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DESIGN AND ANALYSIS OF THE EFFICIENCY OF ZNO/GAAS AND ZNO/ALGAAS/SI-BASED SOLAR CELLS

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Abstract:

The increasing demand for high efficiency solar cell device has continuous research into advanced semiconductor solar cell and optical enhancement techniques. The ZnO is a well-known and widely used material in photovoltaic (PV) industry due to its low cost, abundant material that offers high electron mobility, excellent transparency and wide bandgap. Although silicon (Si) is commonly paired with ZnO due to its superior performance, previous study has demonstrated that ZnO/GaAs solar cell structure exhibits good optoelectronic properties and higher theoretical conversion efficiency. Besides, the solar cell could be improved by widening the bandgap of the structures by forming a triple-heterojunction solar cell. The ZnO/AlGaAs/Si solar cell was proposed as a new design of the solar cell structures and numerically investigates to analyse the performance and the efficiency of the solar cell. However, research on this device structure remains

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limited compared with conventional solar cell. The device performance was evaluated by using Personal Computer 1-Dimensional (PC1D) simulation under the standard AM1.5G illumination, which 0.1W/cm^2 and one-sun condition. The I_{SC}, V_{OC}, P_{max}, fill factor (FF) and efficiency were used to evaluate the device performance. Compared to the ZnO/GaAs solar cell, the ZnO/AlGaAs/Si increased the electrical properties with I_{SC} from 3.253A to 3.870A, P_{max} from 1.954W to 2.418W, and V_{OC} from 0.7130V to 0.7417V. This increment could increase the efficiency from 17.76% to 21.98%. These results can be attributed by the AlGaAs layer, which improves band alignment and increases photocurrent generation by allowing more incident photons to be transmitted to the silicon absorber due to its larger bandgap.

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Introduction

Nowadays, technology is growing rapidly worldwide, and it also consumes a lot of energy. The use of non-renewable energy for a long time may cause the extinction of the energy source. So, the concept of substituting non-renewable energy with renewable energy was embraced by academicians and society. The renewable energy includes solar, wind, hydropower, geothermal, and many others. This energy will bring many benefits, particularly worldwide. It could increase environmental sustainability, be cleaner (Ahmed et al., 2025), less polluting, have less carbon emission, and be more sustainable. Electricity is frequently produced by using solar energy, a renewable energy source. Therefore, the solar cell was developed to directly (Ji et al., 2022) convert it by employing photovoltaic effect.

In the modern photovoltaic industry, crystalline silicon (Si) is a common component of solar cells. However, researchers discovered that zinc oxide (ZnO) may be thoroughly described to increase solar cell efficiency. ZnO thin film also possesses outstanding optical and electrical properties, but is cheap to produce (Zhang & Tang, 2020). ZnO-based materials exhibit potential for use in photovoltaic, thermal, and piezoelectric energy harvesting applications (Zhou et al., 2017). Also, ZnO is a highly conductive n-type thin layer in the visible range. When concentrated, its broad band energy is approximately 3.37 eV at room temperature (Jin & Tang, 2021) (Bondour et al., 2019). Hence, ZnO/ Si solar cells have been enhanced and are used and sold in the market. But ZnO/GaAs solar cells have some advantages over ZnO/Si heterojunction solar cells compared to the ZnO/Si solar cells (Zhang & Tang, 2020). Gallium arsenide (GaAs) was discovered to exhibit good qualities that make it suitable for use in solar cells. The low direct bandgap (1.42 eV) of GaAs (Papež et al., 2021) makes it a good material

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to be used for diodes and photovoltaic (PV) cells. However, the optimum value of the parameter has not yet been found, and researchers are studying to find the optimum value that can be used.

In this paper, a multi-junction solar cell is chosen because it can overcome the limitation of the efficiency of the single junction. Multi-junction solar cells (MJSCs), which are many layers of semiconductors with various band gaps to absorb more sunlight, are the most advanced technologies in this sector (Ziani et al., 2024). AlGaAs/GaAs/Si tandem solar cells with a surface texture depth and angle of 3µm and 54.4 degrees, respectively, and two-layer ARC have an efficiency of 33.87% (Sathya & Supriya, 2017). According to Dimroth et al., the GaInP/AlGaAs/Si solar cell achieves 34.1% of the efficiency of a triple-heterojunction solar cell, demonstrating higher performance (Dimroth et al., 2020). The combinations of zinc oxide (ZnO) and III-IV semiconductor with silicon (Si) absorbers will be designed and will be simulated in this paper using PC1D software simulation. This is one of the materials, known to be widely used in the PV industry and needed in the market, ZnO. It has a large bandgap with 3.37eV (Jin & Tang, 2021) (Boudour et al., 2019) at room temperature, which is suitable to be used as n-type. ZnO has good optical and electrical properties that can lead to a good device (Zhang & Tang, 2020). Therefore, this paper proposes and numerically investigates both solar cells, ZnO/GaAs and ZnO/AlGaAs/Si to analyse the performance and determine the efficiency by using the PC1D simulation.

Theory And Calculation

The multijunction solar cell enables the use of multiple materials in a series of materials. It has been claimed to be able to extend the wavelength. The cell device stacking is important to improve the photon absorption when it is traveling through the cell device to the absorber. As seen in Figure 1, the ZnO/AlGaAs/Si solar cell had band gap combinations of 3.37/1.817/1.124 eV and was stacked based on its bandgap. High-energy photons were absorbed by placing the highest band gap at the top, while low-energy photons were absorbed by placing the lowest band gap at the bottom. The same method was used to arrange the ZnO/GaAs solar cell.

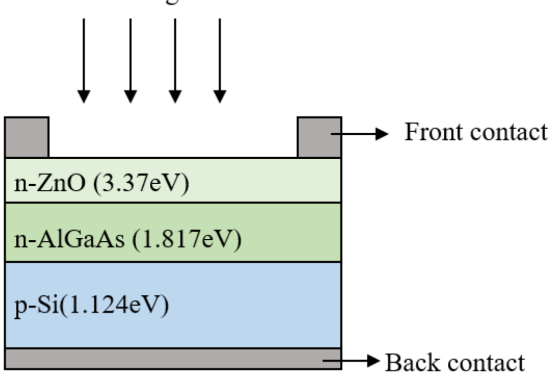

Figure 1: The Schematic Diagram of the ZnO/AlGaAs/Si Solar Cell

Determining the efficiency of a solar cell is important to understand the solar cell's behavior. According to Eq. (1), the electrical parameters, maximum power output (P_{max}), open circuit voltage (V_{OC}), and short circuit current (I_{SC}) are needed to calculate efficiency,

$$\eta = \frac{I_{SC}\ X\ V_{OC}\ X\ FF}{P_{in}} \text{ X } 100\% \quad (1)$$

where P_{in} represents the power input after the light intensity and device area are multiplied, which is $P_{in} = 110cm^2 \, X \, 0.1Wcm^{-2}$. Besides the electrical parameters, the fill factor (FF) also needs to be calculated and mathematically represented by;

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

Optimising the fill factor results in a squarer I-V characteristic curve for the solar PV module (Deb Kumar, 2014).

Simulation Works

The PC1D simulation software has been applied to both of the solar cells. It helps the researcher to predict the behaviour of the solar cell before conducting experiments. In addition, the PC1D simulations offer a range of benefits to the researcher, such as time and cost savings. However, the software is easily accessible and permits user-defined changes because the parameters can be changed simply clicking on the required layers or connections in the schematic of the device (Haug et al., 2013)(Sepeai et al., 2013). Moreover, the PC1D simulation files also contain the list of parameters and materials. Table 1 represents the list of parameters set for the ZnO/GaAs solar cell in the PC1D simulation. Throughout the simulation, both solar cells were continuously configured in the "device" section. The solar cell's area is 110 cm^2 because of its practical size and easily comprehensible features. Besides, the device performance was evaluated under the standard AM1.5G illumination, which 0.1W/cm^2 and one-sun condition. For the double-heterojunction, we have to set up two regions for the substrates. In the first region, the first layer, ZnO, has been set up, which has a number of important parameters. The intrinsic concentration and n-type doping have been set up with 1.1×10^{-9} and 1×10^{18} cm^{-3}, respectively. At the same time, the second layer, GaAs, has been applied in the second region. The intrinsic concentration and p-type doping have been set up with 1.0×10^{9} and 5×10^{15} cm^{-3}, respectively. The thickness of both materials was optimised by Manoua et al. (Manoua et al., 2023) with 0.2µm and 100µm for ZnO and GaAs, respectively. The thickness of the substrates is required to be optimal as it can affect the solar cell's efficiency (Roslan et al., 2025).

Table 1: The Parameters of ZnO/GaAs Solar Cell Via PC1D Modelling

Parameter	Value	References
DEVICE		
Area of The Device	110 cm^2	(Jamaluddin et al., 2024)
Surface texturization	None	
Surface charge	None	
Reflectivity of the exterior front surface	10%	(Jamaluddin et al., 2024)
Reflectivity of the exterior rear surface	None	
Optical reflectivity inside	None	
REGION 1		
Thickness	0.2µm	(Manoua et al., 2023)
Material	ZnO	

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Dielectric constant	7.9	
Bandgap	3.289 eV	
Concentration of intrinsic carriers at 300K	1.1×10^{-9}	
Refractive index	2.00	
Background doping in the n-type	1×10^{18} cm^{-3}	
Bulk recombination time, $\tau_n = \tau_p$	1000µs	
REGION 2		
Thickness	100µm	(Manoua et al., 2023)
Material	GaAs	
Dielectric constant	13.18	
Band gap energy	1.424 eV	
Intrinsic concentration at 300 K	1×10^{9}	
Refractive index	3.66	
Background doping in the p-type	5×10^{15} cm^{-3}	(Jin & Tang, 2021)(Kao et al., 2019)
Bulk recombination time, $\tau_n = \tau_p$	1000µs	
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		

Additionally, the PC1D simulation program was also applied to the ZnO/AlGaAs/Si solar cell. Parameters needed for the PC1D simulation setup can be seen in Table 2. For triple-heterojunction solar cells, the placement of three regions of materials has been done according to their name as it contains three different materials. The substrate materials were properly placed together depending on the region they belong to, with ZnO material being placed at "REGION 1" while the other two, AlGaAs and Si materials, were placed in regions 2 and 3, respectively. Materials for the n-type semiconductor need to have thinness more than those for the p-type semiconductor to increase absorption of light and electron-hole pair generation in the material. As a result, the thickness of ZnO, AlGaAs, and Si materials was 0.1µm, 0.6µm, and 300µm, respectively. In addition to the thickness, the doping concentration also played a significant role in improving the solar cell efficiency. The doping concentrations for the n-type materials ZnO and AlGaAs were 1×10^{19} cm^{-3} and 1×10^{17} cm^{-3}, respectively (Naim et al., 2022), however, indicated that the doping for Si was 1.1×10^{17} cm^{-3}. The bulk lifetime of recombination was set to 1000µs for all substrates. Other parameters were taken from the PC1D file.

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Table 2: The Parameters of ZnO/AlGaAs/Si Solar Cell Via PC1D Modelling

Parameter	Value	References
DEVICE		
Device area	110cm^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	0.1µm	(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	1.1x10^{-9}	
Refractive index	2.00	
N-type background doping	1x10^{19} cm^{-3}	(Chandran et al., 2023)
Bulk recombination, $\tau_n = \tau_p$	1000µs	
Front-surface recombination, $S_n = S_p$	Enable	
REGION 2		
Thickness	0.6µm	
Material	AlGaAs	
Dielectric constant	12.24	
Band gap	1.817eV	
Intrinsic concentration at 300K	1754	
Refractive index	3.81	
N-type background doping	1x10^{17} cm^{-3}	
Bulk recombination, $\tau_n = \tau_p$	1000µs	
Front-surface recombination, $S_n = S_p$	70000	
REGION 3		
Thickness	300µm	
Material	Si	
Dielectric constant	11.9	
Band gap	1.124eV	
Intrinsic concentration at 300K	1x10^{10}	
Refractive index	3.48	
P-type background doping	1.1x10^{17} cm^{-3}	(Naim et al., 2022)
Bulk recombination, $\tau_n = \tau_p$	1000µs	
Front-surface recombination, $S_n = S_p$	Enable	
EXCITATION		
Excitation from	one-sun	
Excitation mode	Transient,16 timesteps	
Temperature	25℃	
Base circuit	-0.8 to 0.8 V	
Collector circuit	Zero	
Primary light source	Enabled	

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

The excitation mode for both devices was set up with the “ONE-SUN” mode, as it will provide P_{max}, V_{OC}, and I_{SC} as a result which are needed to determine the efficiency of a solar cell. The intensity was used to calculate the power input using an equation. To observe and collect the data on the quantum efficiency, the excitation mode will be changed to “SCAN-QE” mode. Other parameters will be set up by default.

Results And Discussions

The result of the bare ZnO/GaAs is shown in Table 3. The photovoltaic parameters for the ZnO/GaAs solar cell are 3.253A, 1.954W, and 0.7130V for I_{SC}, P_{max}, and V_{OC} respectively, which can determine the efficiency of the device as 17.76%. In contrast, Debarli (Debarli, 2022) discovered that the reference n-ZnO/p-GaAs solar cell had an efficiency of up to 8.31% in the experimental study. In addition, Manoua et al. (Manoua et al., 2023) managed to obtain an efficiency of 21.21% with Atlas Silvaco software. The small variation in efficiency is because of different software. Kowsar et al. (Kowsar et al., 2025) discussed several software used in solar cell simulation methods, which highlights the different modelling and computational methods used in different simulators, which may lead to different expected solar cell performance.

Table 3: Electrical Characteristics of ZnO/GaAs-based 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

Additionally, under the same conditions, the ZnO/AlGaAs/Si solar cell's efficiency was examined, which is 21.98%. The device’s electrical properties are displayed in Table 4. It was found that the values for I_{SC}, P_{max}, and V_{OC} were, respectively, 3.870A, 2.418W, and 0.7417V. The AlGaAs/Si solar cell outperformed the III-V/Si multijunction solar cells by 12.7%, according to experiments conducted by Xiong et al. (2018). Additionally, Roy et al. (2023) used PC1D modelling with a surface texture depth of 3μm to obtain an efficiency of 22.3% for AlGaAs/Si solar cells. Jamaluddin et al. increased a ZnO/Si solar cell's efficiency to 22.27% in the absence of an anti-reflective coating (2024). The results show that the substrate materials have promising applications in dual junction solar cells.

Dimroth et al. (Dimroth et al., 2020) and Sathya & Supriya (Sathya & Supriya, 2017) have successfully obtained a high efficiency of more than 30%. The key to the success of high efficiency improvement in the solar cell is the use of the ARC along with the surface texturing, which can minimise the reflectance and indirectly maximise the efficiency of the solar cell. Although it is anticipated that surface texturing with multi-layer anti-reflection coating may enhance the optical performance, in a few reviews and experimental works, it has been shown

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that the additional etching, masking, and coating processes are more complicated than planar or uncoupled processes, and have low yield and high cost (Kim et al., 2020)(Law et al., 2023).

Table 4: Data of PC1D Simulation ZnO/AlGaAs/Si 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 (%)
3.870	2.418	0.7417	0.8424	21.98

The difference in results generated by the PC1D simulation shows that the triple-heterojunction is more efficient than the dual-heterojunction solar cell. This device can more effectively capture some portions of the solar spectrum by adding junctions, each of which is designed around a particular bandgap (Raisa et al., 2025). By properly matching the current and reducing recombination loss, such a setup can increase the theoretical maximum photocurrent and open-circuit voltage.

Figure 2 illustrates how the solar cell performs electrically in various environmental settings (Olayiwola et al., 2024). The solar cells based on ZnO/AlGaAs/Si demonstrate higher current than the ZnO/GaAs-based solar cell. According to Eq. (1), the efficiency is proportional to current and voltage. Also, as shown in the graph of ZnO/GaAs, the current appeared to be between 3.10A and 3.20A, and the ZnO/AlGaAs/Si reached 3.870A at zero voltage (V=0). As the voltage increased, the current for both devices was constant until a sudden decrease that occurred at a voltage between 0.60V and 0.70V. The change from the diode to power generation is represented by the drop at V_{OC}.

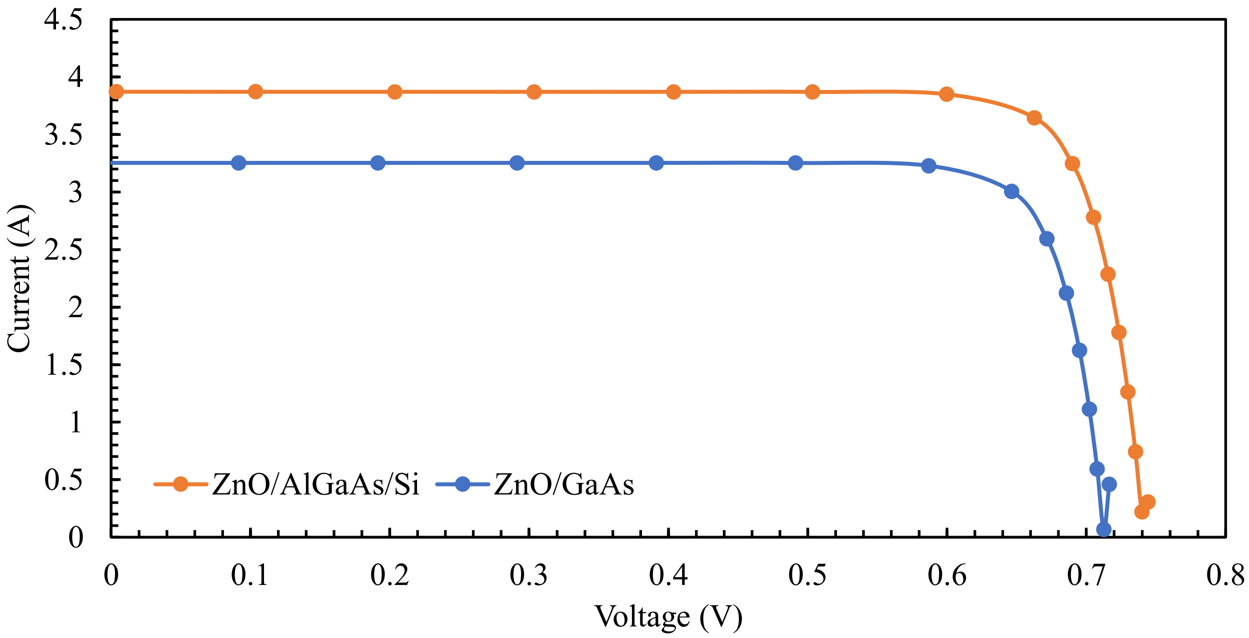

Figure 2: The Electrical Characteristics of Different Solar Cell Devices

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Additionally, under the "SCAN-QE" excitation mode at various wavelengths, the PC1D simulation provides the external quantum efficiency (EQE). According to James et al. (2024), the number of carriers produced within the solar cell divided by the number of photons of necessary energy that are incident upon the solar cell from the outside is known as the EQE. Figure 3 illustrates that at short wavelengths, the ZnO/GaAs solar cell has a high proportion of EQE, but the ZnO/AlGaAs/Si solar cell has a low percentage. This is because the bandgap of the absorber could influence the absorption of photons at a particular wavelength. At the ZnO/GaAs solar cell, GaAs as the absorber material with a bandgap 1.424eV tend to have a high EQE percentage at short wavelengths. Long-wavelength photons are more effectively collected by the Si at the rear of the ZnO/AlGaAs/Si solar cell (Kao et al., 2019). However, at a wavelength of 1200 nm, both devices exhibit an EQE of 0%.

Due mostly to greater optical and electrical losses, the ZnO/AlGaAs/Si solar cell has a lower overall EQE than the ZnO/GaAs device. More parasitic absorption, reflection, and interface recombination result from photons having to pass through numerous layers of ZnO, AlGaAs, and Si before they can reach the Si absorber in ZnO/AlGaAs/Si. On the other hand, incident light with a high absorption coefficient and fewer heterointerfaces in the GaAs are eliminated by the ZnO/GaAs structure, which permits more effective carrier generation and collection and, thus, a higher EQE. Despite the direct bandgap of GaAs, the indirect bandgap of Si also helps in reducing absorption at or below the visible wavelengths. Even while ZnO/AlGaAs/Si has a better efficiency than ZnO/GaAs, this is due to its superior electrical performance rather than EQE production.

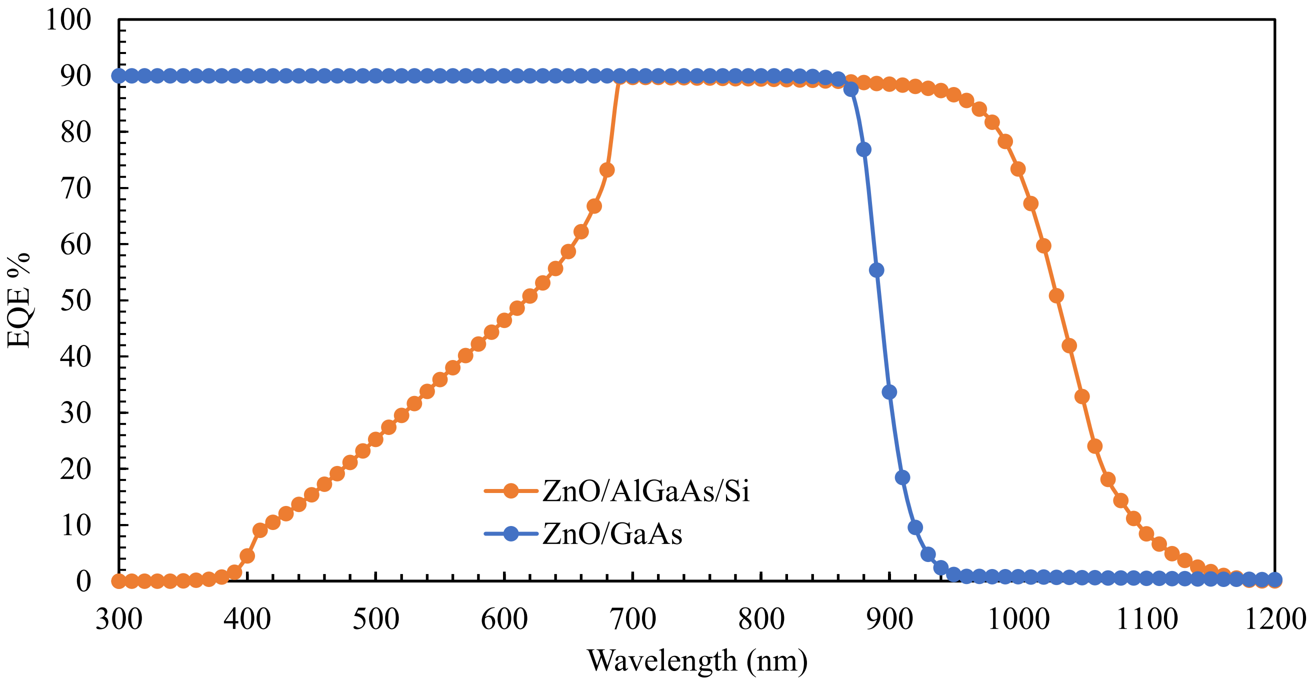

Figure 3: The EQE Curve for ZnO/GaAs and ZnO/AlGaAs/Si-Based Solar Cells

Conclusion

Solar cells based on ZnO/GaAs and ZnO/AlGaAs/Si have already demonstrated the good performance of the electrical parameters and efficiency. The ZnO/GaAs solar cell's acquired photovoltaic characteristics are 3.253A, 1.954W, and 0.7130V for I_{SC}, P_{max}, and V_{OC} respectively, meanwhile, the ZnO/AlGaAs/Si solar cell produced I_{SC} of 3.870A, P_{max} of

2.418W, and V_{OC} of 0.7417V. The ZnO/AlGaAs/Si solar cell successful outperform the ZnO/GaAs with an efficiency of 21.98% and 17.76%, respectively. Introducing methods that can boost efficiency, like implementing an anti-reflective coating and texturing the surface to lower reflectance, can lead to further improvement. In addition, an improvement is required to attain optimal performance when comparing the ZnO/AlGaAs/Si solar cell results with earlier research.

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