Performance Analysis of Graded Bandgap p-i-n Junction Solar Cell

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Abstract

A graded bandgap p-i-n junction solar cell is proposed. The main purpose of graded bandgap is to ensure more efficient absorption of photons. The efficiency will increase according to the load current. Here we use quaternary semiconductor material GaInAsP because it is easy to change the bandgap of this material without changing the lattice constant and we can change the bandgap over a wide region by changing their compositions. We have performed numerical calculation for energy gap and lattice parameter by changing the composition of the materials. From the compositions we get the maximum band gap 1.3723eV that we have to put on the top of the p-i-n solar cell, because the high frequency photon's penetration depth is low. Then we put an intrinsic material between p and n type doped material (here we use intrinsic material as graded $Ga_xIn_{1-x}As_{1-y}P_y$ and which is not doped at all). Finally at the bottom we put n-type material of minimum band gap 0.5135 eV. We allow ± 0.05 % mismatch in lattice parameter between InP substrate and our active materials. We assumed the parameters such as effective density of states in the conduction band and valance band as independent of the bandgap. Assumed total number of electrons and holes are same and the reflectivity of sunlight for short circuit current calculation is neglected in the model. In this model the short circuit current, open circuit voltage, fill factor and finally efficiency are calculated. And efficiency of our designed graded bandgap p-i-n junction solar cell is around 18.42%. This value is for one sun concentration of sunlight. According to our efficiency it is expected that the proposed model can be used for better efficiency rather than other same category solar cells.

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EWU, Dhaka

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Approval

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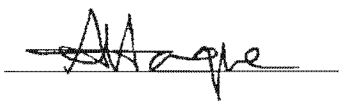

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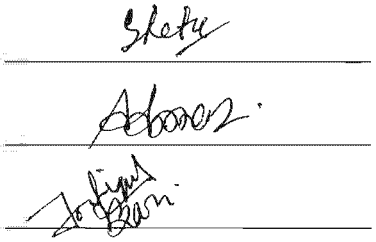

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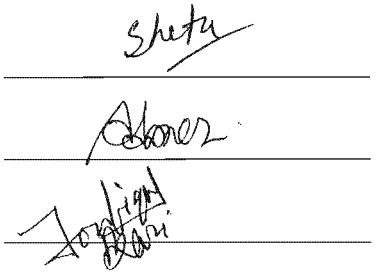

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Chapter 1

Introduction

A solar cell is formed by a light sensitive p-n junction semiconductor where the photons of the sunlight are absorbed. Every photon has its own energy. If the energy of the photon is greater than or equal to the energy needed to transfer electron from the valance band to the conduction band, it will contribute to the output of the solar cell. After generating the free electrons, a path is found towards the p-type semiconductor (As the rule goes "unlike charges attract each other"). through an external path. If an external path is not available there, the process of generating free electrons stops. The probability of releasing electrons by the photons depends on the amount of light absorbed by the cell's surface. More absorption implies more electron release, and hence more electricity will generate [1]. Figure 1.1 shows how solar cell works.

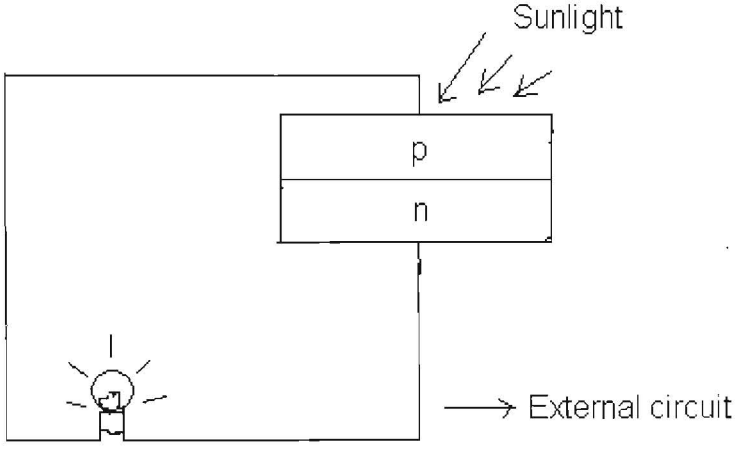

Figure 1.1: Generalized diagram showing how solar cell works.

1.1 Background

Solar cells are used for converting the photon energy to electrical energy. When sunlight falls on the solar cell, the materials absorb the photons (if the photon's energy is equal or greater than the energy gap of that material) and produce electricity. In 1839, the French physicist Antoine-César Becquerel started the work for developing the solar cells [2]. By experimenting with a solid electrode in an electrolyte solution, he observed that when light fell upon the electrode, the voltage developed in electrode. After a long period (around 50 years) the first true solar cells were constructed by Charles Fritts using junctions formed which were coated by the semiconductor selenium with an ultrathin, which is nearly transparent, layer made of gold. But the devices were very inefficient for use, because it could transform the absorbed light's energy to electrical energy and the efficiency was less than 1 percent of the absorbed light. In 1927, for the solution of that problem, other metal semiconductor-junction solar cells were discovered which was made of copper and the semiconductor copper oxide. In 1930s in the fields of light-sensitive devices, both the selenium cell and the copper oxide cell were being employed, such as photometers, for use in photography. The early solar cell had energy-conversion efficiency less than 1 percent. In 1941, this problem was finally overcome with the development of the silicon solar cell by Russell Ohl [3]. A silicon solar cell was invented in 1954 by three American researchers G.L. Pearson, Daryl Chapin, and Calvin Fuller, which had 6-percent energy-conversion efficiency using direct sunlight's photons [4]. By the late 1980s not only silicon cells but also those made of Gallium Arsenide which was capable of more than 20 percent efficiency had been fabricated. After that a concentrator solar cell was invented in1989. A concentrator is made of different types of lenses (it may be concave or convex) and which is used to increase the intensity of the sunlight. The concentrators are put above the solar cell and the solar cells are put on the focus of the lenses. By increasing the intensity of the collected energy and by using this type of solar cell efficiency can be increased [2]. Figure 1.2 shows a simple p-n solar cell.

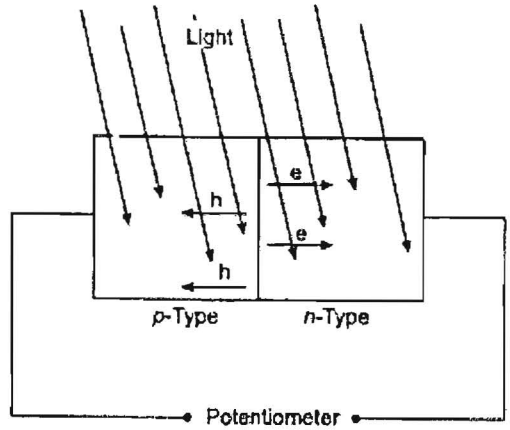

Figure 1.2: A p-n junction solar cell.

People move towards the solar cells, because it is environment friendly. Solar cell generates electricity using sunlight's photon, thus solar panels do not produce any pollution compared to burning fossil fuels. Fossil fuel power plant produces electricity by burning fuel, so it produces large amount of toxic gases, which is released into the atmosphere. Figure 1.3 shows global carbon emission by fossil fuel plant. From the graph we can see that the emission of carbon is low up to since 1900, but it increases exponentially after 1900. In 1980, the global carbon emission by fossil fuel is around above 200 billion tons, which is very high amount of carbon [5].

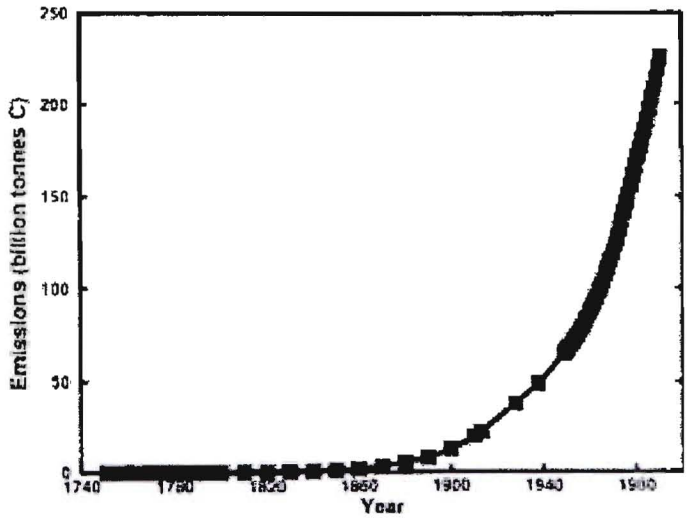

Figure1.3: Global Carbon emission by fossil fuel plant. [5]

For the consumers, solar panels can free the individual from the national grid, because the consumer does not have to pay any bill to the utility company.

1.2 Operating Principle of a Solar Cell

Solar cell is one type of p-n junction and it can produce directly electricity by using the energy of sunlight. Two cases we can consider when sunlight falls on the solar cell. If the energy of photon is less than the band gap of that material (by which solar cell is made), then that photon should not be absorbed by the material. Another thing could happen that is, if the photon energy is equal or greater than the band gap of that material, then the photon is absorbed by that material. This is the most desirable case. By absorbing those photons the electron-hole pair is created, because after absorbing the one photon one electron jumps to the conduction band and hole is created in valence band. As electrons and holes are charge opposite to each other, so they move in two different directions. So there will appear a potential difference. This potential difference will create the electricity and that current is supplied to the load. Solar cell acts as a current source. It always gives a steady current. Figure 1.4 shows a p-n junction with resistive load [6]. Though zero bias voltage is applied to the junction, an electric field still exists in space charge region. The incident photon can generate electron-hole pair in the space charge region that will be swept out producing photocurrent IL in the reverse bias direction.

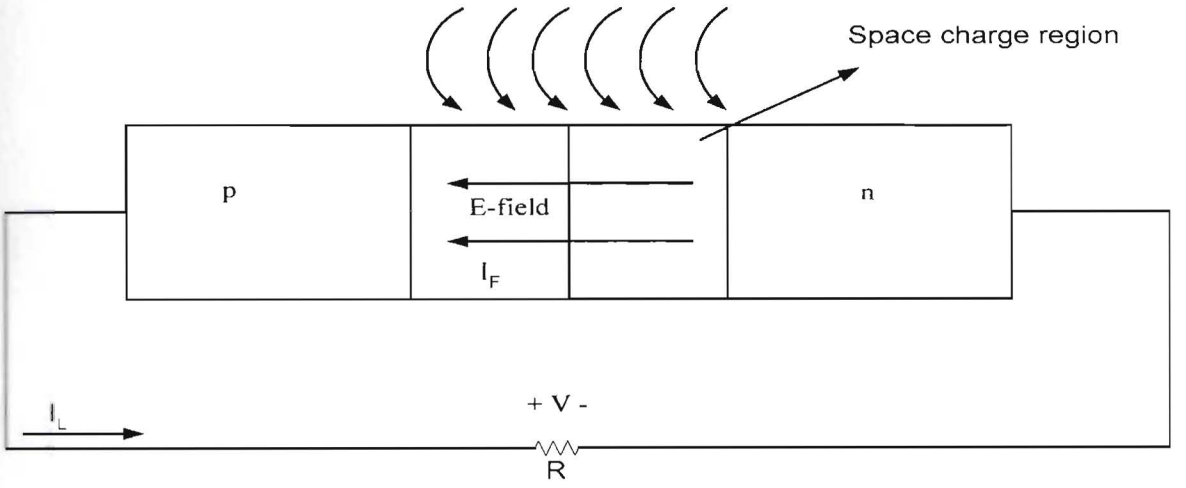

Figure 1.4: A p-n junction solar cell with resistive load.

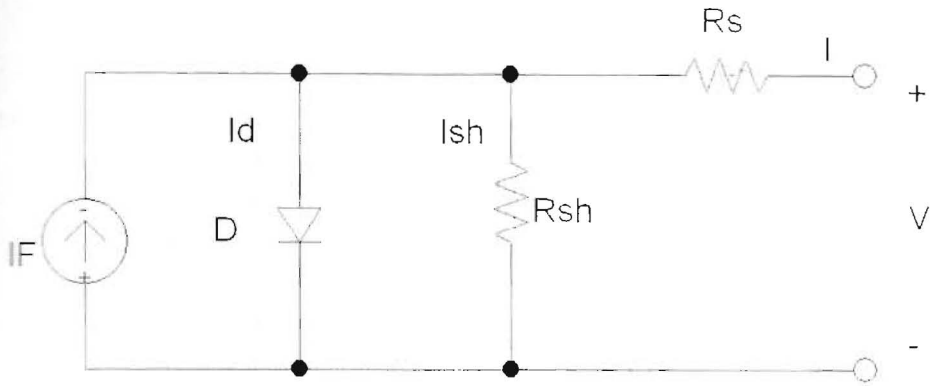

Figure1.5: The equivalent circuit of a solar cell.

We can model an equivalent circuit which will help to understand the electronic behavior of a solar cell. Figure 1.5 shows the equivalent circuit diagram of a solar cell. An ideal solar cell may be represented by a current source in parallel with a diode [7]. But in practical case no solar cell is ideal. The photons are absorbed by the cell which will produce a current. That current is called as short circuit current (when the load resistance is zero). But that current is not same as the load current, because the solar cell has its own resistance. So a shunt resistance and a series resistance component are added to the model. The efficiency of the cell will increase if the shunt resistance is too high and the series resistance is very low.

1.3 Literature Review

Research is going on solar cell and the researchers are trying to increase the efficiency of solar cell. The efficiency of solar cell achieved dramatic improvements when the focus shifted from Si towards GaAs and III-V semiconductor compound system. In 1980 several types of III-V solar cells had been tested and by 1984 first GaAs solar cell wad developed [8]. After that by using the concentrator on solar cell, we can get maximum conversion of around 37% of absorbing sunlight to electrical energy. Then researchers move toward to hetero-junction solar cell. Hetero-junction solar cells consist of two different types of materials. Hetero-junction is a contact point between

two layers of different crystalline semiconductors. Hetero-junction is different from homo-junction semiconductor materials due to its unequal bandgaps. In hetero-junction solar cells, we use two different types of semiconductor materials and those materials have unique band gap, because of that these type of solar cell can absorb two different energized photons [8]. That device gives us a satisfactory efficiency. After that the researchers try to analyze the property of multi-junction solar cells. Multi-junction solar cell consists of different layers. First two or more than two solar cells are created individually and then the cells are mechanically stacked, one on top of the other. By using this type of solar cell we can transform the absorbed light's energy to electrical energy and which has a high efficiency. Because in multi-junction solar cells we use different types of semiconductor materials, which have different bandgaps, so the multi-junction solar cell can absorb different energized photons. Thus the efficiency of multi-junction solar cell is higher than hetero-junction or compound semiconductor solar cell. A multi-junction solar cell is developed by the researchers of the Fraunhofer Institute for Solar Energy Systems (ISE which is a German company) and they achieved a record efficiency of 41.1% for the conversion of sunlight into electricity [9]. They used a concentrator above the multi-junction solar cell. The sunlight is concentrated by a factor of 454. Their multi-junction is around 5 mm^2 and made of GaInP, GaInAs on a Ge substrate. Photo of the solar cell which has highest efficiency (41.1%) is shown in Figure 1.6.

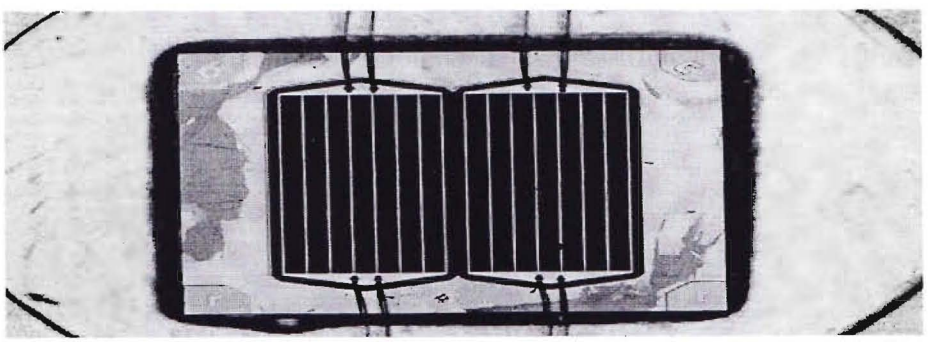

Figure 1.6: Photo of the new world record solar cell made of $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ with a cell area of 5.09 mm^2. [9]

1.4 Objective

In our project we are interested to design a graded bandgap p-i-n junction solar cell to improve efficiency by causing absorption of wider spectrum of sunlight. There are mainly two ways to grade a junction. One is putting an impurity that means doping the materials and another is by changing the compositions of the materials. The main purpose of graded bandgap is to ensure more efficient absorption of photons. Then finally the efficiency will increase according to the load current. Here we use quaternary semiconductor material GaInAsP because it is easy to change the bandgap of this material without changing the lattice constant and we can change the band gap over a wide region by changing their composition. Then we model our solar cell and finally we analyze the performance parameters such as short circuit current, open circuit voltage, fill factor & efficiency.

Chapter 2

Review of Different Types of Solar Cells

There are three main elements of solar cells such as: (1) a semiconductor; (2) a semiconductor junction; and (3) conductive contacts. Semiconductors such as silicon may be doped n-type or p-type. When an n-type silicon and p-type silicon interface with each other, a region is created in the solar cell which is called the semiconductor junction. The semiconductor absorbs light. The energy from the light may be transferred to the valence electron of an atom in a silicon layer, which allows the valence electron to escape its bound state leaving behind a hole. These photo-generated electrons and holes are separated by the electric field associated with the p-n junction. The conductive contacts allow current to flow from the solar cell to an external circuit [10].

In this chapter, we have mainly focused on solar cells having three different kinds of junctions such as: (1) homo-junction; (2) hetero-junction and (3) multi-junction.

2.1 Homo-Junction Solar Cell

A homo-junction solar cell is one kind of device whose p and n type materials are exactly same. Silicon (Si) solar cell or Gallium Arsenide (GaAs) cell is the perfect example of this kind of solar cell. In other words, when similar semiconductor materials interface with each other a homo-junction is formed between the layers of those materials. Bandgaps of those materials are equal but typically their doping is different. A solar cell having such junction is called homo-junction solar cell [11]. To explain how homo-junction solar cell works, we have discussed about the crystalline silicon solar cell. Figure 2.1 and 2.2 shows the functionality of homo-junction solar cell and energy band diagram of p-n homo-junction solar cell in thermal equilibrium respectively.

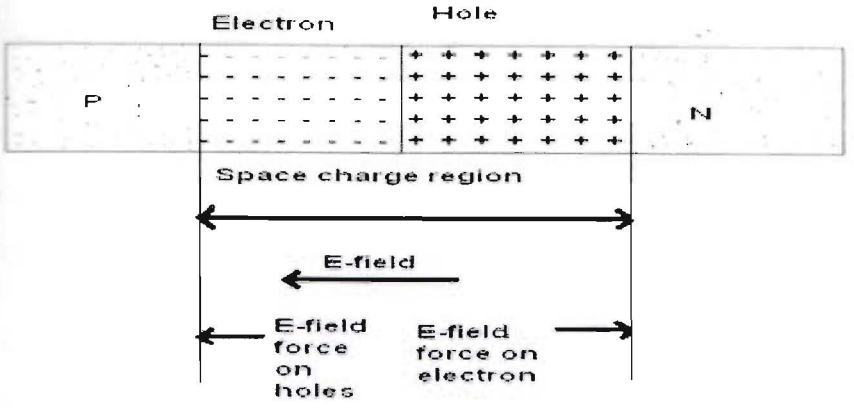

Figure 2.1: The electric field and the force acting on the charged carriers.

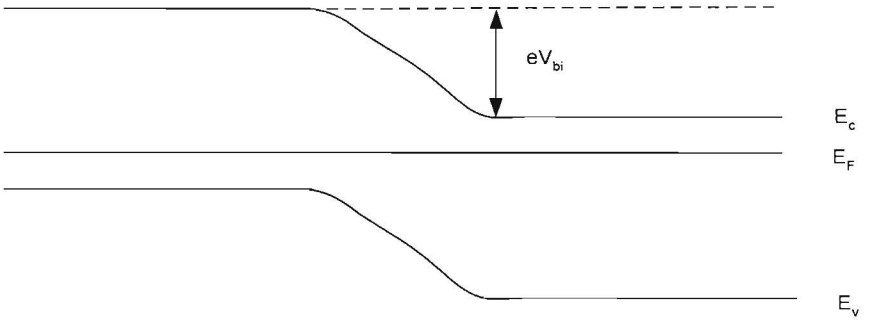

Figure 2.2: Energy band diagram of p-n homo-junction solar cell in thermal equilibrium.

Two separate pieces of silicon are electrically neutral. When they are put together interesting part begins. Without an electric field, the cell wouldn't work. When the n-type and p-type silicon come into contact, the electric field is created automatically. Suddenly, the free electrons on the n side have a tendency to fill up into the holes on the p side. All the free electrons do not fill all the free holes. If they do so, then the whole arrangement wouldn't be very useful. However, right at the junction, they mix with each other and form a barrier which makes a harder situation for electrons on the n side to cross over to the p side. Eventually, equilibrium is reached, and we have an electric field separating the two sides. This electric field acts as a diode which allows electrons to flow from the p side to the n side. It's like a summit - electrons can easily go down the summit (to the n side), but can't climb it (to the p side). When light hits the solar cell in the form of photon, its energy breaks apart electron-hole pairs. Each photon with sufficient energy will normally extract exactly one electron with same number of hole as well. If this happens

close enough to the electric field or if free electron and free hole happen to wander into its range of influence, the field will send the electron to the n side and the hole to the p side. This causes further disruption of electrical neutrality and if an external current path is provided, then the electrons will flow through the path to the p side to combine with holes that the electric field sent there. The flow of electrons creates the current, and the cell's electric field causes a voltage. If the current is multiplied with the voltage, then the power is formed [12].

Homo-junction cells using direct-gap semiconductor materials have not that much desired efficiencies. Homo-junction solar cells can absorb those photons only around the bandgap energy, so for higher energized photons, a significant fraction of energy is wasted.

2.2 Hetero-Junction Solar Cell

When two semiconductors with different bandgap energies interface with each other, then a hetero-junction is formed [13]. Two different roles occur among the top and bottom layers in a hetero-junction solar cell. The top layer which is specified by window layer is a material with a high bandgap selected for its transparency to light. Almost all incidents light is allowed to reach the bottom layer by the window, which is a material with low bandgap that readily absorbs light. After that electrons and holes are generated by the light which is very near about the junction. Through this process, it is convenient to separate the electrons and holes effectively before they can recombine. Hetero-junction devices have a natural advantage rather than homo-junction devices, which require materials that can be, doped both p- type and n-type. A high-band gap window layer reduces the cell's series resistance. Highly conductive material can be used to make the window and without reducing the transmittance of light the thickness can be increased. As a result, light-generated electrons can easily flow laterally in the window layer to reach an electrical contact [14]. In thermal equilibrium a typical p-n hetero-junction energy band diagram is shown in Figure 2.3.

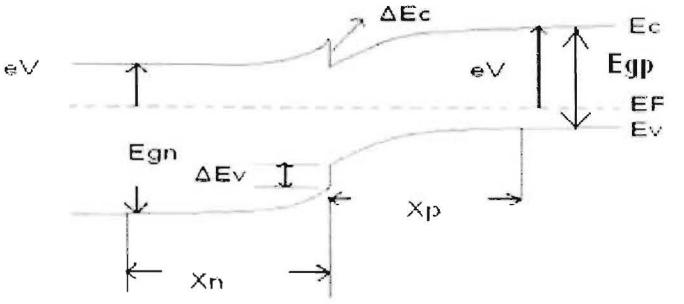

Figure 2.3: The energy band diagram of n-p hetero-junction in thermal equilibrium.

Here it is assumed that photons are incident on the wide bandgap material. Photon which is less than Egn going across the wide band gap material operates as an optical window and photon which is greater than Egp are absorbed in the narrow bandgap material. Excess carriers within a diffusion length of the junction and created in the space charge region are collected on average which produce the photocurrent. High energy photons are absorbed in the depletion region of the narrow band gap material if Egn is sufficiently large. Particularly at the shorter wavelength, hetero-junction solar cell has better characteristics rather than a homo-junction cell.

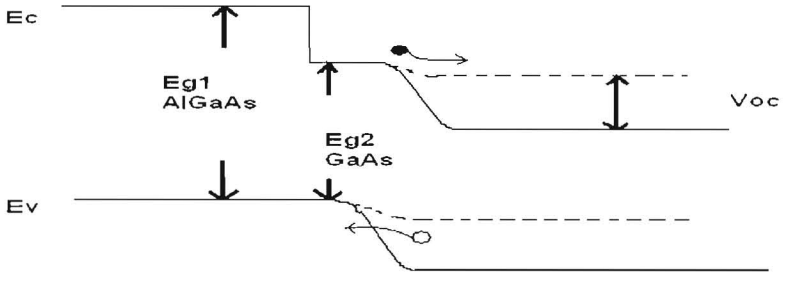

Figure 2.4: Band diagram of Hetero-junction solar cell.

After forming a p-n homo-junction a wide band gap material is grown on top which acts as an optical window for photon energy less than Eg1. Photons with energies in between Eg1 and Eg2 will generate excess carriers in the homo-junction and photons with energies greater than Eg1

will generate excess carriers in the window type material. In the narrow band gap material, if the absorption coefficient is high then within a single diffusion length of the junction, all of the excess carriers will be generated. So the collection efficiency will be very high. Figure 2.4 shows a energy band diagram of a hetero-junction solar cell using different compositions of AlGaAs and GaAs [13].

2.3 Multi-Junction Solar Cell

Multi-junction solar cell is one kind of high efficiency solar cell, which has multiple layers of individual solar cells with several band gaps. Individual solar cell in multi-junction solar cell can be a homo-junction, a hetero-junction or it could be a p-i-n junction. Multi-junction solar cell can absorb different portion of the solar spectrum to convert sunlight energy into electrical energy by each solar cell at greater efficiency [15]. In a single layer or band gap solar cell efficiency is limited due to the inability of p-n junction to absorb a broad range of photons in the solar spectrum. Photons below the band gap in blue spectrum either pass through the solar cell or due to molecular demonstration, are converted into heat. Energy of photons above the band gap in the red spectrum is also lost because only the energy necessary to generate electron hole pair is used. So, the remaining energy is converted into heat [16]. Multi-junction solar cell was first developed and introduced for satellite power applications, where cost was not the main issue but the main issue was to increase the efficiency.

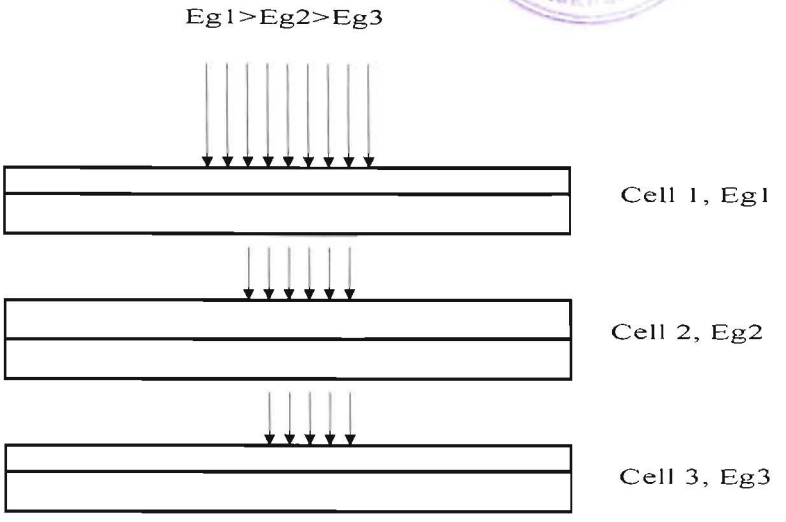

Figure 2.5: Multi-junction solar cell.

Here in this figure 2.5 we can see the diagram of multi-junction solar cell of three layers. For first, Eg_1 band (cell1) is absorbing those photons which have higher energy than cell2. Then Eg_2 band (cell2), is absorbing those photons which have higher energy than cell3. Finally (cell3) is absorbing those photons which have lowest energy. Different band gap materials are combined in such a way that high energy photons are converted into electricity with high energy band gap & low energy photons are converted with low energy band gap materials. As a result, each photon of different energy is converted more efficiently. As the cells in multi-junction solar cell are connected in series, so the voltage arrangement is higher & the current arrangement is lower. So, due to low current, the resistive losses of the cell can be minimized [17].

Chapter 3

Properties of Compound Semiconductor Materials

In this chapter we have discussed about different types of binary semiconductor materials that form GaInAsP quaternary materials.

3.1 Binary materials

A compound semiconductor is a semiconductor compound composed of elements from two or more different groups of the table. Binary semiconductor compounds consist of two materials such as GaAs, GaP, InAs, and InP etc. Binary semiconductor compounds have a fix energy gap and lattice constant. As an example, Gallium Arsenide has 1.424eV band gap. So this material can absorb only those photons which have minimum energy 1.424eV. The wave length correspond of 1.424eV is around 783 nm for gallium arsenide. That means by using GaAs we can absorb those photons which have maximum 783nm wave length. Figure 3.1 shows the solar spectrum.

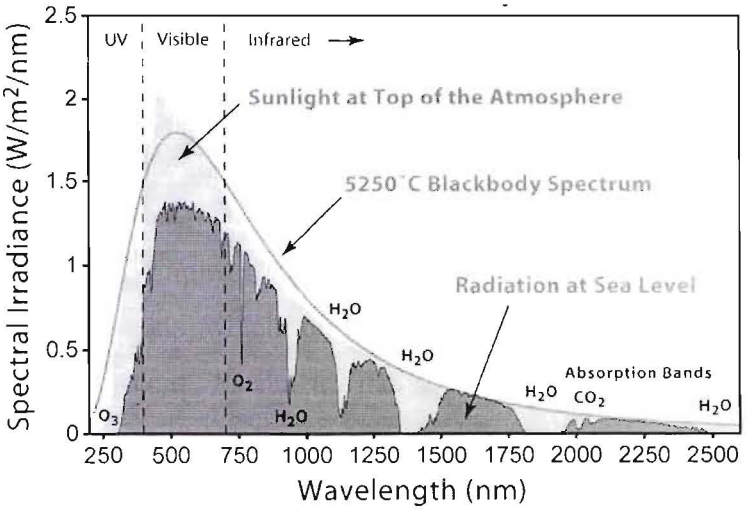

Figure 3.1: Solar radiation spectrum. [18]

Here we mainly discuss different types of binary materials with their basic properties.

3.1.1 Gallium Arsenide

GaAs consists of two elements Gallium (III) and Arsenic (V). So it is an III-V semiconductor. The bandgap for GaAs is 1.424eV and it has direct bandgap [19].

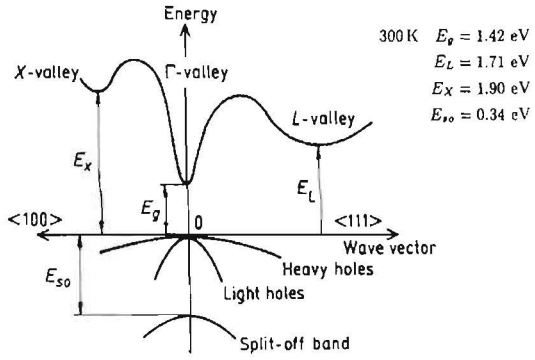

Figure 3.2: Band diagram of GaAs. [19]

GaAs is used in high efficiency solar cells and it is one of the most important applications of Gallium Arsenide.

3.1.2 Gallium Phosphide

GaP consists of two elements Gallium (III) and Phosphorus (V). It is also an III-V semiconductor material, which has an indirect bandgap of 2.26 eV [19].

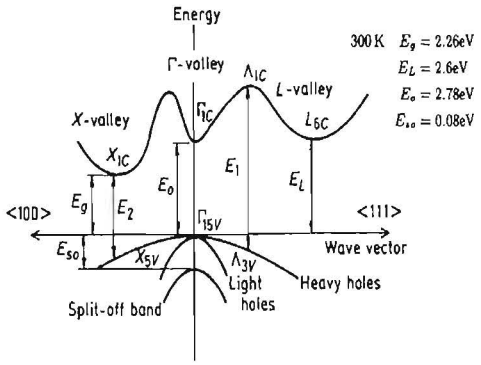

Figure 3.3: Band diagram of GaP. [19]

3.1.3 Indium Phosphide

InP consists of two elements Gallium (III) and Phosphorus (V). It is an III- V semiconductor material, which has a direct bandgap of 1.34eV. The properties of InP and GaAs are similar [19].

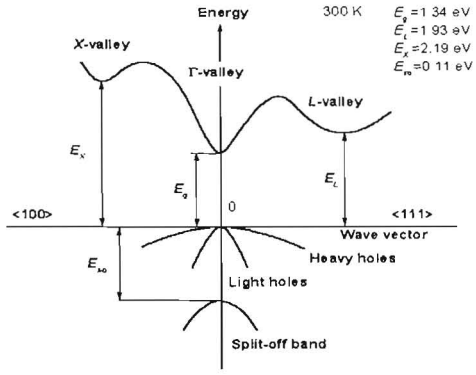

Figure 3.4: Band diagram of InP. [19]

3.1.4 Indium Arsenide

Indium Arsenide is a material, which has 0.354eV band gap. It is also an III- V semiconductor material and this material has direct bandgap [19].

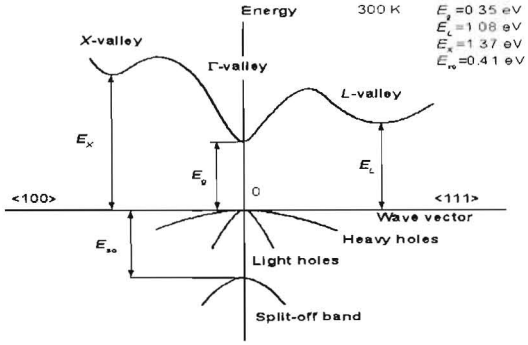

Figure3.5: Band diagram of InAs. [19]

The most common similarity between all binary (that we studied) semiconductor materials have zinc blended crystal structure.

3.2 Quaternary GaInAsP Materials on InP Substrate

We have to consider two cases before choosing our substrate materials. One of the important cases is that the substrate material should be cost effective, because substrate material is not the main part of the cells (because it's not absorbing the photon energy). The most important case is that the lattice constant of the substrate should be matched with the active semiconductor materials (but a little mismatch is acceptable). Here active semiconductor material means which part of the solar cell is associated with absorbing photon's energy. For our project we choose substrate as InP and active semiconductor material as GaInAsP. We choose InP because its lattice constant is pretty close with GaInAsP. The lattice constant of InP is 5.8687 Å. Lattice constant of $Ga_{0.47}In_{0.53}As_yP_{1-y}$ is 5.8687 Å at 300K [19]. So for this composition we can see that the lattice constant is identical with InP. Because of that we use Quaternary GaInAsP materials on InP substrate.

3.3 Why Choose This Material

In our project we use quaternary semiconductor material which is GaInAsP. Because we can easily control the lattice parameter and bandgap of this material. If we vary the composition then we can get bandgap and lattice constant as a range. For $Ga_xIn_{1-x}As_yP_{1-y}$, where the compositions are x and y which are also called mole fractions. Now if we vary composition of x and y, then the range for bandgap is 2.073-0.354 eV. This means that our solar cell can absorb a large portion of sunlight's spectrum. This is much desired case for our project, because if we could absorb large portion of sunlight's spectrum that means the efficiency of our solar cell will increase. But we can not take above banggap range, because for that composition that we get the range, the lattice parameter of GaInAsP could be mismatched with the substrate InP and this case will be discussed later.

3.4 Energy Gap Relationships

In this section we present the relationship to calculate the bandgap of GaInAsP. For that purpose first we have to know for which composition, we want to calculate the bandgap. Now the formula for finding the bandgap of quaternary materials in terms of the bandgaps of ternary semiconductor materials is given below [20]:

$$Q_{x,y} = \frac{[x(1-x)[yT_{ABC}(x) + (1-y)T_{ABD}(x)] + y(1-y)[xT_{ACD}(y) + (1-x)T_{BCD}(y)]]}{x(1-x) + y(1-y)} \quad 3.1$$

Let's assume, $T_{ABC}(x) = T_{GaInAs}$

The formula for finding the bandgap of ternary materials in terms of the bandgaps of binary semiconductor materials is given below [20]:

$$T_{ABC}(x) = xB_{AB} + (1-x)B_{BC} - x(1-x)C_{ABC} \quad 3.2$$

Where, 'C_{ABC}' is an empirical bowing parameter. According to Vegard's law, $C_{ABC} = 0$ for the lattice constant. However, strong bowing is often observed for energy gap. Experimentally, bowing parameters determined the direct bandgap.

Now we want to calculate,

$$T_{ABC}(x) = xB_{GaAs} + (1-x)B_{InAs} - x(1-x)C_{GaInAs}$$

Again, $T_{ABD}(x) = T_{GaInP}$

$$T_{ABD}(x) = xB_{GaP} + (1-x)B_{InP} - x(1-x)C_{GaInP}$$

Again, $T_{ACD}(y) = T_{GaAsP}(y)$

$$T_{ACD}(y) = yB_{GaAs} + (1-y)B_{GaP} - y(1-y)C_{GaAsP}$$

Again, $T_{BCD}(y) = T_{InAsP}(y)$

$$T_{BCD}(y) = yB_{InAs} + (1-y)B_{InP} - y(1-y)C_{InAsP}$$

$$\text{Now, } Q_{x,y} = \frac{[x(1-x)[yT_{ABC}(x) + (1-y)T_{ABD}(x)] + y(1-y)[xT_{ACD}(y) + (1-x)T_{BCD}(y)]]}{x(1-x) + y(1-y)}$$

Another formula for finding the bandgap of quaternary material is [19]:

$$Q=1.35 +0.668x -1.068y +0.758x^2 +0.078y^2-0.069xy -0.332x^2y +0.03xy^2 \text{ eV} \quad 3.3$$

3.5 Lattice Parameter Relationships

When we model any solar cell then we have to consider one important issue and that is lattice constant mismatch. The lattice constant of our quaternary semiconductor material (GaInAsP) should be matched with the substrate material (InP). If the lattice constant is not matched then the whole property that we consider could be changed. The formula of lattice constant of quaternary semiconductor is given below [21]:

$$\text{Lattice constant} = 5.87+0.18x-0.42y+0.02xy \text{ Å} \quad 3.4$$

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Analysis of Material Properties

4.1 Energy Gap Analysis

Now if we vary the composition of x and y from 0 to 1 respectively of $Ga_xIn_{1-x}As_yP_{1-y}$, then we get a surface, where the maximum energy gap is 2.0731 eV and minimum band gap is 0.354 eV.

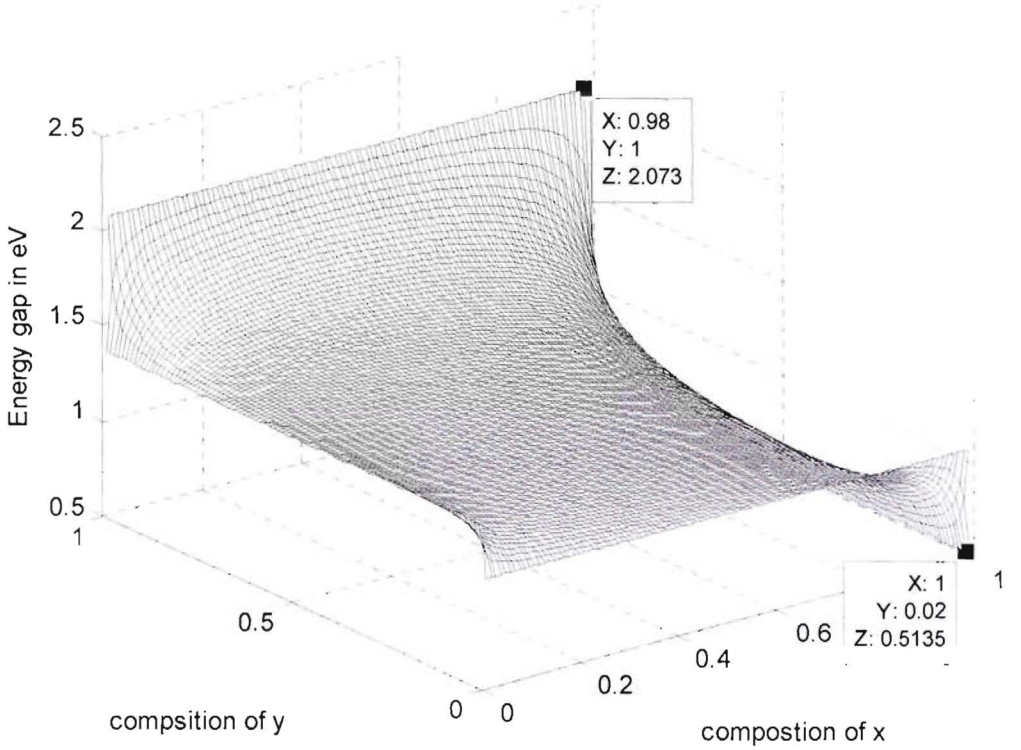


Figure 4.1: Bandgap vs. composition

Figure 4.1 is about the bandgap vs. composition and from MATLAB plot we can see the maximum, minimum bandgap and as well as their corresponding composition also. The lattice constant at maximum and minimum bandgap are respectively 5.6620 Å and 5.4540 Å.

4.2 Lattice Parameter Analysis and Simulation

Now if we vary the composition then we get a surface for lattice constant and the maximum and minimum lattice constant are 6.042 Å and 5.452 Å. Figure 4.2 shows the surface for lattice constant while we are varying the composition. From figure we can see that the range of lattice constant is from 6.042 Å and 5.452 Å.

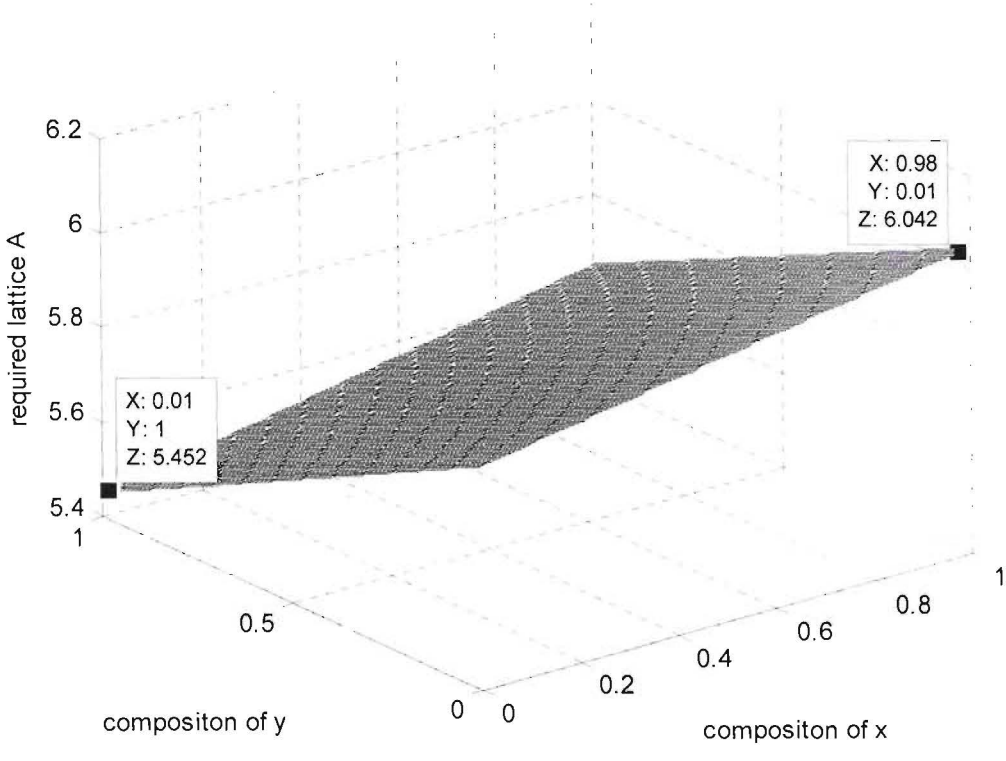


Figure 4.2: Lattice constant vs. composition

4.2.1 Lattice Constant under Certain Condition

Here we consider that ±0.05% lattice constant mismatch with InP is acceptable. Now the surface for required lattice constant is showed in figure 4.3:

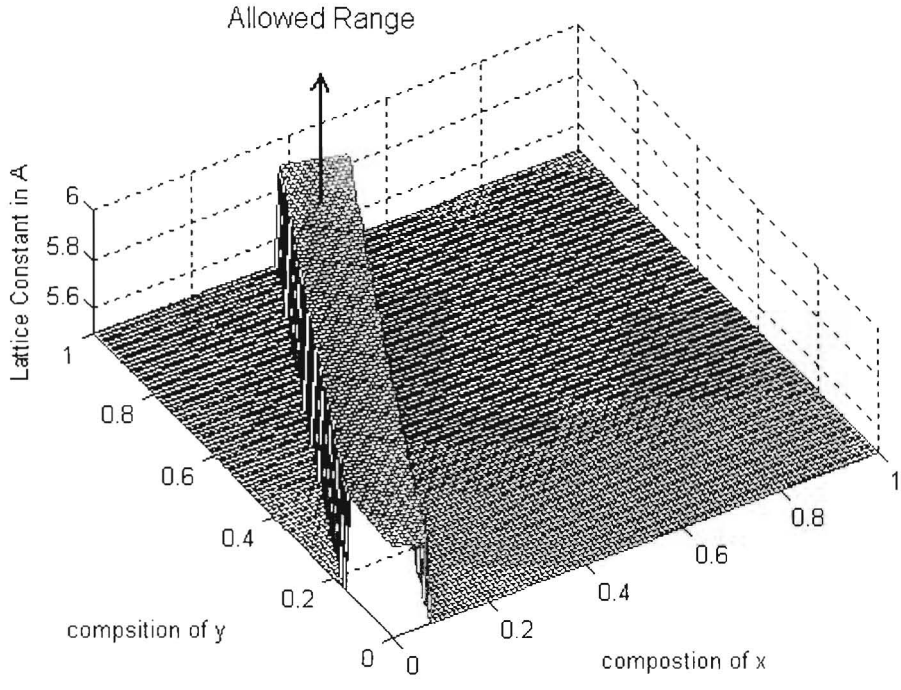


Figure 4.3: required lattice constant vs. composition

4.3 Analysis under Restricted Lattice Constant

Under ± 0.05% lattice constant mismatch, the maximum and minimum lattice constants are 5.8980 Å and 5.8394 Å and the corresponding compositions are x=0.3800, y=1 and x=0.2400, y=0.3800 respectively. Again at maximum and minimum lattice constant the corresponding energy gaps are 0.5135 eV and 1.2013 eV respectively. Now maximum and minimum bandgaps are 1.3763 eV and 0.5135 eV. At maximum bandgap, Lattice constant and composition are respectively 5.8658 Å and x=0.0100, y=0. At minimum bandgap, Lattice constant and composition are respectively 5.8980 Å and x=0.3800, y=1. These restricted values of the compositions and bandgaps will be used to design the graded p-i-n solar cell.

Chapter 5

Modeling and Analysis of p-i-n and p-n Solar Cells Parameter

In this chapter we first model our desired p-i-n solar cell first. For this purpose we have to find out the penetration depth for maximum and minimum bandgap. Maximum and minimum bandgap are respectively 1.3763 eV and 0.5135 eV, and their corresponding wave lengths are respectively 901 nm and 2416 nm. We put at the top the material for which we can get higher bandgap, because the penetration depth for high frequency is low and for low frequency the penetration depth is high. So we put at the bottom the material for which the bandgap is lower. Then we analyze and try to find out the expression for few basic parameters of p-n solar cell such as the short circuit current, open circuit voltage, fill factor and efficiency. The p-n junction analysis is very important because we want to develop a graded p-i-n solar cell with the help of p-n junction analysis.

5.1 Model p-i-n Solar Cell

Our solar cell can absorb maximum 1.3763 eV energized photon and the corresponding wave length of that photon is 901 nm. The minimum energy absorbed by the cell is 0.5135 eV and the corresponding wave length of that photon is 2416 nm. So our solar cell can absorb those photons which have the wave length between 901 nm-2416 nm. Figure 5.1 shows the solar spectrum and the bounded region shows the area that our solar cell can absorb.

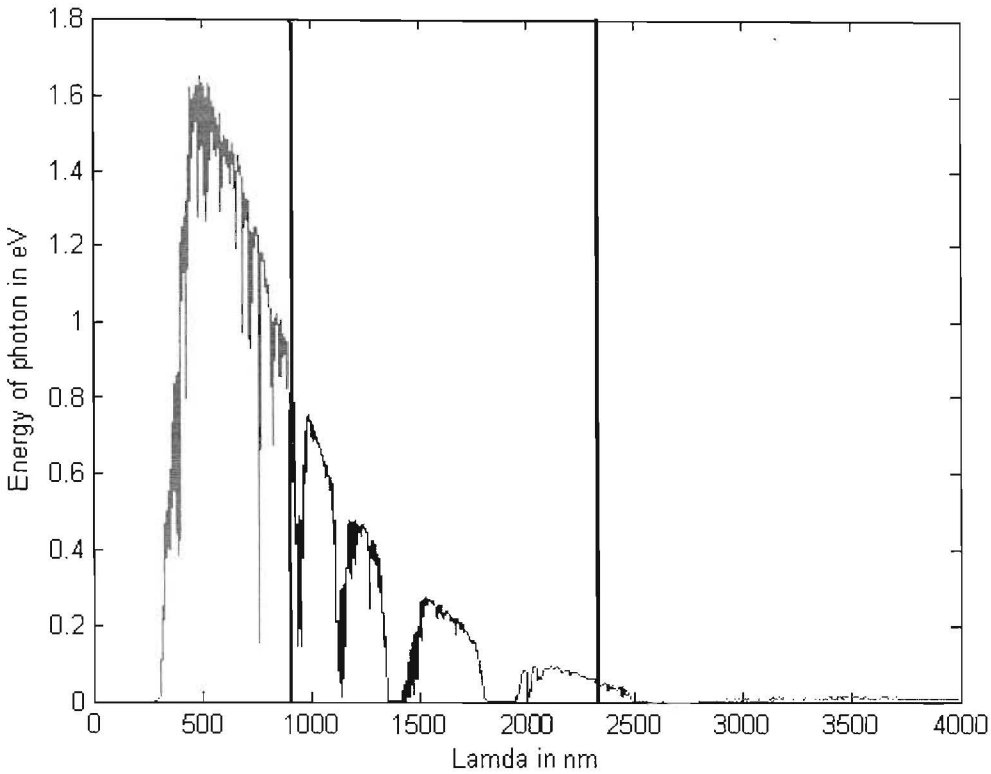


Figure 5.1: Solar spectrum and the absorbed wavelength in nm

Now we want to calculate the percentage of solar spectrum that our solar cell could absorb.

The total energy of solar spectrum is 100.04 (mW/cm^2) and energy within the allowed range is 30.65067 (mW/cm^2). So our modeled solar cell can absorb 30.6393% from the solar spectrum.

Now we want to calculate the penetration depth for those photons which have energy of 1.3763 eV and 0.5135 eV respectively. For this calculation we use MATLAB software and the MATLAB plots for this calculation are shown in figure 5.2 and figure 5.3 respectively.

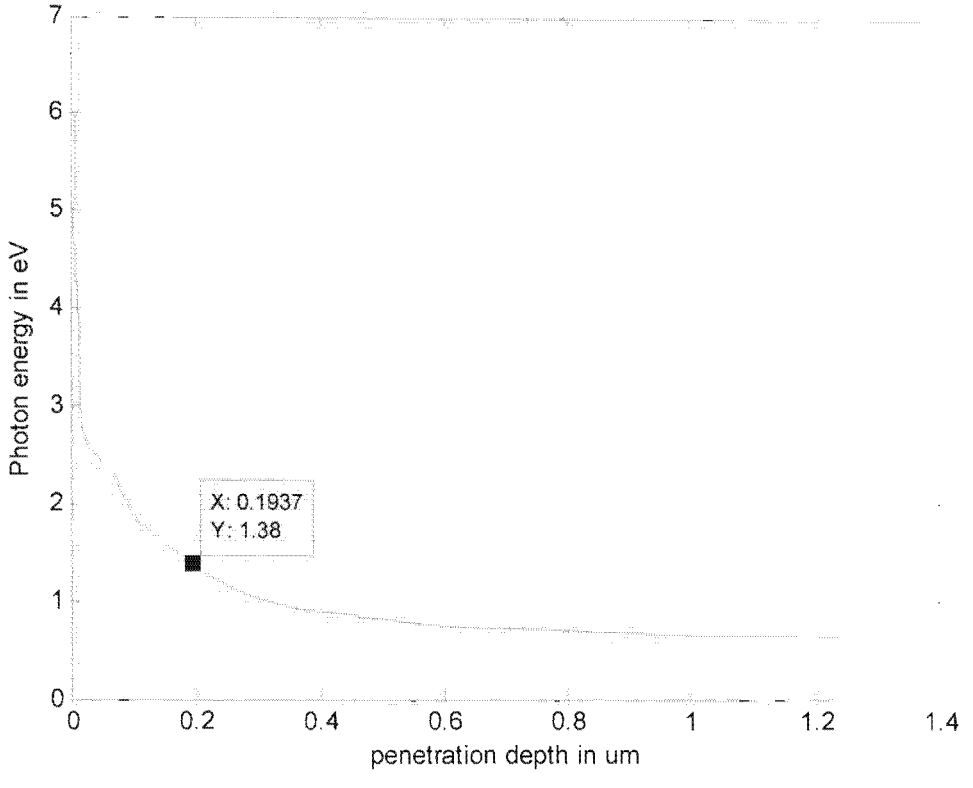


Figure 5.1: Penetration depth vs. Photon energy for 1.37 eV

Figure 5.2 shows the penetration depth for the photon which has energy around 1.37 eV and from the plot we can see that the penetration depth for that energized photon is around 0.20 um.

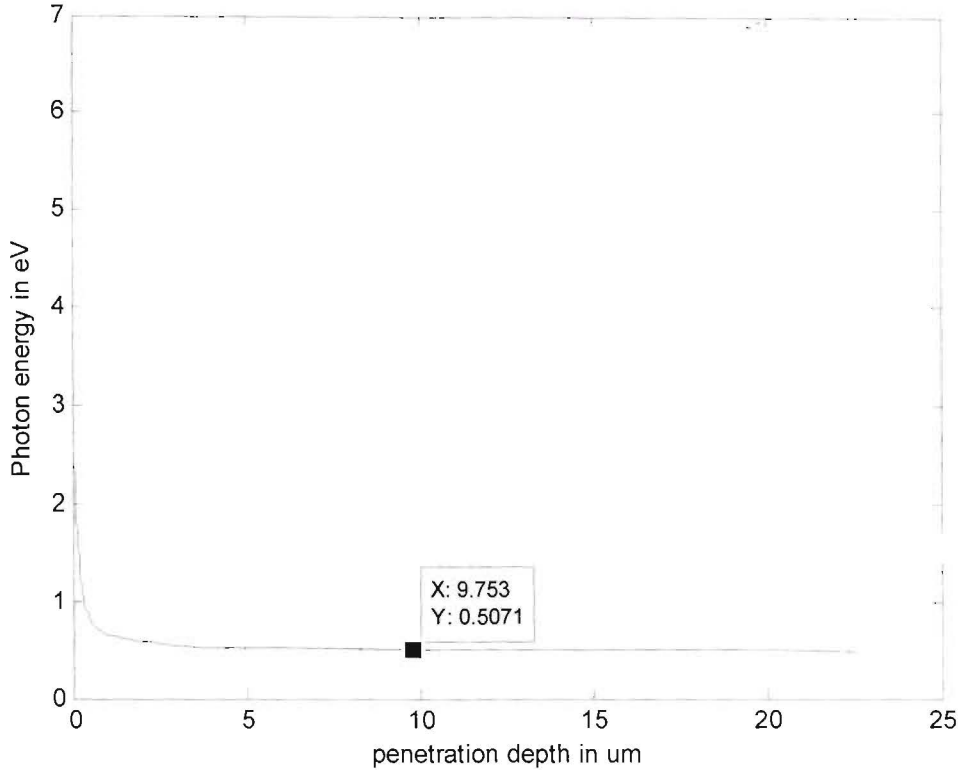


Figure 5.2: Penetration depth vs. Photon energy for 0.5135 eV

Figure 5.3 shows the penetration depth for the photon which has energy around 0.5135 eV and from the plot we can see that the penetration depth for that energized photon is around 10 um.

Now we can design our p-i-n solar cell, because we got every parameter to design our desire solar cell. Figure 5.4 shows our designed p-i-n solar cell. For the composition we get the bandgap 1.3723 eV that we have to put on the top of the p-i-n solar cell, because the high frequency photon's penetration depth is low. Then we put an intrinsic material between p and n type doped material (here we use intrinsic material as graded $Ga_xIn_{1-x}As_{1-y}P_y$ and which is not doped at all). Finally at the bottom we put n-type material.

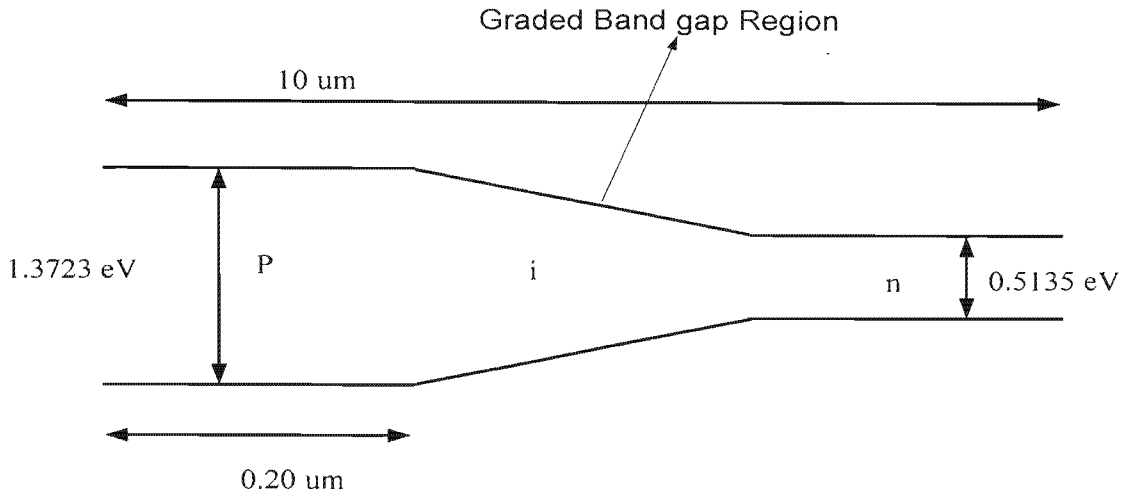


Figure 5.4: Modeled p-i-n solar cell.

5.2 p-n Solar Cell Analysis

To analyze a solar cell we have to find out few basic parameters. These parameters are very important, because these parameters give us an idea about that solar cell. The basic parameters of a solar cell are given below:

1. I_{SC} (Short circuit current),
2. Voc (open circuit voltage),
3. η (efficiency),
4. FF (fill factor).

5.3 Short Circuit Current

Short circuit current is measured when the external load resistance equals to zero. The voltage developed when terminals are isolated (infinite load resistance) is called open circuit voltage. The diagram of an ideal p-n solar cell is shown in figure 5.5.

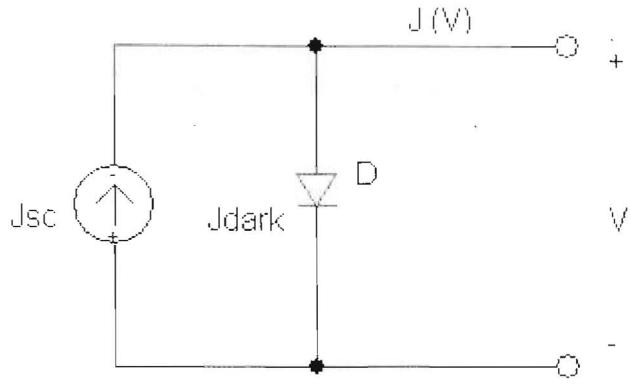


Figure 5.5: Circuit diagram of an ideal p-n solar cell.

The net current density, $J(V) = J_{SC} - J_{DARK}(V)$

$$= J_{SC} - J_O \left(e^{\frac{qV}{K_B T}} - 1\right) \quad 5.1$$

Now we want to find the expression of the dark current. When a load is present, a potential difference develops between the terminals of the cell. This potential difference generates a current which acts in the opposite direction to the photocurrent. This reverse current is usually called the dark current. The dark current equation is given below [22]:

$$J_o = \frac{eD_P P_{no}}{L_P} + \frac{eD_n n_{po}}{L_n} \quad 5.2$$

$$J = J_O \left(e^{\frac{qV}{K_B T}} - 1\right) \quad 5.3$$

$$\therefore J_{DARK} = J_O \left(e^{\frac{qV}{K_B T}} - 1\right) \quad 5.4$$

The photocurrent generated by a solar cell under illumination at short circuit is dependent on the incident light. The equation for short circuit current and photons flux density are given below [23]:

$$\text{Now, } J_{SC} = e \int b_S(E) Q_E(E) dE \quad 5.5$$

Where, bs(E) is the incident spectral photon flux density and $Q_E(E)$ is the quantum efficiency.

$$\therefore b_S(E) = \frac{2F_S}{h^3C^2}\left(\frac{E^2}{e^{\frac{E}{K_B T_S}-1}}\right) \qquad 5.6$$

Where, C is the velocity of light, T_S is the surface temperature of sun; K_B Boltzmann constant, Fs is a geometrical factor which arise from integrating over relevant angular range. Just at the surface of black body this range is a hemisphere and Fs= π and away from the surface the angular range is reduced and Fs= $\pi\sin^2\theta_{sun}$. Where θ_{sun} is the half angle subtended by the radiating body to the point where the flux is measured. For the sun as seen from the earth θ_{sun} is equal to 0.26°

5.4 Open Circuit Voltage

Open circuit voltage is another important basic parameter. When the contacts are isolated, the potential difference has its maximum value and then it is called open circuit voltage. It can express in bellowing way [24].

$$\therefore V_{OC} = \frac{K_B T}{e}\ln\left[\frac{J_{SC}}{J_O} + 1\right] \qquad 5.7$$

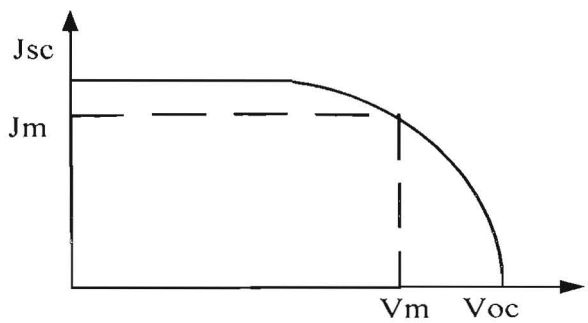


Figure 5.6: maximum power point

Figure 5.6 shows the maximum power point.

5.5 Fill Factor

From fill factor (FF) we can get overall behavior of a solar cell. Fill Factor is the ratio of the available power at the maximum power point (P_m) divided by the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}). The mathematical expression is given below [25]:

$$FF = \frac{V_m \times I_m}{V_{OC} \times I_{SC}} \quad 5.8$$

We can control the fill factor by controlling series and shunt resistances. To a have higher fill factor we have to increase the shunt resistance (R_{sh}) and decrease the series resistance R_s.

5.6 Efficiency

Energy conversion efficiency of a solar cell, which is the percentage of power converted to electrical energy and collected energy, when a solar cell is connected to an electrical circuit [25]. This term is calculated using the ratio of the maximum power point, P_m, divided by the input light irradiance.

$$\eta = \frac{V_m \times I_m}{E_K \times A_C} \quad 5.9$$

Where, 'A_C' is surface area of solar cell. E_K is the input sunlight irradiance.

Chapter 6

Graded p-i-n solar cell analysis

The topics of this chapter can be divided into two parts and those are p-i-n solar cell analysis and graded p-i-n solar cell analysis. In this chapter first we have discussed about the p-i-n solar cell and tried to find out the expression of few basic parameters such as short circuit current, open circuit voltage of graded p-i-n solar cell. Figure 6.1 shows that energy band diagram of graded p-i-n solar cell.

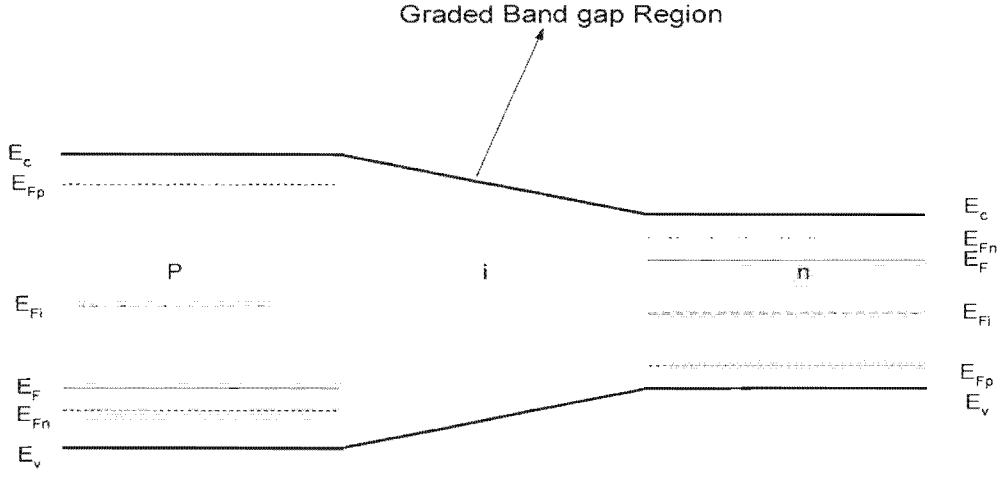


Figure 6.1: Energy band diagram of graded p-i-n solar cell.

Where, E_{Fn} and E_{Fp} are Quasi- Fermi energy levels. E_{Fi} is the intrinsic Fermi level.

6.1 Graded p-i-n Solar Cell Analysis

Here we first discussed about the p-i-n solar cell. Few basic equations for p-i-n solar cell are given below and then we modify the equation for the graded p-i-n solar cell [23].

$$\text{We know that, } np = n_i^2 \left(e^{\frac{eV}{K_B T}}\right) \qquad 6.1$$

$$\text{Again, } n = n_i\, e^{\frac{E_{Fn}-E_i}{K_B T}} \tag{6.2}$$

$$P = ni\, e^{\frac{Ei-E_{Fp}}{k_B T}}$$

$$\text{Recombination} : J_{rec} = q\int_{-w_p}^{w_n} U dx \tag{6.3}$$

Where, 'U' is the recombination rate per unit volume. W_n and W_p are the depletion region width of n side and p side. E_{Fn} and E_{Fp} are Quasi- Fermi energy levels; n_i is the intrinsic carrier concentration.

Now generation due to light,

$$J_{gen} = \int_{-w_p}^{w_n} J_{gen}(E)dE \tag{6.4}$$

$$J_{gen} = -q\int_{-w_p}^{w_n} g(E)dE \tag{6.5}$$

Now, we know that the recombination rate per unit volume is given below:

$$U = \frac{np-n_i^2}{\tau_p(p+p_i)+\tau_n(n+n_i)} \tag{6.6}$$

By putting the value of recombination rate per unit volume to equation 6.3, we get

$$\therefore J_{rec} = q\int_{-w_p}^{w_n} \frac{np-n_i^2}{\tau_p(p+p_i)+\tau_n(n+n_i)} dx \tag{6.7}$$

Here we modify the above equations for graded p-i-n solar cell.

$$\text{We know that, } np = n_i(x)^2 \left(e^{\frac{eV}{K_B T}}\right) \tag{6.8}$$

$$\text{Again, } n = n_i(x)e^{\frac{E_{Fn}-Ei}{K_B T}} \tag{6.9}$$

$$p = n_i(x)e^{\frac{Ei-E_{Fp}}{K_B T}} \tag{6.10}$$

From equation 6.6 we get recombination rate per unit volume for graded p-i-n solar cell is given below:

$$U = \frac{np(x)-n_i^2(x)}{\tau_p(p+p_i(x))+\tau_n(n+n_i(x))} \quad 6.11$$

From equation 6.7,

$$\therefore J_{rec} = q\int_{-w_p}^{w_n} \frac{np(x)-n_i^2(x)}{\tau_p(p+p_i(x))+\tau_n(n+n_i(x))}dx \quad 6.12$$

$$\therefore J_{dark} = q\int_{-w_p}^{w_n} \frac{np(x)-n_i^2(x)}{\tau_p(p+p_i(x))+\tau_n(n+n_i(x))}dx \quad 6.13$$

$$\text{Short circuit current, } Jsc = \int q(1-R(x))b_S e^{-\alpha(x)x_p}\left(1-e^{-\alpha(x)x_i}\right)dE \quad 6.14$$

Where R is the reflectivity of sunlight, α is the absorption coefficient, and x_i is the length of the intrinsic region of the graded p-i-n solar cell, $b_s(E)$ is the incident spectral photon flux density, τ_p and τ_n are the electron and hole life time. W_n and W_p are the depletion region width of n side and p side.

We can calculate the efficiency and the fill factor from the equation 5.8 and 5.9 respectively. We calculate the short circuit current from the equation 6.14 and then we calculate numerically open circuit voltage from the equation 6.13. At the voltage when the dark current is equal to the short circuit current that voltage is called the open circuit voltage. All calculations are performed at one sun concentration of sunlight without considering any concentrators. The calculated short circuit current is 17.4911 (mA/cm^2) and the open circuit voltage is around 1.33 V.

Figure 6.2 shows that load current vs. the voltage. From the figure we can see that at around 1.33 V the load current became zero.

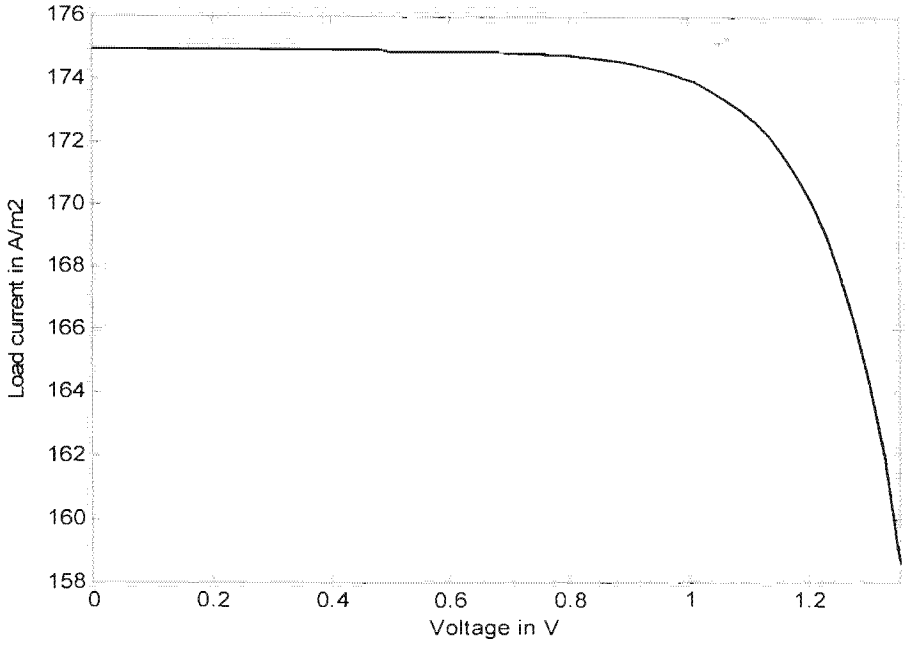


Figure 6.2: Load current vs. Voltage of modeled graded p-i-n solar cell.

Figure 6.3 shows that the maximum power point. From figure we can see that the maximum power is around 18.42 (mW/cm^2).

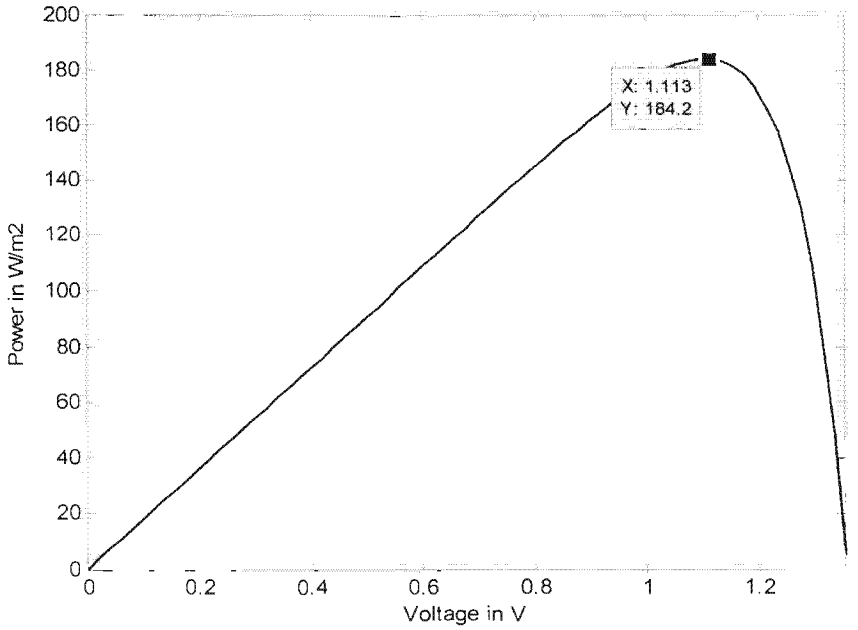


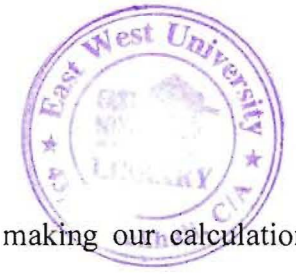
Figure 6.3: Maximum power point of modeled graded p-i-n solar cell.

Fill Factor and efficiency of our designed graded bandgap p-i-n junction solar cell are around 0.792 and 18.42% respectively. According to our efficiency we can say that our designed graded p-i-n junction solar cell is good compared to other types of solar cell. Because if we see the other types of solar cell like, Polymer solar cell its efficiency is 5%, Amorphous Silicon solar cell is (5-7%), Thin-film solar cell is (10-12%), Polycrystalline solar cell is (13-15%) and Mono-crystalline solar cell is 18% efficiencies [2][3]. So compare to all other solar cells our solar cell efficiency is better. So if we take our graded bandgap p-i-n junction to make a solar cell it is expected that the proposed model can be used for better efficiency rather than other category solar cells.

Conclusion

7.1 Summary

In our project, we have developed a graded bandgap p-i-n junction solar cell by using GaInAsP semiconductor material. The main purposes of graded bandgap are, we choose GaInAsP as active semiconductor material of solar cell and InP as substrate, because its lattice constant are pretty close with GaInAsP also to ensure more efficient absorption of photons. The efficiency will increase according to the load current. Here we use quaternary semiconductor material GaInAsP because it is easy to change the bandgap of this material without changing the lattice constant and we can change the bandgap over a wide region by changing their compositions. We have performed numerical calculation for energy gap and lattice parameter by changing the composition of the materials. From the compositions we get the bandgap 1.3723eV that we have to put on the top of the p-i-n solar ceil, because the high frequency photon's penetration depth is low. Then we put an intrinsic material between p and n type doped material. Finally at the bottom we put n-type material of bandgap 0.5135 eV. We consider ± 0.05 % mismatch in lattice parameter between substrate and our active materials. We assumed the parameters such as effective density of states in the conduction band and valance band as constant. We have neglected recombination of electrons for making our calculation easy. Also we have used $\pm 0.05\%$ mismatch in lattice parameter to cover wider range from sunlight spectrum. Assumed total number of electrons and holes are same, and the reflectivity of sunlight for short circuit current calculation is neglected in the model. In this model the short circuit current is 17.4911(mA/cm^2), open circuit voltage is around 1.33 V, fill factor is 0.792 and finally efficiency is 18.42% calculated. And the obtained efficiency is good for solar cells not using concentrators. It is expected that the proposed model can be used for better efficiency rather than other same category solar cells.



7.2 Future Works

We have neglected few parameters for making our calculation easy. We have used ±0.05% mismatch in lattice parameter to cover wider range from sunlight spectrum. But in future this mismatch can be increased to cover wider range. We have used GaInAsP to design our graded p-i-n solar cell but in future other quaternary materials can be used to increase efficiency. We assumed the parameters such as effective density of states in the conduction band and valance band as constant. We have assumed reflectivity of the cell is equal to zero for making our calculation easy, but in future the value of reflectivity of sunlight by the cell can be calculated perfectly to get more accurate efficiency. Assumed total number of electrons and holes are same and we doped the material with 10^{15} cm^3 impurity atoms, but in future the impurity atoms can be calculated for which the efficiency of the cell can be increased. We took some reasonable values for calculating length for p-side & intrinsic side (i). The length for p-side & intrinsic side (i) can be calculated perfectly to get more reasonable efficiency in future. In our analysis we have not optimized the design of the proposed solar cell to maximize efficiency. Design optimization of this structure in future should result in an increase in the efficiency of the proposed solar cell.

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