Simulation Model of Silicon Solar Cell

1) Objective

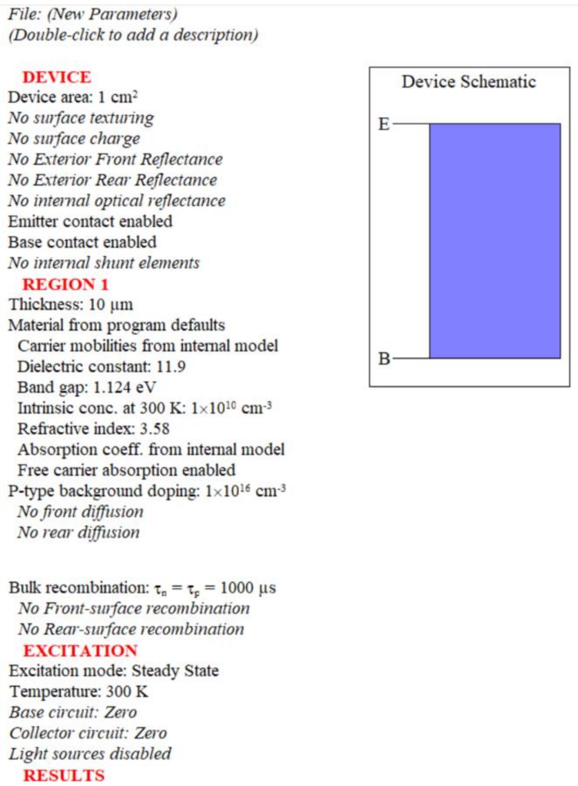
The objective is to achieve simulation model of Solar Cell using the simulation software PC1D. We are making the model in order to understand the behavior of practical Solar Cell. We will also calculate the Efficiency and Fill Factor of the Solar Cell, by changing other parameters and also conclude the dependency.

2) Theory

2.1 Introduction of PC1D

The numerical simulation software PC1D stands for Personal Computer One Dimensional. PC1D is the most commonly used of the commercially available solar cell modelling programs. Its advantage is its speed, user interface and continual updates to the latest cell models. It is used to simulate new device performance and also for new users to develop an understanding of device physics. It allows simulating the behaviour of photovoltaic structures based on semiconductor by respecting to one-dimensional (axial symmetry).

The PC1D contains libraries files with the parameters of the crystalline semiconductors used in the photovoltaic technology as the GaAS, Si, InP etc. The main window of PC1D is as follows:



DEVICE section contains the general information about the device which we want to simulate.

REGION section is very important section because it is used to add single or multiple regions to simulate. We can also modify here the type of material used, its thickness, doping type and concentration etc. There is given only 1 region but we can have a maximum of 5 regions and we must have at least 1 region.

In the EXCITATION section we introduce the parameter of excitation to the device we selected and according to which we are going to simulate the device and record the results.

In the RESULT section we will get the result according to the device selected and excitation applied. Results will be like Short Circuit Current, Open Circuit Voltage, and Maximum Base Power Output etc.

At the right side we can see Device Schematic simply shows the device and region we are selected. According to the doping applied colour of the regions also changes. If we will apply Surface Texturing then it will also be reflected in the schematic shown.

2.2 Introduction of Solar Cell

Solar cell is a device that converts an optical input into current. A solar cell is an example of a photovoltaic device which means a device that generates voltage when exposed to light. The photovoltaic effect was discovered by Alexander-Edmond Becquerel in 1839, in a junction formed between an electrode (platinum) and an electrolyte (silver chloride). The first photovoltaic device was built, using a Si pn junction, by Russell Ohl in 1939. The functioning of a solar cell is similar to the photodiode (photodetector). It is a photodiode that is unbiased and connected to a load (i.e. impedence). There are three qualitative differences between a solar cell and photodetector

- A photodiode works on a narrow range of wavelength while solar cells need to work over a broad spectral range (solar spectrum).
- Solar cells are typically wide area devices to maximize exposure.
- In photodiodes the metric is quantum efficiency, which defines the signal to noise ratio, while for solar cells, it is the power conversion efficiency which is the power delivered per incident solar energy. Usually, solar cells and the external load they are connected to are designed to maximize the delivered power.

2.3 Working of Solar Cell

A simple solar cell is a pn junction diode. The schematic of the device is shown in figure 2. The n region is heavily doped and thin so that the light can penetrate through it easily. The p region is lightly doped so that most of the depletion region lies in the p side. The penetration depends on the wavelength and the absorption coefficient increases as the wavelength decreases. Electron hole pairs (EHPs) are mainly created in the depletion region and due to the built-in potential and electric field, electrons move to the n region and the holes to the p region. When an external load is applied, the excess electrons travel through the load to recombine with the excess holes. Electrons and holes are also generated with the p and n regions, as seen from figure 2. The shorter wavelengths (higher absorption coefficient) are absorbed in the n region and the longer wavelengths are absorbed in the bulk of the p region. Some of the EHPs generated in these regions can also contribute to the current. Typically, these are EHPs that are generated within the minority.

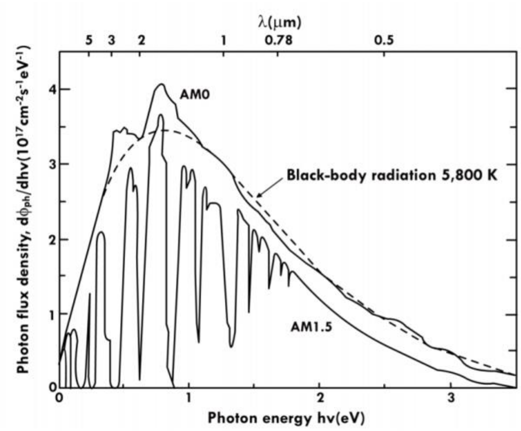


Fig-1

Solar spectrum plotted as photon flux density vs. energy for AM0 and AM1.5. The difference in the spectra is due to the absorption/scattering by the atmosphere.

carrier diffusion length, L_e for electrons in the p side and L_h for holes in the n side. Carriers produced in this region can also diffuse into the depletion region and contribute to the current. Thus, the total width of the region that contributes to the solar cell current is $w_d + L_e + L_h$, where w_d is the depletion width. This is shown in figure 3. The carriers are extracted by metal electrodes on either side. A finger electrode is used on the top to make the electrical contact, so that there is sufficient surface for the light to penetrate. The arrangement of the top electrode is shown in figure 4. Consider a solar cell made of Si. The band gap, E_g, is 1.1 eV so that wavelength above 1.1 µm is not absorbed since the energy is lower than the band gap. Thus any λ greater than 1.1 µm has negligible absorption. For λ much smaller than 1.1 µm the absorption coefficient is very high and the EHPs are generated near the surface and can get trapped near the surface defects. So there is an optimum range of wavelengths where EHPs can contribute to photocurrent, shown in figure 3.

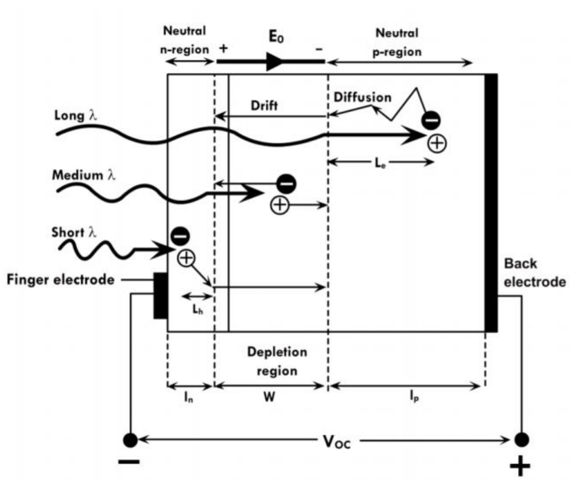


Fig-2

Principle of operation of a pn junction solar cell. Radiation is absorbed in the depletion region and produces electrons and holes. These are separated by the built-in potential. Depending on the wavelength and the thickness different parts of the device can absorb different regions of the solar spectrum.

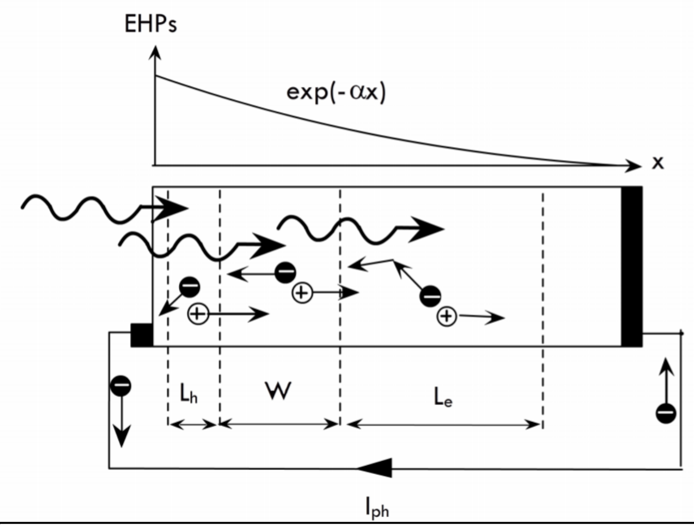


Fig-3

Photogenerated carriers in a solar cell due to absorption of light. w is the width of the depletion region, while L_h and L_e are minority carrier diffusion lengths in the n and p regions. The amount of absorption reduces with depth and hence the depletion region must be close to the surface to maximize absorption. This is achieved by having a thin n region.

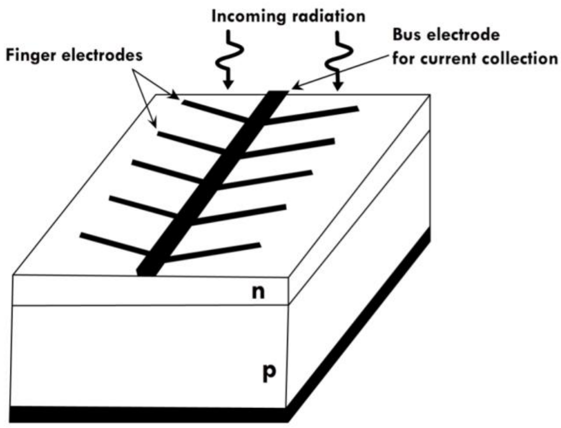


Fig-4

Finger electrodes on a pn junction solar cell. The design consists of a single bus electrode for carrying current and finger electrodes that are thin enough so that sufficient light can be absorbed by the solar cell.

3) Simulation and Results

3.1 Simulator parameters for Silicon Solar Cell

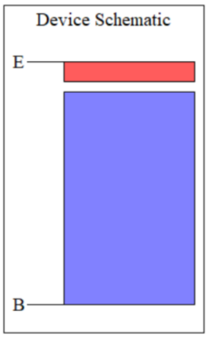
We made several simulations to see the influence of various parameters on the efficiency of solar cells. We chose to use the silicon as material composing cells simulated because this is semi-conductor the most used actually in the industry of the photovoltaic.

The basic cell since which we began our simulations is a silicon solar cell. We selected a total thickness of 100µm and a surface of $100\ cm^2$. All settings and parameters of the cell are shown in the following figure:

DEVICE
Device area: 110 cm^2
No surface texturing
No surface charge
No Exterior Front Reflectance
No Exterior Rear Reflectance
No internal optical reflectance
Emitter contact enabled
Base contact enabled
No internal shunt elements
REGION 1
Thickness: 10 μm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.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
Thickness: 100 μm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.abs
Free carrier absorption enabled
P-type background doping: 1×10^{16} 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



3.2 Changing Exterior Front Reflectance from 5% to 20%

DEVICE
Device area: 110 cm^2
No surface texturing
No surface charge
Exterior Front Reflectance: 5%
No Exterior Rear Reflectance
No internal optical reflectance
Emitter contact enabled
Base contact enabled
No internal shunt elements

REGION 1
Thickness: 10 μm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.abs
Free carrier absorption enabled
N-type background doping: 1×10^{18} cm^{-3}
No front diffusion
No rear diffusion

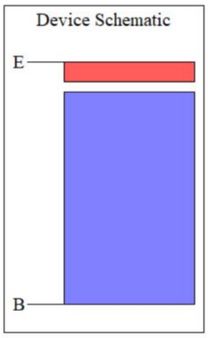
Bulk recombination: $\tau_n = \tau_p = 1000$ μs
No Front-surface recombination
No Rear-surface recombination

REGION 2
Thickness: 100 μm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.abs
Free carrier absorption enabled
P-type background doping: 1×10^{16} 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

RESULTS
Short-circuit Ib: -3.915 amps
Max base power out: 2.400 watts
Open-circuit Vb: 0.7321 volts



<u>For Exterior Front Reflectance = 5%</u>

Short Circuit Current, $I_{SC} = -3.915\ A$

Open Circuit Voltage, $V_{OC} = 0.7321\ V$

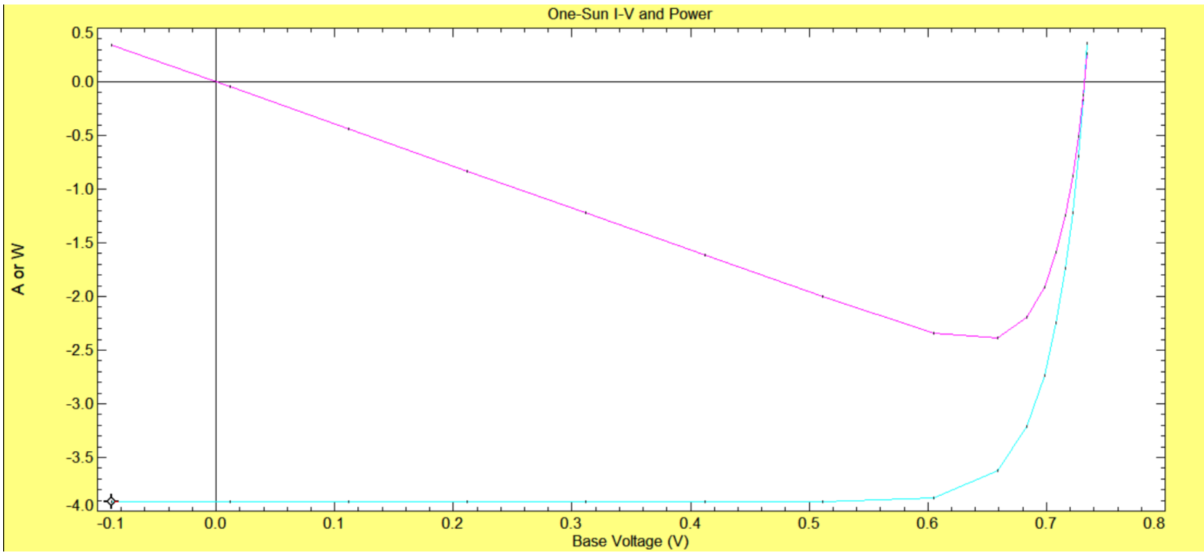
Maximum Base Power Output, $P_M = 2.400\ W$

Power Input, $P_I = 0.1 \times 110 = 11\ W$

Efficiency, $\eta = \frac{P_M}{P_I} \times 100\% = \frac{2.400}{11} \times 100\% = 21.818\%$

Fill Factor, $FF = \frac{P_M}{I_{SC} \times V_{OC}} \times 100\% = \frac{2.400}{3.915 \times 0.7321} \times 100\% = 83.735\%$

Characteristics:



For Exterior Front Reflectance = 10%

Short Circuit Current, $I_{SC} = -3.709\ A$

Open Circuit Voltage, $V_{OC} = 0.7306\ V$

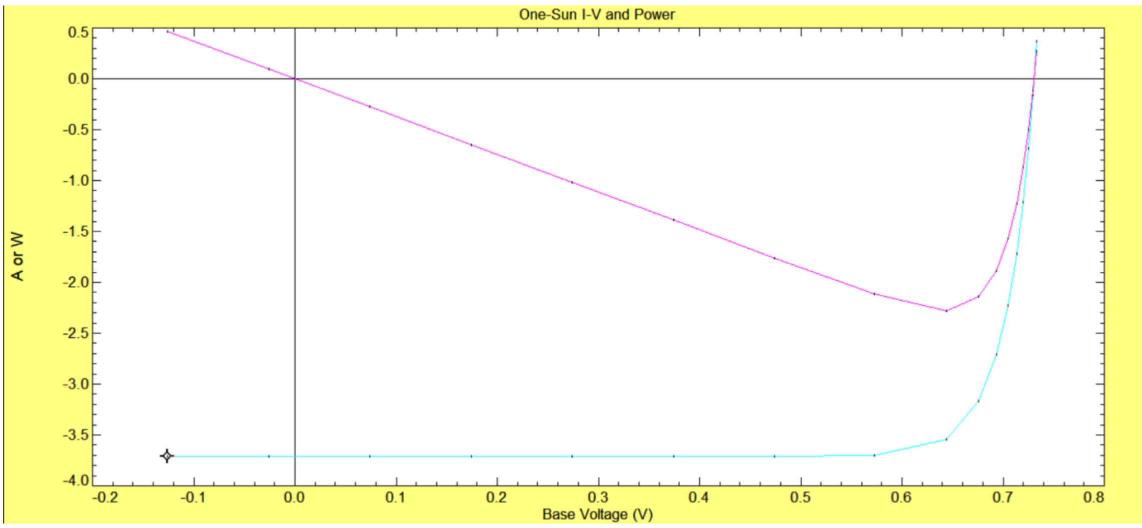
Maximum Base Power Output, $P_M = 2.280\ W$

Power Input, $P_I = 0.1 \times 110 = 11\ W$

Efficiency, $\eta = \frac{P_M}{P_I} \times 100\% = \frac{2.28}{11} \times 100\% = 20.727\%$

Fill Factor, $FF = \frac{P_M}{I_{SC} \times V_{OC}} \times 100\% = \frac{2.280}{3.709 \times 0.7306} \times 100\% = 84.13\%$

Characteristics:



For Exterior Front Reflectance = 15%

Short Circuit Current, $I_{SC} = -3.503\ A$

Open Circuit Voltage, $V_{OC} = 0.7291\ V$

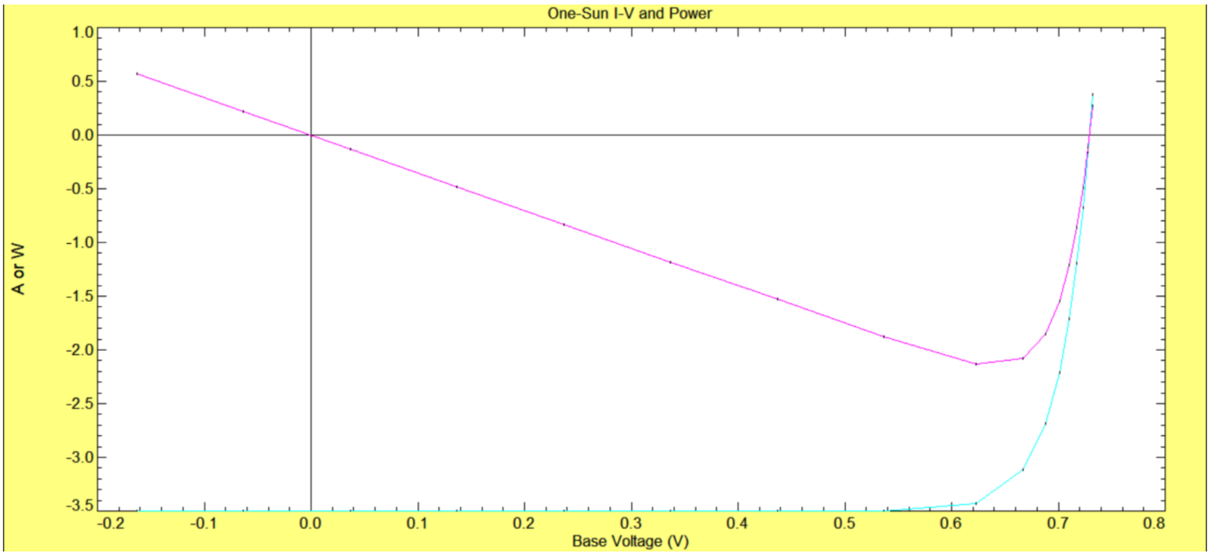
Maximum Base Power Output, $P_M = 2.151\ W$

Power Input, $P_I = 0.1 \times 110 = 11\ W$

Efficiency, $\eta = \frac{P_M}{P_I} \times 100\% = \frac{2.151}{11} \times 100\% = 19.554\%$

Fill Factor, $FF = \frac{P_M}{I_{SC} \times V_{OC}} \times 100\% = \frac{2.151}{3.503 \times 0.7291} \times 100\% = 84.220\%$

Characteristics:



<u>For Exterior Front Reflectance = 20%</u>

Short Circuit Current, $I_{SC} = -3.297\ A$

Open Circuit Voltage, $V_{OC} = 0.7274\ V$

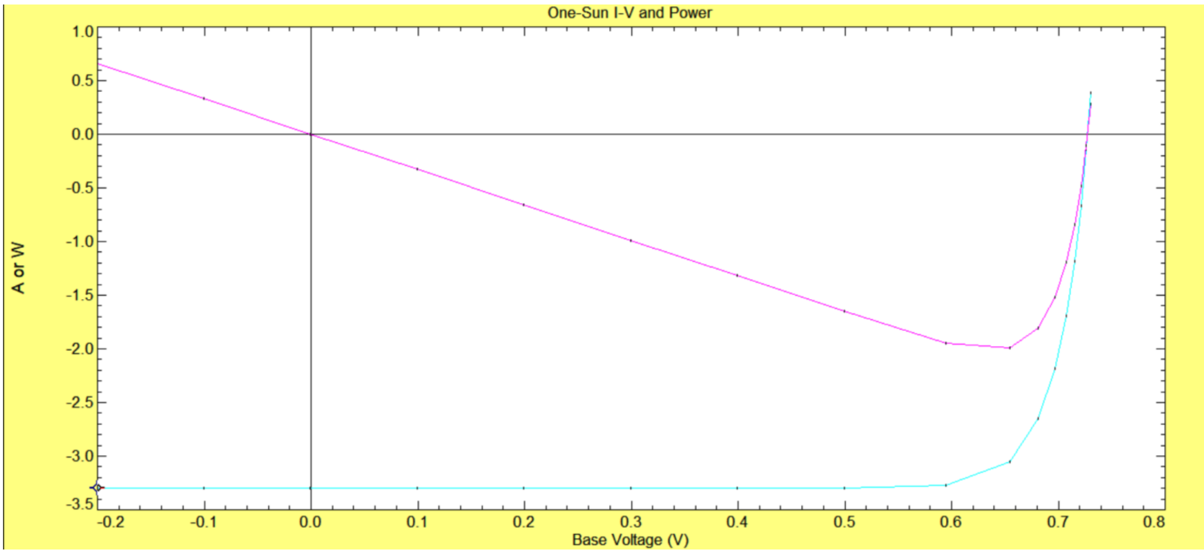
Maximum Base Power Output, $P_M = 2.006\ W$

Power Input, $P_I = 0.1 \times 110 = 11\ W$

Efficiency, $\eta = \frac{P_M}{P_I} \times 100\% = \frac{2.006}{11} \times 100\% = 18.236\%$

Fill Factor, $FF = \frac{P_M}{I_{SC} \times V_{OC}} \times 100\% = \frac{2.006}{3.297 \times 0.7274} \times 100\% = 83.645\%$

Characteristics:



3.3 Taking Front Surface Texture at 10% Front Surface Reflectance

DEVICE
Device area: 110 cm^2
Front surface texture depth: 3 µm
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: 10 µm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.abs
Free carrier absorption enabled
N-type background doping: 1×10^{18} cm^{-3}
No front diffusion
No rear diffusion

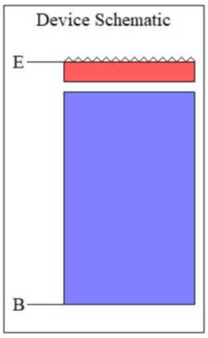
Bulk recombination: $\tau_n = \tau_p = 1000$ µs
No Front-surface recombination
No Rear-surface recombination

REGION 2
Thickness: 100 µm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.abs
Free carrier absorption enabled
P-type background doping: 1×10^{16} 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

RESULTS
Short-circuit Ib: -3.766 amps
Max base power out: 2.311 watts
Open-circuit Vb: 0.7304 volts



Short Circuit Current, $I_{SC} = -3.766\ A$

Open Circuit Voltage, $V_{OC} = 0.7304\ V$

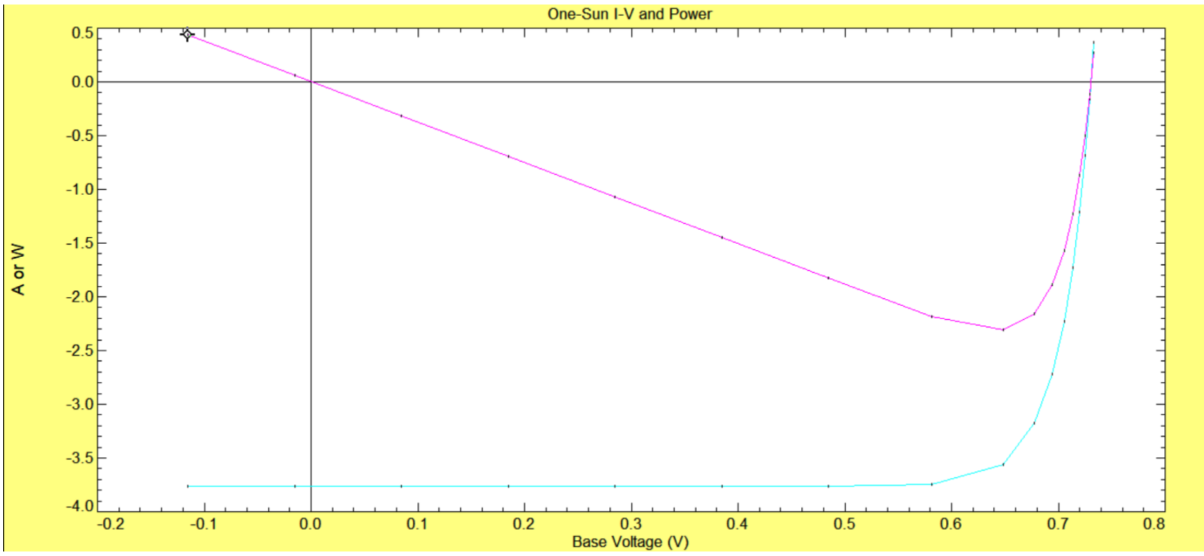
Maximum Base Power Output, $P_M = 2.311\ W$

Power Input, $P_I = 0.1 \times 110 = 11\ W$

Efficiency, $\eta = \frac{P_M}{P_I} \times 100\% = \frac{2.311}{11} \times 100\% = 21.010\%$

Fill Factor, $FF = \frac{P_M}{I_{SC} \times V_{OC}} \times 100\% = \frac{2.311}{3.766 \times 0.7304} \times 100\% = 84.015\%$

Characteristics:



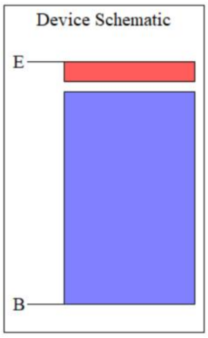
3.4 Taking Excitation from “scan-qe.exc” at 10% Front Surface Reflectance

DEVICE

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: 10 µm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.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

Thickness: 100 µm
Material from si.mat
Carrier mobilities from internal model
Dielectric constant: 11.9
Band gap: 1.124 eV
Intrinsic conc. at 300 K: 1×10^{10} cm^{-3}
Refractive index from si.inr
Absorption coeff. from si300.abs
Free carrier absorption enabled
P-type background doping: 1×10^{16} 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 scan-qe.exc
Excitation mode: Transient, 90 timesteps
Temperature: 300 K
Base circuit: Zero

Collector circuit: Zero
Primary light source enabled
Constant intensity: 1×10^{-3} W cm^{-2}
Monochrome, wavelength from 300 to 1200 nm
Secondary light source disabled

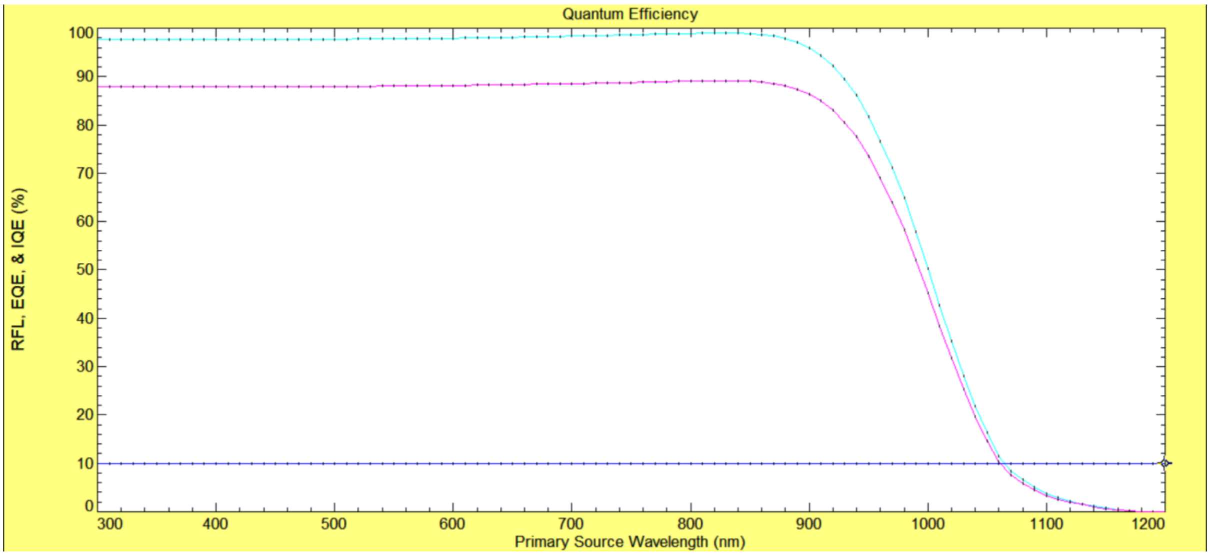
RESULTS

Short-circuit Ib: -0.0234 amps
Max base power out: 1.297e-28 watts

Short Circuit Current, $I_{SC} = -0.0234\ A$

Maximum Base Power Output, $P_M = 1.297e{-}28\ W$

Characteristics:



4) Conclusions

We made simulation model of Solar Cell using the simulation software PC1D. We also calculated the Efficiency and Fill Factor of solar cell after changing Exterior front surface reflectance. We saw that when we increase the Exterior front reflectance then the Efficiency is decreasing and Fill Factor is increasing. But just when Exterior front surface reflectance was 20% then Efficiency was still decreasing but Fill Factor also decreases.

We also applied Front Surface Texture and we got that the Efficiency increases and Fill Factor decreases as compared to the non-front surface textured solar cell model. We also got the Quantum Efficiency Curve.

Finally, we have completed the project and achieved simulation model of solar cell, got the characteristics and also concluded the dependency of parameters.

5) References

- Principles of Electronic Materials - S.O. Kasap
- D.A. Clugston, P.A. Basore, PC1D version 5: 32-bit solar cell modelling on personal computers Conference Record of the 26th IEEE Photovoltaic Specialists Conference (1997), pp. 207–210.