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# **SIMULATION OF HETEROJUNCTION SOLAR CELL AND ANALYSIS OF IT BY VARYING DIFFERENT PARAMETERS**

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*A dissertation submitted in partial fulfilment of  
the requirement for the degree of*

**MASTER OF TECHNOLOGY  
IN  
NANOSCIENCE & TECHNOLOGY**

*by*

**PAVAN SINGH**

**Roll No. – 2K12/NST/12**

Under the Supervision of  
**DR. RISHU CHAUJAR**



**DEPARTMENT OF APPLIED PHYSICS  
DELHI TECHNOLOGICAL UNIVERSITY  
(FORMERLY DELHI COLLEGE OF ENGINEERING)  
NEW DELHI-110042**

**June 2014**

# **CERTIFICATE**

*This is to certify that the dissertation entitled “Simulation of Heterojunction Solar Cell and Analysis of It by Varying Different Parameters” is being submitted by me, Pavan Singh bearing roll no. 2K12/NST/12 to the Delhi Technological University, New Delhi for the degree of Master of Technology in Nano Science and Technology, run by Applied Physics Department. The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.*

---

**Pavan Singh**

*Candidate*

*Department of Applied Physics*

*Delhi Technological University*

*New Delhi, India*

---

**Dr. Rishu Chaujar**

*Supervisor*

*Department of Engineering Physics*

*Delhi Technological University*

*New Delhi, India*

---

**Prof. S.C.Sharma**

*Head of Department*

*Department of Applied Physics*

*Delhi Technological University*

*New Delhi, India*

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***Pavan Singh***

Roll No.: 2K12/NST/12

Dept. of Applied Physics

Delhi Technological University

## **ABSTRACT**

In this thesis, simulation of heterojunction solar cell has been carried out and it has been demonstrated how different parameter variations such as width, relaxation time and beam affect its performance in terms of efficiency and spectral response. A virtual wafer fabrication tool (VWFT), Silvaco ATLAS has been used for analysis of three layer InGaP/GaAs/Ge solar cell to obtain a high efficiency solar cell. Initially, width is varied, then on a definite width relaxation time has been changed and with each variation, different parameters of solar cell has been obtained via Silvaco ATLAS and corresponding I-V curve has been plotted. The author chose to vary these parameters as on variation of these parameters, the efficiency is improved, photogeneration rate ameliorated and so, current and power also increases.  $\tau_{n}$  and  $\tau_{p}$  are relaxation time of electrons and holes respectively. When relaxation time is increased, time for electrons and holes to recombine also increases and therefore, electrons and holes contribute more to current, current density and short circuit voltage. This, thus, results in an increase in the fill factor, power and efficiency. As the intensity of Sun increases, the number of photons falling per unit surface area of solar cell increases, thus creating a lot of holes and electrons which increases the current and voltage leading to an increase in the fill factor, power and efficiency. Further, the impact of width has been studied on the solar cell performance.

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**CHAPTER 1**

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**INTRODUCTION AND HISTORY OF SOLAR CELL**

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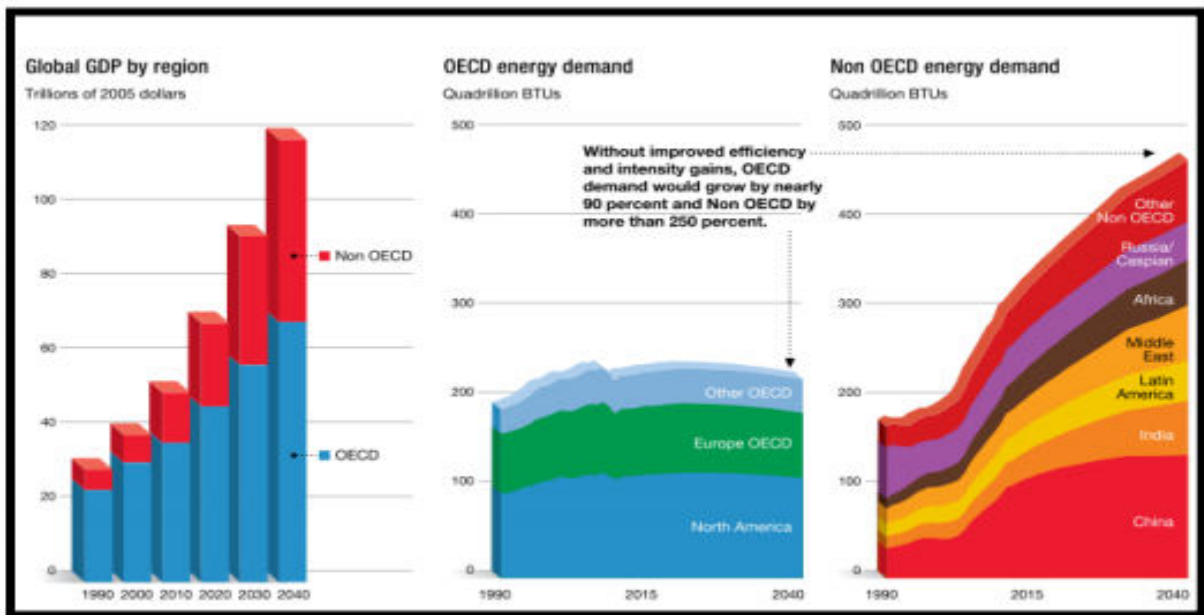
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**1.1. INTRODUCTION**

Alternative energy has become very popular now a day. One of the alternative energy forms that have proven very useful for space and terrestrial applications is photovoltaic cells. Solar cell over comes this problem as it is light in weight which is prime concern in space craft [1]. Solar cell becomes even more important when it is compared with conventional fuel cost of space craft and satellite. We can not supply the required fuel to a satellite if once established in orbit so we have to depend on solar cell so solar cell efficiency must be improved. On earth we have limited conventional energy resources so first what we do is to use it intelligently and then find the other resources. Solar cell is one of them as one day in future we will not have conventional energy resources intact. They are being explored with rapid pace. As the demand for photovoltaic cells is increasing day by day, its ability to fulfill a wide range of needs must improve, as well as its efficiency too must be ameliorated. Initially, photovoltaic cells were single-junction, but in later time, the use of multi junction solar cells were developed that proved to be a more efficient means of using solar energy [2]. Since their manufacturing cost is more, these multi junction solar cells need improvement in their efficiency. Technology is improving day by day and solar cell is being simulated at different platforms. Semiconductor technology has been developed very fast in last some decades and a lot of research work has been done. These semiconductors can be used to form solar cell and can also be used in formation of hetero junction solar cell to improve the solar cell efficiency. Solar cell efficiency can be improved by tracking the sun light. Sun tracking systems is an application of the Machine Vision (MV) and collaboration with Data Acquisition (DAQ) to systems by using a web camera as a sensor and sound card as an output channel to drive a motor [3]. According to International Energy Outlook report 2011, the energy demand of the world will increase by 53%, from 505 quadrillion BTU in 2008 to 770 quadrillion BTU in 2035. After the economic downturn of 2008-2009 as the world economy tries to recover, the global energy demand however increases strongly due to strong economic growth and

increase in population. The growth in economy for OECD countries rises at the rate of 2% per year whereas for the non-OECD nations, the growth rate is expected to be faster at 4.5% [4] that can be seen in figure 1.1.

Petroleum is the world's number one source of energy, with oil accounting for more than 1/3 of the total energy consumed. In 2007, there was a 30% increase in spending on construction of renewable energy facilities, for a total of \$71 billion [5, 6]. Not only are oil and other fossil fuels non-renewable, they contribute to another of the world's scariest problems: climate change. Fossil fuel combustion accounts for 62% of the global warming potential of all anthropogenic greenhouse gases [7].

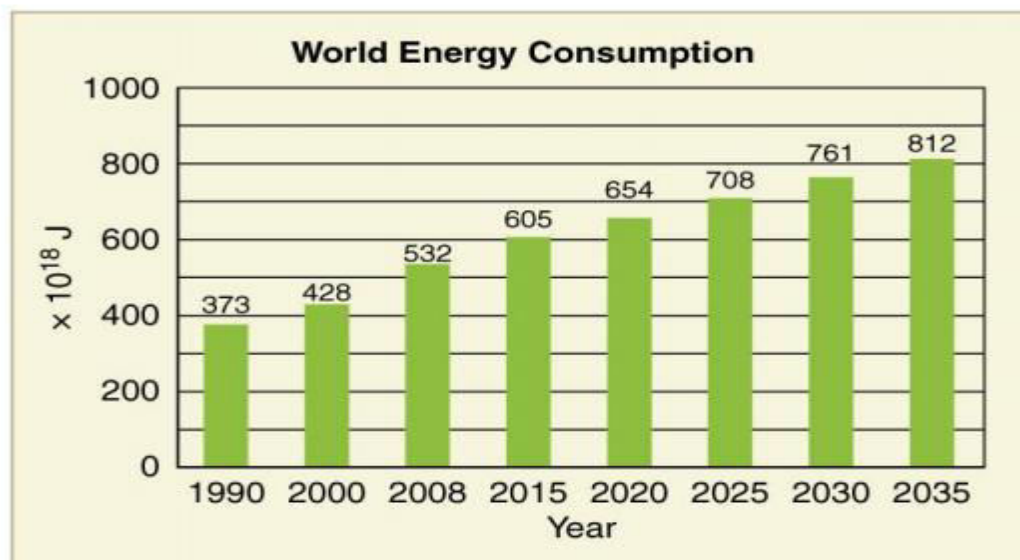


**Figure 1.1.** Global GDP by region (in trillions of 2005 dollars) (b) Energy demand of OECD nations (in Quadrillion of BTUs). (c) Energy demand of non-OECD nations (in Quadrillion of BTUs) [4].

Another consequence of using fossil fuels is the emission of greenhouse gases. The primary greenhouse gases (GHGs) present in the earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide and ozone. These gases trap heat in the atmosphere thus leading to global warming and unwanted climate changes. The burning of fossil fuels has contributed to 40% rise in the concentration of carbon dioxide in the atmosphere from 280 ppm to 400 ppm [8].

In today's world the demand for fossil fuels as described earlier is increasing in proportion to the world population. Development is important but not at the cost of destroying the very world we

live in. In a report produced by the Intergovernmental Panel on Climate Change, a panel assembled by the United Nations in 2007, the threat due to greenhouse gases were outlined (GHGs). The anthropogenic greenhouse gas emission along with the global rise in energy demands are one of the pressing issues we face today. These issues need to be resolved at the earliest in order to ensure a bright future for our future generations. Thus, the need of the hour is sustainable development. The need for sustainable development has accelerated research in the areas of renewable sources of energy such as - solar energy. When it comes to renewable sources of energy, solar energy easily takes the lead. Incoming solar radiation intensity is around  $1000 \text{ W/m}^2$  indicating that roughly  $1.5 \times 10^7 \text{ W}$  hits the earth's surface. This is over 500 times the global demand for power. This shows that undoubtedly solar power is going to be one of the prime sources of energy in the coming decades. Thus, the need of the hour is to avoid the over exploitation of these fossil fuels and to rely on renewable sources of energy such as solar energy, wind energy and hydroelectricity to fulfill the energy demands of the coming generations. Solar energy is by far the renewable energy source with the greatest potential (Table 1.1). Here, our focus is on solar energy. Figure 1.2 shows the current and the predicted world energy consumption.



**Figure 1.2.** World energy consumption [9].

**Table 1.1.**Energy available for harvesting from different sources compared to the global Energy demand [10]

| <b>Global consumption</b> | <b>Hydro</b> | <b>Geothermal</b> | <b>Wind</b> | <b>Solar</b> |
|---------------------------|--------------|-------------------|-------------|--------------|
| 15 TW                     | 7.2 TW       | 32 TW             | 870 TW      | 86,000 TW    |

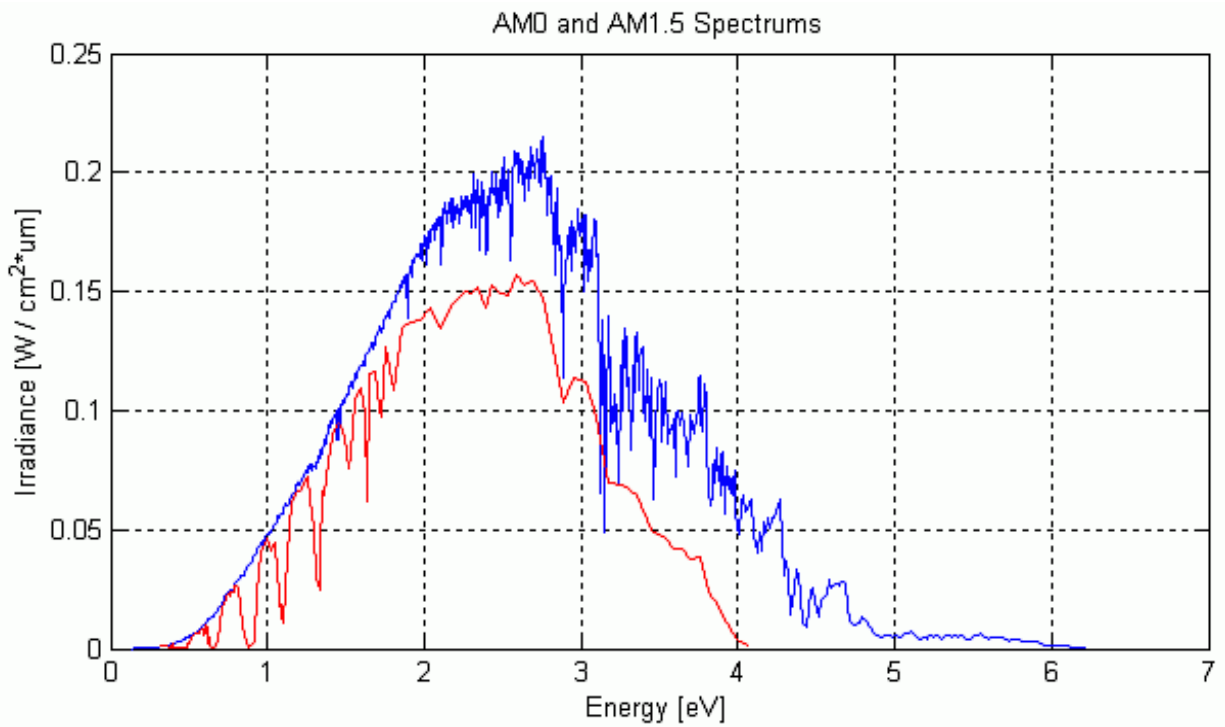
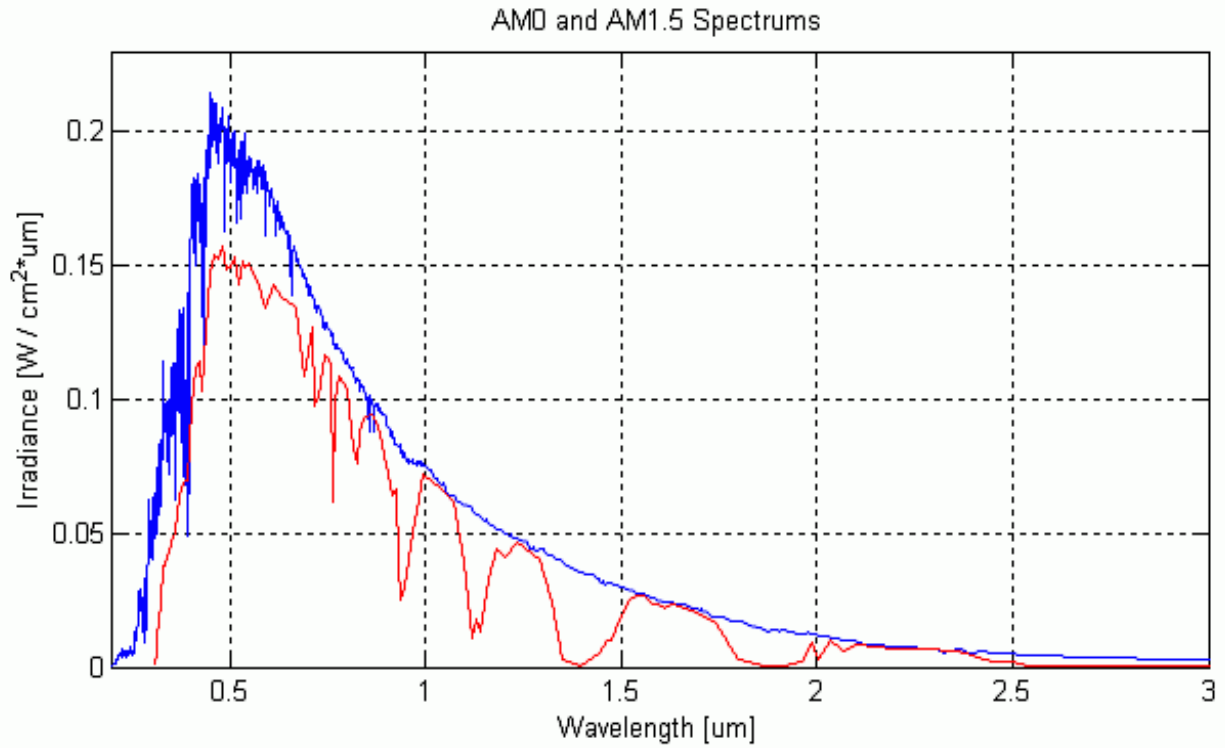
## 1.2 SOLAR CELL :

Photovoltaic industry has grown over 40% over the last decade and it can be majorly attributed to the advancement in silicon based technologies. Cost, sustainability and environmental issues are still the major concern. Competitive technologies have also emerged in the past few decades such as Organic solar cells and dye sensitized solar cells, but low efficiency, lifetime and durability issues make it very difficult for them to challenge the silicon solar cells at least for the next decade or so [11].

Solar cell as we know is a semiconducting device. It converts solar energy into electrical energy (photovoltaic effect). Light which is made up of packets of energy, called photons, its energy depends on the frequency, or colour, of the light. The solar spectrum covers ultra violet to infrared wavelength ranges. Only 30% of incident light energy is in the visible light range, while over 50% is in the infrared range (Figure 1.3).

The photons in UV and visible range have enough energy to pump electrons in semiconducting material, and this can be effectively used for charge generation. However, IR waves are too weak to generate electricity using conventional PV technology.

In space, the air mass number (AM0) is zero because all of the energy sent out by the Sun at that location is receive because the atmosphere of earth does not create any hindrance and dissipate it as it does on Earth surface. For terrestrial application AM1.0 and AM1.5 is used in which AM1.5 is very commonly used. Air mass spectrum has been shown in figure 1.3.



**Figure1.3** AM0 (blue) and AM1.5 (red) solar energy spectral distributions [12].

## **1.3 DIFFERENT GENERATIONS OF SOLAR CELLS**

Solar cells can be best classified in terms of generations i.e. the development and variations in solar cells with time. So far there have been three such generations of solar cells as follows:

### **1.3.1 FIRST GENERATION**

Single PN junction silicon solar cells come under first generation PVs. This category of solar cells is the most commercialized one covering 90 % of the photovoltaic market. [13]. The most important parameter of the performance of a solar cell is its Power conversion efficiency (PCE), i.e. the percentage of incoming solar radiation that is converted to usable power by the solar cell. So far, the highest theoretical efficiency that is reported by Shockley and Queissier, 33% for any type of single cell solar cell with a band gap of 1.1eV [14]. Kerr et al. calculated that for a 90 $\mu$ m thick single junction solar cell to be 29% [15].

### **1.3.2 SECOND GENERATION**

The cost related limitations of the first generation solar cells has shifted the focus of the researchers on the development of more cost effective second generation thin film solar cells [16]. The trick behind the reduction in costs of these solar cells lies in the use of less material for their generation. The thin films are only a few micrometers thick which is much less than the crystalline silicon based cells. So use of less material and lower manufacturing costs enables manufacturers to produce and hence sell panels at a comparatively much lower cost. The second generation includes amorphous silicon (mentioned above) and two more that are made up of non-silicon materials – cadmium telluride (CdTe) and copper indium gallium di selenide (CIGS). These solar cells are fabricated by sputtering, physical vapour deposition, and plasma-enhanced chemical vapour deposition. The highest recorded efficiency is as good as 19.6% [16], which is not very far from the crystalline silicon results. This combination of moderately high efficiency and low manufacturing costs makes the second generation solar cells a good area of interest for the researchers.

### **1.3.3 THIRD GENERATION**

This generation marked a completely new era in the development of solar cells giving birth to a totally new direction of research and development, i.e. multijunction cells, dye-sensitized cells (DSCs), and organic photovoltaic (OPVs). This approach was also an effort to bring down the



costs of solar cells further. Multijunction solar cells aim at maximizing the efficiency and thereby reducing the relative cost or increasing power to cost ratio. These cells contain multiple cells, with different band gaps, stacked over one another so that they can capture maximum region of solar radiation spectrum. A specific combination of the stack can be made to perfectly match the spectrum and result in the efficiency that can even exceed that reported by Shockley and Queisser. The theoretical efficiency limit has reached up to 66% [17]. The laboratories have already witnessed 40% for triple - junction stacked PVs. In 2008, the National Renewable Energy Laboratory (NREL) reported a world record efficiency for a thin triple-junction gallium indium phosphide and gallium indium arsenide cell to be 41.6% [18] (see Figure 1.4). Organic photovoltaic uses polymers for light absorption and even for the PN junction with highest recorded efficiency to be 9.2% [19]. This is not a favorable efficiency however they can be compensated their low cost.

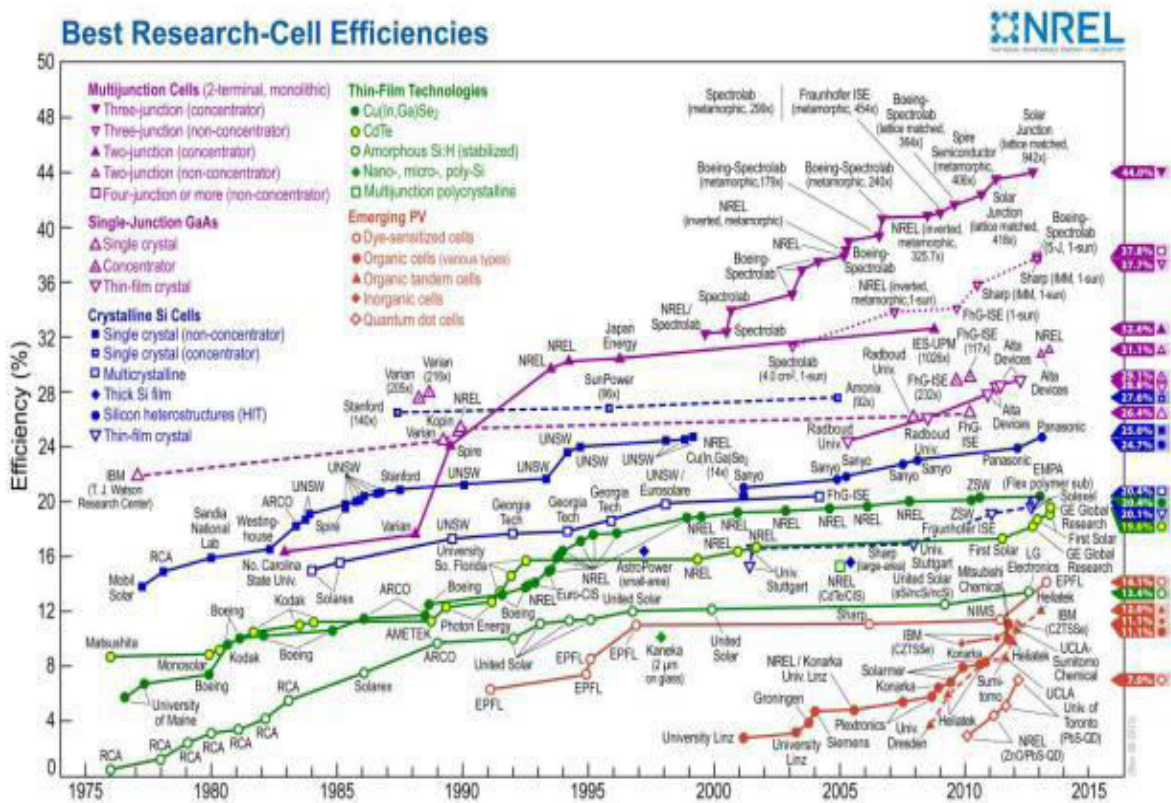


Figure 1.4. The highest recorded efficiencies of a variety of photovoltaic cells [20].

The Silvaco Software has been used for integrated simulation and analysis of electronic design and circuits. One of the major components of this tool is the Virtual Wafer Fabrication (VWF) package. With VWF, the ATLAS tool can be used for designing and development of all types of semiconductor and VLSI devices, from simple BJT to EEPROMs [21].

Hetero junction solar cell is very hot topic in world now a days, a lot of research work is being carried out in this direction because of its ability to provide highly efficient solar cell. This thesis is continuation of work of Prof. Sherif Michael of NPS. In this thesis basic concept of hetero junction solar cell is taken from Prof. S. Michael but window material of this solar cell is different to Prof. Michael solar cell and then there is variation of width, relaxation time and beam.

#### **1.4. THESIS ORGANISATION**

Chapter 2 includes the basics of semiconductor and solar cell. Here it has includes the basics of p-n junction. In this chapter we come to know how p-n junction is formed and how current flows, it also includes the basics of solar cell. In this chapter we come to know the different parameters of solar cell that is required to know solar cell. Chapter 3 includes the software Silvaco Atlas that has been used for this thesis. In Chapter 4 simulated solar cell and tonypplot structure has been shown. In Chapter 5, different parameters of simulated solar cell have been varied and graph has been plotted. Chapter 6 concludes the simulation and future proposal for the simulated solar cell has been included.

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CHAPTER 2

**BASICS OF SEMICONDUCTOR PHYSICS AND SOLAR CELL**

The properties of the semiconductor material determine the characteristics of the solar cell so before going in detail of the solar cells, it is necessary to understand the basic concept of semiconductors.

**2.1. CLASSIFICATION OF MATERIALS**

Materials can be classified according to its conductivity as conductor, insulator or semiconductor. Conductor has highest conductivity and insulator lowest but the semiconductor material has the conductivity of between them which is shown in figure 2.1.

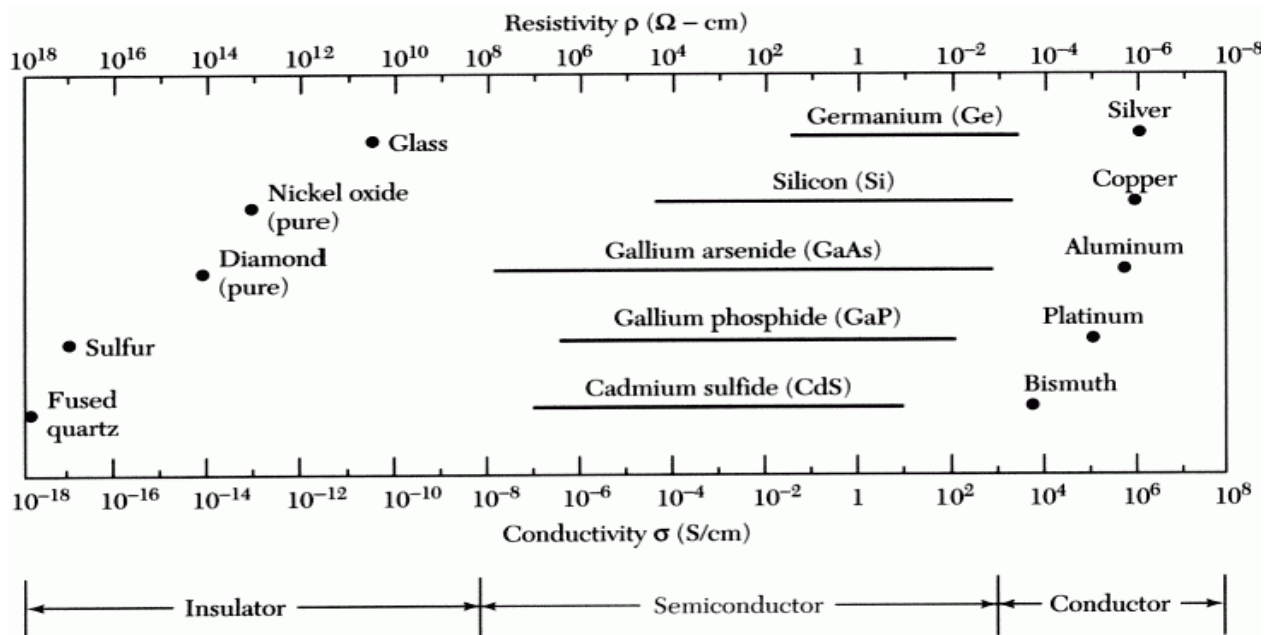


Figure 2.1. Conductivity of different materials [1]

Semiconductors are found in elemental form as Silicon (Si) and Germanium (Ge) belonging to group IV of the periodic table. Semiconductor can be made not only from the group IV compounds but also from elements from groups III and V, respectively.

## 2.2. DOPING AND CONDUCTION IN SEMICONDUCTOR

A semiconductor at absolute zero temperature is unable to conduct heat or electricity [2]. All of the electrons of semiconductor are bonded. The electrons acquire kinetic energy as the temperature is increased and become free to move into the conduction band. These electrons are able to conduct charge and current in opposite direction. The areas left by these electrons in the valence band become vacant, these are called holes. As the temperature of the semiconductor increases, the number of free electrons and holes also increases. Therefore, the conductivity of the semiconductor is directly proportional to temperature [3]. Photoconductivity is exposing the semiconductor with light energy larger than the semiconductor's band gap. Doping is addition of impurities to the semiconductor material. Figure 2.2 shows n-type and p-type doping. The atom of the semiconductor is represented by the blue circle and a +4. When silicon atoms have to n-doped, atoms from group V of the periodic table are added. Each added group V atom provides an extra electron to donate after bonding with four electrons. When silicon atoms have to p-doped, the atoms from group III of the periodic table are added [4]. Each group III atom has one less electron than silicon so a hole is created. Doping increases the number of carriers in the semiconductor material so conductivity increases.

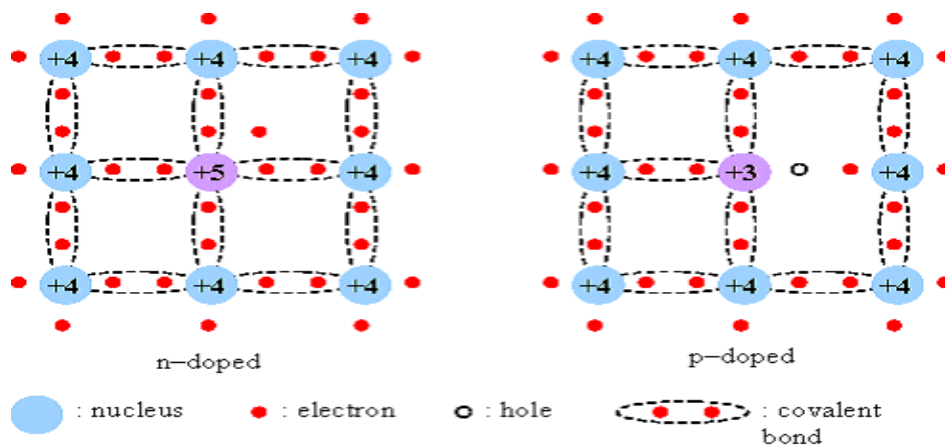
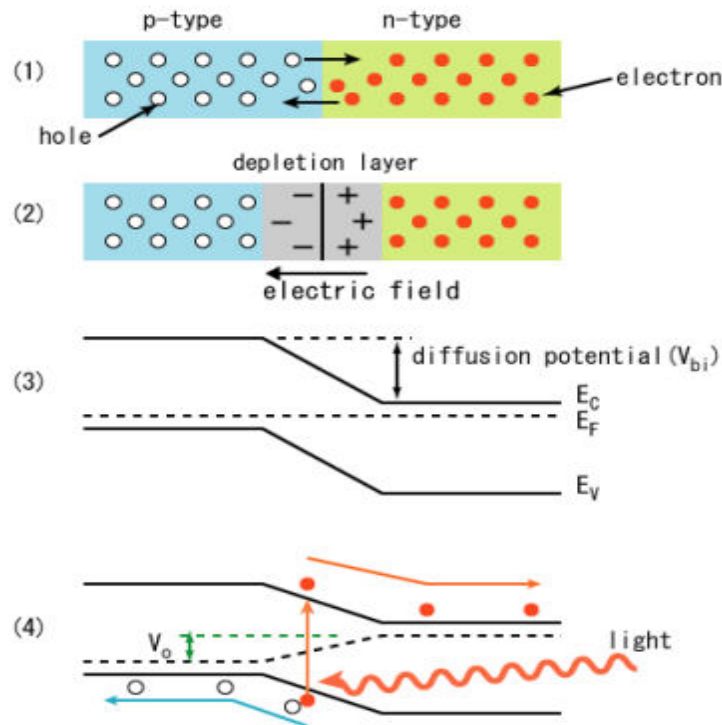


Figure 2.2. Doping: n-type and p-type [5]

An intrinsic semiconductor is a pure semiconductor with a negligible amount of impurity atoms [6].

### 2.3. PN JUNCTION

A p-n junction or diode can be used in many semiconductor device applications. The formation of a p-n junction at the interface of junction helps to control the electrical characteristics of the material. A p-n junction forms only when the one side material is doped with acceptors (p), and the other side is doped with donors (n). Initially when junction forms, there is a large majority carrier density gradient at the junction. When the material tries to come into equilibrium holes will diffuse from the p-region into the n-region, and electrons in the n-region, will diffuse into the p-region, as illustrated in Figure 2.3.



**Figure 2.3.**The pn-junction of an inorganic solar cell (open circuit); 1) electrons close to the junction, or boundary, diffuse into the p-type region; 2) charge builds up along the interface of the two materials, creating an electric field that opposes the flow of electrons; 3) the conduction and valence bands; 4) a photon excites an electron into the conduction band, and the electron and its positive hole are forced to opposite ends of the cell by the intrinsic electric field [6].

When majority carriers diffuse from higher to lower concentration, they will recombine with the minority carriers, forming a depletion region, until no external electric field is applied. The depletion, or space charge region, is that area at the junction where the majority carriers have diffused and left behind oppositely charged atoms which is shown in figure 2.3.

## **2.4. THERMO PHOTOVOLTAIC SOLAR CELL**

Thermo photovoltaic solar uses the material that has properties of generating the electricity when exposed to electromagnetic radiation. These materials can be found in different group of periodic table of element such as single element of group IV element(Silicon and Germanium) while n-ary semiconductor material are made from III and V group material. These materials have properties of between the metal and insulator so these are called semiconductor materials.

## **2.5. PHOTOELECTRIC EFFECT**

The photoelectric effect is a phenomenon in which a photon of sufficient energy is absorbed by an electron. The photoelectric effect was first observed by Heinrich Hertz in 1887 during his experiments with EM radiation [7]. A number of scientists worked on it over the years to find the cause of photoelectric effect but did not succeed.

In 1905, Albert Einstein developed his competing theory of light quanta, which held that ordinary light behaved as if it were a stream of individual localized units of energy [7]. The energy accepted by electron is given by frequency of the incident light, when multiplied by Planck's constant. And this value of energy would only be sufficient to release electrons from certain materials (i.e., vacuum level).

Einstein was awarded Nobel Prize in Physics in 1921 for his theory which was eventually proven correct. From Einstein theory it is clear that it is the frequency of light, and not its intensity which determines whether an electron will be freed from a given material or not when illuminated by a source.

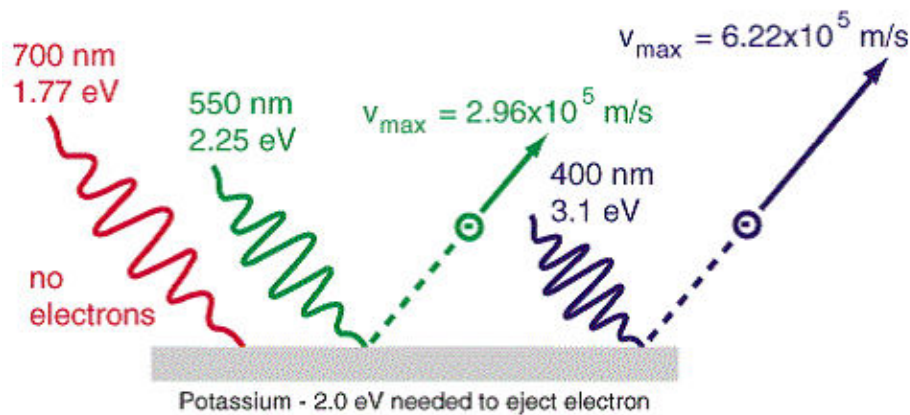
The relation between frequency and energy of the photon is

$$E=h\nu$$



Where  $h$  is Planck's constant with value  $6.626 \times 10^{-34}$  J·s and  $\nu$  is the frequency of the incident light. The energy of the photon is transferred to electron in the form of kinetic energy that extracts the electron from its atom. This process is shown below in Figure 2.4 for a material in a vacuum. In this example we can see that only two of the three incoming photons have sufficient energy to free electrons from the receiving material and excess photon energy is converted into additional kinetic energy thus velocity of the freed electron increases.

There is taken an example of potassium which requires 2.0 eV energy for breaking the bond and releasing the electron hole pair. When photon with energy less than 2.0eV falls on surface of K then it is not absorbed by K atom but when photon with energy greater than 2.0eV falls on surface then it is absorbed and electron and hole pair is generated.



**Figure 2.4.**The release of electrons via photoelectric effect [5]

This process is somewhat different in semiconductor in which energy required to excite the electron is equal to difference in valence and conduction band energy called band gap energy  $E_g$ . Extra energy absorbed by an electron is dissipated in the form of heat and in the mean time when electron goes into conduction band there generates a positive vacancy in the valance band called holes. Now this holes and electron both are responsible for the net current flow.

Designing a solar cell is a very tedious task as variation of any parameter or any material largely affects the performance of solar cell. There are five main characteristic that is used to determine

the quality of solar cell are open circuit voltage  $V_{oc}$ , the short circuit current  $I_{sc}$ , the maximum power  $P_{max}$ , the fill factor  $FF$ , and the efficiency  $\eta$ .

A solar cell is basically a p-n junction with a resistive load where even without applying bias voltage there is an electric field in the depletion region. When photons fall on junction with high enough energy then it creates electron-hole pairs in the depletion region that on moving creates a photocurrent  $I_L$  in the reverse-bias direction. Due to this photocurrent there develops a voltage drop across the load, which forward-biases the p-n junction. The forward-bias voltage, in turn, creates a forward-bias current  $I_F$  which opposes the photocurrent [6]. The resulting net p-n junction current  $I$  is

$$I = I_L - I_F. \quad (1)$$

The photocurrent is always in the reverse-bias direction, which also causes the net solar cell current to flow in the reverse-bias direction. The p-n junction representation of a solar cell is shown in figure 2.5.

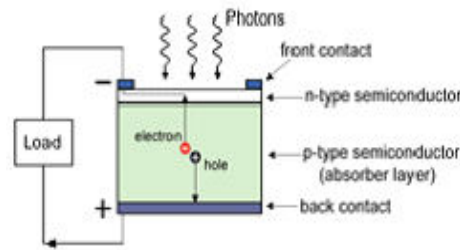


Figure 2.5.P-N junction representation of a solar cell [5].

There are two important limiting parameters of a solar cell which are short circuit current and open circuit voltage.

Short circuit current is value of current when the load resistance is zero i.e. no resistance, causing the voltage also to be zero. Then short circuit current is given by

$$I = I_{sc} = I_L. \quad (2)$$

Open circuit voltage is calculated under the open circuit condition in which load resistance is infinite and the current is zero. The open circuit voltage can then be given by

$$V_{oc} = V_t \ln(1 + I_L / I_{sc}) \quad (3)$$

Where  $V_t$  is the thermal voltage.

Every solar cell has a unique I-V curve which start from zero voltage that is called short circuit current  $I_{sc}$  and ends where voltage is  $V_{oc}$  and current is zero. The main purpose of the solar cell is to deliver power to a load. The maximum power can be calculated from maximum power rectangle that is formed within the I-V curve and is created by drawing straight lines outward from the maximum current and voltage points. An I-V curve for a solar cell with a maximum power rectangle is illustrated in Figure 2.6. Points A and B in Figure 2.6 illustrate two possible power rectangles for this solar cell.

The maximum power is given by

$$P_{max} = V_{max} I_{max} . \tag{4}$$

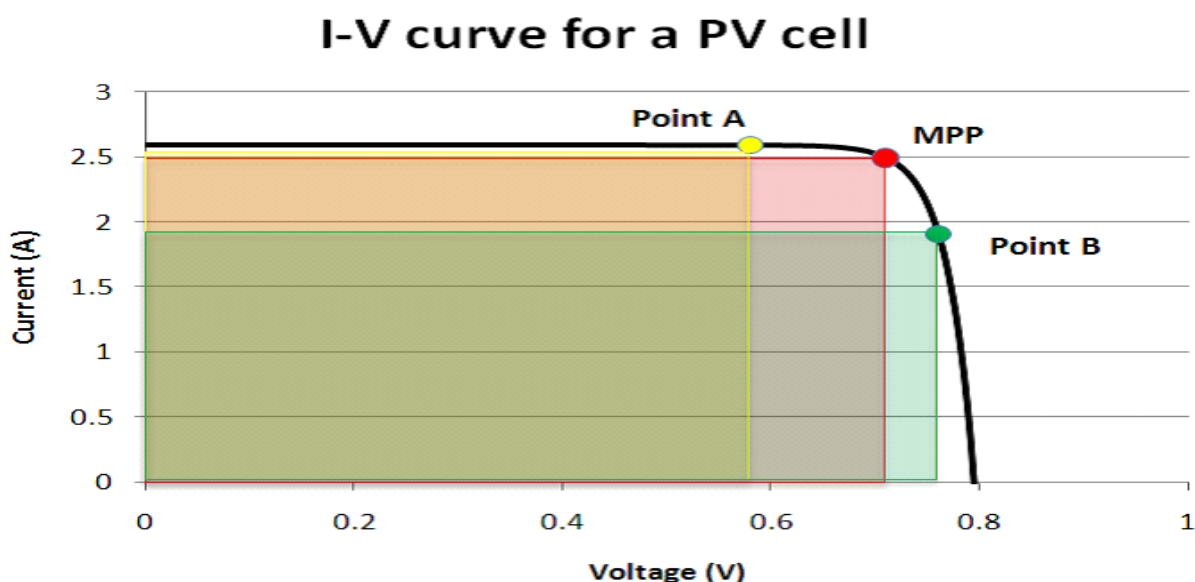


Figure 2.6. I-V curve for a photovoltaic cell showing its maximum power rectangle [8]

The fill factor FF is given by the ratio of the maximum power to the power obtained by multiplication of open circuit voltage and short circuit current. Fill factor FF equation is given by

$$FF = P_{max} / V_{oc} I_{sc} \tag{5}$$

The fill factor denotes the greatest possible maximum power for the given solar cell. If the fill factor is one, the I-V curve will become a perfect rectangle.

Efficiency is the most important parameter of a solar cell. Advantage of high efficiency cell is it allows smaller cell to produce the same amount or more power than a larger cell. A larger cell

costs more to build as compare to smaller one but also costs much more to put into space. The calculation for efficiency can be done as

$$\eta = P_{\max} / P_{\text{in}} \quad (6)$$

where  $P_{\text{in}}$  is the input power from the sun that depends on the air mass number of where the cell is located in relation to the Sun.

## 2.6. MULTIJUNCTION SOLAR CELL

We are living in the world where energy crisis is increasing day by day and solar cell is one of the best solutions for it. But previously made solar cell does not have very good efficiency so to improve this multijunction solar cells are used [9]. Reason for ameliorate efficiency is the different IV characteristic of different layer. Different material absorbs different wavelength light which shows the different levels of input power from Sun [10].

The semiconductors accepting the highest range of energy band gap are placed on top of those accepting smaller one. So in this thesis where three cell are stacked, InGaP cell is placed on top and Ge cell is placed on bottom and GaAs cell is placed in middle [11].

Photon energy,  $E$  as a function of  $h$ , Planck's constant ( $4.136 \times 10^{-15}$  eV-s), and  $c$ , the speed of light can be given as

$$E = hc/\lambda$$

From above relation it is clear that energy,  $E$  is inversely proportional to wavelength,  $\lambda$ .

Thus it is clear that top layer of InGaP receives highest energy falling on the surface and lower one is transferred to lower layer till the Ge layer. Ge has very low band gap energy so it absorbs almost all solar cell spectrum and the photons that has been passed through its upper layer [12].

## 2.7. STACKED SOLAR CELL

For construction of three-junction solar cell it is necessary to understand the different components that have been used to make this solar cell [12].

Basic stacked solar cell structure is shown in figure 2.7.

|                |
|----------------|
| CONTACT        |
| WINDOW         |
| EMITTER        |
| BASE           |
| BSF            |
| BUFFER         |
| TUNNEL EMITTER |
| TUNNEL BASE    |
| CONTACT        |

**Figure 2.7.**Basic stacked solar cell component [13].

### 2.7.1. CONTACTS

Contacts are made on top and bottom of a solar cell from where current flows and given to load. Top contact is made anywhere on top covering 2-8% of surface area to prevent recombination and shadowing while bottom contact is made on the whole bottom surface to prevent recombination and act as reflector to force back the light to solar cell.

### 2.7.2. WINDOW

Window is made of material having very high band gap energy so that it collects the maximum light as almost transparent to light. Window layer is highly conducive for electron allowing it to pass without increasing the solar cell series resistance.

### 2.7.3 EMITTER AND BASE

Emitter and base here are simply the n and p junction used in electronics that has been introduced in this thesis too. Emitter are n-type and base are p-type.

#### **2.7.4. BACK SURFACE FIELD**

Above the BSF region there is base region so it makes p-p+ junction. The built in voltage of this junction reflects the minority carrier so short circuit voltage of solar cell increases. The addition of the BSF layer between base and buffer layer shares the applied voltage between the n-p and p-p+ junction, which decreases the dark current in the cell.

#### **2.7.5. TUNNEL JUNCTION**

If the layers are just stacked one above one then there will be problem of formation of parasitic p-n junction and voltage drop across this parasitic p-n junction will become too large to overcome. So to solve this problem a thin highly doped p-n junction is placed between these layers which act as a transition layer. Without using the tunnel junction we cannot make a three junction solar cell.

#### **2.7.6. BUFFER**

Buffer layer is made to achieve high open circuit voltage.

### **2.8. FACTORS AFFECTING SOLAR CELL PERFORMANCE**

There are mainly five types of factors that affect a lot to solar cell performance [10] and these are

#### **2.8.1. REFLECTION**

All the light that fall on the surface of solar cell is not absorbed by solar cell so it is not converted efficiently into light energy. The amount of reflection can be controlled by antireflection coating or texturing or both [14,15].

#### **2.8.2. CONDUCTORS**

Conductors are used to collect the electrons at top of solar cell thus utilizing 8% of total area. The spacing of conductor is very important in designing of solar cell to stop the electron hole recombination that is why the surface area cannot be reduced. So effective light energy that is to be converted into electrical energy is reduced and results in reduced efficiency.

### **2.8.3. TEMPERATURE**

Owing to lattice vibrations the flow of charges results in increase in temperature and internal resistance with charge and flow produce heat. Also the photon with greater energy produces heat. So we can say that the performance of a solar cell degrades other than optimum temperature.

### **2.8.4. DEFECTS**

There may be different type of defect in the material being used for solar cell manufacturing. These defects create problem in recombination. The number of defects increases when cell is exposed in the space environment.

### **2.8.5. RECOMBINATION**

Recombination of electron and hole can occur before its utilization. Recombination may be direct or indirect. So we will have to prevent from it.

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## CHAPTER 3

# SOFTWARE USED FOR ANALYSIS AND SIMULATION

### 3.1. BRIEF OVERVIEW

It is very expensive and time consuming to make a solar cell and test it for the desired result. Silicon Valley Company (Silvaco) has created ATLAS, a technology computer aided design (TCAD) software program that has been used in this thesis to simulate the performance of solar cell.

### 3.2. SILVACO ATLAS

ATLAS is a physically based two- and three-dimensional device simulator of semiconductor devices. It is able to predict the electrical characteristics of specified solar cell structures [1]. The programs that Silvaco offers as tools to create specific semiconductor devices to simulate with ATLAS and the different type of results that ATLAS is capable of producing are shown in Figure 3.1.

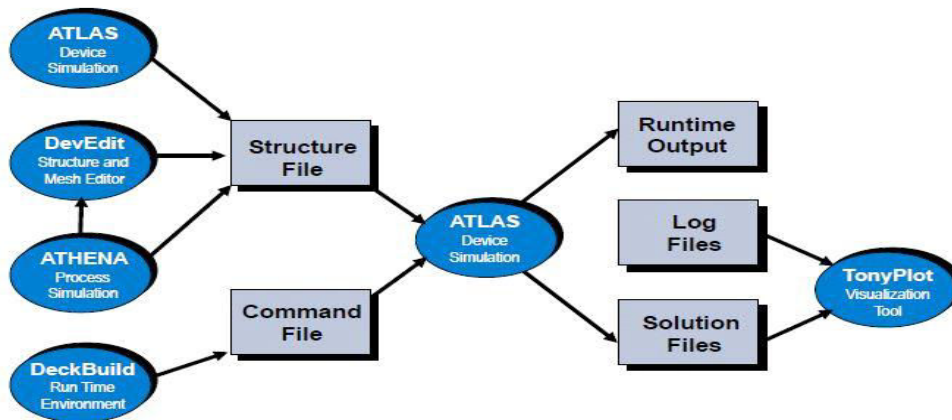


Figure 3.1.ATLAS Inputs and Outputs [2].

Since DeckBuild is capable of specifying the entire solar cell structure, it is the only input used in this thesis. The programmer builds the structure in the DeckBuild run-time environment where ATLAS is called to conduct the device simulation and gives the results as a run-time output or in log files. The programmer activates ATLAS in DeckBuild using the line: go atlas DeckBuild also contains a sequence of statements with set parameters used to build and simulate the semiconductor device. Each of these lines of code has the general form:

<STATEMENT><PARAMETER>=<VALUE>

In each statement, the parameters may have four different types of values: real, integer, character, or logical [3]. The following is a sample line of code for DeckBuild.

DOPING N.TYPE CONC=1.0e16 REGION-1 OUTFILE=my.dop

In this line of code, “DOPING” is the statement and the remaining are examples of logical, real, integer, and character parameters, respectively [3]. Although the statement must come first in any line of code, the order of the parameters is arbitrary. The spelling of any parameters may be shortened as long as enough letters are present to distinguish it from any other possible parameter. Any logical parameter may be set to false by preceding it with the ^ symbol. A programmer inserts a comment within the DeckBuild lines of code by preceding it with the # symbol. The programmer must give the statements in DeckBuild in a specific order; otherwise, ATLAS generates errors or gives incorrect results. The different groups of statements and the order in which the programmer is to give them are shown in Figure 3.2.

| <i>Group</i>                            | — | <i>Statements</i>                          |
|---|---|--|
| <b>1. Structure Specification</b>       | — | MESH<br>REGION<br>ELECTRODE<br>DOPING      |
| <b>2. Material Models Specification</b> | — | MATERIAL<br>MODELS<br>CONTACT<br>INTERFACE |
| <b>3. Numerical Method Selection</b>    | — | METHOD                                     |
| <b>4. Solution Specification</b>        | — | LOG<br>SOLVE<br>LOAD<br>SAVE               |
| <b>5. Results Analysis</b>              | — | EXTRACT<br>TONYPLOT                        |

**Figure 3.2.** Order of Statements in ATLAS [2]

### 3.3. Constants

To make it easier to change the design of the solar cell for numerous simulations, the programmer uses set commands to define common variables specifying the design of the solar cell. The following is an example of a set command in DeckBuild:

```
set x=0.51
```

This command defines the mole fraction of In<sub>1-x</sub>Ga<sub>x</sub>P and allows it to be easily changed for different solar cell designs. The programmer can change the design of the solar cell more quickly this way since x and many other variables like it are used more than once in the DeckBuild lines of code. For example, x is used later where the material's composition is specified by x.comp=\$x. The \$ symbol means that a pre-defined variable is to be used as the x.comp value. Matlab is used in this thesis to run DeckBuild and iterate the specified variables, such as emitter thickness and emitter doping, given in the set commands to see how different solar cell designs perform. The programmer is able to run many simulations by changing two variables at a time.

### 3.4. Structure

After specifying the set commands, the programmer defines the mesh, regions, electrodes, and doping of the structure.

#### 3.4.1. Mesh

The meshing is a set of horizontal and vertical lines that make a grid for building the structure. The programmer specifies these lines with commands in the following form:

```
X.MESH LOCATION=<VALUE> SPACING=<VALUE>
```

```
Y.MESH LOCATION=<VALUE> SPACING=<VALUE>
```

An example of a mesh created for ATLAS is given in Figure 3.3.

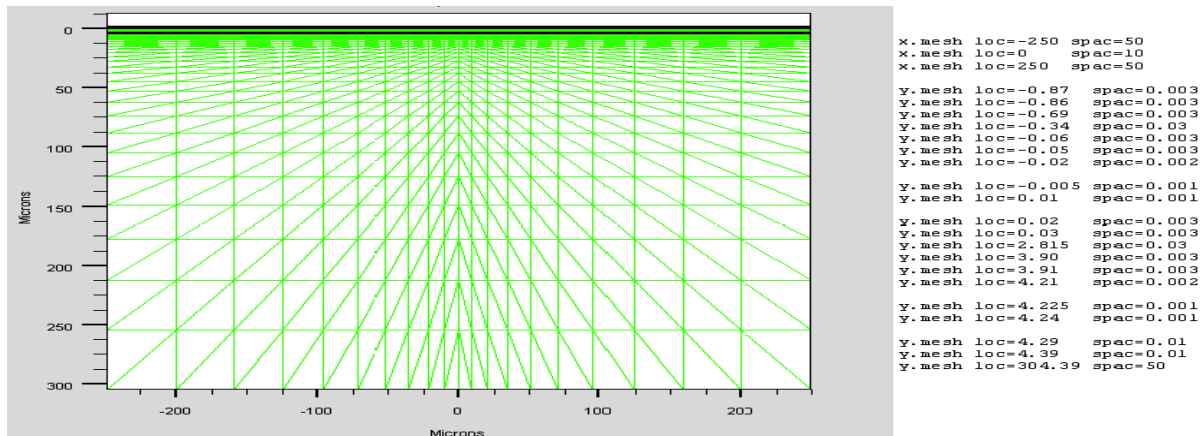


Figure 3.3. Mesh Defined [4].

The solar cell's electrical characteristics are evaluated at each crossing of the horizontal and vertical lines defined in the mesh to determine the solar cell's overall performance.

Quantum tunnel mesh is a special type of grid specification used to simulate tunnel junctions in multijunction solar cells [5]. Similar to the regular meshing, the programmer uses the following general format in quantum tunnel mesh statements:

QTX.MESH LOCATION=<VALUE> SPACING=<VALUE>

QTY.MESH LOCATION=<VALUE> SPACING=<VALUE>

This special mesh is required to measure the current flow through the tunnel junction and lies over the other mesh previously created. Since the flow of current is in the y direction through the tunnel junction, the spacing in this direction is very fine, whereas the spacing in the x direction is much larger. The following are examples of typical quantum tunnel mesh statements for one tunnel junction.

qtx.meshloc=-250 spac=50

qtx.meshloc=0 spac=10

qtx.meshloc=250 spac=50

qty.meshloc=4.225 spac=0.001

qty.meshloc=4.2325 spac=0.00005

qty.meshloc=4.24 spac=0.001

Although additional QTY.MESH statements are required for any remaining tunnel junctions in the solar cell, the QTX.MESH statements are sufficient for all tunnel junctions that exist in the solar cell.

### **3.4.2. Regions**

The programmer further defines the solar cell by specifying the different materials in the regions of the structure. The following general code is used for this:

REGION number=<interger><material\_type><position parameters>

In this example, the \ character means that the command continues on the next line. The following is an example of a regions statement used in DeckBuild:

```
regionnum=3 material=InGaPx.comp=0.51 x.min=- 250 x.max=250 y.min=-0.86 y.max=-0.69
```

Up to 200 regions may be defined in ATLAS and a large number of materials are available for use. For materials with a specific mole fraction, the x and y composition fractions (X.COMP and Y.COMP, respectively) are to be specified in the region statements. The position parameters are specified using X.MIN, X.MAX, Y.MIN, and Y.MAX parameters. The programmer must specify a material for every portion of the structure defined by the mesh statements [4].

### 3.4.3. Electrodes

The next portion of the structure specification commands defines the electrodes. The general format for these commands is of the following form:

ELECTRODE NAME=<electrode name><position\_parameters>

For example, the following are statements for electrodes used in DeckBuild:

```
electrode name=cathode x.min=-5 x.max=5 y.min=-0.92 y.max=-0.92
electrode name=anode x.min=-250 x.max=250 y.min=304.31 y.max=304.31
```

Although up to 50 electrodes can be specified in the program, only the anode and cathode are needed for single-layer solar cells [6]. For multijunction solar cells, an electrode is added for every tunnel junction that exists. The anode is gold and only covers a small percentage of the top, usually eight percent or less. The cathode covers the entire bottom surface of the solar cell.

### 3.4.4. Doping

The last portion of the structure specification is the doping specified for each region of the solar cell. The general form of the doping statements is as follows:

DOPING <distribution\_type><dopant\_type><position\_parameters>

The doping statements specify the type and amount of doping in each section of the solar cell. The two following doping statements illustrate how this is done.

```
doping uniform region=3 n.typeconc=4.64e17
```

```
doping uniform region=4 p.typeconc=1e17
```

The doping can be n- or p-type with either uniform, Gaussian, or complementary error function distribution specified.

### **3.5. Material Models**

The material models specification consists of commands for specifying the materials, models, contacts, and interfaces of the solar cell.

#### **3.5.1. Materials**

The programmer defines the materials of the solar cell in DeckBuild using the following format:

```
MATERIAL <identification><material_parameters>
```

The programmer can give the material identification in several ways. The material may be specified by a particular region or name that it has been given in previous lines of code, or the material statement might be given for all materials of its type. The following examples illustrate the different ways the material may be identified.

```
MATERIAL MATERIAL=InGaP EG300=1.9 MUN=1945
```

```
MATERIAL REGION=4 TAUN0=1e-7 TAUP0=1e-7
```

```
MATERIAL NAME=base NC300=1.3e20 NV300=1.28e19
```

Electron affinity (AFFINITY), room temperature band gap (EG300), electron (MUN) and hole (MUP) mobility, electron (TAUN0) and hole (TAUP0) recombination lifetimes, valence (NV300) and conduction (NC300) band density of states, and other material parameters are often defined for semiconductors [7]. Otherwise, ATLAS uses a default value if a material parameter is not specified.

### 3.5.2. Models

A programmer specifies the physical models using MODELS and IMPACT statements of the following form.

MODELS <physical\_model><model-dependent\_parameters><general\_parameters>

However, the physical models may be specified for specific materials by using the following format.

MODELS MATERIAL=<material><physical\_models> \  
 <model-dependent\_parameters><general\_parameters>

The physical models consist of five classes: mobility, recombination, carrier statistics, impact ionization, and tunneling [8]. The models that are used depend on the materials of the solar cell, and that is why they can be specified for only one material or the whole cell, if appropriate. A summary of the model parameters used in this thesis is presented in Table 3.1.

| Parameter                        | Syntax      | Explanation   |
|----------------------------------|-------------|---|
| Shockley-Read-Hall               | SRH         | Recombination model that uses fixed minority carrier lifetimes; should be used in most simulations  |
| Bandgap Narrowing                | BGN         | Carrier statistics model that is important in heavily doped regions   |
| Operating Temperature            | TEMPERATURE | Parameter that specifies the operating temperature  |
| Model and Parameter Verification | PRINT       | Parameter that lists in the runtime output the models and parameters used during the simulation to allow for verification of correct modeling |

Table 3.1. Basic Models [8]



To properly simulate solar cells with tunnel junctions, additional models are required. Models that deal directly with tunnel junctions are applied. A summary of some of the models to use with the tunnel junctions of multijunction solar cells is given in Table 3.2.

| Parameter                  | Syntax                      | Explanation   |
|----------------------------|-----------------------------|---|
| Band-to-Band<br>(standard) | BBT.STD                     | For direct transitions;<br>required with very high fields |
| Klaassen Band-to-Band      | BBT.KL                      | Includes direct and indirect transitions                  |
| Non-local Band-to-Band     | BBT.NONLOCAL                | For non-local band-to-band tunneling                      |
| BBT.NLDERIVS               | Includes non-local coupling |   |

Table 3.2. Tunnel junction model [8]

The BBT.STD and BBT.KL models can be used together with the BBT.NONLOCAL and BBT.NLDERIVS models or separate. Together, they often lead to results that are more accurate but require more time to calculate.

### 3.5.3. Contacts

The CONTACT statement is used to describe the electrodes. These statements are of the following form:

CONTACT NAME=<name><property\_specification>

The CONTACT statements are not required if the properties of the electrodes need no special designation or modification [9].

### 3.5.4. Interfaces

The INTERFACE statement is used to specify the interface charge density and surface recombination velocity at interfaces between semiconductors and insulators [2]. The INTERFACE statement is given in the following format.

INTERFACE <parameters><interface\_dimensions>

However, interface properties are not specified in the solar cells simulated in this thesis.

### **3.6. Light Beams**

For solar cell simulation, it is important to specify a light source. A programmer can accomplish this with one line of code. The following is an example of this.

```
BEAM NUMBER=1 X.ORIGIN=0 Y.ORIGIN=-5 ANGLE=90 \  
BACK.REFL POWER.FILE=AM0nrel.spec \  
WAVE1.START=0.12 WAVE1.END=2.4 WAVE1.NUM=1500
```

This statement completely describes the light source. The exact location and angle of the light relative to the solar cell is specified. The power file containing information about the sun is used. The range of wavelengths is also specified along with the number of beams to use in this range of wavelengths [10]. BACK.REFL makes sure the reflection of sunlight off the surface of the solar cell is taken into account.

### **3.7. Numerical Methods**

The METHOD statement is the only statement in the numerical methods specification. A variety of numerical methods exists for making calculations to determine semiconductor device behavior. Among these methods, three basic types of techniques for calculating the solutions exist [8]: decoupled (GUMMEL), fully coupled (NEWTON), and decoupled and fully coupled (BLOCK). The METHOD statement is given in the following general format.

```
METHOD <methods>
```

The NEWTON method is the most preferred method used and is, therefore, the default method. However, as the following example illustrates, the programmer can specify more than one method to use on the models that are appropriate for them [11].

```
METHOD GUMMEL BLOCK NEWTON
```

### **3.8. Solution**

The solution specification consists of LOG, SOLVE, LOAD, and SAVE statements.

#### **3.8.1. Log**

The LOG statement is used to capture all the terminal characteristics calculated by ATLAS in a specified file. The following general format is used for the LOG statement.

LOG OUTFILE=<filename>

The filename has the .log file extension. The creation of this log file makes it possible to save all the I-V characteristics of the solar cell.

### 3.8.2. Solve

The SOLVE statement is used to calculate specified bias points. This statement is of the following basic format.

SOLVE <bias\_points>

The bias points can be single points or multiple points that are stepped from an initial point to a final point, as the following example illustrates.

SOLVE vanode=0.0 vstep=0.05 vfinal=2.4 name=anode

In order to obtain convergence for the equations used to calculate these bias points, it is important to give a good initial guess prior to this line of code.

### 3.8.3. Load

The LOAD statement loads previous solutions from files as initial guesses to other bias points [1]. This statement is of the following form.

LOAD INFILE=<filename>

If more than one file is to be loaded, the following format is used.

LOAD IN1FILE=<filename> IN2FILE=<filename>

### 3.8.4. Save

The SAVE statement saves all node point information into an output file [1]. The general format for this statement is as follows.

SAVE OUTFILE=<filename>

The mesh, electrodes, doping, and region boundaries are stored in the file along with all electrical data from the last solution if a SOLVE statement precedes the SAVE statement.

### 3.9. Results

The results analysis consists of EXTRACT and TONYPLOT statements that specify how to handle the solutions calculated in the ATLAS simulation.

#### 3.9.1. Extract

The EXTRACT statement allows device parameters to be displayed in the run-time output. The EXTRACT statement operates on the previous solved curve or structure file and by default uses the currently open log file [1]. However, the name of a file to be used can be specified before the extraction routine by using the following form of code.

```
EXTRACT INITIAL INFILE="<filename>"
```

Then a series of EXTRACT statements can follow to display the desired device parameters. The following is an example of an EXTRACT statement used to extract the open-circuit voltage of the solar cell's I-V characteristics.

```
EXTRACT NAME="Voc" X.VAL from CURVE(v."anode," i."cathode") where Y.VAL=0.0
```

Not only will the results of the extraction commands be displayed in the run-time output but also will be by default stored in the file results.final. However, the results can be stored in a different file by specifying it at the end of the EXTRACT statements. The following code is added on the end of each EXTRACT statement to save the extraction in a specific file.

```
DATAFILE="<filename>"
```

The same file can be used to store the results of all EXTRACT statements.

#### 3.9.2. Tonyplot

The TONYPLOT statement starts the graphical post-processor TonyPlot [12]. This statement gives the specific file to be graphically displayed in TonyPlot. For example, the following is a command used to plot the I-V curve.

```
TONYPLOT IVcurve.dat
```

The dat file in this example was created from the EXTRACT commands as follows.

```
EXTRACT NAME="iv" \CURVE(v."anode," i."cathode") OUTFILE="IVcurve.dat"
```

Besides plotting the results with TonyPlot, the log files are interpreted and plotted using Matlab script files.

## REFERENCES

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## CHAPTER 4

## SIMULATION AND STRUCTURAL DETAILS OF HETEROJUNCTION SOLAR CELL

### 4.1. SIMULATION OF HETEROJUNCTION SOLAR CELL

The solar cell simulated in this thesis has been constructed on Silvaco ATLAS software using codes and then it has been analyzed to get different parameters. Basic two dimensional structure of the solar cell is shown in figure 4.1.

|        |                |        |                |
|--------|----------------|--------|----------------|
| Vacuum | (0.05micron)   |        |                |
| AlGaAs | (0.01 micron)  | 5e19   | Window         |
| InGaP  | (0.17 micron)  | 5e17   | Emitter        |
| InGaP  | (0.63 micron)  | 1e17   | Base           |
| InGaP  | (0.01 micron)  | 5e19   | BSF            |
| AlGaAs | (0.03 micron)  | 1e18   | Buffer         |
| InGaP  | (0.015 micron) | 8e18   | Tunnel Emitter |
| InGaP  | (0.015 micron) | 1e19   | Tunnel Base    |
| AlGaAs | (0.01 micron)  | 5e17   | Window         |
| GaAs   | (0.01 micron)  | 4.5e15 | Emitter        |
| GaAs   | (3.87 micron)  | 1e17   | Base           |
| InGaP  | (0.01 micron)  | 5e19   | BSF            |
| GaAs   | (0.3 micron)   | 7e18   | Buffer         |
| GaAs   | (0.015 micron) | 8e18   | Tunnel Emitter |
| GaAs   | (0.015 micron) | 1e19   | Tunnel Base    |
| AlGaAs | (0.05 micron)  | 7e18   | Window         |
| Ge     | (0.1 micron)   | 1e19   | Emitter        |
| Ge     | (300 micron)   | 1e16   | Substrate      |

**Figure 4.1.**Basic 2-d structure of heterojunction solar cell

The basic approach to form the hetero junction solar cell is that the highest band gap material should be on top of solar cell and lowest band gap material needs to be on the bottom and the material with intermediate band gap will be in the middle [1]. Highest band gap material will absorb the light and remaining will be absorbed by middle cell and lowest cell made of germanium will absorb the remaining light because it has the lowest band gap i.e. highest wavelength. Each layer must be perfectly matched with upper and lower layer [2].

The above structure has been made starting from window to ending tunnel base structure [3]

## 4.2. STRUCTURE OF SOLAR CELL FROM TONYPLOT

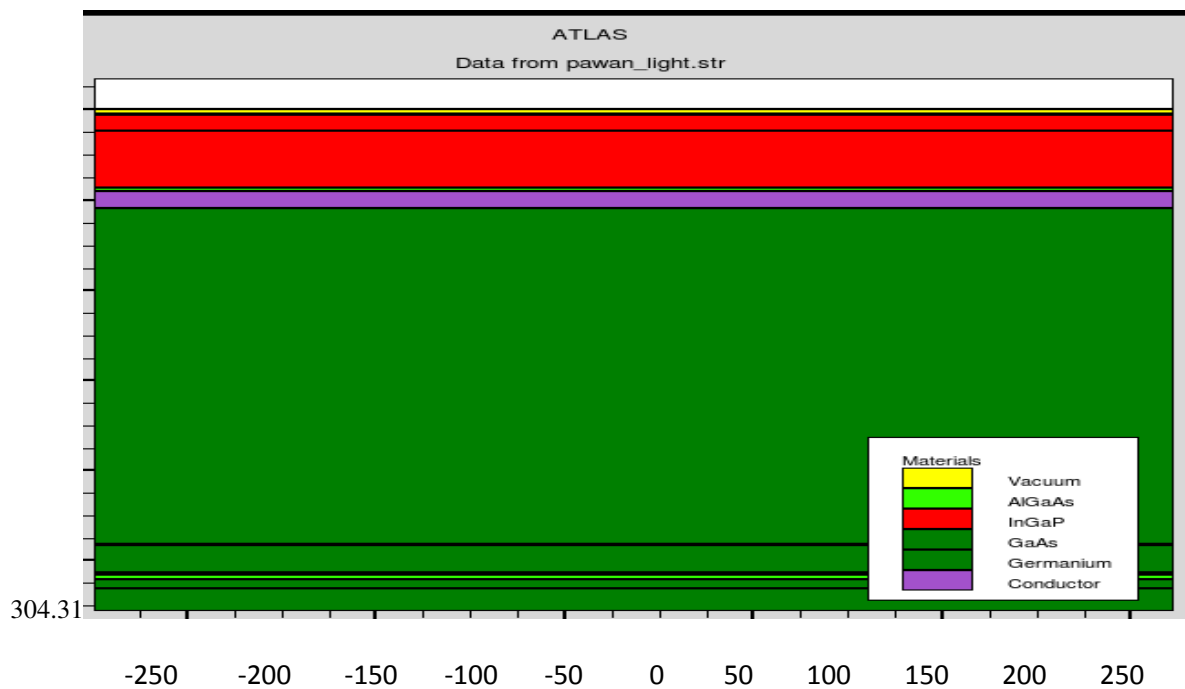


Figure4.2.Tonyplot structure of solar cell

Above structure in figure 4.2 has been made with width 550 micro meter and height 304.31 micrometer. For this air mass 1.5 has been used [4]. Different parameters and tonyplot data obtained for this structure is shown below-

### 4.3 NET DOPING ACROSS SIMULATED SOLAR CELL

The plot shown below in figure 4.3 shows the net doping across the hetero junction solar cell in which base is lightly doped, emitter is moderately doped and tunnel junction is highly doped. Tunnel junction is highly doped that is why photo generation here is highest [5]. Each material can be doped by any dopant to the desired concentration. This can be done in a regular uniform way, in a linear or even a Gaussian distribution. Non-standard doping profiles can also be inputted from other TCAD programs or from custom ASCII files [6].

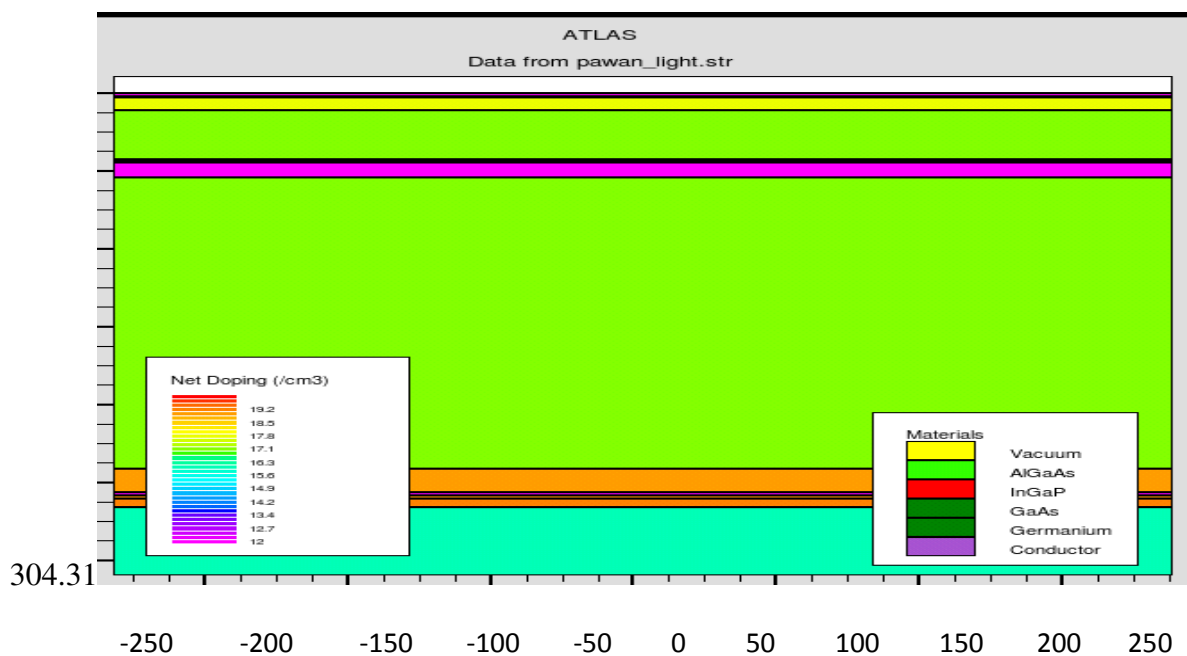


Figure4.3.NetDoping

### 4.4 PHOTOGENERATION RATE

We have seen earlier that electrons can be excited with heat and that atoms can be ionized to produce EHP's. Another way to offer such energy to a material is photons (*photogeneration*), thus light [7].

From the following tony plot figure, it is clear that photo generation is maximum near the tunnel area and current flows due to the movement of electrons and holes generated due to these photons [8]. Photogeneration rate thus obtained is shown in figure 4.4.



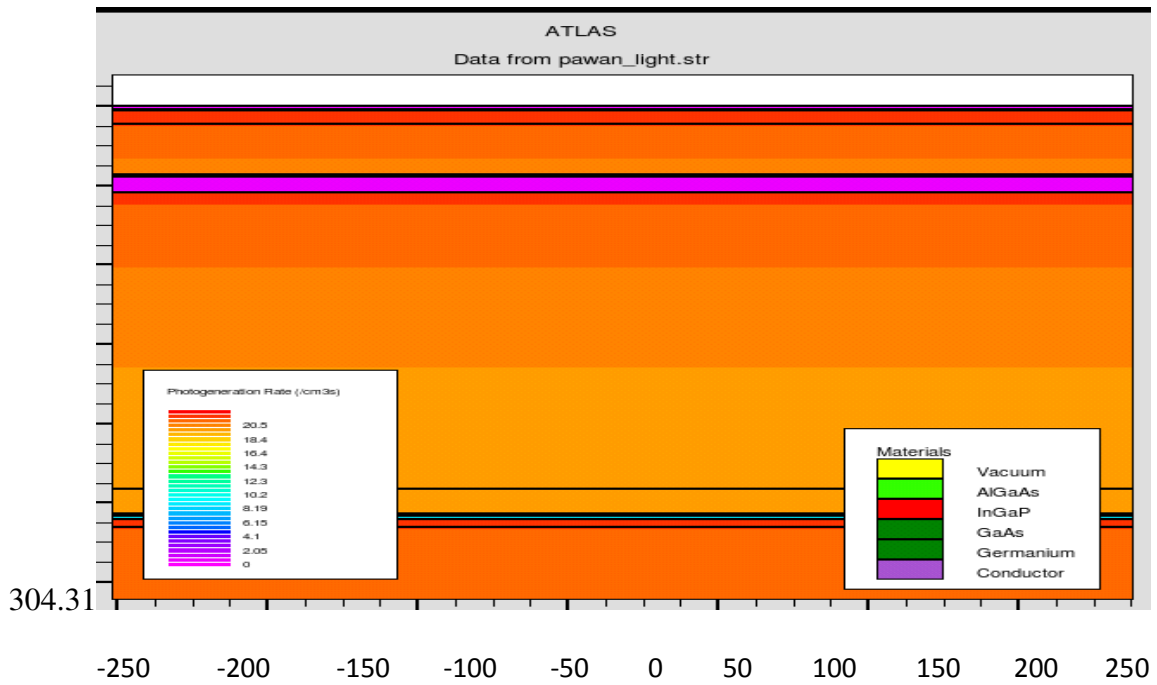


Figure4.4.Photogeneration rate

#### 4.5. POTENTIAL DEVELOPED

Potential obtained in the formed solar cell has been shown in figure 4.5.

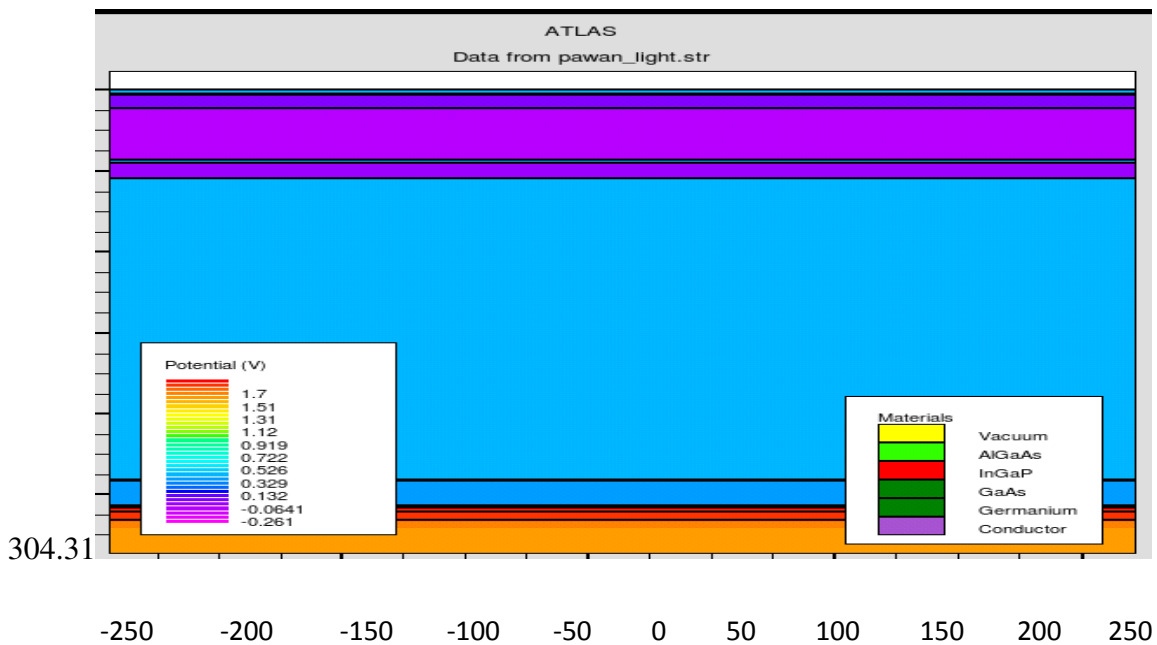


Figure 4.5. Potential developed

From the figure 4.4 it is clear that the photo generation rate is maximum near the tunnel junction so there will be maximum electrons and holes that will contribute to current by flowing in opposite direction. Since the current flow is maximum here therefore the potential developed will also be maximum near tunnel junction and minimum near top as shown in Fig. 4.5 [9].

#### 4.6. I-V CURVE OF STRUCTURE.

I-V curve of the simulated structure is shown in figure 4.6. The curve shown is in fourth quadrant so it generates energy that given structure works and data obtained for this solar cell is correct [10]. Efficiency is the most important parameter of a solar cell. Advantage of high efficiency cell is it allows smaller cell to produce the same amount or more power than a larger cell. A larger cell costs more to build as compare to smaller one but also costs much more to put into space [11].

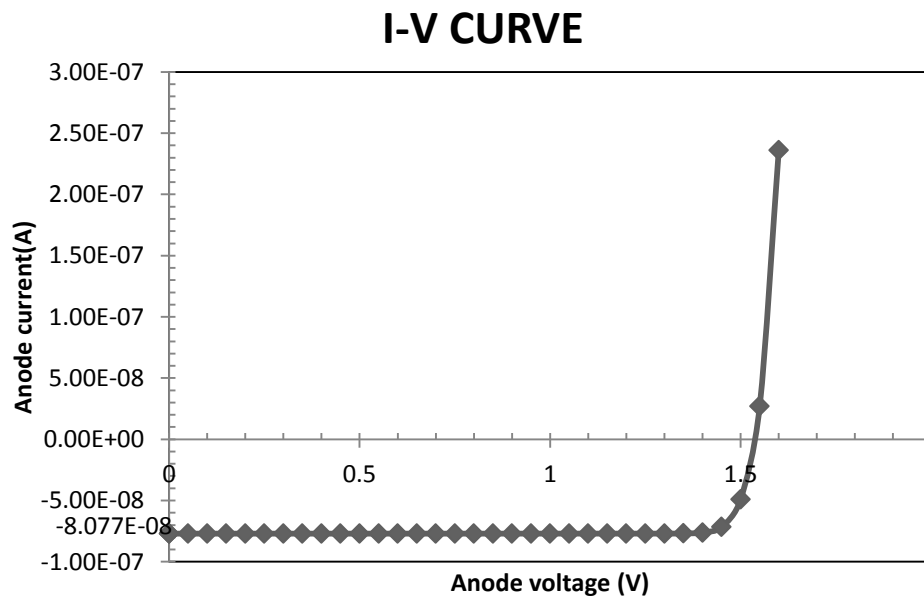


Figure 4.6.I-V curve

Different parameters obtained from this I-V curve is given below-

$$I_{sc} = 8.0772e-08$$

$$J_{sc} = 14.6858$$

$$V_{oc} = 1.53234$$

$$P_m = 1.11799e-07$$

$$V_m = 1.4$$

$$I_m = 7.98564e-04$$

$$FF = 0.903279$$

$$Eff_i = 20.3271$$

At this moment, the triple MJ cell with the highest efficiency (29.3%) published is built by Spectrolab [12].

## REFERENCES

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## CHAPTER 5

### ANALYSIS OF SIMULATED SOLAR CELL BY VARYING DIFFERENT PARAMETERS

The solar cell made in chapter 4 is of width 550 micro meter. Now the impact of varying the width has been studied on the performance of solar cell. In addition to width, beam and tau has also been varied and result has been obtained [1].

#### 5.1. VARIATION OF TAUN AND TAUP

Taun and taup are relaxation time of electrons and holes respectively. Stating that “a silicon wafer has a long lifetime” usually means minority carriers generated in the bulk of the wafer by light or other means will persist for a long time before recombining.

Different parameters on variation of taun and taup are shown in the table 5.1.

|       | Taun=Taup=1e-7 (s)         | Taun=Taup=1e-6 (s)         | Taun=Taup=1e-5 (s)         | Taun=Taup=1e-4 (s)        |
|-------|----------------------------|----------------------------|----------------------------|---------------------------|
| Isc   | 7.11925e-07 A              | 7.1587e-08 A               | 7.27463e-08                | 7.33451e-08 A             |
| Jsc   | 14.2385 mA/cm <sup>2</sup> | 14.3174 mA/cm <sup>2</sup> | 14.5493 mA/cm <sup>2</sup> | 14.669 mA/cm <sup>2</sup> |
| Voc   | 1.46514 V                  | 1.50454 V                  | 1.52516 V                  | 1.53228 V                 |
| Pm    | 9.29839e-08 Watt           | 9.65036e-08 Watt           | 1.00385e-07 Watt           | 1.01519e-07 Watt          |
| Vm    | 1.35 V                     | 1.4 V                      | 1.4 V                      | 1.4 V                     |
| Im    | 6.8877e-08 A               | 6.89311e-08 A              | 7.17036e-08 A              | 7.25136e-08 A             |
| FF    | 0.891443                   | 0.895995                   | 0.904779                   | 0.903313                  |
| Effi. | 18.5968                    | 19.3007                    | 20.077                     | 20.3038                   |

**Table 5.1.** Different parameters on variation of taun and taup

According to data of table 5.1 different graph has been plotted for Isc, Jsc, Voc, Pm, Vm, Im, FF, Effi. with variation of taun and taup.

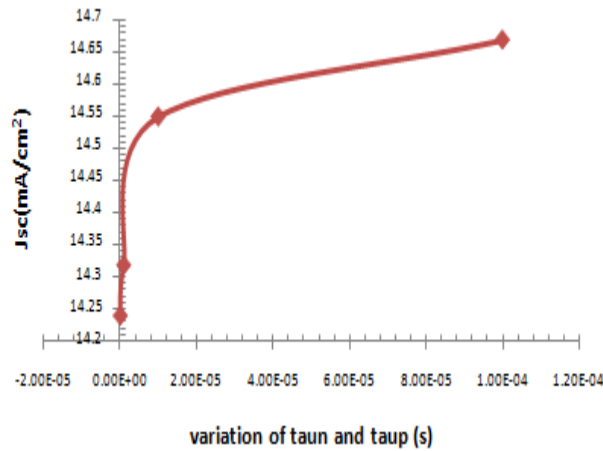


Figure 5.1.

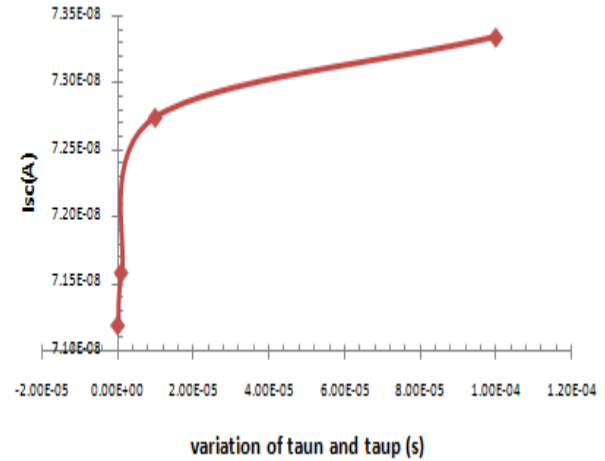


Figure 5.2.

Auger lifetime is inversely proportional to square of carrier concentration. Recombination rate is proportional to carrier concentration. If there is no excess carrier then recombination rate will be zero. Relaxation time is inversely proportional to recombination rate thus when relaxation time is increased then time for electrons and holes to recombine [2] decreases therefore electrons and holes contribute more to current, current density and short circuit voltage [3] that is clear from figure 5.1 and figure 5.2.

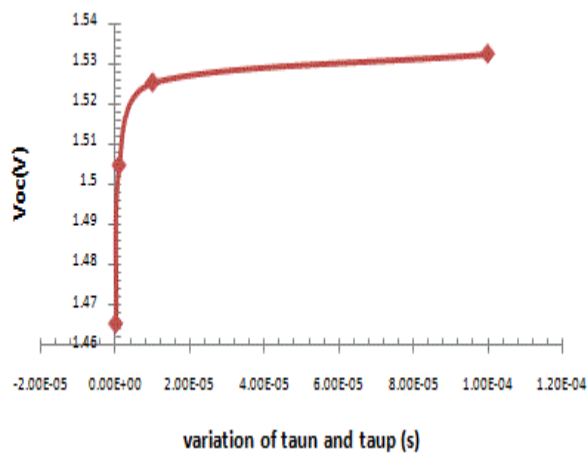


Figure 5.3.

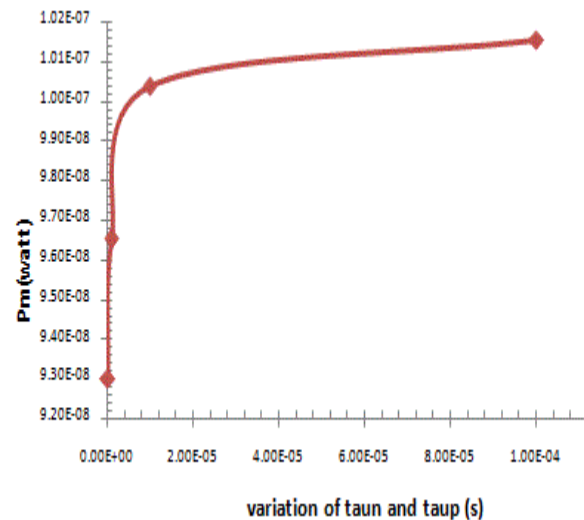


Figure 5.4.

With increase in relaxation time diffusion length also increases. So this increase in diffusion length corresponds to increase in photogeneration thus current also increases. This increased

current lead it to increase in voltage, Figure 5.3 and figure 5.4 show the increase in open circuit voltage and maximum power with increase in relaxation time. Above plot shows the rapid variation initially and moderate variation in the end.

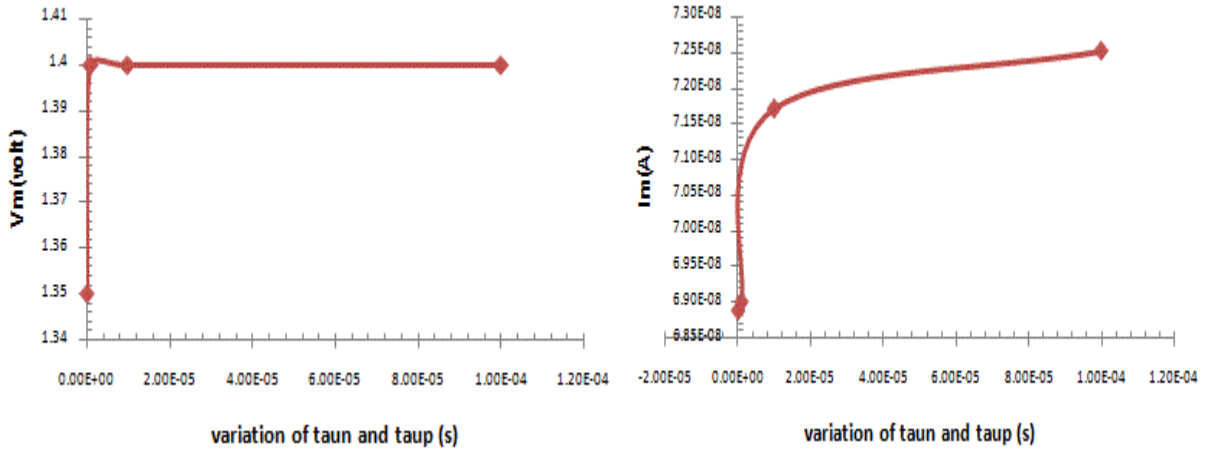


Figure 5.5.

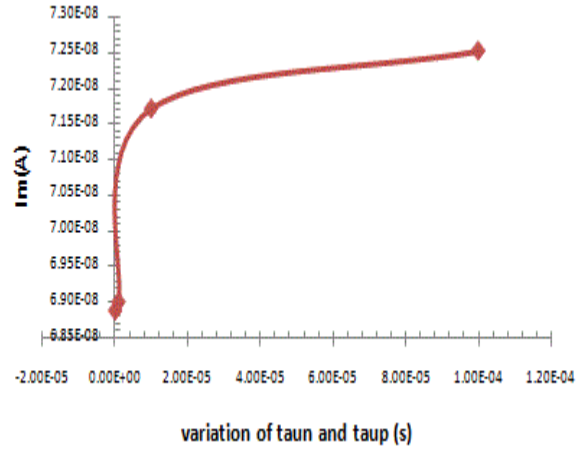


Figure 5.6.

Figure 5.5 shows that initially there is sudden increase in maximum voltage but after that it becomes constant whereas figure 5.6 show the rapid increase in maximum current due to increased photogeneration. Now it is clear from plot that maximum current is increasing and maximum voltage first increasing then constant therefore power increases as it is multiplication of them which has been shown in figure 5.4.

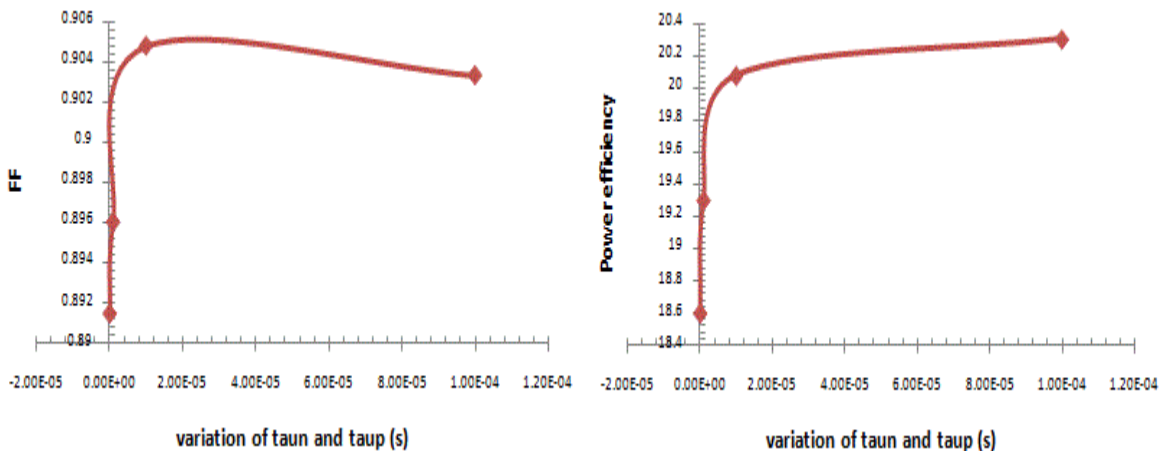


Figure 5.7.

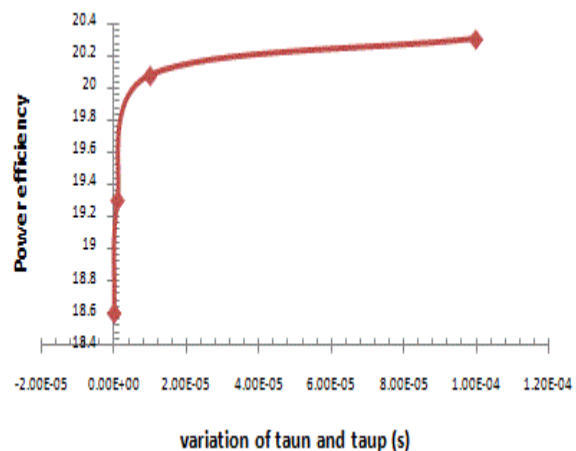


Figure 5.8.

Photogeneration rate increases with increase in relaxation time therefore efficiency also increases [4]. Figure 5.7 shows fill factor which increases initially but decreases slightly in the end. Increase in efficiency which is our prime concern has been shown in figure 5.8.

### 5.2. VARIATION OF WIDTH

Now taking the  $\tau_{aun} = \tau_{aup} = 1e-4$  and beam intensity  $b1=1.0$ , width of solar cell has been varied to different values and corresponding parameters have been extracted from Silvaco ATLAS. This data obtained is shown in table 5.2.

| Width=450 micron | Width=500 micron           | Width=525 micron          | Width=550 micron           |                            |
|------------------|----------------------------|---------------------------|----------------------------|----------------------------|
| Isc              | 6.59195e-08 A              | 7.33451e-08 A             | 7.7058e-08 A               | 8.0772e-08 A               |
| Jsc              | 14.6488 mA/cm <sup>2</sup> | 14.669 mA/cm <sup>2</sup> | 14.6777 mA/cm <sup>2</sup> | 14.6858 mA/cm <sup>2</sup> |
| Voc              | 1.53222 V                  | 1.53228 V                 | 1.53231 V                  | 1.53234 V                  |
| Pm               | 9.12408e-08 Watt           | 1.01519e-07 Watt          | 1.06658e-07 Watt           | 1.11799e-07 Watt           |
| Vm               | 1.4 V                      | 1.4 V                     | 1.4 V                      | 1.4 V                      |
| Im               | 6.5172e-08 A               | 7.25136e-08 A             | 7.61843e-08 A              | 7.98564e-08 A              |
| FF               | 0.903346                   | 0.903313                  | 0.903294                   | 0.903279                   |
| Effi.            | 20.2757                    | 20.3038                   | 20.3158                    | 20.3271                    |

Table 5.2. Different parameters on variation of width

Data obtained from above table has been plotted in graph below with variation of width.

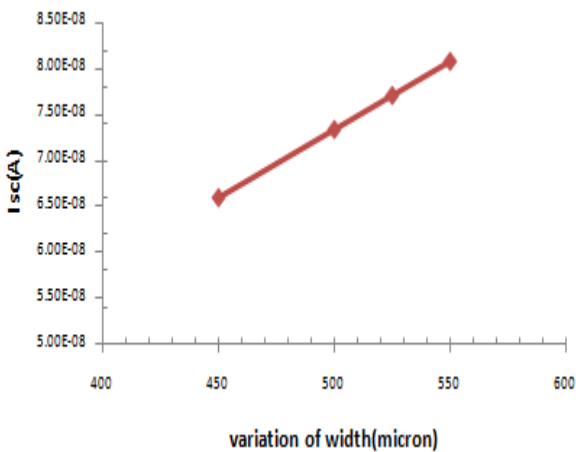


Figure 5.9.

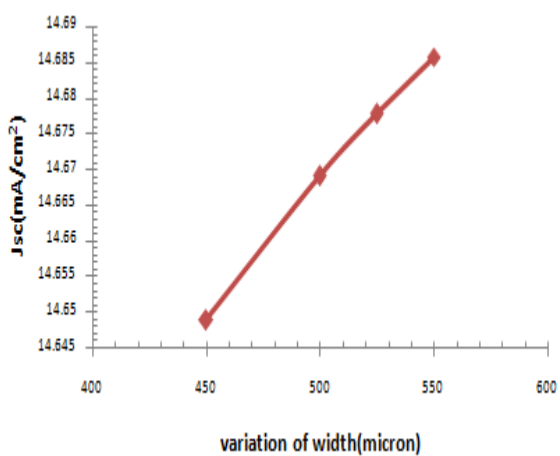


Figure 5.10.



As the width is increasing then light collected by the solar cell also increases thus number of photon received by the solar cell increases with increase in width [5]. These increased photons create more holes and electrons which contribute in total current and voltage drop. This increase in current and current density can be seen in figure 5.9 and figure 5.10.

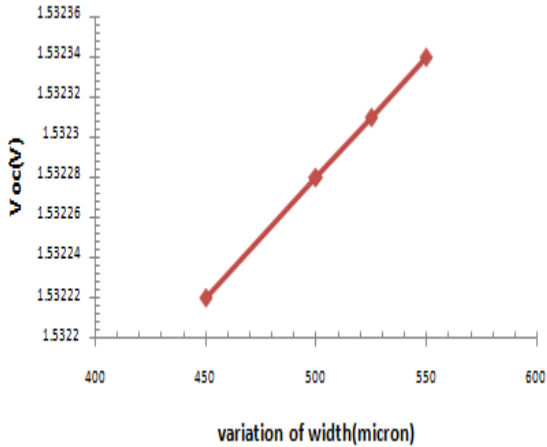


Figure 5.11.

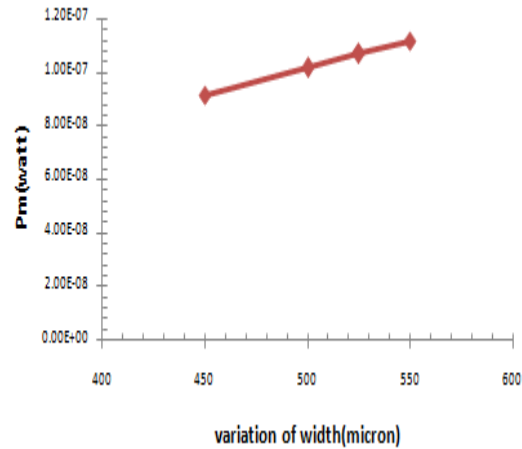


Figure 5.12.

As short circuit current increases with increase in width so open circuit voltage also increases with increase in width which is shown in figure 5.11 but maximum voltage does not change due to shunt resistance.

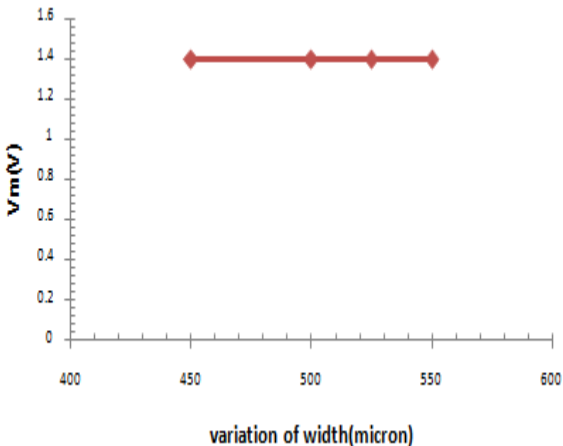


Figure 5.13.

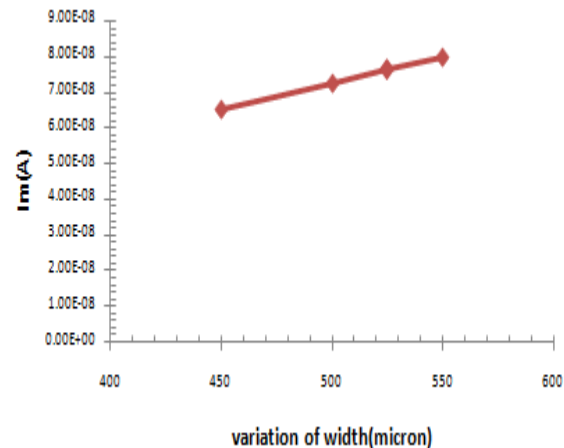


Figure 5.14.

Figure 5.13 shows that there is no variation in maximum voltage with increase in width but figure 5.14 shows maximum current increases with increase in width due to increased photon

collection with increase in width. Now it is clear from plot that maximum current is increasing and maximum voltage is constant therefore power increases as it is multiplication of them which has been shown in figure 5.12.

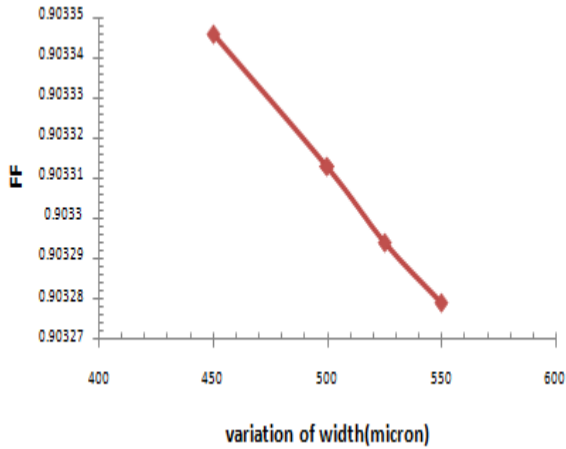


Figure 5.15.

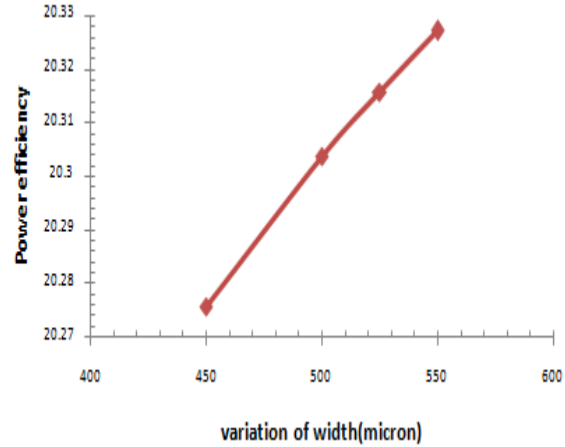


Figure 5.16.

From figure 5.15 it is clear that fill factor decreases slightly with increase in width but even then it is more than 90%. Since voltage and current both are increasing then efficiency also increases which has been shown in figure 5.16.

### 5.3. VARIATION OF BEAM

This variation has been done on solar cell with width 450 micron and relaxation time  $\tau_{\text{aun}} = \tau_{\text{aup}} = 1e-4$  and beam of Sun has been varied i.e. intensity of light has been changed so temperature also changes [7] and different parameters of solar cell has been found. The light intensity on a solar cell is called the number of suns, where 1 sun corresponds to standard illumination at AM1.5 or  $1\text{kW/m}^2$ . In space, the air mass number (AM0) is zero because all of the energy sent out by the Sun at that location is receive because the atmosphere of earth does not create any hindrance and dissipate it as it does on Earth surface. For terrestrial application AM1.0 and AM1.5 is used in which AM1.5 is very commonly used [8].

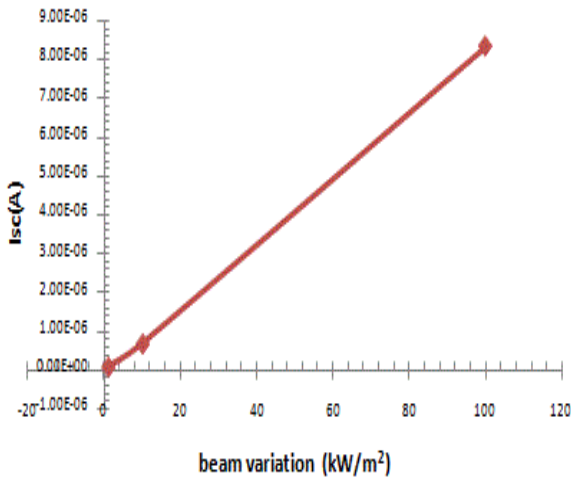
Different values that have been found on variation of beam is shown in table 5.3 below.

|       | Beam intensity<br>B1=1kW/m <sup>2</sup> | Beam intensity<br>B1=1e01 kW/m <sup>2</sup> | Beam intensity<br>B1=1e02 kW/m <sup>2</sup> |
|-------|---|---|---|
| Isc   | 6.59196e-08 A                           | 6.59233e-07 A                               | 8.32128e-06 A                               |
| Jsc   | 14.6488 mA/cm <sup>2</sup>              | 146.496 mA/cm <sup>2</sup>                  | 1849.17 mA/cm <sup>2</sup>                  |
| Voc   | 1.55642 V                               | 1.605 V                                     | 1.16483 V                                   |
| Pm    | 9.26809e-08 Watt                        | 9.50982e-07 Watt                            | 5.24405e-06 Watt                            |
| Vm    | 1.45 V                                  | 1.499 V                                     | 0.75 V                                      |
| Im    | 6.3917e-08 A                            | 6.33992e-07 A                               | 6.99207e-06 A                               |
| FF    | 0.903335                                | 0.89879                                     | 0.541021                                    |
| Effi. | 20.5958                                 | 21.1329                                     | 11.6534                                     |

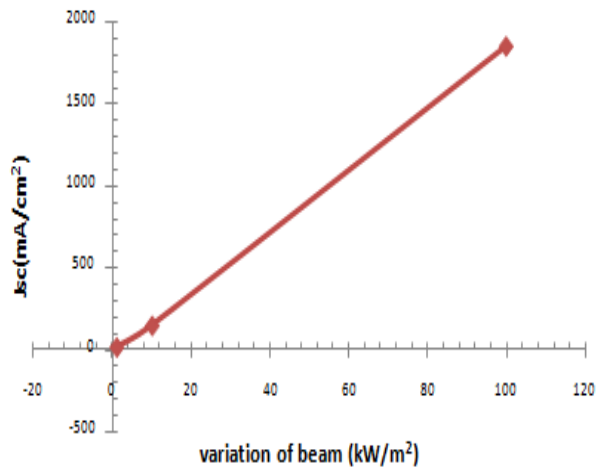
**Table 5.3.** Different parameters on variation of beam.

The values required for the purposes of this research are the  $n$  and  $k$  for wavelengths in the range of 0.2nm to 6nm [9].

Now the data obtained from above table has been plotted in graph varying the beam.



**Figure 5.17.**



**Figure 5.18.**

As the intensity of Sun increases then number of photons falling per unit surface area of solar cell increases thus creating a lot of holes and electrons which increases the current and current density. This increase in current and current density has been shown in figure 5.17 and figure 5.18. Open circuit voltage increases initially but later it decreases because of logarithmic

dependence of the open circuit voltage on short circuit. Therefore, under beam variation,  $V_{oc}$  depends logarithmically with light intensity [12].

Open circuit voltage variation has been shown in figure 5.19.

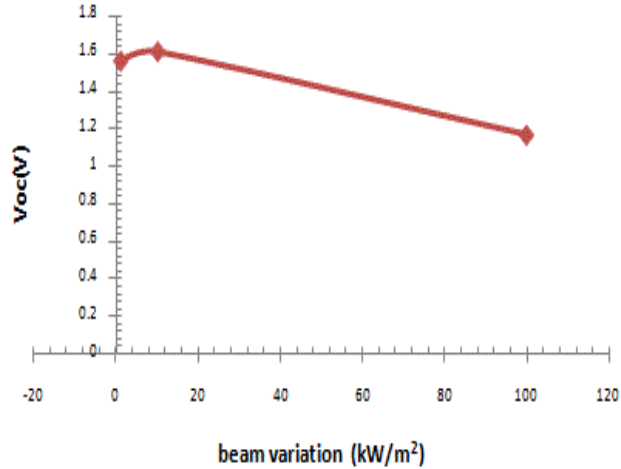


Figure 5.19.

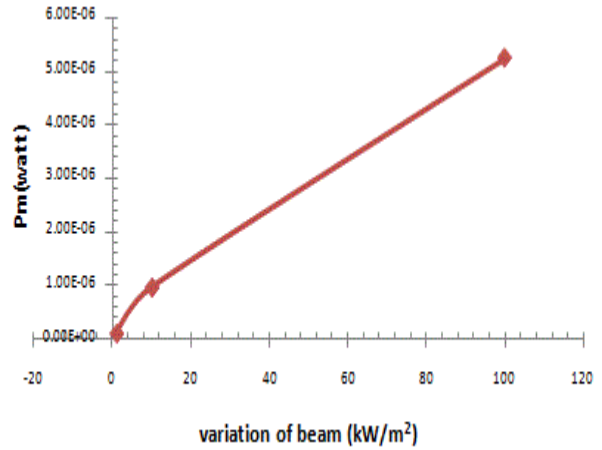


Figure 5.20.

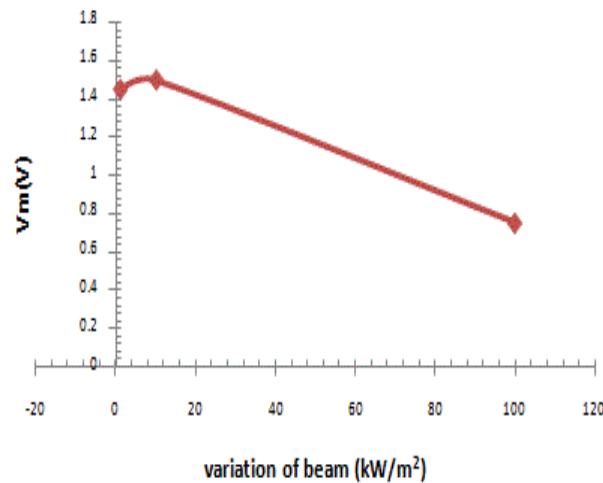


Figure 5.21.

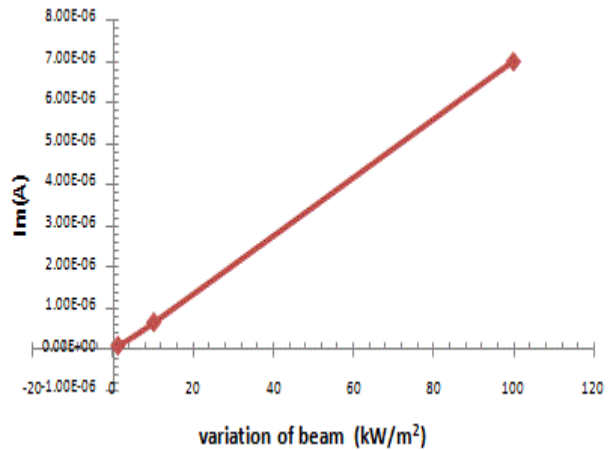


Figure 5.22.

Figure 5.21 shows initial increase in maximum voltage and later decrease in maximum voltage due to its logarithmic dependency on light intensity. While figure 5.22 shows the constant increase in maximum current with increase in light intensity because of more electron-hole pair

generation. Maximum current increases with more pace than decrease of maximum voltage thus maximum power increases with increase of intensity of light which can be seen in figure 5.20.

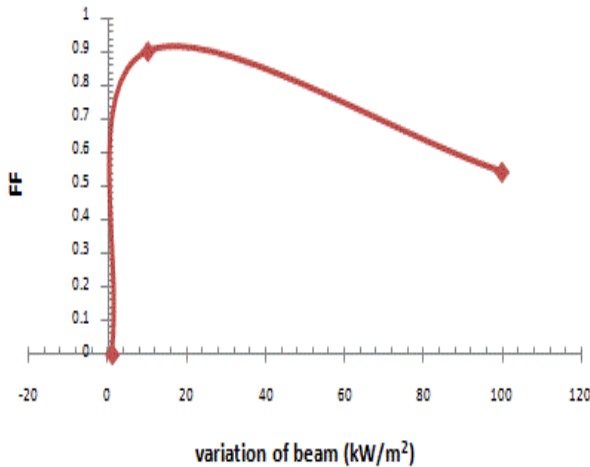


Figure 5.23.

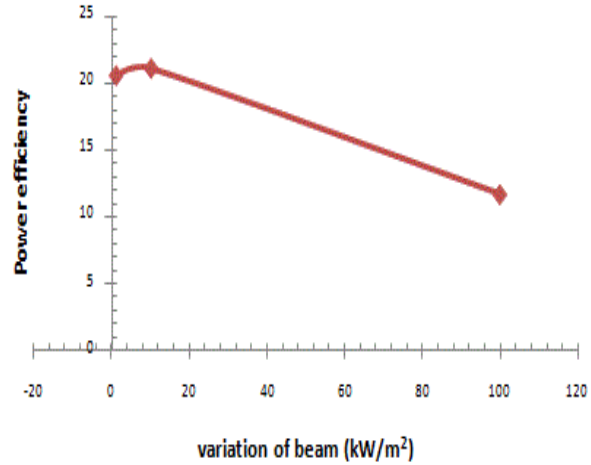


Figure 5.24.

When intensity is increased gradually then fill factor and efficiency both increases with it to a peak but after that peak there comes gradual degradation because incident power also increases linearly with concentration which is shown figure 5.23 and figure 5.24. Instead, the efficiency benefits arise from logarithmic dependence of the open circuit voltage on short circuit. Therefore, under beam variation,  $V_{oc}$  increases logarithmically with light intensity [12].

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## CHAPTER 6

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### CONCLUSION AND FUTURE PROPOSAL

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Now a days solar cell testing is very expensive and time consuming process so it becomes necessary to develop the solar cell such that it becomes cost effective and less time consuming. So the simulation becomes very effective in this case [1]. This thesis is expected to help the solar industry to reduce the cost and simplify the understanding of variation of different parameters.

In this thesis a solar cell has been designed and then all the important parameters has been obtained by varying its width,  $\tau_{n1}$ ,  $\tau_{p1}$  and beam. Different graphs have also been plotted.

First of all solar cell has been simulated using Silvaco ATLAS then its different structural plot has been obtained by TONYPLOT and shown. Further, for this simulated solar cell, different parameters has been found by changing the relaxation time and obtained parameters shows that the efficiency increases with increase in relaxation time.

Now obtained solar cell at maximum relaxation time is taken and width of the solar cell has been varied. Obtained parameters of solar cell shows the maximum efficiency is at maximum width.

In the last solar taken at maximum relaxation time and width= 450 micron then intensity of light fall on it has been changed. Data obtained shows that maximum efficiency is at beam intensity of  $1e01$ .

There are several elements that can change the efficiency of solar cell. Some of them have been shown in this thesis and is expected that in future by varying these as well as other parameters different result with good efficiency might be found [1].

Following changes in the simulated heterojunction solar cell can lead it to change in the performance thus becoming the future research topic-

1. The impact of non-uniform doping in the solar cell may be analyzed [2].
2. We can also change the width of different layers and analyze the device behaviour [2].
3. We can perform the texturing over the surface of the formed hetero junction solar cell [3].
4. We can use quantum dots in place of tunnel junction between different layers that can improve the performance of simulated solar cell [4].
5. We can use porous silicon on surface of solar cell. Technology for obtaining porous layer by chemical etching can be applied after contact grid formation. It is shown that as a result of a porous layer, efficiency of solar cells increased by 20-30% on average [5].



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