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Numerical simulation and characterization of solar cells based on GaAs/p-Si: influence on thickness and doping concentration dependence

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ABSTRACT

Rapid urbanization and industrialization have had a substantial impact on the global growth in energy consumption over the last two decades. Solar energy is seen as an essential energy source capable of meeting this demand in a cost-effective and ecologically normal manner. In this study, we overcome this gap by using numerical simulations and experimental characterizations to look into the influence of thickness and doping concentration on the photovoltaic performance of GaAs/p-Si solar power cells. Our objective is to determine optimal design parameters that optimize power conversion efficiency while considering practical restrictions like manufacturability and cost-effectiveness. The most effective solar cells, which can be used to make a very efficient model, have an emitter thickness and base thickness of 0.1 µm (doping = 1×10^{15} cm^{-3}) and 100 µm (doping = 1×10^{17} cm^{-3}) with an efficiency of 24.02% and 24.77%. To further improve the efficiency and expansion of GaAs/p-Si solar cells, future research may investigate advanced methods and combine multiple designs with cutting-edge materials.

Keywords: *GaAs, Silicon, Solar cells, PC1D, Efficiency*

1. INTRODUCTION

The population of the earth has been exposed to challenging environmental issues and a severe energy crisis since the start of the twenty-first century. Clean energy sources come in various forms, including solar, hydro, wind, biomass, thermal, and waves. Malaysia's potential for biomass, solar, and hydro is considerable. Solar cells are an offering and a possible crucial technological advance, representing the next phase of renewable energy sources for human society [1]. Solar panels, also referred to as photovoltaic cells, are semiconductor gadgets that transform sunlight into electricity. They are essential for producing energy.

GaAs is known as a bandgap semiconductor, with an energy of 1.42 eV, making it a popular choice for solar cells. GaAs-based solar energy cells have been widely adopted among Si-based semiconductors for reasons such as a direct bandgap, better carrier mobility than silicon, capacity to function in a larger temperature variety than silicon, and a greater absorbing efficiency over silicon [2]. GaAs consists of several different band structure properties and is recognized with greater accuracy than any other semiconductor [3]. There are also other papers that studied about GaAs properties to prove the direct band gap for photonic applications [4] and nanotubes [5]. Additionally, GaAs semiconductors have bandgap values that align well with the optimal absorption range for technology. These features, combined with their attributes, have resulted in GaAs being widely utilized in various fields such as optoelectronics, microwave devices, and power electronics. In summary, GaAs semiconductors provide a foundation for creating high-performance devices in technological sectors [6]. Silicon is easily accessible and has infinite elements and some electric insulators that can be used to make solar cell panels. There are actually a pair of semiconductors: intrinsic and supply. Silicon is a semiconductor composed of extrinsic metals. A pure substance is an innate semiconductor with no contaminants added to enhance conductance.

The window layer, typically composed of n-type GaAs, plays a crucial role in reducing recombination rates and improving efficiency. By adjusting the thickness of this layer, researchers can control the light absorption and carrier generation within the solar cell [7]. The emitter layer, usually made of n-type GaAs, is responsible for facilitating the extraction of photo-generated carriers. These affect the efficiency of carrier collection and electron-hole pair separation within the solar cell. The base layer, typically p-type Si, serves as the region where electron-hole pairs are generated and separated. The back surface field (BSF) Layer, composed of p-type Si, helps reduce surface recombination velocity and enhance the overall efficiency of the solar cell devices [7].

Doping concentration involves deliberately introducing impurities into a semiconductor material to alter its electrical characteristics. For solar cells, doping concentration is an important component in shaping the device performance as well as efficiency [8].

Optimising the doping concentration in the base layer (p-type Si) is crucial for maximising the effectiveness and performance of the solar cell devices [7]. The influence of doping concentration in the window layer and absorber layer on solar cell efficiency also affected the productivity and efficacy of the cells. In 2020, Devendra *et al.* [6] utilised PC1D software to model AlGaAs/GaAs solar cells with four layers. The structure included n-AlGaAs as the window layer, n-GaAs as the emitter layer, p-GaAs as the base layer, and p-AlGaAs as the BFS layer. The experiment focused on analysing the implications of base layer doping concentration with thickness variations. Optimal results were achieved with a base layer thickness of 2.2 µm and a doping concentration of 1×10^{16} cm^{-3}, resulting in a peak conversion efficiency of 31.1%.

Any simulated program needs to keep up with new developments in research using experiments, models of theory, and technological device settings for work. PC1D is the most common simulation programme in the photoelectric field. PC1D has been referenced at least 20 times in scientific publications in the last year [9]. As a result, the program's rapid development must be maintained. A journal article has already discussed the new free-carrier absorption model and its importance for the spectral analysis of cells [10]. The research also shows that increasing the light-trapping of near bandgap wavelengths is much less advantageous than originally anticipated, which was not covered in that paper. Several critical device parameters can be found by comparing a computed IQE curve to an experimental one. Performing such a match in previous PC1D editions was time-consuming. Version 5 enables rapid comparison by showing research information along with simulated outcomes on one single graph within PC1D. To match the experimental findings at near bandgap wavelengths, the PC1D model must have a higher value for the rear optical reflectance and a lower front-surface recombination velocity at the blue end of the spectrum [10].

2. METHODOLOGY

This section describes the simulation carried out by the PC1D program. Table 1 provides an overview of the initial set of parameters that were used in the simulation before moving to a new set. In this study, the main parameter was p-Si/n-GaAs solar cells, which led to the identification of the most effective simulation of solar cells. This research altered thickness and doping concentration.

Figure 1 is a diagram of the GaAs/p-Si solar cell. In this work, the base layer of the solar cell was made of p-Si, while the emitter layer was made of n-GaAs. The area for the solar cell device has been set in Table 1, which is 10 cm^2. The bandgaps of GaAs and Si, which are 1.424 eV and 1.124 eV, respectively, have been used in this simulation. The Si substrate thickness is 160 µm, and for the GaAs substrate, it is 0.1 µm. For the doping concentration, the n-region and p-region have been set to 1×10^{16} cm^{-3} for both regions. For more information about the data input for the PC1D, see Table 1.

The files used in this simulation for excitation mode are "one-sun.exc". This is because the investigation must acquire the short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power output values (P_{max}). Belarbi *et al.* [11] reported that "one-sun.exc" restored the values of I_{sc}, V_{oc}, and P_{max}.

A solar cell's P_{max}, V_{oc}, and I_{sc} are all measures of how well it performs. The fill factor and efficiency are computed in the study using a certain equation. Equation (1) gives the fill factor's expression. The solar cell's efficiency as in Equation (2) may then be estimated using the fill factor [12].

$$FF = P_{mp}/I_{sc}V_{oc} \quad (1)$$

$$\eta = I_{sc}V_{oc}FF/P_{in} \quad (2)$$

$$P_{max} = \text{Percentage } \eta \times P_{in} \quad (3)$$

$$P_{in} = \text{Standard Insolation} \times \text{Area of Panel} \quad (4)$$

$$\text{Standard Insolation} = 1\ \text{kW/m}^2 \quad (5)$$

Table 1. The simulated structure of the GaAs/p-Si based solar cell

Parameter	Value	
Device Area (cm^2)	10	
Region (layer)	n-GaAs	p-Si
Thickness (µm)	0.1	160
Band gap (eV)	1.424	1.124
Intrinsic conc. at 300K (cm^{-3})	2.59×10^6	1.00×10^{10}
Background doping (cm^{-3})	1.00×10^{16}	1.00×10^{16}
Bulk recombination lifetime (µs)	0.4	1000
Recombination velocity (front surface) (µs)	70,000	-
Recombination velocity (back surface) (µs)	-	-
Excitation mode	One-sun (transient; 16 timesteps)	
Spectrum	AM1.5G	
Intensity (W/cm^2)	0.1	
Temperature (°C)	25	

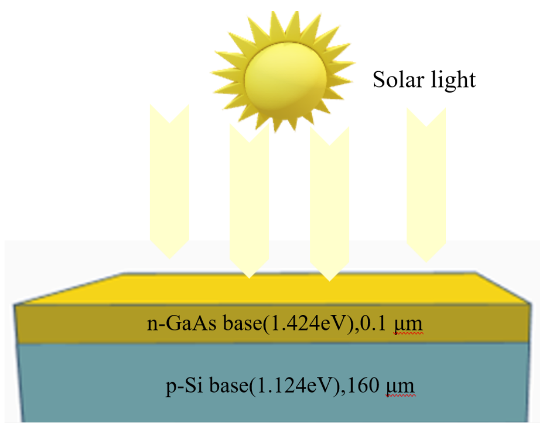

Figure 1. A diagram of GaAs/p-Si based solar cell

3. RESULTS AND DISCUSSION

In this part, the result of a simulation of a solar cell based on GaAs/p-Si using PC1D software has been discussed. The efficiency of the p-Si/n-GaAs solar cell can be obtained by adjusting the thickness and doping concentration parameters. From the PC1D software, the results of I_{sc}, V_{oc} and P_{max} can demonstrate the outcomes of the p-Si/n-GaAs solar cell panels by finding the efficiency and the IV characteristic. To obtain the most efficient solar cell model, the parameters were changed and the results from the simulation were compared. Hence, using the results, one may create a solar cell model with high efficiency based on the values chosen for each parameter.

Figure 2 shows the IV characteristic graph of the thickness of n-GaAs region, which is the GaAs layer. The altering of thickness starts from 0.1 µm until 2 µm. From this graph it is proven that the thickness of the n-GaAs region will affect the efficiency of the solar cell. The center of the curve matches the thinnest layer of GaAs (0.1 µm).

Table 2 shows the decrease in efficiency with the increasing thickness of GaAs from 24.02% at 0.1 µm to 14.02% at 2 µm. This can be proven by the fact that the thickness influenced the solar cell efficiency. Once the result value received from locked at the I_{sc} was increasing in the range of the V_{oc}, thus the efficiency of the solar cell also grows, which is directly linked to the accelerating rate of power absorbed [13]. Increasing layer thickness resulted in conversely decreasing outcomes and eventually decreasing efficiency [14]. The short-circuit current of a solar cell is determined by its area, incident light spectrum, photon count, and material parameters [15]. Short circuit current falls significantly when carriers recombine. Open circuit voltage is the maximum voltage generated through a photovoltaic cell once there is no current flowing through it [16]. Hence, as shown in Figure 3, the most efficient of GaAs/p-Si was at 0.1 µm at 24.02% efficiency with V_{oc} = 0.7416 V, I_{sc} = 0.3886 A, P_{max} = 0.2402 W and FF = 0.83345.

The effect of silicon thickness upon the GaAs/p-Si solar cell structure has been explained. Figure 4 depicts how thicknesses at the substrate made from silicon have an effect on the effectiveness of the GaAs/p-Si photovoltaic device.

The findings indicate the amount of thickness of the silicon matter in GaAs/p-Si solar energy cells could affect the effectiveness of them. Figure 4 shows that a GaAs substrate thickness of 150 µm results in the best current reading, while a thickness of 30 µm yields the lowest current value. The outcome of increased layer thickness in the p-region was gradually rises in efficiency [17]. A restriction in this variable has been identified using PC1D. As the p-region thicknesses got closer to 300 µm, energy turned it down. In Table 3, it is shown that increasing the thickness of the p-region from 30 µm to 150 µm also increases the I_{sc} due to the rise in the number of charge carriers [16]. Thus, recombination of charge carriers also increased and affected the value of V_{oc} by decreasing it from 0.7767 V to 0.7432 V. Hence, as shown in Figure 5, the most efficient of GaAs/p-Si was at 150 µm at 24.01% efficiency with V_{oc} = 0.7432 V, I_{sc} = 0.3873 A, P_{max} = 0.2401 W and FF = 0.83414.

Figure 6 shows the effect of variety doping concentration on GaAs/p-Si solar cells. To find the optimal efficiency for a solar cell, doping concentration plays an important role in efficiency estimates [13]. Figure 6 shows the outcome of the effect of doping concentration at the GaAs substrate from 1×10^{15} cm^{-3} to 1×10^{20} cm^{-3}, respectively.

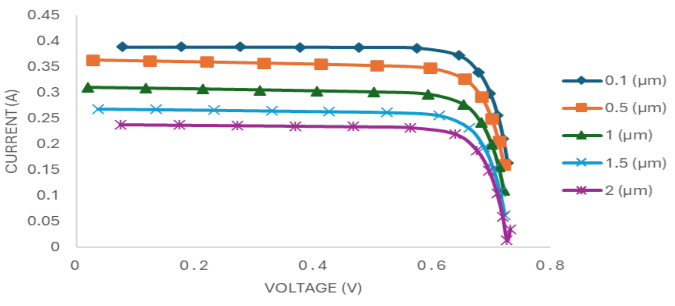

Figure 2. Variation of I_{sc} and V_{oc} with thickness of n-region

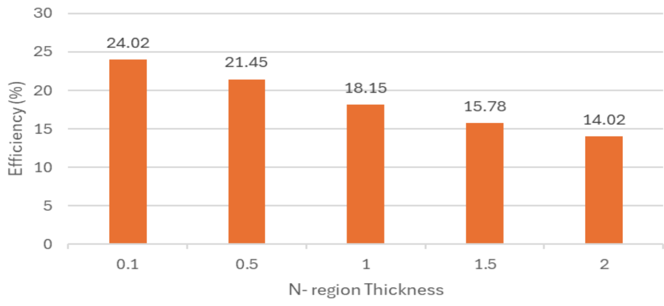

Figure 3. Efficiency with n-region thickness

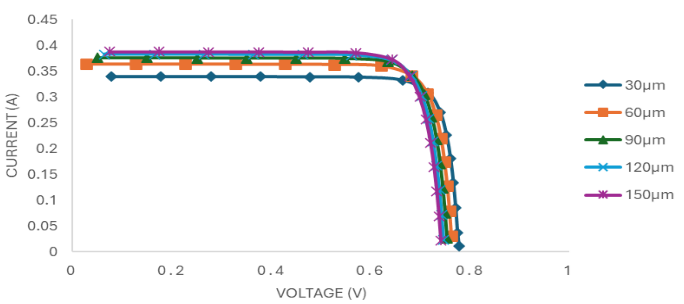

Figure 4. I_{sc} and V_{oc} differ with the thickness of the p-region

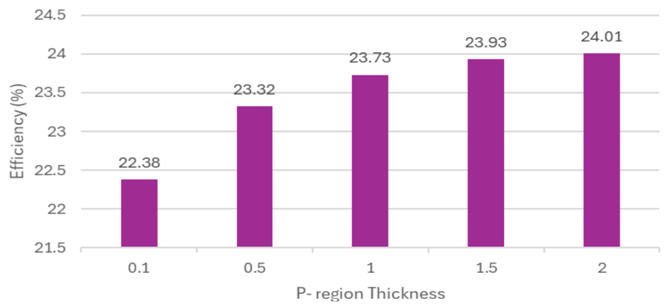

Figure 5. Efficiency with p-region thickness

Table 2. Different thicknesses of GaAs/p-Si solar cells in the n-region

N-region thickness (µm)	I_{SC} (A)	V_{OC} (V)	P_{max} (W)	Fill Factor	Efficiency (%)
0.1	0.3886	0.7416	0.2402	0.8335	24.02
0.5	0.3643	0.7387	0.2145	0.7971	21.45
1.0	0.3101	0.7343	0.1815	0.7971	18.15
1.5	0.2686	0.7305	0.1578	0.8042	15.78
2.0	0.2382	0.7272	0.1402	0.8094	14.02

Table 3. Different thicknesses of GaAs/p-Si solar cells in the p-region

P-region thickness (µm)	I_{SC} (A)	V_{OC} (V)	P_{max} (W)	Fill Factor	Efficiency (%)
30	0.3392	0.7767	0.2238	0.8495	22.38
60	0.3636	0.7635	0.2332	0.8400	23.32
90	0.3752	0.7549	0.2373	0.8378	23.73
120	0.3823	07485	0.2393	0.8363	23.93
150	0.3873	0.7432	0.2401	0.8341	24.01

The result of the different doping concentrations from 1×10^{15} cm^{-3} to 1×10^{16} cm^{-3} shows the same efficiency, which is 24.02%. As shown in Table 4 and Figure 7, as the doping concentration increases, the efficiency of the solar cell decreases.

High levels of doping concentration can impact the transport characteristics of carriers within the solar cell. Elevated doping levels introduce additional defects and impurities into the material, resulting in heightened carrier scattering and diminished carrier mobility [18]. Therefore, the most optimal doping concentration that can give the best efficiency is between 1×10^{15} cm^{-3} and 1×10^{16} cm^{-3}.

In this study, the varying doping concentrations over the p-region of the GaAs/p-Si solar cell outcome have been shown in Figure 8. The different doping concentrations that have been used in this study are from 1×10^{15} cm^{-3} and 1×10^{20} cm^{-3}. The GaAs/p-Si solar cell achieves its greatest effectiveness of 25.22% with a doping concentration of 1×10^{17} cm^{-3}. The lowest efficiency that is obtained from Figure 9 is 1×10^{20} cm^{-3}. Table 5 indicates the effect of multiple doping concentrations in the p-region on solar panel performance.

Excessive doping concentration affects solar power cells' conversion rate by decreasing light transmission, absorption, and greater recombination rates [14]. Elevated doping concentrations can worsen surface recombination effects, where charge carriers are lost at the semiconductor material's surface. Higher doping levels can elevate surface recombination velocities, thereby impeding the collection of generated carriers and diminishing the efficiency of the solar cell [16]. As a result, the most optimal doping concentration that can give the best efficiency is 1×10^{17} cm^{-3} as shown in Figure 9.

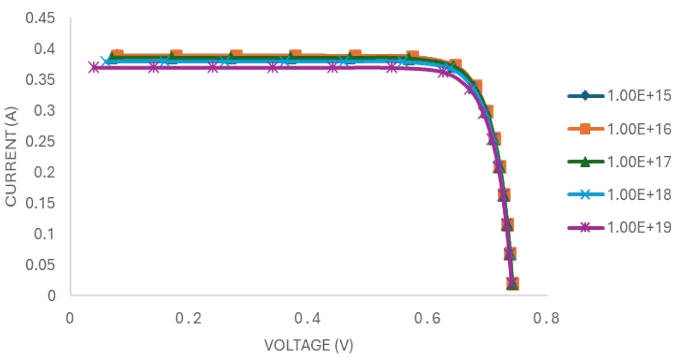

Figure 6. Variation of I_{sc} and V_{oc} with doping concentration of n-region

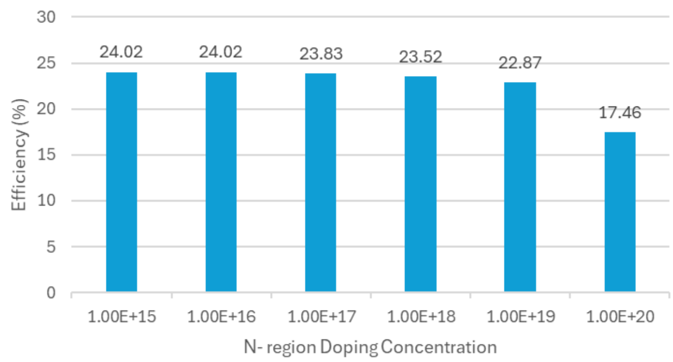

Figure 7. Efficiency with n-region doping concentration

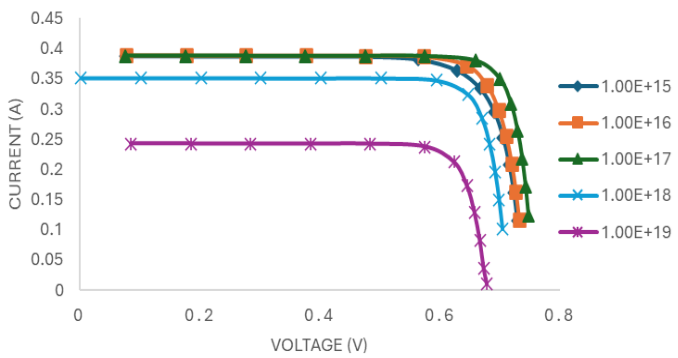

Figure 8. Variation of I_{sc} and V_{oc} with doping concentration of n-region

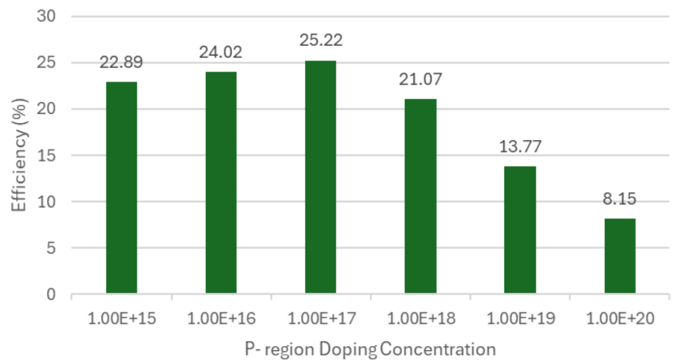

Figure 9. Efficiency with p-region doping concentration

Table 4. Result on different doping concentration at n-region GaAs/p-Si solar cell

N-region doping conc. (cm^{-3})	I_{SC} (A)	V_{OC} (V)	P_{max} (W)	Fill Factor	Efficiency (%)
1×10^{15}	0.3887	0.7414	0.2402	0.83350	24.02
1×10^{16}	0.3886	0.7416	0.2402	0.83349	24.02
1×10^{17}	0.3848	0.7414	0.2383	0.83529	23.83
1×10^{18}	0.3792	0.7411	0.2352	0.83694	23.52
1×10^{19}	0.3694	0.7404	0.2287	0.83619	22.87
1×10^{20}	0.2859	0.7333	0.1746	0.83281	17.46

Table 5. Result on different doping concentration at p-region GaAs/p-Si solar cell

P-region doping conc. (cm^{-3})	I_{SC} (A)	V_{OC} (V)	P_{max} (W)	Fill Factor	Efficiency (%)
1×10^{15}	0.3876	0.7386	0.2289	0.7996	22.89
1×10^{16}	0.3886	0.7416	0.2402	0.8335	24.02
1×10^{17}	0.3880	0.7554	0.2522	0.8605	25.22
1×10^{18}	0.3509	0.7127	0.2107	0.8425	21.07
1×10^{19}	0.2424	0.6772	0.1377	0.8389	13.77
1×10^{20}	0.1544	0.6373	0.0815	0.8283	8.15

4. CONCLUSION

In conclusion, the optimization of the GaAs/p-Si solar cell was successfully simulated by using numerical simulation PC1D simulation. The optimal efficiency has been achieved as the thickness of the GaAs substrate and the silicon substrate increases to 0.1 µm and 150 µm, respectively. Moreover, when the doping concentration of the p-region and n-region increase, the efficiency of the solar cell decreases. The optimal doping concentrations for the two regions are 1×10^{17} cm^{-3} for p-region and 1×10^{16} cm^{-3} for n-region.

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