Numerical Simulation Model of Multijunction Solar Cell

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Abstract: Multi-junction solar cells play an important and significant role in the Concentrated Photovoltaic (CPV) Systems. Recent developments in Concentrated Photovoltaic concerning high power production and cost effective- ness along with better efficiency are due to the advancements in multi-junction cells. Boeing SpectroLab Inc. has introduced a Multi-junction solar cell employing tunnel junctions which improves efficiency up to 40%.

This paper presents a simulation model of the generalized Multi-junction solar cell. The model adopts a mathematical approach in order to simulate and investigate the cell characterization curves including current density and power curves with respect to the applied voltage for different concentration levels and number of junctions and by varying the material properties of the multi-junctions and the tunneling layer.

The proposed simulation model simulates the performance characteristics of two different natures of multi-junction solar cells including InGaP/GaAs Dual-junction Solar Cell (DJSC) with tunneling layer of InGaP and InGaP /GaAs/Ge Triple-Junction Solar Cell (TJSC) with tunneling layer of GaAs. Simulation results are presented in this paper which is in agreement with experimental results.

Key–Words: Modeling, Multi-junction Solar Cell, Simulation, Tunnel Junction

1 INTRODUCTION

The modernization in photovoltaic systems has led to recent research in the new generation of solar cell which use large spectrum of solar radiation for better efficiency. Multi-junction solar cell (MJSC) is a combination of different type of photovoltaic junctions stacked over one another via homo-junctions, intrinsic materials or tunnel junctions. Different solar cells have different bandgap energies and physical properties. Combining several of these solar cells allows it to efficiently capture and convert a large range of photon wavelengths into electrical power. Presently, MJSCs are capable of generating approximately twice as much power as the conventional solar cells [1–6].

Theoretical efficiency of around 30% was obtained by Boeing Spectrolab Inc. with a state-of-art triple junction GaInP/GaInAs/Ge solar cell. This cell is designed to produce V_{OC} =2.651V, I_{SC} = 17.73mA/cm^2, has efficiency = 29.3% and the fill factor = 84.3% [7].

The studies show that much higher efficiencies can be achieved by increasing the number of solar cell layers [1]. This involves an innovative concept of Concentrated Photovoltaics (CPV) in which light is concentrated over the panel via reflectors. The solar concentration level is usually divided into four regions. As the concentration level increases, Multi-junction does not only face tracking and thermal management issues but the resultant increase in current densities also influences the stability of the tunnel junction [8–12].

There are many publications over the microscopic electrical to the miscopy molecular level modeling and experimental viewpoints on Multi-junction Solar cell. Thus, a large number of models are to consider for just only observing the characteristics performance of Multi-junction Solar cell.

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Above all, this is also the fact that all models are not compatible with each other. This makes selection quite hard and perplexing. The paper proposes the strategy and methodology for modeling multi-junction solar cell and observes the characteristics performance of MJSC for different environmental condition. A complete physical level model is developed in MATLAB/Simulink.

Figure 1 Right: Dual Junction Solar Cell Prototype Structure, Left: Triple Junction Solar Cell Prototype.

Table 1: Parametric values of tunnel junctions [4].

	Peak Voltage (mV)	Peak Current (mA)	Ip /Iv Ratio	Doping Concentration (/cm3)	Bandgap (eV)
GaAs/GaAs	195	35	12/1	8e-18/1e-19	5.65
GaInP/GaInP	140	40	9/7	8e-18/1e-19	1.9

2 MULTI-JUNCTION SOLAR CELL STRUCTURE

Consider the MJSC of structure shown in Fig. 1. This triple junction consists of a GaInP solar cell as the top layer, GaAs in the middle, and Ge layer as a bottom layer of the solar cell. And Double junction consists of InGaP as top cell and GaAs as bottom cell.

Moreover, as shown in Fig. 1 these are joined together with a special junction called tunnel junction and are also provided with window layers. Window layer prevents surface recombination and smooth out the lattice change by introducing a gradient between the materials. The band gap of this material is selected such that it is higher than that of the cells below it. The thickness of the window is selected such as not to affect the photon efficiency greatly. The window junction solves the problem of lattice mismatch, but that of connecting different cells with one another is solved by creating a tunnel junction instead of a normal junction.

The tunnel junction allows bi-directional current. On other hand, each cell acts as a current source and all the cells are connected in series in a multi-junction cell, therefore the resultant current is limited to the smallest current source. To produce more current the cell absorbs more photons leaving less photon for the next cell in line. Therefore the last cell might produce the least current and limit the overall current output. Hence a compromise between thickness and shadowing must be reached to ensure optimal power production.

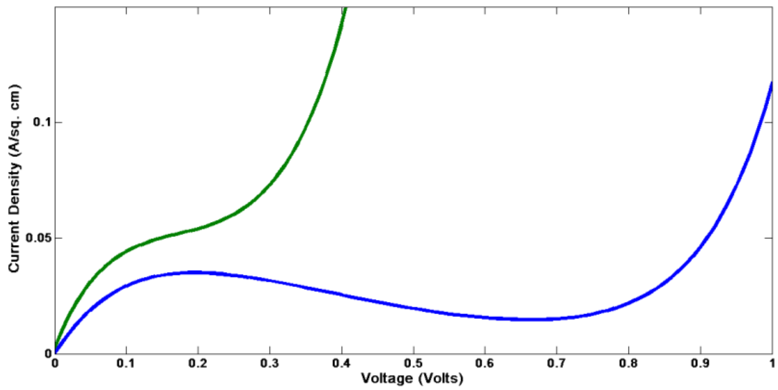

Figure 2 IV Curve of GaAs-GaAs and GaInAs-GaInAs.

3 COMPARISON BETWEEN TUNNEL LAYERS

Researchers have proposed many tunneling materials for combination of multiple solar cells so to form efficient multi-junction solar cell. Usually, the multi-junction PV cells contain tunnel junctions of GaAs/GaAs, InGaP/GaAs, AlInAs/GaInP and GaInP/GaInP. The two structures which are in discussion contain tunnel junction of GaAs/GaAs and GaInP/GaInP with window and buffer layer of AlGaAs.

For both junctions with an ideal I-V characteristic, its peak voltage and current and specific resistivity along with their doping concentration are given in Table 1. I-V characteristics by generalized tunnel junction model for both junctions are shown in Fig. 2. The nonlinear nature of junction is apparent i.e., the output current cell depend on the cells terminal operating voltage and temperature. It is been found that the three region of GaAs/GaAs junction is evidently vivid; in one region it has negative resistance. However, In GaInP/GaInP junction, negative resistance does not exist. Though, the carrier flow is faster in GaInP rather than GaAs, and that is why tunnel junctions are considered for combination of different cells for production of multijunction solar cell.

4 PHYSICAL MODEL

The physical structure of the MJSC could easily be generalized as a solar cell connection in series with tunnel diode.

4.1 SOLAR CELL MODEL

A general mathematical model of current/voltage characteristics for a PV cell has been discussed in literature[13–16].

The general photovoltaic cell model consists of a parallel connected photo current source, a diode, a resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow. The voltage- current characteristics of a solar cell is given as

$$J = J_L - J_o \left\{ exp\left[\frac{q(V + J_{r_s})}{nkT} \right] - 1 \right\} - \frac{(V + J_{r_s})}{r_{SH}}$$

Where;

J current density (A/cm^2),

J_L photogenerated current density (A/cm^2),

J_0 reverse saturation current density (A/cm^2),

r_S specific series resistance (Ω-cm^2),

r_{SH} specific shunt resistance (Ω-cm^2).

4.2 TUNNEL JUNCTION MODEL

Tunneling in a MJSC refers to the phenomenon of the fast movement of carriers across the potential barrier. A tunnel diode has three working regions; positive differential resistance region, negative differential resistance region and again a positive differential resistance region. A general I-V characteristic of Tunnel Diode is shown in Fig. 3. The voltage/current characteristics of a tunnel diode is given as

$$J_{TOTAL} = \frac{V(t)}{V_p} J_T + J_X + J_{TH}$$

Here

$$J_T = J_P e^{1-\frac{V(t)}{V_P}}$$

$$J_X = J_V e^{A_2(V(t)-V_V)}$$

$$J_{TH} = J_S(e^{\frac{qV(t)}{kT}} - 1)$$

where

J_{TOTAL} Total current density of tunnel diode.

J_T Closed-form expression of the tunneling current density which describes the behavior particular to the tunnel diode.

J_X Excess tunneling current density

J_{TH} Normal diode characteristic equation.

J_P Peak current density

V_P Corresponding peak voltage.

J_V Peak current density

V_V Corresponding peak voltage.

A_2 Excess current prefactor

J_S Saturation current density,

q Charge of an electron,

k Boltzmann's constant,

T Temperature in degrees Kelvin.

It should be noted that Jp and Vp are strongly influenced by the doping concentration and doping profile of the material. Valley currents depend on the peak current density of the tunnel layer; normally the ratio of GaAs peak current density and valley current density is 1/12 while the Ge tunneling layer has a ratio of 1 and GaInP tunneling layer has a ratio of 7/9.

4.3 MULTI-JUNCTION MODEL

The solar cell in the model is the collective representation of all photovoltaic junctions having short-circuited cur- rent as its series-matched current as discussed earlier. Furthermore, the collective model also incorporates series and parallel resistances whereas the open-circuit voltage is the sum of the junction voltages.

The tunnel diode, because of a highly non-linear relationship between its current density and applied voltage, causes an undesirable situation when it is modeled in series with a Multijunction solar cell model. Therefore two different cases should be considered so as to understand the tunneling effect.

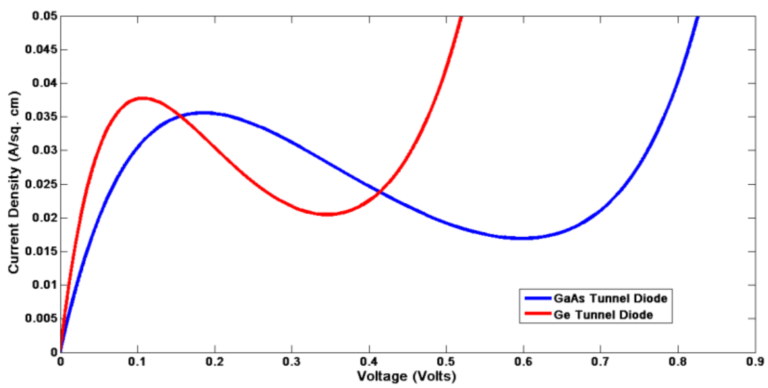

Figure 3 General I-V characteristics of Tunnel Diode.

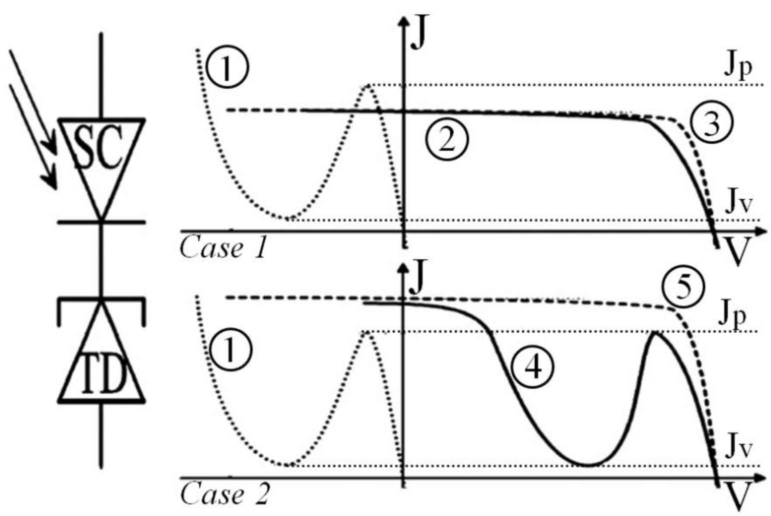

Figure 4 Effect of Tunneling Layer in Solar Cell [17].

Case1: if the overall photon generated current density J is less than the peak current density of the tunnel junction J_p, then the cell tunneling would only have a very small ohmic resistance and can be modeled as a wire connection between the two cells of a MJSC.

Case2: if the irradiation is increased and J crosses the peak current density of tunnel junction J_p, the three available modes of the tunnel junction are available and a dip appears in the current density. Fig. 2 shows the two discussed cases at different level of solar concentration. Curve 1 shows the IV curve of tunnel diode, curve 3 and 5 shows solar IV curve at different irradiation, and curve 2 and 4 illustrates resulting IV curve [17–19].

5 SIMULATION MODEL

The MATLAB/Simulink model of the tunneling layer of a multi-junction solar cell has been derived from its physical model as discussed in the previous section. The model is used to simulate and investigate the performance characteristics of the tunneling layer. This model can be used to simulate the effect of doping concentration, peak current density and peak voltage of the tunneling layer of a multi-junction solar cell. Fig. 5 show the block diagram of the developed Model.

Capacitance block in the figure above models the junction capacitance of the tunneling layer. This block essentially executes the realistic behavior of the tunnel layer and determines its current density in all three working regions. Whereas, the model takes peak current density (J_P), respective peak voltage (V_P), forward voltage (V_F), doping concentration (D_c), Internal Resistance (R) and Junction Capacitance (C_j) as input parameters.

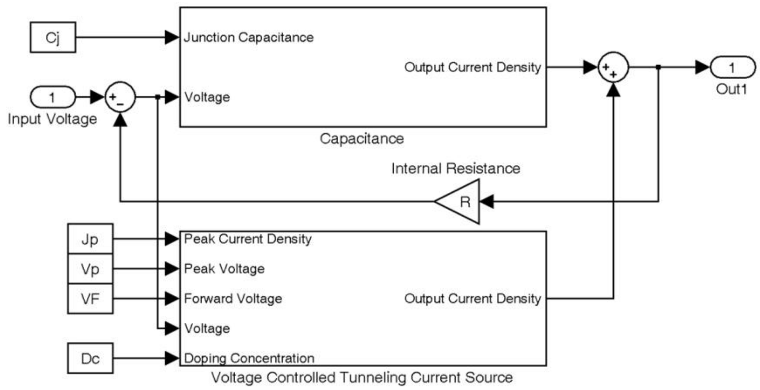

Figure 5 Block Diagram of the Tunnel Junction.

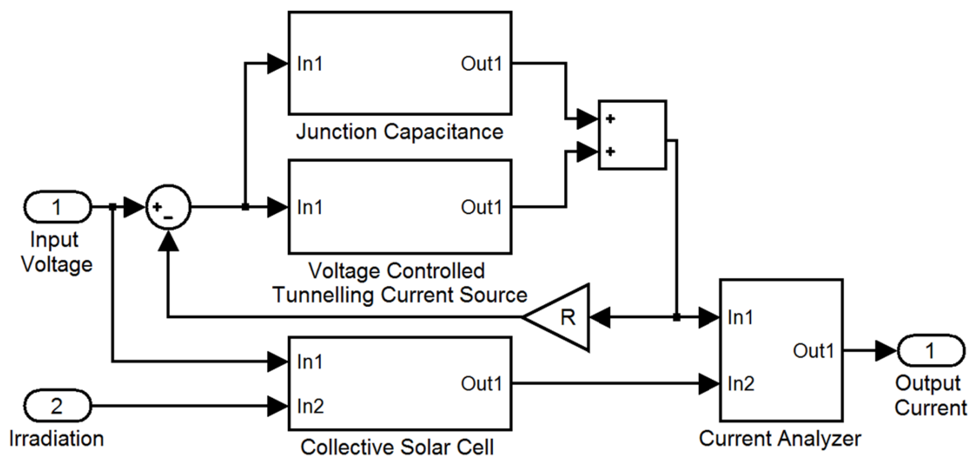

Figure 6 MATLAB simulation block diagram.

It is important to build a generalized model suitable for all of the MJSCs which can be used to design and analyze performance characteristics of different materials. A generalized MJSC model is built using Matlab/Simulink to illustrate and verify its nonlinear I-V and P-V output characteristics under different levels of irradiation. The proposed model is implemented as shown in Fig. 6.

6 SIMULATION RESULT

A GaInP/GaAs/Ge triple-junction solar cell with GaAs tunneling junction and GaInP /GaAs dual junction solar cell with GaInP tunneling junction is considered for the simulation of this model. The model assumes that all serial resistances are small enough, such that hysteresis behavior will not be observed in the characteristics of the structure with solar cell and tunnel diode. Secondly, the simulations are performed at constant temperature of 300 kelvin, so effects of temperature change are not modeled. By including these parameters, this model could represent a more detailed operation of MJSC. In Table 2 combination of GaInP, GaAs and Ge solar cells in multi-junction cell via window layer and tunnel layer, has resulted in higher open-circuit voltages than their individual respective cells. However, it is observed that because of series-current matching, the collective cell current has been reduced to 17.73mA/cm^2 with V_{OC} =2.651V and similarly the second cell structure is measured to produce V_{OC} =2.48V, I_{SC} = 19mA/cm^2. The parametric values of GaAs/GaAs and GaInP/GaInP tunnel junctions are given in Table 3.

Table 2: Open circuit voltage, short circuit current and energy bandgap of individual and integrated cells

[9].

	V_{OC} (volts)	I_{SC} (mA/cm^2)	Eg (eV)
GaInP Cell	1.3	11	1.9
GaAs Cell	1.424	25.2	0.93
Ge Cell	0.245	45.6	0.66
Triple Junction Cell	2.651	17.73	3.91
Dual Junction Cell	2.48	19	2.8

Table 3: Major Parameters for GaInP, GaAs and Ge [9].

	Lattice Constant(A0)	Permittivity (es /e0)	Affinity (eV)	e− effective mass (m^*e/m_0)	h+ effective mass (m^*h/m_0)	e− mobility (cm2 /V.s)	h+ mobility (cm2 /V.s)	e− density of states NC (/cm3)	h+ density of states NV (/cm3)
Ge	5.66	16	4	1.57	0.28	3900	1800	1.04E+19	6.00E+18
GaAs	5.56	13.1	4.07	0.063	0.5	8800	400	4.70E+17	7.00E+18
GaInP	5.65	11.6	4.16	3	0.64	1945	141	1.30E+20	1.28E+19

It can be observed from Figs. 7, 8, 9 and 10 that with increase of solar insolation, the short-circuit current of the cell increases, and the maximum power output increases as well. Because open-circuit voltage is logarithmical dependent on irradiance. As discussed in earlier section, tunnel layer provide lowest resistive path to carriers up till the generating current is less than the peak current of the tunnel junction. But when the irradiation increases the photo current density of solar greater than peak current density of tunneling, then tunneling results in dip in structure 1 whereas there does not exist any dip in structure 2.

However, the slight slant in the I V curve of the structure 2 is because the GaInP junction does not contain dip in their characteristic performance. Whereas, the dip caused by GaAs junction keeps on increasing because of two major reasons; firstly, the valley current of the tunnel junction depends over the current peak current of the tunnel junction. Moreover, the peak occurring during the backward sweep also corresponds to J_{peak}, but may be lower. Secondly, the potentials across the tunnel also alter which produces effect on the internal negative differential resistance of tunnel that results a modification in valley voltage [11]. It is also evident from Fig. 8 that after getting the current density of solar cell greater than tunnel peak current density, the peak power of the system is disturbed.

Moreover, the power curve is now having two different peaks in structure, which make it impossible for system to track maximum power point. However, the power under the curve for both structures is reduced which is for sure not desirable.

The simulation results transcribe that for lower level of concentration, the Multijunction Solar cell with GaAs tunnel junction would be better choice. Increase in the level of solar insolation, this tunnel junction provides negative resistive path to the carries, instead of facilitating the cell with their negligible resistance path. This could be managed by increasing the peak tunneling current of the GaAs junction but this problem would remain there i.e. Whenever it cell current crosses the peak tunneling current - there would be dramatic change in its performance. This alteration in cell performance is either has to be compensated by the power system or cell should only be deployed to the area which have insolation level falls in to its operating range. This could be one of the trades of triple-junction solar cell.

On other hand, the second structure with GaInP is quite effective because it does not face such a drastic change in performance at different levels of insolation. However, it also alters the projected curve of the PV cell. But even then it does not need any its power system and control.

Since structure two is dual junction solar, so it has lower optical absorption capability rather than triple-junction solar cell. Dual junction solar cell can absorb maximum optical wavelength of 0.9 µm whereas triple junction solar cell can absorb maximum optical wavelength of 1.8 µm. It means dual junction solar cell is wasting the energy carried by the photons which have wavelength greater than 0.9. However, triple junction solar cell can utilize two times more energy carrying photons rather than dual junction solar cell. This is the trade-off of dual junction solar cell.

In short, these simulations indicated the two major trades off of the two multi-junction solar cell structures. Though, it seems that GaInP junction is used instead of GaAs but it could complex the triple junction solar cell as well as uneconomical.

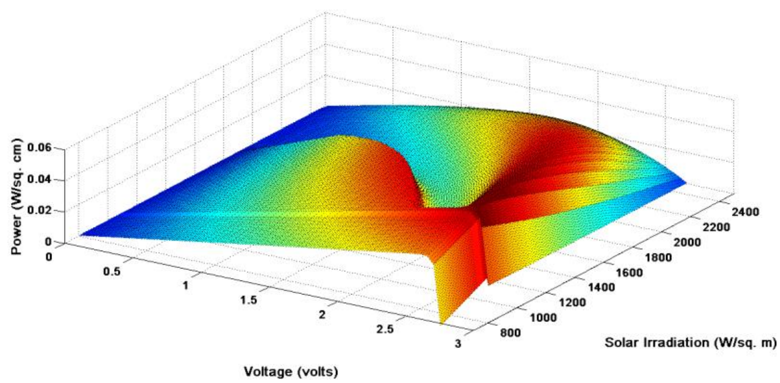

Figure 7 Power and Applied Voltage Characteristic Curve for Varying Irradiation of Triple Junction Solar Cell (InGaP/GaAs/Ge).

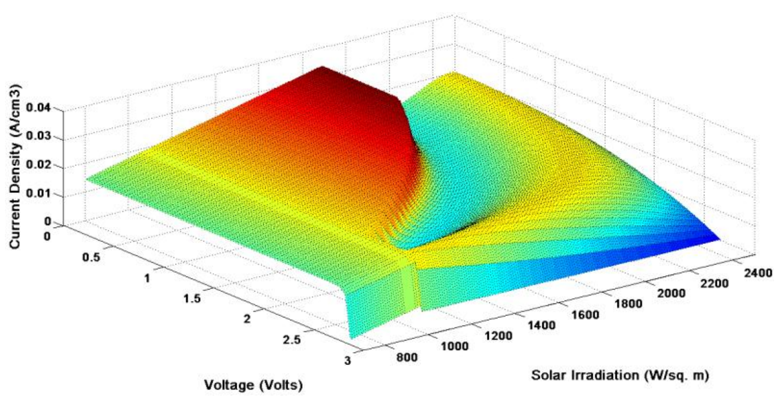

Figure 8 Current Density and Applied Voltage Characteristic Curve for Varying Irradiation of Triple Junction Solar Cell.

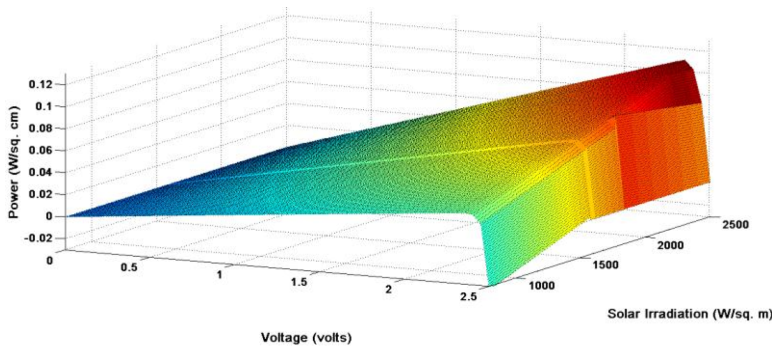

Figure 9 Power and Applied Voltage Characteristic Curve for Varying Irradiation of Dual Junction Solar Cell (InGaP/GaAs).

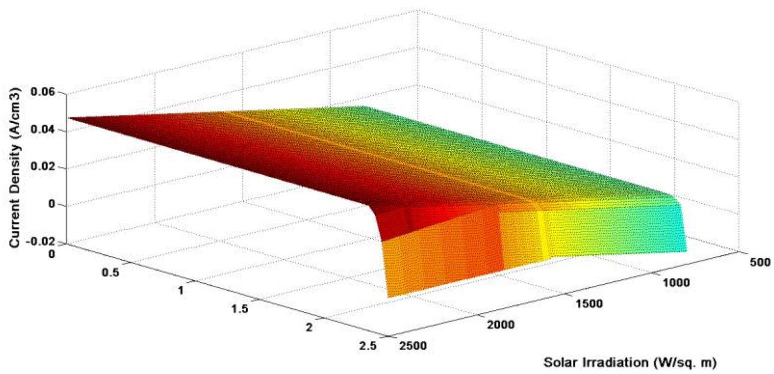

Figure 10 Current Density and Applied Voltage Characteristic Curve for Varying Irradiation of Dual Junction Solar Cell.

7 CONCLUSION

Tunneling is a significant aspect of charge transport in multi-junction solar cells. Tunneling layer provides low resistive and efficient functionality where a particle tunnels through a barrier that it classically could not surmount. In a conventional junction, conduction takes place while the junction is forward biased whereas, a forward-biased tunnel junction gives rise to three functional regions where an increase in forward voltage is accompanied by a decrease in forward current. Theoretically, all three regions of tunnel junctions are described by exponential functions. Because of this peculiar IV characteristics, tunnel junction has a significance affect in Multijunction Solar Cell.

Simulation model of a multi-junction solar cell is presented. The results of the simulation transcribe the behavior of multi-junction solar cell. When its current density is lower than the peak current density of tunnel junction, output of the characteristics appear normal. However, when its current density is higher than the peak current density of tunnel junction, a dip appears in output characteristics.

The tunnel junction plays an important role in characterization of the structure of a multi-junction solar cell. This effect must be considered while developing either the module/array of a triple-junction solar or dual junction solar cell for Concentrated PV applications.

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