	0.7429	0.8488	23.25
800	1.473	2.324	135.78	86.059	4.052	2.540	0.7428	0.8439	23.09
900	1.472	2.310	152.85	97.403	4.013	2.501	0.7425	0.8394	22.74
1000	1.471	2.301	169.95	108.648	3.967	2.473	0.7422	0.8399	22.48
1100	1.470	2.296	187.07	119.774	3.923	2.448	0.7420	0.8410	22.25
1200	1.469	2.290	204.22	131.004	3.894	2.431	0.7418	0.8416	22.10
ZnO/TiO ₂ ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	ZnO	TiO ₂	ZnO	TiO ₂					
250	2.388	2.46	26.173	25.407	3.360	2.084	0.7381	0.8403	18.95
300	2.404	3.326	31.198	22.550	2.822	1.738	0.7337	0.8394	15.80
400	2.114	2.68	47.304	37.313	3.494	2.180	0.7392	0.8441	19.82
500	1.968	2.48	63.516	50.403	3.825	2.388	0.7415	0.8420	21.72
600	1.913	2.404	78.411	62.396	3.957	2.468	0.7423	0.8402	22.44
700	1.883	2.364	92.937	74.027	3.999	2.493	0.7425	0.8396	22.66

800	1.864	2.341	107.296	85.434	3.988	2.486	0.7423	0.8398	22.60
900	1.851	2.325	121.556	96.774	3.948	2.462	0.7421	0.8403	22.38
1000	1.833	2.313	150.027	108.085	3.850	2.406	0.7415	0.8428	21.87
1100	1.862	2.305	161.117	119.306	3.803	2.379	0.7412	0.8440	21.63
1200	3.200	2.298	93.75	130.548	3.051	1.899	0.7358	0.8459	17.26
ZnO/ZnS ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	ZnO	ZnS	ZnO	ZnS					
250	2.388	2.600	26.173	24.038	3.275	2.035	0.7375	0.8425	18.50
300	2.404	2.570	31.198	29.183	3.263	2.029	0.7374	0.8433	18.45
400	2.114	2.560	47.304	39.063	3.553	2.222	0.7396	0.8456	20.20
500	1.968	2.421	63.516	51.632	3.841	2.398	0.7416	0.8419	21.80
600	1.913	2.363	78.411	63.479	3.963	2.471	0.7423	0.8400	22.46
700	1.883	2.332	92.937	75.043	4.001	2.494	0.7425	0.8395	22.67
800	1.864	2.324	107.296	86.059	3.989	2.487	0.7424	0.8398	22.61
900	1.851	2.310	121.556	97.403	3.950	2.463	0.7421	0.8402	22.39
1000	1.833	2.301	150.027	108.648	3.854	2.408	0.7415	0.8426	21.89
1100	1.862	2.296	161.117	119.774	3.807	2.381	0.7413	0.8437	21.65
1200	3.200	2.290	93.75	131.004	3.052	1.900	0.7358	0.8461	17.27
ZnO/Si ₃ N ₄ ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	ZnO	Si ₃ N ₄	ZnO	Si ₃ N ₄					
250	2.388	2.289	26.173	27.304	3.464	2.158	0.7389	0.8431	19.62
300	2.404	2.167	31.198	34.610	3.487	2.174	0.7390	0.8437	19.76
400	2.114	2.070	47.304	48.309	3.716	2.328	0.7407	0.8458	21.16
500	1.968	2.030	63.516	61.576	3.860	2.412	0.7416	0.8426	21.93
600	1.913	2.020	78.411	74.257	3.921	2.447	0.7420	0.8411	22.25
700	1.883	2.003	92.937	87.369	3.942	2.459	0.7421	0.8406	22.35
800	1.864	1.996	107.296	100.200	3.946	2.461	0.7421	0.8404	22.37
900	1.851	1.991	121.556	113.009	3.940	2.458	0.7421	0.8407	22.35
1000	1.833	1.985	150.027	138.539	3.924	2.448	0.7420	0.8408	22.25
1100	1.862	1.985	161.117	138.539	3.900	2.435	0.7419	0.8416	22.14
1200	3.200	1.983	93.75	151.286	3.055	1.901	0.7358	0.8457	17.28
Si ₃ N ₄ /TiO ₂ ARC									
λ	Refractive index		Thickness (nm)		I_{SC}	P_{max}	V_{OC}	FF	η (%)

(nm)	Si ₃ N ₄	TiO ₂	Si ₃ N ₄	TiO ₂	(A)	(W)	(V)		
250	2.289	2.46	27.304	25.407	3.409	2.113	0.7385	0.8393	19.21
300	2.167	3.326	34.610	22.550	2.925	1.812	0.7347	0.8432	16.47
400	2.070	2.68	48.309	37.313	3.518	2.197	0.7394	0.8446	19.97
500	2.030	2.48	61.576	50.403	3.800	2.378	0.7413	0.8442	21.62
600	2.020	2.404	74.257	62.396	3.890	2.429	0.7418	0.8418	22.08
700	2.003	2.364	87.369	74.027	3.925	2.449	0.7420	0.8409	22.26
800	1.996	2.341	100.200	85.434	3.911	2.441	0.7419	0.8413	22.19
900	1.991	2.325	113.009	96.774	3.873	2.419	0.7416	0.8422	21.99
1000	1.985	2.313	138.539	108.085	3.786	2.369	0.7411	0.8443	21.54
1100	1.985	2.305	138.539	119.306	3.782	2.367	0.7411	0.8445	21.52
1200	1.983	2.298	151.286	130.548	3.754	2.351	0.7409	0.8453	21.37
Si ₃ N ₄ /ZnS ARC									
λ (nm)	Refractive index		Thickness (nm)		I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	Si ₃ N ₄	ZnS	Si ₃ N ₄	ZnS					
250	2.289	2.600	27.304	24.038	3.323	2.063	0.7378	0.8415	18.75
300	2.167	2.570	34.610	29.183	3.395	2.105	0.7384	0.8397	19.14
400	2.070	2.560	48.309	39.063	3.579	2.240	0.7398	0.8460	20.36
500	2.030	2.421	61.576	51.632	3.800	2.378	0.7413	0.8442	21.62
600	2.020	2.363	74.257	63.479	3.891	2.430	0.7418	0.8419	22.09
700	2.003	2.332	87.369	75.043	3.923	2.448	0.7420	0.8410	22.25
800	1.996	2.324	100.200	86.059	3.910	2.440	0.7419	0.8411	22.18
900	1.991	2.310	113.009	97.403	3.874	2.419	0.7416	0.8420	21.99
1000	1.985	2.301	138.539	108.648	3.789	2.371	0.7411	0.8444	21.55
1100	1.985	2.296	138.539	119.774	3.784	2.368	0.7411	0.8444	21.53
1200	1.983	2.290	151.286	131.004	3.757	2.352	0.7409	0.8450	21.38

By using the results obtained, several curves can be drawn to observe the performance of the solar cell. Thus, the I_{SC} values at each wavelength are used, as shown in Figure 5.8(a). Based on the curves, SiO₂/ZnO, represented by the yellow curve, was closely followed by SiO₂/Si₃N₄, shown in the orange curve, as both pairs have only a slight difference for the I_{SC} values. The only significant difference that can be seen for both pairs was at wavelengths of 300 nm and 1200 nm, where SiO₂/ZnO DLARC has lower I_{SC} values at both wavelengths. Meanwhile, other curves were observable, having lower values but close to each other. Besides, the V_{OC} values can

also be plotted against wavelength, as presented in Figure 5.8(b). The pattern of the V_{OC} curves was almost identical to the I_{SC} curves, with both the highest DLARC pairs also drawn closely. This slight difference can affect the performance value. According to the results in Table 5.3, the SiO₂/ZnO pair outperformed SiO₂/Si₃N₄ by only 0.10%.

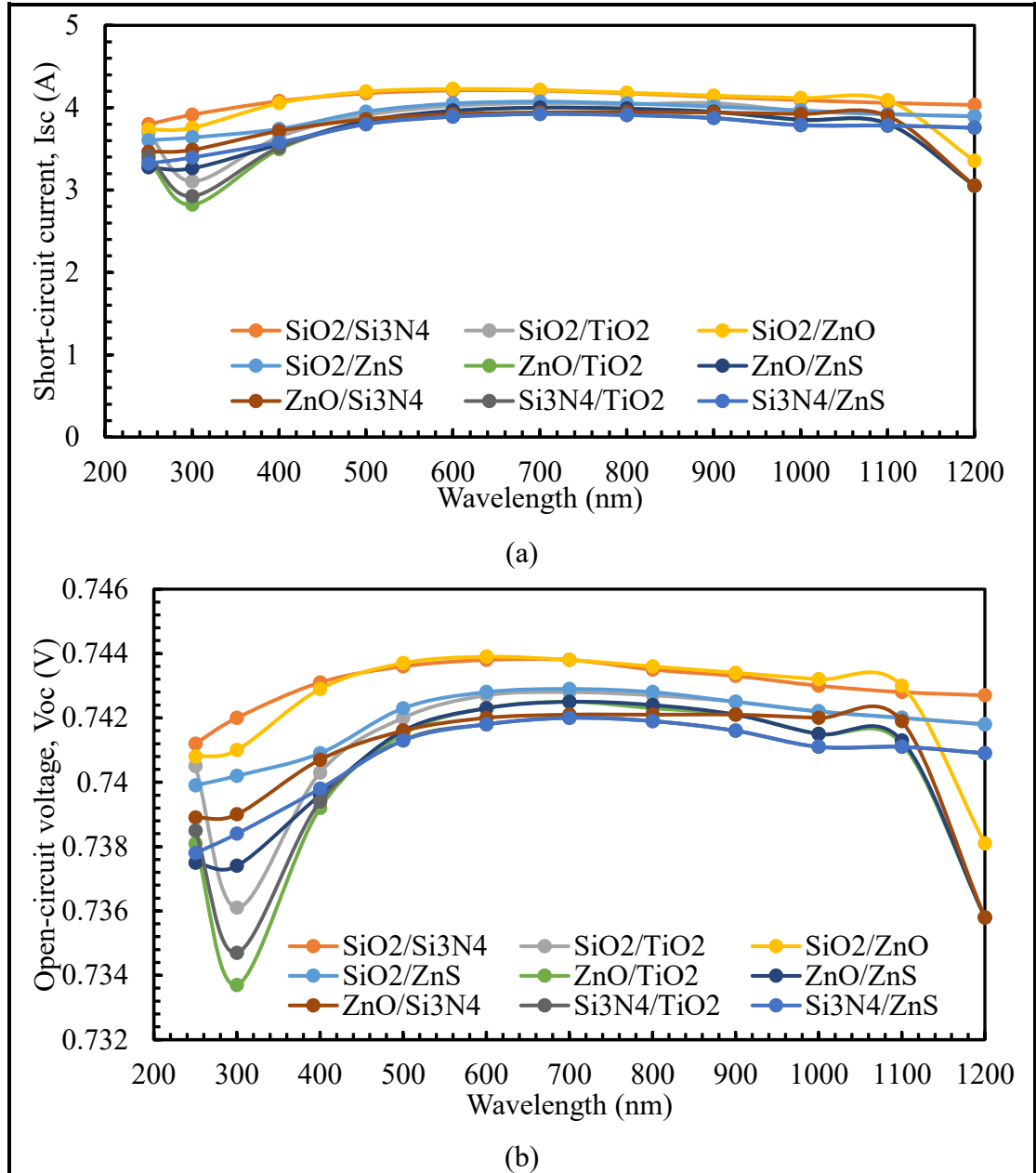


Figure 5.8 The Curve of Short-Circuit Current (a) and Open-Circuit Voltage (b) Against Wavelength for ZnO/AlGaAs/Si Solar Cell with DLARC

Figure 5.9 shows the curve of reflectance percentage for all nine pairs, including the uncoated solar cell, which can be used to analyze the performance of the DLARC in various pairs on top of the solar cell. All the schemes were drawn differently, which

shows that each pair of ARCs would develop different results across the wavelengths. As can be seen, the uncoated cell, represented by the blue curve, had a constant percentage of reflectance of 10% from 300nm – 1200nm. For the reflectance curve, the lowest percentage means the ARCs work efficiently on top of the cell. Based on the Figure 5.9, $\text{SiO}_2/\text{Si}_3\text{N}_4$, $\text{SiO}_2/\text{TiO}_2$, SiO_2/ZnO , SiO_2/ZnS , ZnO/TiO_2 , ZnO/ZnS , $\text{ZnO}/\text{Si}_3\text{N}_4$, $\text{Si}_3\text{N}_4/\text{TiO}_2$ and $\text{Si}_3\text{N}_4/\text{ZnS}$ were achieved 0.126%, 1.566%, 0.805%, 1.248%, 1.405%, 1.741%, 7.355%, 3.201% and 3.689% of the reflectance percentage. Overall, $\text{ZnO}/\text{Si}_3\text{N}_4$ recorded the best percentage; nevertheless, the efficiency is not the highest due to the possibility that it might lose energy in the device because of the heat in the material (Hussein and Hamzah, 2025). Efficiency is determined by the conversion of optimal absorption energy, not just the amount of light absorbed.

Based on the curve, at a wavelength of 300nm, ZnO/TiO_2 , ZnO/ZnS , $\text{Si}_3\text{N}_4/\text{TiO}_2$, and $\text{Si}_3\text{N}_4/\text{ZnS}$ were observed to have high percentage reflectance. The error occurred due to the unsteady transition of the refractive index from air to the substrates. It can be seen that the sudden increase of the refractive index from the air ($n = 1.00$) to the first layer of the ARC, which is ZnO ($n = 2.404$), and Si_3N_4 ($n = 2.167$). Based on Fresnel's equation, the reflectance can be caused by the greater difference in refractive index (Yap et al., 2025). The usage of a double-layer ARC to smooth the transition of the refractive index from the air to the substrates. It has been clearly proven that the refractive index plays a significant role in controlling the absorption of photons and reducing the reflectance with an appropriate value of the refractive index. The exact regulation of film thickness and refractive index is critical to the ARC's optimal optical performance for solar cells (Addie et al., 2022).

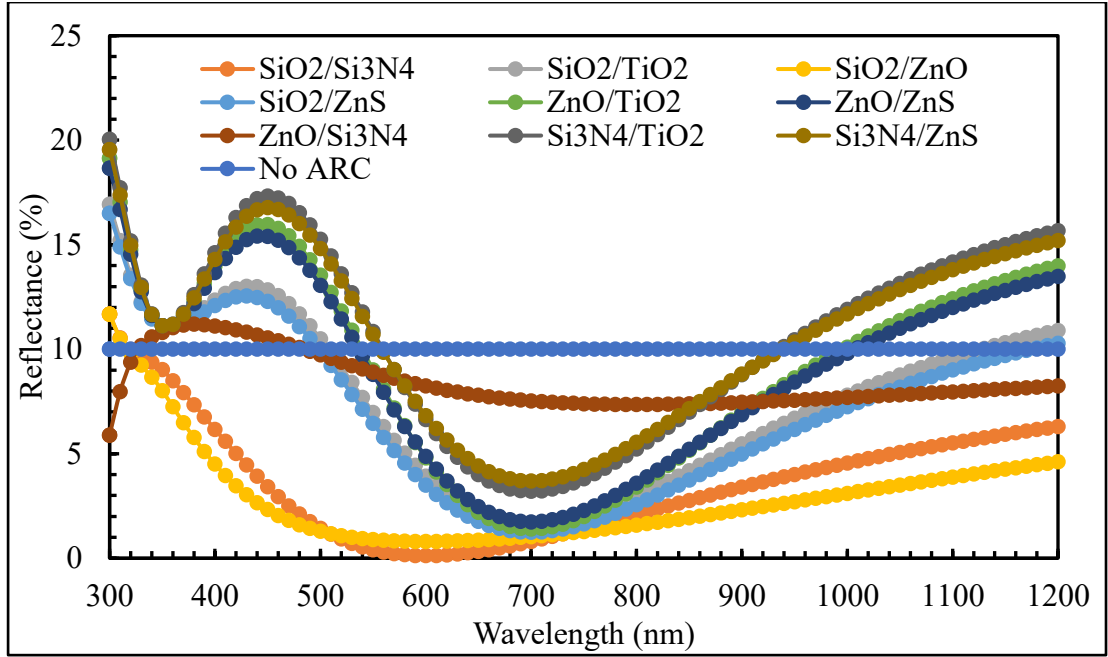


Figure 5.9 The Reflectance Curve for ZnO/AlGaAs/Si with Uncoated and Coated Double-Layer

Besides that, QE graphs can also be used to observe the behavior of a solar cell. QE is the ratio of incident photons at a certain wavelength to the number of electrons contributing to photogenerated electricity (Choe, 2020). The EQE curves were drawn using the results from PC1D simulation, as illustrated in Figure 5.10. External quantum efficiency is the term used to describe the difference between the number of charge carriers produced by the solar cell and the number of incident photons of the specified energy that are irradiated inwards onto the solar cell (James et al., 2024). All the curves were plotted closely, including the uncoated solar cell. It can be seen that all curves reached almost 0% of EQE at 300nm and slowly increased between 400nm – 700nm. Then, some of the curves become relatively constant, and the rest of the pairs start to slightly decrease. However, beyond 1000nm, there's a noticeable sudden decrease to 0% at a wavelength of 1200nm.

The highest EQE percentage for SiO₂/Si₃N₄, SiO₂/TiO₂, SiO₂/ZnO, SiO₂/ZnS, ZnO/TiO₂, ZnO/ZnS, ZnO/Si₃N₄, Si₃N₄/TiO₂, Si₃N₄/ZnS and no ARC are 99.02%, 98.13%, 98.72%, 98.45%, 98.29%, 97.96%, 92.22%, 96.50%, 96.02% and 89.76% respectively. Out of these schemes, SiO₂/Si₃N₄, indicated by the orange curve, was observed to have the best EQE percentage and was drawn closely with SiO₂/ZnO. An error may be caused by the recombination of the charges before reaching to external circuit (Zhang et al., 2017), especially when there is an imbalance of electrons and

holes. Then, these recombination charges will release the energy through heat. This action could lead to a reduction in efficiency, but the percentage of EQE remains high, as the EQE will collect the ratio of charge carriers to the number of photons that the device was produced at a specified wavelength.

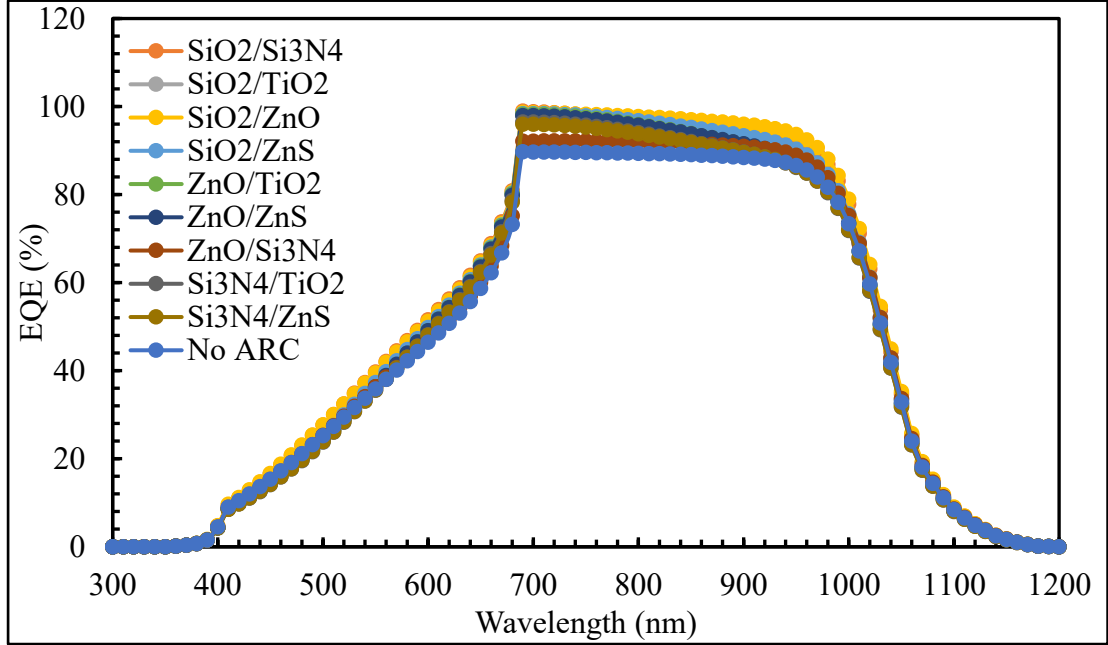


Figure 5.10 The EQE Curve for ZnO/AlGaAs/Si Solar Cell with Uncoated and Coated of Double-Layer ARC

5.3.3 Triple-Layer Anti-Reflective Coating (TLARC)

As a more advanced solution to reduce the reflectance, a triple-layer ARC can be used on top of the solar cell. The triple-layer ARC has complex methods, but it will be able to capture light in a wider range of wavelengths than single and double-layer. Sharma (2022) found that the triple-layer ARC is non-reflective in a wide range of wavelengths between 400nm and 1200nm. Additionally, it will result in enhanced short-circuit current, increased power output, improved external quantum efficiency, and higher efficiency. The materials were arranged appropriately according to their refractive index. Set up the ARC based on the refractive index by placing the lowest refractive index on the top of the layer (ARC₁) and accompanied by the higher refractive index in the second layer (ARC₂), and the triple-layer (ARC₃) for destructive interference to occur, as shown in Figure 5.11.

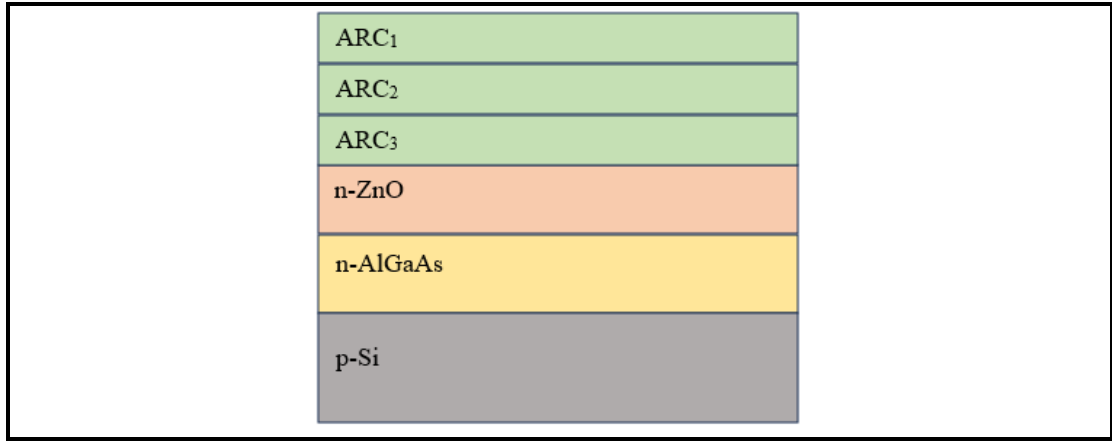


Figure 5.11 The Schematic Diagram of TLARC Configuration on ZnO/AlGaAs/Si Solar Cell

Table 5.4 shows full data by PC1D simulation for ZnO/AlGaAs/Si solar cell with triple-layer ARCs, including the value optimization of refractive index and thickness for each material. As can be seen, all schemes obtained higher efficiency than the cell without using a triple-layer ARC. The major contribution in this structure is the choice of materials with an appropriate amount of thickness and refractive index, as it will allow the photons to pass through the maximum amount. Hence, out of eight schemes, SiO₂/ZnO/Si₃N₄ recorded the highest efficiency among other schemes with 24.16% at a wavelength of 600nm. It produced 4.203A, 2.658W and 0.7439V for I_{SC} , P_{max} and V_{OC} which results in 0.8501 of the fill factors. The SiO₂/ZnO/Si₃N₄ successfully improved the solar cell by 2.18% from the uncoated cell. Besides that, SiO₂/Si₃N₄/ZnS obtained 24.07% of the efficiency as the second highest, which resulted from I_{SC} , P_{max} and V_{OC} with 4.215A, 2.648W, and 0.7438V. Meanwhile, ZnO/Si₃N₄/ZnS is the least efficient was obtained in this triple-layer scheme with 21.99% which is almost the same as the bare device. The value of I_{SC} and P_{max} between both structures with and without ARC were slightly different, with 0.002A and 0.001W only. This small difference can affect the value of efficiency.

The quarter-wave optical thickness and appropriate value of refractive index were calculated for each material across the wavelengths, so that destructive interference effectively surpasses the reflectance. However, some errors might occur due to its unstable arrangement at certain wavelengths, which causes the reflectance to increase. The lowest efficiency across the wavelengths was observed by ZnO/TiO₂/ZnS, with an efficiency of 16.50% at a wavelength of 300nm. As can be seen, the value of the refractive index for the triplets is not in sequence, which causes

the reflectance to increase and the transmittance to decrease. The arrangement of the refractive index from the air has suddenly increased to the first layer, which is ZnO ($n = 2.404$), followed by TiO_2 with 3.326, and ended with ZnS with 2.570. This poor impedance matching will cause the destructive interference conditions to become hard to satisfy, which will result in high reflectance and low I_{SC} value with 2.929A. Hence, as the wavelengths increase, the refractive index also changes for each material. At a wavelength of 600nm, the value of I_{SC} and efficiency was improved with 4.032A and 22.79%, respectively, as the refractive index changed to an appropriate value to form a gradual arrangement. However, the ZnO/ TiO_2 /ZnS is not a suitable triple-layer ARC to be used on the ZnO/AlGaAs/Si solar cell.

Table 5.4
Data of PC1D Simulation for ZnO/AlGaAs/Si Solar Cell with TLARC

SiO ₂ /Si ₃ N ₄ /ZnO ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	Si ₃ N ₄	ZnO	SiO ₂	Si ₃ N ₄	ZnO					
250	1.520	2.289	2.388	41.12	27.304	26.173	3.667	2.298	0.7404	0.8460	20.89
300	1.510	2.167	2.404	49.67	34.610	31.198	3.834	2.393	0.7415	0.8417	21.75
400	1.500	2.070	2.114	66.67	48.309	47.304	4.095	2.568	0.7432	0.8438	23.35
500	1.482	2.030	1.968	84.35	61.576	63.516	4.164	2.615	0.7436	0.8445	23.77
600	1.480	2.020	1.913	101.35	74.257	78.411	4.176	2.623	0.7436	0.8447	23.85
700	1.474	2.003	1.883	118.72	87.369	92.937	4.171	2.620	0.7435	0.8449	23.82
800	1.473	1.996	1.864	135.78	100.200	107.296	4.147	2.608	0.7434	0.8460	23.71
900	1.472	1.991	1.851	152.85	113.009	121.556	4.111	2.583	0.7431	0.8455	23.48
1000	1.471	1.985	1.833	169.95	138.539	150.027	4.078	2.560	0.7430	0.8449	23.27
1100	1.470	1.985	1.862	187.07	138.539	161.117	4.046	2.536	0.7428	0.8438	23.05
1200	1.469	1.983	3.200	204.22	151.286	93.75	3.661	2.293	0.7403	0.8461	20.85

SiO ₂ /Si ₃ N ₄ /ZnS ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	Si ₃ N ₄	ZnS	SiO ₂	Si ₃ N ₄	ZnS					
250	1.520	2.289	2.600	41.12	27.304	24.038	3.580	2.240	0.7398	0.8458	20.36
300	1.510	2.167	2.570	49.67	34.610	29.183	3.777	2.361	0.7412	0.8434	21.46
400	1.500	2.070	2.560	66.67	48.309	39.063	4.028	2.507	0.7428	0.8379	22.79
500	1.482	2.030	2.421	84.35	61.576	51.632	4.179	2.625	0.7436	0.8447	23.86
600	1.480	2.020	2.363	101.35	74.257	63.479	4.215	2.648	0.7438	0.8446	24.07
700	1.474	2.003	2.332	118.72	87.369	75.043	4.185	2.629	0.7436	0.8448	23.90
800	1.473	1.996	2.324	135.78	100.200	86.059	4.128	2.594	0.7433	0.8454	23.58
900	1.472	1.991	2.310	152.85	113.009	97.403	4.084	2.564	0.7430	0.8450	23.31
1000	1.471	1.985	2.301	169.95	138.539	108.648	4.044	2.521	0.7427	0.8394	22.92
1100	1.470	1.985	2.296	187.07	138.539	119.774	4.027	2.510	0.7426	0.8393	22.82
1200	1.469	1.983	2.290	204.22	151.286	131.004	4.004	2.496	0.7425	0.8396	22.69
SiO ₂ /Si ₃ N ₄ /TiO ₂ ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	Si ₃ N ₄	TiO ₂	SiO ₂	Si ₃ N ₄	TiO ₂					

250	1.520	2.289	2.46	41.12	27.304	25.407	3.639	2.279	0.7402	0.8461	20.72
300	1.510	2.167	3.326	49.67	34.610	22.550	3.437	2.131	0.7388	0.8392	19.37
400	1.500	2.070	2.68	66.67	48.309	37.313	3.985	2.480	0.7425	0.8382	22.55
500	1.482	2.030	2.48	84.35	61.576	50.403	4.162	2.614	0.7435	0.8447	23.76
600	1.480	2.020	2.404	101.35	74.257	62.396	4.204	2.642	0.7437	0.8450	24.02
700	1.474	2.003	2.364	118.72	87.369	74.027	4.175	2.622	0.7436	0.8446	23.84
800	1.473	1.996	2.341	135.78	100.200	85.434	4.122	2.590	0.7432	0.8454	23.55
900	1.472	1.991	2.325	152.85	113.009	96.774	4.079	2.560	0.7429	0.8448	23.27
1000	1.471	1.985	2.313	169.95	138.539	108.085	4.041	2.518	0.7427	0.8390	22.89
1100	1.470	1.985	2.305	187.07	138.539	119.306	4.025	2.508	0.7426	0.8391	22.80
1200	1.469	1.983	2.298	204.22	151.286	130.548	4.002	2.495	0.7425	0.8396	22.68
SiO ₂ /ZnO/TiO ₂ ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	SiO ₂	ZnO	TiO ₂	SiO ₂	ZnO	TiO ₂					
250	1.520	2.388	2.46	41.12	26.173	25.407	3.578	2.239	0.7398	0.8459	20.35
300	1.510	2.404	3.326	49.67	31.198	22.550	3.314	2.059	0.7379	0.8420	18.72
400	1.500	2.114	2.680	66.67	47.304	37.313	3.974	2.474	0.7424	0.8386	22.49
500	1.482	1.968	2.480	84.35	63.516	50.403	4.155	2.609	0.7435	0.8445	23.72

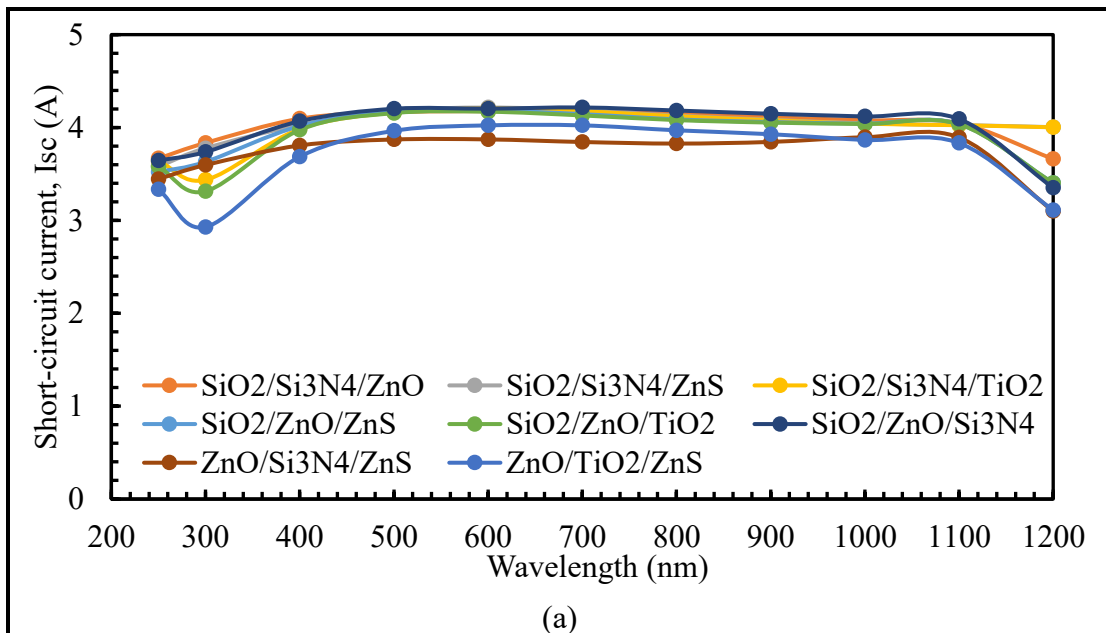
600	1.480	1.913	2.404	101.35	78.411	62.396	4.170	2.619	0.7435	0.8447	23.81
700	1.474	1.883	2.364	118.72	92.937	74.027	4.130	2.592	0.7433	0.8443	23.56
800	1.473	1.864	2.341	135.78	107.296	85.434	4.080	2.561	0.7430	0.8448	23.28
900	1.472	1.851	2.325	152.85	121.556	96.774	4.053	2.541	0.7428	0.8440	23.10
1000	1.471	1.833	2.313	169.95	150.027	108.085	4.038	2.517	0.7427	0.8393	22.88
1100	1.470	1.862	2.305	187.07	161.117	119.306	4.035	2.515	0.7427	0.8392	22.86
1200	1.469	3.200	2.298	204.22	93.75	130.548	3.403	2.110	0.7385	0.8396	19.18
SiO ₂ /ZnO/Si ₃ N ₄ ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	η (%)
	SiO ₂	ZnO	Si ₃ N ₄	SiO ₂	ZnO	Si ₃ N ₄					
250	1.520	2.388	2.289	41.12	26.173	27.304	3.645	2.283	0.7402	0.8462	20.75
300	1.510	2.404	2.167	49.67	31.198	34.610	3.737	2.341	0.7409	0.8455	21.28
400	1.500	2.114	2.070	66.67	47.304	48.309	4.068	2.549	0.7430	0.8433	23.17
500	1.482	1.968	2.030	84.35	63.516	61.576	4.202	2.641	0.7438	0.8450	24.01
600	1.480	1.913	2.020	101.35	78.411	74.257	4.230	2.658	0.7439	0.8447	24.16
700	1.474	1.883	2.003	118.72	92.937	87.369	4.216	2.649	0.7438	0.8447	24.08
800	1.473	1.864	1.996	135.78	107.296	100.200	4.183	2.632	0.7436	0.8462	23.93
900	1.472	1.851	1.991	152.85	121.556	113.009	4.148	2.608	0.7434	0.8458	23.71

1000	1.471	1.833	1.985	169.95	150.027	138.539	4.119	2.588	0.7432	0.8454	23.53
1100	1.470	1.862	1.985	187.07	161.117	138.539	4.091	2.568	0.7430	0.8448	23.35
1200	1.469	3.200	1.983	204.22	93.750	151.286	3.350	2.079	0.7381	0.8408	18.90
ZnO/TiO ₂ /ZnS ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	ZnO	TiO ₂	ZnS	ZnO	TiO ₂	ZnS					
250	2.388	2.46	2.600	26.173	25.407	24.038	3.335	2.071	0.7380	0.8414	18.83
300	2.404	3.326	2.570	31.198	22.550	29.183	2.929	1.815	0.7348	0.8433	16.50
400	2.114	2.680	2.560	47.304	37.313	39.063	3.686	2.310	0.7406	0.8462	21.00
500	1.968	2.480	2.421	63.516	50.403	51.632	3.964	2.472	0.7423	0.8401	22.47
600	1.913	2.404	2.363	78.411	62.396	63.479	4.023	2.507	0.7426	0.8392	22.79
700	1.883	2.364	2.332	92.937	74.027	75.043	4.023	2.507	0.7426	0.8392	22.79
800	1.864	2.341	2.324	107.296	85.434	86.059	3.970	2.475	0.7423	0.8399	22.50
900	1.851	2.325	2.310	121.556	96.774	97.403	3.928	2.451	0.7420	0.8409	22.28
1000	1.833	2.313	2.301	150.027	108.085	108.648	3.866	2.415	0.7416	0.8423	21.95
1100	1.862	2.305	2.296	161.117	119.306	119.774	3.833	2.396	0.7414	0.8431	21.78
1200	3.200	2.298	2.290	93.75	130.548	131.004	3.111	1.938	0.7362	0.8462	17.62
SiO ₂ /ZnO/ZnS ARC											

λ (nm)	Refractive index			Thickness, d (nm)			I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	SiO ₂	ZnO	ZnS	SiO ₂	ZnO	ZnS					
250	1.520	2.388	2.600	41.12	26.173	24.038	3.521	2.199	0.7394	0.8447	19.99
300	1.510	2.404	2.570	49.67	31.198	29.183	3.631	2.275	0.7402	0.8465	20.68
400	1.500	2.114	2.560	66.67	47.304	39.063	4.016	2.499	0.7427	0.8378	22.72
500	1.482	1.968	2.421	84.35	63.516	51.632	4.175	2.622	0.7436	0.8446	23.84
600	1.480	1.913	2.363	101.35	78.411	63.479	4.185	2.629	0.7436	0.8448	23.90
700	1.474	1.883	2.332	118.72	92.937	75.043	4.144	2.602	0.7434	0.8446	23.65
800	1.473	1.864	2.324	135.78	107.296	86.059	4.088	2.566	0.7430	0.8448	23.33
900	1.472	1.851	2.310	152.85	121.556	97.403	4.059	2.546	0.7428	0.8444	23.15
1000	1.471	1.833	2.301	169.95	150.027	108.648	4.042	2.520	0.7427	0.8394	22.91
1100	1.470	1.862	2.296	187.07	161.117	119.774	4.037	2.517	0.7427	0.8395	22.88
1200	1.469	3.200	2.290	204.22	93.750	131.004	3.402	2.110	0.7385	0.8398	19.18
ZnO/Si ₃ N ₄ /ZnS ARC											
λ (nm)	Refractive index			Thickness, d (nm)			I_{sc} (A)	P_{max} (W)	V_{oc} (V)	FF	η (%)
	ZnO	Si ₃ N ₄	ZnS	ZnO	Si ₃ N ₄	ZnS					
250	2.388	2.289	2.600	26.173	27.304	24.038	3.446	2.137	0.7388	0.8394	19.43

300	2.404	2.167	2.570	31.198	34.610	29.183	3.596	2.251	0.7399	0.8460	20.46
400	2.114	2.070	2.560	47.304	48.309	39.063	3.807	2.381	0.7412	0.8438	21.65
500	1.968	2.030	2.421	63.516	61.576	51.632	3.871	2.417	0.7416	0.8419	21.97
600	1.913	2.020	2.363	78.411	74.257	63.479	3.872	2.419	0.7417	0.8423	21.99
700	1.883	2.003	2.332	92.937	87.369	75.043	3.844	2.403	0.7415	0.8431	21.85
800	1.864	1.996	2.324	107.296	100.200	86.059	3.827	2.393	0.7414	0.8434	21.75
900	1.851	1.991	2.310	121.556	113.009	97.403	3.845	2.404	0.7415	0.8432	21.85
1000	1.833	1.985	2.301	150.027	138.539	108.648	3.895	2.432	0.7418	0.8417	22.11
1100	1.862	1.985	2.296	161.117	138.539	119.774	3.892	2.430	0.7418	0.8417	22.09
1200	3.200	1.983	2.290	93.75	151.286	131.004	3.099	1.930	0.7361	0.8461	17.55

From the results generated, a few curves can be drawn to compare and observe the performance of the solar cell. Figure 5.12(a) displays eight curves representing each scheme for their value short-circuit current and open-circuit voltage in Figure 5.12(b) throughout the wavelength 250nm – 1200nm. As can be seen in both curves, SiO₂/ZnO/Si₃N₄, represented by the dark blue curve, achieved 4.216A and 0.7439 as the highest current value and voltage, respectively. It followed closely with other pair materials as well, except SiO₂/ZnO/ZnS and ZnO/Si₃N₄/ZnS in the short-circuit current curve. This slight difference in current value can have a huge impact on the percentage of efficiency. This can be seen in Figure 5.12(a), at wavelength 600nm, for SiO₂/Si₃N₄/ZnO, SiO₂/Si₃N₄/ZnS, SiO₂/Si₃N₄/TiO₂, SiO₂/ZnO/ZnS, SiO₂/ZnO/TiO₂, ZnO/Si₃N₄/ZnS and ZnO/TiO₂/ZnS TLARC the short-circuit current is 4.176A, 4.215A, 4.204A, 4.185A, 4.170A, 3.872A and 4.023A respectively. Open-circuit voltage also achieved high voltage at 600nm, with 0.7436V, 0.7438V, 0.7437V, 0.7436V, 0.7435V, 0.7417V, and 0.7426V for SiO₂/Si₃N₄/ZnO, SiO₂/Si₃N₄/ZnS, SiO₂/Si₃N₄/TiO₂, SiO₂/ZnO/ZnS, SiO₂/ZnO/TiO₂, ZnO/Si₃N₄/ZnS, and ZnO/TiO₂/ZnS accordingly.



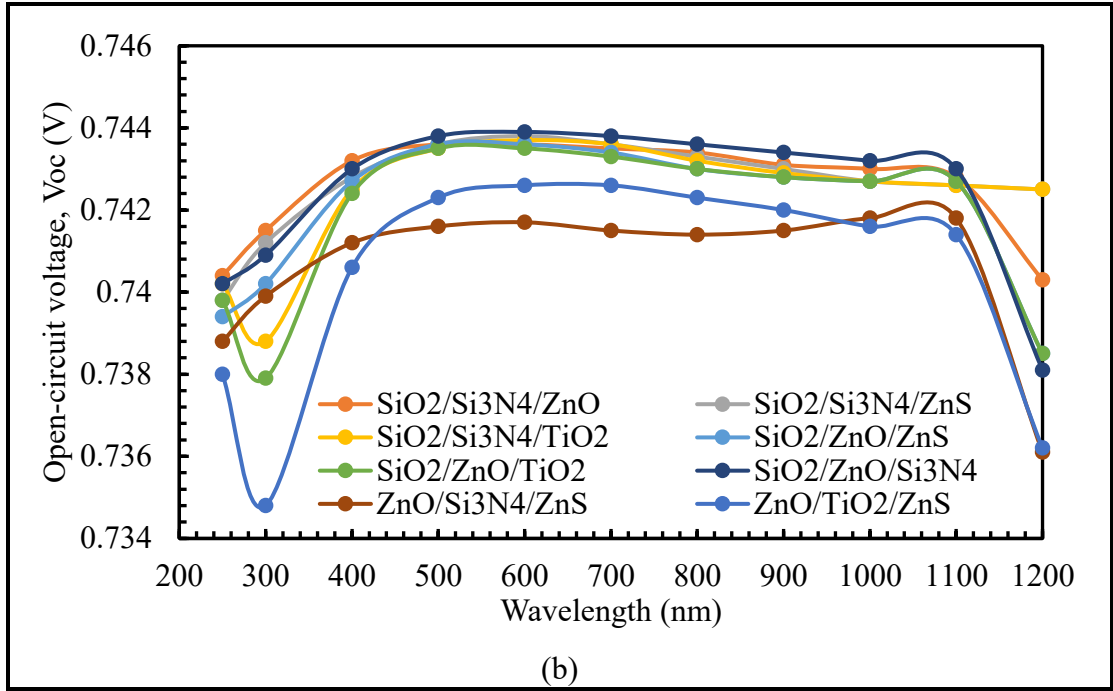


Figure 5.12 The Curves of Short-Circuit Current (a) and Open-Circuit Voltage (b) Against Wavelength for ZnO/AlGaAs/Si with Triple-Layer ARC

In Figure 5.13, the percentage of the reflectance curve was drawn, consisting of all schemes, including the bare device. The percentage of reflectance refers to the reflectance that occurred along the wavelength after implementing the ARC on the top of the solar cell. Based on the curve, the bare device has 10% of the percentage of reflectance along the wavelength. To determine the best triplet materials with good performance, the percentage must be below the bare device's percentage. According to the results in Table 5.4, all schemes achieved the highest efficiency at a wavelength of 600nm. It is seen that a wavelength at 600nm, the percentage reflectance for SiO₂/Si₃N₄/ZnO, SiO₂/Si₃N₄/ZnS, SiO₂/Si₃N₄/TiO₂, SiO₂/ZnO/ZnS, SiO₂/ZnO/TiO₂, SiO₂/ZnO/Si₃N₄, ZnO/Si₃N₄/ZnS and ZnO/TiO₂/ZnS TLARC were reported as 0.008%, 3.984%, 4.668%, 6.312%, 7.144%, 0.991%, 18.423% and 7.697%, respectively. The reflectance minima do not always occur at the same wavelength, mainly because this wavelength roughly matches the AM1.5G solar spectrum maximum and the strong absorption area of AlGaAs and Si. Overall, even though SiO₂/ZnO/Si₃N₄ obtained the highest efficiency, the lowest reflectance percentage was held by SiO₂/Si₃N₄/ZnO. Other reflectance curves, however, show a sharp decline after two peaks, followed by a subsequent increase. Based on this observation, a triple-layer ARC works well in reducing the light reflectance.

Six schemes can be seen as having two peaks for both high and low reflectance percentages. According to Ismail et al. (2016) and Costa et al. (2021), each layer in the TLARC serves as a thin-film cavity. The interference of light reflected at the interfaces creates constructive and destructive interference at particular wavelengths, resulting in alternating reflectance maxima and minima. The two observed peaks are indicative of distinct resonance circumstances resulting from the refractive-index contrasts and optical thicknesses of the various layers. For example, constructive interference between the top and middle layers may produce one peak, whereas interference between the semiconductor interface and the deeper layers may provide the second peak. The existence of two peaks emphasizes the complexity of multilayer interference: broader suppression of reflectance throughout the spectrum is essential for optimizing photocurrent and efficiency, while a narrow minimum can offer exceptionally low reflectance at a specific wavelength. Therefore, understanding both optimizing the refractive index and thickness is important to achieve high efficiency of the solar cell.

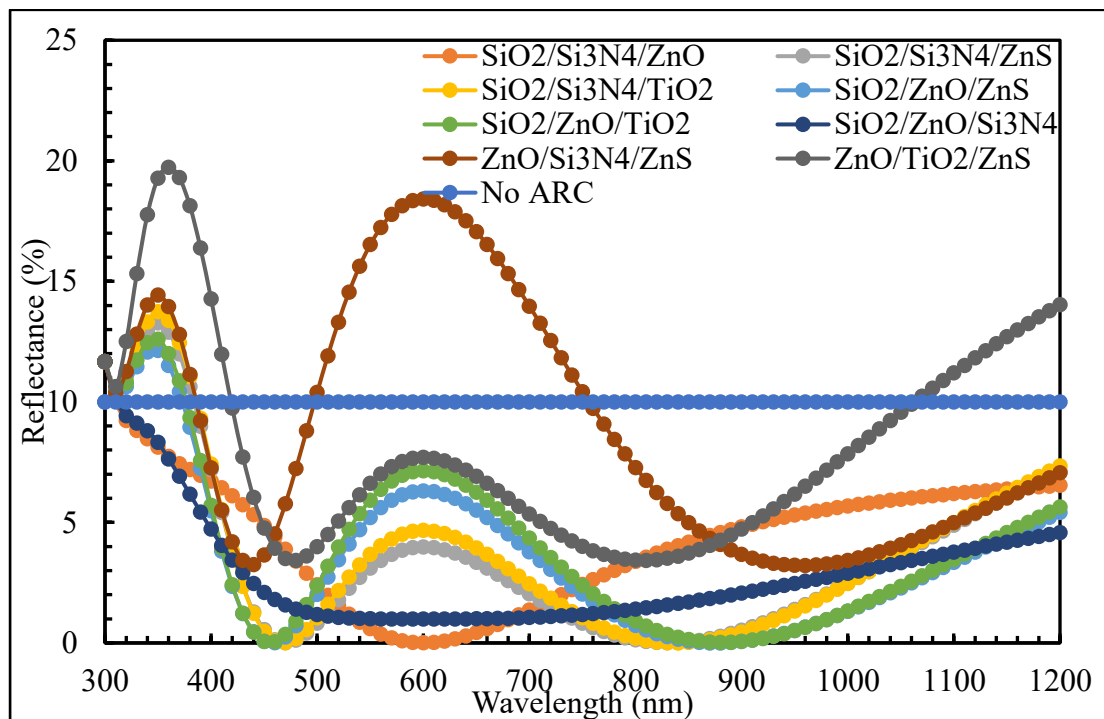


Figure 5.13 The Reflectance Curves of ZnO/AlGaAs/Si Solar Cells with Uncoated and Coated of Triple-Layer ARC

Next, one important technique for characterizing solar cells is the QE calculation, which measures the efficiency of light transfer to electrons as a function of the wavelength of the impinging light (Karmalawi et al., 2020). Figure 5.14 shows EQE

curves, which are the difference between the quantity of charge carriers produced by the solar cell and the quantity of incoming photons of the specified energy that are irradiated onto the solar cell from the environmental source (James et al., 2024). Reflection at the front surface may cause a significant portion of light photons to be lost, particularly when there is a significant index mismatch between the air and semiconductor (Gaudel et al., 2025). Therefore, reducing the number of photons entering the absorber also reduces the EQE.

All schemes were developed in the same pattern and closely followed one another, based on the curves. It started with a constantly low percentage and has two points of sudden increase at 400nm and 690nm. Then, all the curves have a constant value of EQE percentage and slowly decrease at 1000nm until they reach 0% at 1200nm. Overall, the dark blue curve signifies that $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ can be seen as it has achieved the highest EQE percentage with 98.68% at 700nm. From all the observations, it can be confirmed that $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ will be the most suitable triple-layer ARC for ZnO/AlGaAs/Si solar cells.

$\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ acts as a graded index between the air and the device, which may lower reflectance and indirectly increase the EQE percentage. A smoother index transition from air to ZnO/AlGaAs/Si solar cells is produced by the low-index SiO_2 , the intermediate ZnO, and the high-index Si_3N_4 , which decreasing Fresnel reflection at every interface as opposed to a single, sharp air or semiconductor barrier. Over a broad spectral range, this lowers the net reflected power. Hence, the suitable refractive index with a gradual arrangement can reduce the reflectance on the surface, which will increase the percentage of EQE.

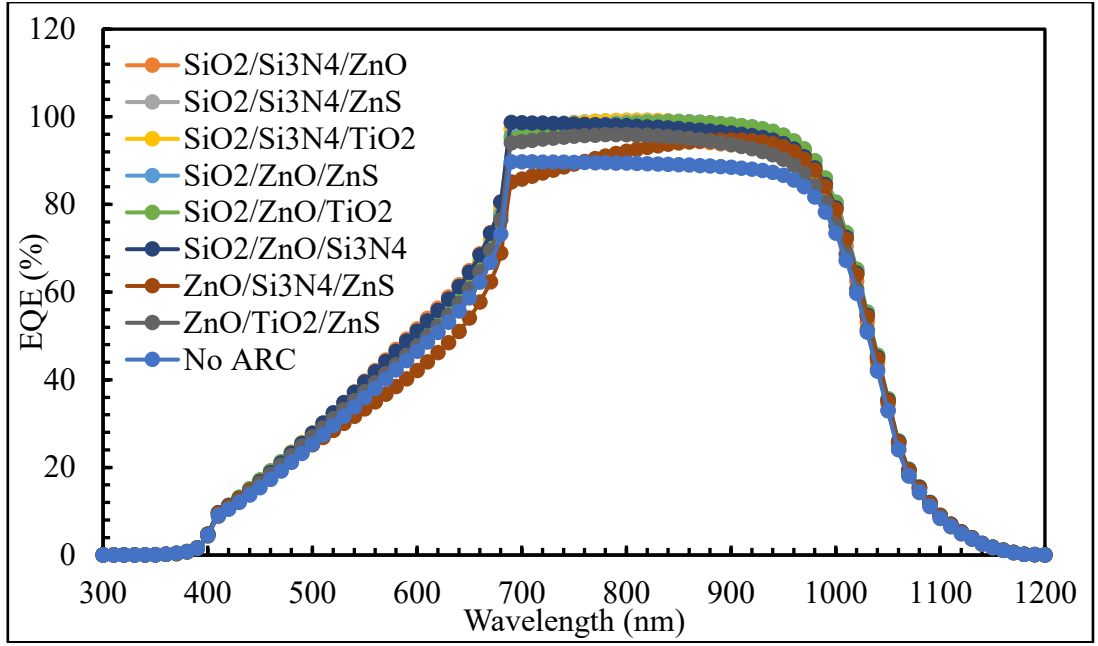


Figure 5.14 The EQE Curve for ZnO/AlGaAs/Si Solar Cell with Uncoated and Coated of Triple-Layer ARC

Table 5.5 shows a comparison of the results between previous and this study. The difference between device and ARC structure, approaches and methods will lead to a different results and analysis. Xiong et al. (2018) and Roy et al. (2023) have same device structure, AlGaAs/Si solar cell, yet the methods and approaches are different. Hence, the difficulties to compare between the study is limited due to lack of literature which it unable to validate the experimental and simulation findings. Besides, the physics model that have been used by many researchers by simulation is difference. Based on the analysis in this study, it is clear that ZnO/AlGaAs/Si solar cell as a triple-heterojunction solar could achieve higher efficiency than the ZnO/GaAs solar cell. The electrical parameters for uncoated were increased significantly after implementing the ARC on top of the solar cell which led to increment of the efficiency. For the coated cell, it is clearly can be seen that the TLARC by $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ achieved the highest efficiency with 24.16% due to greater reduction of wideband reflectance. Hence, $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ could be the most suitable configuration of ARC based on the findings in this study.

Table 5.5
Comparison of Study Results with Previous Study

ARC Structure	ARC Materials	I_{sc} (A)	P_{max} (W)	V_{oc} (V)	η (%)	References
Uncoated	-	-	-	1.6300	12.70	Xiong et al. (2018)
Uncoated	-	0.0398	0.0223	0.6852	22.30	Roy et al. (2023)
DLARC	SiO ₂ /TiO ₂	3.902	2.575	0.7635	23.41	Jamaluddin et al. (2024)
DLARC	-	-	-	3.177	34.10	Dimroth et al. (2020)
DLARC + surface textured	-	-	3.387	1.244	33.87	Sathya and Supriya (2017)
Uncoated	-	3.870	2.418	0.7417	21.98	This study
SLARC	SiO ₂	4.215	2.649	0.7438	24.08	
DLARC	SiO ₂ /ZnO	4.227	2.636	0.7439	24.15	
TLARC	SiO ₂ /ZnO/Si ₃ N ₄	4.203	2.658	0.7439	24.16	

5.4 Summary

The performance of the ZnO/AlGaAs/Si solar cell was investigated using a variable ARC arrangement. An uncoated device reached 21.98% efficiency, which was restricted by a large amount of optical reflection at the front surface. This was increased to 24.08% upon the introduction of a single-layer ARC (SiO₂) to eliminate the refractive index mismatch and enhance light absorption. More improvement was noted on the double-layer ARC (SiO₂/ZnO), which had an efficiency of 24.15%, because it was enhanced through better antireflection over a wide band because the profile of the refractive index. The maximum of 24.16% was achieved with a triple-layer ARC (SiO₂/ZnO/ Si₃N₄) that offers optimum optical connection in the broadest spectrum of wavelengths. The returns to increasing the number of ARC layers are however low meaning that there are only small gains in efficiency between the DLARC and TLARC. This implies that at SLARC, the performance of devices becomes more and more constrained by non-optical losses, and one must trade the enhancement of efficiency by the complexity of fabrication.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The invention of ZnO/GaAs and ZnO/AlGaAs/Si solar cells with various types of anti-reflective coatings using PC1D simulation software was successfully carried out under simulated conditions. The bare ZnO/GaAs solar cell was simulated to observe its performance, including the efficiency, before applying the coating on top of it. The ZnO/GaAs solar cell resulted in the I_{SC} of 3.253A, P_{max} of 1.954W, V_{OC} of 0.7130V, and a power conversion efficiency of 17.76%. The efficiency of the bare device can be improved by widening the band gap value through adding a layer to the structure. Therefore, the ZnO/AlGaAs/Si solar cell was modelled to study the structure's performance as a new device design to enhance the efficiency. The PC1D simulation successfully prompted I_{SC} of 3.870A, P_{max} of 2.418W, V_{OC} of 0.7417V and the efficiency of 21.98% for the ZnO/AlGaAs/Si solar cell. The enhancements in parameters and efficiency from ZnO/GaAs to ZnO/AlGaAs/Si demonstrate that the stacking of multiple materials into a few layers of a solar cell using appropriate material parameters can improve overall performance.

In this study, the usage of various types of ARCs on top of a solar cell to achieve the lowest reflectance and increase the absorption of photons, which indirectly increases the efficiency. The design and modelling of the ARCs on top of cell devices were carefully calculated for achieving an optimized value of the refractive index and thickness. It was discovered that varying the thickness and refractive index could change the value of the efficiency, either boosting or dropping. These ARCs were simulated successfully by using PC1D simulation software at wavelengths between 250nm – 1200nm. For a ZnO/GaAs solar cell, SiO₂ as a single-layer ARC achieved the highest efficiency among the other three materials, with 19.62% at a wavelength of 600nm. The electrical parameters were produced I_{SC} of 3.551A, P_{max} of 2.158W, and V_{OC} of 0.7152V. The SiO₂ successfully reduces the reflectance to 0.21% from 10% of the bare device. Moreover, the ZnO/AlGaAs/Si solar cell also recorded that SiO₂ has high efficiency as an SLARC at a wavelength of 600nm. The solar cell with SLARC

resulted in I_{SC} of 4.215A, P_{max} of 2.649W, and V_{OC} of 0.7438V with the efficiency of 24.08%. As is evident, the SiO_2 is the best material for SLARC that can be used on both devices to boost the performance and the efficiency of the solar cell. However, a single-layer could reduce a reflectance at specified wavelengths only which it will be a limitation for the solar cell to achieve high efficiency in wider wavelengths.

Therefore, a double-layer ARC was arranged specifically according to the refractive index to optimize the performance of the solar cell. Both devices, ZnO/GaAs and ZnO/AlGaAs/Si solar cells, were observed to have the high efficiency with the same pair of DLARC, which is SiO_2/ZnO at a wavelength of 600nm. For ZnO/GaAs, SiO_2/ZnO could improve the efficiency by 19.64% which resulted in I_{SC} of 3.555A, P_{max} of 2.160W, and V_{OC} of 0.7153V. Meanwhile, the ZnO/AlGaAs/Si solar cell successfully achieved 24.15% efficiency with I_{SC} of 4.227A, P_{max} of 2.636W, and V_{OC} of 0.7439V. On top of that, the SiO_2/ZnO could reduce the reflectance by 0.805% for both devices, ZnO/GaAs and ZnO/AlGaAs/Si. However, the lowest reflectance was achieved by $\text{SiO}_2/\text{Si}_3\text{N}_4$, which could possibly be a great pair of the double-layer ARC, yet its efficiency is not the highest. This discrepancy may have arisen from several factors that can be adjusted or mitigated, such as, increment of surface recombination, and mismatch refractive index. Overall, the SiO_2/ZnO will be an ideal pair of the DLARC of solar cell to reduce the reflectance and maximize the performance for further study despite of narrowed operational bandwidth.

Besides that, adding another layer to the ARC to become triple-layer would be complicated and excessive cost to design, yet it can help to boost the performance in wider wavelengths. For the ZnO/GaAs solar cell, the highest efficiency was obtained by $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ with a power conversion efficiency of 19.65%. The electrical parameters that were provided by the PC1D simulation resulted in I_{SC} of 3.556A, P_{max} of 2.161W, and V_{OC} of 0.7153V. For the ZnO/AlGaAs/Si solar cell, the $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ also becomes the ideal TLARC for achieving the highest efficiency, which resulted in I_{SC} of 4.203A, P_{max} of 2.658W, V_{OC} of 0.7439V, and the efficiency of 24.16%. Applying different materials in appropriate arrangements according to its refractive index and thickness could help to identify the best pair of the TLARC that could be used as an ARC on the solar cell. Compared to other materials, using the results generated by PC1D simulation software, it was proven that $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$ is the most suitable as a triple-layer ARC for the solar cell.

6.2 Recommendations

The recommendations are necessary to address the errors that occurred in this study, enabling future researchers to build upon it. The first error regarding the Si_3N_4 as a single-layer ARC on ZnO/GaAs solar cell was observed, which has the same efficiency at wavelengths of 900nm – 1200nm. Besides that, the efficiency along the wavelength seems lower than the uncoated cell device. The result shows that the Si_3N_4 is not suitable to be applied as a single-layer on the ZnO/GaAs solar cell, despite that the refractive index is in a good range across the wavelength. Hence, choosing another material as a single-layer ARC that can offer better refractive index matching and stronger broadband transparency is suitable to be applied on the ZnO/GaAs solar cell.

Apart from that, the error occurred in the double-layer and triple-layer for both devices, which are SiO_2/ZnO and $\text{SiO}_2/\text{ZnO}/\text{Si}_3\text{N}_4$, respectively, did not obtain the lowest reflectance percentage, despite both pairs achieving the highest efficiency. When the coating reduces reflection preferentially in the high-photon-flux spectral region when parasitic absorption in competing coatings reduces delivered photons, or when the deposition/process improves electrical properties, leading to higher IQE, the device efficiency can be increased with a non-minimal measured reflectance. Hence, to diagnose this error, measure the absorptance and re-optimize the coating to reconcile the reflectance.

Furthermore, the ZnO/AlGaAs/Si solar cell was a promising structure as a triple heterojunction solar cell. However, the lattice mismatch between ZnO and AlGaAs could reduce the efficiency and cause dislocations as the crystal attempts to relax the strain. These dislocations will shorten the lifespan of minority carriers and increase interface recombination velocity. Therefore, replacing the n-ZnO in the structure with a material that is suitable and matches the lattice could significantly improve the performance and the efficiency. Besides, as ZnO is widely used in the PV industry due to its properties and ability to achieve high efficiency, further enhancement can be made by studying and finding the optimal and suitable parameters to be stacked as a triple-heterojunction together with AlGaAs and Si.

This study observed the performance of the ZnO/GaAs solar cell together with various types of ARCs. A few parameters play a significant role in designing the ARC to satisfy the destructive interference conditions for reducing the reflectance, such as

thickness and refractive index. Based on the results that were generated by the PC1D simulation, the parameters vary as the refractive index and thickness change across the wavelength, which could determine the best types of ARCS at specified wavelengths with the highest efficiency. In addition, the results could determine that the enhancement of the efficiency can be done by reducing the reflectance and increasing the absorption by implementing the ARCs. Moreover, the ZnO/AlGaAs/Si structure has been studied to develop new device designs that enhance performance. Various ARCS were also applied to the device to reduce reflectance and evaluate efficiency using the PC1D simulation under the same conditions. The results for both uncoated and coated cells showed improvements over the ZnO/GaAs solar cell, with and without ARCS. This demonstrates that the triple-heterojunction can achieve high efficiency and has the potential for commercialization in the market and the PV industry.

Further study for both structures with ARCS is needed to enhance the structure with good efficiency by using the findings and results in this study to assist the next study. Based on its properties and studies by researchers before, each material and ARCS were used as they will give a benefit to the solar cell with suitable parameters that could help to increase the efficiency. Therefore, by doing this study, all of the mentioned objectives have been adequately accomplished.

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Fatinah Najwa binti Roslan obtained a Bachelor of Science in Physics (Hons.) in 2025 at Universiti Teknologi Mara (UiTM), Arau, Perlis. Then, she furthered her studies in Master of Science (Applied Physics) at Universiti Teknologi Mara (UiTM), Shah Alam, Selangor. Her master's thesis, MSc thesis, involves designing and analyzing the ZnO/GaAs and ZnO/AlGaAs/Si solar cell using various anti-reflective coatings (ARCs) by using PC1D simulation software.

LIST OF CONFERENCES

Fatinah Najwa Roslan, Mohd Zaki Mohd Yusoff, Madhiyah Yahaya Bermakai, Babar Hussain, Siti Aisyah Zawawi, “Design And Analysis of The Efficiency of ZnO/GaAs and ZnO/AlGaAs/Si-Based Solar Cells”, 8th Kuala Lumpur International Conference on Education, Economics and Technology 2026 (KLICEET2026).

Eric Ross Anak Wallace, Fatinah Najwa Roslan, Mohd Zaki Mohd Yusoff, “PC1D Analysis of TiO₂ Antireflection Coating on GaAs-Based Solar Cells”, International Energy Colloquium 2026 (InEC2026).

LIST OF INNOVATION

Fatinah Najwa Roslan, Mohd Zaki Mohd Yusoff, Madhiyah Yahaya Bermakai, Babar Hussain, Siti Aisyah Zawawi, “Next-Gen High-Efficiency ZnO/GaAs Solar Cell with Advanced Double Layer Anti-Reflective Coating (DLARC) Engineering”, 2nd SDG Innovation@IBSD :Building A Resilient Country.

LIST OF PUBLICATIONS

- Roslan, F. N., Yusoff, M. Z. M., Bermakai, M. Y., Hussain, B., & Zawawi, S. A. (2026). Design And Analysis of the Efficiency of ZnO/GaAs And ZnO/AlGaAs/Si-Based Solar Cells. *International Journal of Innovation and Industrial Revolution (IJIREV)*, 8(25), 530–541.
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