Indian Journal of Pure & Applied Physics
Vol. 64, February 2026, pp. 123-132
DOI: 10.56042/ijpap.v64i2.21294

Numerical Modelling of High Efficiency ZnO/GaAs Solar Cells Using Triple-Layer Anti-Reflective Coating

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Received:5th July 2025; accepted:7th January 2026

The choice of substrate's material plays a vital role in achieving good efficiency. Zinc oxide (ZnO) and gallium arsenide (GaAs) were thus selected as n-type and p-type, respectively, because of their properties that can help generate high current and voltage, which will indirectly result in high efficiency. However, reflectance of light still occurred due to the design of the solar cell. Applying a triple-layer anti-reflective coating (TLARC) on the top of the n-ZnO/p-GaAs solar cell was applied in this work to reduce the reflectance and maximise the transmittance. A broad wavelength range of 250 nm to 1,200 nm was used to analyse all nine triplet materials of the triple-layer anti-reflective coating (TLARC). The efficiency of solar cells was investigated by using Personal Computer 1-Dimensional (PC1D) simulation. The parameters used to simulate PC1D are the maximum power output (P_{max}), open-circuit voltage (V_{OC}), and short-circuit current (I_{SC}). There are various trios of materials that have been chosen as a triple-layer anti-reflective coating (TLARC) to study on the top of n-ZnO/p-GaAs solar cells. $SiO_2/Si_3N_4/ZnO$, $SiO_2/Si_3N_4/ZnS$, $SiO_2/Si_3N_4/TiO_2$, $SiO_2/ZnO/ZnS$, $SiO_2/ZnO/TiO_2$, $SiO_2/ZnO/Si_3N_4$, $ZnO/Si_3N_4/TiO_2$, $ZnO/Si_3N_4/ZnS$, and ZnO/ TiO_2/ZnS were selected to be used as a TLARC. We found that the efficiency of the n-ZnO/p-GaAs solar cell without using any anti-reflective coating (ARC) was reported as 17.76 %, and it increased to 19.65 % after $SiO_2/ZnO/Si_3N_4$ layers were applied on the top of the solar cell.

Keywords: Zinc oxide (ZnO), Gallium arsenide (GaAs), Solar cells, Triple-layer anti-reflective coating (TLARC), PC1D software simulation

1 Introduction

No living thing, most importantly humankind, can afford to go without energy to support their daily lives fully. Additionally, due to the high technology era, there has been a growth in energy use demands. Energy is categorized into two types, which are renewable energy and non-renewable energy. The use of renewable energy in this modern era is a good solution to prevent the extinction of non-renewable energy, such as fossil fuels, coal, petroleum, and natural gas. One of the renewable energies that is widely used is solar energy, which is capable of generating electricity by absorbing the photons from the sun. All living things receive energy from the sun, beginning with photosynthesis. Plants collect solar radiation and transform it into stored energy for growth and development, sustaining life on Earth[1].

In addition, a previous researcher invented a technology known as photovoltaic (PV) or solar cells, which allows solar energy to produce electricity. Using the photoelectric effect, the solar cell will directly transform light energy into electric energy[2]. A photon in sunlight will strike the top of the solar cell and generate charge carriers such as holes (p-type) and electrons (n-type). Numerous researchers have studied solar cells with various materials and methods to determine the best efficiency and performance.

Crystalline silicon is currently widely used in solar cells in the photovoltaic industry. However, researchers found out that zinc oxide (ZnO) has advantageous characteristics that can improve the efficiency of solar cells and is slowly growing in the PV market. Excellent electrical and optical qualities

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are also present in ZnO thin film, but its production costs are modest[3]. It has become a potential functional semiconductor material that has many innovative applications due to its massive binding energy of free excitons and direct and wide band gap in the near-UV spectral regime[4]. Nevertheless, ZnO coating can also be combined with various p-type absorber materials to serve as an active layer to single heterojunction solar cells in conjunction with being an antireflective layer[5], such as silicon (Si) and gallium arsenide (GaAs). To enhance the performance of n-ZnO/p-Si solar cells, a significant amount of research has been conducted to improve the efficiency of silicon materials, which can lead to higher overall efficiency. Just like ZnO, researchers found out that GaAs is a good material that can be used in a solar cell due to its good characteristics. GaAs's 1.42 eV direct bandgap makes it appropriate for diode and PV cell applications as well[6]. Characteristics of III-IV materials, including GaAs, that enable it to be used to design highly efficient solar cells include high optical absorption coefficients, direct energy band gaps, and favourable minority carrier lifetime and mobility values[7]. Yet, ZnO/GaAs solar cells outperform ZnO/Si heterojunction solar cells in some ways when compared to ZnO/Si solar cells[3]. Nevertheless, the optimisation value of n-ZnO/p-GaAs is still being conducted by many techniques, including doping zinc oxide with magnesium[8] as well as experimenting with different thicknesses and concentrations of carrier n-ZnO/p-GaAs[5].

High solar cell efficiency requires a low percentage of light reflection to maximise transmission. There exist several methods for lowering light reflectance. Applying triple-layer anti-reflective coating (TLARC) will be the method used in this paper to lessen reflection caused by planar solar cells. The goal of creating anti-reflection films is to minimise transmission while closely matching the refractive index of the substrate coated with the film to that of the incident medium[2,9]. To ensure the anti-reflective coating (ARC) works efficiently, the choice of material and the arrangement of the materials to combine as a triple-layer ARC will play a vital role and affect the performance of solar cells. Every type of material has its own refractive index in a specified wavelength, which helps arrange the layers from lower to higher refractive index in order for destructive interference to happen. Hence, in this work, a triple-layer ARC with a specified refractive index and thickness had been arranged and used to study the efficiency of the n-ZnO/p-GaAs solar cell along the wavelength of 250 nm – 1,200 nm by using the Personal Computer 1-Dimensional (PC1D) simulation software, where this range is typically used for evaluating the solar cell's performance.

2 Theory and Calculations

The idea of the triple-layer ARC is the same as that of other types of ARCS. The researchers found that single, double, and triple layers work efficiently as an ARC 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[10]. 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 centre of the V-shaped film with an equal thickness[2,11]. There are various trios of materials that have been chosen as a TLARC to study on the top of n-ZnO/p-GaAs solar cells. $SiO_2/Si_3N_4/ZnO$, $SiO_2/Si_3N_4/ZnS$, $SiO_2/Si_3N_4/TiO_2$, $SiO_2/ZnO/ZnS$, $SiO_2/ZnO/TiO_2$, $SiO_2/ZnO/Si_3N_4$, $ZnO/Si_3N_4/TiO_2$, $ZnO/Si_3N_4/ZnS$, and ZnO/ TiO_2/ZnS are chosen to be used as a TLARC[12]. These materials were arranged according to their refractive index from lower to higher, as shown in Fig. 1 (a). Only a restricted range of reflectivity is decreased by single- and double-layer ARC. Triple-layer ARC is extensively used to increase silicon solar cells' current density and conversion efficiency[13]. Moreover, Fig. 1 (b) illustrates an energy band diagram of a solar cell using a triple layer consisting of the conduction band and valence band.

Furthermore, the triple-layer ARC was conducted in a specified wavelength range between 250 nm and 1,200 nm. The sun's spectrum spans this range, which is why these wavelengths are used[12]. The refractive index and thickness of the ARC will change as the wavelength increases. To reduce reflection, a transparent substance with a refractive index and a quarter-wavelength coating is utilised[14]. Thus, the required optimum thickness can be calculated for each specified wavelength by using Eq. (1).

$$d = \frac{\lambda_0}{4\ X\ n_{ARC}} \qquad \dots (1)$$

where d is the ARC's thickness and λ_0 is the refractive index (n_{ARC}) of an anti-reflection coating at a specific wavelength.

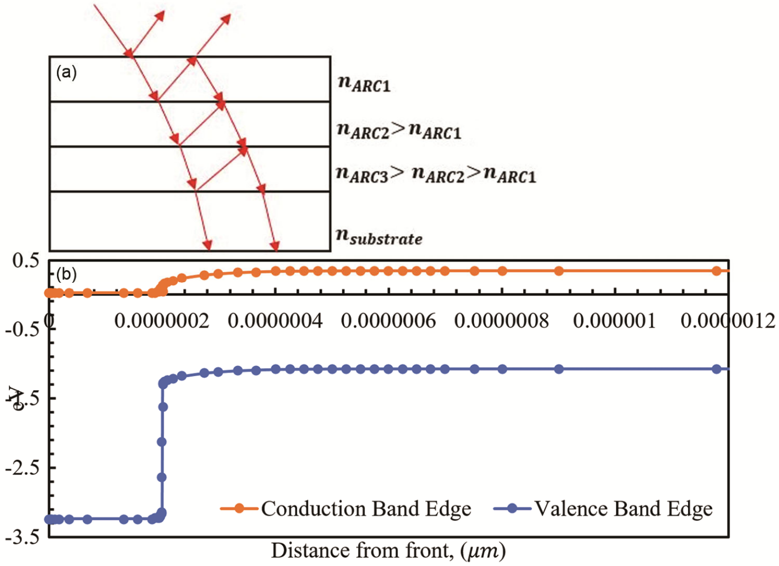


Fig. 1 — Schematic diagram of (a) refractive index of triple layer ARC, and (b) energy band diagram

In this work, the solar cell was examined using Personal Computer 1-Dimensional (PC1D) simulation. Table 1 shows the parameter values for ZnO and GaAs as substrate material. The device area[15], exterior front reflectance[15], ZnO thickness[5], GaAs thickness[5], p-type background doping[16,17] are important parameters.

A few parameters will emerge as the simulation's outcome with these values, which are the maximum power output (P_{max}), open-circuit voltage (V_{OC}), and short-circuit current (I_{SC}). A formula that determines fill factor requires these parameters, and the efficiency of the solar cell also needs them. The fill factor can be calculated using the equation below.

$$FF = \frac{P_{max}}{I_{SC}\ X\ V_{OC}} \qquad \dots (2)$$

One of the important electrical metrics used to measure the performance of solar cells is the fill factor (FF)[18]. Furthermore, the efficiency of a solar cell can be evaluated by using Eq. (3).

$$\eta = \frac{I_{SC}\ X\ V_{OC}\ X\ FF}{P_{in}}\ \text{X}\ 100\% \qquad \dots (3)$$

where η represents solar cell efficiency and P_{in}, or solar power input, is calculated by multiplying the device area of the solar cell by a constant intensity, as in Eq. (4).

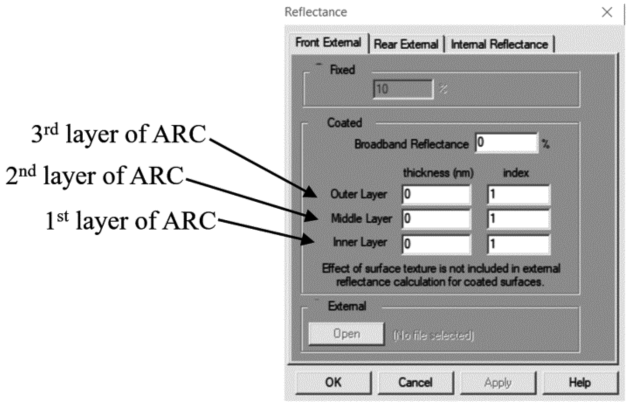
$$P_{in} = 100\ cm^2\ X\ 0.1\text{W}\ cm^{-2} \qquad \dots (4)$$

3 Simulation Work

There are numerous kinds of simulators available for use by all researchers. The PC1D simulation was chosen to be used in this work. Numerous researchers

Table 1 — The parameters of zinc oxide and gallium arsenide solar cell using PC1D simulation

Parameter	Value
DEVICE	
Device are	110 cm^2
Surface texturing	None
Surface charge	None
Exterior front reflectance	10%
Exterior rear reflectance	None
Internal optical reflectance	None
REGION 1	
Thickness	0.2 µm
Material	ZnO
Dielectric constant	7.9
Band gap	3.289 eV
Intrinsic concentration at 300K	$1.1 \text{x} 10^{-9}$
Refractive index	2.00
N-type background doping	$1 \text{x} 10^{18}$ cm^{-3}
Bulk recombination, $\tau_n = \tau_p$	1,000 µs
REGION 2	
Thickness	100 µm
Material	GaAs
Dielectric constant	13.18
Band gap	1.424 eV
Intrinsic concentration at 300K	$1 \text{x} 10^{9}$
Refractive index	3.66
P-type background doping	$5 \text{x} 10^{15}$ cm^{-3}
Bulk recombination, $\tau_n = \tau_p$	1,000 µs
EXCITATION	
Excitation from	one-sun
Excitation mode	Transient, 16 time steps
Temperature	25 ℃
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	



Fixed 10 %

Coated

Broadband Reflectance 0 %

	thickness (nm)	index
Outer Layer	0	1
Middle Layer	0	1
Inner Layer	0	1

Effect of surface texture is not included in external reflectance calculation for coated surfaces.

Fig. 2 — Settings of Triple Layer Anti-Reflective Coating (TLARC) in PC1D Simulation

utilized PC1D to model different kinds of solar cells before undertaking experiments to confirm that their ideas were feasible[19]. Furthermore, its free availability and proven reliability have also become reasons why PC1D simulation is useful for researchers. PC1D can determine the solar cell's current-voltage characteristics and spectrum quantum efficiency by altering the applied bias or the excitation light source's wavelength. It also offers a wide range of other output data possibilities in both the spatial and time domains[20].

The PC1D simulation will generate three important parameters for researchers to identify the effectiveness of the solar cell, such as the maximum power output (P_{max}), open-circuit voltage (V_{OC}), and short-circuit current (I_{SC}). By using this information, the efficiency of a solar cell can be determined by using Eq. (3). However, to achieve good value in these parameters, there will be some factors that need to be emphasized. The use of ARC, the choice of substrate materials, the optimization of substrate values, and other factors are important. These factors will contribute to high efficiency with the right value of parameters.

The parameters of the device have been set up in the “DEVICE” section. The device area of the solar cell that has been used in this study is 110 cm^2, and for non-ARC, exterior front reflectance was fixed as 10 %. Triple-layer ARC thickness and refractive index will be added by setting it up in the exterior front reflectance section under “coated”. The first layer with a lower refractive index was set in the “outer layer” and followed by the second and third layers in the “middle layer” and “inner layer”, respectively, as shown in Fig. 2. Next, ZnO functions as the n-type and is placed in REGION 1, while GaAs functions as the p-type and is placed in REGION 2. The thickness of the substrate plays an important role in preventing bulk recombination from happening. A thicker absorber may also result in a lower fill factor by increasing the recombination losses of charge carriers inside the solar cell[21]. The optimum thickness values for n-zinc oxide (n-ZnO) and p-gallium arsenide (p-GaAs) were found by other work[5], and they are 0.2 μm and 100 μm, respectively. Furthermore, the value of p-type doping was set by using values that were found by other works[16,17], which is 5x10^{15} cm^{-3}. Besides that, the excitation was set up by using the “ONE-SUN” default in the simulation. Other parameters were set up by default in the PC1D simulation, as shown in Table 1 and Figs. 3 (a) and (b).

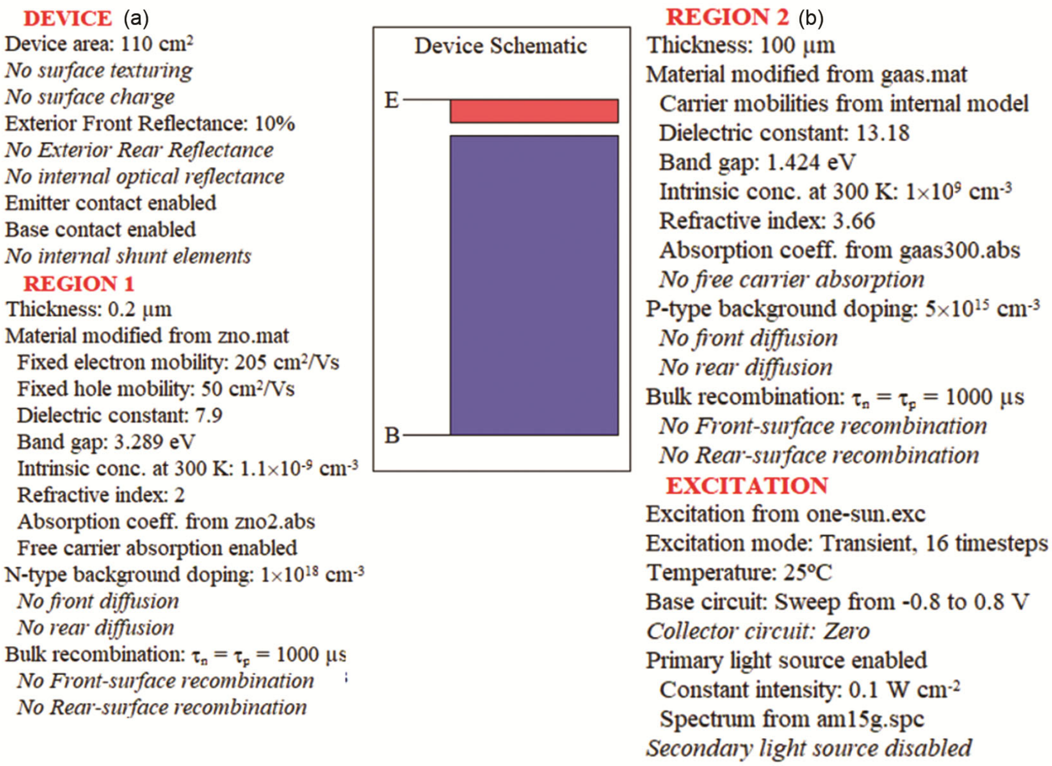
4 Results and Discussion

The efficiency of the n-ZnO/p-GaAs solar cell was examined without using any ARC using the PC1D simulation. All the parameters were set up as in Table 1 and generate short-circuit current (I_{SC}), maximum power output (P_{max}) and open-circuit voltage (V_{OC}) respectively. The results were 3.253A, 1.954W, and 0.7130V, respectively. With this outcome, Eqs. (2) and (3) can be used appropriately to compute the solar cell's fill factor and efficiency. Following equation-based calculation, the fill factor was found to be 0.8425, resulting in an efficiency of roughly 17.76 %, as shown in Table 2. Furthermore, numerous researchers studied n-ZnO/p-GaAs solar cells by using various methods and types of simulation. The ZnO/GaAs provides the efficiency of a solar cell with 8.31% in experimental way[22]. Besides that, the solar cell had studied by an Atlas Silvaco Software simulation and successfully achieved 21.21% for the efficiency[5]. These minor variations resulted from different methods and simulations being used. the various software that may be used in the solar cell simulation process in order to illustrate the differences in modelling and computational techniques used by various simulators[23]. This could lead to differences in the anticipated efficiency of solar cells.

Besides the three key parameters, the PC1D simulation also provides several graphs for analysing the results. Based on the result in Table 2, the graph of current vs voltage (I-V) for the n-ZnO/p-GaAs solar cell without using any ARC can be created as shown in Fig. 4. The graph shows when the voltage is zero, the maximum current achieved was 3.25 A. Meanwhile, at some point in the voltage range

Table 2 — Data of PC1D simulation of the uncoated n-ZnO/p-GaAs solar cell

Short-circuit current, $I_{SC}\ (A)$	Maximum power output, $P_{max}\ (W)$	Open-circuit voltage, $V_{OC}\ (V)$	Fill Factor, FF	Efficiency, η (%)
3.253	1.954	0.7130	0.8425	17.76


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

REGION 2 (b)
Thickness: 100 µm
Material modified from gaas.mat
Carrier mobilities from internal model
Dielectric constant: 13.18
Band gap: 1.424 eV
Intrinsic conc. at 300 K: 1×10^{9} cm^{-3}
Refractive index: 3.66
Absorption coeff. from gaas300.abs
No free carrier absorption
P-type background doping: 5×10^{15} cm^{-3}
No front diffusion
No rear diffusion
Bulk recombination: $\tau_n = \tau_p$ = 1000 µs
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

Fig. 3 — Settings parameter of "DEVICE" and "REGION 1" (a) and "REGION 2" and "EXCITATION" (b) in PC1D simulation

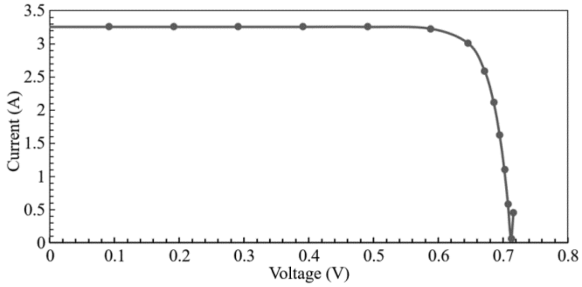


Fig. 4 — Graph of I-V curve for uncoated ZnO/GaAs solar cell

between 0.60 V and 0.65 V, the current will start to drop to zero. At this phase, the abrupt drop at V_{OC} signifies the transition from diode-like behaviour to power generation. The maximum power can be obtained when the current and voltage are at the highest point, which are 3.01 A and 0.65 V, respectively, by multiplying both these parameters.

The efficiency of the n-ZnO/p-GaAs solar cell can be improved by using the TLARC on the top of the solar cell. An ARC can be an important component to reduce the reflection and increase the transmission and efficiency of the solar cell. In this paper, $SiO_2/Si_3N_4/ZnO$, $SiO_2/Si_3N_4/ZnS$, $SiO_2/Si_3N_4/TiO_2$, $SiO_2/ZnO/ZnS$, $SiO_2/ZnO/TiO_2$, $SiO_2/ZnO/Si_3N_4$, $ZnO/Si_3N_4/TiO_2$, $ZnO/Si_3N_4/ZnS$, and $ZnO/\ TiO_2/ZnS$ will be TLARC's material, and it will be stacked according to their refractive index from low to high.

Based on Table 3, important parameters were recorded to determine the efficiency of solar cells that were produced by the PC1D simulation, which are short-circuit current (I_{SC}), maximum power output (P_{max}) and open-circuit voltage (V_{OC}). Besides that, in the range 250 nm – 1,200 nm, the value of the refractive index and thickness for each material was changed as the wavelength increased. The difference in value of the refractive index and thickness will affect the performance and efficiency of the solar cell, which indirectly can determine the most effective at a specified wavelength. Among six schemes, the highest efficiency achieved was 19.65 % by using $SiO_2/ZnO/Si_3N_4$ as a triple-layer ARC on top of a ZnO/GaAs solar cell. The PC1D simulation simulates these pairs and generates an I_{SC} of 3.556 A, P_{max} of 2.161 W, and V_{OC} of 0.7153 V. Fill factor can be

Table 3 — Data of PC1D simulation for the n-ZnO/p-GaAs solar cell with TLARC

$SiO_2/Si_3N_4/ZnO$ ARC

Wavelength,λ	Refractive index			Thickness, d (nm)			I_{SC}	P_{max}	V_{OC}	FF	Efficiency
(nm)	SiO_2	Si_3N_4	ZnO	SiO_2	Si_3N_4	ZnO	(A)	(W)	(V)		(%)
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

$SiO_2/Si_3N_4/ZnS$ ARC

Wavelength,λ	Refractive index			Thickness, d (nm)			I_{SC}	P_{max}	V_{OC}	FF	Efficiency
(nm)	SiO_2	Si_3N_4	ZnS	SiO_2	Si_3N_4	ZnS	(A)	(W)	(V)		(%)
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

$SiO_2/Si_3N_4/TiO_2$ ARC

Wavelength,λ	Refractive index			Thickness, d (nm)			I_{SC}	P_{max}	V_{OC}	FF	Efficiency
(nm)	SiO_2	Si_3N_4	TiO_2	SiO_2	Si_3N_4	TiO_2	(A)	(W)	(V)		(%)
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

Wavelength,λ	Refractive index			Thickness, d (nm)			I_{SC}	P_{max}	V_{OC}	FF	Efficiency
(nm)	SiO_2	ZnO	TiO_2	SiO_2	ZnO	TiO_2	(A)	(W)	(V)		(%)
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

(*Contd.*)

Table 3 — Data of PC1D simulation for the n-ZnO/p-GaAs solar cell with TLARC (*Contd.*)

$SiO_2/ZnO/Si_3N_4$ ARC

Wavelength, λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	Efficiency (%)
	SiO_2	ZnO	Si_3N_4	SiO_2	ZnO	Si_3N_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	1.50	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	1.48	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

Wavelength, λ (nm)	Refractive index			Thickness, d (nm)			I_{SC} (A)	P_{max} (W)	V_{OC} (V)	FF	Efficiency (%)
	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

calculated by using Eq. (2), which results in approximately 0.8496. The arrangement of the $SiO_2/ZnO/Si_3N_4$ becomes the main factor of the high efficiency. The refractive index was gradually increased from the air to the substrate, except for the last layer of the ARC to the n-ZnO $[n_{air}(1.00) > n_{SiO2}(1.48) > n_{ZnO}(1.913) > n_{Si3N4}(2.020) < n_{n-ZnO}(2.00)]$. This gradual arrangement could build the destructive interference efficiently. Furthermore, $SiO_2/Si_3N_4/ZnS$ recorded the second-highest efficiency, which is 19.53 % at wavelengths of 500 nm and 600 nm. The I_{SC} values for these two wavelengths differ; for 500 nm and 600 nm, they are 3.536 A and 2.535 A, respectively. The fact that this difference occurred because the thickness of all three materials at a wavelength of 600 nm was greater than at a wavelength of 500 nm. However, the values of P_{max} and V_{OC} were the same for both wavelengths, which are 2.148 W and 0.7151 V, which will produce the same efficiency. The lowest efficiency recorded is 18.70% with 0.8472 as a fill factor for $ZnO/TiO_2/ZnS$ as a triple-layer ARC. It generates 3.400 A, 2.057 W, and 0.7141 V for I_{SC}, P_{max}, and V_{OC}, respectively.

By using the results obtained in Table 3, a graph of short-circuit current vs wavelength and open-circuit voltage vs wavelength can be created to analyse the efficacy of the solar cell. Based on Fig. 5 (a), all six triplet materials were achieving a consistently high value of current. $SiO_2/ZnO/Si_3N_4$ started to increase at 400 nm with 3.472 A and consistently produced high values, slightly higher than those of other materials. However, the current begins to drop at 1,100 nm, reaching 3.366 A. Also, at 6,000 nm, the current of $SiO_2/Si_3N_4/ZnS$ had a sudden drop, while other materials were having high current values. Additionally, in Fig. 5 (b), the open-circuit voltage was analysed for all materials. The graph of $ZnO/TiO_2/ZnS$ shows the lowest value of voltage from 250 nm to 1,200 nm wavelength, but the pattern of the graph is the same as that of other materials, which is the sudden drop at 300 nm and slight increase between 1,000 nm and 1,100 nm. Meanwhile, $SiO_2/ZnO/Si_3N_4$ still achieved consistency of high voltage and dropped at 1,100 nm with 0.7142 V. While other materials were having a sudden drop at 1,100 nm, $SiO_2/Si_3N_4/ZnS$ had a

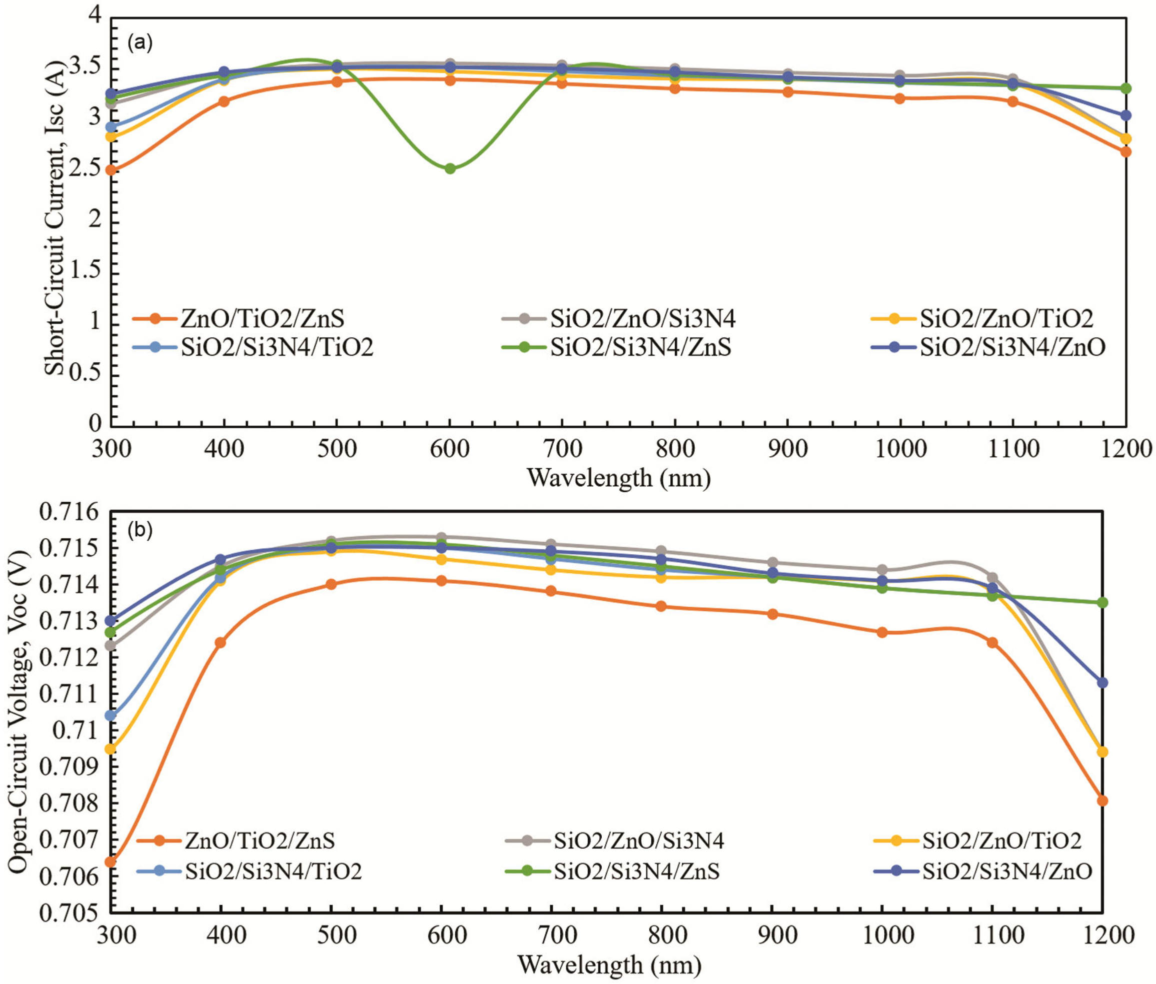


Fig. 5 — Graph of short-circuit current vs wavelength (a) open-circuit voltage vs wavelength and (b) for n-ZnO/p-GaAs with a triple-layer ARC

consistent voltage value to 1,200 nm and achieved the highest value, which is 0.7135 V at 1,200 nm.

By comparing the uncoated and coated n-ZnO/p-GaAs solar cell, it can be determined that applying TLARC can help to improve the function of the solar cell by reducing the reflectance of light and increasing the transmission. The analysis of the cell efficiency and short-circuit current specifically demonstrates the positive impacts of ARC[24]. In addition, optimisation of refractive index and thickness plays a vital role in this simulation in generating good efficiency in specified wavelengths. Also, numerous researchers found that the n-ZnO/p-GaAs solar cell itself is promising good efficiency.

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 Fig. 6 (a). $SiO_2/ZnO/Si_3N_4$, as represented by the green curve, shows a constantly low percentage of reflectance and recorded 0.991 % at a wavelength of 600 nm. This curve shows that $SiO_2/ZnO/Si_3N_4$ can work as a triple-layer ARC with efficiency in a broad-spectrum range. Moreover, Table 3 shows that out of the six schemes, $ZnO/TiO_2/ZnS$ had the lowest efficiency, indicating a high reflectance of the solar cell. $ZnO/TiO_2/ZnS$, shown by the blue curve in Fig. 6 (a), proved to have the highest percentage of reflectance. However, some of the curves occurred lower than the solar cell without using ARC, which indicates the TLARC gives a good chance of reducing the reflectance.

The curve for a few schemes can be seen to have two peaks across the wavelength. A multilayer ARC expands the range of relatively low reflectivity by having numerous reflectivity minima at different wavelengths[25]. This double-peak behaviour indicates poor impedance matching and wavelength-dependent cancellation, which will lead to low EQE. This curve

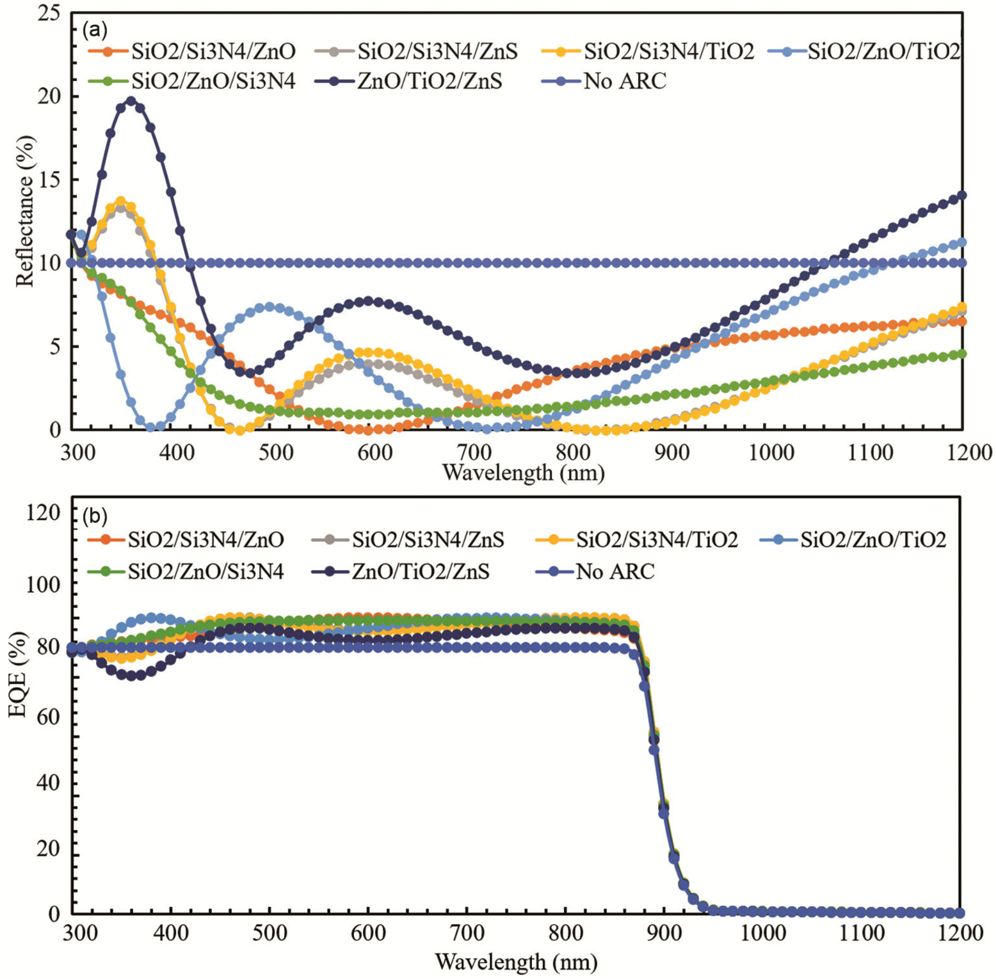


Fig. 6 — (a) The percentage of reflectance, and (b) The external quantum efficiency curves of ZnO/GaAs with uncoated and coated of a various triple-layer ARC

was drawn when the arrangement is not gradual or not aligned; that causes their destructive interference to occur at different wavelengths. In contrast, the curve with the highest efficiency shows only one broad reflectance minimum because the gradient refractive index and thickness are optimally tuned.

Additionally, one crucial technique used to monitor how solar cells behave within a certain wavelength range is the measurement of external quantum efficiency, or EQE[26], as shown in Fig. 6 (b). 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 $SiO_2/ZnO/Si_3N_4$ represented by the green curve, with 19.65% of the efficiency, achieved 99.01 % of EQE at a wavelength of 600 nm. In addition, $SiO_2/Si_3N_4/ZnO$ recorded the highest percentage of EQE with 99.99 %, which is represented by the orange curve, but the efficiency was slightly lower than that of $SiO_2/ZnO/Si_3N_4$.

This seeming paradox is justified by the fact that EQE at all wavelengths is only one of the indicators of overall performance; the sum of all photocurrent times the AM1.5G spectrum and electrical terms determines the final power conversion efficiency. Besides that, the triple-layer ARCs incorporate several conditions of interference because a layer brings with it another optical thickness. Without optimisation of optical thicknesses jointly, there is a risk that the reflectance spectrum will exist in over one minimum and maximum; this effect varies and attracts the EQE curve. It is hoped that the stack of $SiO_2/Si_3N_4/ZnO$ would lead to an even sharper minimum in the destructive interference at a particular wavelength, such that the measured peak EQE would be almost equal to one. Comparatively, it appears that $SiO_2/ZnO/Si_3N_4$ produces a better spectral and uniform antireflection.

5 Conclusion

The effectiveness of ZnO/GaAs solar cells can be enhanced by applying a triple-layer anti-reflective coating (TLARC) on top of the solar cell, thereby reducing reflectance and increasing transmission. To maximise light absorption owing to destructive interference, all of the triplet materials were organised based on their thickness and refractive index at a specified wavelength between 250 nm and 1,200 nm. Out of six schemes, the PC1D simulation generates the results for each wavelength and shows that the $SiO_2/ZnO/Si_3N_4$ as a TLARC successfully increases the efficiency of the solar cell from 17.76 % (uncoated) to 19.65 % at a wavelength of 600 nm. This can be further enhanced by using alternative n-type materials, such as ZnO, as the substrate, and also identifying other appropriate materials that can be used in the ARC. The changes will have the capacity to improve the performance of the device since the triple heterojunction can offer effective efficiency at a wide wavelength.

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