

DESIGN AND DEGRADATION PERFORMANCE ANALYSIS OF A 3JUNCTION SOLAR CELL USING PC1D

Preeti Jha¹, Dr.Vibha Tiwari²
¹Mtech,VISI, Technocrats Institute of Technology

²Electronics and Communication, Technocrats Institute of Technology

Abstract — This paper presents the detailed performance analysis of Multifunction solar cell InGaP/GaAs/Ge (3Junction) using PC1D (Personal computer in one dimension). The modeling of solar cells depends heavily on the intrinsic and extrinsic properties of the material. The parameters of cells like doping level, thicknesses of the base and emitter layers lead to optimal performances of cell, effect of each parameter is studied and analyzed. These results are used to increase the efficiency of multi-junction solar cells. Also analysis of degradation of cell is done to assess the life time of Solar Cell after continuous irradiation.

Keywords - PC1D, efficiency, InGaP, Multijunction, EQE.

I. INTRODUCTION

All This Photovoltaic (PV) technology converts the solar or light energy into electrical energy without any consumption of conventional form of energy and hence the global photovoltaic market is booming over the decades [1]. The main problem of this technology is low conversion ratio of solar energy into electrical form. Prior optimization of various parameters leading to increase in its efficiency is done. PC1D and PC2D are one of the most commonly used and commercially available solar cell modeling programs. Its success is based on its speed, user interface and continuous updates for the latest cell models [2]. PC1D solves the fully coupled non-linear equations for the quasi-1-D transport of electrons & holes in crystalline semiconductor devices. The maximum solar conversion efficiency is defined by Shockley–Queisser limit which is 33.7% for a single p-n junction with a band gap of 1.1 eV (typical for silicon) [3]. III-V compounds have become the basic materials for modern optoelectronic devices. III-V compounds such as gallium arsenide (GaAs), Aluminum Gallium Arsenide (AlGaAs), and Indium Phosphide (InP) have the characteristics that allow fabrication of high efficiency solar cells. Some of the characteristics of these materials are direct energy band gaps, high optical absorption coefficients, and good values of minority carrier lifetimes and mobilities [4]. Theoretically, a single junction silicon cell gives 25% efficiency, a 3Junction and 4junction are around 40% and 50% respectively. Optimizing this efficiency level of multi-junction solar cell and analyzing its characteristic features is the objective of our work. The paper is organized as followed. In Section II, design parameters are discussed. Section III gives the design and working of single junction solar cell, section IV presents the simulation and optimization solar cell. Section V discusses the degradation effect on solar cell.

II. DESIGN PARAMETERS OF 3J SOLAR CELL

Photon efficiency (at each wavelength) can be defined as the work extracted from a photon divided by its input energy. The various factors that lead to the design of solar cell with high efficiency are discussed here in detail.

A. MATERIAL AND STRUCTURE.

The material used for manufacturing should have efficient light absorption, efficient charge separation and efficient charge transport. The amorphous and crystalline structure of substrate also greatly determines the efficiency. Crystalline silicon can absorb 40 times more light than the amorphous silicon, as well as amorphous structure is more prone to light induced degradation (LID). The most important criterion in designing these cells is to make the thickness of individual subcell layers smaller than the diffusion length in order to keep the collection efficiency close to unity[5].

B. DOPING CONCENTRATION.

Emitter as well as base doping concentration highly influence the efficiency of the cell as very low doping concentration do not generate sufficient amount of charge carriers and very high doping concentrations lead to increase in recombination rates of charge carriers.

C. RECOMBINATION VELOCITY.

Recombination is the processes by which the electron-hole pairs are lost due to the rapid transition of an excited electron from conduction band to an unoccupied state in valence band [6]. Surface recombination has a major impact both on the short-circuit current and on the open-circuit voltage. High recombination rates at the top

surface have particularly detrimental impact on the short-circuit current since top surface also corresponds to the highest generation region of carriers in the solar cell.

D. ANTIREFLECTIVE COATING MATERIAL.

The reflection of light from surface of cell is one the important parameter in determining the efficiency of cell. More the light is reflected, less is efficiency obtained. So, in order to reduce the reflection, an antireflective layer of materials having good absorption coefficient is made its epitaxial layer.

E. SURFACE TEXTURIZATION.

Surface texturization increases the light trapping capacity of the solar cell resulting in efficiency improvement. Texturized surface is also known as saw dust surface. Various techniques like micro porous silicon etching, wet chemical etching etc are used for surface texturization.

III. DESIGN AND WORKING

In a MJ cell, the semiconductor with the highest band gap is used as the top layer. Band gaps are then reduced with each further layer. This design maximizes photon energy extraction as the top layer absorbs the highest energy photons allowing photons with less energy to transmit through. The bottom layer then absorbs all remaining photons above its band gap. Thin film technology is used during design of our multi-junction solar cells. The area of the cell will be of the order of 1-10 cm². The thickness of individual sub cells is different depending on their absorption coefficients and current generation capabilities.

To enhance the absorption of sunlight:

1. Texturing of front surface is done to reduce reflectivity and increase the optical path length. Light trapping is improved by using inverted pyramids.
2. Contacts are embedded as shading of the front surface by metal contacts reduces the surface area available to the incident

light. Reduced contact area increases the available surface area but increases the resistance. A large contact area can be achieved without increasing the surface shading by embedding the contacts in the solar cell.

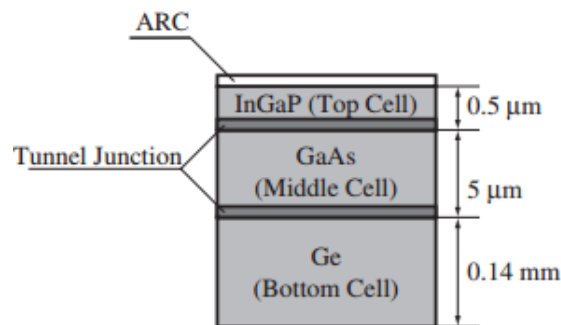


Fig 1 : Basic Design Of 3J Solar Cell

IV. SIMULATION AND OPTIMIZATION IN PC1D

A. SIMULATION.

The constant parameters in this simulation were base resistance, internal conductor and light intensity that were set at 0.0015Ω, 0.3 S and 0.1 W/cm², respectively, in one sun excitation mode [2,3]. The spectrum used in this design was AM1.5 G. Initially, the electronic parameters for single Junction like front doping concentration, bulk doping concentration, recombination velocity were varied within the experimental values range and the optimum values were obtained [7]. The I-V and P-V characteristics of the single junction solar cell is shown fig 3. The I-V curve of a solar cell is the superposition of the I-V curve of a simple diode with the current generated from illumination of diode with sunlight. The current generated due to the illumination flows in opposite direction with respect to diode, hence shifts the I-V curve in fourth quadrant. Since, the power is generated so conventionally current is assumed to be positive. Illumination of cell adds to the normal and dark currents in the diode which is given by Eq 1. Once the optimal values for each junction are obtained, a 3Junction Solar cell is designed using those values by arranging the sub-cells in decreasing energy band gap. In this model, when AM1.5 light illuminates the cell, the InGaP cell absorbs only the light of wavelength shorter than 700 nm. The GaAs cell absorbs light of only the medium wavelength (600–900 nm) since the light of shorter wavelength is

absorbed into the p-type InGaP filtering layer. The Ge cell absorbs light of wavelength only longer than 800 nm for the same reason [7].

Using Eq 3, Efficiency of the Cell is calculated

$$FF = \frac{V_{max} I_{max}}{V_{oc} I_{sc}} \quad (2)$$

$$\eta = \frac{\sum_{i=0}^N FF^i V_{oc}^i I_{sc}^i}{P_s} \quad (3)$$

P_s = Max Power Obtained

B. OPTIMIZATION.

1. MATERIAL AND STRUCTURE.

The thickness of the top layers was varied from 0.1 μm to 1 μm , thickness of region 2 GaAs was varied from 2 μm to 50 μm . Since the absorption coefficient of Ge is very less thickness is varied from 100 μm to 150 μm . The simulation values are tabulated in Table1.

2. EMITTER DOPING CONCENTRATION OPTIMIZATION:

The emitter level concentration was varied from $1\text{E}16 \text{ cm}^{-3}$ to $1\text{E}21 \text{ cm}^{-3}$ keeping all other parameters constant. For Ge, V_{oc} , P_{max} , Fill Factor and efficiency increases till $1\text{E}18 \text{ cm}^{-3}$ and then decreases at concentration of $1\text{E}21 \text{ cm}^{-3}$. And the same trend is followed by GaAs till $3\text{E}16 \text{ cm}^{-3}$. At very high doping, the recombination velocity of minority charge carriers increases which reduces the bulk lifetime and hence efficiency. For InGaP, the doping concentration is less as compared to Ge and GaAs. The emitter doping concentration highly influences V_{oc} and has relatively little impact on I_{sc} . This performance can be explained by sheet resistance values. For lightly doped emitters, large sheet resistances lead to high series resistance and poor fill factors [2].

3. BACKGROUND DOPING CONCENTRATION OPTIMIZATION:

The substrate doping concentration is also an important parameter in efficiency calculations. Keeping the emitter doping concentration, constant at $1\text{E}18 \text{ cm}^{-3}$, $3\text{E}16 \text{ cm}^{-3}$ and $3\text{E}14 \text{ cm}^{-3}$ for Ge, GaAs and InGaP respectively, the p-type doping was varied from $1\text{E}14 \text{ cm}^{-3}$ to $1\text{E}20 \text{ cm}^{-3}$. The efficiency, V_{oc} , I_{sc} and ff initially increases and then decreases rapidly; this is due to the fact that higher concentration leads in reduction of minority carrier lifetime.

4. OPTIMIZATION OF RECOMBINATION VELOCITY AND CARRIER LIFETIME:

Both the parameters are function of temperature and doping concentrations. For Silicon the carrier life time experimentally inversely varies from 1E-10 sec to 1E-3 sec when the donor concentration is varied from $1\text{E}12 \text{ cm}^{-3}$ to $1\text{E}20 \text{ cm}^{-3}$. Surface recombination rate depending on treatment of Ge surface lies in the range between 10^2 to $(6-8)10^4 \text{ cm/s}$ similarly for GaAs it is between $1\text{E}4$ to $6\text{E}4 \text{ cm/s}$.

	InGaP		
Parameters	T=.1 μm	T=.5 μm	T=1 μm
Voc(V)	.7709	.7603	.7479
Jsc(mA/cm ²)	36.66	38.45	38.14
Pmax	2.444	2.558	2.551
Efficiency(%)	24.43	25.58	25.51

	GaAs		
Parameters	T=1 μm	T=5 μm	T=10 μm
V _{oc} (V)	1.041	1.025	1.01
J _{sc} (mA/cm ²)	63	31.5	15.75
P _{max}	2.88	2.826	2.769
Efficiency	28.8	28.26	27.69

	Ge		
Parameters	T=50 μm	T=140 μm	T=200 μm
V _{oc} (V)	1.041	1.025	1.01
J _{sc} (mA/cm ²)	63	31.5	15.75
P _{max}	2.88	2.826	2.769
Efficiency	28.8	28.26	27.69

Table 1. Variation Of Efficiency With Thickness Of Single Cell.

	InGaP		
Bck Doping (cm ⁻³)	1x10 ¹³	1x10 ¹⁴	1x10 ¹⁵
V _{oc} (V)	.7479	.7479	.7479
J _{sc} (mA/cm ²)	39.74	39.74	39.74
P _{max}	1.275	2.551	3.826
Efficiency	2.444	2.444	2.444

	GaAs		
Bck Doping (cm ⁻³)	1x10 ¹⁵	1x10 ¹⁶	1x10 ¹⁷
V _{oc} (V)	1.041	1.041	1.041
J _{sc} (mA/cm ²)	31.5	31.5	31.51
P _{max}	1.448	2.888	5.742
Efficiency (%)	28.96	28.88	28.71

	Germanium		
Bck Doping (cm ⁻³)	1x10 ¹⁶	1x10 ¹⁷	1x10 ¹⁸
V _{oc} (V)	1.041	1.031	1.010
J _{sc} (mA/cm ²)	63	31.5	15.75
P _{max}	2.88	2.826	2.769
Efficiency	28.8	28.26	27.69

Table.2. Variation In Efficiency With Background Doping

V. DEGRADTION MODELLING

To study the impact of LID, each sub cell is illuminated separately in order to avoid the convergence: an InGaP cell, a GaAs cell under a p-type InGaP filtering layer, and a Ge cell under a p-type GaAs filtering layer. It is assumed that these cells are connected in series. The p-type InGaP filtering layer on the GaAs cell was set to have the same structure and physical properties as those of the GaAs middle cell (thickness, carrier lifetime, carrier concentration, surface recombination velocity, and so on). However, the filtering layer did not have n⁺-emitter and p⁺-back surface field (BSF) layer. This is the same for the p-type GaAs filtering layer on the Ge cell. In this case, it is possible to assume that the short-circuit current (I_{SC}) of 3J solar cell is equal to the lowest I_{SC} in the three sub-cells (thus, InGaP, GaAs, and Ge), eq 4 and the open-circuit voltage (V_{OC}) of 3J cell is the sum of their V_{OC}.

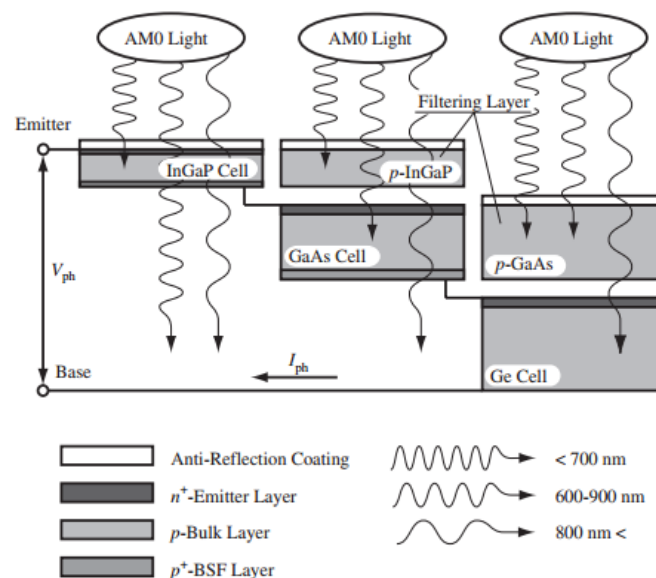


Fig.2. Schematic Diagram Of Degradation Of Cell

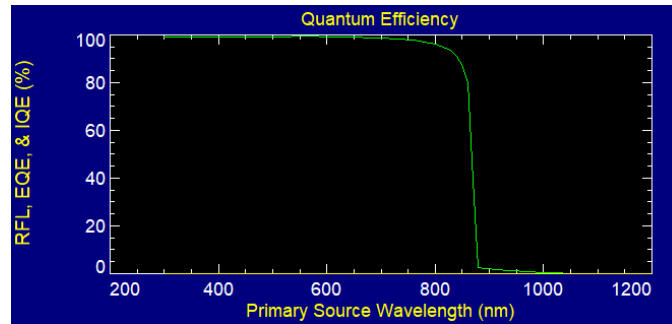


Fig.3. Degradation of GaAs cell

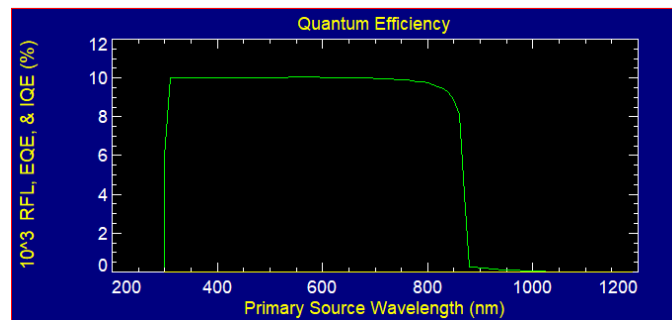


Fig.4. Degradation In EQE After Irradiation

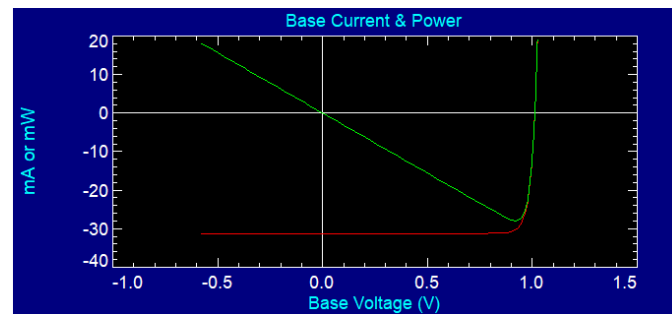


Fig.5. Current Voltage curve of 3J cell

RESULTS

The optimized values obtained after simulation are tabulated in Table 3 for InGaP/GaAs/Ge and the results are concluded.

- For Single subcell it was observed that V_{oc} is independent of area and depends inversely upon the thickness. For a 3J cell, Efficiency / P_{out} is independent of area and varies differently with the thickness of each layer.
- However P_{max} and efficiency don't follow any specific trend with thickness. Current density does not show much variation with area and thickness.
- Efficiency and power both exhibit inversely proportional trend with area and thickness.
- The maximum efficiency obtained when single junction cells were designed for InGaP it was 31.21%, for GaAs was 28.88% and for Ge 24.08%. The doping concentration required for InGaP was less as compared to GaAs,
- Similarly for GaAs it was very less as compared to Ge sub-cell to achieve the highest efficiency of respective cells.
- When all the three cells stacked over each other to form a 3Junction cell, the efficiency obtained was 32.80%. The optimized values are mentioned in Table 3.
- The External Quantum Efficiency (EQE) of GaAs and Ge cell are degraded intensely by proton irradiation at $10^{14}/cm^2$. However, InGaP cell remained after this irradiation. Hence we can say that the InGaP cell has superior radiation hardness compared to the GaAs and Ge cells. It can be also seen that degradation of the Ge cell occurs from the longer wavelength region. It should also be noted that the InGaP .EQE of longer wavelength is mainly deteriorated by proton irradiations that have above 150keV, while that of shorter wavelength is also intensely deteriorated in the case of the 30keV proton irradiation. Overall efficiency before illumination is 31.28 % and

after degradation is estimated around 25.7 % i.e the degradation curve of Isc and Voc are in good agreement with the Theoretical data available with variation of around 7%.

Process Parameters	InGaP	GaAs	Ge
Thickness (μm)	.5	5	140
Background Doping (cm^{-3})	7×10^{14}	4×10^{18}	7×10^{16}
Fr. Surface Doping (cm^{-3})	6×10^{16}	6×10^{18}	9×10^{16}
Band gap (eV)	1.833	1.424	.664
Dielectric constant	11.8	13.18	16
Intrinsic concentration (cm^{-3})	1200	1.79×10^6	1200
Front surface texture depth (μm)	.5	1	1
Bulk Recombination time (T_n)	.05 μs	500 μs	20000 μs
Bulk Recombination time (T_p)	1 μs	500 μs	40000 μs

Table III. Optimized Parameters For The 3junction Cell

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