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Impact of the Single-Layer Anti-Reflective Coating (Slarc) on the Photovoltaic Properties of ZnO/AlGaAs/Si Solar Cells

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ABSTRACT

A triple heterojunction solar cell is reported to achieve high efficiency with appropriate parameters. In this study, a zinc oxide/aluminium gallium arsenide/silicon (ZnO/AlGaAs/Si) solar cell was incorporated into a new triple heterojunction solar cell design to investigate the performance of the solar cell. Furthermore, applying an anti-reflective coating (ARC) on top of the cell can enhance its performance by reducing light reflectance. In this work, silicon dioxide, ZnO, and silicon nitride were selected as materials for a single-layer anti-reflective coating (SLARC). The thickness and refractive index values for each material were calculated to determine the optimum values for wavelengths between 250 and 1,200 nm. The device was analyzed using a personal computer 1-dimensional simulation under AM1.5G conditions at one-sun illumination. The reflectance of Si_3N_4 was higher than that of the cell without ARC. Moreover, Si_3N_4 only achieved lower reflectance than the other materials over a narrow wavelength of approximately 300 nm. The cell efficiency increased from 21.98% to 24.08% after applying an SLARC using silicon dioxide.

1. Introduction

Energy is the most important resource for all living organisms, especially humans, for continuing their daily lives effectively. Moreover, living in an era of advanced technology has led to an increase in energy demand. However, the use of non-renewable energy for an extended period, such as fossil fuels, can lead to the depletion of these sources. Thus, the idea of replacing the main source of energy from non-renewable to renewable energy sources non-renewable energy with renewable alternatives has been widely accepted in recent years. Numerous advantages can be gained when using renewable energy sources, such as solar, wind, hydro, geothermal, and biomass, including greater sustainability, cleaner [1], reduced pollution, lower carbon emissions, and environmental friendliness. Among these, solar energy has drawn the interest of individuals and industries as a primary energy source. Solar energy has much potential as it is a limitless source. The average solar intensity exceeds 2,800 kWh/m^2 per year and more than 7.5 kWh/m^2 daily [2]. Therefore, the enormous amount of solar

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energy that can be produced every day makes it a particularly attractive resource for electricity generation.

A solar cell is a technological device that directly converts light energy into electrical energy [3] by using the photoelectric effect. Photons strike the top of the cell, exciting the electron and leaving a hole behind. Photons with energy equal to the energy gap of the semiconductor material are absorbed when light strikes a p-n junction (the n-type semiconductor area facing the sunlight), producing electrons and holes as charge carriers [4]. This solar device is now widely used in various applications, ranging from small gadgets like remote sensors and calculators to large-scale power plants that can supply electricity to the grid [5]. Currently, researchers are studying additional methods to improve the performance of solar cells.

A heterojunction solar cell is a combination of two or more materials with different band gaps and electron properties. Given that multiple p-n junction semiconductor sublayer solar cells surpass the Shockley-Queisser photoconversion efficiency limit of traditional photovoltaic (PV) cells, these solar cells can capture a wider range of solar wavelengths [6]. The most commonly used multijunction combination is the triple heterojunction is the most common, as previous studies have demonstrated high power conversion efficiencies. Aluminium gallium arsenide/gallium arsenide/silicon (AlGaAs/GaAs/Si) tandem solar cells achieved 33.87% efficiency, with a surface texture depth and angle of 3 μm and 54.4°, respectively, utilising a double-layer anti-reflective coating (ARC) [7]. Meanwhile, indium gallium phosphide/AlGaAs/Si solar cells were developed by Dimroth F. et al. [8], which attained 34.1% efficiency. Unlike earlier studies that used different material systems for triple heterojunction solar cells, the current study introduces a zinc oxide (ZnO)/AlGaAs/Si structure to explore new device designs to enhance performance. The choice of each material is based on its different bandgaps, properties, and advantages. Zinc oxide is widely used in the PV industry and is in high demand in the market. Its bandgap is 3.37 eV at room temperature [9, 10], which makes it the most suitable n-type material. Furthermore, its refractive index is low (2.00) compared to other materials, which helps to reduce reflectance optimally. Zinc oxide possesses good electrical and optical qualities, which can give benefits to the device [11]. Moreover, AlGaAs has a substantial band gap energy, acting as a back surface field, and a window layer is used to improve performance [12]. In this study, both ZnO and AlGaAs function as n-type materials, with Si as the p-type material. Silicon is a well-established material in solar cell technology globally due to its characteristics and ability to achieve high efficiency. Multijunction solar cells are required to enhance solar energy conversion efficiency and reduce production costs [5].

Applying an ARC to a solar cell can further enhance the its efficiency of a multijunction solar cell [13]. Two media with different refractive indices reflect light on a variety of surfaces [14]. The rationale of applying an ARC is that reflectance occurs when light strikes the top of the cell, resulting in low photon absorption. Various factors need to be considered when using an ARC for absorption and light transmission, such as the number of layers, refractive index, and material thickness. In this study, a single-layer anti-reflective coating (SLARC) selected to evaluate its effectiveness in improving the efficiency of a ZnO/AlGaAs/Si solar cell using PC1D (Personal Computer 1-Dimensional) simulation. Furthermore, the required thickness and refractive index for each proposed material were calculated and optimized over the wavelength range of 250 and 1,200 nm.

2. Theory and Calculations

The solar spectrum can only be absorbed by single-junction solar cells in a limited range [5]. Thus, multijunction solar cells were invented to overcome this limitation. Different band gaps in each layer can help absorb more photons across a wider wavelength range. Figure 1 shows the arrangement of layers for a triple heterojunction according to their bandgap values. The layer with the widest bandgap (ZnO) is placed at the top of the cell, followed by AlGaAs with an intermediate bandgap, and Si, which has the narrowest bandgap.

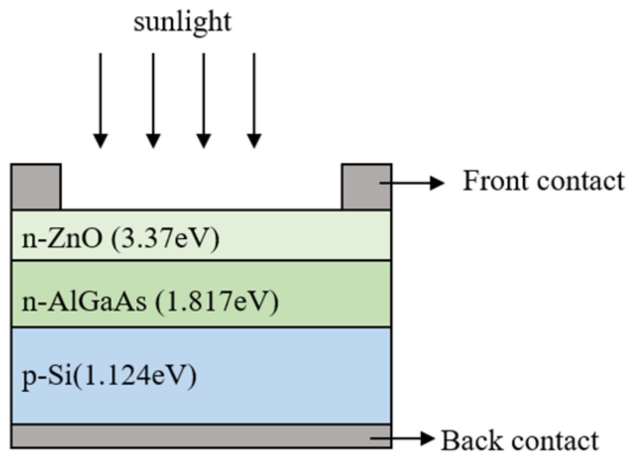

Fig. 1. Schematic diagram of the layer arrangement in a ZnO/AlGaAs/Si triple heterojunction solar cell.

Apart from that, the idea behind the SLARC is to reduce the reflection of light in a specified wavelength range. The idea of light phase variations and the relationship between reflectivity and refractive index are employed by ARCs to reduce reflection [15]. The selection of ARC materials is important for reducing reflection, as each material has its own characteristics. Thus, silicon dioxide (SiO_2), ZnO, and silicon nitride (Si_3N_4) are used to reduce reflectance, which directly increases the efficiency of the solar cell. These SLARC materials on top of an n-ZnO/p-Si solar cell in the wavelength range of 250–1,200 nm, have been studied by Hashmi et al. [15]. The materials for the SLARC are placed on top of the appropriately arranged base cell, as depicted in Figure 2(a), based on their refractive index. Destructive interference occurs when the arrangement of the ARC material is lower than the first substrate layer, which is n-

ZnO. Furthermore, Figure 2(b) shows the energy gap for the conduction and valence bands of the solar cell. Electrons in a solid occupy the valence band, which is an energy band, until it is full. Once the valence band is filled, electrons begin to fill the conduction band as well.

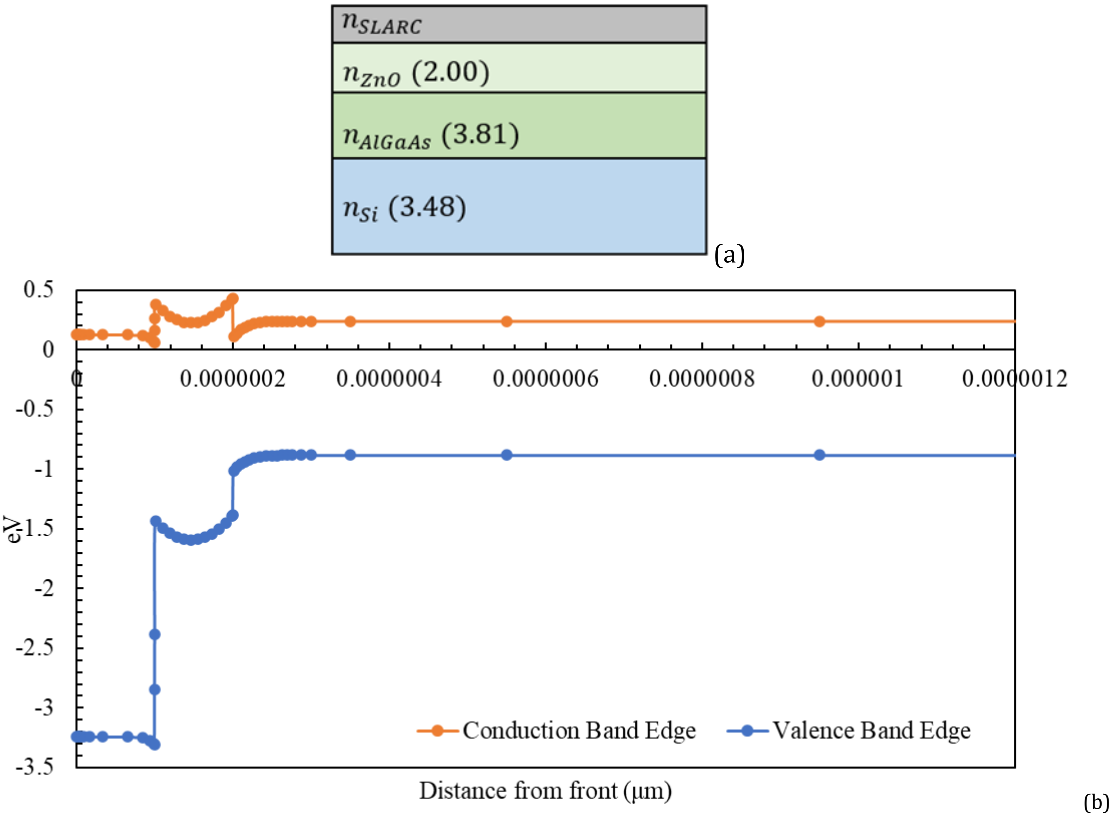

Fig. 2. (a) Schematic diagram (b) and energy gap of the ZnO/AlGaAs/Si tandem solar cell.

Furthermore, the refractive index and thickness play a crucial role in the ARC, enabling it to functionally reduce reflectance. As the wavelength increases, both the refractive index and thickness values change, as they depend on each other. Both parameters of the ARC can be calculated using Eq. (1) and Eq. (2), respectively.

$$n_{ARC} = \sqrt{n_{air} X\, n_{arc}(\lambda_0)} \quad (1)$$

$$d = \frac{\lambda_0}{4 \times n_{ARC}} \quad (2)$$

where n_{air} is the refractive index, n_{arc} is the refractive index of the ARC at the specified wavelength, λ_0, and d is the required thickness. It is widely known that a single-layer coating with a quarter-wavelength optical thickness can reduce normal-incidence reflection at a particular wavelength, often 600 nm [16].

This study was conducted using the PC1D simulation, which provides important parameters to calculate the efficiency of a solar cell. The short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), and maximum power output (P_{max}) were generated under one-sun excitation, which will be useful data. To determine the efficiency, the fill factor must be calculated and can be represented mathematically as follows:

$$FF = \frac{P_{max}}{I_{SC} \times V_{OC}} \quad (3)$$

The I-V characteristic curve of the solar PV module becomes squarer when the fill factor is optimised [17]. Using the fill factor above, the efficiency can be calculated using Eq. (4).

$$\eta = \frac{I_{SC}\, X\, V_{OC}\, X\, FF}{P_{in}} \times 100\% \quad (4)$$

where P_{in} is the power input when the device area is multiplied by the light intensity, which is $P_{in} = 110\ cm^2 \times 0.1\ \mathrm{W}\ cm^{-2}$. These calculations will provide the data to evaluate the effectiveness and efficiency of the solar cell.

3. Simulation Work

A PC1D simulation was chosen to simulate the ZnO/AlGaAs/Si solar cell due to its advantages. This software was originally developed at the University of New South Wales (UNSW) to help researchers study their devices prior to conducting experiments to prove its feasibility [18]. Furthermore, PC1D is a free program that can be used to assess basic cell properties, such as thickness, surface texture, spectrum, and bulk quality [19]. It also provides several files containing optimized material parameters, which can be used for free and modified according to the user's preferences. This enables the simulation of the behaviour of semiconductor-based photovoltaic systems in one dimension (under axial symmetry) [20]. The results generated I_{SC}, V_{OC}, and P_{max}, which contribute to important calculations.

Table 1 shows the parameters of the device required for the PC1D simulation. A device area of 110 cm^2 was chosen because it provides a standard and convenient size to study the solar cell. Moreover, Jamaluddin et al. [21] demonstrated good photovoltaic performance with a device area of 110 cm^2. The exterior front reflectance of the bare device was set to 10%. The substrate materials were arranged properly according to the region's number: ZnO was placed at the top of the solar cell ("REGION 1"), followed by AlGaAs at "REGION 2" and Si at "REGION 3". The thickness of the n-type materials (ZnO and AlGaAs) must be thinner than the p-type material (Si). In order to maximise light absorption and the generation of free electron-hole pairs in that area, the material with the higher energy level must be comparatively thicker [22]. Thus, the thicknesses of ZnO, AlGaAs, and Si were 0.1, 0.6, and 300 μm, respectively. Other than thickness, the doping concentration of each material is significant for increasing the efficiency of the solar cell. The n-type doping concentrations for both ZnO and AlGaAs were set to 1 × 10^{17} cm^{-3}. Meanwhile, for the p-type material, Naim et al. [23] found that Si has good doping at 1.1 × 10^{17} cm^{-3}. Bulk recombination length was set to 1,000 μm for all substrate materials. Other parameters were used the default values from the PC1D file. This study was simulated under the same excitation, which is "ONE-SUN". This excitation provides I_{SC}, V_{OC}, and P_{max} as the output.

The temperature was maintained at 25 °C, and the mode was set to transient with 16 timesteps. The light intensity and spectrum were set to 0.1 W cm^{-2} and AM1.5G. The light intensity was used to calculate the power for determining efficiency as per Eq. (4). In order to achieve the quantum efficiency (QE) results, the excitation was changed to "SCAN-QE".

Table 1. Parameter settings for the ZnO/AlGaAs/Si solar cell using PC1D simulation.

Parameter	Value	References
DEVICE		
Device area	110 cm^2	[21]
Surface texturing	None	
Surface charge	None	
Exterior front reflectance	10%	[21]
Exterior rear reflectance	None	
REGION 1		
Thickness	0.1 μm	[24]
Material	ZnO	
Fixed electron mobility	20 cm^2/Vs	[24]
Fixed hole mobility	10 cm^2/Vs	[24]
Dielectric constant	86	[24]
Band gap	3.37 eV	[24]
Intrinsic concentration at 300 K	1.1 × 10^{-9}	
Refractive index	2.00	
N-type background doping	1 × 10^{19} cm^{-3}	[24]
Bulk recombination, $\tau_n = \tau_p$	1,000 μs	
Front-surface recombination, $S_n = S_p$	Enable	
REGION 2		
Thickness	0.6 μm	
Material	AlGaAs	

Dielectric constant	12.24
Band gap	1.817 eV
Intrinsic concentration at 300 K	1,754
Refractive index	3.81
N-type background doping	1 × 10^{17} cm^{-3}
Bulk recombination, $\tau_n = \tau_p$	1,000 µs
Front-surface recombination, $S_n = S_p$	70,000
REGION 3	
Thickness	300 µm
Material	Si
Dielectric constant	11.9
Band gap	1.124 eV
Intrinsic concentration at 300 K	1 × 10^{10}
Refractive index	3.48
P-type background doping	1.1 × 10^{17} cm^{-3} [23]
Bulk recombination, $\tau_n = \tau_p$	1,000 µs
Front-surface recombination, $S_n = S_p$	Enable
EXCITATION	
Excitation form	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	

4. Results and Discussion

The efficiency of the ZnO/AlGaAs/Si solar cell without applying ARC was determined through simulation using the parameters listed in Table 1. The resulting values of the I_{SC}, P_{max}, and V_{OC} are presented in Table 2, as 3.870 A, 2.418 W, and 0.7417 V, respectively. Using Eq. (3), the fill factor was calculated to be 0.8424, corresponding to an efficiency of 21.98% efficiency. Xiong et al. [25] investigated an AlGaAs/Si solar cell to evaluate the performance of a III–V/Si multijunction configuration, achieving an efficiency of 12.7%. achieving an efficiency of 12.7%. Meanwhile, Roy et al. [5] achieved 22.3% efficiency for an AlGaAs/Si dual-junction solar cell using PC1D simulated in a surface texture depth of 3 μm. For the ZnO/Si solar cell, Jamaluddin et al. [21] studied the device without applying any ARC using PC1D simulation and obtained an efficiency of 22.27%.

Each dual heterojunction structure has demonstrated excellent photovoltaic performance in previous studies. Thus, ZnO, AlGaAs, and Si were combined to form a triple heterojunction structure to further enhance device performance. However, different efficiency percentages were obtained depending on the specific parameter values investigated.

Fig. 3 shows the current-voltage (I-V) curve of the solar cell obtained from the PC1D simulation results. This curve is significant to researchers as it illustrates the electrical behaviour of the device [26]. Based on the graph, when the voltage is zero, the current flow is 3.870 A, which corresponds to the short-circuit current (I_{SC}). As the voltage increases, the current gradually decreases until, at approximately 0.6627 V, it drops sharply to 3.65 A. This point represents the maximum power point, defined as the product of current and voltage at the peak output condition.

Table .2 Data for the ZnO/AlGaAs/Si solar cell without ARC.

Short-Circuit Current, I_{SC} (A)	Maximum Power Output, P_{max} (W)	Open-Circuit Voltage, V_{OC} (V)	Fill Factor, FF	Efficiency, η (%)
3.870	2.418	0.7417	0.8424	21.98

Table 3. Data for the SLARC on the ZnO/AlGaAs/Si solar cell

SiO_2							
Wavelength, λ (nm)	Refractive Index, n	Thickness, d (nm)	I_{SC} (A)	P_{max} (W)	V_{OC} (V)	Fill Factor, FF	Efficiency, 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
1,000	1.471	169.95	4.088	2.566	0.7430	0.8448	23.33
1,100	1.470	187.07	4.053	2.541	0.7428	0.8440	23.10
1,200	1.469	204.22	4.027	2.510	0.7427	0.8392	22.82

Si$_3$N$_4$							
Wavelength, λ (nm)	Refractive Index, n	Thickness, d (nm)	I_{SC} (A)	P_{max} (W)	V_{OC} (V)	Fill Factor, FF	Efficiency, 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
1,000	1.985	138.539	3.831	2.395	0.7414	0.8432	21.77
1,100	1.985	138.539	3.831	2.395	0.7414	0.8432	21.77
1,200	1.983	151.286	3.832	2.396	0.7414	0.8434	21.78
ZnO							
Wavelength, λ (nm)	Refractive Index, n	Thickness, d (nm)	I_{SC} (A)	P_{max} (W)	V_{OC} (V)	Fill Factor, FF	Efficiency, 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
1,000	1.841	135.800	3.922	2.447	0.7420	0.8409	22.25
1,100	1.833	150.027	3.897	2.433	0.7418	0.8416	22.12
1,200	1.826	164.294	3.056	1.902	0.7358	0.8459	17.29

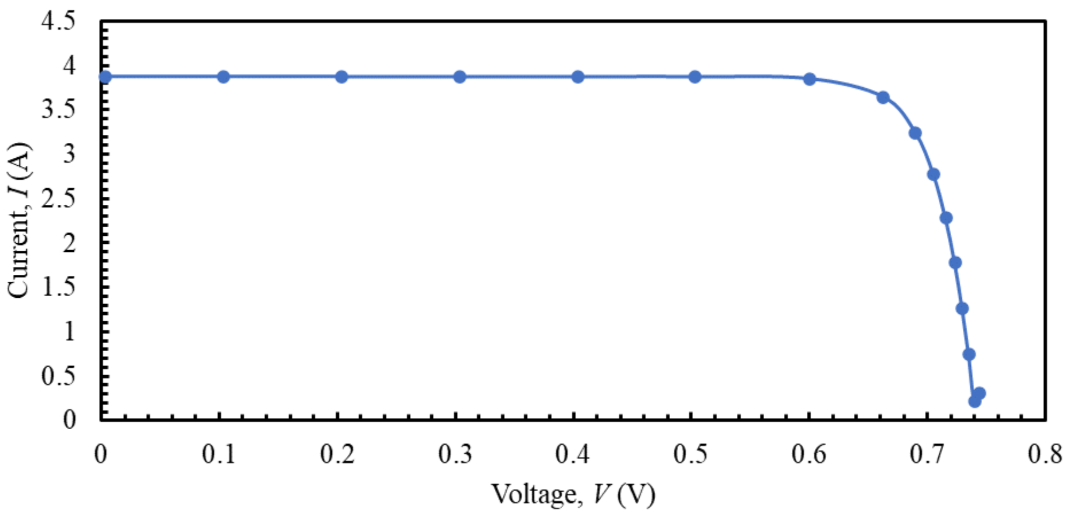

Fig. 3. The I-V curve for the ZnO/AlGaAs/Si solar cell without ARC.

Although the uncoated cell demonstrates promising performance, further enhancement can be achieved by implementing an SLARC on top of the ZnO/AlGaAs/Si solar cell. Table 3 shows the complete dataset for SiO_2, ZnO, and Si_3N_4 as materials for the SLARC at the wavelength range of 250–1,200 nm, together with the required thickness and refractive index.

Based on Table 3, the required values of refractive index and thickness varied with wavelength, producing different values for I_{SC}, P_{max}, V_{OC}, and efficiency. Among the materials studied, SiO_2 as an SLARC achieved the highest efficiency of all materials tested with 24.08% and a fill factor of 0.8449 at a wavelength of 600 nm under AM1.5G conditions. The corresponding values of I_{SC}, P_{max}, and V_{OC} were 4.215 A, 2.649 W, and 0.7438 V, respectively. Furthermore, the efficiency of SiO_2 at wavelengths between 250 and 1,200 nm was higher than that of a solar cell without any ARC. The main factor behind this observation is that the refractive index of SiO_2 is lower than that of n-ZnO, which leads to destructive interference between the two reflected waves, thereby reducing light reflectance. The use of SiO_2 as an SLARC on a silicon solar cell resulted in an 9.43% efficiency, as determined using Silvaco TCAD software [27]. Kanmaz I. [28] successfully increased efficiency from 14.63% to 18.95% by applying SiO_2 on top of a crystalline silicon cell with an optimum thickness. Next, ZnO recorded the second-highest efficiency at 22.38% with I_{SC}, P_{max}, and V_{OC} values of 3.947 A, 2.462 W, and 0.7422 V, respectively. The improvement in efficiency after applying ZnO as an SLARC was 0.40% only. Lastly, Si_3N_4 produced the lowest efficiency among the materials and bare devices, recording 21.78% at 1,200 nm. The values of I_{SC}, P_{max}, and V_{OC} were 3.874 A, 2.212 W, and 0.7387 V, respectively, resulting in a fill factor of 0.7730. The refractive index and thickness for each material play a vital role, as they are dependent on each other.

Based on the results obtained, the I-V curve can be drawn, which consists of all three materials of the SLARC: SiO_2, ZnO, and Si_3N_4, represented by the orange, blue, and grey curves, respectively, as shown in Figure 4. When the voltage is zero, SiO_2 has the highest current of 4.22 A, followed by ZnO and Si_3N_4, with currents of 3.95 A and 3.83 A, respectively. Silicon dioxide is clearly the best light-trapping material, which may reduce reflectance and enhance performance when used as an SLARC on top of ZnO/AlGaAs/Si solar cells. Furthermore, when the voltage is approximately 0.64 V, the current for all materials drops to zero, resulting in an almost identical value of V_{OC} for all three materials, although SiO_2 records a slightly higher value.

From the results, several graphs can be drawn to analyze the performance of the solar cell. Figures 5(a) and (b) show the curves of I_{SC} and V_{OC} as functions of wavelength. In both graphs, SiO_2, represented by the orange curve, shows constantly high values of current and voltage as the wavelength increases. This curve reflects the results for SiO_2 in Table 3, which show a high percentage of performance. Meanwhile, ZnO, represented by the blue curve, displays low current and voltage at short wavelengths between 250 and 400 nm. However, these values slowly increase from 500 nm onwards, resulting in good performance over a broad wavelength range. On the other hand, Si_3N_4 (grey curve) shows that the curve has the lowest values among the materials, except at short wavelengths between 250 and 400 nm, where it produces higher values than ZnO.

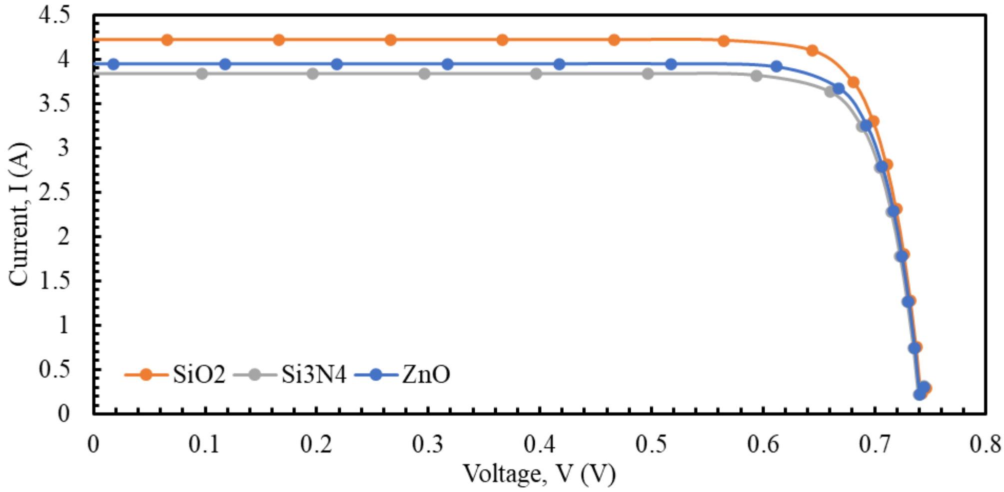

Fig. 4. The I-V curve of the ZnO/AlGaAs/Si solar cell with SLARC.

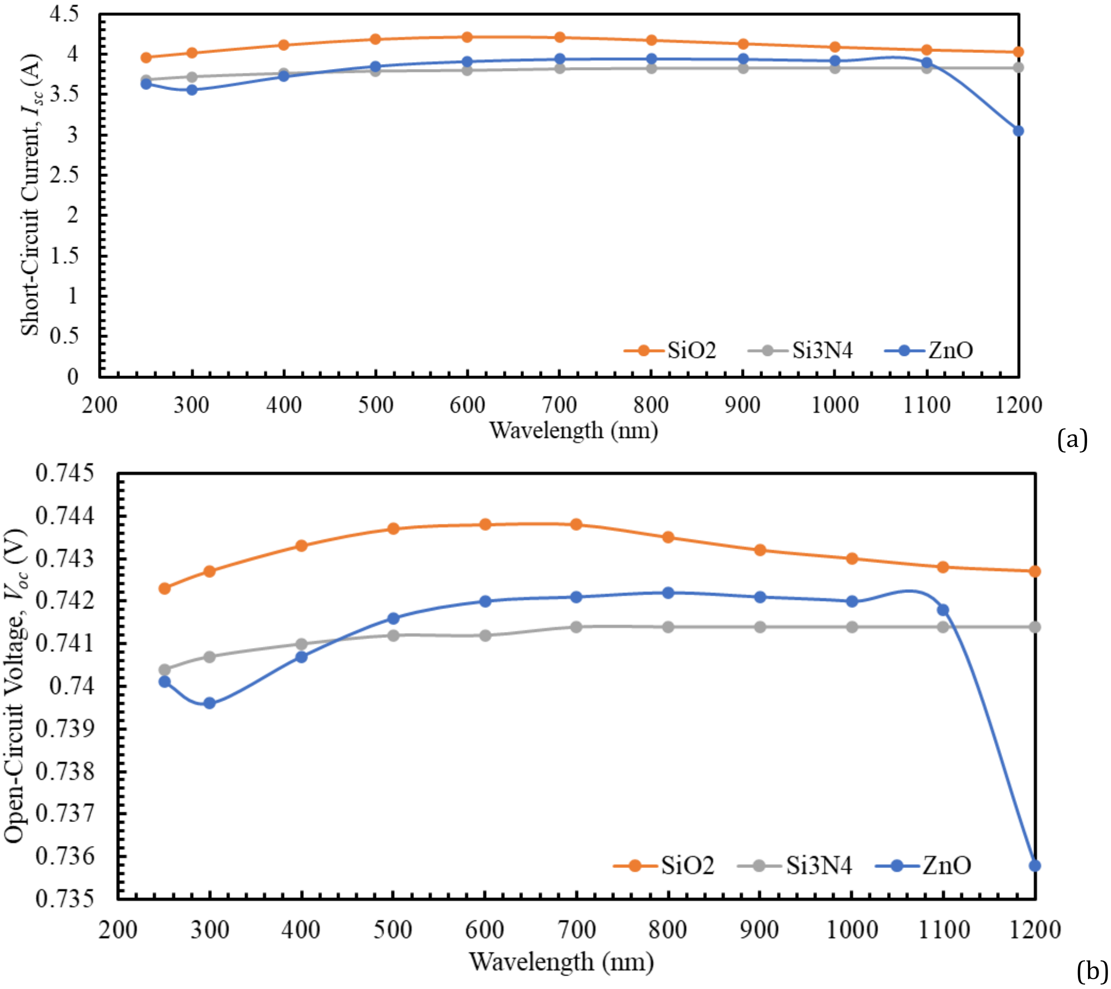

Fig. 5. Graphs of current (a) and voltage (b) as functions of wavelength for the ZnO/AlGaAs/Si solar cell with SLARC.

In addition to the curves shown in Figure 5, the PC1D simulation also provides QE and reflectance curves for analysis. Thus, the external quantum efficiency (EQE) curve was plotted in Figure 6. This parameter represents the difference between the number of charge carriers produced by the solar cell and the number of incident photons of a specified energy irradiated onto the solar cell from the outside [29]. All schemes began at almost 0% EQE in the wavelength range of 300–400 nm and then increased slowly thereafter. The solar cell without an ARC achieved an EQE value of 89.74%. Based on the curve, SiO_2 has the highest value of EQE with 99.01%. When the percentage of EQE is nearly 100%, it indicates that the photons are almost fully absorbed by the cell. Meanwhile, ZnO and Si_3N_4 recorded EQE values of only 92.31% and 88.72%, respectively. However, at a wavelength of 1,000 nm, all three materials began to decrease, with approximately similar EQE percentage at higher wavelengths.

Applying an ARC on top of the solar cell can reduce reflectance and enhance the overall efficiency of the device. However, depending on the material properties, certain ARCs may reflect more light rather than allowing it to be absorbed by the cell. Thus, the reflectance curve is significant for researchers when analyzing the performance of the device cell. Figure 7 shows the reflectance curves of the ZnO/AlGaAs/Si solar cell with and without a SLARC. The solar cell without an ARC recorded a reflectance of about 10% from 300 to 1,200 nm. Silicon dioxide, represented by the orange curve, achieved the lowest reflectance at 600 nm, with only 0.21%. In comparison, the reflectance curve for ZnO was slightly higher than that of the cell without ARC; however, it slowly decreased at 500 nm. The lowest reflectance of ZnO, shown by the grey curve, was 7.25% at a wavelength of 800 nm. The reflectance of Si_3N_4 was higher than that of the cell without ARC, as confirmed in Table 3, which also recorded the lowest efficiency. Moreover, Si_3N_4 only achieved lower reflectance than the other materials over a narrow wavelength of approximately 300 nm, with a reflectance of 8.35%.

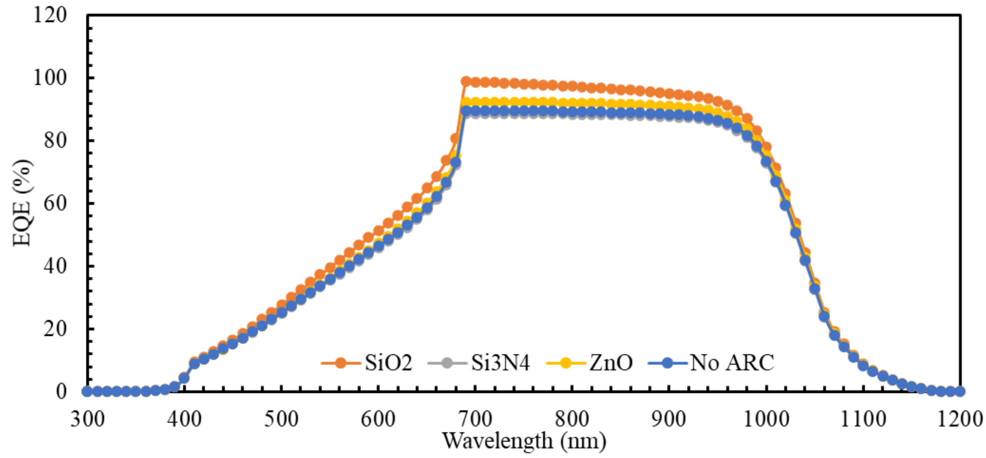

Fig. 6. EQE curves of ZnO/AlGaAs/Si solar cells with and without SLARC.

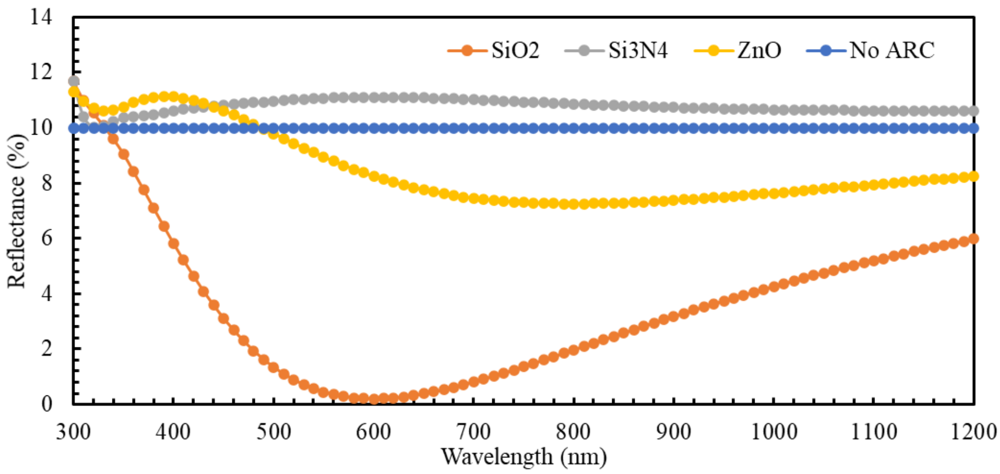

Fig. 7. Reflectance curves of ZnO/AlGaAs/Si solar cells with and without SLARC.

5. Conclusion

In this study, a triple heterojunction solar cell incorporating new materials was introduced to improve the performance of the solar cell. The semiconductor of the subcell consists of a ZnO/AlGaAs/Si solar cell with bandgap values of 3.37, 1.817, and 1.124 eV, respectively. The base cell produced an efficiency of 21.98%, I_{SC} of 3.870 A, P_{max} of 2.418 W, and V_{OC} of 0.7417 V under AM1.5G conditions, and a reflectance of 10%. The use of an SLARC was proposed to increase efficiency and lower reflectance. Among all three ARC materials, SiO_2 recorded the highest efficiency with 24.08%, I_{SC} of 4.215 A, P_{max} of 2.649 W, and V_{OC} of 0.7438 V, with the reflectance reduced to 0.21%. The improvement in the efficiency after applying the ARC was only 2.1%. Further improvement can be achieved by applying more layers of ARC with suitable materials, as they would absorb more photons across a broad wavelength range in the solar spectrum. Additionally, replacing n-ZnO with a more suitable lattice-matched material could improve absorption.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Conceptualization and study design: F.N. Roslan, M.Z.M. Yusoff
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