Modeling of Tunnel Junction of Multi-junction Solar Cell

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Abstract: - Multi-Junction Solar Cell is the latest solar cell technology with theoretic efficiency of more than 40%. One of the significant phenomena which augmented the efficiency of the cell is introduction of tunnel junction. Its three different exponential operating regions allow charges to transport from one cell to another with low resistive, high optical transmissivity and high peak tunneling current density. This work presents the development of generalize model of tunnel layer using MATLAB Simulink package. This effort helps simulate and analyze the current density and voltage (JV) curve of the tunnel layer of a Multi-junction photovoltaic cell. Using this model and accounting for the doping concentration of the junction, a good agreement between the measured and simulated JV curves of GaAs tunnel layer and Ge tunnel layer is expected.

Key-Words: - GaAs, Germanium, Modeling, Multi-junction Solar Cell, Simulation, Tunnel Junction.

1 Nomenclature

J_{TOTAL}	Total current density of tunnel diode
J_T	Closed-form expression of the tunneling current density
J_X	Excess tunneling current density
J_{TH}	Normal diode characteristic equation
J_P	Peak current density
$V(t)$	Corresponding total voltage
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
V_F	Forward voltage of the tunnel diode
N_A	Acceptor concentration
N_D	Donor concentration
n_i	Intrinsic concentration
C_j	junction capacitance
C_{T_0}	zero bias depletion capacitance
ϕ	built-in barrier potential
Γ	capacitance power law parameter
V_j	junction voltage

2 Introduction

The modernization in photovoltaic technology has lead the recent research in the new solar cell generation; focusing on the consumption of wider spectrum for better range of efficiencies. Theoretically, multi-junction (MJ) solar cells are capable of generating approximately twice as much as power as the conventional solar cells. Efficiency of around 39% was achieved with multi-junction solar cell by Boeing Spectrolab Inc. which is state of the art triple junction GaInP/GaInAs/Ge solar cell with concentration of few hundred suns.

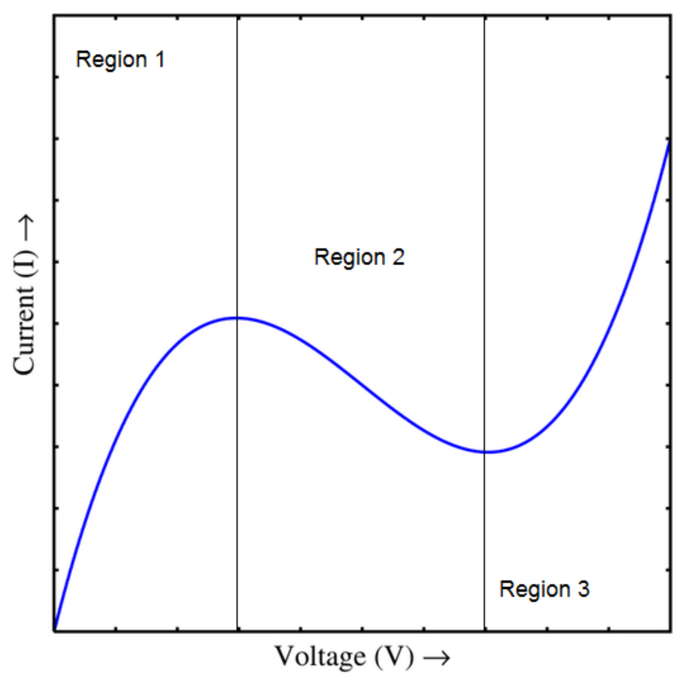

Fig.1 I-V characteristics of tunneling layer

In this monolithically grown multi-junction solar cell, all the cells are inter-connected via tunnel junction. This junction helps achieve low electrical resistivity, high optical transmissivity and high peak tunneling current density. [1-3]

However, the tunneling junction produces an issue of stability in multijunction solar cells because of its unique performance characteristics. The typical current density and applied voltage characteristics of tunneling layer can be divided in to three major regions as shown in Fig.1.

The First region is usually called positive differential resistance region in which current increases as the voltage increases. The second region is called negative differential resistance where current decreases as the voltage increases. The third region is again a positive differential resistance region. Due to this complex electrical behavior of tunneling, it produces a critical effect between the different layers. [4,6]

Since last few years, researches have been directed to optimize, analyze and investigate the effect of tunneling junction in multi-junction solar cells; an accurate and reliable modeling is desirable which can accelerate the optimization procedure. [6-8]

This paper presents the Simulink model of a tunneling layer of multi-junction solar cells, because simulation techniques are always the most cost effective way to investigate and analyze the different effects. The proposed model can be used to simulate the effects of doping concentration, peak current density and peak voltage of the tunneling layer of the Multi-junction solar cell.

The paper is organized such that section II of the paper discusses the physical model of the tunneling layer. Section III explains the proposed Simulink model and section IV presents the simulation of the performance characteristics of tunneling for different doping concentration. Lastly, section V concludes the paper with the analysis of the results.

3 Physical modeling of tunnel junction

Tunneling in a multi-junction solar cell refers to the phenomenon of the fast movement of carriers across the potential barrier. The uniqueness of tunnel diode is that it has three working regions. Referencing [9] for general model of the tunnel diode, which contains a voltage controlled current source in parallel with the junction capacitance and has a series resistance describing its internal resistance to the current flow, as shown in Fig. 2. The voltage/current density characteristic equation of a tunnel is given by Eq. 1.

$$J_{TOTAL} = \frac{V(t)}{V_p} J_T + J_X + J_{TH} \quad (1)$$

Here

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

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

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

It is worth mentioning here that J_P and $V_P$is strongly influenced by the doping concentration and doping profile of the material.

The forward voltage of this device is the same as that of a diode as shown by Eq. 2. [10]

$$V_F = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \quad (2)$$

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 1/6. [11]

$$C_j = \begin{cases} \dfrac{C_{T_0}}{\left(1-\frac{V_j}{\phi}\right)^{\Gamma}} & -V_j > 0 \\ \dfrac{C_{T_0}+V_j\left(C_{T_0}V_j+\frac{\Gamma C_{T_0}}{\phi}\right)}{1+e^{10(V_j-0.8\phi)}} + \dfrac{C_{T_0}}{\Gamma^{0.2}\left(e^{10\left(0.8\phi-V_j\right)}+1\right)} & -V_j < 0 \end{cases} \quad (3)$$

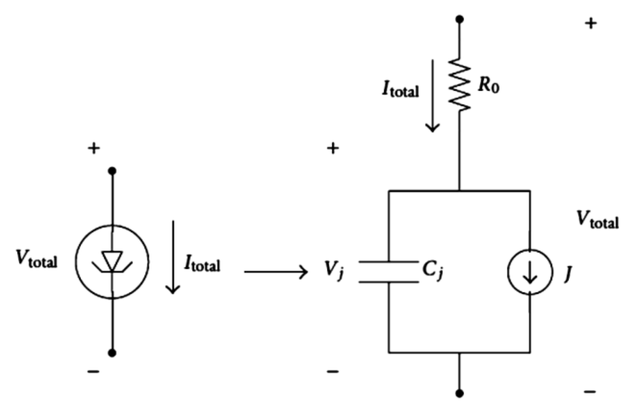

Fig. 2. Esaki Tunnel diode circuit model

4 Generalize Simulink modeling

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. 3 shows 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

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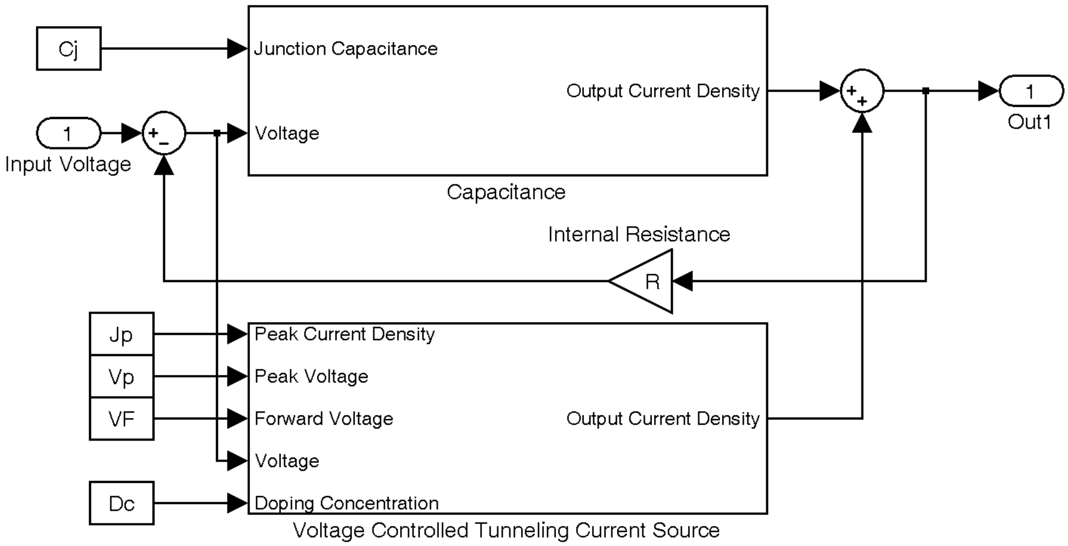

Fig. 3 Block Diagram of the Tunnel Junction

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.

5 Simulation Results

For the simulation of this Simulink Model, a Gallium Arsenide (GaAs) and a Germanium (Ge) layer is considered. Table I shows realistic values for peak current density, respective peak voltage, junction capacitance , respective doping concentration and forward voltage of the tunnel layer for the mentioned materials. [12, 13]

Fig. 4.shows the current density against voltage curves for different values of doping concentration as described in Table I for GaAs. Fig 5.shows the current density against voltage curves for different values of doping concentration for Ge tunneling layer. It could be observed clearly from the simulation that by increasing the doping concentration, the peak current density and voltage also increases.

Moreover, it could also be observed that the ratio of the peak current density and valley current density of GaAs is 1/12 and for Ge is 1/6. It is also evident from the simulations that the peak current density of the tunneling layer is same for peak voltage and forward voltage. It means that simulation produced by the model is in good agreement with realistic behavior of the tunneling layer.

6 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.

TABLE I. PARAMETERS OF GERMANIUM AND GALLIUM ARSENIDE

Material	J_P (mA)	V_P (mV)	V_F (mV)	C_j (pF)	D_c (cm-3)
Germanium	5	70	480	3	2.14E+17
	10	80	500	8	3.15E+17
	20	90	540	20	6.80E+17
	50	100	565	50	1.10E+18
	100	110	575	100	1.33E+18
Gallium Arsenide	5	135	1050	3	1.23E+15
	10	115	1100	8	3.23E+15
	20	175	1125	20	5.22E+15
	50	195	1150	50	8.45E+15
	100	205	1175	100	1.37E+16

In this paper, tunnel junction is modeled as non-linear device which have three different regions of working. Each region is expressed by exponential functions. Thus, the sum of these exponential equations collectively represents the functionality of tunnel junction. Matlab/Simulink is used to model the tunneling layer of the monolithic multi-junction solar cells. Applying the experimental tunneling parameters to the model, it is observed that the model has a good concurrence with the stated performance of tunnel junction. .

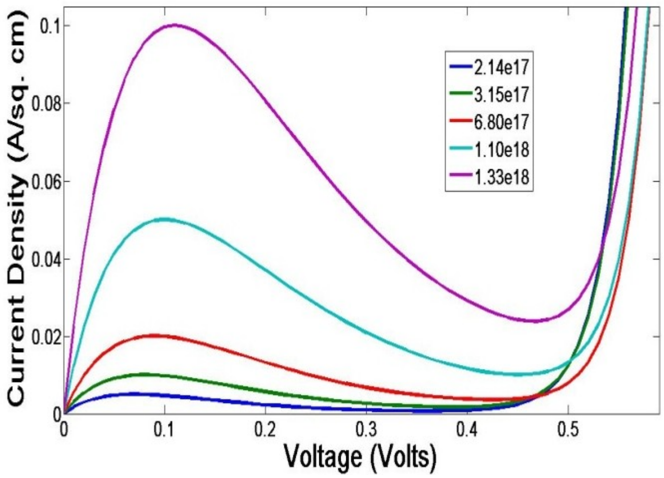

Fig. 4 J-V Characteristics with different Doping Concentration of GaAs

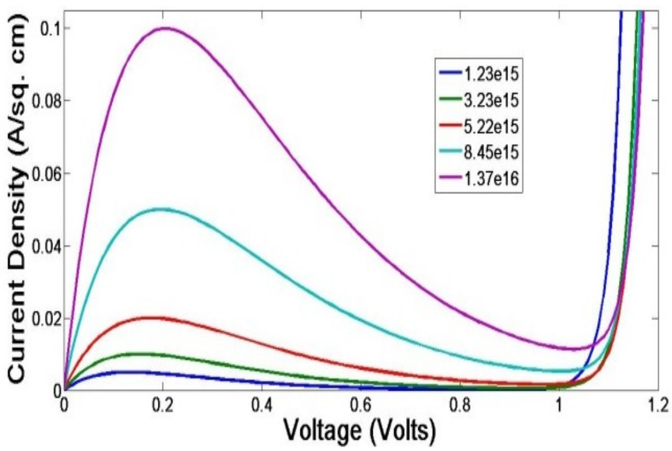

Fig. 5 J-V Characteristics with different Doping Concentration of Ge

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9 Biblography

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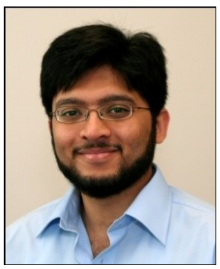

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