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DESIGN OF A THIN FILM TRIPLE JUNCTION InP/GaAs/Ge SOLAR CELL AND ITS PERFORMANCE EVALUATION WITH TRIPLE JUNCTION Si SOLAR CELL BY SOFTWARE SIMULATION

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Abstract—*Solar energy is one of the renewable energy sources obtained from sun, an ultimate source of energy from which electricity can be produced using photovoltaic effect. Multi-junction solar cell is widely used device for the conversion of solar energy directly into electricity. With the adaptation of different materials the performance of multi junction solar cell can be improved. But the drawbacks involves with multi-junction cell is its high manufacturing cost. In case of triple junction solar cell the maximum theoretical efficiency is 50% [1]. In this paper a thin-film triple junction InP/GaAs/Ge solar cell is designed and simulated by taking various parameters at their optimum level to yield a maximum efficiency. The designed thin fil*m InP/GaAs/Ge solar cell is then compared with triple junction Si solar cell. For the simulation of the designed cell PC1D solar cell simulation software is used.

Index Terms— Triple junction, Thin film, Band gap, PC1D solar cell simulation software.

1. INTRODUCTION

Multi-junction solar cells are a new technology that offers extremely high efficiencies compared to traditional solar cells made of a single layer of semiconductor material. Depending on particular technology multi-junction solar cell are capable of generating about twice as much power under the same conditions as traditional solar cells made of silicon. The solar cell operation is based on the ability of semiconductors to convert sunlight directly into electricity by electron-hole pair (EHP) in the material due to the photoelectric effect. In the conversion process, the incident energy of light creates mobile charged particles in the semiconductor which are then separated by the device structure and produce electrical current [2]. The n region is designed to be thin while the depletion region is thick. If the EHP is generated in the depletion region, the built-in electric field drifts the electron and hole apart. The result is a current through the device. If the EHP is generated in the n or p regions, the electron and hole drift in random directions and may or may not become part of the photocurrent [3].

2. BASIC CONCEPT OF MULTIJUNCTION CELL

With a traditional single layer solar cell, much of the energy of incident light is not converted into electricity. If an incident photon has less energy than the band gap of the semiconductor material, the photon cannot be absorbed since there is not enough energy to excite an electron from the conduction band to the valence band. Therefore, none of the light with less energy than the band gap is used in the solar cell. Multi-junction solar cells can make better use of the solar spectrum by having multiple semiconductor layers with different band gaps. Each layer is made of a different material, which usually is an III-V semiconductor, and absorbs a different portion of the spectrum. The top layer has the largest band gap so that only the most energetic photons are absorbed in this layer. Less energetic photons must pass through the top layer since they are not energetic enough to generate EHPs in the material. Each layer going from the top to the bottom has a smaller band gap than the previous. Therefore, each layer absorbs the photons that have energies greater than the band gap of that layer and less than the band gap of the higher layer. The most common form of multi-junction solar cell consists of three layers, which is called a triple-junction solar cell [4].

3. DESIGN CONSIDERATIONS

Multi-junction solar cell has some important design consideration which must be carefully chosen to obtain the desired optimum performance. These may be specified as:
1) Band gap of the different material
2) Lattice constant of the material
3) Current matching of the device.

3.1 Band gap

Ideally the difference between adjacent layers of the solar cell is approximately constant so that each layer can absorb an equal amount of the spectrum of incident light. Since the amount of excess energy from light converted to heat is equal to the difference between the photon energy and the band gap of the absorbing material, the difference between band gaps should be made as small as possible. Also the solar cell should take advantage of as much of the spectrum as possible so the top layer should have a high band gap and the bottom layer should have a small band gap that can absorb as much of the spectrum as possible. Clearly there is a design tradeoff for a given number of layers of a multi-junction solar cell between having the band gaps differ by a small amount and have the band gaps cover a large range of the spectrum. Triple-junction solar cells currently in production are made of GaInP, GaAs, and Ge, which have band gaps of 1.8 eV, 1.4 eV, and 0.7 eV, respectively [5]

3.2 Lattice Constant

In multi-junction solar cells, the different semiconductor layers are grown directly on top of the other layers using the same substrate. As a result of this method, the lattice constant, which describes the spacing of the molecules of a crystal structure, must be the same for all of the layers. Research at the National Renewable Energy Laboratory (NREL) showed that a lattice mismatch as small as 0.01% significantly decreases the current produced by the solar cell [7]. The restriction of each semiconductor material having the same lattice constant significantly decreases the number of materials that may be used that are created by combining different amounts of the two materials.

3.3 Current Matching

Since the current flows through a solar cell from the top to the bottom, the layers of a multi-junction solar cell are in series. Therefore, the current passing through each layer must be the same and the current produced by the solar cell is limited by the layer that produces the least amount of current. For maximum efficiency, the cell must be designed so that each layer produces the exact same current. The current is proportional to the number of photons absorbed in each layer. The two most important factors in determining the thickness of each layer is the number of photons in the spectrum that the layer should absorb and the absorption constant of the material. The light intensity decreases exponentially with penetration depth into a material where the exponential constant is called the absorption constant. A layer with a low absorption constant must be made thicker since on average a photon must pass through more of the material before it is absorbed. Properly designing the thickness of each semiconductor material based on these factors will match the current produced by each layer.

4. CELL DESIGN

In this study two triple junction thin film solar cell is designed. Three same layer of silicon is used for triple junction silicon solar cell. Another cell is constituted by three different materials instead of silicon for three layers. These materials are Indium phosphide (InP), Gallium Arsenide (GaAs) and Germanium (Ge) respectively for top, middle and bottom layer.

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4.1 Material Selection

Material should be chosen depending on its availability and absorption constant. Silicon and InP/GaAs/Ge are chosen for triple junction thin film solar cell material. Silicon is most available in the nature and the cost of this material is lower compared to other material. InP/GaAs/Ge cell costs higher than silicon but the absorption constant is higher, so the efficiency gained is larger.

4.2 Thin film Decomposition

Thin films can be deposited on flexible material substrate such as glass, stainless steel, and plastic. “Thin” is a relative term, but most deposition techniques control layer thickness within a few tens of nanometers [6]. PECVD is a process used in the manufacturing of the deposition of thin films on the semiconductors which require low temperature. PECVD stands for Plasma Enhanced Chemical Vapor Deposition and it is used to deposit materials like high quality Silicon dioxide and films can be deposited at as low temperatures. Plasma is an essential part of this process and this is why it is called plasma enhanced. This is due to the fact that because of plasma the process has different advantages. One of these is deposition at low temperature which works great for materials which are temperature sensitive or that get their characteristics changed at high temperatures. Plasma is a partially ionized gas in which a certain amount of electrons are free thus leaving atoms with positive and negative charges. Thus, it responds very well to electromagnetic fields. Also, plasma has different characteristics of solids, liquids, and gases and thus plasma is considered as a distinct state of matter. Plasma does not have a definite shape or volume unless it is enclosed by a container. However, unlike a gas, it is greatly influenced by a magnetic field. It can also form structures such as beams and filaments. The PECVD process uses an electrical energy to create a glow discharge which is plasma, thus the energy is transferred into a gas mixture.

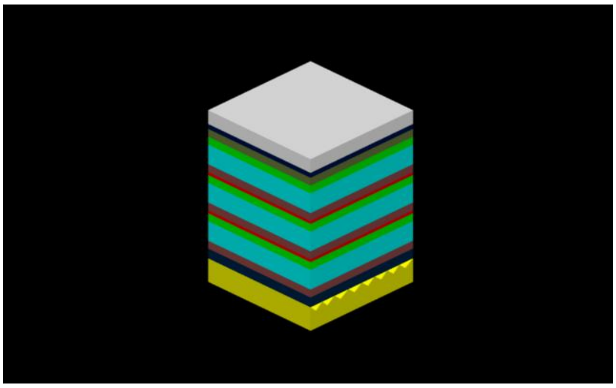

Fig1: Triple junction thin film solar cell

4.3 Top Contact

To reduce the shadowing loss Transparent conducting Oxide (TCO) is used on the top surface of cell which collects the charge carriers. The TCO, typically n+ SnO, constitutes the front contact of the cell [7]. Transparent conducting films act both as a window for light to pass through to the active material beneath (where carrier generation occurs) and as an ohmic contact for carrier transport out of the photovoltaic. Transparent materials possess band gaps with energies corresponding to wavelengths which are shorter than the visible range (380 nm to 750 nm).

4.4 Surface Texture

The surface texture is seen like a pyramid. Light incident on the side of a pyramid will be reflected onto another pyramid instead of being lost. The reflectivity of bare Si is reduced from about 35% for flat surfaces to around 20% for the textured surface; the addition of an antireflection coating reduces the overall reflection to a few percent [9]. The reduced reflection enhances both

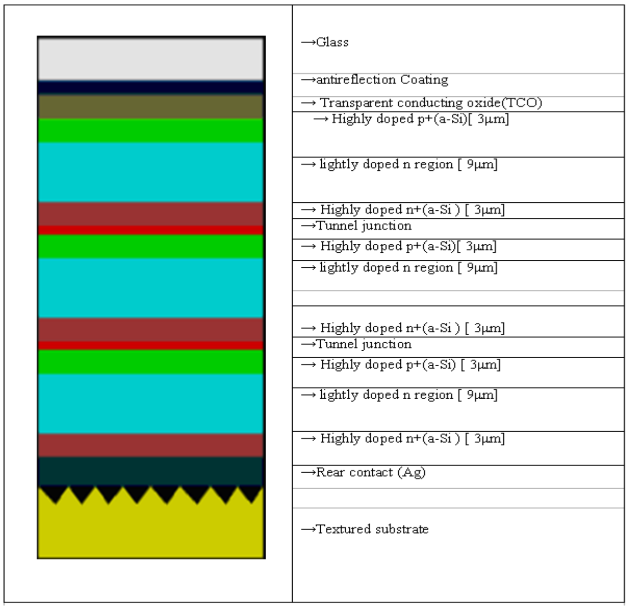

Fig2: Different layer for Triple junction thin film silicon solar cell

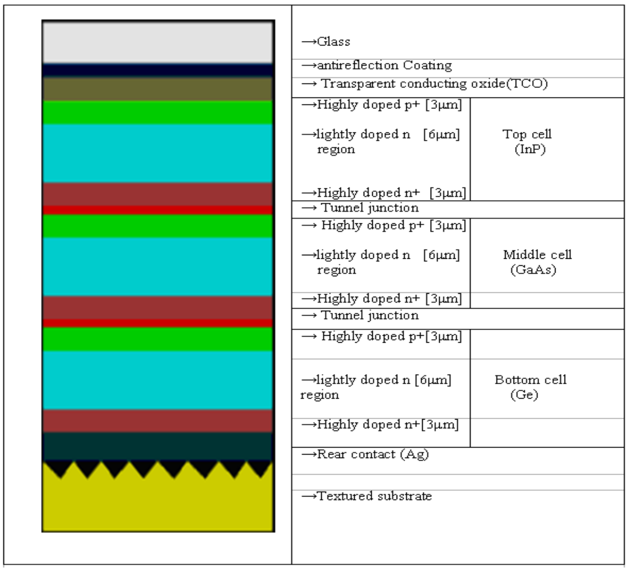

Fig3: Different layer for Triple junction thin film InP/GaAs/Ge solar cell

the short circuit current and open circuit voltage, which in turn improves cell efficiency.

4.5 Tunnel Junction

The main goal of tunnel junctions is to provide a low electrical resistance and optically low-loss connection between two sub cells [8]. Without it, the n-doped region of the top cell would be directly connected with the p-doped region of the middle cell. Hence, a pn junction with opposite direction to the others would appear between the top cell and the middle cell. Consequently, the photovoltage would be lower than if there would be no parasitic diode. In order to decrease this effect, we use a tunnel junction. It is simply a wide band gap highly doped diode.

5. SIMULATION

In this study two multi-junction solar cells are designed with different materials. Now for simulation PC1D solar cell simulation software (PC1D version 5.9) is used. Simulation model include a 100cm^2 silicon solar cell with optimum parameters including series resistance and shunt conductance. For InP/GaAs/Ge cell same 100cm^2 areas is considered to compare the efficiency achieved with the silicon solar cell.

5.1 Simulation Parameter

For silicon based triple junction solar cell and InP/GaAs/Ge cell the following simulation parameter is used for the three regions.

Table 1: Region 1 parameter (for InP/GaAs/Ge cell)

Cell parameter	Triple junction thin film cell
Internal optical reflectance	enabled
Front surface first bounce	92%
Front surface subsequent bounce	92%
Front surface	Nontextured
Region thickness	12 μm
Material	InP
Dielectric constant	12.1
Band gap	1.36eV
Intrinsic concentration (at 300K)	8×10^{16} cm^{-3}
Free carrier recombination	enabled
N- type background doping	1×10^{18} cm^{-3}
First front diffusion	P-type, $1 \times 10^{19} cm^{-3}$ peak
First rear diffusion	N-type, $1.91 \times 10^{19} cm^{-3}$ peak
Bulk recombination ($\tau_n = \tau_p$)	7.208 μs
Front surface recombination	400 cm/s
Rear surface recombination	400 cm/s

Table2: Region 2 parameter (for InP/GaAs/Ge cell)

Cell parameter	Triple junction thin film cell
Region thickness	12 μm
Material	GaAs
Dielectric constant	13.18
Band gap	1.324eV
Intrinsic concentration (at 300K)	3.59×10^{6} cm^{-3}
Free carrier recombination	Enabled
N- type background doping	1×10^{18} cm^{-3}
First front diffusion	P-type, $1 \times 10^{17} cm^{-3}$ peak
First rear diffusion	N-type, $1.91 \times 10^{19} cm^{-3}$ peak
Bulk recombination	7.208 μs
Front surface recombination	400 cm/s
Rear surface recombination	400 cm/s

Table 3: Region 3 parameter (for InP/GaAs/Ge cell)

Cell parameter	Triple junction thin film cell
Region thickness	15 μm
Material	Si
Dielectric constant	11.9
Band gap	1.123eV
Intrinsic concentration (at 300K)	1×10^{10} cm^{-3}
Free carrier recombination	Enabled
N- type background doping	1×10^{17} cm^{-3}
First front diffusion	P-type, $1 \times 10^{19} cm^{-3}$ peak
First rear diffusion	N-type, $1.91 \times 10^{18} cm^{-3}$ peak
Bulk recombination ($\tau_n = \tau_p$	7.208 μs
Front surface recombination	100 cm/s
Rear surface recombination	100 cm/s

Table5: Region 1 parameter (for silicon cell)

Cell parameter	Triple junction thin film cell
Internal optical reflectance	enabled
Front surface first bounce	92%
Front surface subsequent bounce	92%
Front surface	Nontextured
Region thickness	15 μm
Material	Si
Dielectric constant	11.9
Band gap	1.124eV
Intrinsic concentration (at 300K)	1×10^{10} cm^{-3}
Free carrier recombination	enabled
N- type background doping	1×10^{17} cm^{-3}
First front diffusion	P-type, $1 \times 10^{19} cm^{-3}$ peak
First rear diffusion	N-type, $1.91 \times 10^{18} cm^{-3}$ peak
Bulk recombination ($\tau_n = \tau_p$)	7.208 μs
Front surface recombination	100 cm/s
Rear surface recombination	100 cm/s

Table 6: Region 3 parameter (for silicon cell)

Cell parameter	Triple junction thin film cell
Region thickness	15 μm
Rear surface first bounce	98%
Rear surface subsequent Bounce	98%
Material	Si
Dielectric constant	11.9
Band gap	1.12eV
Intrinsic concentration (at 300K)	1×10^{10} cm^{-3}
N- type background doping	1×10^{17} cm^{-3}
First front diffusion	P-type, $1 \times 10^{19} cm^{-3}$ peak
First rear diffusion	N-type, $1.91 \times 10^{18} cm^{-3}$ peak
Bulk recombination ($\tau_n = \tau_p$)	7.208 μs
Front surface recombination	100 cm/s
Rear surface recombination	100 cm/s
Rear surface textured depth	3 μm
Textured angle	54.74 degrees

Table 4: Region 2 parameter (for silicon cell)

Cell parameter	Triple junction thin film cell
Region thickness	15 μm
Material	Si
Dielectric constant	11.9
Band gap	1.123eV
Intrinsic concentration (at 300K)	1×10^{10} cm^{-3}
Free carrier recombination	Enabled
N- type background doping	1×10^{17} cm^{-3}
First front diffusion	P-type, $1 \times 10^{19} cm^{-3}$ peak
First rear diffusion	N-type, $1.91 \times 10^{18} cm^{-3}$ peak
Bulk recombination ($\tau_n = \tau_p$)	7.208 μs
Front surface recombination	100 cm/s
Rear surface recombination	100 cm/s

6. RESULT AND DISCUSSION

6.1 Simulation Result

Under standard test condition (AM1.5, 25^0C, 1000W/m^2) the simulation result is found for InP/GaAs/Ge triple junction solar cell which is shown in table-5. Again, under standard test condition (AM1.5, 25^0C, 1000W/m^2) the simulation result is found for triple junction silicon solar cell which is shown in table 6.

The result shows that Silicon based design is used to lower the fabrication cost (with the expense of lower efficiency) and compound material of InP/GaAs/Ge is used to increase the efficiency.

Table 5: Simulation result of InP/GaAs/Ge triple junction solar cell

Short circuit current I_{sc} (Amp)	Current density J_{sc} (mA/cm^2)	Maximum power output P_m (Watt)	Open circuit voltage V_{oc} (volt)	Fill factor FF= (P_m/ V_{OC} × I_{sc})×100 %	Efficiency η= (P_m/E×Ac)×100%
2.638	26.38	2.30	0.996	87.52%	23%

Table 6: Simulation result of triple junction Si solar cell

Short circuit current I_{sc} (Amp)	Current density J_{sc} (mA/cm^2)	Maximum power output P_m (Watt)	Open circuit voltage, V_{oc}(volt)	Fill factor FF= (P_m/ V_{OC} × I_{sc})×100 %	Efficiency η= (P_m/E×Ac) ×100%
3.696	36.96	2.087	0.682	82.79%	20.87%

6.2 Simulation Graph

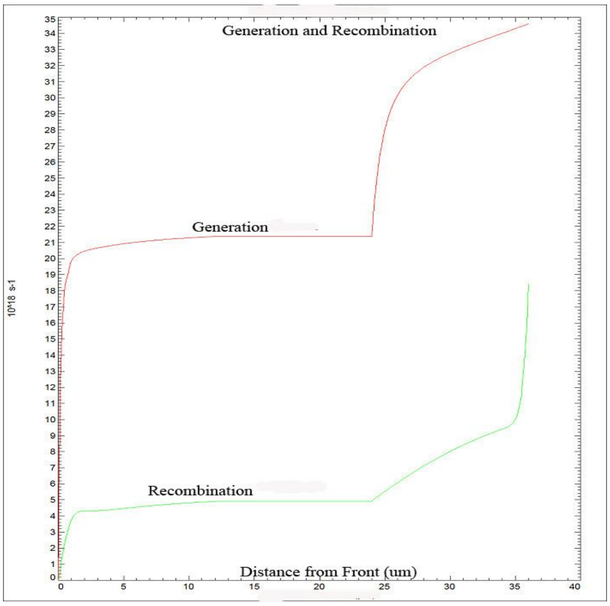

Fig 4: Distance vs. Generation & Recombination curve for InP/GaAs/Ge cell

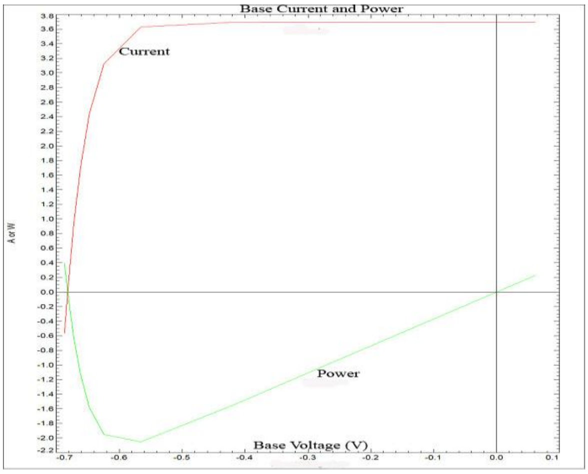

Fig 5**:** Base voltage vs. Current & Power curve for InP/GaAs/Ge cell

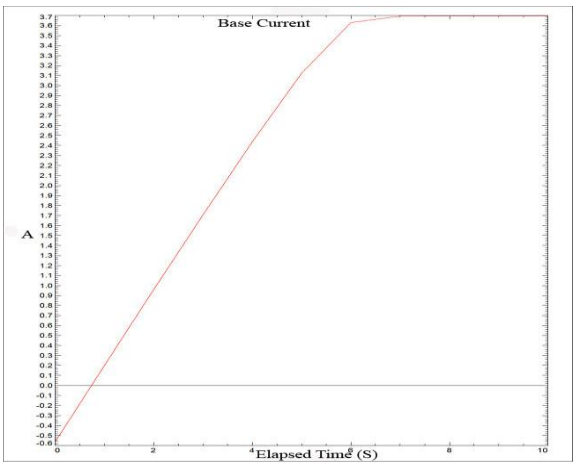

Fig 6: Elapsed time vs. current curve for triple junction silicon solar cell

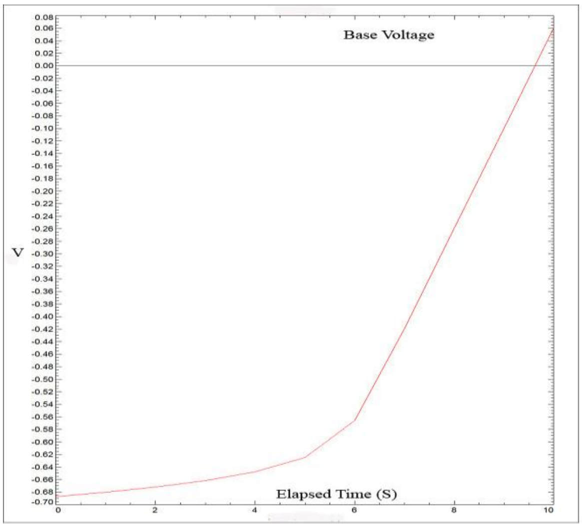

Fig 7: Elapsed time vs. Voltage curve for triple junction silicon solar cell

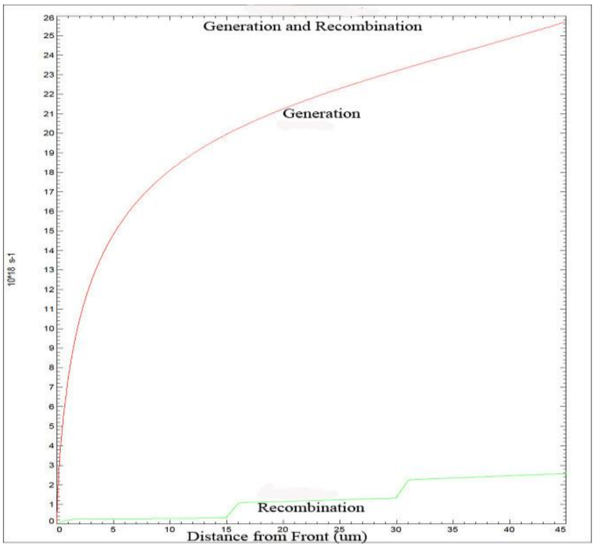

Fig 8: Distance vs. Generation & Recombination curve for triple junction silicon solar cell

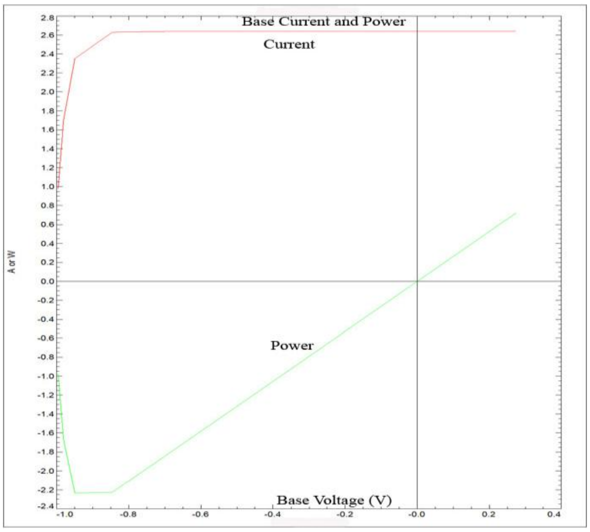

Fig 9: Voltage vs. Current & Power curve for triple junction silicon solar cell

Due to the some limitations of simulation software the obtained efficiency is lower than the practical efficiency. Simulation result shows that for $100cm^2$ triple junction silicon solar cells the maximum power output is 2.086 watt with corresponding efficiency of 20.86%. But for the same $100cm^2$ InP/GaAs/Ge cell the efficiency is 23%. This is due to the fact that direct band gap material has absorption constant higher than silicon. So InP/GaAs/Ge cell can absorb more photon energy than silicon. From the generation and recombination curve of electron-hole pair (EHP) it is seen that recombination rate is much lower than generation rate. To attain higher efficiency the recombination rate should be kept as small as possible.

7. CONCLUSION

Though solar cell efficiency is much lower than the other source of energy we cannot overlook this renewable source of energy as demand of energy is ever increasing. From PC1D simulation result it is found that using multi-junction structure of solar cell the efficiency is significantly increased. The research about multi-junction solar cell throughout the world is ongoing. If the fabrication cost of the multi-junction cell is minimized it will be an incredible source of energy with higher efficiency and as solar cell requires a little maintenance with longer lifetime it will be a solution of power crisis for the developing countries.

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