Influence of Mole Fraction, Front and Back Contact on the Photovoltaic Performance of $Al_xGa_{1-x}As$ / $Al_xIn_{1-x}As$ /$Ga_xIn_{1-x}As$ Heterojunction Solar Cell

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DECLARATION OF CANDIDATES

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Energy is essential to life, along with all living creatures. Energy is needed in every aspect of life. But, recently, the traditional sources of energy are going to extinct. That is why people are getting interested in renewable energy. Among all the sources of renewable energy sun is the best source. Solar energy can be collected from the Sun, and as long as the Sun lives, this energy can be produced. The total power of solar radiation touching the surface of the atmosphere immediately facing the Sun is approximately 1,360 watts per square meter. Solar cells can generate 15-20% of energy from this. In some cases, it can even hit 42%. In this thesis book, variation in the photovoltaic performance of $Al_xGa_{1-x}As/Al_xIn_{1-x}As/\ Ga_xIn_{1-x}As$ heterojunction solar cell has been studied by changing the mole fraction (x) and front and back contact parameter (PHIBO and PHIBL) of the solar cell. Simulations were done using the one-dimension(1D) simulation program '*Analysis of Microelectronic and Photonic Structures*' (AMPS 1D) software. With the help of this software light J-V characteristics curve was obtained for different combinations of alloy composition of the layer materials. Also, the effect of changing PHIBO and PHIBL on this curve (Under AM1.5G) was observed. For understanding the effect of mole fractions, three designs were made for different combinations of the mole fraction. Among these three designs, the best result was achieved for x = 0.8, 0.5, and 0.9 with 21.426% efficiency for top, middle and bottom layers. For this design, it was observed that the solar cell's photovoltaic performance by increasing PHIBO (keeping PHIBL constant) and PHIBL (keeping PHIBO constant). By increasing PHIBO and decreasing PHIBL, the performance got better and, the highest efficiency (30.435%) is for PHIBO = 2.3eV and PHIBL = 0.2eV among all the combinations. In this book, we have thoroughly discussed the process of our research and works.

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CHAPTER 1

1.1 Introduction

1.1.1 Renewable Energy

Renewable energy is energy produced from sources that are not depleting in human life. Wind, solar, geothermal, biomass and hydropower are some of the most common examples. It contrasts with non-renewable sources such as fossil fuels.

A renewable energy resource can be used repeatedly as it can be replaced naturally. It cannot be depleted and is capable of being an infinite stream of renewable energy. This means that the sources of this energy are alternative to the most widely used nonsustainable sources. A renewable resource has an everlasting supply, such as solar energy, wind energy. As there are plenty of natural sources of energy, also several renewable energy technologies are there. Generally, green energy technologies generate power, heat, or mechanical energy by transforming these services into electricity or power.

Although green energy is often thought of as emerging technology, natural energy has long been used for heating, shipping, illumination, and more. The wind-powered the ships to cross the seas and the windmills to ground the grain. The Sun provided warmth through the day and allowed the fires to last into the evening. But in the last 500 years or so, people have gradually become cheaper, dirtier sources of energy, such as coal and fragrant gas.

Renewable energy accounts for 13.5% of the world's overall energy consumption and 22% of its power supply[1].

1.1.2 Types of Renewable Energy

The most popular renewable energy sources are:

- Solar Energy
- Wind Energy
- Hydro Energy
- Tidal Energy
- Geothermal Energy
- Biomass Energy

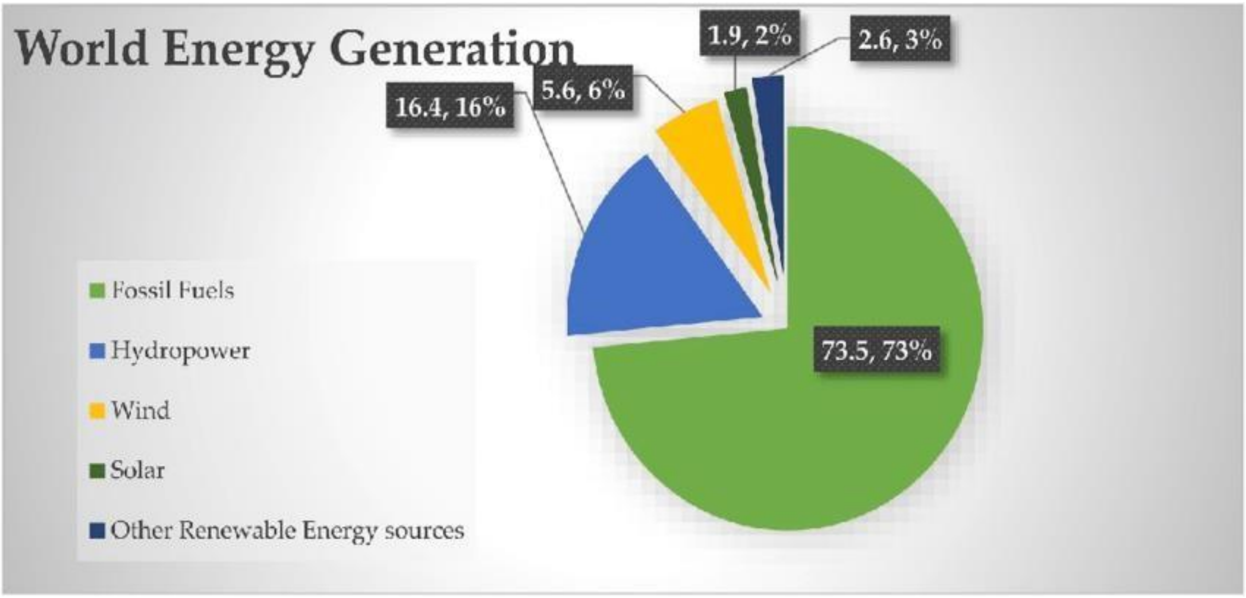

Figure 1: Approximate share of renewable energy sources.

1.2 Solar Energy

Sunlight is one of the most plentiful and easily accessible energy opportunities on our planet. The sum of solar radiation that hits the Earth's surface in one hour is more than the planet's overall energy needs for the whole year. While it seems like a great source of green energy, the amount of solar energy we will use depends on the time of day and the year's season.

The practical endlessness of sunshine is one of the advantages of solar energy. There is a continuous supply of solar energy with the equipment to exploit it, making fossil fuels obsolete. They are also improving public health and environmental standards by focusing on solar energy rather than fossil fuels. Solar energy can also lower energy costs in the long term and reduce energy bills in the short term. Several national, state, and federal governments often promote solar energy investment by offering rebates or tax credits.

Solar energy is used globally and is increasingly common for electricity production or heating and desalination of water. Solar power is being developed in two main ways:

- **Photovoltaics (PV),** often known as solar cells, are electronic instruments that directly turn sunlight into electricity. A typical solar cell is perhaps the picture that people would recall in the panels mounted on the houses and the calculators.

- **Concentrated solar power (CSP)** uses mirrors to concentrate the Sun's rays. These heatfluid rays produce steam to drive the turbine and generate electricity. CSP is used to produce electricity in large-scale power stations.

Figure 2: Solar energy

In this thesis book, we have shown the use of solar cells for utilizing solar energy.

1.2.1 Why Solar Energy

Using solar as a source of renewable energy offers significant advantages over other methods of energy generation, including the following:

- **A Clean and Renewable energy Resource:** Solar energy will never deplete. We can use this energy again and again, and it is a continuous source of clean energy.

- **An alternative to fossil fuels:** Solar energy is a big alternative to fossil fuels like coal, natural gas, oil. In the future, there may be a situation that fossil fuels will not be that much available. Then solar energy will become a huge alternative.

- **No environmental Pollution:** The burning of fossil fuels causes pollution of air and water. But in case of solar energy, it is entirely natural. There is no such issue of environmental pollution.

- **Low Maintenance Costs:** Once a solar cell is installed, it has a minimal maintenance cost as it has no moving parts.

- **Reduces electricity bills:** If we can use solar energy for our daily work not remaining fully dependent on utility power, we can reduce our electricity bill to a large extent.

- **Constantly advancing technology:** With the passage of time, many new technologies are continuously adding to this solar energy field.

1.3 Solar Cell

Solar cells, or photovoltaic cells, are an electrical system that converts light energy directly into electrical energy through a photoelectric effect, a physical and chemical phenomenon. This type of photoelectric cell, known as a device whose electrical properties, such as current, voltage, or resistance, vary once exposed to sunlight. Individual solar cell systems can be assembled to form modules, otherwise known as solar panels. A familiar single-junction solar silicon cell produces a maximum open-circuit voltage of approximately 0.5 to 0.6 volts[2]. Solar cells can be classified as photovoltaic, regardless of whether the source is sunlight or artificial light. In addition to generating electricity, it can be used as a photodetector (e.g., infrared detectors), detecting electromagnetic radiation near the visible spectrum or determining light intensity. The operation of a photovoltaic cell (PV) involves three basic characteristics:

- The emission of light by forming either electron-hole pairs or excisions.
- Division with carriers of different kinds of charges.
- Different extraction of these carriers into an external circuit. The solar panel, on the other side, supplies heat by absorbing sunlight for either direct heating or indirect electrical power generation from heat.

Solar cells are arranged into large groups called arrays, consisting of many individual cells, which will act as primary electrical power stations, turning sunlight into electrical energy for delivery to manufacturing, business, and residential consumers. Solar cells in much smaller configurations, commonly known as solar cell panels or solar panels, have been installed on top of buildings by homeowners to complement or upgrade their conventional electrical grid. Solar cell panels often provide electrical energy in many distant regional areas where traditional electrical energy supplies are either inaccessible or costly to install. Since they have no mechanical components that could require repairs or fuel to be refilled, photovoltaics cells provide electricity to many space installations, from communications and weather satellites to space stations. (Solar power is inadequate for space probes sent to the solar system's outer planets due to radiant radiation diffusion at a distance from the Sun.) Solar cells are also used for consumer products, such as electronic games, pocket calculators, and portable radios.

1.3.1 Solar Cell Structure And Operation

Solar cells have the same general structure, whether found in a central power station, a satellite, or a calculator. Light passes the system through an optical coating or antireflective film that reduces the leakage of light through reflection; essentially captures the light falling on the solar cell by facilitating its transfer to the energy-conversion layers below. The three energy-conversion layers underneath the anti-reflective layer are the upper junction layer, the absorption layer, the heart of the system, and the rear junction layer. Two extra electrical contact layers are required to bring the electrical current out to the applied loads and back into the cell, thereby completing the electrical circuit. The electrical interaction layer on the edge of the cell where light arrives is ordinarily present in some grid pattern. It is made of an intense conductor, such as a metal. Although the metal blocks are light, the grid lines are as narrow and closely spaced as practicable without affecting the cell's current set. The back electrical interaction layer does not have any opposite limits. It essentially functions as an electrical link and hence occupies the entire back surface of the cell structure. Since the back layer would still be a stable electrical conductor, it is often made of metal. Because much of the energy in sunlight and artificial light is within the visible spectrum of electromagnetic radiation, the solar cell absorber should be efficient at absorbing the radiation at these wavelengths. Materials that strongly absorb visible light belong to a class of substances known as semiconductors. Semiconductors with a depth of approximately one-hundredth of a centimeter or less will absorb all incident visible light; because the junction-forming and contact layers are much smaller, the solar cell's thickness is that of the absorber.

When the light hits on the solar cell, the absorber layer's electrons are excited from a lowenergy. They are attached to specific atoms in the material to a higher "active state" to pass across reliable. In the absence of intersection layers, these "free" electrons are in spontaneous motion, such that there is no oriented direct current. However, the introduction of intersection layers induces an integrated electrical field that develops a photovoltaic effect. In effect, the electrical field provides mutual momentum to electrons flowing past electrical touch layers through an external circuit to do productive work.

The materials used for the two intersection layers have to be different from the absorbing material to generate the built-in electrical field and bear the electrical current. They could either be different semiconductors (or the same semiconductor with various forms of conductivity), or they may be metal and semiconductor. The material for producing different solar cell layers is precisely The same as those used to produce solid state electronics and microelectronics diodes and transistors. Solar cells and microelectronic chips have the same fundamental technologies. However, in the manufacture of solar cells, one attempts to build a massive system since its power is proportional to the focal plane. In microelectronics, the aim is to develop nanometer-scale electronic components to improve their efficiency and running speed within semiconductor chips or integrated circuits.

1.3.2 Types of Solar Cell

Solar cells are commonly named for the semiconductor material they are constructed of. These materials may have unique properties to trap sunlight. Some cells are engineered to withstand sunlight that hits the Earth's surface, while some are adapted for space use. Solar cells are either one sheet of light-absorbing material or several physical arrangements to take advantage of different absorbing and load separating mechanisms. Solar cells are divided into the first, second, and third-generation cells. The firstgeneration cells known as organic, traditional, or wafer-based cells are made of crystalline silicon, a commercially prevalent PV technology that involves polysilicon and monocrystalline silicon. Second-generation cells are thin-film solar cells that comprise amorphous silicon, CdTe, and CIGS cells. They are economically significant in utilitarian photovoltaic energy plants, built-in photovoltaic systems, or small stand-alone power systems. The third-generation solar cells consist of a range of thin-film technologies that have still not been economically deployed. They are also in the phase of testing or production. People use organic ingredients, often organometallic substances and inorganic matter. While their efficiency was poor and the absorber material's performance was too low for industrial applications, much research is being invested in these technologies. They promise to achieve the target of manufacturing low-cost, highefficiency solar cells.

"First-generation" panels include silicon solar cells. They are made from a single silicon crystal (monocrystalline) or cut from a silicon block made up of many crystals (multicrystalline).

"Second-generation" thin-film solar cells are cheaper to manufacture than conventional silicon cells because they demand a reduced volume of building materials. As the name suggests, thin-film PV cells are mechanically thin technology that has been introduced to photovoltaics.

1.3.3 Applications of Solar Cell

Nowadays, the areas in which we can utilize solar cells are growing. By exploring innovative materials and next-generation technology, we enable solar cells throughout a wide variety of applications and places.

- **Solar farms:** Many acres of solar panels will supply utilitarian power—from tens of megawatts to more than one gigawatt of energy. These vast networks, using solar panels, provide electricity to local or provincial grids.

Figure 3: Solar Farm

- **Remote Locations:** It is often not cost-effective, easy, or practicable to expand transmission lines to places where electricity is required. Solar cells may be the solution for residential villages, villages in developed countries, lighthouses, offshore platforms, and distant medical centers.

Figure 4: Solar Cell in a remote location

- **Stand-Alone Power:** In rural or isolated places, solar cells can power stand-alone batteries, instruments, and meters. It will satisfy any need for electricity for parking lots, temporary street signs, emergency devices, wireless communications, flow gauges, external watchtowers, road lights, and much more.

Figure 5: Solar Cell for water irrigation pump

- **Power in Space:** From the outset, the solar cell has been the primary energy source for satellites. High-efficiency photovoltaics have provided fuel to projects including the International Space Station and land rovers on the surface of Mars. It will be an essential part of space and lunar discovery.

Figure 6: Solar Cell for power in space

- **Building-Related Needs:** In homes, solar panels installed on roofs or the surface will provide electricity. PV content may also be built into a building framework, such as walls, roof tiles, or cladding, to fulfill a dual function. Often, awnings and underground parking may be protected with a solar cell to provide shade and electricity.

Figure 7: Solar Cell facade building

- **Military Uses:** Lightweight, compact thin-film solar cells may support applications that are vital to robustness. Military personnel can bring portable PV for powering electronic devices on the field or at distant bases.

Figure 8: Solar Cell military uses

- **Transportation:** Solar cells can supply backup power to automobiles and vessels. Automotive sunroofs can have on-board energy PV or charging batteries. Lightweight PV may also be shaped as an airframe to support high-altitude power aircraft.

Figure 9: Solar-powered boat

1.4 Literature Review

Nowadays, traditional energy sources are going to an extinct. But, we need energy for our daily life. The primary sources of energy are coal, oil, biomass, nuclear, and so on. But the problem is we can't use these twice, and the amount of these sources is limited on the Earth. So, if we depend on these sources in the future, we may face a crisis on energy sources. That's why scientists concentrate on renewable energy sources like solar, wind, water, and so on. Solar energy is the most efficient and effective renewable energy source. To utilize this energy, people are working on solar cells. Researchers have developed the main configuration of solar cells and now working on increasing efficiency. In the future, people will depend on solar energy as the other sources of energy are going to extinct soon. Among all the solar cell heterojunction types, solar cells have attracted much attention because of their high efficiency. Till now, the highest efficiency is 23.5% for c-Si heterojunction solar cells [3]. People are recently interested in III-V ternary alloy materials because they offer greater flexibility for optimizing efficiency. So far, the highest efficiency for ternary alloy heterojunction solar cell[4] is 21.39%. It was gained by changing the mole fraction of "$Al_xGa_{1-x}As$/ $Al_xIn_{1-x}As$/ $Ga_xIn_{1-x}As$" composition. Front and back contact play a vital role in improving solar cells, which is not mentioned in that particular research. A solution has been proposed to enhance efficiency by changing the front and back contact material's work function.

1.4.1 Existing Problem

The highest efficiency of the solar cell is now 23.5% which is not satisfactory. With this efficiency, we can't depend on solar energy. And also, very few have worked on three-layer ternary alloy heterojunction solar cells. So, it is new in this field, and the researcher could not reach these solar cells' potential.

1.5 Thesis Objectives

- Showing the influence of mole fraction on the photovoltaic performance of heterojunction solar cells.
- Showing the effect of the front and back interaction parameters on the efficiency of solar heterojunction cells.
- Achieving an improved efficiency by setting the suitable value of the front and back contact work function.
- Optimizing for design performance and target reliability.

1.6 Thesis organization

This thesis is intended to show the influence of mole fraction, front and back contact parameters on the photovoltaic performance of a heterojunction solar cell.

- In **chapter 2**, the Methodology of our work with the heterojunction solar cell, structure of the solar cell, and the parameters used for the simulation are described.
- In **chapter 3**, Software (AMPS 1D) implementation of different designs and the simulation process are discussed.
- In **chapter 4**, the results and outputs of different simulation designs are compared and discussed.
- In **chapter 5,** the conclusion is made on the thesis, which ends with the future scopes of study.

CHAPTER 2

2.1 Heterojunction Solar Cell

Heterojunction solar cells are composed of at least two different materials: semiconductors, semiconductors, a metal, semiconductor, and electrolyte. We will consider the first of these three types.
A photovoltaic cell combines two functions that permit the conversion of photon flux to electric power:

(i) Numerous semiconductors efficiently absorb solar radiation;
(ii) A space charge can be introduced in a semiconductor when made into a diode.

All types of solar cells rely on the light absorption properties of semiconductors. The absorption process of interest here occurs through an electron's excitation from the valence to the conduction band.

Heterojunction solar cells incorporate two related innovations as one cell: a crystalline silicon cell covered by two layers of indistinct "thin-film" silicone. These technologies allow for more resources to be processed relative to the use of either technology alone.

The most popular form of solar cells is constructed of either monocrystalline or polycrystalline silicon. Silicon crystals are formed into blocks and then sliced into thin sheets, typically with a diamond wire tool, to shape single cells.

A less popular kind of solar cell is a thin film composed of different materials, and one of those is amorphous silicon. Unlike crystalline silicon, amorphous silicon does not have a standard crystalline form. Instead, the molecules of silicon are ordered arbitrarily.

By itself, amorphous silicon is less effective in turning sunlight into electrical energy. It does, however, benefit from less expensive processing. This reduced cost and stability in the form of materials on which amorphous silicon can be deposited are several essential benefits.

Traditional crystalline silicon sandwiched with heterojunction solar cells has amorphous silicon deposited on its front and back surfaces. This results in a few thin-film solar layers that absorb additional photons that the central crystalline silicon wafer might not absorb.

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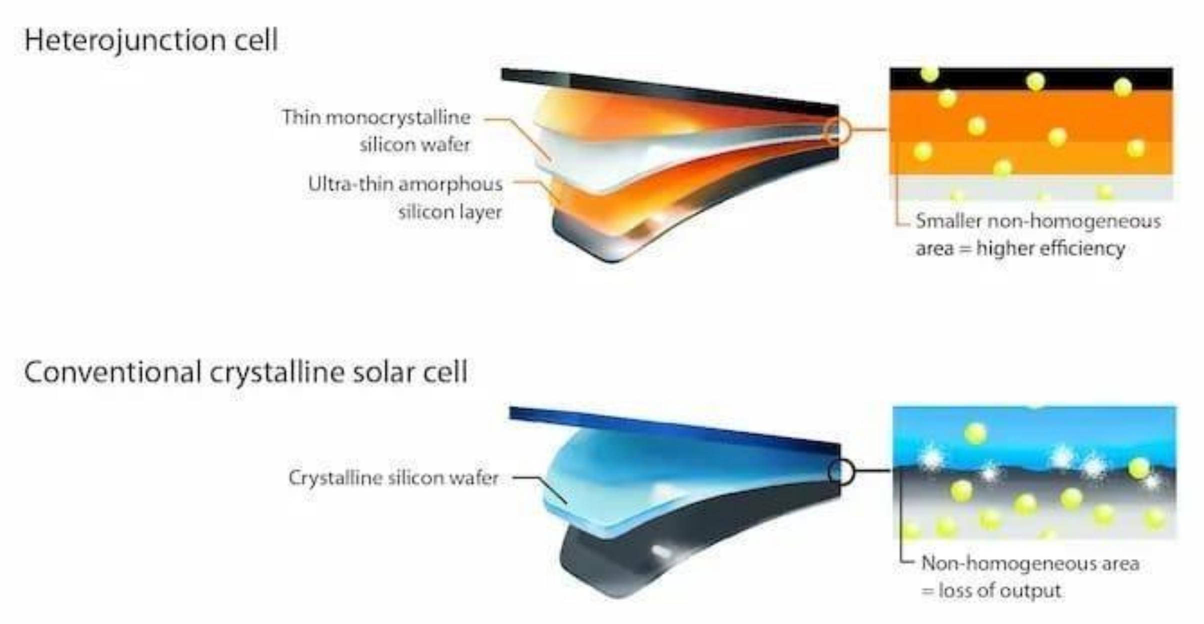

Figure 10: Diagram of heterojunction solar cell

2.1.1 Efficiency of Heterojunction Solar Cell

The performance of the solar panel applies to how much light a solar cell transforms into electricity. The better the efficiency, the more energy we're going to get from the panel with the same amount of light. It can be an essential function for rooftop installation with a small capacity.

Efficiency has been slowly rising over the years as factories continue to find strategies to get more energy from the same amount of sunshine. Although each technology has hit its limits, scientists and researchers continue to find new ways of keeping productivity rising in their arsenal of tricks.

One of the new developments in the world of commercial solar panels is heterojunction solar cells.

A solar cell is composed of a thin material that absorbs a portion of the sunlight that reaches it. It is not entirely invisible. However, some sunlight passes straight through the cell, and some of it even bounces off the floor.

Heterojunction solar technology takes advantage of this by constructing a solar panel of three separate photovoltaic material layers. The middle layer of monocrystalline silicone performs much of the job of converting sunshine into electricity.

There is a topmost part of amorphous thin-film silicon that captures some sunlight until it reaches the crystalline layer, and it even absorbs some sunlight that mirrors the layers below. It is tiny because much of the sunlight is passing in. And even so, it provides sufficient additional energy to make the extra expense worthy.

There is another thin-film coating on the rear of the crystalline silicon. It absorbs the sunlight passing across the first two layers. If the panel is a glass-on-glass type with a translucent rear panel, this thin-film coating can add a large amount of energy due to sunlight reflecting from the Earth.

The heterojunction solar panel will improve 21% or more efficiencies by constructing a sandwich sheet with three separate photovoltaic layers. This is equivalent to panels using various systems to improve performance.

2.1.2 Advantages of Heterojunction Solar Cell

The key benefits of heterojunction solar cells over traditional crystalline silicon cells are:

- Higher efficiency.
- Potentially reduced costs compared to other methods used to increase efficiency.
- Lower coefficient of temperature.

The heterojunction panels' quality currently ranges from 19.9% to 21.7%, with the latest HJT panels from REC Solar[5]. In addition, some methods used by manufacturers to achieve too high efficiency may be more expensive.

HJT panels can have an edge in their high-temperature efficiency since they are less efficient at extreme temperatures. It is a well-known occurrence.

One benefit of thin-film solar is, it has a higher coefficient of temperature than crystalline silicon. This means that high temperatures have a lower effect on thin-film than typical crystalline silicon.

With two thin-film silicone membranes, heterojunction panels benefit traditional solar panels by retaining high efficiency as temperature increases.

2.2 Methodology and Simulation Model

2.2.1 $Al_xGa_{1-x}As$/ $Al_xIn_{1-x}As$/ $Ga_xIn_{1-x}As$ Heterojunction Solar cell

In modern days, energy has become a serious problem due to shortages and environmental pollution caused by fossil fuels. To solve this problem, researchers are focusing on renewable energy sources like hydropower, biomass, solar, wind. Among these sources, solar energy [3] is the best of all solutions as this energy has no impact on environmental pollution and also clean and renewable. The best way to use solar energy is the solar cells. Nowadays, many high-efficiency solar cells are heterojunction. We used III-V ternary alloys [4] for the heterojunction solar cells component as materials as we could vary the bandgap by changing the alloy composition. We worked with $Al_xGa_{1-x}As$, $Al_xIn_{1-x}As$, and $Ga_xIn_{1-x}As$ as top, middle, and bottom layers among the ternary alloys. Changing the molar fraction x from 0.1 to 0.9, we varied the alloy composition of all three layers. The energy gap compositions also varied due to this change. There is a transition point for the top layer ($Al_xGa_{1-x}As$) and the middle layer ($Al_xIn_{1-x}As$). After which, the material becomes direct bandgap [6] material from indirect bandgap material. But the bottom layer ($Ga_xIn_{1-x}As$) is direct bandgap material for all values of x.

Figure 11: Schematic Diagram of $Al_xGa_{1-x}As$/ $Al_xIn_{1-x}As$/ $Ga_xIn_{1-x}As$ Heterojunction solar cell

Table 1 shows the alloys according to the layer with layer thickness, molar fraction range, bandgap range, and transition point. [7]

Layer	Alloy Composition	Layer Thickness (µm)	Doping Type	Molar Fraction Range	Energy Gap Range (eV)	Transition Point
Top	$Al_xGa_{1-x}As$ [5]	0.01	n-type	x = 0.1 - 0.9	1.55 – 2.13	x = 0.45
Middle	$Al_xIn_{1-x}As$ [6]	100	p-type		0.5 – 2.05	x = 0.65
Bottom	$Ga_xIn_{1-x}As$ [7]	3	p-type		0.43 – 1.28	Direct bandgap material. No transition point

Table 1: Alloys according to the layer with layer thickness, molar fraction range, bandgap range, and transition point.

After designing the solar cell for the highest efficiency in molar fraction, we focused on the front and back contact as it significantly impacted the solar cell's efficiency. We worked with the work function (φ) among the front and back contact parameters [8]. Which is φ_{bO} (PHIBO) for front contact and φ_{bL} (PHIBL) for back contact. For a suitable combination of these two parameters, we found the highest efficiency.

2.2.2 Why This Material

We have used III-V ternary alloys, which are $Al_xGa_{1-x}As/Al_xIn_{1-x}As/Ga_xIn_{1-x}As$ for heterojunction solar cells. Because:

- Bandgap energy can be significantly varied by changing their alloy compositions.
- Various optical properties like absorption coefficient, refractive index. It can be varied.
- As constituents of solar cells, ternary alloys can offer great flexibility for optimization towards higher efficiency.

2.2.3 Photovoltaic performance of $Al_xGa_{1-x}As$/ $Al_xIn_{1-x}As$/ $Ga_xIn_{1-x}As$ Heterojunction Solar cell

The overall photovoltaic performance of a heterojunction solar cell depends on the following factors:

- Open circuit voltage (V_{oc})
- Short circuit current density (J_{sc})
- Fill Factor (FF)
- Efficiency (η (%))

- **Open circuit voltage (V_{oc}):** The open-circuit voltage, V_{oc}, is the highest voltage available from the solar cell, which exists at zero current. The open-circuit voltage refers to the sum of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is seen in the IV curve below.

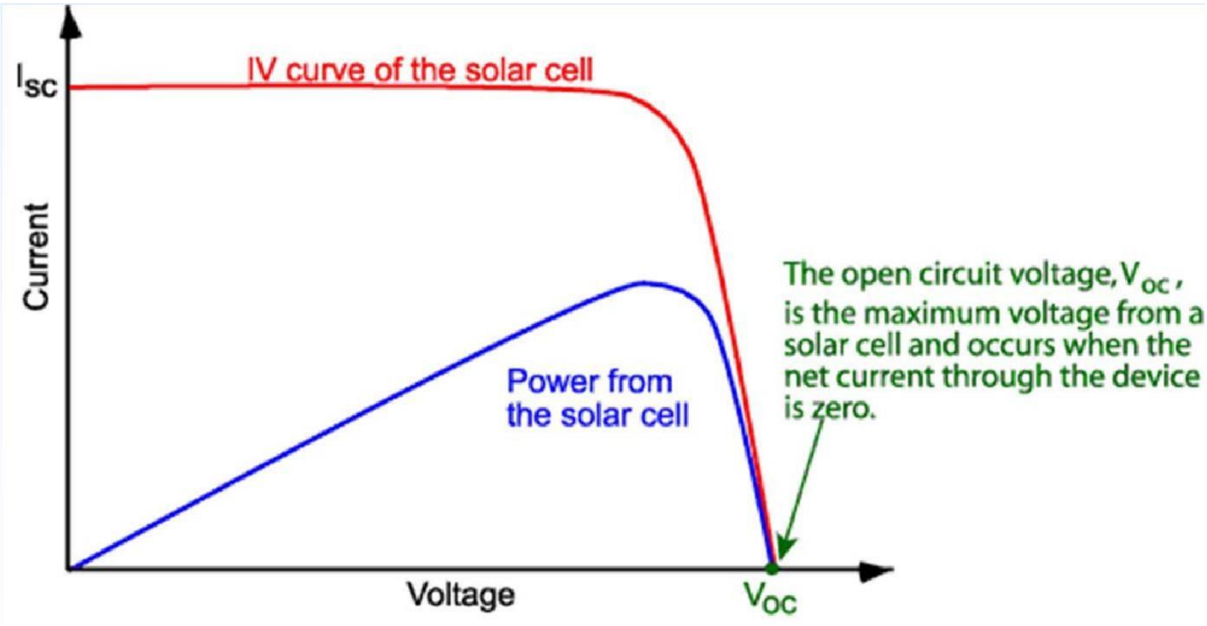

Figure 12: Open Circuit voltage of a solar cell

- **Short circuit current density (J_{sc}):** The short-circuit current (I_{sc}) is the current across the solar cell when the voltage is zero through the solar cell (i.e., when the solar cell is short-circuited). The density of this current is called the short circuit density of the current (J_{sc}). Typically written as Isc, the short-circuit current is seen on the IV curve below..

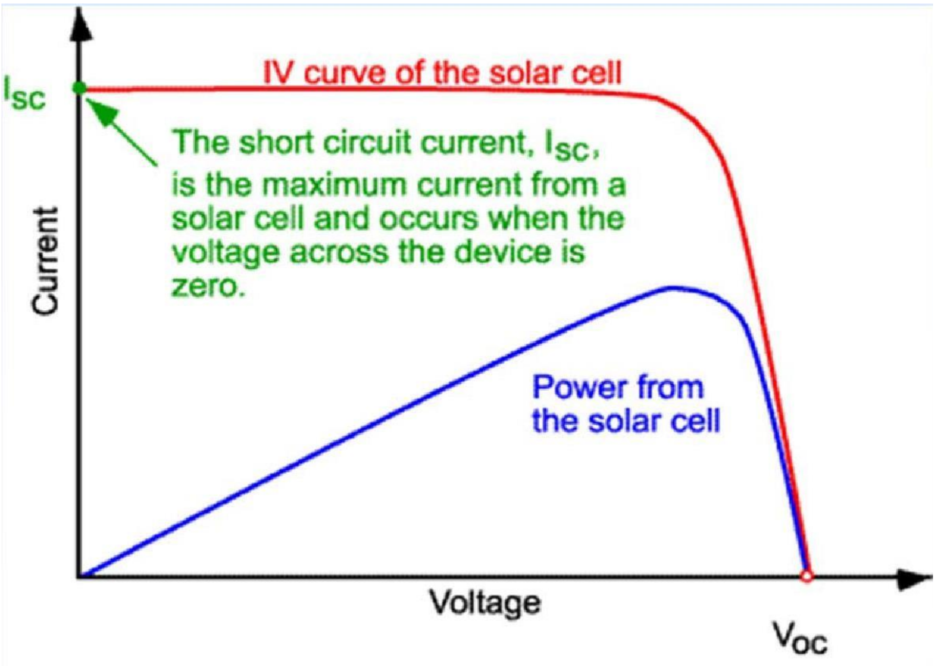

Figure 13: Short Circuit current of a solar cell

- **Fill Factor (FF):** At both of the operating points corresponding to I_{sc} and V_{oc}, the solar cell's power is zero. The "fill factor" (FF) is the parameter that, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. Fill factor is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. Graphically, the FF is a measure of the "squareness" of the solar cell and is also the largest rectangle area that will fit in the IV curve. The FF is illustrated below:

$$\text{Fill Factor, FF} = \frac{P_{mp}}{V_{oc} \times I_{sc}} = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}}$$

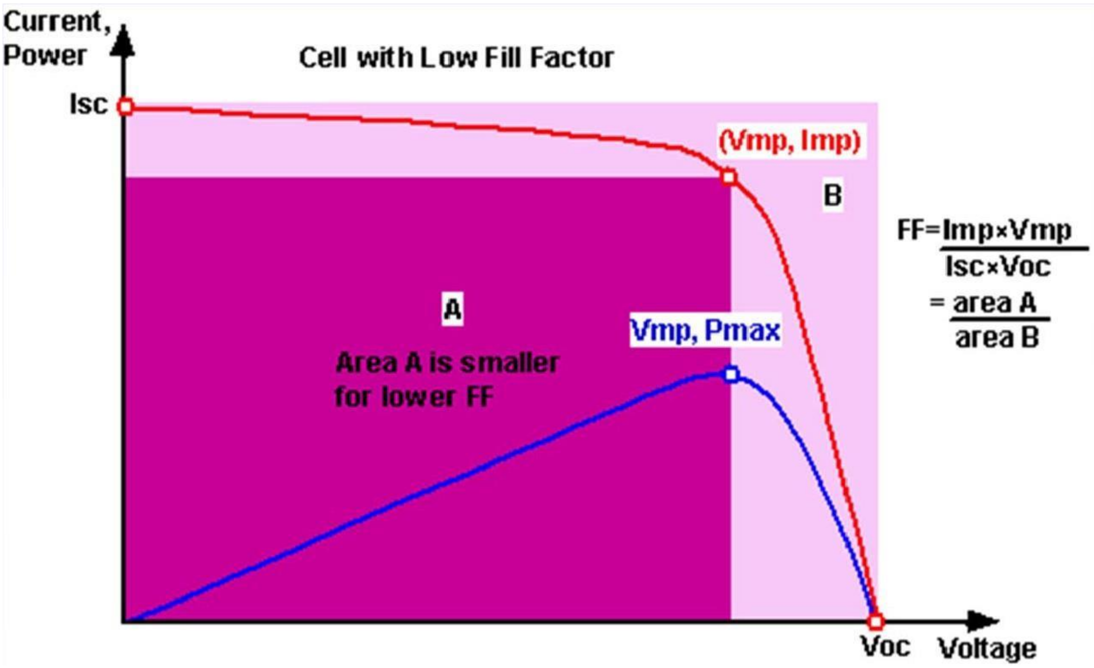

Figure 14: Fill Factor of a solar cell

Graph of cell output current (red line) and power (blue line) as a voltage function. Also shown are the cell short-circuit current (Isc) and open-circuit voltage (Voc) points, as well as the maximum power point (Vmp, Imp).

- **Efficiency:** The efficiency of a solar cell, also known as the power conversion efficiency(PCE), represents the ratio of the output electrical power at the maximum power point on the IV curve and the incident light power – typically using a standard AM1.5G simulated solar spectrum. It is determined as the fraction of incident power which is converted to electricity and defined as:

$$\text{Efficiency, } \eta = \frac{P_{out}}{P_{in}} = \frac{V_{mp} \times I_{mp}}{P_{in}} = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}}$$

Where,
V_{oc} is the open-circuit voltage;
I_{sc} is the short-circuit current;
FF is the fill factor; η is the efficiency.

2.2.4 Working Process

We followed some steps for doing the simulation of our heterojunction solar cell. For simulation purposes, we used the software AMPS - 1D.

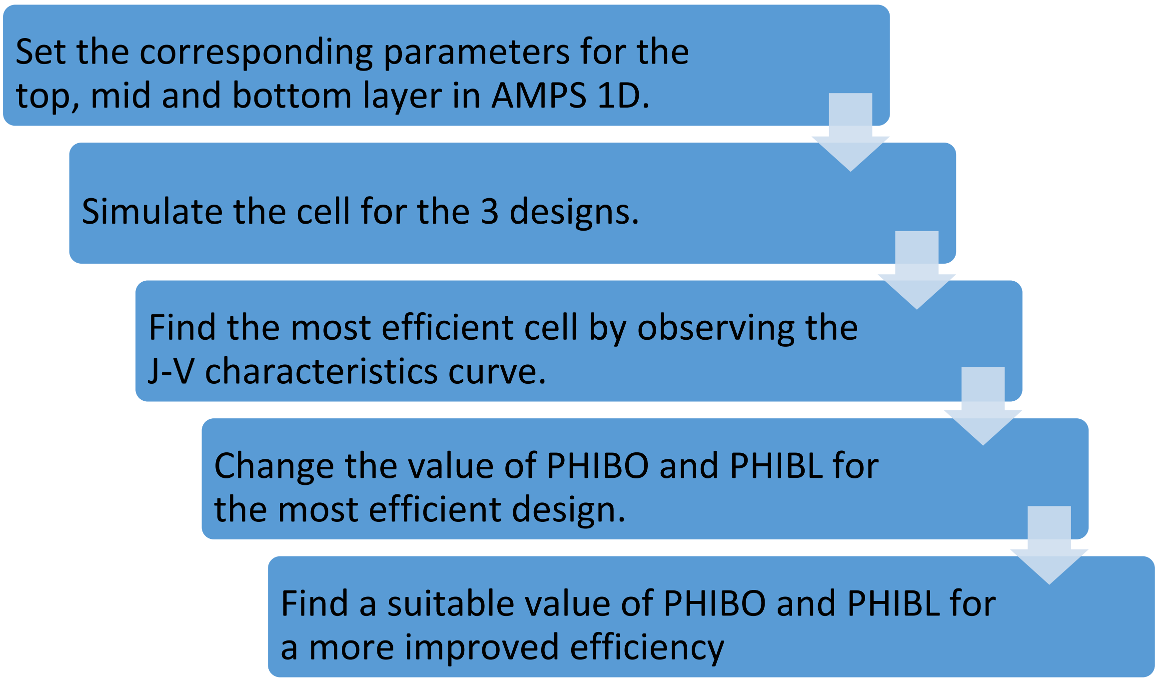

Figure 15: Working Process

Using the AMPS – 1D software, we made three designs of $Al_xGa_{1-x}As/Al_xIn_{1-x}As/Ga_xIn_{1-x}As$ heterojunction solar cell. We took the different mole fraction (x) values for the top, middle, and bottom layers for three different designs. Simulations were conducted for these designs with their respective parameter values, and the light J-V characteristics curves were obtained under AM1.5G solar spectrum. We can observe the open-circuit voltage (V_{oc}) and short circuit current density (J_{sc}) from these curves. We also got the value of Fill Factor (FF) [9] and efficiency (η) using the following equations respectively:

$$FF = \frac{P_{mp}}{V_{oc} \times I_{sc}} = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} =$$

$$\eta = \; = \frac{V_{mp} \times I^{mp}}{} = V_{oc} \times I_{sc} \times FF \; \frac{}{P_{out}}$$

Pin Pin Pin

28

Here ,

V_{oc} = Open circuit voltage (V)
J_{sc} = Short circuit current density (Am^{-2})
FF = Fill factor

Thus, by analyzing these values (V_{oc}, J_{sc}, FF), we can compare our three designs' photovoltaic performance and understand the effect of mole fraction (x) on their performance. Later on, among the three designs, we analyzed the effect of front and back contact parameters (φ_{bO} and φ_{bL}) on the third design for which we got the highest efficiency. PHIBO is the difference between the work function of the front contact and the semiconductor's electron affinity. Similarly, PHIBL is the difference between the back contact's work function and the associated semiconductor's electron affinity. We have mainly analyzed the effect of changing the PHIBO and PHIBL on solar cell performance.

2.3 Different Parameters and Their Values for Simulation

PHIBO is the difference between the front interface's work function and the corresponding semiconductor's electron affinity. Similarly, the PHIBL is the contrast between the work function of the back interface and the electron affinity of the corresponding semiconductor.

Contact parameters	Description
PHIBO (φ_{bO})	$E_c - E_f$ at x = 0 (eV)
PHIBL (φ_{bL})	$E_c - E_f$ at x = L (eV)

Table 2: Front and back contact's boundary condition of AMPS-1D

Surface recombination can have a major impact both on the short-circuit current and on the open-circuit voltage. High recombination rates at the top surface have a significantly detrimental impact on the short-circuit current. The top surface also corresponds to the highest generation region of carriers in the solar cell. A measure of recombination rate between electrons and holes at the surface of a semiconductor, equal to the component of the electron or hole current density normal to the surface divided by the excess electron or hole volume charge density close to the surface.

Contact Parameters	Values (cm/sec)	Description
SNO (front contact)	$1X10^7$	Electrons at x = 0 interface
SPO (front contact)	$1X10^7$	Holes at x = 0 interface
SNL (back contact)	$1X10^7$	Electron at x = L interface
SPL (back contact)	$1X10^7$	Holes at x = L interface

Table 3: AMPS-1D surface recombination speed

Here, SNO and SPO are the surface recombination speed of the front contact electrons and holes. Similarly, SNL and SPL are the surface recombination speed of the back contact electrons and holes.

The reflection coefficient is a parameter that describes how much light is reflected by an impedance discontinuity in the transmission medium. Every semiconductor material has its reflection co-efficient, and this value is the indicator that how much of the incident light will be reflected by the material.

Contact Parameter	Values	Description
RF	0.01	Reflection coefficient at x = 0
RB	0.99	Reflection coefficient at x = L

Table 4: Reflective coefficient for light impinging on the front and back surfaces.

Here, RF 0.01 means that the front contact can reflect 1% of the incident light, and RB 0.99 means that the back contact can reflect 99% of the incident light.

Now we will discuss about some general parameters and their values for the simulation purpose in AMPS-1D. We have used some properties of the layer materials as the input of the simulation. These properties are briefly discussed below:

- **Relative Permittivity:** The relative permittivity known as the dielectric constant indicates how easily a material can become polarized by an electric field's imposition on an insulator. Relative permittivity is the ratio of the permittivity of a substance to the permittivity of space or vacuum.

Relative permittivity can be expressed as,

$\varepsilon_r = \varepsilon / \varepsilon_0$

where,

ε_r = Relative permittivity - or dielectric constant

ε = permittivity of substance ($C^2/(N\ m^2)$)

ε_0 = Permittivity of vacuum or free space ($8.854187817 \times 10^{-12}\ C^2/(N\ m^2)$)

- **Electron and Hole Mobility**: Electron mobility describes how fast an electron will pass via a metal or semiconductor when forced through an electrical field. There is an equivalent amount of holes, called hole mobility. In particular, the term carrier mobility corresponds to both electron and hole mobility.

  Electron and hole mobility are special electrical mobility cases of charged particles in the fluid under the electrical field. As an electrical field E is applied over a piece of metal, the electrons respond by traveling at an average velocity called drift velocity.

  For electrons, $V_n = \mu_n E$

  So, $\mu_n = V_n / E$

Where,

V_n = Drift velocity of electrons

μ_n = Mobility of electrons

E = Applied electric field

For holes, $V_p = \mu_p E$

So, $\mu_p = V_p / E$

Where,

V_p = Drift velocity of holes

μ_p = Mobility of holes

E = applied electric field

- **Acceptor or Donor Concentration:** In a pure semiconductor, the electron concentration in the conduction band and the hole concentration in the valence band are usually minimal compared to the number of available energy states. These concentrations can be changed by many orders of magnitude by doping, which means adding to a semiconductor impurity atoms that can "donate" electrons to the conduction or "accept" electrons from the valence band, creating holes. Both donors and acceptors are referred to as dopants. The concentration of these dopants is called acceptor and donor concentration.

- **Effective Density of States in the Conduction and Valance Band:** The effective density of states (DOS) in the conduction and the valence bands are expressed by the following theoretical expressions:

$$N_c = 2 \,.\, M_c \,.\, (2 \,.\, \pi \,.\, m_n .\, k_B .\, T_L / h_2)_{3/2}$$

$$N_v = 2 \,.\, (2 .\, \pi .\, m_p .\, k_B .\, T_L / h_2)_{3/2}$$

Where M_c represents the number of equivalent energy minima in the conduction band.

Properties	$Al_xGa_{1-x}As$	$Al_xIn_{1-x}As$	$Ga_xIn_{1-x}As$
Relative Permittivity, EPS	12.8	12.14	14.45
Electron Mobility, μ_n (cm^2/V-s)	205.8	1050.24	7222
Hole Mobility, μ_p(cm^2/V-s)	96.4	514.1	960.76

Acceptor or Donor concentration (cm^{-3})	1 x 10^{19}	1 x 10^{16}	1 x 10^{19}
Effective density of states in the conduction band (cm^{-3})	1.54 x 10^{19}	2.8 x 10^{18}	2.36 x 10^{18}
Effective density of states in the valance band (cm^{-3})	1 .03x 10^{18}	1.01 x 10^{17}	1.02 x 10^{17}

Table 5: Specific parameters[10],[11],[12] used to simulate the AMPS-1D solar cell.

Front Contact	Back Contact
PHIBO = 1.54 eV	PHIBL = 0.2 eV
SNO = 1X10^{7}	SNL = 1X10^{7}
SPO = 1X10^{7}	SPL = 1X10^{7}
RF = 0.01	RB = 0.99

Table 6: The values of front and back contact parameters.

The temperature of 300K was used as default, and AM1.5 illuminations have been used to obtain all the data. When we changed the mole fraction (x), the layer materials' bandgap energy was also affected. Changes in electrical properties are marginal. So we took almost the same meaning for all the layers.

Air mass (AM) is defined as the direct sunbeam's path length through the atmosphere expressed as a ratio relative to the Sun at the zenith (a zenith is an imaginary point directly above a particular location). The more atmosphere sunlight passes through, the greater the attenuation. Air Mass 0 indicates that the sunlight has not interacted with any of the Earth's atmosphere.

AM1.5 atmosphere thickness represents a zenith angle of z=48.2°.

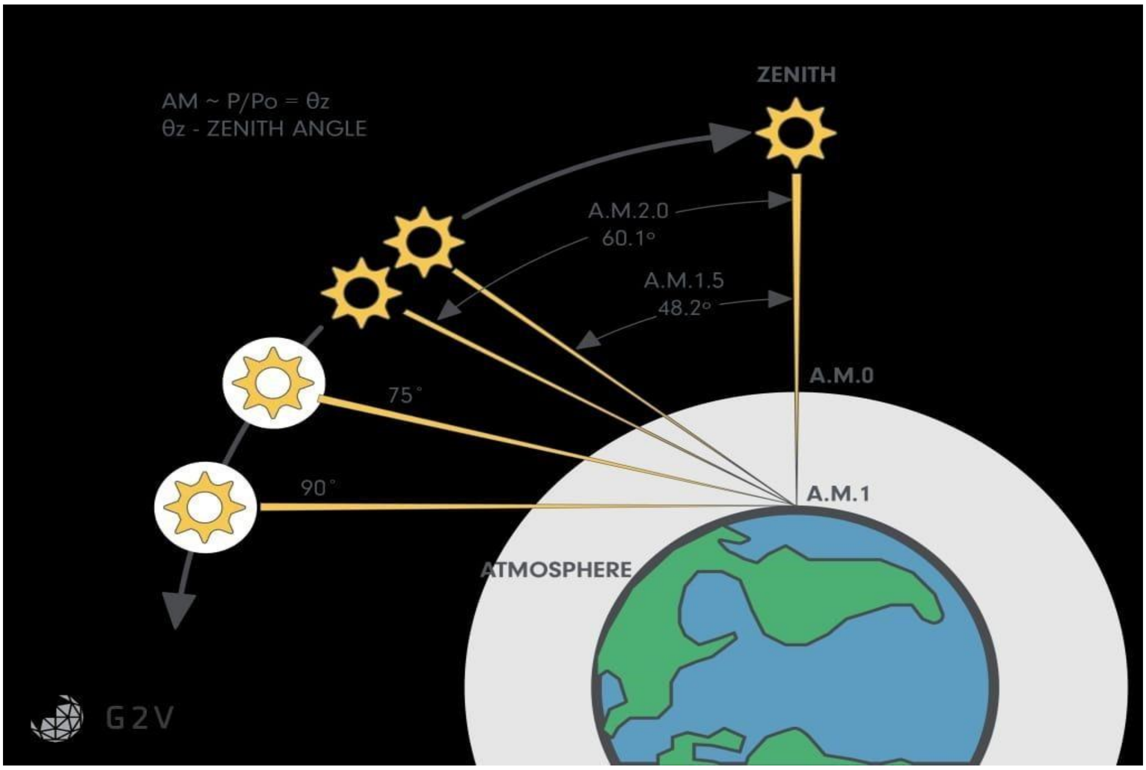

Figure 16: Air Mass and Zenith angle

CHAPTER 3

3.1 Software Preface

Simulations were done using the one-dimension (1D) simulation program 'Analysis of Microelectronic and Photonic Structures' (AMPS 1D). We simulated all the solar cell designs and checked the front and back contact parameter's influence using this software. We get the output values numerically and also graphically from this software.

3.1.1 About The Software

AMPS stands for Analysis of Microelectronic and Photonic Structures. It was engineered to be a very general and versatile computer simulation tool for analyzing device physics and device design. It is a one-dimensional (1-D) device physics code that applies to any twoterminal device. It can be for diode, sensor, photo-diode, and photovoltaic device analysis.

The AMPS-1D PC program is now used by over 70 groups worldwide for detector and solar cell analysis. It has proved to be a powerful tool in understanding device operation and physics for single crystal, polycrystalline and amorphous structures.

This software can simulate the output characteristics of hetero-structured semiconductor devices. We can compute dark I-V characteristics, light I-V characteristics, and solar cells' efficiency (or any other two-terminal device) with this software.

Figure 17: 'Analysis of Microelectronic and Photonic Structures' (AMPS 1D).

3.1.2 Why AMPS-1D

AMPS-1D is used for cell and detector layout, material sensitivity tests, and parameter collection. Optimum configuration and light and voltage bias conditions can also be determined in the material extraction parameter feature.

Many successful simulations of different solar cells are done using this software. For comparing and analyzing the photovoltaic performance of different solar cells, this software is widely used. We can get the output both numerically and graphically from this software.

3.2 Simulation Process

We need to follow some steps for the simulation. At first, we have to open a new case. After opening a new case, we get the following window:

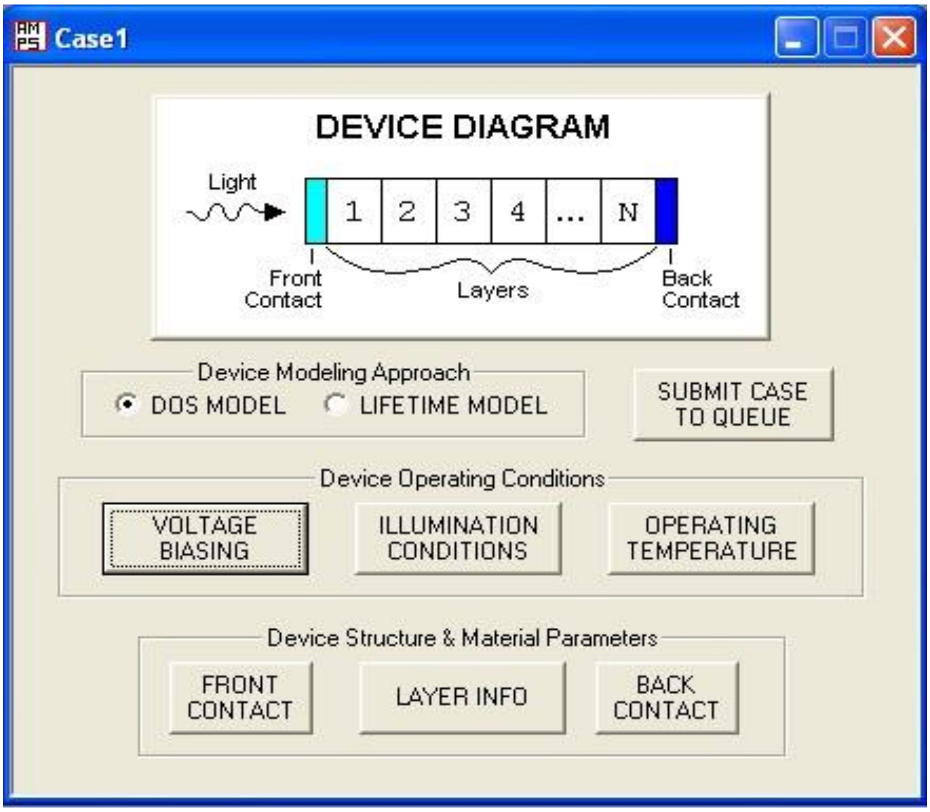

Figure 18: Opening a new case.

We have to select the DOS Model. From the window, we can see that there are three operating conditions:

- Voltage Biasing
- Illumination Conditions
- Operating Temperature

Under all these operating conditions, there are some parameters. We have to find out those parameter values for a particular material. Also, some calculations are required here.

Under device structure and material parameters, there are three sections:

- Front Contact
- Layer Info
- Back Contact

We have to set all the parameter values under each section for the simulation. Now we will discuss about all these parameters and their values step by step:

- **Voltage Biasing:** In voltage biasing, we get the following window:

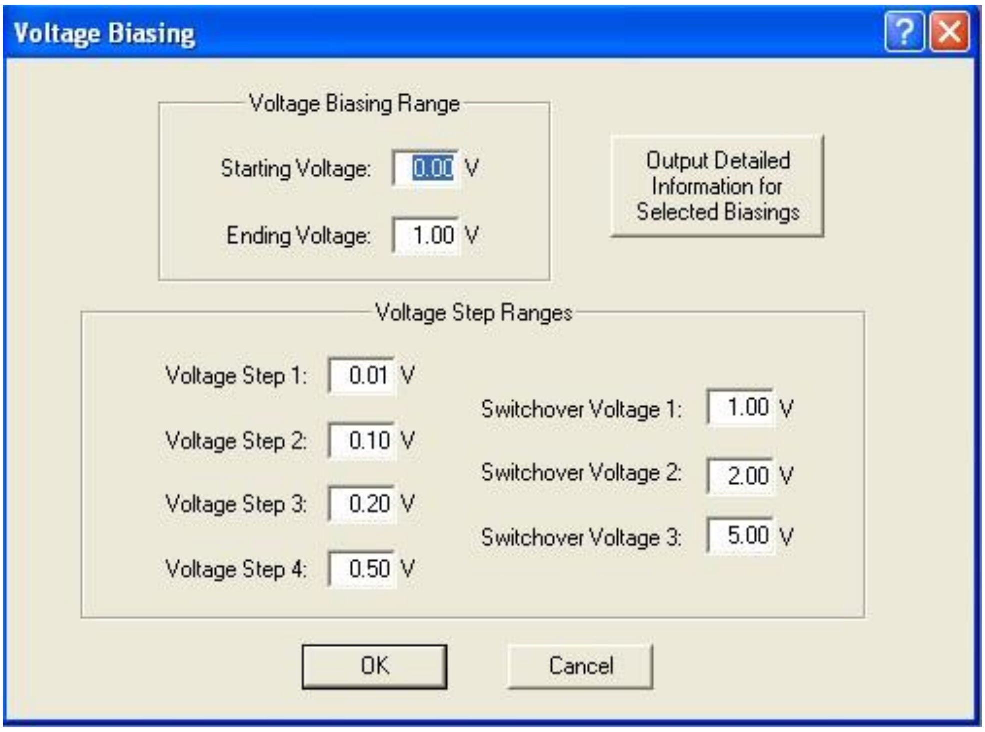

Figure 19: Voltage Biasing.

We can see we have to set the starting voltage and ending voltage for selecting the voltage biasing range from the window. Then we have to set the voltage steps and switchover voltages accordingly.

- **Illumination Conditions:** Here, we get the following window:

Figure 20: Illumination Conditions.

For our solar cell simulation, we have to keep the light on. We have to analyze the Just Light I-V characteristics.

Now under spectrum parameters, we get the following window:

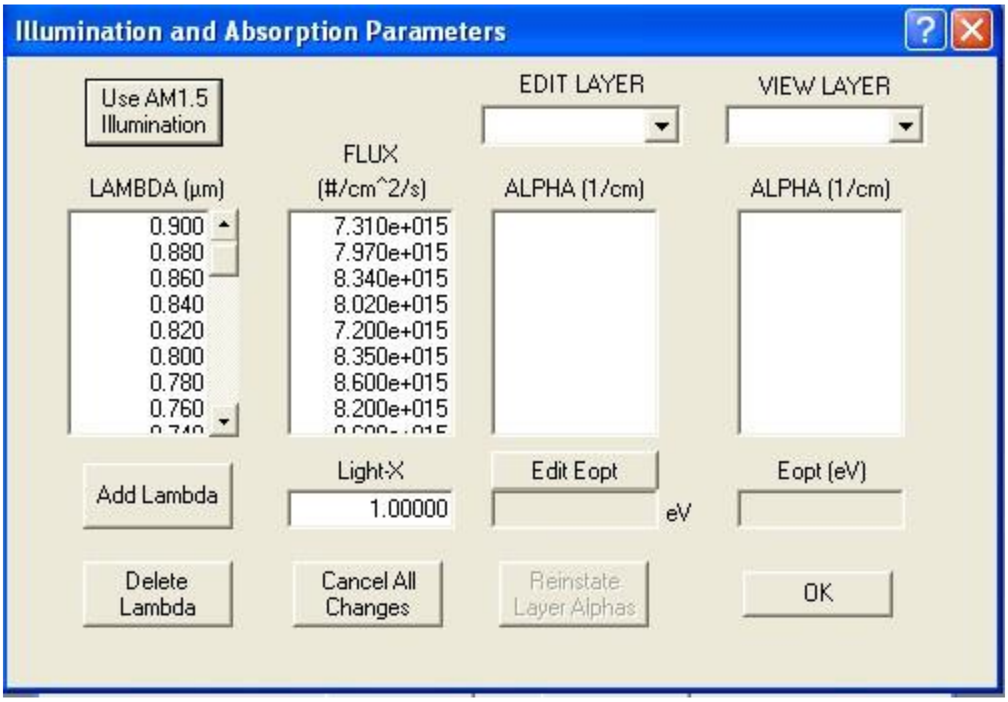

Figure 21: Illumination and Absorption Parameters.

We have used AM1.5 Illumination. This illumination will create some Lambda and Flux values by default. We can also add some more values of Lambda. For these Lambda and Flux values, we have to calculate the corresponding Alpha values. Then we have to set the E_{opt}.

We can also compare Alpha's values between two different layers with the help of the view layer.

- **Operating Temperature:**

Figure 22: Operating Temperature

We have taken 300K as the device operating temperature. Generally, this temperature is taken as a standard for solar cell simulation in this software.

- **Front Contact:**

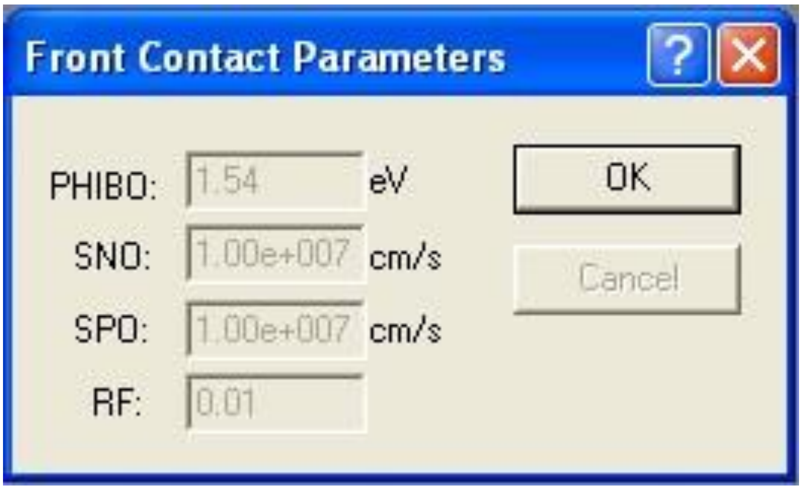

Figure 23: Front Contact Parameters

Here we have 4 parameters under front contact. The surface recombination speed of electrons (SNO) and holes (SPO) at the front contact are generally taken as $1x10^7$ cm/s. We also have to set the value of work function (PHIBO) and reflection co-efficient for the front contact. For front contact, we have taken the reflection coefficient value of 0.01.

- **Layer Info:** From this section, we can add layers to our solar cell. At each layer, there are some general layer parameters and also some device and layer grid parameters.

  We have to calculate all the layer parameters of a specific layer and use those values as input for the simulation. We can also change the layer thickness from here by setting the center grid spacing according to the layer thickness. We can also view the Band Tail parameters and Gap State parameters from here.

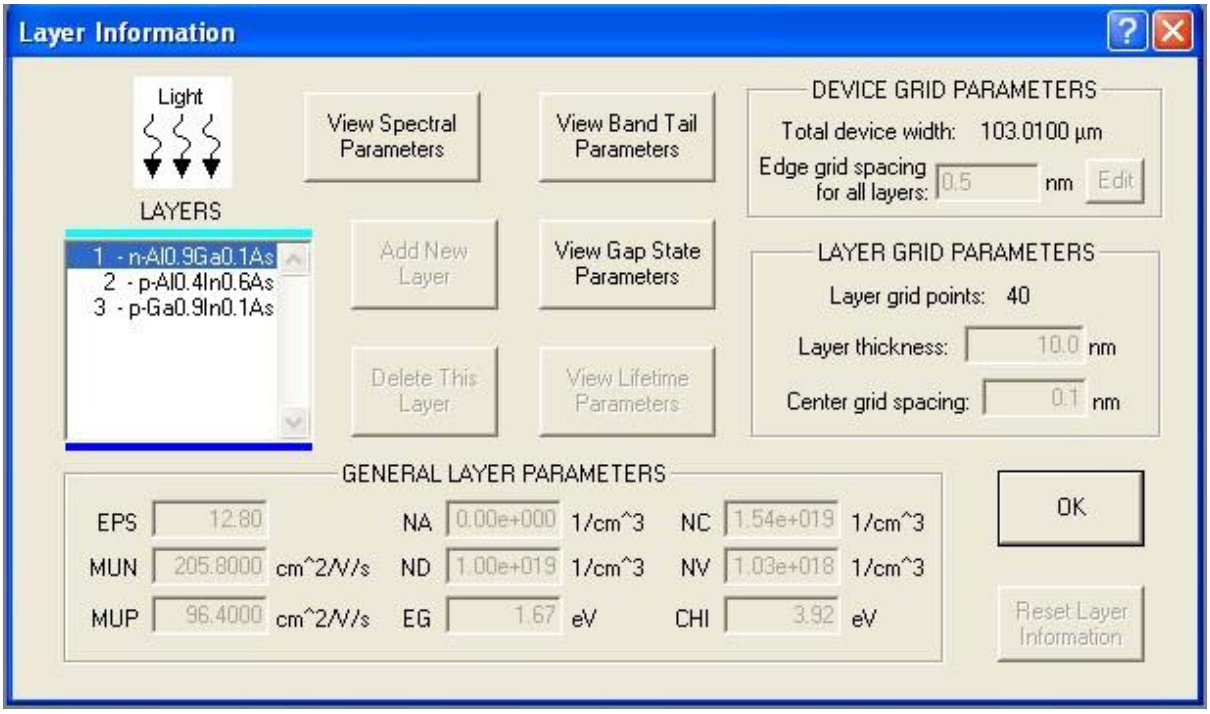

Figure 24: Layer Information

- **Back Contact:**

Figure 25: Back Contact Parameters.

Here we have 4 parameters under back contacts, like front contact. The surface recombination speed of electrons (SNL) and holes (SPL) at the back contact are generally taken as $1x10^7$ cm/s. We also have to set the work function value (PHIBL) and reflection coefficient for the back contact. For back contact, we have taken the reflection coefficient value of 0.99.

After setting the value of all those parameters mentioned above, we have to submit the new case to the queue. It will take some time to be queued, and after submission, it will show 'Reset case for editing.' That means if we want to make some change in our designed solar cell, then we have to reset the case for editing.

Finally, from the above graph section, we can easily see the output we want. After plotting the graph, we will see the values of open-circuit voltage, short circuit current, fill factor, and efficiency as an output result. From these values, we can easily compare and analyze the photovoltaic performance of our solar cell.

CHAPTER 4

4.1 Results and Discussions

For getting our expected output from the simulation, we have gone through a trial and error method. We have taken different combinations of mole fractions for the top, mid, and bottom layers and run our simulation. From all the simulation outputs, we took three designs particularly and found the one which gives the best photovoltaic performance. We took the mole fraction combinations arbitrarily. After finding the best one, we varied the value of PHIBO and PHIBL to see the influence on photovoltaic performance. Thus we found suitable values of PHIBO and PHIBL for more improved efficiency of the best design.

The output of the three designs are discussed below:

4.1.1 First Design

For the first design we took the value of mole fraction x = 0.2, 0.3 and 0.4 respectively for top ($Al_xGa_{1-x}As$), middle ($Al_xIn_{1-x}As$) and bottom ($Ga_xIn_{1-x}As$) layer. We took these values arbitrarily based on the trial and error method. The corresponding bandgap energy for these mole fractions(x) are 1.67 eV, 1 eV, and 0.68 eV, respectively, for the top, middle, and bottom layers. After simulating the first design using these values, we got the light J-V characteristics graph, shown in Figure 25.

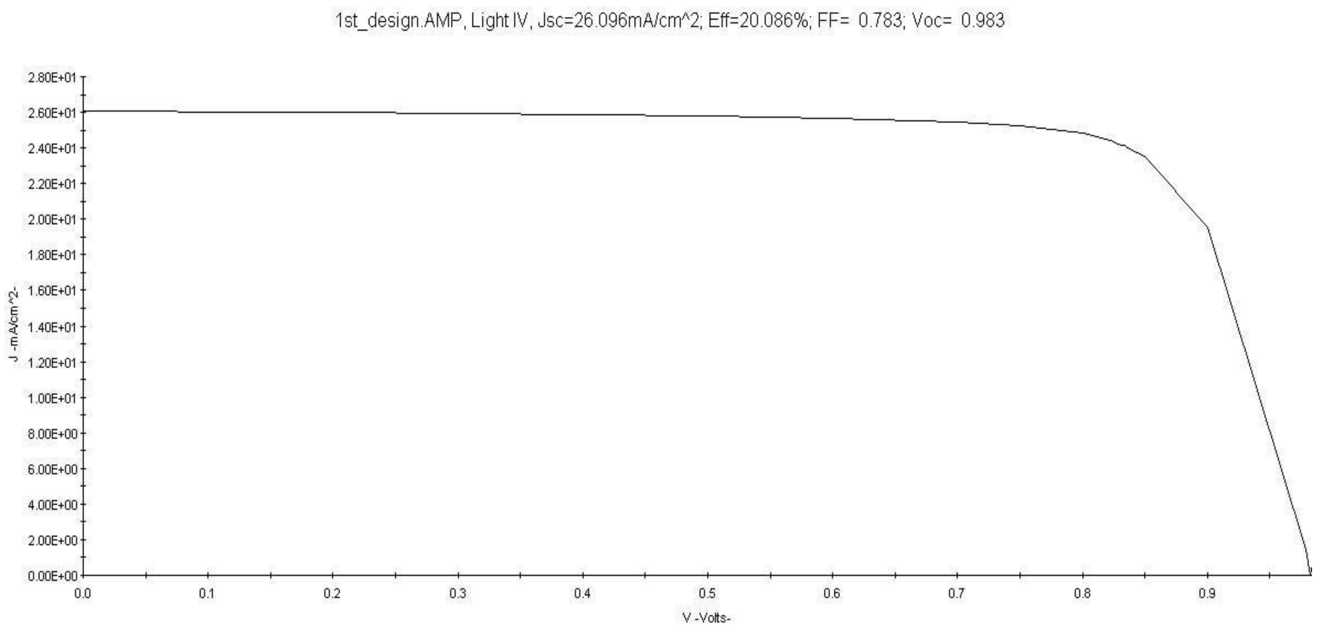

Figure 26: Output of the first design.

From the graph, we can find that the open-circuit voltage, Voc is 0.983 V, short circuit current density Jsc is 26.096 mA/cm^2. We can calculate Fill Factor's values and efficiency from these two values, which are 0.783 and 20.086%.

The following table shows the output values we got from this design:

Layer	Mole Fraction (x)	Bandgap Energy (eV)	J_{sc}(mA/cm^2)	V_{oc} (V)	FF	η (%)
Top Layer	0.2	1.67	26.096	0.983	0.783	20.086
Mid Layer	0.3	1				
Bottom Layer	0.4	0.68				

Table 7: Output values of the first design

4.1.2 Second Design

For the second design, we took the value of mole fraction x = 0.4, 0.5, and 0.6, respectively, for the top ($Al_xGa_{1-x}As$), middle ($Al_xIn_{1-x}As$) and bottom ($Ga_xIn_{1-x}As$) layer. We took these values arbitrarily based on the trial and error method. The corresponding bandgap energy for these mole fractions(x) are 1.92 eV, 1.48 eV, and 0.89 eV, respectively, for the top, middle, and bottom layers. After simulating the second design using these values, we got the light J-V characteristics graph, shown in Figure 26.

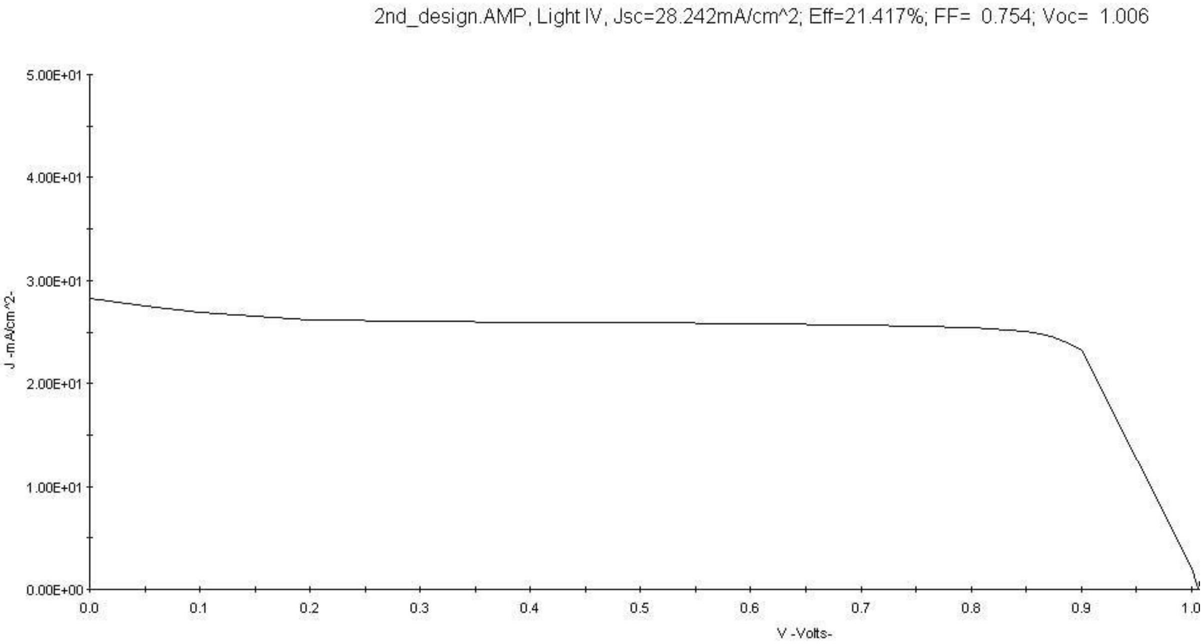

Figure 27: Output of the second design.

From the graph, we can find that the open-circuit voltage, Voc is 1.006 V, short circuit current density Jsc is 28.242 mA/cm^2. We can calculate Fill Factor's values and efficiency from these two values, which are 0.754 and 21.417%.

The following table shows the output values we got from this design:

Layer	Mole Fraction (x)	Bandgap Energy (eV)	J_{sc}(mA/cm^2)	V_{oc} (V)	FF	η (%)
Top Layer	0.4	1.92	28.242	1.006	0.754	21.417
Mid Layer	0.5	1.48				
Bottom Layer	0.6	0.89				

Table 8: Output values of the second design

From this table, we can observe that the efficiency is 21.417% for the second design. So, efficiency has increased by 1.331% than the first design.

4.1.3 Third Design

For the third design, we took the value of mole fraction x = 0.8, 0.5, and 0.9, respectively, for the top ($Al_xGa_{1-x}As$), middle ($Al_xIn_{1-x}As$) and bottom ($Ga_xIn_{1-x}As$) layer. We took these values arbitrarily based on the trial and error method. The corresponding bandgap energy for these mole fractions(x) are 2.09 eV, 1.48 eV, and 1.28 eV, respectively, for the top, middle, and bottom layers. After simulating the third design using these values, we got the light J-V characteristics graph, shown in Figure 27.

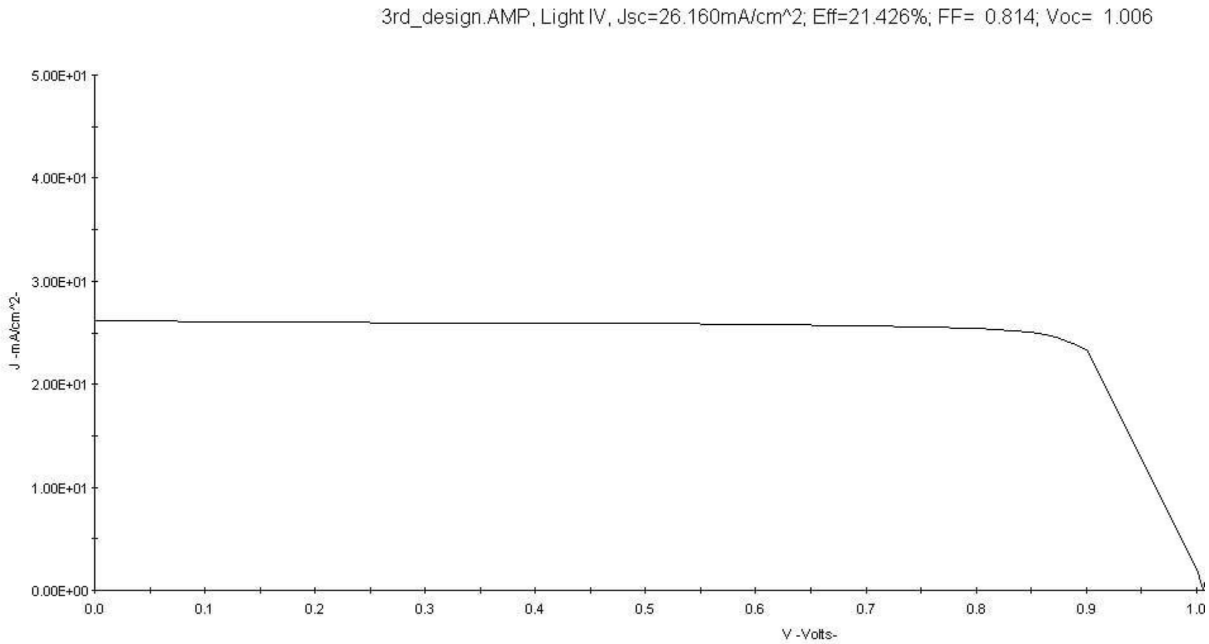

Figure 28: Output of the third design.

From the graph, we can find that the open-circuit voltage, Voc is 1.006 V, short circuit current density Jsc is 26.16 mA/cm^2. We can calculate Fill Factor's values and efficiency from these two values, which are 0.814 and 21.426%.

The following table shows the output values we got from this design:

Layer	Mole Fraction (x)	Bandgap Energy (eV)	J_{sc}(mA/ cm^2)	V_{oc} (V)	FF	η (%)
Top Layer	0.8	2.09	26.16	1.006	0.814	21.426
Mid Layer	0.5	1.48				
Bottom Layer	0.9	1.28				

Table 9: Output values of the third design

From this table, we can observe that the efficiency is 21.426% for the third design. So, efficiency has increased by 0.009% than the second design.

So, among all these three designs with the different combinations of mole fraction(x) of the layers, we get the third design's highest efficiency.

4.1.4 Influence of Front and Back Contact Parameters

Now we will see the influence of the front contact parameter PHIBO and back contact parameter PHIBL on the third design's photovoltaic performance. Our target is to find a suitable value of PHIBO and PHIBL, for which we will get a more improved efficiency of the third design.

Front and back contact has a significant impact on the photovoltaic performance of the solar cell. For converting the light energy into electrical energy, the radiation needs to penetrate through the depletion layer. The conversion phenomenon will start when the photon will hit the neutral atoms and break them into a free electron and positive charge. So the phenomenon largely depends upon the properties of the front contact. How much radiation will reach up to the depletion layer will depend on the front contact.

On the other hand, how much radiation will get back into the cell depends on the back contact properties.

Now we will see the effect of changing the front and back contact parameter on the solar cell's photovoltaic performance.

4.1.5 Front Contact

For the third design, the front contact parameters were used as given in Table 6. In this case, we will keep the back contact parameter (PHIBL) constant. We will now change the value of the front contact parameter (PHIBO) and observe its effect on the solar cell's photovoltaic performance.

The changes in the output due to the change in PHIBO are shown through the following table:

PHIBO (eV)	η (%)	J_{sc}(mA/cm^2)	V_{oc} (V)	FF
1.2	13.139	25.962	0.666	0.760
1.4	17.994	26.065	0.866	0.797
1.6	22.903	26.201	1.066	0.820
1.8	27.747	26.421	1.265	0.830
2.0	30.310	26.902	1.413	0.797
2.2	30.424	27.612	1.412	0.780
2.3	30.435	27.985	1.509	0.772

Table 10: The change in the output values due to a change in PHIBO.

So from the table, we can see that with an increase in the value of PHIBO, the value of efficiency, short circuit current density, and open-circuit voltage also increase. The Fill factor increases up to a certain value (PHIBO = 1.8eV), and then suddenly, it starts to decrease. We know the Fill factor is the ratio of maximum power to the product of short circuit current density and open-circuit voltage. As short circuit current density and open-circuit voltage increase with PHIBO, the Fill factor's value gradually decreases after a certain point.

With the help of these output values, we plotted four graphs:

(i) PHIBO vs. η
(ii) PHIBO vs. Voc
(iii) PHIBO vs. Jsc
(iv) PHIBO vs. FF

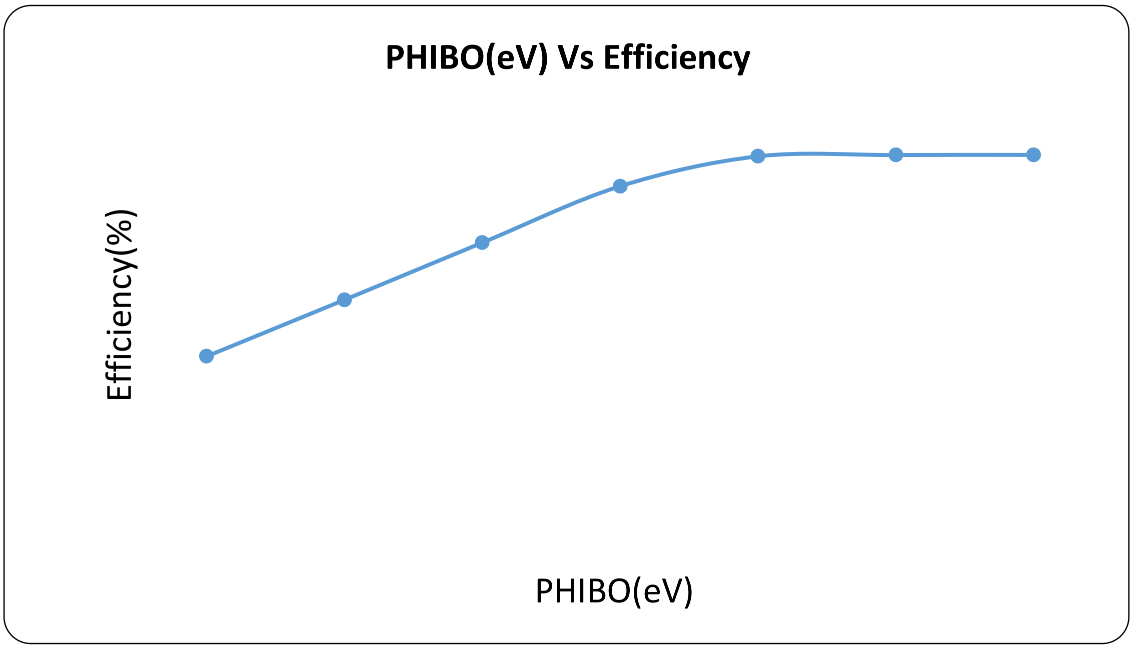

Figure 29: PHIBO vs. η

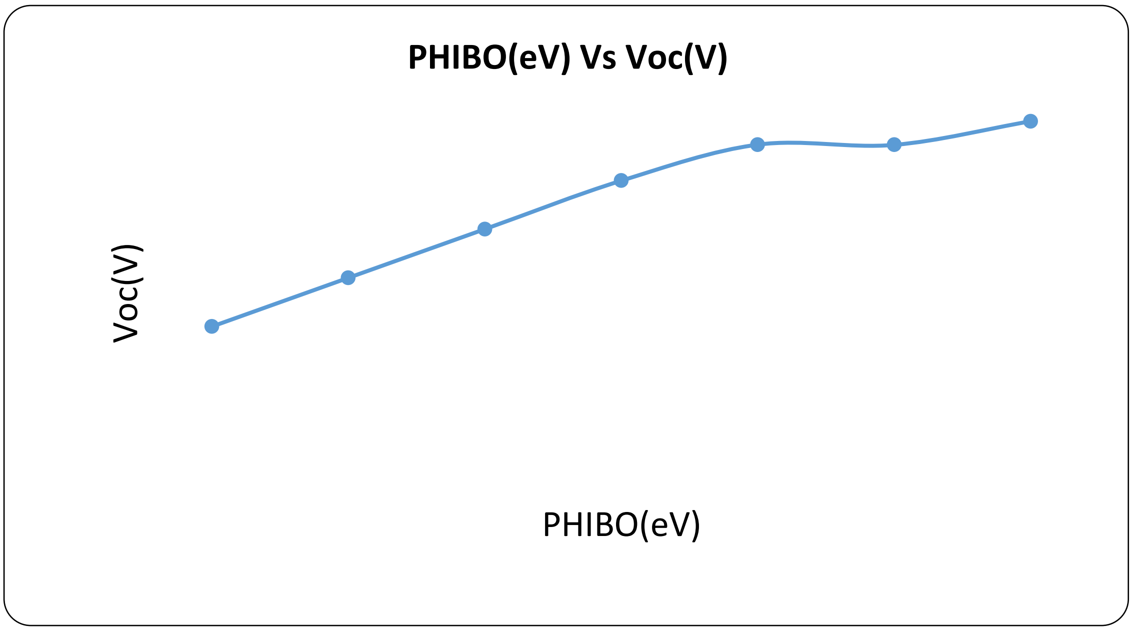

Figure 30: PHIBO vs. Voc

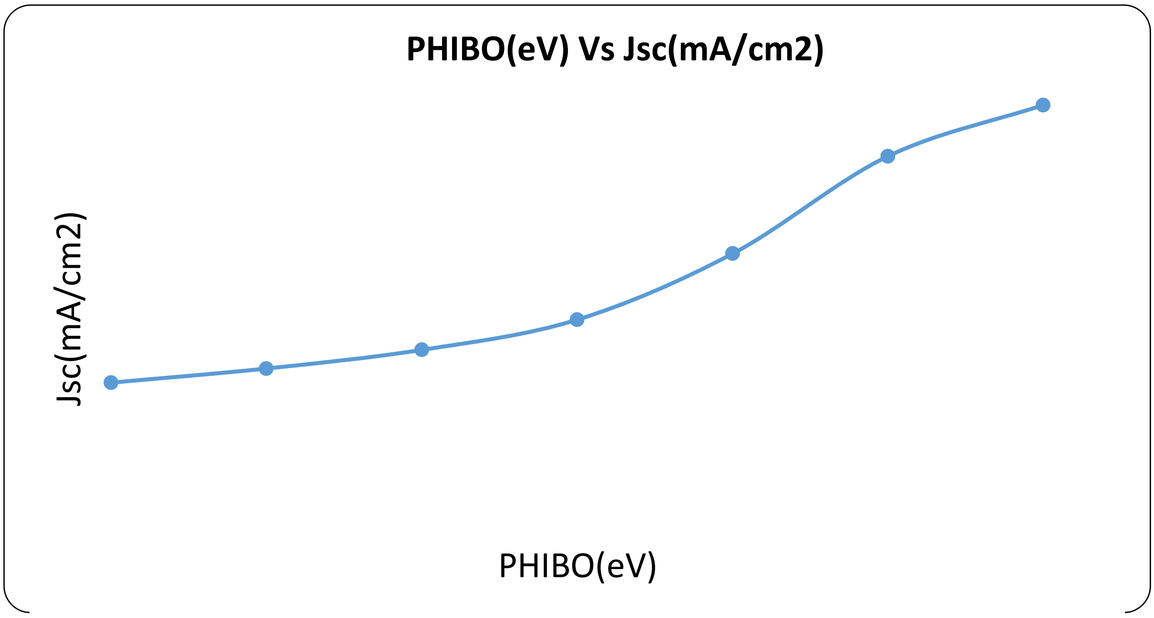

Figure 31: PHIBO vs. Jsc

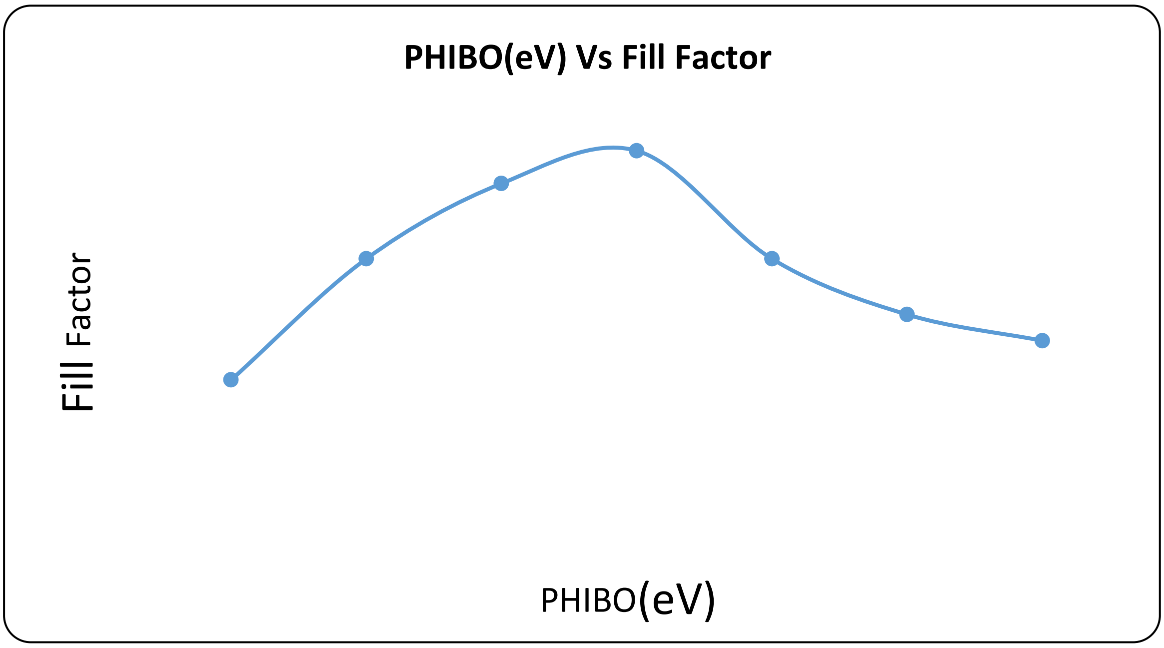

Figure 32: PHIBO vs. FF

From these graphs, we can easily understand the effect of changing PHIBO on the solar cell's photovoltaic performance. We can see that at PHIBO = 2.3 eV, the efficiency is the highest, 30.435% but the Fill factor decreases. If we increase PHIBO further, the Fill factor will decrease more, degrade the cell's performance. So considering all the parameter values, we can say at PHIBO = 2.3 eV, we get the best photovoltaic performance.

4.1.6 Back Contact

For the third design, the back contact parameters were used as given in Table 6. In this case, we will keep the front contact parameter (PHIBO) constant. We will now change the back contact parameter (PHIBL) value and observe its effect on the solar cell's photovoltaic performance.

The changes in the output due to the change in PHIBL are shown through the following table:

PHIBL (eV)	η (%)	J_{sc}(mA/cm^2)	V_{oc} (V)	FF
0.2	21.426	26.160	1.006	0.814

0.4	21.405	26.159	1.006	0.813
0.6	18.657	26.082	1.006	0.711
0.7	16.229	26.015	1.006	0.620

Table 11: The change in the output values due to change in PHIBL.

So from the table, we can see that with an increase in the value of PHIBL, the value of efficiency, short circuit current density, and Fill factor decrease. But the open-circuit voltage remains constant. The open-circuit voltage mostly depends on the front contact parameter (PHIBO), which is constant in this case. Moreover, most of the radiation is absorbed in the front contact. Very few can reach up to the back contact. This is why the open-circuit voltage remains constant.

With the help of these output values, w e plotted four graphs:

(i) PHIBL vs. η
(ii) PHIBL vs. Voc
(iii) PHIBL vs. Jsc
(iv) PHIBL vs. FF

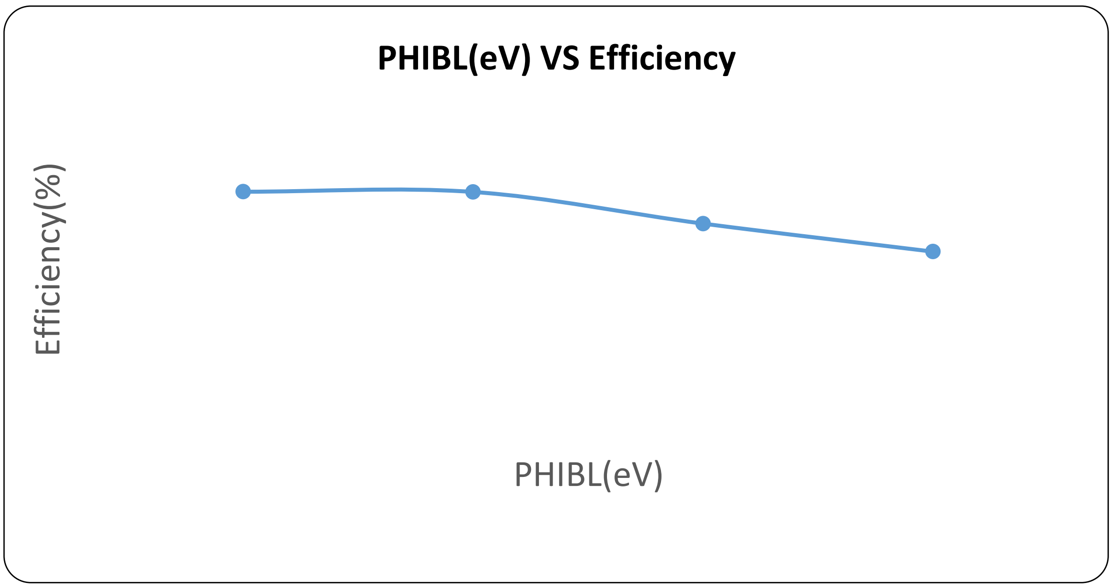

Figure 33: PHIBL vs. η

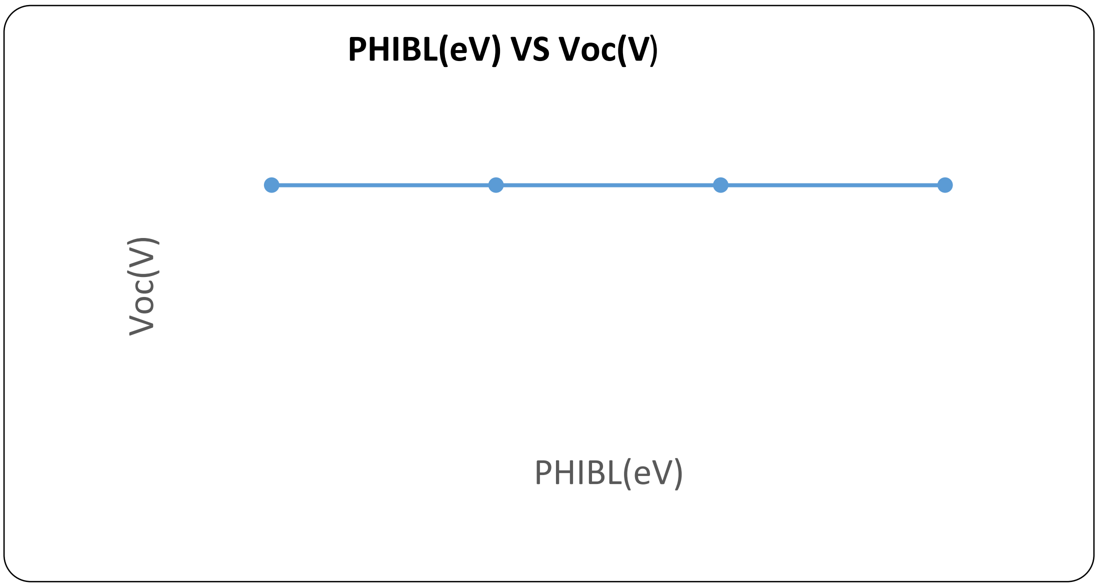

Figure 34: PHIBL vs. Voc

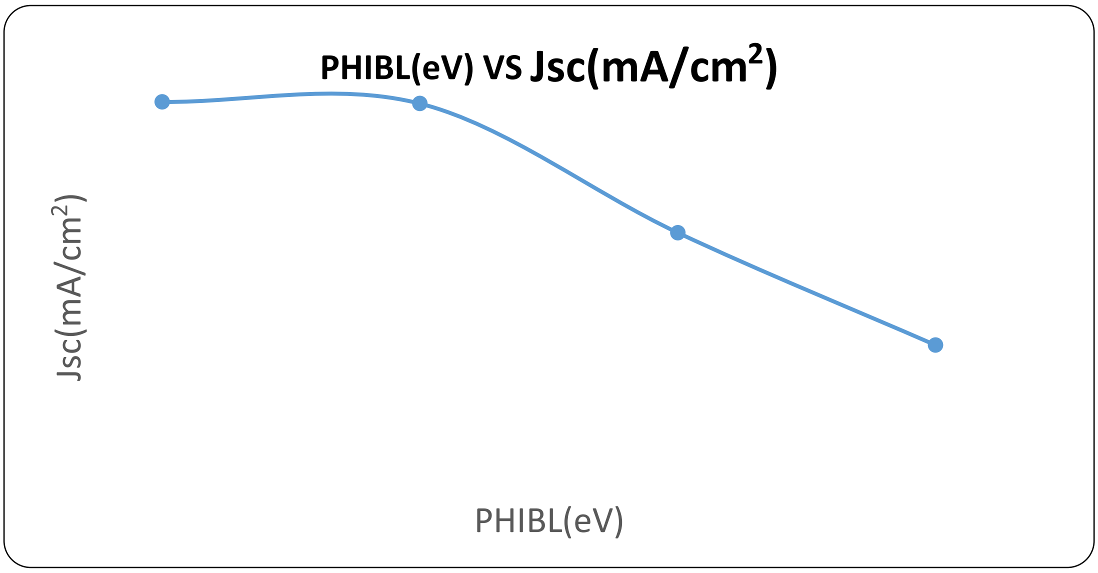

Figure 35: PHIBL vs. Jsc

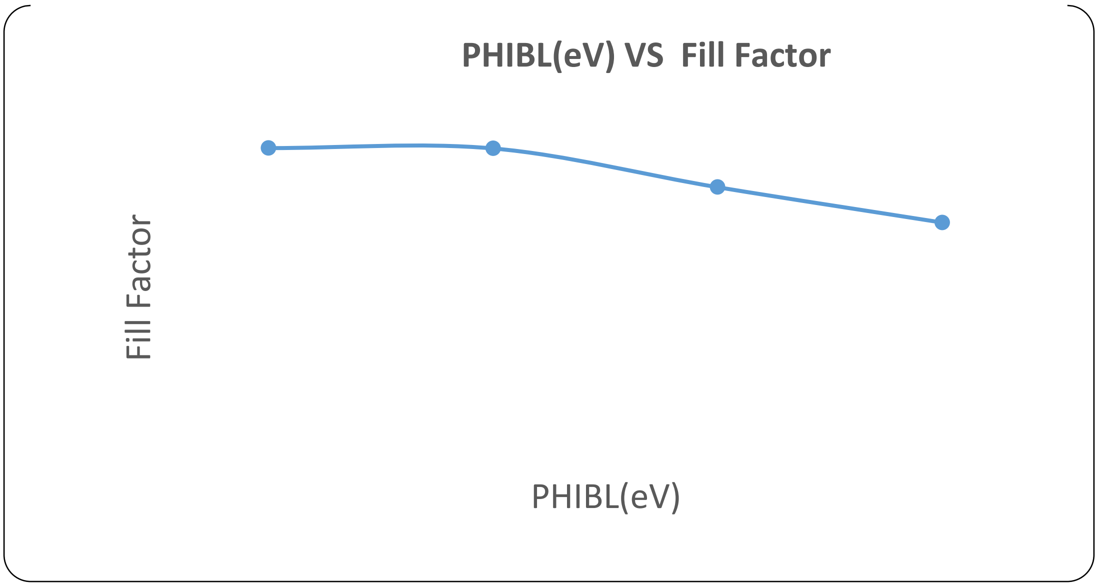

Figure 36: PHIBL vs. FF

From these graphs, we can easily understand the effect of changing PHIBL on the solar cell's photovoltaic performance. We can see that at PHIBL = 0.7 eV, the efficiency is the lowest, 16.229%. The open-circuit voltage remains constant. If we increase PHIBL further, then the Fill factor, short circuit current density, and efficiency will decrease, which will degrade the cell's performance. So considering all the parameter values, we can say at PHIBL = 0.2 eV, we get the best photovoltaic performance.

If we consider the overall case, we will find that for PHIBO = 2.3 eV and PHIBL = 0.2 eV, we get the highest efficiency of 30.435%.

4.1.7 Result Summary

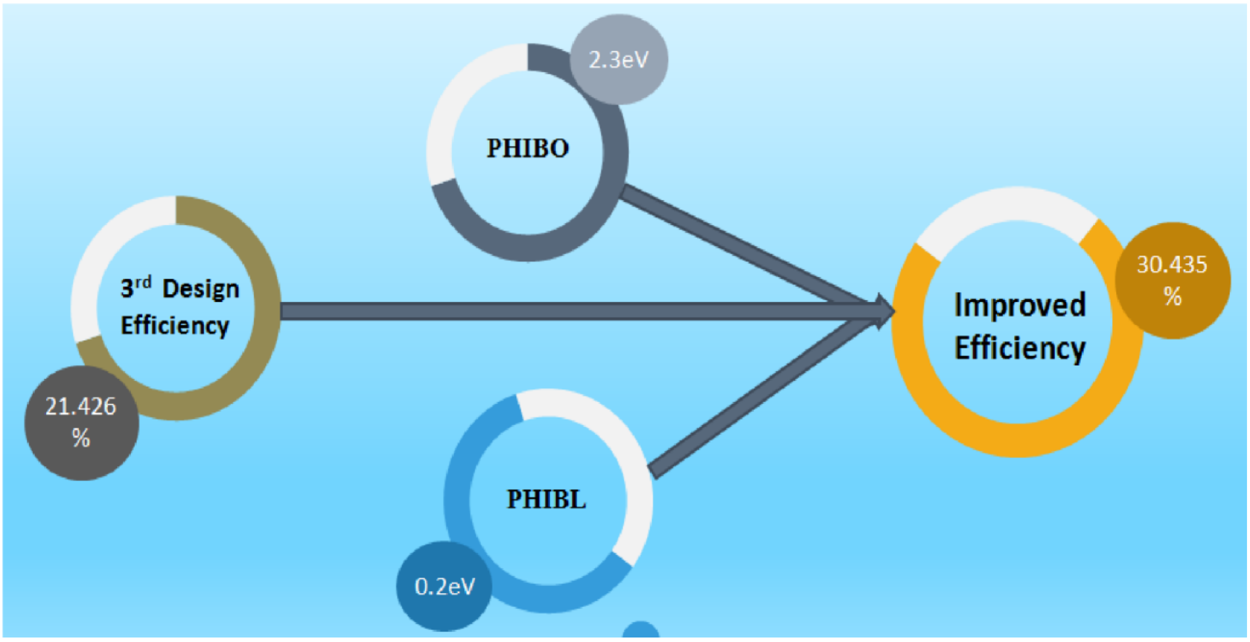

Figure 37: Result Summary

By setting the value of PHIBO = 2.3 eV and PHIBL = 0.2 eV, we can improve the third design's efficiency to a value of 30.435% from 21.426%.

So the efficiency of the third design has increased by 9.009%.

CHAPTER 5

5.1 Summary

Energy is essential to life, along with all living creatures. Energy is needed in every aspect of life. The primary sources of energy are coal, oil, biomass, nuclear, and so on. But the problem is we can't use these twice, and the amount of these sources is limited on the Earth. Recently, the traditional sources of energy are going to extinct. That is why people are getting interested in renewable energy sources like solar, wind, water, and so on. Solar energy is the most efficient and effective renewable energy source among all the sources of renewable energy. In the future, people will depend on solar energy as the other sources of energy are going to extinct soon. Solar energy can be collected from the Sun, and as long as the Sun lives, this energy can be produced. The total power of solar radiation touching the surface of the atmosphere immediately facing the Sun is approximately 1,360 watts per square meter. To utilize this energy, people are working on solar cells. Solar cells can generate 15-20% of energy from this. In some cases, it can even hit 42%.

Researchers have developed the main configuration of solar cells and now working on increasing efficiency. Among all the solar cell heterojunction types, solar cells have attracted much attention because of their high efficiency. Till now, the highest efficiency is 23.5% for c-Si heterojunction solar cells. People are recently interested in III-V ternary alloy materials because they offer greater flexibility for optimizing efficiency. So far, the highest efficiency for ternary alloy heterojunction solar cell is 21.39% which was gained by changing the mole fraction of "$Al_xGa_{1-x}As$/ $Al_xIn_{1-x}As$/ $Ga_xIn_{1-x}As$" composition.

In order to increase the efficiency of the solar cells, we have thoroughly studied the problems and the proposals. After going through many papers on this topic, we found some places for improving solar cell efficiency that hasn't been introduced yet. That's why we have introduced variation in the photovoltaic performance of $Al_xGa_{1-x}As$/$Al_xIn_{1-x}As$/ $Ga_xIn_{1-x}As$ heterojunction solar cell has been studied by changing the mole fraction (x) and front and back contact parameter (PHIBO and PHIBL) of the solar cell. Simulations were done using the one-dimension(1D) simulation program '*Analysis of Microelectronic and Photonic Structures*' (AMPS 1D) software. With the help of this software light J-V characteristics curve was obtained for different combinations of alloy composition of the layer materials. Also, the effect of changing PHIBO and PHIBL on this curve (Under AM1.5G) was observed. Everything is discussed in detail for a better understanding throughout the book. Here is an overlook of the book.

Chapter 1 – The importance of solar energy as a renewable energy source as well as the solar cell that utilizes this energy are discussed. Also, the structure of the solar cells, their types, and applications are discussed. The recent problem and our proposed solution are discussed in this chapter.

Chapter 2 – The proposed solar cell type, efficiency, and advantages are discussed in detail. A detailed discussion on the simulation model and the parameters used during the work are given in this chapter.

Chapter 3 – The used software, its parameters, and why this software has been used are discussed in this chapter. Mainly this chapter is about the simulation processes.

Chapter 4 – This chapter is all about results and discussion. The final result of our work is shown. And also, how the simulation was done, the output of the simulations, the effects on other parameters after changing the specific parameters are all discussed in this chapter.

Chapter 5 – The summary and the conclusions are in this chapter.

5.2 Conclusions

After a thorough study, we found that for a different combination of mole fractions(x), the corresponding bandgap energy changes, and we get different output values. We have designed three configurations with the different mole fractions of our alloys. Among all the three designs, for the second design, we got the highest short circuit current density (J_{sc} = 28.242 mA/cm^2). For the third, we got the highest efficiency (η = 21.426%), highest Fill Factor (FF = 0.814), and highest open-circuit voltage (V_{oc} = 1.006 V) as our primary concern is efficiency. Hence, we took the third design solar cell's photovoltaic performances as it gives us the highest efficiency among the three designs. After finding the best performance with the mole fraction change, we focused on increasing it slightly by changing the front and back contact parameters PHIBO and PHIBL. So, for the third design, we found that if we increase PHIBO and keep the other parameter values unchanged, the efficiency increases. So we continuously increased it. And at 2.3 eV, we found that efficiency becomes 30.435%. We didn't increase the PHIBO further as the short circuit current density was decreasing. After getting the higher efficiency for PHIBO, we started to increase the PHIBL. We saw that by increasing PHIBL, the efficiency was decreasing. We took PHIBL till 0.7 eV and saw that the efficiency decreased to 16.229%. Later we took PHIBL at 0.2 eV, and the efficiency increased to 30.435%. The back contact reflects the light inside the solar cells so that no energy loss occurs.

In reality, no material can reflect 100% light. So we can say for PHIBO 2.3 eV and PHIBL = 0.2 eV, we get the highest efficiency (η) 30.435%. By setting the suitable value of PHIBO and PHIBL, we have increased the third design's efficiency by 9.009%.

5.3 Future Development

There are some scopes of development of our heterojunction solar cell:

- **Lattice Mismatch:** Lattice mismatch between the layers gives a critical layer thickness. One way to solve the lattice mismatch problem between two adjacent layers is to apply a buffer layer in between, which will have an intermediate lattice constant.

- **Fabrication Cost:** Focus was mainly given to the cell's photovoltaic performance, but material and fabrication cost was not considered while proposing the design. So there is a scope of developing a design that is efficient and at the same time cost-effective.

- **Electrical Properties:** When we change the mole fraction (x), the layer materials' bandgap energy also changes. Change in the electrical properties is negligible. So we took approximately the same value for all the layers. For more accurate analysis, we can make the changes in electrical properties under consideration.

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