SIMULATION ON THE EFFECT OF N-LAYER THIN FILM THICKNESS ON EFFICIENCY OF SILICON-BASED SOLAR CELL USING SILVACO TCAD TOOLS

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Abstract – **Types of materials uses and solar cell structures affect the efficiency of solar cell. The effect of n-layer thin film thickness on efficiency of the solar cell was investigated by using Silvaco physically-based device simulator, ATHENA and ATLAS to model the effects of n-layer thin film thickness on solar cell output characteristics. Increase the n-layer thin film thickness will increase the short circuit current, spectral response as well the efficiency of solar cell. The n-layer of solar cell should be thin enough to increase the life time of minority carrier. The resulting output characteristics of the virtual solar cell, illuminated with a simulated Air Mass Zero (AM0) solar spectrum, were compared to published experimental measurements for silicon-based solar cells of the same dimensions. It is found that the efficiency of virtual silicon solar cell is within the efficiency range of published experimental which is from 15% to 24%. The simulation result shows that n-GaAs/p-Si solar cell has performed the highest efficiency with 15.87% at the thickness of n-layer is 0.5µm. The result of this research has proven that the use of silicon as solar cell substrate has achieved high efficiency energy conversion.**

Keywords: Silicon (Si), Atlas, Athena, band gap (Eg), short circuit current, open circuit voltage, and Air Mass Zero (AM0).

I. INTRODUCTION

The present growing interest in photovoltaic conversion is a consequence of the concern to identify future sources of energy that will be inexpensive as well as consistent with the maintenance and safety of the environment. Traditional sources of energy-fossil fuels such as coal, petroleum, and natural gas are running out as presently foreseeable rates of use are projected into the near future [1].

One of the most important problems to be solved in solar cell design is efficiency. Rapid advances in material science now make it possible for new vistas in solar energy conversions system. The uses of certain semiconductor materials such as Silicon (Si) and Gallium Arsenide (GaAs) as solar cell material able to give higher efficiency of energy conversion. Several factors that lead silicon to be widely used in constructing solar cells are because of cost effectiveness, easy in getting silicon source, and also due to silicon stability.

A. OBJECTIVES

The main objectives of this project are to study the effect of solar cell efficiency when varying the thickness of n-layer and to study the effect and characteristic of solar cell when using different n-layer material by focus on the silicon substrate doped with n-type materials in order to get high efficiency and replace the uses of GaAs as a substrate for solar cell.

B. METHODOLOGY

The scope of this project is to simulate a silicon-based solar cell to predict their efficiencies by using Silvaco TCAD frameworks Athena and Atlas. This tool is very helpful to verify solar cell properties such as efficiency, open circuit voltage and short circuit current when illuminating with AM0 solar spectrum before solar cell fabrication process is started. Input parameter, structure, type of material and the technology uses to perform fabrication process of solar cell are done in Athena framework.

The resulting output is a complete structure (cross section) of solar cells. The properties of solar cell such as the photogeneration rate, electron density and recombination rate can be measured from the output structure. The complete solar cell structure which view in Tonyplot diagram will be illuminated with AM0 solar simulator in Atlas framework. After completing beaming process in this framework, the resulted current-voltage (I-V) characteristic will be used to calculate the efficiency of solar cells.

C. Solar Cell Basics

Solar cell is a device that converts the energy or photons from sun into electrical energy. The energy of these photons depends on the light wavelengths. The formation of the space charge region in a p-n junction and the associated electrical field are vital to the operation of solar cells. A simplest form of solar cell is a p-n junction in which the surface of solar cell must be of n-layer where the illumination process occurs [2] with contacts on both ends to extract current. As light enters the solar cell, photons will impart energy to the electrons within the space charge region [3]. Those photons with energy greater than Eg will free an electron and create a hole, known as an electron-hole pair (EHP). EHP's created in the space charge region will be immediately separated by the electric field within the region [4]. The electron will drift towards the negative end of the electric field while the hole will drift towards the positive end as shown in figure 1. When the hole reaches the p-type region, it will make this region positive. Likewise, the electron will make the n-type region negative [3]. An open circuit voltage is then created between the positive p-side and the negative n-side. EHP's created by photons outside the space charge region of the solar cell will diffuse based on carrier concentrations as there is no electric field with which to interact. The minority carrier of an EHP created within close proximity to the space charge region can travel the distance to the space charge region and be swept by the electric field adding to the potential charge in the solar cell [4]. The distance, called the minority carrier diffusion length, is the mean distance an electron, Le, or hole, Lh, can travel before recombining with an opposite charge [3]. If an EHP is created outside the minority carrier diffusion length, the minority carrier will recombine with an opposite charge and will not add to the accumulation of potential charge in the cell [4]. The n-layer are design very narrow typically 0.2µm or less, in order to make most of the photons are absorbed within the depletion region, and within the neutral p-side and photogenerate EHPs in this region [5]. The electron diffusion length is longer than hole diffusion length, because of this reason, the n-side will be illuminating region in order to make minority carrier diffusion length, Le as long as possible [5]. Another reason for design very narrow n-layer is to make longer minority carrier diffusion length, Lh in order to balance the photogenerated EHP due to the surface recombination.

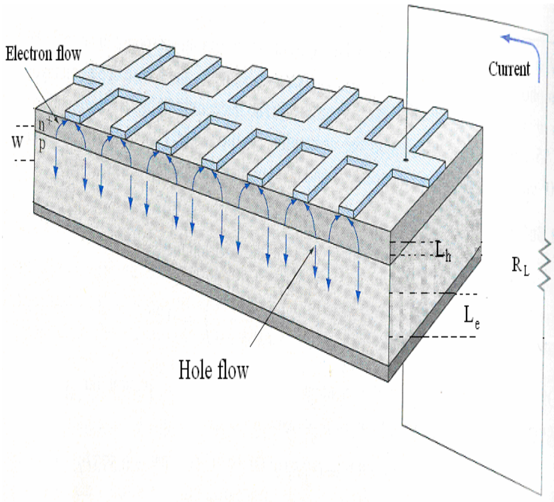

Figure 1: A solar cell with integrated circuits [2].

D. Performance of Solar Cell

Solar cell output characteristics can vary depending on cell configurations, types of material used, doping levels, and region thicknesses [7]. In order to compare various cells, several standard parameters have been established. The behaviour of a solar cell can be characterized using three parameter, the open circuit Voc, the short circuit current Isc and the fill factor, FF as shown in figure 2 [7,6].

The open circuit voltage, V_{oc} is defined as the voltage output from solar cell when the load impedance is much larger than the device impedance which means that no current is flowing and it is the maximum possible voltage [7]. V_{oc} can be measured between the cathode and anode of a solar cell when the current is zero. The short circuit current, I_{sc} is the current output when the load impedance is much smaller than the device impedance and it is the maximum possible current. [7]. I_{sc} can be measured when the cathode and anode are short circuit and voltage is zero.

The fill factor, FF is the ratio of maximum power solar cell can produce to the theoretical limit if both voltages and current are simultaneously at the maximum [6]. Equation 1 shows the mathematical equation to calculate fill factor of a solar cell from solar cell maximum power point and efficiency. Equation 2 is a mathematical equation to calculate fill factor of solar cell using normalized voltage, V_{oc1}, while Equation 3 shows a mathematical equation to calculate $V_{oc1.}$

$$FF = Pm/(Voc \times Isc)$$
$$= (\eta \times A \times E)/(Voc \times Isc) \qquad \text{Equation 1}$$

$$FF = \frac{(Vocx - \ln(Vocx + 0.72))}{(Vocx + 1)} \qquad \text{Equation 2}$$

$$Vocx = Voc /(kT / q) \qquad \text{Equation 3}$$

The energy conversion efficiency, η, is the percentage of power converted from absorbed light to electrical energy, when a solar cell is connected to an electrical circuit [2, 8].

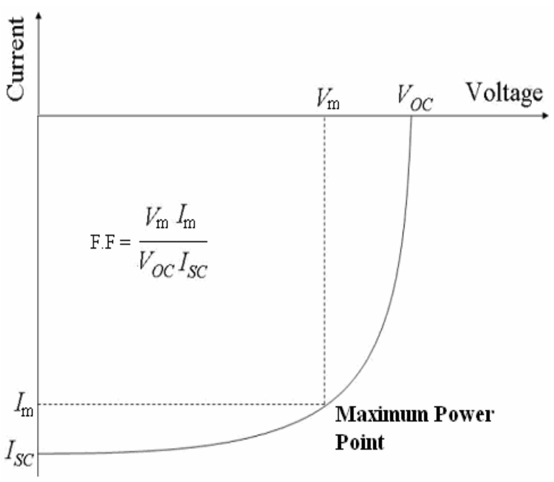

Figure 2: Typical current-voltage characteristics of a solar cell under illumination [3, 6].

The efficiency can be calculated using the ratio of maximum power point, P_m, divided by the input light irradiance or power density at AM0, E and the surface area of the solar cell, A with the value of $0.135 W/cm^2$, as shown in Equation 4.

$$\eta = Pm /(A \times E)$$
$$= (FF \times Voc \times Isc)/(E \times A) \qquad \text{Equation 4}$$

II. METHODOLOGY

The Silvaco TCAD Tools frameworks, Athena Process Simulation Software and Atlas Device Simulation Software were used to perform and simulate solar cell.

A. Simulation process in Athena Framework

1) Initialized Mesh Grid

The mesh grid used for this thesis is two-dimensional. Therefore, only x and y parameters are defined [3]. The mesh grid is a series of horizontal and vertical lines and spacing between them. This is because, the number of nodes in the grid will influence the simulation durations and accuracies. A coarse or fine mesh determines the accuracy of the simulation. A coarse mesh produces a faster simulation, but less accurate results. While, a fine mesh taking longer simulation time but gives more accurate results.

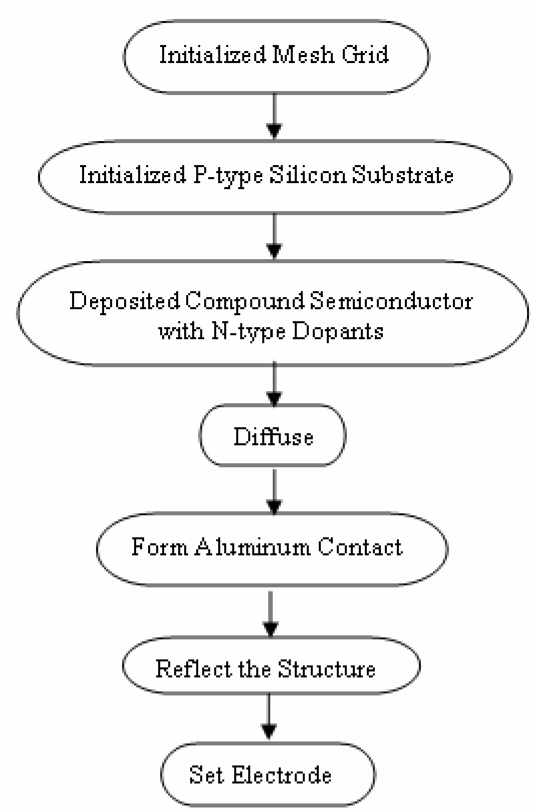

Figure 3: Step to construct solar cell using Athena Frameworks.

2) Initialized P-type Silicon Substrate

Silicon was chosen to be substrate of the solar cell. P-type si was set to become a solar cell substrate and configure as the bottom surface of the solar cell. A bulk substrate being produced is initially doped with 1.0×10^{14} (ions/cm^2) of boron, boron is the only dopant material which is chosen to be used to construct p-type substrate for this project.

3) Deposited Compound Semiconductor with N-type Dopant

To create n layer, the compound semiconductor is doped with phosphorus, the n-type dopant. All the materials that were chosen to be n-type layer were heavily doped with 1.0×10^{19} (/cm^3) concentration of phosphorus to make electron in n-layer diffuse to the p-region to form the p-n junction when illuminating with the sun.

4) Diffuse

The diffusion process was performed by heating up n-type layer in order to get perfect or high ohmic contact of n-layer with p-substrate. A high ohmic contact of the n-type layer and p-type substrate will form a good p-n junction. The diffusion process was done in 10 minutes of time with temperature of 900˚C.

5) Form Aluminum Contact

Aluminum is then deposited on top of the solar cell n-layer surface to be a contact. It was constructed in the center of the structure with the thickness of 0.1µm, which would be used to collect the current-voltage of the solar cell as well as the connector to the load. Contact determines the attributes of the electrode.

6) Reflect the Structure

The structure is then reflected to get the complete structure of the solar cell. This step is done to ensure the uniformity of the dopant within the solar cell. The last step in Athena framework is to set the electrode. The aluminum on the top and bottom of solar cell structures were set as cathode and anode respectively.

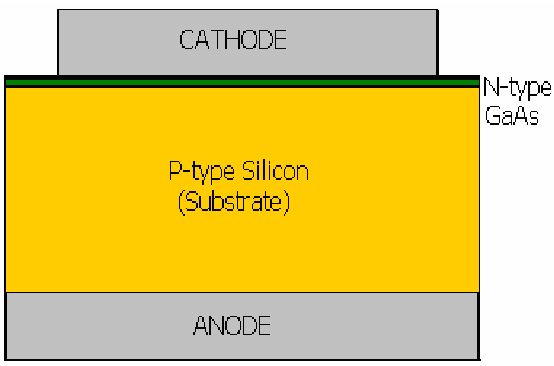

Figure 4: Simulation result for n-GaAs/p-Si solar cell using Athena

B. Simulation process in Atlas Framework

The solar cell structures that are saved in Athena framework is then simulated in Atlas framework. The solar cell is illuminated with AM0 spectrum.

1) Set contact material to be opaque

The contact is set with high imaginary refractive index so that the contact is opaque with the surface of the solar cell in order to avoid the contact from absorbing the light.

2) Lighting the solar cell

The solar cell is simulated using solar cell spectrum from external file named as optoex08_spec which consists of data of wavelength versus light intensity for AM0 solar spectrum. The illumination is defined by the beam statement, where the incident angle was set to 90˚ to make the incidence occurs directly to the surface of the solar cell. The actual power for AM0 solar spectrum was set to 0.135 W/cm^2 and it is defined by the **b1** parameter of the solve statement.

3) Models used

Simulation is done by using conmob and fldmob models. The conmod model means concentration dependent carrier mobilities, while fldmob means electric field dependent carrier mobilities [9]. Types of models being used within the simulation indicate how accurate the results within this simulation, compared with experimental results.

4) Short Circuit Current Simulation

Short circuit current simulation is done to obtain the short circuit current, I_{sc}. This process has been done by illuminating the device with zero voltage on all contacts. The B<n> parameter in the solve statement sets the power of the light defined as beam <n>. Then, an extract statement is used to measure the short circuit current.

5) Open Circuit Voltage Simulation

Open circuit voltage simulation has been done in order to obtain the open circuit voltage, $V_{oc.}$ The system essentially was reset using the command 'solve init' before it started the simulation. The current flow to the device is forced to be zero to obtain the open circuit voltage. After that, the device was illuminated with the beam and then the existed voltage across the device was measured. The essential step to set current to zero is by setting one electrode to have current boundary conditions. This step has done on the cathode using the current parameter of the contact statement. The device was illuminated with icathode=0 and thus gives the open circuit voltage. The voltage is measured using the extract statement.

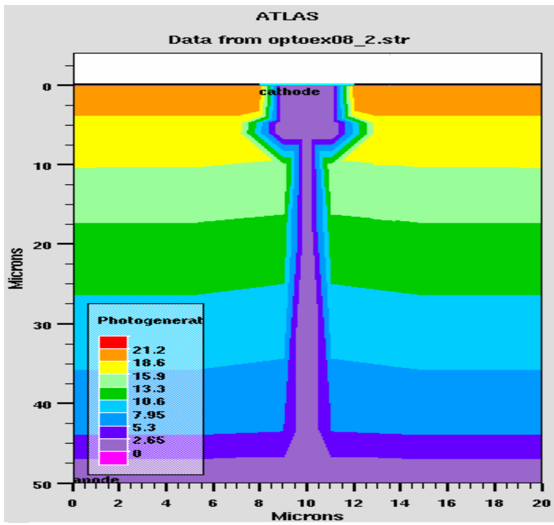

Figure 5: Simulation result for n-GaAs/p-Si solar cell using Atlas

III. RESULTS AND DISCUSSIONS

A. Short Circuit Current, I_{SC}

Table 1: The short circuit current of the solar cells.

Type of Solar Cell	N-type Thin Film Thickness (μm)			
	0.01	0.05	0.1	0.5
	Short Circuit Current (mA)			
n-Si/p-Si	76.15	77.68	79.96	81.09
n-SiGe/ p-Si	75.10	75.69	76.45	80.73
n-3C-SiC/p-Si	0.99	0.94	0.87	1.62
n-GaAs/ p-Si	76.61	76.98	77.69	81.50
n-AlGaAs / p-Si	75.01	75.24	75.79	79.62
n-InGaAs /p-Si	49.36	50.67	51.19	51.41

From the data tabulated in table 1, short circuit current for all solar cell configurations except n-3C-SiC/p-Si solar cell is slightly increasing when the thickness of n-layer increases. The short circuit current for n-3C-SiC/p-Si solar cell is very small and decrease with decreasing of n-layer thickness. It shows that this solar cell produces very less electron hole pairs which are very helpful to produce short circuit current in solar cell. This is may be due to the high conduction band off set opposes the flow of current [10]. The table also shows that the short circuit current produced by n-GaAs/p-Si solar cell is the highest compared to the other types of solar cell. The short circuit current is decreasing when the n-layer is exceeding the maximum thick which is enough for cell to produce maximum electron hole pairs.

B. Open Circuit Voltage, V_{OC}

Table 2: The open circuit voltage of the solar cells.

Type of Solar Cell	N-type Thin Film Thickness (μm)			
	0.01	0.05	0.1	0.5
	Open Circuit Voltage (V)			
n-Si/p-Si	0.249	0.293	0.309	0.351
n-SiGe/ p-Si	0.254	0.290	0.301	0.350
n-3C-SiC/p-Si	0.351	0.350	0.350	0.350
n-GaAs/ p-Si	0.350	0.351	0.351	0.351
n-AlGaAs/ p-Si	0.350	0.350	0.350	0.350
n-InGaAs/ p-Si	0.311	0.323	0.330	0.339

From the data tabulated in table 2, the highest open circuit voltage was produced by n-GaAs/p-Si solar cell. The open circuit voltage for n-GaAs/p-Si solar cell increases slightly as the thickness of n-layer solar cell increases, which means that varying the n-layer thickness does not affect the photon absorption and photogeneration rate. This is quite different compared to open circuit voltage value of n-Si/p-Si and n-SiGe/p-Si solar cell, which vary when the thickness of n-layer vary. It will be resulted from the band gap of n-Si/p-Si and n-SiGe/p-Si solar cell which are lesser than n-GaAs/p-Si solar cell. Theoretically, the optimum value of open circuit voltage is when the band gap of n-layer is 1.4eV, the closer the band gap, the higher the open circuit voltage of solar cell [6]. This is proved when comparing the band gap values of n-GaAs and n-Si which indicates that the band gap values of both materials is 1.43 and 1.12 respectively.

C. Fill Factor, FF

Table 3: The fill factor of the solar cells.

Type of Solar Cell	N-type Thin Film Thickness (μm)			
	0.01	0.05	0.1	0.5
	Fill Factor			
n-Si/p-Si	0.686	0.717	0.725	0.749
n-SiGe/ p-Si	0.690	0.715	0.722	0.748
n-3C-SiC/p-Si	0.749	0.749	0.749	0.749
n-GaAs/ p-Si	0.749	0.749	0.749	0.749
n-AlGaAs/ p-Si	0.748	0.748	0.748	0.748
n-InGaAs/ p-Si	0.728	0.734	0.739	0.742

From the data tabulated in table 3, the fill factor values of all the configurations of solar cell at any thickness are in the range of reasonable efficiency that is from 0.7 to 0.85 [7]. The fill factor values for all configurations of solar cell are slightly increasing when the n-layer thickness increase. The fill factor values are mostly not depending on the thickness of n-layer solar cell but depending on the open circuit voltage value. The recombinations in the depletion region slightly reduce the fill factor of the solar cells [6].

D. Efficiency, η

Regarding the data tabulated in table 4, the efficiency of all types of solar cell configurations except n-3C-SiC/p-Si and n-InGaAs/p-Si have quite high efficiency. The efficiency increases when n-layer thickness of solar cell is increasing

.The maximum n-layer thickness which gives maximum efficiency of solar cell are different depending on the types of material used. Varying the n-layer thickness until exceeded the limit or maximum n-layer thickness of certain materials will reduces the efficiency of solar cell, which is caused by weak photon absorption at high wavelength radiation [7]. This is the reason why the n-layer and p-layer of solar cell should be thick enough to generate more electron-hole pairs. The efficiency of n-3C-SiC/p-Si solar cell is very small because of the large lattice mismatch between 3C-SiC layer and silicon substrate.

Table 4: The efficiency of the solar cells.

Type of Solar Cell	N-type Thin Film Thickness (µm)			
	0.01	0.05	0.1	0.5
	Efficiency (%)			
n-Si/p-Si	9.65	12.09	13.19	15.76
n-SiGe/ p-Si	9.77	11.63	12.31	15.69
n-3C-SiC/p-Si	0.19	0.18	0.17	0.31
n-GaAs/ p-Si	14.89	14.97	15.11	15.87
n-AlGaAs/ p-Si	14.56	14.60	14.71	15.45
n-InGaAs/ p-Si	8.27	8.90	9.25	9.58

E. Photogeneration Rate

The photogeneration rate indicates the volume of photon generated in solar cell. Photogeneration rate will affect the absorption rate of photons in solar cell which is useful to generate electron-hole pairs. In simple sentence, higher photogeneration rate shows that the solar cell has higher photocurrent.

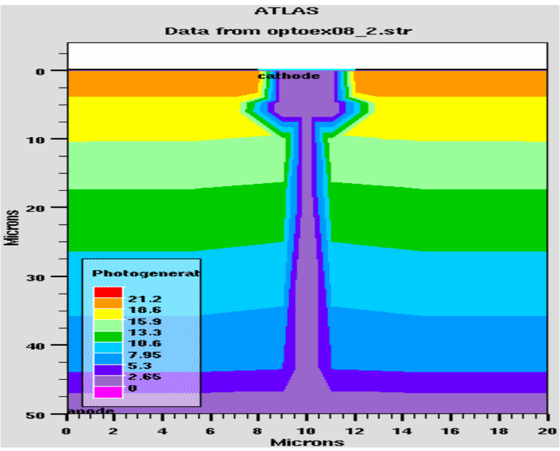

Figure 6: The cross section of photogeneration rate for n-GaAs/p-Si solar cell.

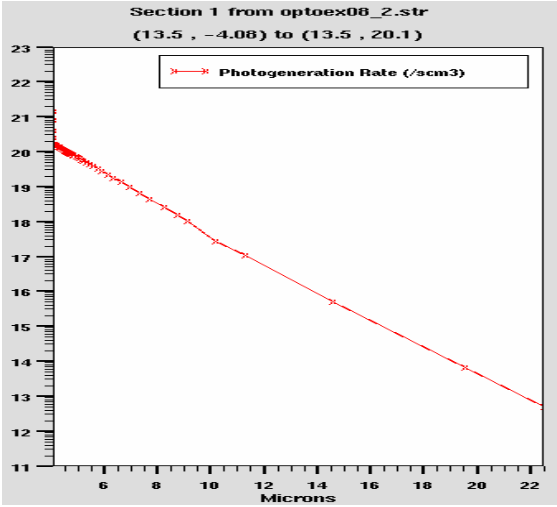

Figure 7: The graph of photogeneration rate for n-GaAs/p-Si solar cell.

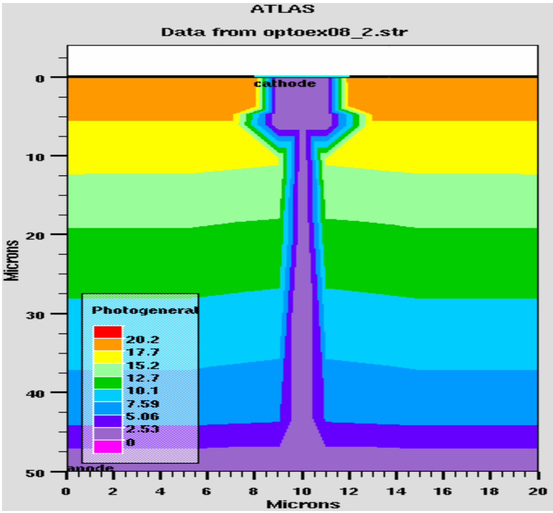

Figure 8: The cross section of photogeneration rate for n-3C-SiC/p-Si solar cell.

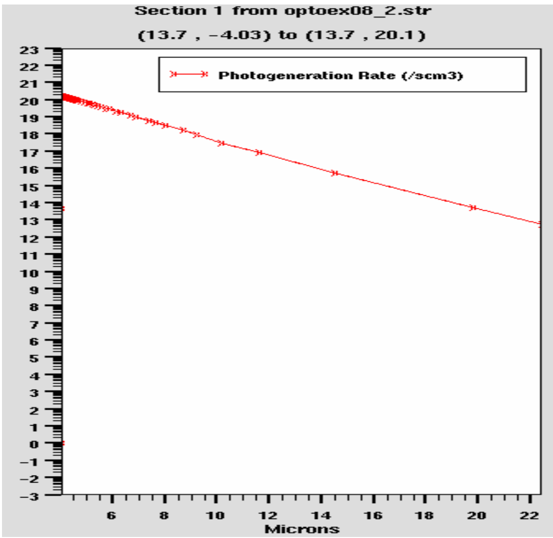

Figure 9: The graph of photogeneration rate for n-3C-SiC/p-si solar cell

Table 5: The photogeneration rate of solar cells.

Type of Solar Cell	N-type Thin Film Thickness (µm)			
	0.01	0.05	0.1	0.5
	Photogeneration rate (/scm3)			
n-Si/p-Si	20.4	20.4	20.4	20.3
n-SiGe/ p-Si	20.3	20.3	20.3	20.3
n-3C-SiC/ p-Si	20.2	20.2	20.2	20.2
n-GaAs/ p-Si	21.2	21.2	21.1	20.9
n-AlGaAs/ p-Si	20.2	20.2	20.2	20.2
n-InGaAs/ p-Si	20.1	20.1	20.1	20.1

Regarding to the tabulated data in table 5, the highest photogeneration rate is produced by n-GaAs/ p-Si solar cell. The other configurations of solar cell have an average photogeneration rate at 20(/scm^3). Regarding to the figure 7, the values of photogeneration rates for n-GaAs/p-Si solar cell are rapidly decreasing when the solar cell thickness is increased compared to the photogeneration rate for n-3C-SiC/p-Si solar cell. This is because of the surface recombination which affects the absorption rate of generated photons.

F. Recombination Rate

Recombination is the process where concentrations decay back to their equilibrium values when the light is switched off. This process can be called as reverse of absorption process [7]. Actually, in solar cell, not all photogenerated electron-hole pair is converting into energy, it being lost by recombination in the surface region.

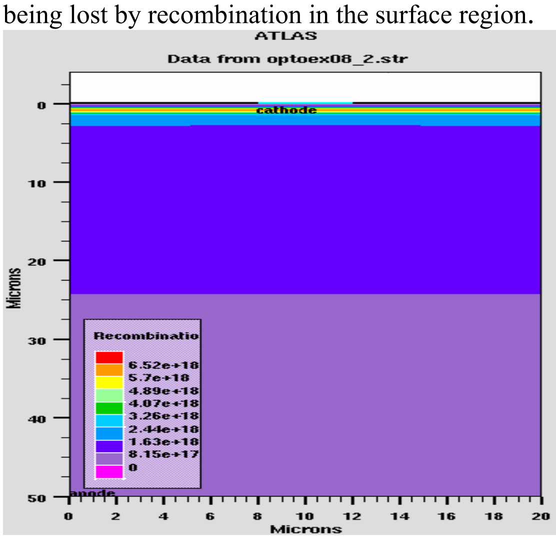

Figure 10: The cross section of recombination rate for n-GaAs/p-si solar cell.

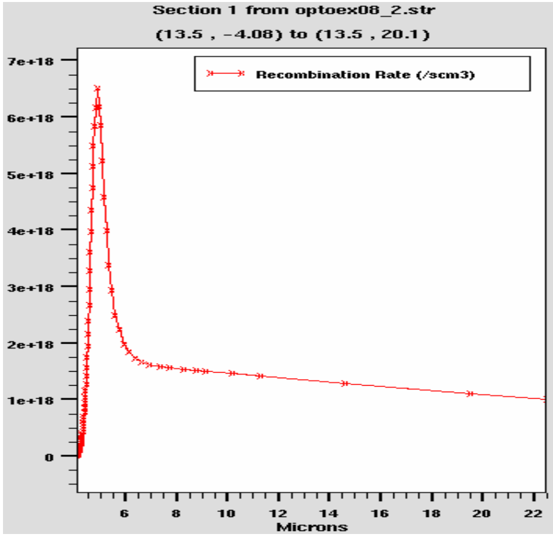

Figure 11: The graph of recombination rate for n-GaAs/p-si solar cell.

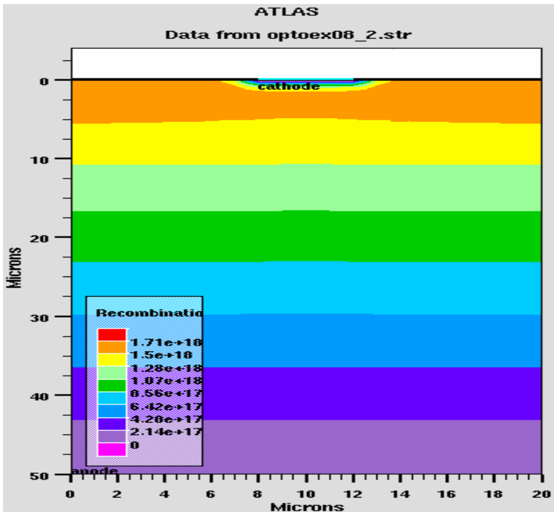

Figure 12: The cross section of recombination rate for n-3C-SiC/p-si solar cell.

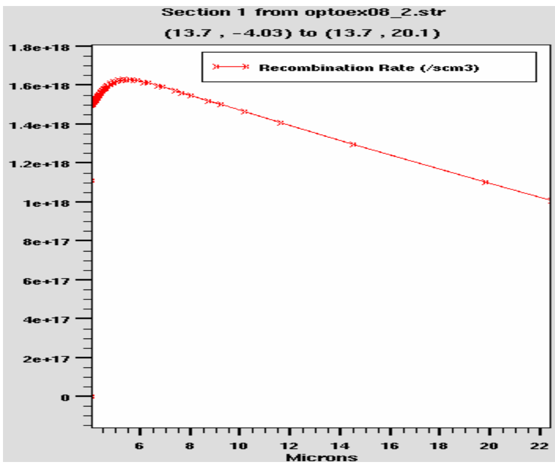

Figure 13: The graph of recombination rate for n-3C-SiC/p-si solar cell

Table 6: The recombination rate of solar cells.

Type of Solar Cell	N-type thin Film Thickness (μm)			
	0.01	0.05	0.1	0.5
	Recombination Rate (/scm3)			
n-Si/p-Si	$6.48e^{18}$	$6.40e^{18}$	$6.40e^{18}$	$6.48e^{18}$
n-SiGe/ p-Si	$6.43e^{18}$	$6.45e^{18}$	$6.37e^{18}$	$6.49e^{18}$
n-3C-SiC/p-Si	$1.71e^{18}$	$1.71e^{18}$	$1.71e^{18}$	$1.7e^{18}$
n-GaAs/ p-Si	$6.52e^{18}$	$6.52e^{18}$	$6.5e^{18}$	$6.53e^{18}$
n-AlGaAs/ p-Si	$6.45e^{18}$	$6.44e^{18}$	$6.42e^{18}$	$6.43e^{18}$
n-InGaAs/ p-Si	$4.95e^{18}$	$5.13e^{18}$	$5.12e^{18}$	$5.12e^{18}$

From the tabulated data in table 6, the recombination rates for all types of solar cells except n-3C-SiC/p-Si are in constant value with average of $6e^{18}$. The recombination rate for n-3C-SiC/p-Si solar cell is small compared to the other types of solar cell. Regarding to the figure 11, the initial value of recombination rate for n-GaAs/p-Si solar cell is high but rapidly decreasing when the solar cell thickness is increased. The 3C-SiC are chosen as candidate material in the application of solar cell due to its low recombination rate, wide band gap, and lower absorption in the visible region, retaining its higher conductivity [10].

IV. CONCLUSIONS

The effects of n-layer thin film thickness were investigated. The simulation was performed using Silvaco TCAD Tools and the simulation result which is recorded in table 4 shows that the efficiency of n-GaAs/p-Si in Air Mass Zero (AM0) is 15.87% with n-layer thickness of 0.5μm. The efficiency of solar cells are depends on many factors such as types material uses, solar cell configurations, number of electron-hole pairs photogenerated and also the velocity of recombination process. Gallium Arsenic (GaAs) is the best material to be n-layer for solar cell with silicon substrate. Silicon is chosen as the main material for solar cell application because of its electrical properties, cost effectiveness and easily available of silicon and also due to the mature technology for silicon based semiconductor fabrication. Implementation of silicon technologies in the long term will further advance thin-film solar cell technology and will ensure continuous price competitiveness. Thin film silicon technology can lead to cost-effective solar cell generation of electrical energy.

V. FUTURE DEVELOPMENT

There are multiple areas that can be explored in future research, in order to increase the performance of solar cell. The research in heterojunction, tandem and lattice matched solar cell with different semiconductor materials can be alternatives which offer potential for high efficiency solar cells. A modern country is also working with multiband materials, such as Zinc Manganese Tellerium Oxide (ZnMnTeO) [11]. This type of material offers a single junction solar cell, but there are multiple band gaps within the single junction. Optimizing the physical parameters of the solar cell such as thickness of each layer of solar cell, band gap distribution for a heterojunction and tandem and the uses of thin film material can be improved to obtain higher efficiency. The most essential point is to obtain the correct optical data for band gaps of materials.

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ACKNOWLEDGEMENT

I would like to express my deepest gratitude, appreciation and thanks to my respected supervisor, Dr. Fuziah binti Sulaiman, my co-supervisor, Associate Professor Dr. Mohamad Rusop bin Mahmood for their guidance, advices, supervision and encouragement in making this project an accomplishment. I also like to say thank you for their priceless help and useful ideas in gaining my knowledge on semiconductor properties. Thank you for their understanding, support, and consistence.

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