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Comparative study on the efficiencies of silicon solar cell

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Abstract: *In this contribution, a comparative study on the theoretical efficiency and experimental efficiency of silicon solar cell has been carried out. By modifying the surface recombination velocity equation and accommodating required standard equations, a modified version of spectral p-n junction model has been developed and by using this model the theoretical efficiencies of silicon solar cell have been simulated as 20.9% and 22% for airmass AM1.5G global and AM 1.5D direct normal under one sun condition respectively using MATLAB (R2010a). The experimental efficiency of this same cell has been determined as 13.5% for airmass AM1.5 by using solar simulator (Sun Simulator K3000 LAB55). Finally, a comparison has been done among these efficiencies and found that the main cause for this deviation among these efficiencies is the short circuit current density.*

Keywords: *Comparative study, experimental efficiency, theoretical efficiency and solar cell.*

I. Introduction

Solar cell is to design for converting the photon of sun light into electron to generate electricity. In literature, conversion efficiency of solar cell is to define as the ratio of output power from the solar cell to incident input power. Based on several standards theoretical model, theoretical efficiency could be simulated by using various high-level programming languages such as matrix laboratory (MATLAB) software or this conversion efficiency could be measured by sun simulator to get laboratory efficiency experimentally. However, study on silicon solar cell was started in mid twentieth century after the invention of p-n junction diode [1]. In 1954, first modern silicon solar cell with efficiency of 6% has been developed in Bell Laboratory [2]. In 1961, William Shockley and Hans Queisser reported the Shockley–Queisser limit or detailed balance limit to evaluate the maximum theoretical efficiency of 33.7% for a single junction solar cell [3]. In 1987, Matthias and Barnnett published another model termed as spectral p-n junction model both for single junction cell and tandem cell for infinity thickness cell (i.e., thickness that can absorbs all incident irradiance equal or greater than the corresponding bandgap of the material) [4] and in 1990, considering the thickness and modifying the reverse saturation current density equation, Sarah Kurtz et al reported a theoretical model for tandem solar cell [5], but in that model, Sarah Kurtz considered zero surface recombination velocity. Over the years, considering the accurate surface recombination velocity, different research groups from all over the world, published different effective theoretical models for solar cell [6-8]. Based on these theoretical models, single junction silicon solar cell has been fabricated in laboratory by using different fabrication methods and instruments and the experimental efficiency of this cell has been measured by different types of Sun Simulators.

This paper is configured in a fashion that theoretical work is elucidated in section-2, experimental work in section-3 and comparative study between these works is carried out in section-4.

II. Theoretical Efficiency

As already mentioned that considering the appropriate thickness and modifying the equation of surface recombination velocity a theoretical model has been developed by accommodating of the spectral p-n junction model, Sarah Kurtz's model and standard equations of solar cell [4, 5, 7, 9, 10]. This model could be utilized both for single junction solar cell as well as multijunction solar cell.

2.1. Methodology

According to this model, the short circuit current density (Jsc) depends on the band gap of silicon, has been determined directly from the ASTM G173-03 reference spectra derived from SMARTS v. 2.9.2 (AM1.5) [11]. The photon flux F is calculated from the irradiance I and wavelength λ [4].

$$J_{sc} = e \times F \qquad (1)$$

$$F = \frac{\lambda I}{hc} \qquad (2)$$

where, e is electronic charge, F is photon flux, h is Plank constant ,λ is wavelength of incident irradiance and c is velocity of light.
The reverse saturation current density, $J_{0,}$ has been calculated as the sum of the currents for the n-type and p-type layers [5].

$$J_0 = e\left(\frac{D_e}{\tau_e}\right)^{\frac{1}{2}} \frac{n_i^2}{N_A}\left(\frac{S_e\left(\frac{\tau_e}{D_e}\right)^{\frac{1}{2}}\cos h\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+\sin h\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}{S_e\left(\frac{\tau_e}{D_e}\right)^{\frac{1}{2}}\sin h\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+\cos h\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}\right) + e\left(\frac{D_h}{\tau_h}\right)^{\frac{1}{2}} \frac{n_i^2}{N_D}\left(\frac{S_h\left(\frac{\tau_h}{D_h}\right)^{\frac{1}{2}}\cos h\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+\sin h\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}{S_h\left(\frac{\tau_h}{D_h}\right)^{\frac{1}{2}}\sin h\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+\cos h\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}\right) \qquad (3)$$

where, D_e is diffusion current constant for electron, D_h is diffusion current constant for hole, τ_e is minority carrier life time for electron, τ_h is minority carrier life time for hole, n_i is intrinsic carrier concentration, N_A is acceptor concentration, N_D is donor concentration, S_e is surface recombination velocity of electron, S_h is surface recombination velocity of hole, X_p is thickness of p-layer and X_n is thickness of n-layer. The diffusion constant $D_{e,}$ and D_h has been calculated from the Einstein's relation-ship:

$$D_e = \frac{kT\mu_e}{e} \qquad (4a)$$

$$D_h = \frac{kT\mu_h}{e} \qquad (4b)$$

Here, μ_e is mobility of electron, μ_h is mobility of hole, k is Boltzmann's constant. The minority carrier life time τ_e and τ_h has been calculated from,

$$\frac{1}{\tau_e} = \frac{1}{\tau_{SRH}} + BN_A \qquad (5a)$$

$$\frac{1}{\tau_h} = \frac{1}{\tau_{SRH}} + BN_D \qquad (5b)$$

Here, τ_{SRH} is Shockley-Read-Hall life time; B is the band-band recombination co-efficient. The surface recombination velocity of electron S_e and hole S_h has been derived as

$$S_e = \frac{D_e}{L_e} = \frac{D_e}{\sqrt{\tau_e D_e}} = \sqrt{\frac{D_e}{\tau_e}} \qquad (6a)$$

$$S_h = \frac{D_h}{L_h} = \frac{D_h}{\sqrt{\tau_h D_h}} = \sqrt{\frac{D_h}{\tau_h}} \qquad (6b)$$

The intrinsic carrier concentration n_i^2 has been calculated from,

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$$

$$n_i^2 = 4M_c M_v \left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{\frac{3}{2}} \exp\left(\frac{-E_g}{kT}\right) \qquad (7)$$

Where N_c and N_v are the densities of state in the conduction and valance band, E_g is band gap of the material, M_c and M_v are number of equivalent minima in the conduction band and valance band, m_e^* and m_h^* are the effective mass of electrons and holes respectively. A cell with band gap E_g when exposed to the solar spectrum, a photon with energy greater than E_g, contributes an energy of E_g to the cell output and the excess energy (> E_g) is wasted as heat.

Then total current density

$$J = J_0\left(e^{\frac{qv}{KT}} - 1\right) - J_{ph} \qquad (7)$$

Open circuit voltage V_{oc} can be calculated from this equation by putting J= 0,

$$V_{oc} = \left(\frac{kT}{e}\right)\ln\left[\left(\frac{J_{sc}}{J_0}\right) + 1\right] \qquad (8)$$

Others parameters such as maximum voltage (Vm), maximum current density (Jm), maximum power (Pmax), fill factor (FF) and efficiency of silicon solar cell have been simulated by using the standard solar cell equations [7, 9, 10].

2.2. Material Parameters

For simulating the reverse saturation current density equation, all optoelectronics parameters of silicon solar cell have been considered at 300K temperature. Some of these parameters are constant and most of these have the fixed values, except thickness and carrier concentration. In literature, to date, there are several dopant of different elements used to increase the conductivity of silicon [12, 13]. So, due to variation of doping elements, donar and acceptor concentration of silicon solar cell could be varied. The optoelectronics parameters of silicon solar cell have been presented in table-1.

Table-1: Material properties of silicon solar cell.

Parameter	Si
λ	1.1077e-6
M_c	1
M_v	1
μ_e	1500 cm^2/Vs [14]
μ_h	450 cm^2/Vs [14]
m_e^*/m_e	0.98 [14]
m_h^*/m_e	0.16 [14]
τ_{SRH}	10^{-5} (s)
B	$7.5\times10^{-10}(s^{-1}cm^3)$
N_A	$1\times10^{15}cm^{-3}$ [15]
N_D	$1\times10^{20}cm^{-3}$ [15]
X_n	$160e^{-9}m$
X_p	$5e^{-6}m$

Table-2: MATLAB simulated results

Parameter	AM1.5G	AM1.5D
Jsc	43.1216 mA/cm^2	40.945 mA/cm^2
De	39 cm^2/s	39 cm^2/s
Dh	12 cm^2/s	12 cm^2/s
τ_e	1.33e-2 cm^2/V s	1.33e-2 cm^2/V s
τ_h	1.33e-7 cm^2/V s	1.33e-7 cm^2/V s
Se	5395.31 cm/sec	5395.31 cm/sec
Sh	9.34e5 cm/sec	9.34e5 cm/sec
Jo	5.37e-9 mA/cm^2	5.37e-9 m A/cm^2
Voc	0.5901 V	0.5888 V
Vm	0.5107 V	0.5093 V
Jm	40.95 mA/cm^2	38.878 mA/cm^2
FF	0.8218	0.8214
η	20.9117 %	22.0016 %

1.3. Matlab Simulated Results

In this model, zero losses from reflection, grid coverage and series resistance have been treated. For efficiency determination, the input power has been used as 1000 Wm^{-2} for AM1.5G and 900 Wm^{-2} for AM1.5D under one sun condition. The table-2 presents the MATLAB (R2010a) simulated results of different performance parameters of the silicon solar cell. As the same optoelectronics properties have been used to simulate the diffusion constant, mobility, surface recombination velocity for both electron and hole, so the same results has been achieved for both conditions. But the variation of efficiencies is due to the intensity of incident irradiance and the input power of AM1.5G and AM1.5D. The theoretical efficiencies of these conditions have been simulated as 20.9 % and 22 % respectively under one sun condition.

III. Experimental Efficiency

3.3. Experimental Results By Sunsimulator

For conducting the experimental study, we have collected a 2×2 cm^2 monocrystalline silicon solar cell, which has been placed on the jig of solar simulator's (Sun Simulator K3000 LAB55) platform at 25°C. Xenon lamp of sun simulator produced light of input power 1000Wm-^{2}. Before taking the result from the solar simulator, calibration has been done with respect to a reference cell. The vertical position of the reference cell has been adjusted such that the major performance parameters of the cell obtained from the simulator match exactly to its specification sheet. By using sun simulator, we have obtained the following results which are presented in the table-3 below.

Table-3: Results from sun simulator

Test Result	
Voc(V) :	0.61
Isc(mA) :	112.868
Jsc(mA/cm^2) :	28.217
Pmax(mW) :	54.091
Vmax(V) :	0.509
Imax(mA) :	106.28
Fill Factor (%):	78.53493
Efficiency (%):	13.5228
R Shunt(Ohm) :	1722.201
R Series(Ohm) :	0.539

IV. Discussion

In this theoretical simulation, the same reverse saturation current density has been found for both atmospheric conditions because the same semiconducting properties of silicon solar cell have been used. Reverse saturation current density play a critical role in theoretical efficiency, could be changed due to the variation of the thickness of n-type and p-type layer of this silicon cell and changing the temperature. Current density Vs voltage (J-V) characteristics curve has been generated based on this model which is very much alike to the I-V characteristics curve found in literature, presented in the following figure -1.

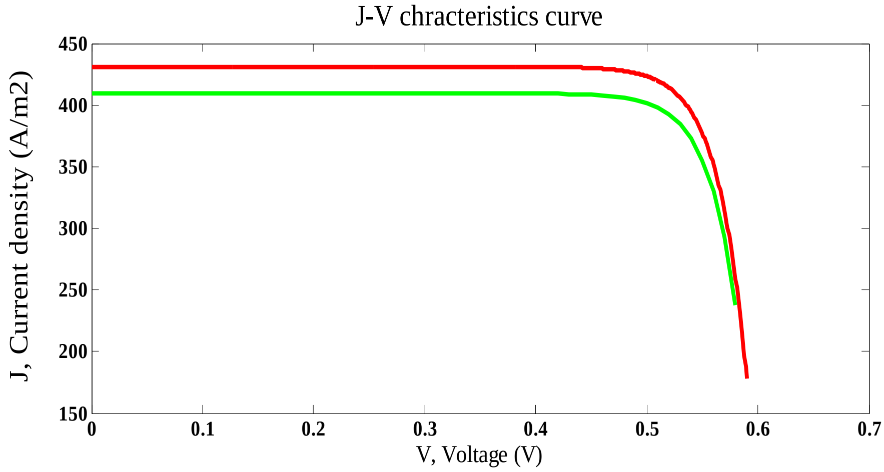

Fig.1. J-V characteristics curve from the theoretical model

The same J-V characteristics curve presented in figure-2 generated by the data obtained from sun simulator. This curve is similar with the theoretical curve. Here it should be mentioned that current density is obtained from theoretical model presented in S.I. unit (A/m^2) but sun simulator provided this curve in a conventional unit of mA/cm^2.

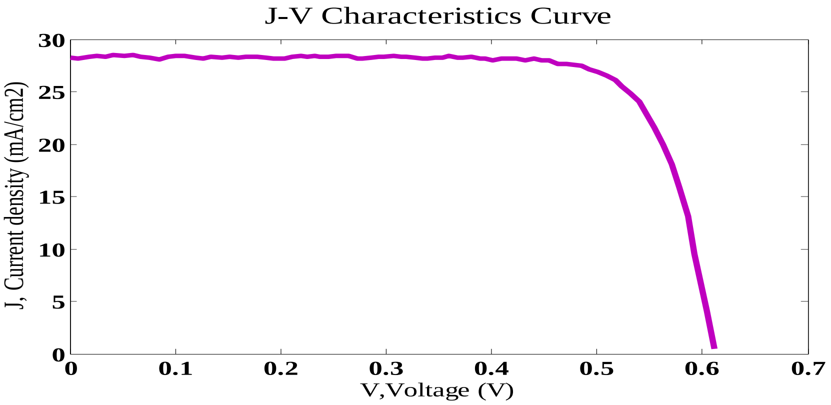

Fig.2. J-V characteristics curve for experimental data from sun simulator

Reference cell and it's placement on the jig is very important because changing the vertical position of the cell on the platform could change the efficiency. Although most of the performance parameters of theoretical and experimental study are almost to the same but it has been observed that some discrepancies exist between these efficiencies. In our theoretical treatment, zero series resistance is considered but in experimental study, it has been found that the series resistance is 0.539 ohm. Again, there is a large variation of short circuit current density and reason behind this discrepancy is zero loss for reflection and grid coverage are treated, but in a practical cell, sun simulator counted these loss factors. Again, open circuit voltages obtained from both types of study are almost equal and it greatly depends on the reverse saturation current density which depends on the material properties. A comparison also carried out between our obtained efficiencies to the highest state-of-the-art efficiencies of silicon solar cell. Maximum laboratory efficiency measured for a single junction monocrystalline silicon solar cell is 25.6% and for multicrystalline silicon solar cell 20.4% [16]. These efficiencies are differ from our efficiencies, reason behind this discrepancy is the open circuit voltage (Voc = 0.74Vfor minocrystalline cell and Voc=0.66V for multicrystalline cell) is greater than from out obtained efficiencies but other parameters are almost same (Jsc = 41.8 mA/cm^2, FF 82.7% for monocrystalline cell and

Jsc=38 mA/cm^2 and FF=80.9% for multicrystalline cell). These results also been compared with our theoretical and experimental results presented in table-4.

Table-4: Comparison of different performance parameters for theoretical and experimental efficiency

Parameter	Theoretical result from MATLAB		Experiment result from sun simulator
	AM1.5G	AM1.5D	
Short-circuit current, Jsc (mA/cm^2)	43.12162	40.94519	28.217
Open-circuit Voltage, Voc (V)	0.5901	0.5888	0.61
Maximum current density, Imax (mA/cm^2)	40.95	38.88	26.57
Maximum voltage, Vmax (V)	0.5107	0.5093	0.509
Fill-Factor	0.8218	0.8214	0.7853493
Efficiency (%)	20.9117%	22.0016%	13.5228

V. Conclusion

Theoretical and experimental efficiency of monocrystalline silicon solar cell has been simulated using MATLAB and sun simulator respectively and comparison among the various performance parameters of both efficiencies have been done. In this model no attempt has been made to account for the effect of thickness in short circuit current density equation which is principally responsible for the observed discrepancy. It has been concluded that, this model would be useful for silicon solar cell performance parameter approximation if thickness is incorporated with short circuit current density equation.

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