Effect of Different Solar Radiation on the Efficiency of $GaInP_2/GaAs/Ge$ based Multi Junction Solar Cell

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***Abstract*—This paper represents the effect of different solar radiance on the efficiency of $GaInP_2$/GaAs/Ge based multi junction solar cell. Solar radiation is different for different air mass. The value of irradiance changes with the different wavelength and different air mass. With the change in the irradiance data, the theoretical efficiency of the multi junction solar cell changes. The whole calculation is based on a modified version of spectral p-n junction solar cell model. The three sub layers are lattice matched and connected in series so that optical transparency and maximum current conductivity through the top and bottom cell can be produced. Short circuit current density, open circuit voltage, maximum current density, maximum power, fill factor and efficiency change with the variation of irradiance for the different air mass. For the simplicity of calculation, there are some assumptions which are necessary. The analysis is done under one sun condition. The result of variation in J-V characteristic for different layers and for different air mass condition is plotted in the graph.**

***Index Terms*—multijunction solar cell, efficiency, air mass, current density, irradiance**

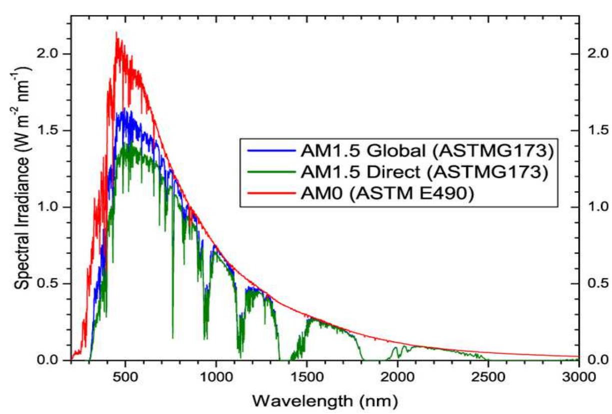

Fig. 1: Spectral irradiance for the different AM

I. INTRODUCTION

Power crisis has been one of the most significant issues all over the world. Scientists and researchers have been working relentlessly to find a solution for this problem. Most of them are doing their work on renewable energy. Because the amount of energy that can be generated from coal, gas or any other petroleum materials is limited. So scientists are more encouraged to work on the renewable energy sources for its unlimited availability. Among all the renewable energy sources, solar energy has got more popularity than all the others. Many works have been done to increase the efficiency of the solar cell.

Single junction solar cell was first introduced. But the efficiency of this solar cell is very low because the maximum efficiency depends on the incident spectrum [1]. The reason working behind that is, there is a good amount of solar spectrum remains unabsorbed due to the single junction. As the absorption is done by only one layer, the energy of the photon greater than the band gap cannot be absorbed by the single junction.

The researchers then developed an idea of converting different parts of solar spectrum that will be incident to the cell. This idea was considered since 1995 [2] [3]. So to reduce the losses and to increase the efficiency of solar cell, multi junction solar cell is introduced. With the innovation of multi junction solar cell, different solar spectrum now can be absorbed by the different layer of the multi junction solar cell. So the losses are reduced that results in increasing the efficiency.

In the figure: 1, it is clearly seen the solar spectra for different air mass [4]. From the figure it is seen that in multi junction solar cell it is possible to absorb most portions of solar radiation by choosing the band gap of different layers.

For the calculations of different parameters of solar cell, many scientists have given different models. First modern silicon solar cell with efficiency of 6 % has been developed in Bell Laboratory in 1954 [5]. In 1961,William Shockley and Hans Queisser reported the maximum theoretical efficiency of

33.7% for a single junction solar cell [6]. Spectral p-n junction model was published both for single junction cell and tandem cell for infinity thickness cell that is the thickness absorbed all incident irradiance equal or greater than thecorresponding band gap of the material [7]. Considering the thickness and modifying the reversesaturation current density equation, a theoretical model for tandem solar cell was reported [8].

For different value of air mass (AM) condition such as AM0,AM 1.5D and AM 1.5G the efficiency of $GaInP_2/GaAs/Ge$ based multijunction solar cell has been calculated in this paper.

In this paper, section II depicts the discussion about solar cell and renewable energy, section III describes the multi junction solar cell model parameters, section IV gives the idea about the assumptions that are made for the calculations as well as the optoelectronic parameters of the different layer materials, section V shows the results for three air mass conditions and then the paper is concluded in the next section.

II. Solar Cell

Renewable energy is derived from naturally regenerative sources like solar, wind, geothermal or hydroelectric actions. Among these sources the demand of solar energy is increasing rapidly for its feasibility in developing countries. A solar cell is an electrical device by which light energy can be converted into electricity. The electrical characteristics of this photoelectric cell vary due to the different intensity of light [9]. There are various types of solar cells. Single crystalline i.e. monosilicon solar cell having commercial efficiency of about 22% is mostly used in integrated circuits and processing units of computers.

Thin film solar cells have semitransparent nature with lower efficiency of about 12-20%.The third generation PV cell or Organic PV cell are used for light absorption or electrical charge transport [10]. Single junction solar cells usually have lower efficiency. Increasing short circuit current density by better light trapping the efficiency can be improved for single junction solar cells [11].

III. Multijunction Solar Cell Model

Single junction solar cells have lower efficiency. Increasing the efficiency of PV cell is the main motto of current generation that is why multi junction solar cell is introduced into modern technology. Multijunction solar cells are constructed by connecting two or more p-n junction layers in series. Multijunction solar cells can generate power over a larger spectrum of sunlight having a higher efficiency than single junction solar cells. The lattice of the materials must be matched with each other to produce the same current in the different layers of multijunction solar cell. Thus the design for this kind of solar cell becomes complex with an increasing cost [12].The efficiency can be increased due to the reduction of top cell thickness. Cells with low surface recombination velocities can also help to increase open circuit voltage, resulting in higher efficiency [1]. The irradiance changes with the change in air mass coefficient. Thus the efficiency can be varied by using different air mass coefficient (AM).

The short circuit current density J_sc can be calculated by using irradiance data [13].

$$J_{sc} = eF \tag{1}$$

Where, F is the photon flux and e is the charge of an electron. Again,

$$F = \frac{\lambda I}{hc} \tag{2}$$

Where, is the wavelength, I is the irradiance, h is the Planck's constant and c is the speed of light.

The reverse saturation current density can be expressed as [1] [7] [8],

$$J_0 = e\sqrt{\frac{D_e}{\tau_e}}\frac{n_i^2}{N_A}\left(\frac{S_e\sqrt{\frac{\tau_e}{D_e}}\cosh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+\sinh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}{S_e\sqrt{\frac{\tau_e}{D_e}}\sinh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+\cosh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}\right) + e\sqrt{\frac{D_h}{\tau_h}}\frac{n_i^2}{N_D}\left(\frac{S_h\sqrt{\frac{\tau_h}{D_h}}\cosh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+\sinh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}{S_h\sqrt{\frac{\tau_h}{D_h}}\sinh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+\cosh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}\right) \tag{3}$$

Where, D_e and D_h are the diffusion current constant for electron and hole respectively. $N_A$is acceptor concentration, N_D is donor concentration, S_e and S_h are the surface recombination for electron and hole respectively, n_i is the intrinsic carrier concentration, τ_e is the minority carrier lifetime for electron and τ_h is the minority carrier lifetime for hole, x_p and x_n are the thickness of p-layer and n-layer respectively.

For the ease of calculation the above equation can be simplified as,

$$J_0 = eS_e\frac{n_i^2}{N_A} + eS_h\frac{n_i^2}{N_D} \tag{4}$$

The diffusion constants can be calculated from the Einstein Relationship,

$$D_e = kT\frac{\mu_e}{e}$$
$$D_h = kT\frac{\mu_h}{e}$$

Where, k is the Boltzmann's constant, μ_e is the electron mobility and μ_h is the hole mobility. The equation for minority carrier lifetime for electron and hole are:

$$\tau_e = \frac{1}{\frac{1}{\tau_{SRH}} + BN_D}$$
$$\tau_h = \frac{1}{\frac{1}{\tau_{SRH}} + BN_D}$$

B is the direct band-band recombination coefficient and is the Shockley-Read-Hall lifetime. The surface recombination velocities for electron and hole can be written as:

$$S_e = \sqrt{\frac{D_e}{\tau_e}}$$

$$S_h = \sqrt{\frac{D_h}{\tau_h}}$$

The intrinsic carrier concentration can be calculated from:

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

Where, M_c and M_v are the densities of states in the conduction and valance band, T is the temperature, E_g is the energy gap of the material, $_e^*$ and m_h^* are the effective mass of electrons and holes respectively, M_c and M_v are the number of equivalent minima in the conduction and valance band. The open circuit voltage can be expressed as:

$$V_{oc} = \left(\frac{kT}{e}\right) \ln\left(\left(\frac{J_{sc}}{J_0}\right) + 1\right) \tag{5}$$

The maximum voltage is:

$$V_m = V_{oc} - \frac{1}{\beta}\ln(1 + \beta V_m)$$

Maximum current density is:

$$J_m = J_{sc}\left(1 - \frac{1}{\beta V_m}\right)$$

The final equation for the efficiency of the solar cell is:

$$\eta = \frac{V_{oc} J_{sc} F.F.}{P_{in}} \times 100\%$$

Where, P_{in} is the input power and F.F. is the fill factor

IV. Assumptions and Parameters

The parameters that are required for calculation of different layers of the semiconductor materials are considered at the temperature of 298K. The input power densities for AM0 is 1353 W/m^2 and for AM1.5G is 1000 W/m^2 and for AM1.5D is 900 W/m^2 [14] [15] [16]. It is also assumed that there are no losses regarding reflection, grid coverage and series resistance. All the calculations are done using the modified versions of standard equations that is the modified version of spectral p-n junction model [1] [8]. The value of irradiance data is gathered from the data provided by ASTM [17].

It has been considered that, there is no carrier generation or recombination in the space charge region, neutral region operates at low injection condition and electric field in neutral region is negligible and photon recycling effects are also negligible.

The optoelectronic parameters are collected for 298K temperature [18] [19] for the different materials used for the three layers.Taking the values of different parameters from the table I, the calculations are done for the various equations that are mentioned in the previous section. The three materials that are chosen for the different layers are lattice matched.

TABLE I: Optoelectronic Parameters [18] [19]

Parameter	$GaInP_2$	$GaAs$	Ge
Band Gap,(E_g) eV	1.9	1.42	0.67
wavelength,(λ) nm	654.28	875	1775
No of Equivalent Minima in Conduction Band (M_c)	1	1	1
No of Equivalent Maxima in Conduction Band (M_v)	3	1	1
electron mobility (η_e) m^2/Vs	0.4	0.2322	0.39
hole mobility (η_h) m^2/Vs	0.02	0.02	0.19
m_c^*/m_e	0.155	0.067	1.64
m_h^*/m_h	0.460	0.473	0.28
Shockley-Read-Hall Lifetime(T_{SRH}) s	10^{-5}	10^{-5}	10^{-5}
Direct band-band recombination co-efficient(B) s^1m^3	7.5×10^{-16}	7.5×10^{-16}	7.5×10^{-16}
Acceptor Concentration (N_A) m^{-3}	1×10^{23}	9×10^{23}	1×10^{23}
Donor Concentration (N_D) m^{-3}	2×10^{24}	7.8×10^{23}	2×10^{24}
Thickness of p-layer(X_p) m	1×10^{-07}	1×10^{-07}	1×10^{-07}
Thickness of n-layer(X_n) m	2.08×10^{-07}	3×10^{-07}	4×10^{-07}
Lattice constant (a) m	5.660×10^{-10}	5.659×10^{-10}	5.646×10^{-10}

Most of the parameters are dependent on the temperature. So if the temperature is changed, the values of these parameters will change. The thickness of the p layer is kept same for the each layer whereas the thickness for the m layer is different for the three layers of the multi junction solar cell.

V. Results

Using the different equations mentioned in section III the following calculations are done. MATLAB is used for the calculations of the different parameters.

In table II the variations of short circuit current density and the open circuit voltage of the three layers for different air mass condition is shown.

Table III depicts the variations in overall current density, total open circuit voltage, maximum voltage, maximum current density, fill factor and efficiency of the solar cell for different solar radiation spectrum for different air mass.

The total leakage current density vs the open circuit voltage for each multi junction solar cell under different air mass solar radiation spectrum is plotted in the graph.

Figure:2 shows the J-V characteristic for solar radiation spectrum under AM0 condition, figure: 3 shows the J-V

TABLE II: Comparison Of Different Layers

Parameters	AM0	AM 1.5 G	AM 1.5D
Top Layer $GaInP_2$			
Short circuit current density(J_{sc1}), A/m^2	828.9520	744.89	674.0564
Open circuit voltage(V_{oc1}), V	1.4387	1.4300	1.4334
Mid Layer $GaAs$			
Short circuit current density(J_{sc2}), A/m^2	658.5420	652.39	623.859
Open circuit voltage(V_{oc2}), V	1.0418	1.0415	1.0404
Bottom Layer Ge			
Short circuit current density(J_{sc3}), A/m^2	251.3022	163.9747	160.1052
Open circuit voltage(V_{oc3}), V	0.1325	0.1216	0.1210

TABLE III: Comparison Of The Total Cell Parameter

Parameters	AM0	AM 1.5 G	AM 1.5D
Short circuit current density(J_{sc}), A/m^2	251.3022	163.9747	160.1052
Total open circuit voltage(V_{oc}), V	2.6129	2.5991	2.5947
Maximum voltage (V_m), V	2.4939	2.4802	2.4759
Maximum current density (J_m), A/m^2	248.7122	162.2754	158.4431
Fill Factor (F.F.)	0.9446	0.9444	0.9443
Power input (P_{in}) , W/m^2	1353	1000	900
Efficiency (η), %	45.8441	40.2482	43.5879

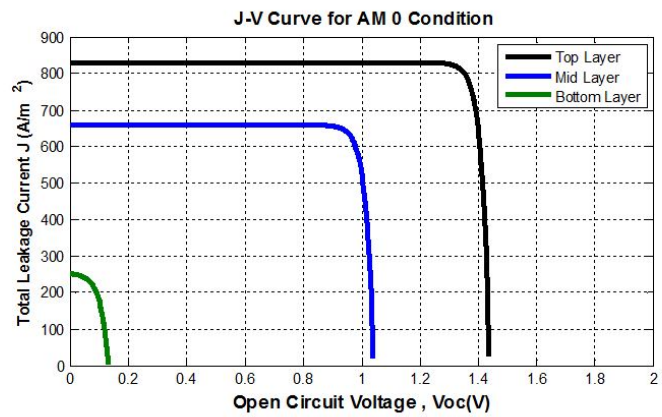

Fig. 2: J-V characteristic for AM0

characteristic for solar radiation spectrum under AM1.5D condition & figure: 4 shows the J-V characteristic for solar radiation spectrum under AM1.5G condition.

The total leakage current density is different for different layer and also for different solar radiation spectrum. The reason behind this is the short circuit density is dependent on the irradiance. The value of irradiance varies for the different wavelength. The wavelength is different for different band gap as well as for different layers for absorption. So as the value of irradiance is varying so does the total leakage current density.

For AM0 condition, the value of irradiance data [20] is higher than that of the AM1.5G and AM1.5D.because AM0 is suitable condition for space where the solar radiation is much more than the earth surface. The data that is used is generated by the American Society for Testing and materials (ASTM). It is one of the most accurate and recognized data for multi junction solar cell which is developed by counting one year average weather of United States of America [14]. Efficiency for AM1.5D is greater than the efficiency for AM1.5G because sunlight hit the solar cell directly in case of AM1.5D and for AM1.5G sunlight hit the solar cell after diffusion.

In the above figures, it is clearly seen that the total leakage current density remains same for a certain increment of open circuit voltage. But after a certain voltage the current density falls. By finding a maximum current and voltage and multiplying them maximum power can found for the solar cell.

In each solar cell, the minimum leakage current is flowing from the bottom layer. So the total cell current density will be the value of the bottom cell current density. So to increase the cell efficiency, the increase of leakage of current density in the bottom cell is necessary.

This characteristic may change in the practical scenario as there are losses. Conditions like carrier recombination in the space charge region, operating injection condition of neutral region, the amount of electric field in the neutral region, effects

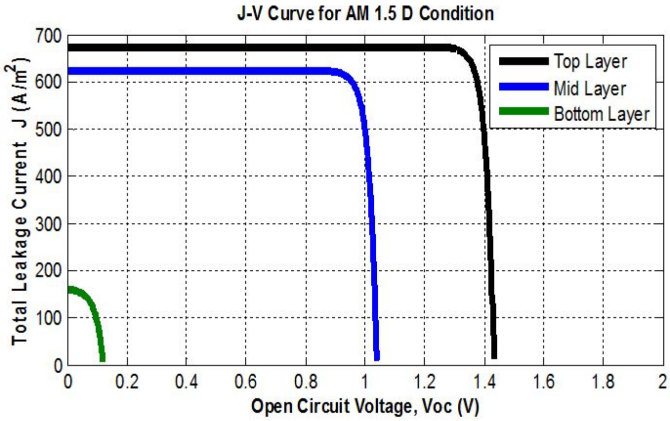

Fig. 3: J-V characteristic for AM1.5D

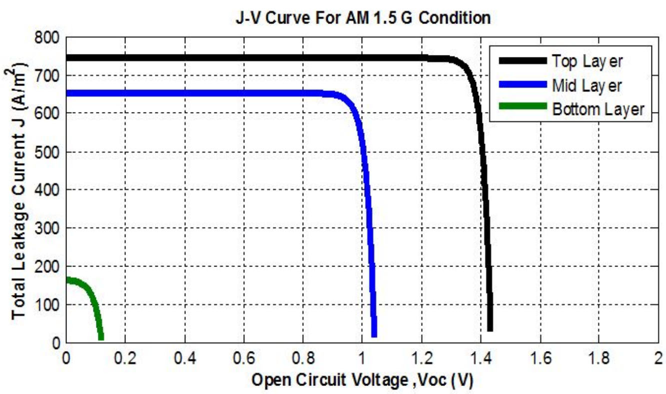

Fig. 4: J-V characteristic for AM1.5G

of photon recycling can cause decrement to the leakage current density and open circuit voltage leads to the reduction in the maximum power resulting in reducing the overall efficiency.

VI. Conclusion

The paper represents the variations in efficiency of GaInP2/GaAs/Ge based multijunction solar cell in different AM conditions such as AM0 , AM1.5D & AM 1.5G. Parameters such as short circuit current density, open circuit voltage also vary in each of the three layers considering change in AM condition. Maximum current density ,maximum voltage & total leakage current for the cell shows a significant change for diverse air mass values. For the three layer solar cell, the minimum current density is found in the bottom cell and it is the current density for the solar cell. As the junctions are connected in series, the open circuit voltage rises as the total open circuit voltage is the summation of three layers open circuit voltages.

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