TCAD Modelling and Characteristic Analysis of Solar PVC

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***Abstract*—**Solar energy has been a cleanest source of energy with zero emission of toxic gases and has a great potential to fulfil the needs of energy for mankind. The best way to harness the solar power is the use of Photovoltaic Cell (solar PVC) which directly converts the solar energy into electricity through the photovoltaic effect. The number of cells electrically connected to each other leads to a photovoltaic network called photovoltaic system. The solar power has overruled the market for many years because of its numerous benefits and applications such as lightning, communication, remote monitoring, disaster relief application and remote site electrification. Despite of all these applications solar energy system has drawbacks of high cost and low efficiency. This paper computes the electrical model of solar photovoltaic system along with the optimization of its optical parameters which gives a detailed understanding of its attained efficiency and cost of the system. Further paper presents TCAD simulation model of single p-n junction amorphous silicon (a-Si) solar PVCs using Virtual fabrication tool-SILVACO(Atlas).

Keywords*-Photovoltaic system, Photo-generated current, Recombination, Short-circuit current, Surface Texturing.*

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I. INTRODUCTION

Renewable energy is the energy that is obtained from the natural occurring processes which can easily be replenished [1]. This form of energy is found in limitless quantity, hence it cannot be exhausted. Renewable energy is being the widely harnessed energy which is being used entire the globe because it acts as an alternate energy sources for all the high cost fossil fuels which are great threat to the environment. The rising demands for the alternate energy sources have led to the need of more sustainable and powerful methods to access this form of energy [2]. Wind, water, tides, sunlight biomass and geothermal heat are some of the renewable energy sources. Solar power is the most developing alternate energy source because of its availability in abundance and zero emission. The process of conversion sunlight into electric power needs the use of solar or photovoltaic cell. This photovoltaic cell comprise of the slices of the semiconducting materials (silicon and germanium are most widely used). The solar cells are connected in a huge electric network of solar panels and are mounted over the surface leading to a huge electrical network called photovoltaic system [3]. These solar panels do not contain any mechanical moving part and hence there are almost negligible breakages. The solar energy generation have several applications within the wide area. The major application of solar power is Remote Area Power Supply (RAPS) [4]. The electricity is provided to the remote areas or areas with small community through a photovoltaic system [5] which uses a battery to provide power during nights. The photovoltaic system act as ideal energy source that meets the lightning needs for fluorescent lights and other low pressure lights. The signals of phones, radio and television travel a long distance to get through amplification this needs a photovoltaic system in repeater stations or the at the travellers' node. Photovoltaic system is of a great importance in remote site where the need of electricity is must and challenging such as remote workshops, camps, hunting lodges.

A. Device Structure

A conventional solar cell behaves like a p-n junction diode. A p-n junction solar cell is also termed as homo-junction solar cell because of the presence of one junction (p-n junction) [6]. The solar cell most commonly known as photovoltaic cell works on the photovoltaic effect under the presence of sunlight. When the photons (small packets of energy) strike the surface of the solar cell then there are three possibilities which may take place:

- The photons may pass through the surface without any absorption which may occur when the energy of the photons is less than the band gap of the semiconducting material used in the cell.
- The photons may reflect from the surface because of the difference in the refractive index of the two materials.
- The photons may get absorbed by the semiconducting material. The photons that are absorbed should have the energy greater than the band gap of the material used.

When the photons of light are absorbed, the electron within the valence band gets enough energy and gets excited and move to conduction band. This leaves an empty space within the valence band which is known as hole. Hence, it is said that the absorbed photon generates an electron-hole pair. The electrons and hole are metastable in nature and they only exist for a short time known as the minority carrier lifetime. Therefore, after this time these electrons and hole may

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recombine and no current will be generated in the solar cell [7]. This functioning is illustrated in basic structure of p-n junction solar cell shown in Fig.-1.

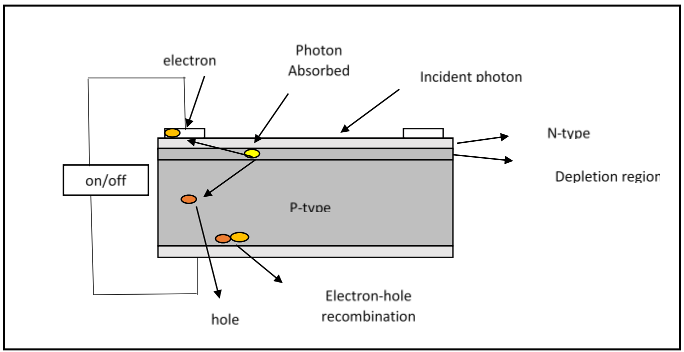

Figure 1. Structure of p-n junction solar cell.

Within the p-n junction solar cell, the barrier potential is being created due to the abrupt change within the carrier concentration of holes and electrons on n-side and p-side within the space charge region or the depletion region which creates an electric field. This direction of electric field is left to right i.e. from n-region to p-region. This electric field in the dark is the major source of separating the charge carriers [8]. For the current to flow within the solar cell, it is necessary that the two type of charge carriers flow towards the different terminals. The connection of an external load to the system helps in drawing a current form the system.

This paper gives a mathematical review on electrical and optical modelling aspects of solar PVC. Section II accentuates on the electrical modelling aspect of solar PVC and various performance parameters and section III highlights optical modelling parameters in detail. The simulation set up parameters for SILVACO-Atlas tool are discussed in section IV. Section V highlights results with snapshots of simulation modelling of Si-solar PVC with its characterization followed by conclusion in section VI.

II. ELECTRICAL MODELLING OF THE DEVICE

The photovoltaic cell is implemented using a diode connected in parallel to a current source. The current of the photovoltaic cell largely depends upon the solar light striking the cell. The overall output parameters such as cost and efficiency can be wisely calculated using the electrical study [9] of photovoltaic cell.

For ideal cell, the equivalent electrical circuit is shown in Fig.-2.

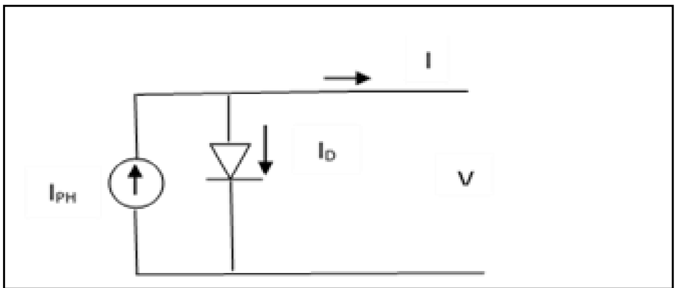

Figure 2. Equivalent circuit of ideal solar cell

In ideal cell, the total current I under illuminated condition is equal to eq(1)

$$I = I_D - I_L \qquad (1)$$

The equivalent circuit when series and shunt resistances are being considered is shown in Fig.-3

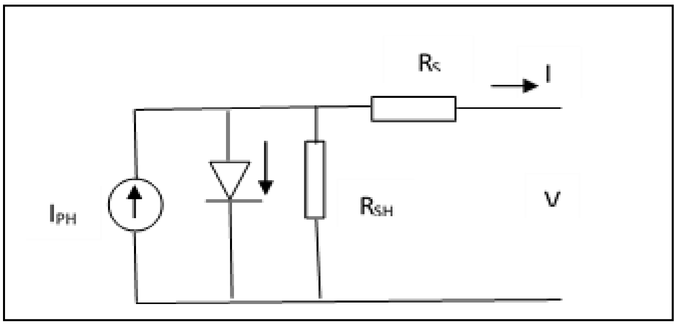

Figure 3. Equivalent circuit of solar cell with series and shunt resistance

Various parameters used in electrical modelling of solar cell are enlisted in TABLE I.

TABLE I. PARAMETERS USED FOR ELECTRICAL MODELLING

I_D	Diode Current	I_{sc}	Short-Circuit Current
I_{ph}	Photovoltaic current	V_{oc}	Open-Circuit Voltage
I_{sh}	Shunt Resistor Current	V_D	Diode Voltage
I_{ref}	Reference current	G	Amount of Solar Radiation
R_s	Series Resistance	I_o	Diode Saturation current
R_{sh}	Shunt Resistance	V_M	Maximum Power Point Voltage
η	Ideality Factor	I_M	Maximum Power Point Current
Q	Electron Charge		
K	Boltzmann Constant	E_g	Diodes Bandwidth
T	Temperature	K_i	Current Temperature Coefficient
P_M	Maximum Power	K_v	Voltage Temperature Coefficient
N_{pc}	Number of Parallel	I_{pv}	PV Battery Output Current
Nsc	Number of Serial	G_{ref}	Amount of Solar Radiation
C_o	Temperature Coefficient	I_e	Electron Current
B	Constant Semiconductor	I_h	Hole Current

On applying Kirchhoff's law to Fig-3

Diode current depends upon the current caused by both electrons and holes hence the total overall

$$I_{pv} = I_{ph} - I_{D1} - I_{D2} - I_{sh} \qquad (2)$$

battery output current (Ipv) in eq (2) of the p-n junction is affected by diode currents too. The current through the diode for the p-n junction, is the total currents generated by the electrons and holes activated by photons mathematical. States of electrons at conduction band and space current at valence band Boltzmann distribution net flows and the space electron current flows shown in eq (3-5).

$$I_e = I_{eo}\left(e^{\frac{qV_D}{kbT}} - 1\right) \qquad (3)$$

$$I_h = I_{ho}\left(e^{\frac{qV_D}{kbT}} - 1\right) \qquad (4)$$

$$I_D = I_e + I_h = I_{eo}\left(e^{\frac{qV_D}{kbT}} - 1\right) \qquad (5)$$

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Where,
Value of q = 1.602*10-19 C
Value of k = 1.381*10-23J/K

Diode current is dependent on temperature, output current and voltage and is thereby represented in eq (6).

$$I_{pil} = I_{ph}\left(1 + C_o(T - 300)\right) - I_O\left(e^{\frac{q(V_{pv}+IR_s)}{\eta kT}} - 1\right) - \frac{(V_{pv} + IR_s)}{I_{sh}} \quad (6)$$

$$V_M = N_{sc} \cdot V_{new} \quad (7)$$

$$I_D = I_O\left(e^{\frac{qV_D}{\eta kT}} - 1\right) = I_O\left(e^{\frac{q(V_{pv}+IR_S)}{\eta kT}} - 1\right) \quad (8)$$

In eq(6) is the ideality factor. This is also known as emissivity factor. This is the most appropriate parameter that explains the behaviour of diode with the predicted and existing theory. The factor gives the explanation regarding the various mechanisms for the moving of charge carriers nearby the junction. If the value of the parameter is 1 then the entire process is due to diffusion and if the value of the parameter is 2 then the recombination process is taken into account. The maximum voltage VM is directly proportional to no. of solar cells serially connected and is represented in eq(7). Eq. (6) is performed by using of eqs. (7-8) to calculate current of solar PVC.

$$I_{sh} = \frac{V_D}{R_{sh}} - \frac{(V_{pv} + IR_s)}{R_{sh}} \quad (9)$$

$$I_{pv} = I_{ph} - I_D - I_{sh} \quad (10)$$

$$Ipv = I_{ph} - I_O\left(e^{\frac{q(V_{pv}+IR_s)}{\eta kT}} - 1\right) - \frac{(V_{pv} + IR_s)}{R_{sh}} \quad (11)$$

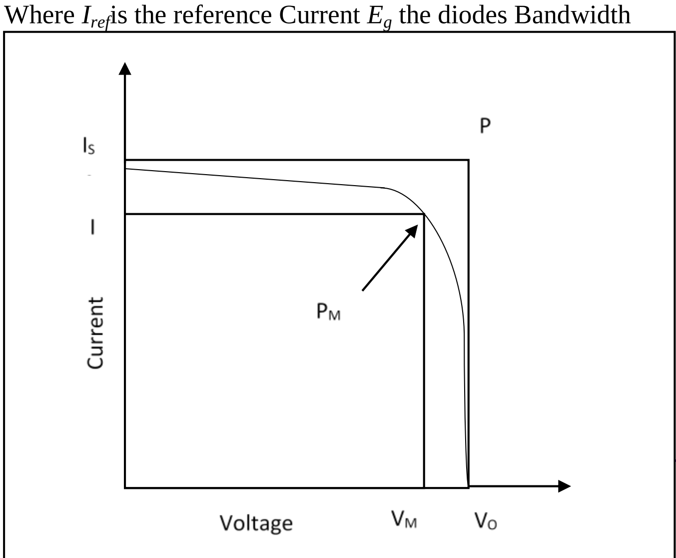
Eq(6) can be rewritten on the basis of temperature in form of eq(13)

$$I_M = N_{pc} \cdot I_{new} \quad (12)$$

$$I_o = I_{ref}\left(\frac{T_c}{T_{cref}}\right)^3 \cdot \exp\left[\left(\frac{qE_g}{nk_b}\right)\left(\frac{1}{T_{cref}} - \frac{1}{T_c}\right)\right] \quad (13)$$

$$I_{ph} = \left[I_{sc} + \alpha(T_c - 25)\right]\frac{G}{G_{ref}} \quad (14)$$

Where $I_{ref}$is the reference Current E_g the diodes Bandwidth



The main parameters of a solar cell are short-circuit current or short-circuit current density, open circuit voltage and fill factor. Study of I-V characteristics of a solar cell is very good way to get through these parameters. Fig. 4 shows the I-V characteristics of an ideal solar or photovoltaic cell.

Figure 4. I-V Characteristics of an ideal solar cell

A. *Short Circuit Current*

The current which is flowing to the external circuit of a solar cell when the solar cell is short-circuited that current is referred to as short-circuit current. The short-circuit current (ISC) is determined by the amount of photon flux is incident on the solar cell which in turn is estimated by the spectrum used [10]. The standardized solar spectrum generally used is AM1.5 (Air Mass). The short-circuit current also depends on the area of the cell. In order to remove this dependency of short-circuit current on area short-circuit current density (JSC) is used which determines the maximum current given by the solar cell. This maximum current of the solar cell rely upon its optical properties such as reflectance and absorption.

B. *Open-Circuit Voltage*

The open-circuit voltage (VOC) is a voltage that can be attained through a solar cell when the current through the external circuit is zero. This is the maximum voltage of a solar cell. The open-circuit voltage is the forward bias voltage in the dark which relates to the photogenerated current density. The open-circuit voltage depends on the short-circuit current and is given by eq(15).
The open-circuit voltage is given by:

$$V_{OC} = \frac{\eta kT}{q}\ln\left(\frac{I_{SC}}{I_O} + 1\right) \quad (15)$$

C. *Fill Factor*

Fill factor is the ratio of the maximum power to the product of short-circuit current (ISC) and open-circuit voltage (VOC). The point on the I-V curve of the solar cell where maximum current and voltage i.e. maximum power is attained that point is known as maximum power point and is given by eq(16).

$$FF = \frac{P_{max}}{I_{sc} * V_{oc}} \quad (17)$$

D. *Efficiency*

The efficiency determines the actual performance of a photovoltaic cell [11]. The efficiency is the measure of the output power to the input power. Mathematically, efficiency is the ratio of maximum power delivered by the solar cell to the input power and is given by eq(17-18):

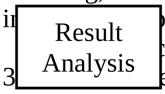
$$\eta = \frac{P_{MAX}}{P_{IN}} \quad (18)$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{IN}} \quad (19)$$

III. OPTICAL MODELLING OF THE DEVICE

A. *Optical Losses*

Some of the light that strikes the surface is reflected back. This may lead to the losses causing to reduce the short-circuit current thereby reducing the power of photovoltaic cell[12]. The light which got reflected could have generated more electron-hole pairs and should have contributed to the overall photo-generated current but it couldn't be possible due to reflection losses.There are many ways to reduce the optical losses that is the use of anti-reflection coating, surface texturing, increasing the thickness of the top layer in order to i tion.



3 tion Coating: The reflection of silicon is almost 3 ection of the bulk semiconducting materials can be a bottleneck in increasing the overall yield of the photovoltaic cell [13]. Anti-reflection coatings are the coating that reduce the reflection capacity of the material. The material usually chosen for anti-reflection is dielectric material which is also used in camera lenses. The thickness of the dielectric material should ne minimum and can be calculated by:

$$d = \frac{\lambda_o}{4\eta_1} \quad (19)$$

Where,
D= thickness of dielectric material
λ_o = wavelength of free space
η_1 = reflective index of dielectric material

Surface Texturing: Surface texturing is the method of reducing the surface reflection by roughing the surface which prevents the light to bounce back to the environment rather get absorbed by the surface.There are many ways through which surface texturing can be achieved. In crystalline silicon, surface texturing is done by using the pyramids structure which are aligned to each other.

B. *Recombination*

In p-n junction solar cell recombination takes place within the depletion or the space charge region, within the bulk material and near the surface of the solar cell. This recombination affects both short-circuit current (Isc) and open-circuit voltage (Voc). In order to increase the electron-hair generated by the photons of the light striking the semiconducting material, there is need to generate the current before they get recombine. Electrons and holes are meta-stable particles i.e. they get recombined after a certain validity of time called minority carrier lifetime. The open-circuit voltage is the voltage at which the short-circuit current and the forward bias diffusion current are equal. The forward bias diffusion current largely depends upon the recombination of the charge carriers. Increase in the recombination will increase the forward bias diffusion current thereby reducing open-circuit voltage.

IV. SIMULATION SET UP PARAMETERS

Ever since, the first solar cell had been introduced in 1883 by Charles Fritts, a tremendous growth has been done by the photovoltaic industry. The single crystalline silicon solar cells has overruled almost 86% of the industry for over the years. This paper showcase the electrical and the optical modelling of the crystalline silicon solar cell using the software SILVACO [14]. It is an electronic device automation software which synthesis the device simulation. In this paper, Atlas tool of Silvaco software is being used for the synthesis of crystalline silicon solar cell. Atlas enables the two as well as the three dimensional simulation of the device. The atlas intake a particular order of the statements.

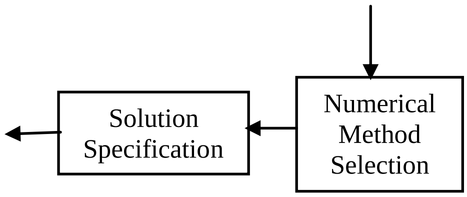


Figure 5. Flowchart of the sequence of the commands of ATLAS Tool

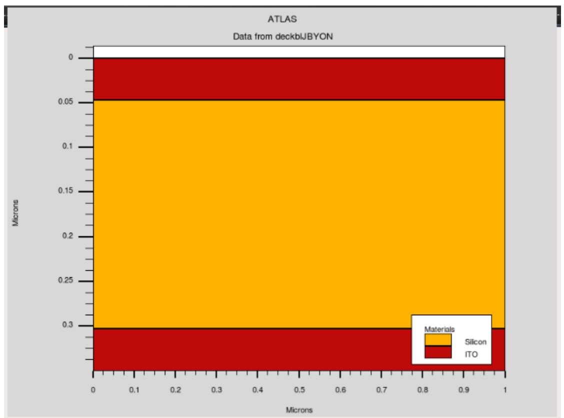
The use of appropriate model and material parameters is necessary for the simulation of devices within the Atlas tool.

TABLE II. MODELS USED FOR SIMULATION

Models	Syntax	Implication
Shockley-Read-Hall	SRH	This is used in most of the simulations and it uses the fixed value of minority carrier lifetime
Auger	AUGER	This model is necessary at high current densities. It take into account the direct transition of three carriers

TABLE III. PARAMETERS OF SILICON USED IN SIMULATION

Parameters	Value
Mobility of holes	20
Mobility of electrons	1.5
Effective density of states (Conduction band)	$2.5*10^{20}$
Effective density of states (Valence band)	$2.5*10^{20}$
Bandgap (eV)	1.72



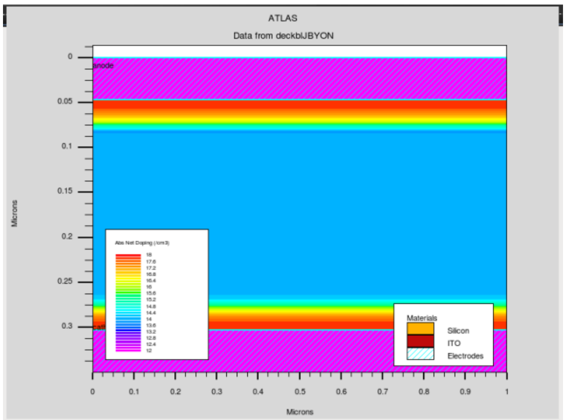


Figure 6. Snapshot of the crystalline silicon solar cell in Silvaco

V. RESULTS

The single crystalline silicon solar cell is being simulated using the Atlas tool [15] of the Silvaco software. The I-V characteristics are being plotted for several defined parameters and models.

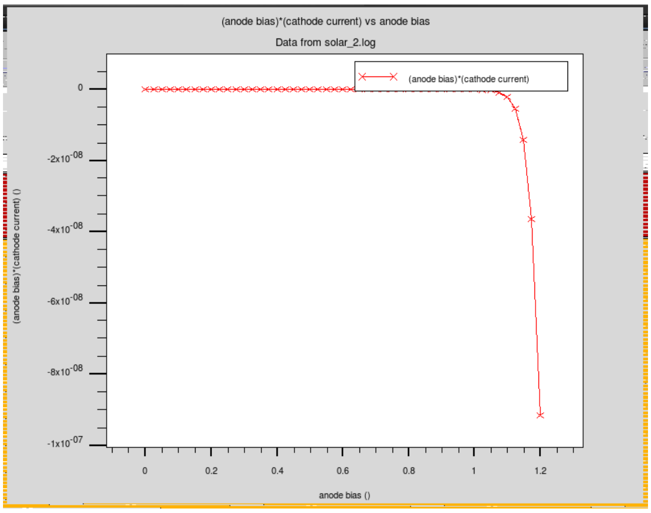


Figure 7. I-V Characteristics of crystalline silicon solar cell

The graph between optical wavelength and conversion efficiency is also plotted and is shown in figure 8.

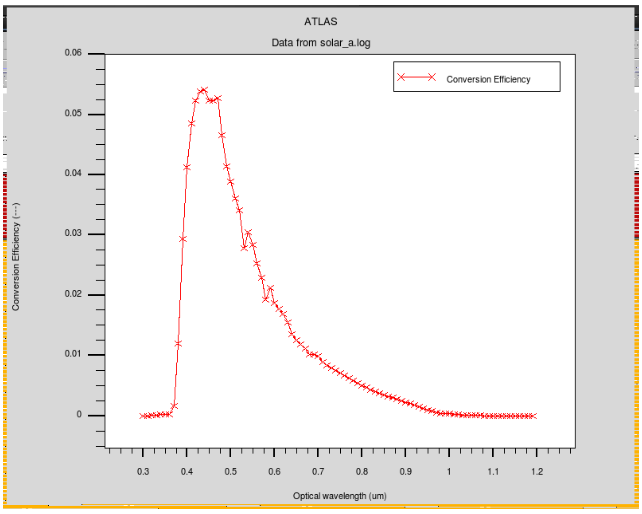


Figure 8. Conversion Efficiency Vs Optical Wavelength

TABLE IV. OUTPUT PARAMETERS OBTAINED BY THE SIMULATION AFTER OPTIMIZATION

Performance Metrics	a-Si Solar PVC
Open circuit Voltage (V_{oc})	1.287
Short circuit current (mA/ cm^2)J_{sc}	10.19
Fill Factor FF	71.843
Efficiency (%)η	9.86

VI. CONCLUSION

Solar cells have shown great rise within the photovoltaic industry for over few decades. Many research and development within this direction has changed the pathway of the photovoltaic industry and leads to a new era where efficiency and cost are the most standard concern. This paper is an effort towards the basic understanding of dependency of the yield of photovoltaic system over the electrical and optical parameters. Using a single layer of crystalline silicon solar cell with optimised thickness and choosing the right parameters leads to the reduction in the cost of the solar cell.The simulated results shows that the parameters such as open circuit voltage, short circuit current, fill factor are essential in determining the efficiency of the solar cell.

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