PHYSICAL MODELING OF MULTI QUANTUM WELL (MQW) P-I-N INGAAS / INALAS SOLAR CELL

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PHYSICAL MODELING OF MULTI QUANTUM WELL (MQW) P-I-N INGAAS / INALAS

SOLAR CELL

By

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LIST OF ABBREVIATIONS

MQW	Multi Quantum Well
OC	Open Circuit
SC	Short Circuit
TCAD	Technology Aided Computer Design
InGaAs	Indium Gallium Arsenide
InAlAs	Indium Aluminium Arsenide

LIST OF SYMBOL

Eg	Energy Gap
αE & βE	Material Specific Constant
T	Temperature
A	Absorption Coefficient
I	Light Intensity
χ^A & χ^B	Electron affinities
E	Energy
h	Planck 's constant
v	Frequency
m_b	Electron Effective Mass
Im	Current at maximum power
Vm	Voltage at maximum power
Voc	Open Circuit Voltage
Isc	Short Circuit Current
Pm	Maximum power

ABSTRACT

Multi Quantum Well Solar Cell is an advanced improvement of the conventional solar cell to overcome problem encounter in a normal solar cell. In a normal solar cell, the photon energy absorption rate is low causing the electron absorption rate to be low directly. A lower electron absorption results in a smaller value of current and voltage generated. Therefore, the introduction of multi-quantum well structure in the intrinsic region of the solar cell was introduced to allow more electron is absorbed and increase the efficiency of the solar cell. The proposed method in this project is to use III-V material which is Indium Gallium Arsenide (InGaAs) and Indium Aluminium Arsenide (InAlAs) as its quantum well material.due to its greater band-gap energy. In addition, to increase the efficiency of the solar cell, in this project, the number of quantum well present and depth of the quantum well varies to study the performance of the multi-quantum well solar cell. The modeling of the multi quantum well solar cell is done by using the Silvaco TCAD software. The result collected in this project is to rate the performance of MQW solar cell are open circuit voltage, short circuit current, fill factor, efficiency, recombination rate, band-gap energy and spectral response. In this research, the increase of the quantum well number and depth, increases the short circuit voltage, efficiency and fill factor. The value of the open circuit voltage was constant even though the quantum well number and depth varies. Finally, to achieve a greater solar cell output value, the number of the quantum well should be high and the quantum well depths should be deeper in order to ensure more absorption of the electron.

ABSTRAK

'Multi Quantum Well Solar Cell' merupakan penambahbaikan maju sel solar konvensional untuk mengatasi masalah masalah dalam sel solar biasa. Dalam sel solar biasa, kadar penyerapan tenaga foton adalah rendah yang menyebabkan kadar penyerapan elektron menjadi rendah secara langsung. Hasil penyerapan elektron yang lebih rendah menjadi nilai yang lebih kecil semasa dan voltan menghasilkan. Oleh itu, pengenalan struktur baik kuantum multi di kawasan intrinsik sel solar telah diperkenalkan untuk membolehkan lebih banyak elektron diserap dan meningkatkan kecekapan sel solar. Kaedah yang dicadangkan dalam projek ini adalah untuk menggunakan bahan III-V iaitu Indium Gallium Arsenide (InGaAs) dan Indium Aluminium Arsenide (InAlAs) sebagai bahan quantumnya kerana tenaga jurang yang lebih besar. Di samping itu, untuk meningkatkan kecekapan sel solar, dalam projek ini, bilangan kuantum yang dan kedalaman kuantum yang berbeza untuk mengkaji prestasi sel suria pelbagai kuantum. Pemodelan 'Multi Quantum Well Solar Cell' dilakukan dengan menggunakan perisian Silvaco TCAD. Hasil yang dikumpulkan dalam penyelidikan ini untuk menilai prestasi sel suria MQW adalah voltan litar terbuka, arus litar pintas, faktor pengisi, kecekapan, kadar rekombinasi, tenaga gelang jeda dan tindak balas spektrum. Dalam kajian ini, peningkatan bilangan dan kedalaman kuantum yang baik, meningkatkan voltan litar pintas, kecekapan dan faktor penambah. Nilai voltan litar terbuka adalah malar walaupun bilangan dan kedalaman kuantum juga berubah. Akhir sekali, untuk mencapai nilai output sel suria yang lebih besar, jumlah kuantum perlu tinggi dan kedalaman kuantum harus mendalam untuk memastikan lebih banyak penyerapan elektron.

CHAPTER 1 : INTRODUCTION

1.1 Research Background and Motivation

The idea of the Multi Quantum Well Solar Cell is one of the steps taken in order to improve the performance of the current solar cell in the terms of its output voltage and current. Besides, the MQW solar cell is designed to support heavy machinery where the supply of electricity is difficult such as the spaceship that located in the space. The first solar cell was designed at the year of 1883 by a New York inventor Charles Fritts by using the selenium and gold as the part of solar cell material [1]. In a simple way of explaining the Multi Quantum Well solar cell is, a solar cell that is created with an extra region containing a certain type of material that allowed the trapping of light energy more thus giving a great output.

A complete modulation of the Multi Quantum Well solar cell contains its cross-section diagram where it shows the type of the material used and also the thickness of material in terms of the y-axis and length of the material in terms of the x-axis. In addition, a complete module of Multi Quantum Well solar cells contains the photogeneration rate at each area of the solar cell. Designing the Multi Quantum Well Solar Cell doesn't fuilfill this project but we need to investigate the electric characteristic of the designed MQW solar cell in order to ensure the designed solar cell fulfill the criteria. The electrical analysis of the Multi Quantum Well Solar Cell is done by testing the output voltage of an open circuit (Voc) and the output current of the short circuit (Isc) current. The solar cell is also tested for its external quantam efficiency that shows the light absorbtion efficiency of the solar cell and also its recombination rate of the electron-hole current in the solar cell.

As the ordinary solar cell, in a Multi Quantum Well solar cell, the sunlight is absorbed by the cell and convert it into energy where a cell can generate about 1 to 2 watts of energy [2]. As the Solar Cell exposed to the sunlight, it is absorbed the sunlight and releases electrons which enters to the external circuit via the wires thus creating electrical energy. The brighter the sunlight, the higher the current generated but the voltage of the cell always remains the same. When the energy absorbed by the photon is not sufficient enough, it transformed as heat energy instead of electrical energy.The uses of the solar cell are due to its renewable energy source and also doesn’t pollute the environment [3].

To date, there not a definite model of Multi Quantum Well (MQW) p-i-n InGaAs/InAIAs solar cell of different parameter by using the Silvaco TCAD software which would be one of the challenges in this project.The designing of the Multi Quantum Well solar cell in this project it doesn’t use silicon but instead, we use III-V semiconductor material type. The III-V semiconductor material is from the combination of material in group III of the periodic table and material from group V of the periodic table. Therefore the material used in our solar cell is Indium Aluminum Arsenide (InAlAs) and Indium Gallium Arsenide (InGaAs) material. The uses of the material are due to its higher bandgap thus giving a good outcome [4]. The modeling of the MQW Solar Cell is done by using Silvaco Atlas software due to its ability to generate the 2-D image of the solar cell and also the output graph of its electrical characteristics such as the output current and voltage. The thickness of each level is differed depending on the quantum well depth and number of quantum well applied [5].

1.2 Problem Statement

The Multi Quantum Well Solar Cell is basically an advance ordinary solar cell that had been improved in many terms replacing the conventional available solar cell. Such improvement covers open circuit voltage, Voc and short circuit current, Isc. The open circuit voltage is when the solar cell is not connected to any load and left open-circuited meanwhile the short-circuit current is obtained when the solar cell is short-circuited [6].

An ordinary solar cell couldn’t absorb higher photon energy making it less efficiency to give its maximum performance and therefore an anlternative way should be taken. Many researchers had designed and simulated the Multi Quantum Well Solar Cell in terms of its structure and types of material used to ensure the efficiency of the solar cell is higher. However, there is still room for improvement in obtaining its outome current-voltage characteristics because there is no specific design for the multi quantum well model used. All the continuous development of the MQW Solar Cell or any ordinary solar cell is done to get an output characteristic that has greater outcome voltage and current value that can be the view from the I-V curve.

The modelling of the multi quantum well solar cell is to gives its best outcome measurable units such as its open circuit voltage, short circuit current, voltage and current at its maximum power, efficiency and fill factors. The parameter variation that could result the outcome value of the MQW solar cell is studied to ensure a robust design obtained.

By modelling the Multi Quantum Well Solar Cell could helps in venturing renewable energy source research as we able to model a solar cell that could support electrical item such as home appliances, space station and electrical car. This could ensure the reduction if the uses in non-renewable energy such as fossil fuels and natural gas.

1.3 Objective

The two objectives of this project are:

1. To model the Multi Quantum Well Solar Cell (MQW) p-i-n InGaAs/InAlAs Solar Cell using the SILVACO TCAD software.
2. To evaluate the effect of varying the number of multi quantum well and its depth on the I-V characteristics of the solar cell.

1.4 Research Scope

In this project, the main scope is designing a solar cell that has multiple quantum wells and the limiting function would be the efficiency of the cell inability to absorb a photon of lower energy than the gap. The design of the MQW Solar Cell is limited to two types of material which is InAlAs and InGaAs and the quantum well material and also the barrier. The intent of designing the MQW Solar Cell is to increase short-circuit current even though the design varies but the outcome should be in the same zone of testing.The overall parameter that is tested are open circuit voltage, short circuit current, fill factor, efficiency, voltage and current at maximum power. The design flow of the diagram also should be p-i-n where the InAlAs material is used as the barrier and InGaAs structure as the quantum well sructure and therefore the design of this MQW Solar Cell should be concentrating on the depth of the well and also the number of quantum well in the material used [7].

1.5 Thesis Structure

This thesis consists of five main chapter that explains more five senses of detail about this task. The first chapter is the introduction of the thesis where it gives the background knowledge information about the topic and it also describes general estimate about the project. It consists of the Introduction, Research Background and Motivation, Problem Statement, Objective, Research Scope and Thesis structure.

The second chapter which is Chapter 2 literature review that contains a detailed idea, concept and working principle of the Multi Quantum Well (MQW) Solar Cell. In this chapter also, the important formula and the theories that should be understood before modeling the MQW Solar Cell. It also covers the output result that should be stimulated after modeling the Solar Cell.

Chapter 3 consists of a methodology part where it covers the flow of the research diagram. Besides, the software used is explained clearly in this chapter. The software used which is SILVACO ATLAS is explained in the terms of operation and simulation.

The following chapter would be chapter 4 that is Result and Research. In this chapter, the result obtains through the simulation of the Multi Quantum Well Solar Cell is discussed in this chapter in terms of its structure and also the I-V curve that shows the characteristic of the output current. The comparison of data between the normal solar cell and MQW Solar Cell is done in the chapter by taking into account the thickness of the material used and also the number of quantum well used.

The final chapter of the thesis would be Conclusion under the chapter 5, which discussed the overall achievement of the project. The future improvement that can be taken to improve the outcome of the project is also discussed in this chapter clearly.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

In this chapter. It covers the technical information and project that includes the theories and formula to be taken into consideration when designing the required element this final year project. The goal of this chapter is to make the reader understand the topic in detail and get a general working principle of this project.

In designing the Multi Quantum Well (MQW) Solar Cell, the basic concept and technical aspect should be discussed in this topic which starting at the basic understanding knowledge of what is semiconductor device and the working principle of it. Then it followed by the working principle of the ordinary solar cell and how does it contribute to the formation of Multi Quantum Well (MQW) Solar Cell. On the other hand, not only explaining about the theories involving the physical modeling of the Multi Quantum Well (MQW) Solar Cell but this chapter also explains about the I-V characteristic and how can it be examined on the model that is created. The aspect of testing the device will also be covered in this chapter.

2.2 Semiconductor

The term semiconductor was used by Alessandro Volta at the year of 1782. No one created semiconductor but instead, the semiconductor was discovered. The first person who discovers the effect of the semiconductor is Michael Faraday in 1833 where he observed the electrical resistance of silver sulfide was inversely proportional to temperature [8].A semiconductor is a device that can work in both ways such as a good conductor like a copper wire or a good insulator like rubber. The common material exists in a semiconductor is silicon and germanium which is doped with the excess or shortage of electron depending on the usage [9]. The working principle of a semiconductor as a conductor or insulator is depended solely on its energy gap as shown in Figure 2.1. Energy bandgap can be defined as the difference of energy in the conduction band and valence band. The properties of this material are tunable and also the conductivity depends on its temperature and also its energy bandgap. Besides, its ability to conduct electricity can be improved by substituting or adding certain donor or acceptor to its crystalline structure [10]. In order for conductivity to takes place, electron should overcome the energy band gap region. It can also absorb light to produce electrical energy and this is where the solar cell was created and became one of the renewable energy sources. The formula of the energy bandgap is given by:

$$Eg(T) = Eg\ (0) - \frac{\alpha E.T^2}{T + \beta E} \qquad \text{(Eq. 2.1) [11]}$$

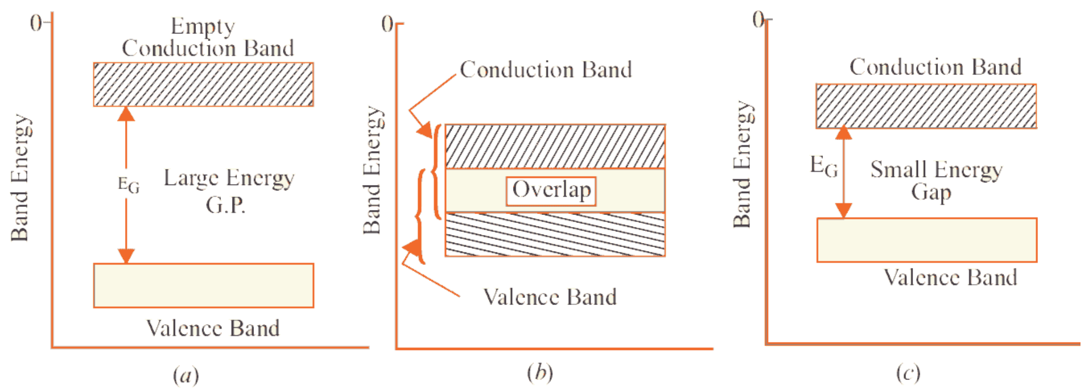

Figure 2.1: Type of Energy Band Gap in (a) insulator, (b) metal and (c) semiconductor [12]

Energy band gap is known as the forbidden energy reason of the electron and this region should be overcome by the electron for the purpose of conductivity. When the temperature increases, the electron gets excited and enter into the conduction band under the excited state. Therefore, the temperature depends on these materials and thermoelectric or Seebeck effect. The temperature is directly proportional to the energy level of the electron. The higher the temperature, the more energy absorbed by the electron and change into its excited state as can be viewed at the graph in Figure 2.2. Then it enters into the conduction band during its excited state.

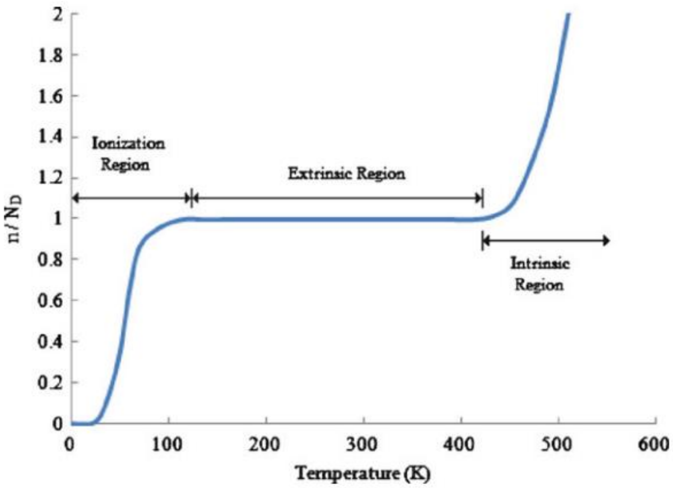

Figure 2.2: Graph of the temperature dependence of semiconductor conductivity in a doped semiconductor [11]

The knowledge of temperature effect in conductivity of the semiconductor is necessary for understanding this project because the Multi Quantum Well Solar Cell that going to design in this project is build up by using the semiconductor material which is InGaAs and InAlAs. The semiconductor material is also used because we are required in using the p-type or n-type material in constructing this solar cell. When the sunlight hits the semiconductor material that used to build the solar cell, the light energy will force some electron to get out from the atom. The released electron travels in an external circuit causing it to be the electricity. The electricity produce also will be stored in the battery to ensure the supply later on as shown in Figure 2.3. Not all the light hits on solar cell exactly, some light energy reflects back and some do transform to heat energy. The suitable wavelength of light hit the solar cell exactly and ensure it produces electricity [12].

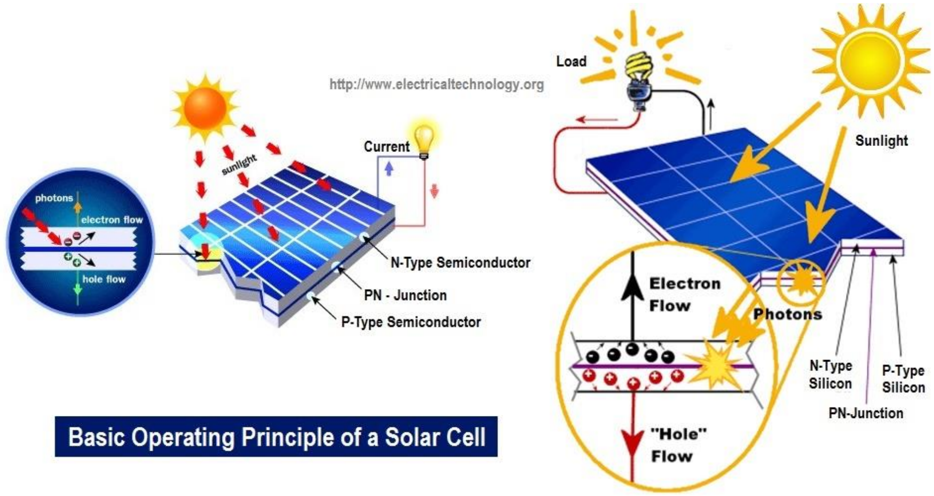

Figure 2.3: Solar cell [14]

Through the Figure 2.3 above that shows the ordinary solar cell, it can understand that semiconductor uses mainly in the solar cell as it can smoothly carry on the task of existing the electron from the valence band to conduction band thus generate electricity easily. Therefore the uses of a conductor don’t make the solar cell to work accurately but with the help of semiconductor material, we can achieve the working theory of the solar cell as desired.

2.3 Junction

The MQW solar cell design must use the p-i-n junction as shown in Figure 2.4 where it is known as a diode that has a p-type and n-type combined semiconductor. The current only flows in one direction at this junction and there are two types of current exist that is thermal-electron current that produces due to thermal excitation of the electron. The other type of current is recombination current when generated as free electron from n-semiconductor drift to p-semiconductor. In a situation with no external voltage, the thermal and recombination current is equal and cancel up each other [13].

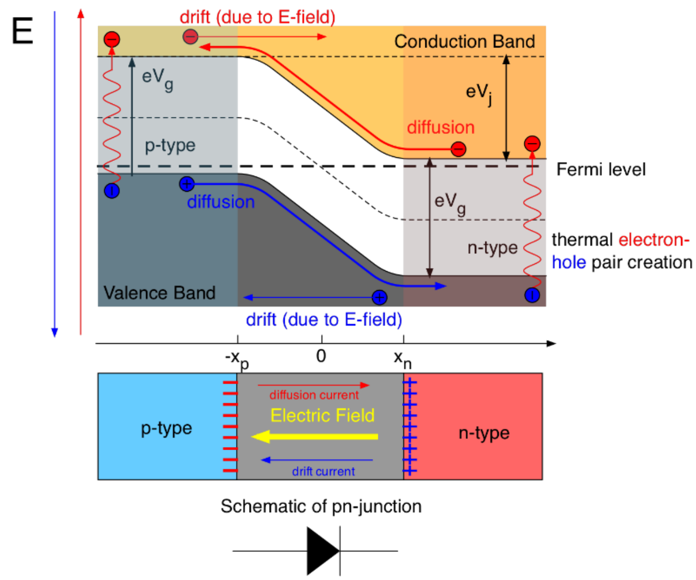

Figure 2.4: p-n junction [16]

The solar cell designed has p-i-n structure that allows the flow of current in only one direction. There will also be an internal voltage of the diode due to its doping concentration and also its material properties.

2.4 III-V Semiconductor Material

The III-V material is born from the combination of material from group three and group five of the periodic table as shown in Figure 2.5 which had given up to twelve type combination of material. The uses of this semiconductor are due to its different lattice constant and also band gap that could give a change to the performance of the semiconductor device such as the Multi-Quantum Well Solar Cell.

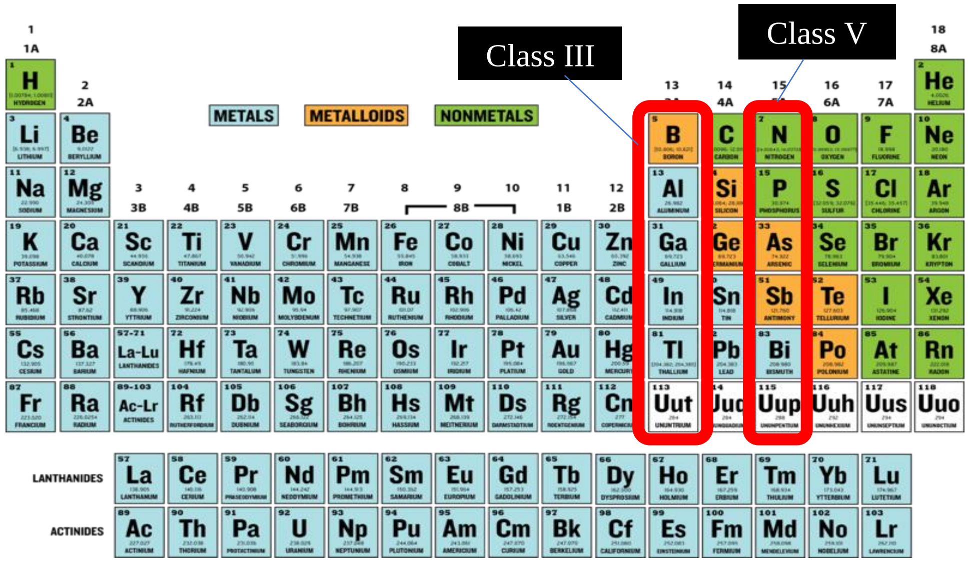

Figure 2.5: The periodic table showing the position of an element of III-V [17]

As shown the location of III-V material in periodic table as in Figure 2.5 above, the III-V material has the atom that is not freely distributed but it has a specific site called as the lattice point and can be separated into two different type of lattice points which is the zincblende and Wurtzite. Meanwhile, lattice constant defined that in a three-dimensional lattice, the distance between the neighboring unit cells is mentioned as the lattice constant. The introduction of a third, fourth or fifth group of the element into this III-V compound causes the changes of is lattice constant and followed by the energy band gap. The various range of bandgap as shown in Figure 2.6 formed by this semiconductor material has eased in constructing the Multi Quantum Well Solar Cell as we have band choice of material and it could deliver a different kind of performance and also currently this is the efficient photovoltaic material exist in the market [14].

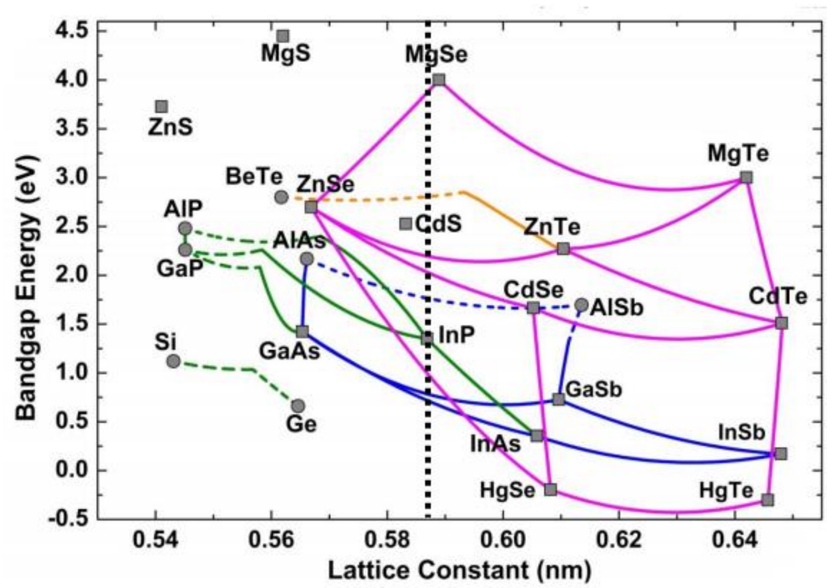

Figure 2.6: Bandgap Energy and Lattice Constant of III-V Semiconductor Material [19]

The most commonly used compound in our physical modeling of Multi Quantum Well Solar Cell is gallium arsenide(GaAs) and Aluminium Arsenide(AlAs) as can be viewed in Figure 2.6 above due to its bandgap and lattice constant and their properties respecively shown in Table 2.1 and 2.2. The material GaAs has a higher electron mobility and velocity due to its higher bandgap.On the other hand, the material AlAs is used in the modeling of the solar cell due to its higher bandgap energy too [15].

Table 2.1: Band Structure symmetry point of gallium-arsenide (GaAs) [21]

Material	Bands	Symmetry points (eV)					Energy Gap (eV)	Fermi Energy	Max/Min Energy band
			$S-band$	P_x-band	P_y+P_z-band	overlapping	0.367	−0.100682	
		L	−11.35070	−6.98844	−1.43231				
	Valence Band	Γ	−13.09560			−0.28436			−0.284356
		X	−10.57010	−7.17211	−2.94762				
Gallium-Arsenide (GaAs)		W	−10.52420	−6.98844	−3.86599 Py −3.63040 Pz				
		L	0.58809	4.35340					
	Conduction Band	Γ				3.48095			0.0829912
		X	1.09320	1.32279					

Table 2.2: Band Structure symmetry point of aluminum-arsenide (AlAs) [21]

Material	Bands		Symmetry points (eV)				Energy Gap (eV)	Fermi Energy	Max/Min Energy band
			$S-band$	P_x-band	P_y+P_z-band	overlapping	1.4235	0.093005	
Aluminium-Arsenide (AlAs)	Valence Band	L	−11.89400	−6.98076	−2.20525				
		Γ	−13.27160	−1.37872	−1.37872	−1.37872			−1.37872
		X	−11.34300	−6.84300	−3.53688				
		W	−11.29710	−6.42974	−4.59300 P_y −4.22566 P_z				
	Conduction Band	L	0.68761	3.30495					
		Γ	0.54985	2.89169					
		X	0.87128	0.04475					0.04475

The modeling of MQW Solar Cell involves the p-i-n design function as the p-n junction is the heart of most of the semiconductor device. The parameter of the material used in designing the solar cell has shown in Table 2.1 and 2.2 above. This is where the semiconductor III-V device took place and we need to form the p-type and n-type region using this III-V semiconductor material. As when the p-n junction is exposed to the light, the formation of electron-hole pair takes place. When the electron got excited in the p-type region, those electrons manage to get into the depletion region and move forward to the n-type region via the electric field and vice-versa for the n-type region. This lead to the formation of forwarding biased current in the solar cell producing DC current as the output of the solar cell [14].

2.5 Light Absorption

In a solar cell, the absorption of light is one of the most important factors in determining the energy produced by the solar cell. Light absorption at solar cell depends solely on its bandgap of energy, Eg. When the bandgap energy is larger than the photon energy, there will no absorption and if the photon energy is larger, the extra energy will be lost to into the lattice vibrations. The absorption coefficient is:

$$A = -\frac{\delta I}{I\delta x}, \qquad \text{(Eq. 2.2) [16]}$$

And by integrating leads to Beer–Lambert law, where *I* is the light intensity and *Io*

The energy incident per unit area per unit time.The absorption increases as the available state in the conduction and valence increases [16].The absorbtion coefficient in different wavelength for the same quantum well material used in this project is shown in Figure 2.7 below.

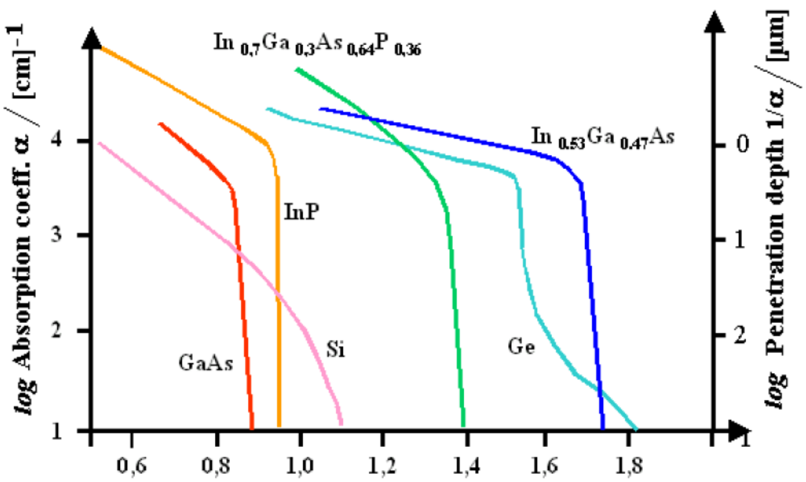

Figure 2.7: Graph of absorption coefficient against light wavelength [22]

2.6 Heterostructures

Heterostructures is the main element should be taken into consideration when designing the semiconductor device as it's a process to ensure the lattice parameter of two material in contact is almost the same. The consequence that may face when designing a compound by ignoring this criterion would cause a large deformation when two substances with a large difference of lattice parameter grow on one another. This indirectly shows that the material chosen to build the MQW solar cell is GaAs and AlAs which has the lattice parameter that almost the same [17].

Many researchers had done some experiment in researching the heterostructures and how can it contribute to the higher efficiency output of the Multi Quantum Well Solar Cell. The method of researcher carried out is by using the material of low difference lattice parameter and setting the thickness to a certain level. The open effect of the open circuit voltage and short circuit current is tested to ensure high performance of the solar cell with a lower cost.

2.6.1 Band Discontinuities

When two material of a different band gap came in contact together is where there is born of heterojunction known as the interference of this formation. During the interference, changes occur at the conduction and valence band energies that lead to band discontinuities which the properties are identified in terms of electrical and optical. The band discontinuation is explained clearly with the aid of the diagram in Figure 2.8 below when two material of different energy bandgap get together in contact [18].

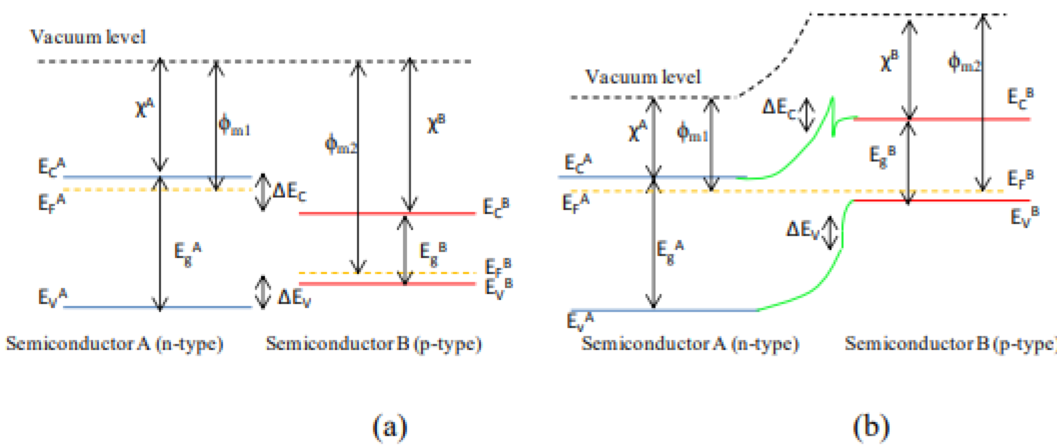

Figure 2.8: Energy band diagrams of two semiconductors (a) in isolation and (b) in contact [24]

The conduction band and valence are labeled with Ec and Ev respectively while Eg stands for band gap and EF is the Fermi level for both the semiconductor (Semiconductor A and B) respectively. Electron affinities are given the symbol of χ^A and χ^B for both the semiconductors.

Bandgap discontinuity is defined as:

$$\Delta Eg = E_g^A - E_g^B \qquad \text{(Eq. 2.3) [18]}$$

The division of ΔEg into the conduction Band and valence band is derived by:

$$\Delta E_C = \chi^A - \chi^B \quad \text{(Eq. 2.4) [18]}$$

$$\Delta E_V = \left(E_g^B - E_g^A\right) - \left(\chi^A - \chi^B\right) \quad \text{(Eq. 2.5) [18]}$$

Which:

$$\Delta E_g = \Delta E_C + \Delta E_V \quad \text{(Eq. 2.6) [18]}$$

This concludes that controlling the flow of electron and holes across the heterostructures enable the band gap discontinuity, ΔEg to be changed as desired by the engineers.

2.6.2 Lattice Selection

The lattice selection and formation of heterojunction have a strong relationship each other and fault in selecting the material with an almost same lattice constant would cause the product defect. Therefore the purpose of choosing a material pair with similar lattice constants would minimize the heterojunction interference. The graph in Figure 2.9 below example of material that have different band gap energy at the same lattice constant.

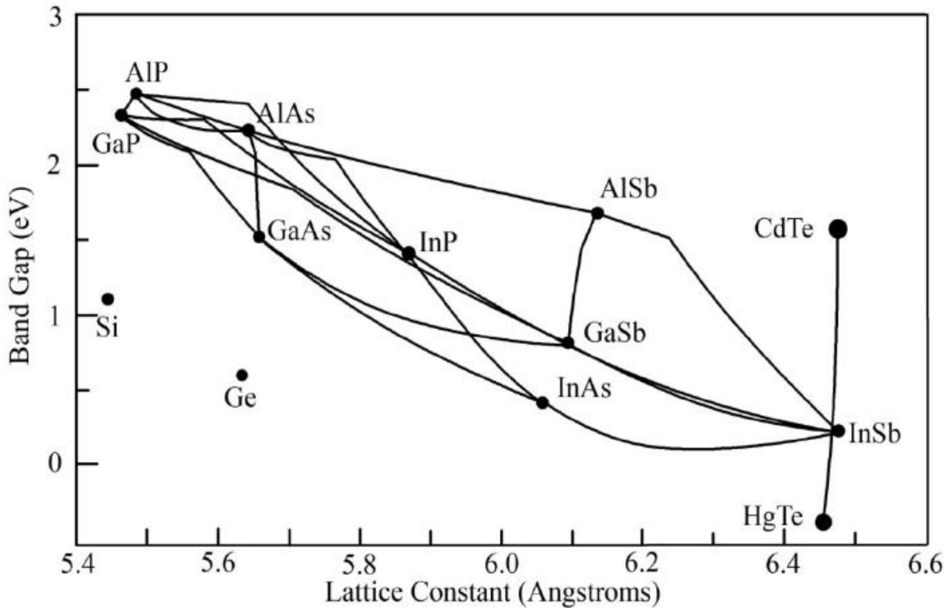

Figure 2.9: Graph of lattice constant for the semiconductor material [25]

The lattice constant for Aluminium Arsenide (AlAs) is about 5.6605 and the lattice constant for Gallium Arsenide (GaAs) is about 5.6533 where both of the material has a minimal lattice constant difference which is 0.0072.

If a wrong material is chosen without taking into the lattice constant into consideration, it can cause both materials to have a drastic change in terms of its crystalline structure. The changes in crystalline structure lead to the formation of dislocation where holes and electron are trapped. This makes the electrical properties of the device to be poor and doesn’t deliver the desired output in the MQW Solar Cell later [18].

2.7 Working Principle of Ordinary Solar Cell

A simple Solar Cell operates under the principle of photovoltaic effect where a voltage is generated at the junction of two different type of material. The main concept of how the current production is due to the photoelectric effect from a material that absorbed sunlight and causes the electron emission as shown in Figure 2.10. This process is assumed that light has an energy quantum and it is described by the formula of:

$$E = hv \quad \text{(Eq. 2.7) [19]}$$

From the formula above, Planck’s constant is denoted by the symbol ‘h’ and whereas frequency is denoted by the symbol ‘v’.

This first task carried out by the solar cell to produce energy is by producing the charge carrier that comes from the effect of photon absorption in the material that produced junction. The absorption of photon lead to the electron in the material gets excited by gaining energy and then transfer from the valence band to the conduction band.

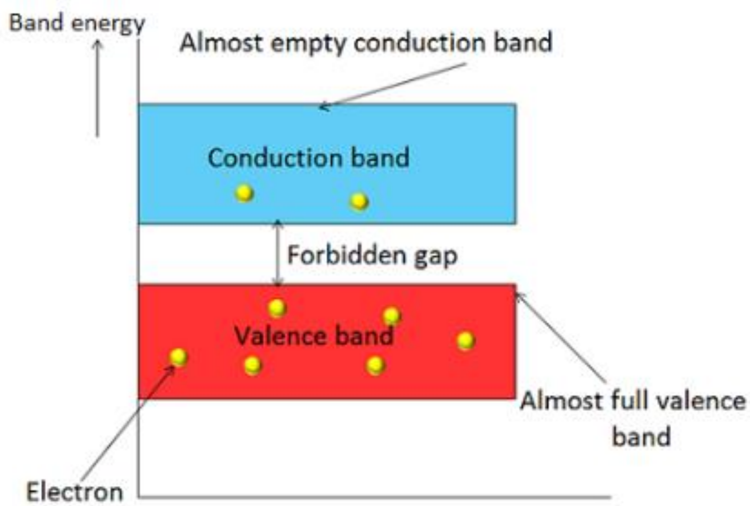

Figure 2.10: The movement of electrons from valence band to conduction band [27]

When the electron is excited as shown in Figure 2.10, from the initial energy bandgap to the higher energy bandgap, an electron-hole pair is formed. Then the electron-hole pair would recombine as usual and get back to its initial energy state. After the recombination of the electron-hole pair, it can be separated again by the help of semipermeable membranes that only allow either electron or photon to get through the membrane. The electron that separated and get into the membrane is the one that gives the electrical supply to lights up the bulb in Figure 2.11. [19].

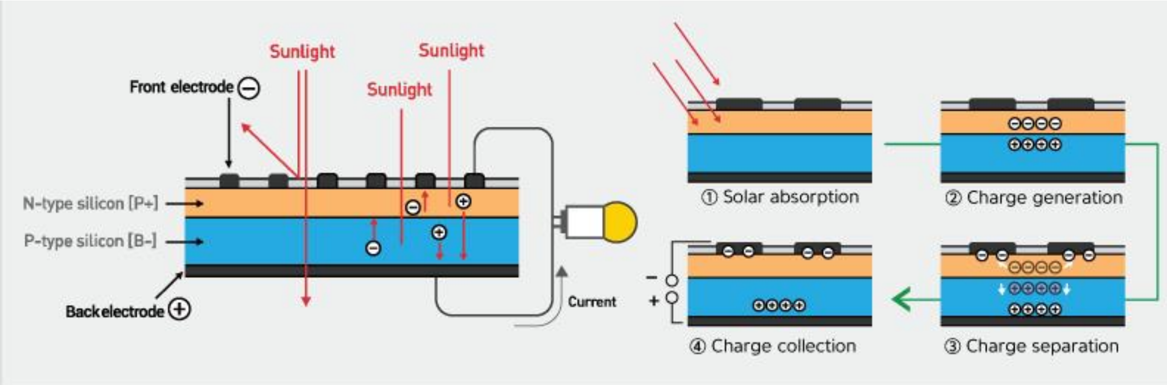

Figure 2.11: The separation of the electron-hole pair [28]

Finally, the separated electron will be moving out from the solar cell through the external circuit as shown in Figure 2.11 above and this is where the electricity is produced. Once the electron passed at the circuit, it will get back into the solar cell and combine with the hole. This process is repeated until the presence of sunlight on the solar cell. The produce charged is also stored in the battery for the future use. The losses that occur in this type of the solar cell is that single bandgap unable to transform photon where the energies are lower than the bandgap energies [19].

2.8 Multi Quantum Well Solar Cell

As discussed in the earlier, the ordinary solar cell as shown in Figure 2.12 below has a disadvantage that is unable to absorb the photons with a lower energy gap. There's where the idea of building up a multi-quantum well solar cell as the cross section shown in Figure 2.13 is generated as the idea is to reduce the losses occur in a basic solar cell thus increase its efficiency. The main goal of the Multi Quantum Well Solar Cell is to increase the short circuit current and also increase the absorption band of the p-i-n junction solar cell. The increase of short-circuit current is due to the higher absorption of a photon of lower energy in the lower bandgap quantum well. On the other hand, the open circuit voltage is decreased due to the high rate of recombination between the electron-hole pair in the quantum well. The idea of this quantum well was proposed by Barnham around the year of 1990, where it states that multi-quantum well is the lower bandgap material that is placed in between the two thick doped semiconductors [7].

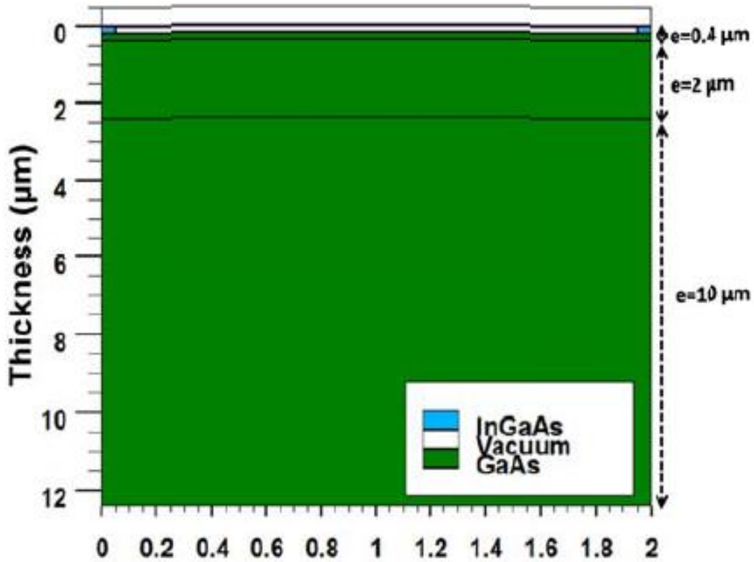

Figure 2.12: Standard p-i-n Solar Cell [7]

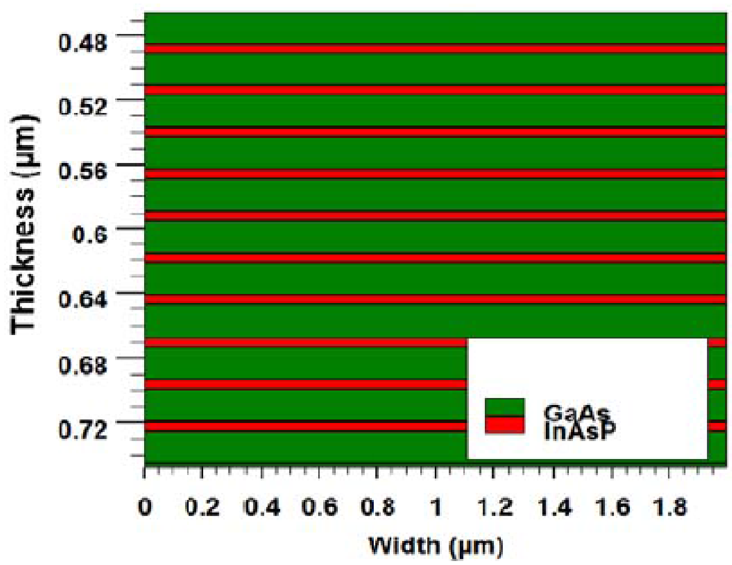

Figure 2.13: A Multi Quantum Well Solar Cell Structure with 10 Multi Quantum Well [7]

The figure above shows the structural diagram for both the ordinary solar cell and MQW solar cell. In can clearly notice that in the MQW solar cell, the quantum well that contain semiconductor substances is placed in the intrinsic region of the solar cell which can be view more clearly in energy-band diagram as in Figure 2.14. The quantum well placed would create a potential barrier and restrict charge carrier [7].

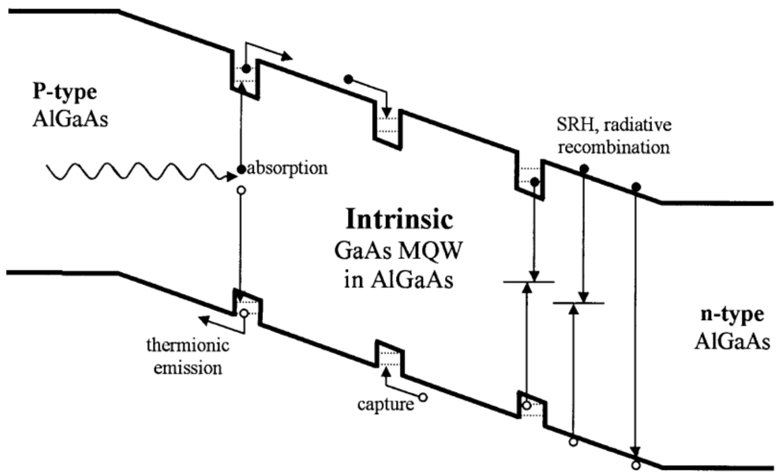

Figure 2.14: Energy Band Diagram of the MQW solar cell. [29]

The energy band diagram of the multi-quantum well solar cell that consist of three quantam well embedded in it. The formation of electron-hole pair occurs at the GaAs quantum well. The photoexcited carriers can get out from the well by thermionic emission or recombination. The escaped carrier is the hero of the MQW solar cell as it contributes to the formation of current in the AlGaAs region. The carrier that is failed to capture by any of the wells ends up being the contributor to the current density [20].

2.8.1 Quantum Well

Quantum well is a semiconductor material that is thin in size and has a potential energy lower than the material surrounding it. Semiconductor quantum well had given a new perspective in mechanics by Esaki and Tsu at the year 1970s. The quantum well is formed by a small band gap material is placed in between two later of higher [18]. As an example, the GaAs material is placed in between the AlAs material in the multi-quantum well solar cell to be designed in this project. This quantum well as shown in Figure 2.15 has the ability to trap the electron and hole then moving in any direction and convert it to a useful energy such as the electrical energy. All the process is influenced by the quantum well thickness and also the material type used.

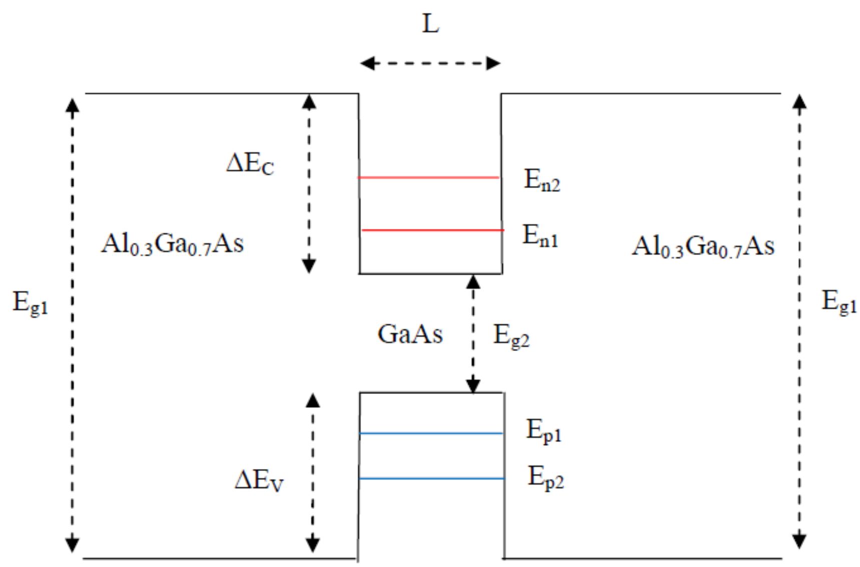

Figure 2.15: Band Diagram of the quantum well [24]

The Figure 2.15 above shows the quantum well energy diagram where it shows the quantum well is placed in between material of higher bandgap. In the well, the electron is allowed to move as their wish in the direction perpendicular to its growth. The quantized energy sub-bands is defined as:

$$E = E_n + \left(\frac{h^2}{2m^*}\right)\left(k_x^2 + k_y^2\right) \quad \text{(Eq. 2.8) [18]}$$

Where,

$$E_n = \left(\frac{h^2\pi^2}{2m^*}\right)\left(\frac{n}{L}\right)^2 \quad \text{(Eq. 2.9) [18]}$$

Discussing the energy-gap, in the quantum well, the energy gap wouldn't be the same as in some semiconductor material in bulk. This is because of the quantization occur at the z-direction as shown in Figure 2.16.

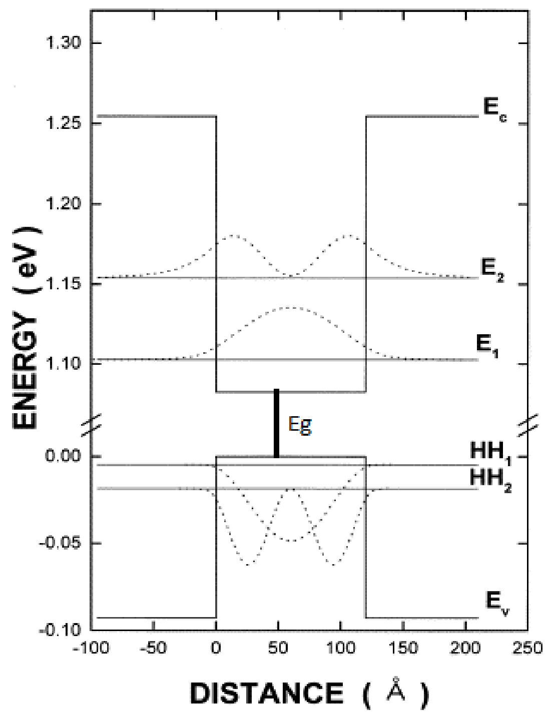

Figure 2.16: Energy Gap of Quantum Well [22]

The energy gap as shown in Figure 2.16 above of the quantum well is defined as:

$$E_{QW} = E_g + \frac{h^2\pi^2}{2m_eL^2} + \frac{h^2\pi^2}{2m_hL^2} \quad \text{(Eq. 2.10) [16]}$$

In designing the multiple quantam well as shown in Figure 2.17 below, the design method becomes complicated as the number of wells increases as well as other characteristics such as depth and height. A deeper the wells have the ability as a better wave-function confinement.

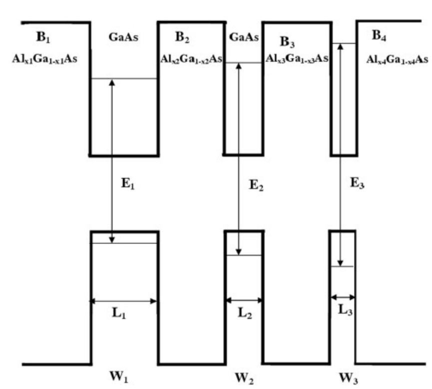

Figure 2.17: Multiple Quantum Well [22]

The barrier between the quantum well will also trap the electron and able to be collected from the material of lower bandgap. Meanwhile, the carrier distribution depends on the barrier thickness and temperature. Building a quantum well with both the InGaAs and InAIAs is quite difficult due to the material lattice mismatch. The structure with the thickness greater than the critical thickness causes the strain to relax thus enable dislocations which lead to drop in system energy. The insertion of InGaAs and InAIAs provides a strong confining potential of the conduction and valence band. Building a deep quantum well is also one of the methods to improve the way of InGaAs and InAIAs stacks [16].

2.8.2 Barrier

The barrier covered up the quantum well structure and it is also one of the important material should be taken into consideration in designing the MQW solar cell. This is because a larger bandgap of material should be chosen at the barrier to cover up the quantum well in order to trap the electron in a single direction. The quantum mechanical tunneling would occur in the quantum well in case the electron with a smaller energy than the barrier pass through the barrier and become the current flow. Besides, it should take into consideration that barrier thickness and transmission coefficient as shown in Figure 2.18 below is inversely proportional [16].

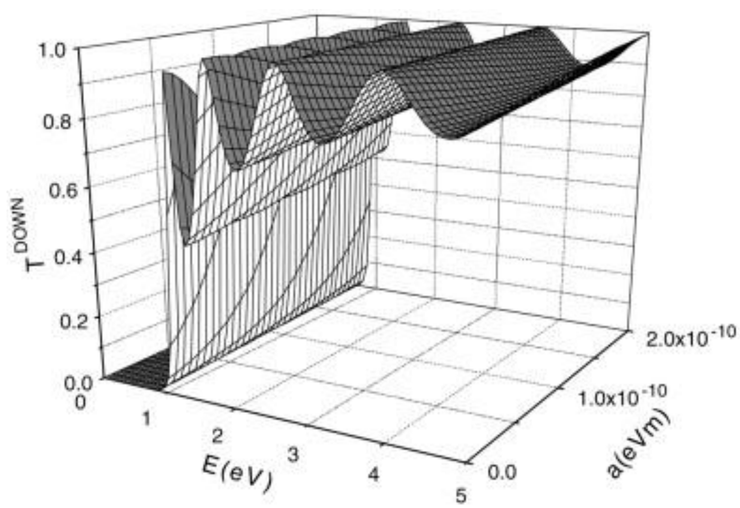

Figure 2.18: Transmission coefficient of the barrier [22]

On the other hand, the carrier distribution is influenced by the thickness of the barrier and also the temperature. The carrier flow increases as the temperature increase in the condition of having a thin barrier. Therefore, carrier flow is directly proportional to temperature but inversely proportional to the barrier thickness [16].

The thickness of the barrier,tb, and current density, J has a close relationship. As discussed earlier, the resonant tunneling current depends on the transmission probability, T [18]:

$$T \propto e^{-2Kt_b} \quad \text{(Eq. 2.11) [18]}$$

Wave vector inside the barrier is:

$$K = \sqrt{\left(\frac{2m_b V}{h^2}\right)} \quad \text{(Eq. 2.12) [18]}$$

Where, m_b is electron effective mass, h is the reduced Plank Constant and V is potential barrier. Therefore the barrier thickness is inversely proportional to transmission probability and current density [18].

2.8.3 Quantum Well Thickness

In the quantum well, the quantization energy can be formulated by:

$$E_n = \left(\frac{\hbar^2\pi^2}{2m_w t_w^2}\right) n^2 \quad \text{(Eq. 2.13) [18]}$$

m_w And t_w is the electron effective mass of the quantum well.

The quantization energy in a multi-quantum well is inversely proportional to the effective mass and reduction of quantum well thickness. In the process of decreasing the quantum well thickness, it could cause a few phenomenon to occur as the production of peak current will happen when the bias voltage is made higher under the first resonant energy level. Then the resonant tunneling increases together with the transmission coefficient. In