B. TECH. PROJECT REPORT

On

MODELLING AND OPTIMIZATION OF CIGS SOLAR CELL MODULES

BY

Nelaturu Sreekanth Reddy

DISCIPLINE OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2018

MODELLING AND OPTIMIZATION OF CIGS SOLAR CELL MODULES

A PROJECT REPORT

Submitted in partial fulfillment of the
requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in
ELECTRICAL ENGINEERING

Submitted by:
Nelaturu Sreekanth Reddy

Guided by:
Dr Vipul Singh,
Associate Professor,
Electrical Engineering,
Indian Institute of Technology Indore

INDIAN INSTITUTE OF TECHNOLOGY INDORE
December 2018

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Modelling and Optimization of CIGS Solar Cell Modules"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in **Electrical Engineering** completed under the supervision of **Dr. Vipul Singh, Associate Professor, Electrical Engineering, IIT Indore** is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Nelaturu Sreekanth Reddy
1500002023
Discipline of Electrical Engineering
Indian Institute of Technology Indore

CERTIFICATE by BTP Guide

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Dr. Vipul Singh,
Associate Professor,
Discipline of Electrical Engineering,
Indian Institute of Technology Indore

Preface

This report on “**Modelling and Optimization of CIGS Solar Cell Modules** " is prepared under the guidance of Dr. Vipul Singh, Associate Professor, Electrical Engineering, IIT Indore

Throughout this report, detailed description of the Modelling and Optimization of Solar Cell Modules is provided. I have studied the effect of varying bandgap, thickness, doping, and temperature at cellular cell and optimized the output. Different series and shunt losses and mismatch losses were studied at modular level. I have tried to the best of my ability and knowledge to explain the content in a lucid manner. I have also added figures to make it more illustrative.

Acknowledgements

I would like to thank my B. Tech Project supervisor **Dr. Vipul Singh** for his constant support in structuring the project and for his valuable feedback throughout the course of this project. He gave me an opportunity to discover and work in such an interesting domain. His guidance proved really valuable in all the difficulties we faced in the course of this project.

I am really grateful to **Mr. Akash Tripathi** who also provided valuable guidance and helped with the problems while working on various technologies. He provided initial pathway for starting the project in the right manner and provided useful directions to proceed along whenever necessary.

I would like to acknowledge the use of AMPS 1D simulation software that was developed by Dr. Fonash's group at Pennsylvania State University (PSU).

We are also thankful to all our family members, friends and colleagues who were a constant source of motivation. We are really grateful to Dept. of Electrical Engineering, IIT Indore for providing with the necessary hardware utilities to complete the project. We offer sincere thanks to everyone who else knowingly or unknowingly helped us complete this project.

Nelaturu Sreekanth Reddy
1500002023
Discipline of Electrical Engineering
Indian Institute of Technology Indore

Abstract

The copper indium gallium diselenide, CuIn1-xGaxSe2 (CIGS), based solar cells have largest efficiencies on the laboratory scale and as well as on the level of large-area modules. In addition to high efficiencies, CIGS thin-film modules exhibit excellent outdoor stability and radiation hardness. Therefore, this combination of high efficiency coupled with stability and radiation hardness makes CIGS a promising material for the low cost, high efficiency solar cells.

In this work a computer model of a CIGS solar cell is built and simulations are performed on model and optimized the design and output. For the simulation, a one dimensional simulation program called an analysis of microelectronic and photonic structures (AMPS-1D) is used to simulate the solar cell structure. Further Matlab Simulink is used for the module level modelling and to study the series, shunt and mismatch losses. The aim of the simulation of CIGS solar cell structure was to check the device performance by varying the bandgap, thickness, doping and temperature of the CIGS absorber layer. The device performance is mainly based on the material parameters, optical parameters, and electrical parameters of each layers used in the structure.

Table of contents

List of Figures

List of Tables

Chapter 1-Introduction

1.1What is a solar cell?

A solar cell (or a "photovoltaic" cell) is a device that converts photons from the sun (solar light) into electricity. In general, a solar cell that includes both solar and nonsolar sources of light (such as photons from incandescent bulbs) is termed a photovoltaic cell. Fundamentally, the device needs to fulfill only two functions: photo generation of charge carriers (electrons and holes) in a light-absorbing material, and separation of the charge carriers to a conductive contact that will transmit the electricity. This conversion is called the photovoltaic effect, and the field of research related to solar cells is known as photovoltaics.

1.1 solar cell

1.2What is the need of solar cell?

Solar energy is a major renewable energy source with the potential to meet many of the challenges facing the world. There are many reasons to promote its share in the energy market. This power source is increasing in popularity because it is versatile with many benefits to people and the environment.

- **Importance to Environmental Protection:**

Sunlight received by earth in one hour is enough to meet the annual energy needs of all people worldwide according to National Renewable Energy Laboratory. In 2015 solar energy was the fastest growing energy sector with a 33% rise according to Bloomberg. The environmental advantages are the main drivers in promoting solar energy.

- **Solar Is Clean and Safe:**

Solar is a safe alternative which can replace current fossil fuels like coal and gas for generation of electricity that produce air, water, and land pollution. World Wide Fund for Nature, also known as the World Wildlife Fund (WWF), notes that electricity generation from fossil fuels causes pollution of air leading to acid rain, damaged forest areas, and affected agricultural production leading to loss of billions of dollars worldwide.

Thousands of liters of water mixed with chemicals are used for extraction of fossil fuels by contaminating the water used, along with nearby water bodies, and also causes earthquakes. Nuclear power pollutes water and land and has caused environmental catastrophes. Use of solar energy will eliminate these unsafe, unclean consequences from using conventional fossil fuels.

- **Prevents Destruction of Habitats:**

Many forests are destroyed for mining raw materials like fossil or nuclear fuels. Trees constantly remove and use carbon dioxide from the air to make their food, and this carbon is then stored in them. When forests are cut for mining raw materials for conventional energy, this major carbon sink disappears and also increases climate change. "Nine out of ten animals on land" live in forests, according to WWF, and a loss of habitats diminishes their populations. Switching to solar power is important to keep these habitats intact for the animals who live there as well as continue to keep the air clean.

- **Combats Climate Change:**

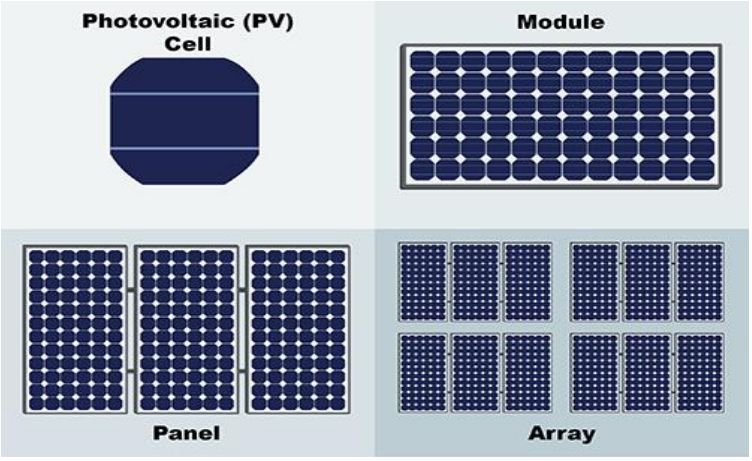
The emissions of greenhouse gases by electric power sector plays an important role in effecting climate. The emissions lead to a rise in global temperatures, and changes in weather patterns leading to a cascade of effects. Heat waves, and increase in disease-spreading insects cause health problems especially for children and the elderly. Climate has led to increase in flooding and hurricanes due to disturbed weather patterns. Higher carbon dioxide concentration is making oceans acidic and killing marine life, like corals. Climate change causes extinct of species from Sub-Arctic Boreal forests to tropical Amazon forests. Higher temperatures result melting of polar ice caps, reducing habitats for wildlife and also increase sea level. This results in submersion and loss of land along the coast, displacing people. Irregular rainfall or increasing droughts affects agriculture and livelihoods of the weaker sections of society globally.

- **Cheap and Reliable Energy Source:**

Technological developments and policy and subsides by the government have reduced the high costs of solar systems. The price of solar PV panels has decreased by 60% and the cost of the solar electricity system by 50% according to the Energy.gov report. So solar energy is now competitive with conventional energy sources. The running costs are less and the initial investment is regained leading to subsequent savings in energy costs according to Greenpeace. This happens because the input for solar energy is free and clean sunlight while fossil fuels are mined and transported over long distance according to another Greenpeace report. The Greenpeace report estimates that the costs to deal with environmental problems from use of "dirty power sources" double or even triple the cost of electricity from conventional sources like coal. Solar energy is important to help offset and potentially eliminate, these additional costs. Apart from environmental benefits we have many social and economic benefits from solar cells.

1.3 Cells/Modules/Panels/Arrays

Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building blocks of PV systems. Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.



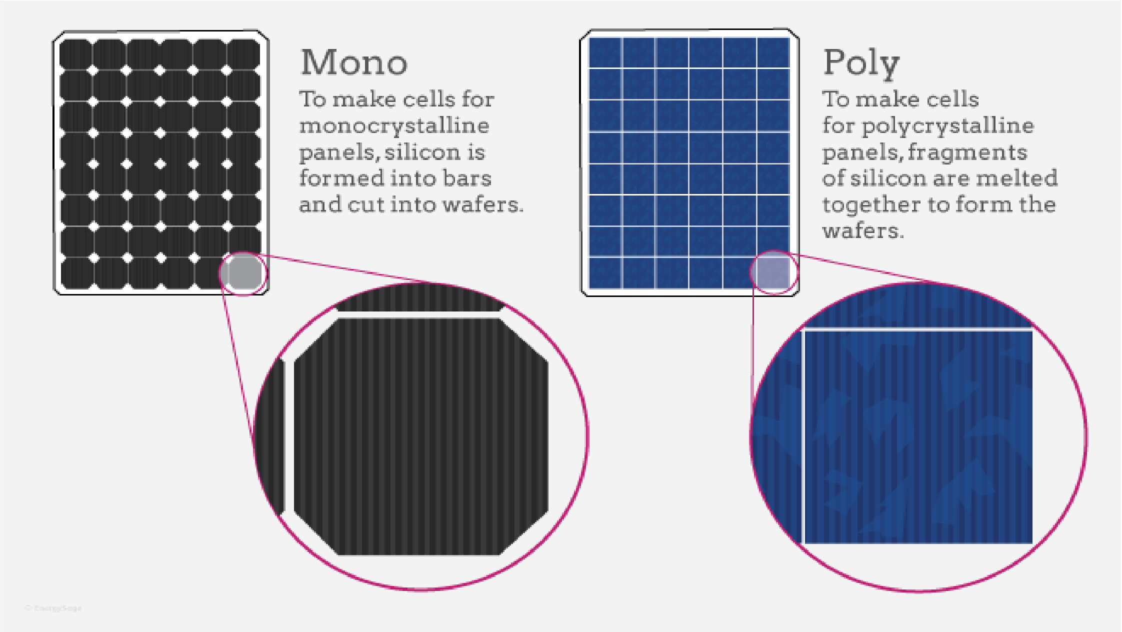
1.2 Photovoltaic cells, modules, panels and arrays

The performance of PV modules and arrays are generally rated according to their maximum DC power output (watts) under Standard Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25 C, and incident solar irradiance level of 1000 W/m2 and under Air Mass 1.5 spectral distribution. Since these conditions are not always typical of how PV modules and arrays operate in the field, actual performance is usually 85 to 90 percent of the STC rating. Today's photovoltaic modules are extremely safe and reliable products, with minimal failure rates and projected service lifetimes of 20 to 30 years. Most major manufacturers offer warranties of 20 or more years for maintaining a high percentage of initial rated power output. When selecting PV modules, look for the product listing, qualification testing and warranty information in the module manufacturer's specifications.

1.4 Types of solar cells

There are three basic types of solar cell. Monocrystalline cells are cut from a silicon ingot grown from a single large crystal of silicon whilst polycrystalline cells are cut from an ingot made up of many smaller crystals. The third type is the amorphous or thin-film solar cell.

Both monocrystalline and polycrystalline solar panels serve the same function in the overall solar PV system: they capture energy from the sun and turn it into electricity. They are also both made from silicon, which is used for solar panels because it is an abundant, very durable element. Many solar panel manufacturers produce both monocrystalline and polycrystalline panels.



1.3 Mono and Polycrystalline panels

- **Monocrystalline solar panels:**

To make solar cells for monocrystalline solar panels, silicon is formed into bars and cut into wafers. These types of panels are called "monocrystalline" to indicate that the silicon used is single-crystal silicon. Because the cell is composed of a single crystal, the electrons that generate a flow of electricity have more room to move. As a result, monocrystalline panels are more efficient than their polycrystalline counterparts.

- **Polycrystalline solar panels:**

Polycrystalline solar panels are also made from silicon. However, instead of using a single crystal of silicon, manufacturers melt many fragments of silicon together to form the wafers for the panel. Polycrystalline solar panels are also referred to as "multi-crystalline," or many-crystal silicon. Because there are many crystals in each cell, there is to less freedom for the electrons to move. As a result polycrystalline solar panels have lower efficiency ratings than monocrystalline panels.

- **Thin film solar panels:**

A thin-film solar cell is a second generation solar cell that is made by depositing one or more thin layers, or thin film (TF) of photovoltaic material on a substrate, such as glass, plastic or metal. Thin-film solar cells are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin-film silicon

Film thickness varies from a few nanometers (nm) to tens of micrometers (µm), much thinner than thin-film's rival technology, the conventional, first-generation crystalline silicon solar cell (c-Si), that uses wafers of up to 200 µm thick. This allows thin film cells to be flexible, and lower in weight. It is used in building integrated photovoltaics and as semi-transparent, photovoltaic glazing material that can be laminated onto windows. Other commercial applications use rigid thin film solar panels (sandwiched between two panes of glass) in some of the world's largest photovoltaic power stations.

Thin-film technology has always been cheaper but less efficient than conventional c-Si technology. However, it has significantly improved over the years. The lab cell efficiency for CdTe and CIGS is now beyond 21 percent, outperforming multicrystalline silicon, the dominant material currently used in most solar PV systems. Accelerated life testing of thin film modules under laboratory conditions measured a somewhat faster degradation compared to conventional PV, while a lifetime of 20 years or more is generally expected. Despite these enhancements, market-share of thin-film never reached more than 20 percent in the last two decades and has been declining in recent years to about 9 percent of worldwide photovoltaic installations in 2013.

1.4 Thin film solar cells

1.5 Advantages and Limitations

- **Advantages of Solar Cells:**
- Renewable energy - The energy can be used both to generate electricity and heat in the house. Renewable energy is recovered from the sun, the wind and waves - which in this case is the sun. Solar cells harness the energy from the sun and transform this into usable electricity.
- Economy-friendly energy - Solar cells provide a great opportunity to create savings on your electric bill since you do not pay for the energy that you generate. At the same time, you have the opportunity to monetize your photovoltaic system, if you have a solar system with a grid connected installation,

you can buy and sell electricity to the collective electricity network. At the same time, you can obtain several grants for solar cells and there will be more economic benefits to be gained in the future.

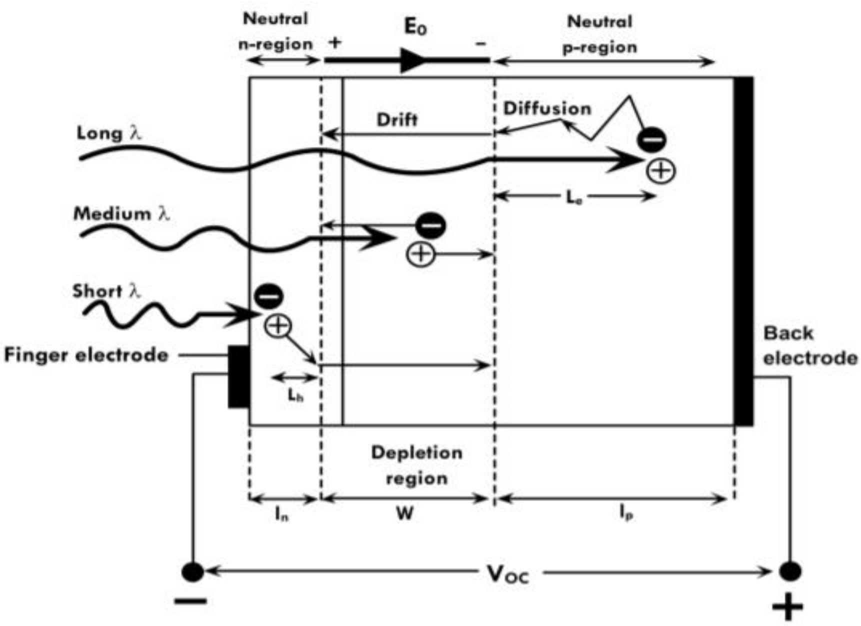
- Environmentally friendly energy - With solar cells occurs almost no pollution. The discharge of waste and pollution is unavoidable in relation to the production of solar cells, the transport of these and when you install them. However, this is a minimal fraction, compared to if one draws its energy from elsewhere.
- Innovative energy - Photovoltaics is a popular topic in green energy and is considered to be a good solution to prevent climate change. Therefore, this is an innovative market under continuous research and development.
- Infinite Energy - When you have the opportunity to extract energy from the sun's rays, this is a source of energy that will never be exhausted, therefore there will always be a source for electricity production.
- Long term energy - PV systems often have a long life and a good durability. At the same time, there is often a guarantee of minimum 20 years on your solar panels, guaranteeing you, should there be any complications.
- Selling energy - If your home has solar cells, it is often easier to sell the property at a higher price.
- **Limitations**:
- Interior needs - Not all households that can satisfy their requirements and get the optimum out of their solar cells yet. Solar cells are very sensitive in terms of their location, which means that if there is shade on your lot, it is difficult to exploit solar installation optimally. The solution to this is that you can be connected to the grid and hence can buy energy from others.
- High investment - One-time cost of acquiring a photovoltaic system and have it installed are relatively high. However, one must bear in mind that producing energy then, is free. The solution to this drawback is that by most banks provide the opportunity to take an energy lending, which gives a low interest to you as a customer who invests in green energy.
- Seasonal energy - Compared to other types of renewable energy, the solar power plant is highly seasonal. The solution to this is to grid connect solar installations and purchase energy from the public electricity network during periods where there is less energy to collect. Investing in a solar battery storage system is also a good choice, since it can store the energy generated during peak hours and make it readily available for cloudy and rainy days.
- Solar cells on your accommodation - It might be harder to install solar panels on older households, as they often have different designs that can provide shade. At the same time flat roofs where drifting snow may fall below the racks, becomes too heavy for a roof with solar cells. Therefore, it is important that you inquire about these things when you obtain offers

Chapter 2-Working of Solar Cells

2.1 Solar cell working:

A simple solar cell is a pn junction diode. The schematic of the device is shown in figure 2.1. The n region is heavily doped and thin so that the light can penetrate through it easily. The p region is lightly doped so that most of the depletion region lies in the p side. The penetration depends on the wavelength and the absorption coefficient increases as the wavelength decreases. Electron hole pairs (EHPs) are mainly created in the depletion region and due to the built-in potential and electric field, electrons move to the n region and the holes to the p region. When an external load is applied, the excess electrons travel through the load to recombine with the excess holes. Electrons and holes are also generated with the p and n regions, as seen from figure 2.1. The shorter wavelengths (higher absorption coefficient) are absorbed in the n region and the longer wavelengths are absorbed in the bulk of the p region. Some of the EHPs generated in these regions can also contribute to the current. Typically, these are EHPs that are generated within the minority carrier diffusion length, Le for electrons in the p side and L_h for holes in the n side. Carriers produced in this region can also diffuse into the depletion region and contribute to the current. Thus, the total width of the region that contributes to the solar cell current is $w_d + L_e + L_h$, where w_d is the depletion width. The carriers are extracted by metal electrodes on either side.

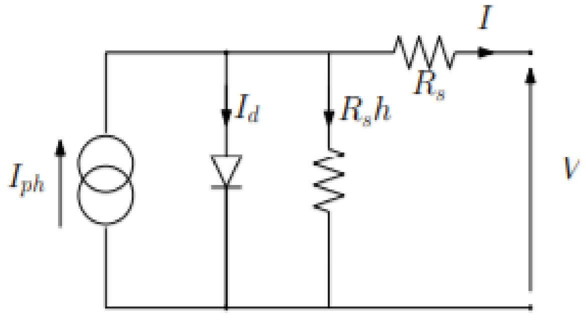
Photo generated carriers in a solar cell due to absorption of light. w is the width of the depletion region, while Lh and Le are minority carrier diffusion lengths in the n and p regions. The amount of absorption reduces with depth and hence the depletion region must be close to the surface to maximize absorption. This is achieved by having a thin n region



2.1 Principle of operation of a PN junction solar cell.

2.2 Solar cell diode model

The single diode equivalent circuit of a solar cell is a current source in parallel with a single diode considering two lumped resistances which are the shunt (or parallel) resistance and the series resistance. The electrical configuration of this model is shown in figure 2.2



2.2 Equivalent electrical circuit of the single diode solar cell model.

The equivalent model is composed from a current source which generates the photocurrent Iph and a single diode representing the diffusion phenomenon traversed by a current Id. The leakage current from the shunt resistance Rsh is the Ish current which is caused by the distributed manufacturing defect inside the solar cell structure. The series resistance Rs reduce the solar cell efficiency by dissipating the power in thermal form through the hole junction substrates. Under illumination, the current I delivered by the cell can be expressed in terms of the photocurrent Iph, the current Id through the diode and the leakage current Ish according to the following relationship.

2.3 Circuit Equations

$$I = I_{ph} - I_d - I_{sh} \qquad (1)$$

The relationship between the currents Id, and the voltage V across, is described by the following equation:

$$I_d = I_s\,[\exp\,[\,(V + R_sI)/\,nV_t] - 1] \qquad (2)$$

The I_{sh} current represents the leakage current caused by the shunt resistance R_{sh}, and its relationship with the voltage V across the cell, could be written as follows:

$$I_{sh} = (V + R_sI)/\,R_{sh} \qquad (3)$$

Substituting the currents Id and I_{sh} by their expressions, equation (1) becomes:

$$I = I_{ph} - I_s\,[\,\exp\,[(V + R_sI)\,/nV_t] - 1] - [(V + R_sI)/\,R_{sh}] \qquad (4)$$

with:

$$V_t = (T_cK)/\,q \qquad (5)$$

where,

• I_s: The reverse saturation current of the diffusion phenomenon,

• n: The quality factor of the diode which is between 1 and 2

• R_s: Lumped Series resistance

• R_{sh}: Lumped Shunt resistance

• T_c: The temperature of the operating cell (°C)

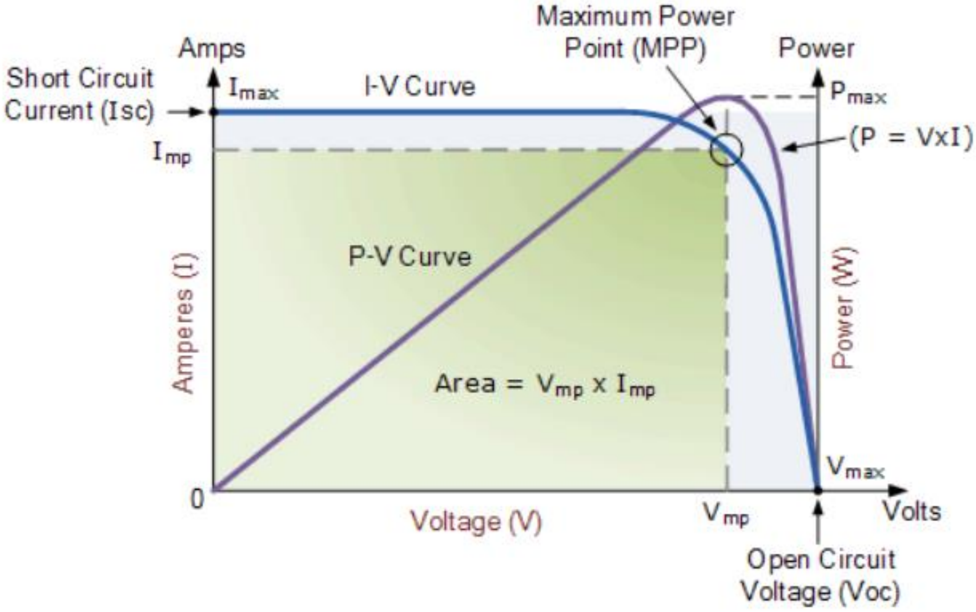
• k: The Boltzmann constant (k = 1.38 × 10−23 J/K)

• q: The charge of an electron (q = 1.6 × 10−19 C).

2.4 Output parameters of a solar cell

- **2.4.1 I-V and P-V characteristics**

  Solar Cell I-V and P-V Characteristic Curves show the current -voltage (I-V) characteristics and power-voltage characteristics(P-V) of a particular photovoltaic (P-V) cell, module or array giving a detailed description of its solar energy conversion ability and efficiency. Knowing the electrical I-V characteristics (more importantly P_{max}) of a solar cell, or panel is critical in determining the device's output performance and solar efficiency.



2.3 I-V and P-V characteristics of a solar cell

- **2.4.2 Short circuit current (Isc)**

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}, the short-circuit current is shown on the IV curve above. The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

when the cell is operated at short circuit, V = 0 and the current I through the terminals is defined as the short-circuit current. It can be shown that for a high-quality solar cell (low R_S and I_0, and high R_{SH}) the short-circuit current I_{SC} is:

$$I_{sc} \approx I_{ph}$$

Where,

I_{ph} = Photo generated current

- **2.4.3 Open circuit voltage (Voc)**

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount 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 shown on the IV curve above. When the cell is operated at open circuit, I = 0 and the voltage across the output terminals is defined as the open-circuit voltage. Assuming the shunt resistance is high enough to neglect the final term of the characteristic equation, the open-circuit voltage V_{OC} is:

$$V_{oc} \approx (NkT/q) \ln (I_{ph}/I_o +1)$$

Where,

n = Diode ideality factor

q = Elementary charge

k = Boltzmann's constant

T = Absolute temperature

I_0 = Reverse saturation current

I_{ph} = Photo generated current

2.4.4 Fill Factor (FF)

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF 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 area of the largest rectangle which will fit in the IV curve.

$$FF = (P_{max}/P_t) = (I_{mp}.\ V_{mp})/(I_{sc}.\ V_{oc})$$

Where,

P_{max}= Maximum power

P_t = Theoretical power

I_{mp} = current corresponding to Pmax

V_{mp} = Voltage corresponds to Pmax

I_{sc} = Short circuit current

V_{oc} = open circuit voltage

2.4.5 Efficiency (η)

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C.

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

$$\eta = V_{oc}\ I_{sc}\ FF/\ P_{in}$$

where,

V_{oc} = Open circuit voltage

I_{sc} = Short circuit current

FF = Fill Factor and P_{in} = Input power

Chapter 3-CIGS Solar cells and synthesis

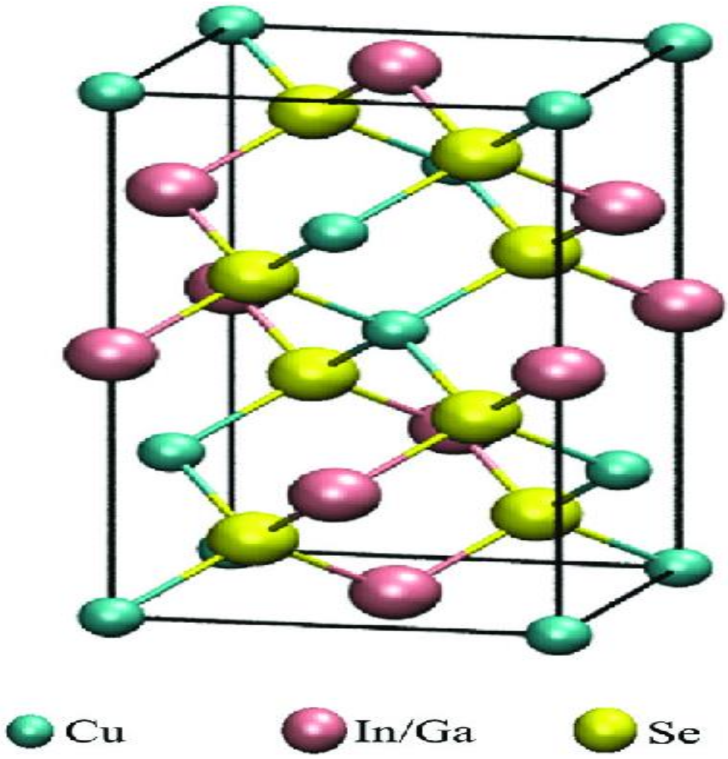
3.1 CIGS solar cells

A copper indium gallium selenide solar cell (CIGS) is a thin-film solar cell used to convert sunlight into electric power. It is manufactured by depositing a thin layer of copper, indium, gallium and selenide on glass or plastic backing, along with electrodes on the front and back to collect current. Because the material has a high absorption coefficient and strongly absorbs sunlight, a much thinner film is required than of other semiconductor materials.

CIGS is one of three mainstream thin-film PV technologies, the other two being cadmium telluride and amorphous silicon. Like these materials, CIGS layers are thin enough to be flexible, allowing them to be deposited on flexible substrates. However, as all of these technologies normally use high-temperature deposition techniques, the best performance normally comes from cells deposited on glass.

3.2 Material properties of CIGS material

CIGS is a I-III-VI_2 compound semiconductor material composed of copper, indium, gallium, and selenium. The material is a solid solution of copper indium selenide (often abbreviated "CIS") and copper gallium selenide, with a chemical formula of $CuIn_xGa_{(1-x)}Se_2$, where the value of x can vary from 1 (pure copper indium selenide) to 0 (pure copper gallium selenide). It is a tetrahedral bonded semiconductor, with the chalcopyrite crystal structure. The bandgap varies continuously with x from about 1.0 eV (for copper indium selenide) to about 1.7 eV (for copper gallium selenide).

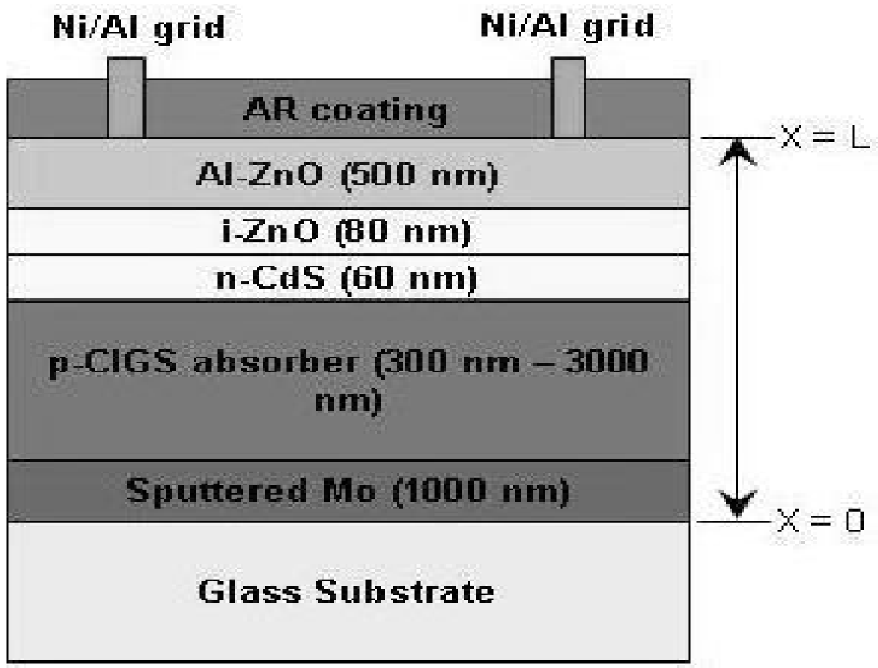


3.1 CIGS chalcopyrite structure

3.3 Structure of CIGS solar cell

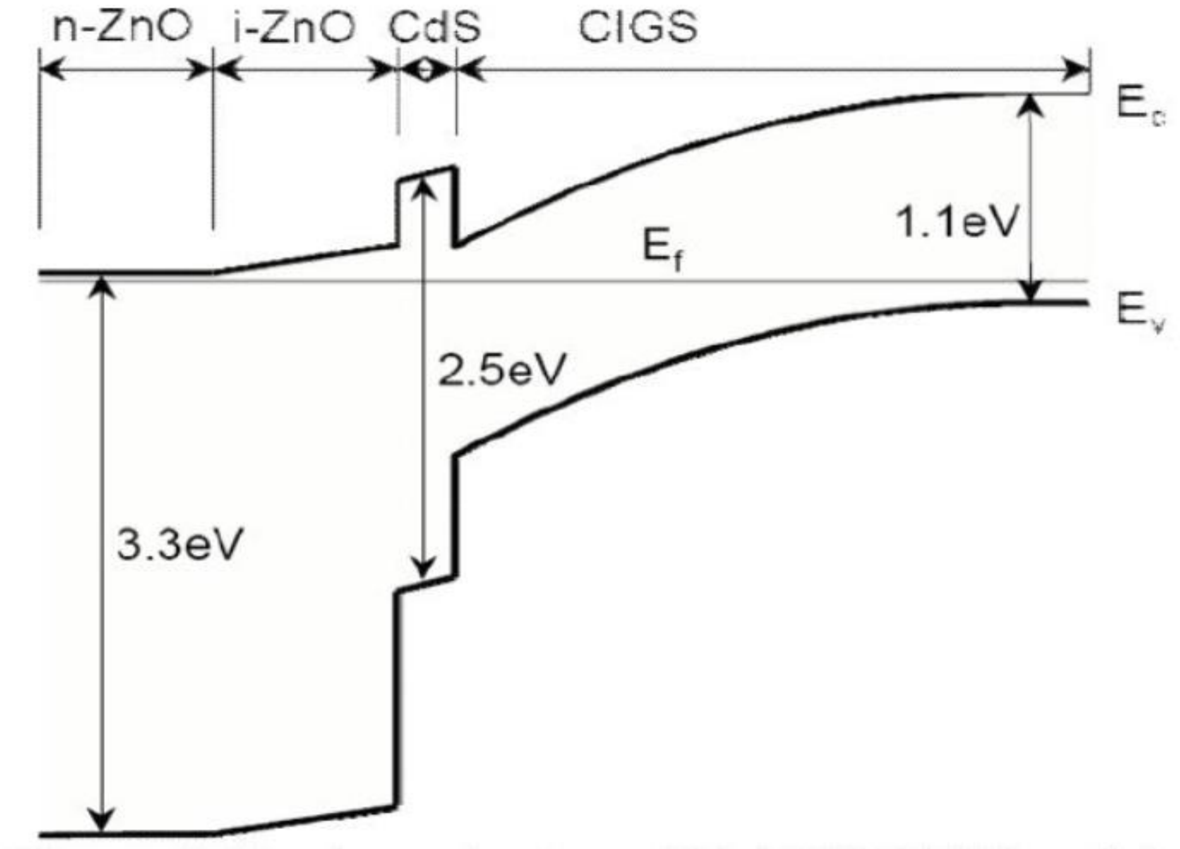
The most common device structure for CIGS solar cells is shown in the diagram (see Figure 3.2: Structure of a CIGS device). Soda-lime glass of about of 1–3 millimeters thickness is commonly used as a substrate, because the glass sheets contains sodium, which has been shown to yield a substantial open-circuit voltage increase, notably through surface and grain boundary defects passivation. However, many companies are also looking at lighter and more flexible substrates such as polyimide or metal foils. A molybdenum (Mo) metal layer is deposited (commonly by sputtering) which serves as the back contact and reflects most unabsorbed light back into the CIGS absorber. Following molybdenum deposition a p-type CIGS absorber layer is grown by one of several unique methods. A thin n-type buffer layer is added on top of the absorber. The buffer is typically cadmium sulfide (CdS) deposited via chemical bath deposition. The buffer is overlaid with a thin, intrinsic zinc oxide layer (i-ZnO) which is capped by a thicker, aluminum (Al) doped ZnO layer. The i-ZnO layer is used to protect the CdS and the absorber layer from sputtering damage while depositing the ZnO: Al window layer, since the latter is usually deposited by DC sputtering, known as a damaging process. The Al doped ZnO serves as a transparent conducting oxide to collect and move electrons out of the cell while absorbing as little light as possible.

The $CuInSe_2$-based materials that are of interest for photovoltaic applications include several elements from groups I, III and VI in the periodic table. These semiconductors are especially attractive for solar applications because of their high optical absorption coefficients and versatile optical and electrical characteristics, which can in principle be manipulated and tuned for a specific need in a given device



3.2 Structure of CIGS device

3.4 Bandgap structure of CIGS solar cells



3.3 Bandgap structure of cigs solar cell

3.5 Comparison with other solar cells

Unlike conventional crystalline silicon cells based on a homojunction, the structure of CIGS cells is a more complex heterojunction system. A direct bandgap material, CIGS has very strong light absorption and a layer of only 1–2 micrometers (μm) is enough to absorb most of the sunlight. By comparison, a much greater thickness of about 160–190 μm is required for crystalline silicon.

The active CIGS-layer can be deposited in a polycrystalline form directly onto molybdenum (Mo) coated on a variety of several different substrates such as glass sheets, steel bands and plastic foils made of polyimide. This uses less energy than smelting large amounts of quartz sand in electric furnaces and growing large crystals, necessary for conventional silicon cells, and thus reduces its time significantly. Also unlike crystalline silicon, these substrates can be flexible.

In the highly competitive PV industry, pressure increased on CIGS manufacturers, leading to the bankruptcy of several companies, as prices for conventional silicon cells declined rapidly in recent years. However, CIGS solar cells have become as efficient as multicrystalline silicon cells the most common type of solar cells. CIGS and CdTe-PV remain the only two commercially successful thin-film technologies in a globally fast-growing PV market.

3.6 Development of CIGS solar cells

The first CIGS based thin film solar cell was based upon the heterojunction between CIGS and a relatively thick layer of CdS. Some disadvantages lead to the choice of extremely reducing the thickness of the CdS layer down to about 50 nm. For CdS conductivity got reduced due to reducing the thickness. Therefore, doped and wide bandgap semiconductor as a window layer in CIGS based thin film solar cell device has been introduced. Nonetheless, the reduced thickness of the buffer layer causes the window layer, to be involved in the heterojunction formation, which directly affects the electronic properties at the CIGS/CdS interface.

Transparent conductive oxide (TCO) used in CIGS based thin film solar cells is a double layer composed of a thin undoped zinc oxide layer, and a thicker aluminum doped zinc oxide (ZnO: Al). The role of these layers in CIGS based thin film solar cells can be summarized as:

- Contribute to the formation of the heterojunction.
- The lateral transport of the photocurrent with the lowest possible ohmic losses.
- The transmission of light to the absorber.

Molybdenum back contact plays an important role in CIGS solar cells. The thermal stability of Mo thin films is indispensable to CIGS solar cells. CIGS films are deposited above 500 °C. Mo has low resistivity, low sheet resistance. In addition to good ohmic contact with the CIGS thin film, it has high reflectivity to reflect the light back to the absorption layer for increasing photon absorption and transforming light energy into power

Chapter 4- Experimental procedure

4.1 Input parameters

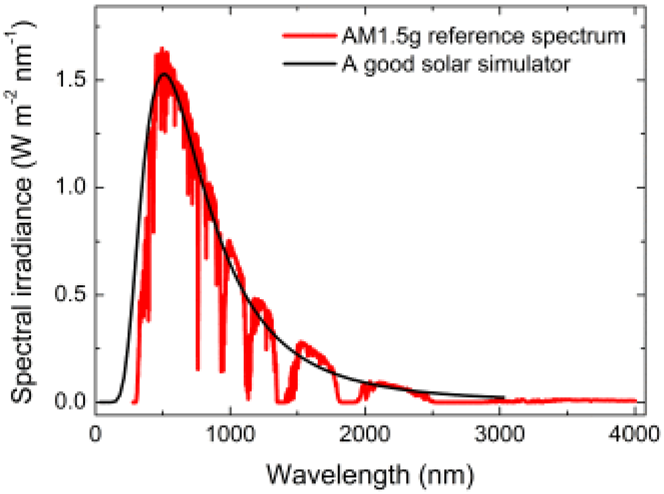
- **AM 1.5 solar irradiance**

  The air mass coefficient defines the direct optical path length through the Earth's atmosphere, expressed as a ratio relative to the path length vertically upwards, i.e. at the zenith. The air mass coefficient can be used to help characterize the solar spectrum after solar radiation has traveled through the atmosphere. The air mass coefficient is commonly used to characterize the performance of solar cells under standardized conditions, and is often referred to using the syntax "AM" followed by a number. "AM1.5" is almost universal when characterizing terrestrial power-generating panels. For a path length L through the atmosphere, and solar radiation incident at angle z relative to the normal to the Earth's surface, the air mass coefficient is:

$$AM = L/L_o \approx 1/\cos z$$

  Where, L_o is the zenith path length (i.e. normal to the Earth's surface) at sea level and z is the zenith angle in degrees.

  The air mass number is thus dependent on the Sun's elevation path through the sky and therefore varies with time of day and with the passing seasons of the year, and with the latitude of the observer.



4.1 AM 1.5 solar radiation spectrum

Solar panels do not generally operate under exactly one atmosphere's thickness: if the sun is at an angle to the Earth's surface the effective thickness will be greater. Many of the world's major population centers, and hence solar installations and industry, across Europe, China, Japan, the United States of America and elsewhere (including northern India, southern Africa and Australia) lie in temperate latitudes. An AM number representing the spectrum at mid-latitudes is therefore much more common.

"AM1.5", 1.5 atmosphere thickness, corresponds to a solar zenith angle of z=48.2°. While the summertime AM number for mid-latitudes during the middle parts of the day is less than 1.5, higher figures apply in the morning and evening and at other times of the year. Therefore, AM1.5 is useful to represent the overall yearly average for mid-latitudes. The specific value of 1.5 has been selected in the 1970s for standardization purposes, based on an analysis of solar irradiance data in the conterminous United States. Since then, the solar industry has been using AM1.5 for all standardized testing or rating of terrestrial solar cells or modules, including those used in concentrating systems.

- **Material properties used for simulation**

Parameter	**Zno:Al**	**i-Zno**	**Cds**	**CIGS**
d(μm)	0.5	0.2	0.05	3
E	9	9	10	13.6
E_g(eV)	3.3	3.3	2.4	1.18
X(eV)	4.4	4.4	4.2	4.5
$N_c(1/cm^3)$	$2.2*10^{18}$	$2.2*10^{18}$	$2.2*10^{18}$	$2.2*10^{18}$
$N_v(1/cm^3)$	$1.8*10^{19}$	$1.8*10^{19}$	$1.8*10^{19}$	$1.8*10^{19}$
μn (cm^2/V.s)	50	50	10	300
Mp (cm^2/V.s)	5	5	1	30
Nd($1/cm^3$)	$1*10^{17}$	0	$1.1*10^{18}$	0
Na($1/cm^3$)	0	0	0	$2*10^{16}$

4.1 Simulation Material Properties of CIGS solar cells

Parameter	Zno:al	zno	cds	CIGS
Defect Type	donor	donor	acceptor	donor
Energy level(eV)	1.65	1.65	1.2	0.6
Deviation(eV)	0.1	0.1	0.1	0.1
σ_n(cm^2)	1e^{-12}	1e^{-12}	1e^{-17}	1e^{-13}
σ_p(cm^2)	1e^{-15}	1e^{-15}	1e^{-12}	1e^{-15}
N_t(cm^{-3})	1e^{17}	1e^{17}	1e^{18}	1e^{14}

4.2 Simulation material Gaussian defects for CIGS solar cell

Parameter	Front Contact	Back Contact
Φ_b(eV)	0	0.9
S_n(cm/s)	1e7	2e7
S_p(cm/s)	1e7	2e7
RF	0.03	0.8

4.3 Contact parameters applied for the simulation

Where, d = Layer thickness,

ε = Permittivity,

X = Electron affinity,

N_c/ N_v = Effective density of states in the conduction/valance band

μ_n/μ_p = Mobility of electrons/holes,

N_d/ N_a = Doping concentration,

σ_n/ σ_p = Capture cross section of electrons/holes,

N_t = Defect concentration

Φ_b = Potential barrier height,

S_n/ S_p = Surface recombination velocity of electrons/holes

4.2 AMPS 1D Modelling

What is AMPS?

AMPS stands for **A**nalysis of **M**icroelectronic and **P**hotonic **S**tructures. It was engineered to be a very general and versatile computer simulation tool for the analysis of device physics and device design. It is a one-dimensional (1-D) device physics code which is applicable to any two terminal devices. It can be for diode, sensor, photo-diode, and photovoltaic device analysis.

The objective of AMPS is to teach how material properties (e.g., band gap, affinity, doping, mobility's, doping, gap state defect distributions in the bulk and at interfaces, etc.) and device design/structure together control device physics and thereby device response to light, impressed voltage, and temperature. AMPS allows users to learn the "whys" of device response to a given situation (i.e., light bias, voltage bias, and temperature) through exploring and comparing band diagram, current component, recombination, generation, and electric field plots available from AMPS as a function of light intensity, voltage, temperature, and position.

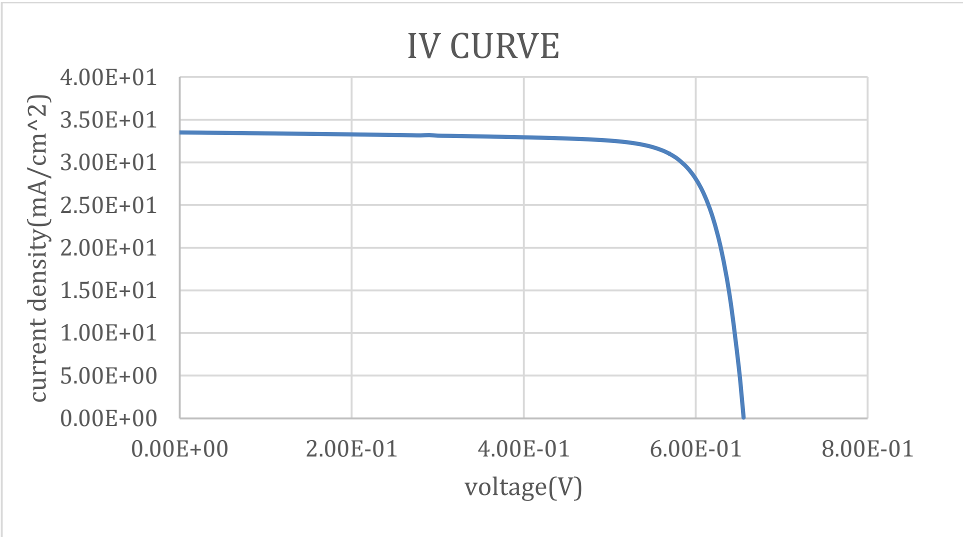
Capabilities

AMPS-1D is currently capable of:

- Generating I-V characteristics under illumination and without illumination.
- Generating QE (SR) for solar cells and photo diodes under voltage and light bias.
- Treating devices composed of single crystal, poly-crystalline, or amorphous materials, or any combination thereof.

4.3 Simulation results

I have simulated the CIGS solar cell using default parameter values in AMPS-1D simulation software. I have obtained Short circuit current density(Jsc), Open circuit voltage (Voc), Fill Factor (FF), Efficiency (η) and Quantum efficiency(QE). In this simulation we are getting negative Voc because in AMPS -1D anode and cathode are fixed, if our P type layer is at top then we will get positive Voc and if our P type layer is at bottom of the cell then we will get negative Voc.



4.2 I-V curve for default values

Output values:

Current density(Jsc) =33.295 mA/cm^2

Open circuit voltage(Voc) = 0.67 V

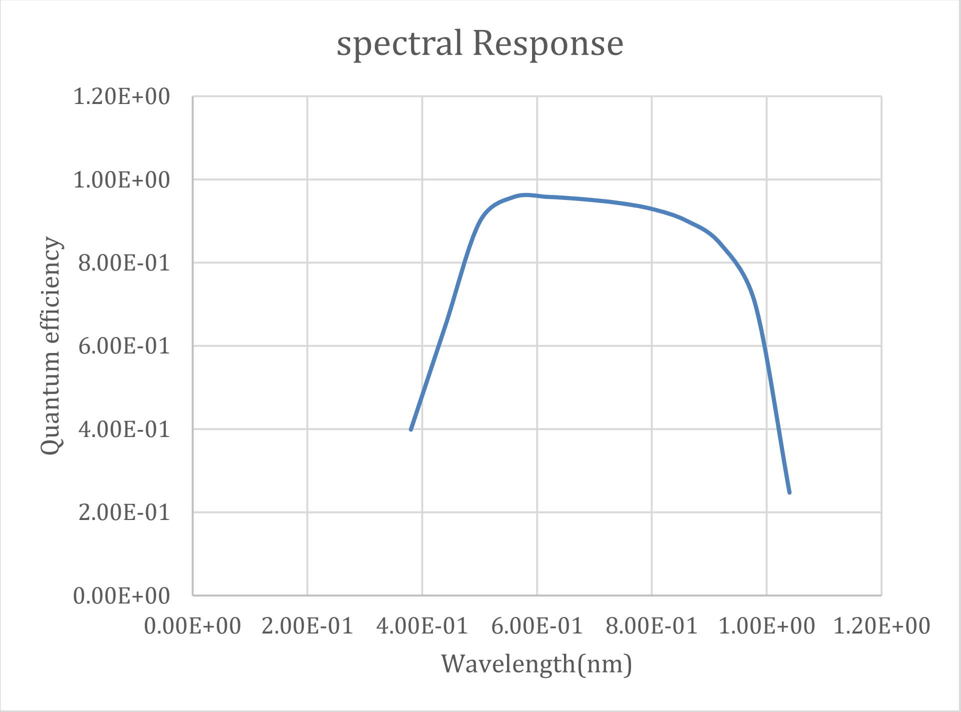
Fill Factor(FF) = 80.7%

Efficiency(η) = 17.982%

Spectral response

The spectral response is conceptually similar to the quantum efficiency. The quantum efficiency gives the number of electrons output by the solar cell compared to the number of photons incident on the device, while the spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell. The ideal spectral response is limited at long wavelengths by the inability of the semiconductor to absorb photons with energies below the band gap. This limit is the same as that encountered in quantum efficiency curves. However, unlike the square shape of QE curves, the spectral response decreases at small photon wavelengths. At these wavelengths, each photon has a large energy, and hence the ratio of photons to power is reduced. Any energy above the band gap energy is not utilized by the solar cell and instead goes to heating the solar cell. The inability to fully utilize the incident energy at high energies, and the inability to absorb low energies of light represents a significant power loss in solar cells consisting of a single p-n junction.

Spectral response is important since it is the spectral response that is measured from a solar cell, and from this the quantum efficiency is calculated. The quantum efficiency can be determined from the spectral response by replacing the power of the light at a particular wavelength with the photon flux for that wavelength.



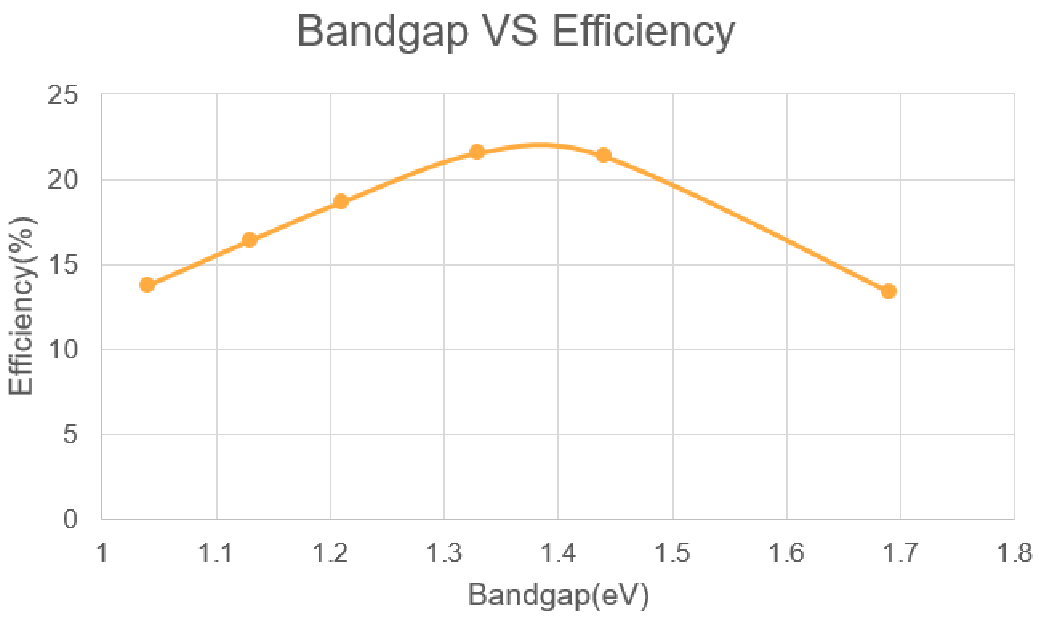
4.3 spectral response of CIGS solar cells

4.4 Effect of bandgap on efficiency

The material is a solid solution of copper indium selenide and copper gallium selenide, with a chemical formula of $CuIn_xGa_{(1-x)}Se_2$The value of x can vary from 1 (pure copper indium selenide) to 0 (pure copper gallium selenide). The band gap varies continuously with *x* from about 1.0 eV (for copper indium selenide) to about 1.7 eV (for copper gallium selenide). Simulations were performed for different values of band gaps and results were taken.

Eg(eV)	**Jsc(mA/cm2)**	**Voc(V)**
1.04	33.281	0.53
1.13	33.154	0.619
1.21	33.064	0.699
1.33	32.931	0.819
1.44	32.760	0.91
1.69	32.131	0.937

4.4 Jsc and Voc for different bandgap values



4.4 Bandgap verses efficiency

Results and conclusions

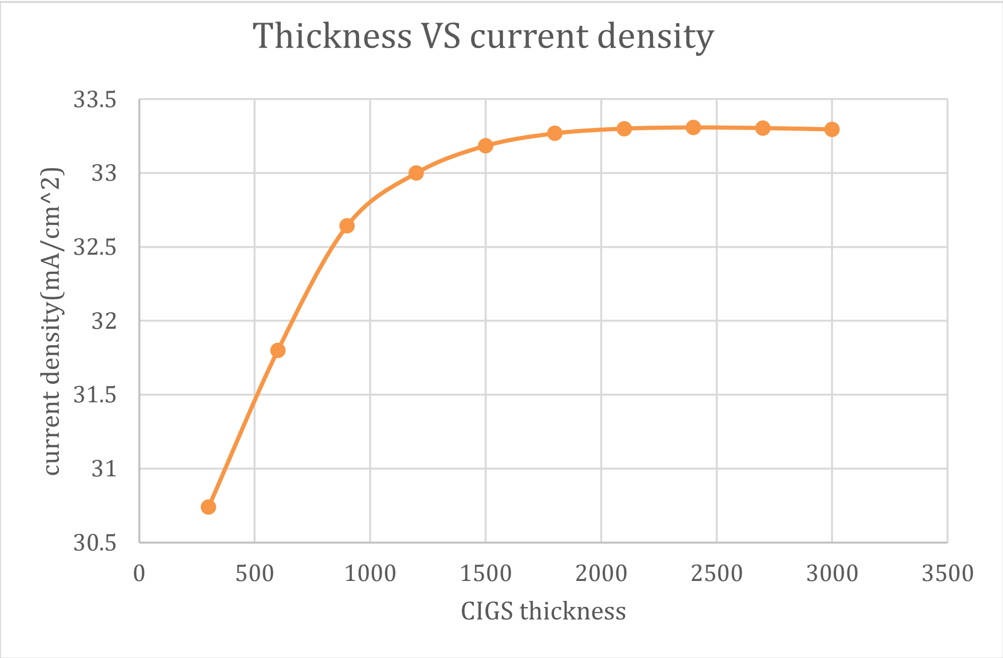
•The bandgap energy of the CuIn1-xGaxSe2 (CIGS) films is varied in the range from 1 to 1.7 eV with the corresponding Ga content in the CIGS films from x = 0 to 1

• As the p-CIGS layer is the absorber layer called base, increasing the bandgap of this layer reduces the absorption within this layer and therefore the short-circuit current decreases.

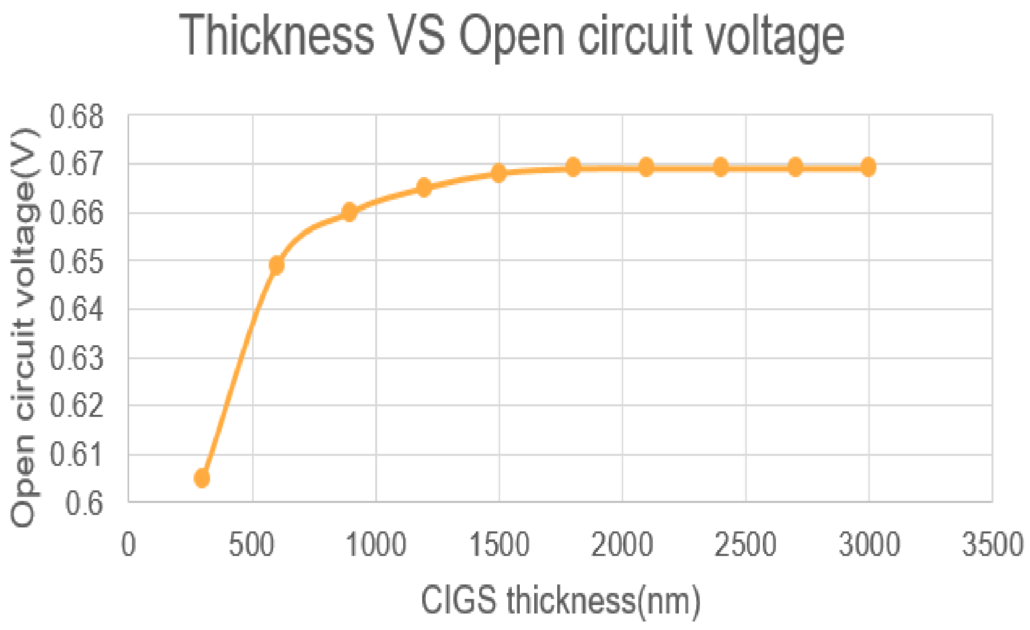
•However, the open circuit voltage increases, as it varied linearly with the bandgap. The compromise between these two phenomena leads to an optimal band gap value of 1.33 eV giving a conversion efficiency of about 21.531%.

4.5 Effect of thickness

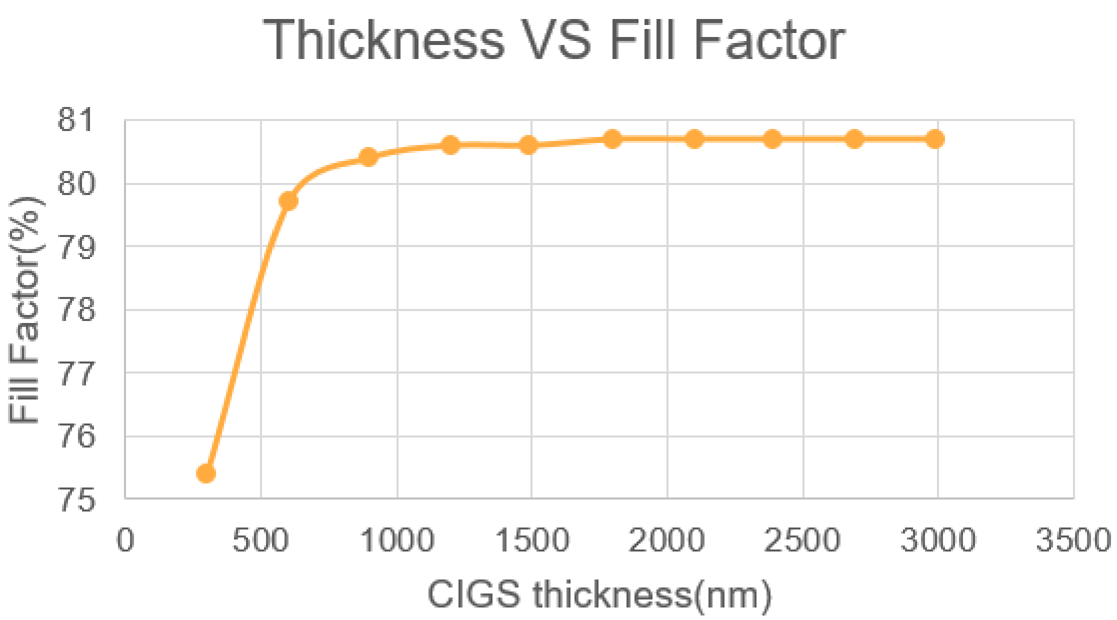
The thickness of the CIGS absorber layer was varied from 300nm to 3000nm.By changing the thickness change in short circuit current density, open circuit voltage, fill factor and efficiency were observed.



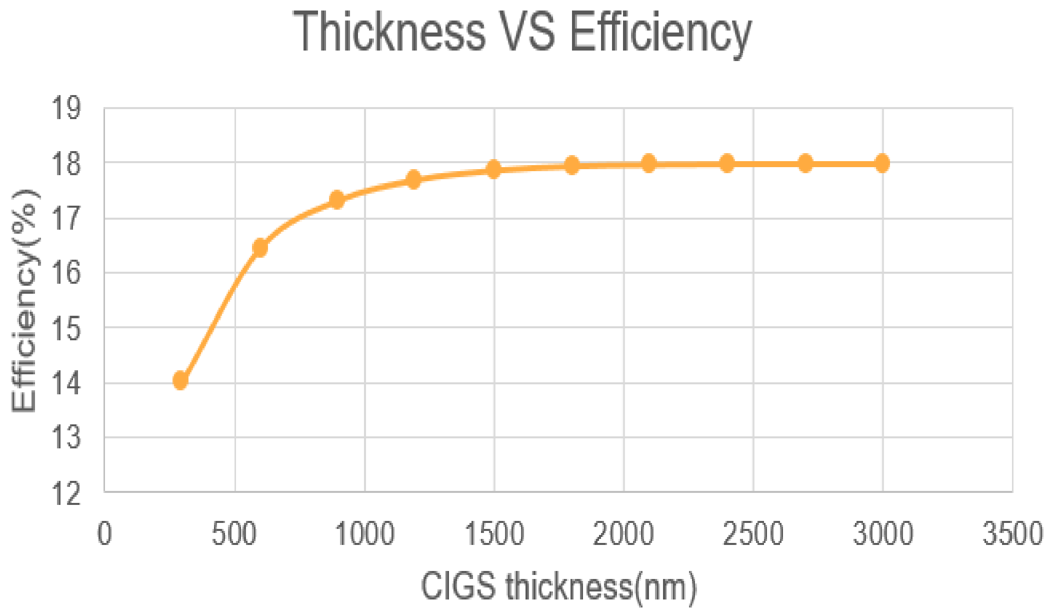
4.5 Short circuit current density verses CIGS thickness



4.6 Open circuit voltage verses CIGS thickness



4.7 Fill Factor verses CIGS thickness



4.8 Efficiency verses CIGS thickness

Results and conclusions

•The increase in the conversion efficiency is mainly due to the increase in the p-type CuIn1-xGaxSe2 absorber layer.

• As the p type layer is increased more photons with longer wavelength can be collected in the absorber layer.

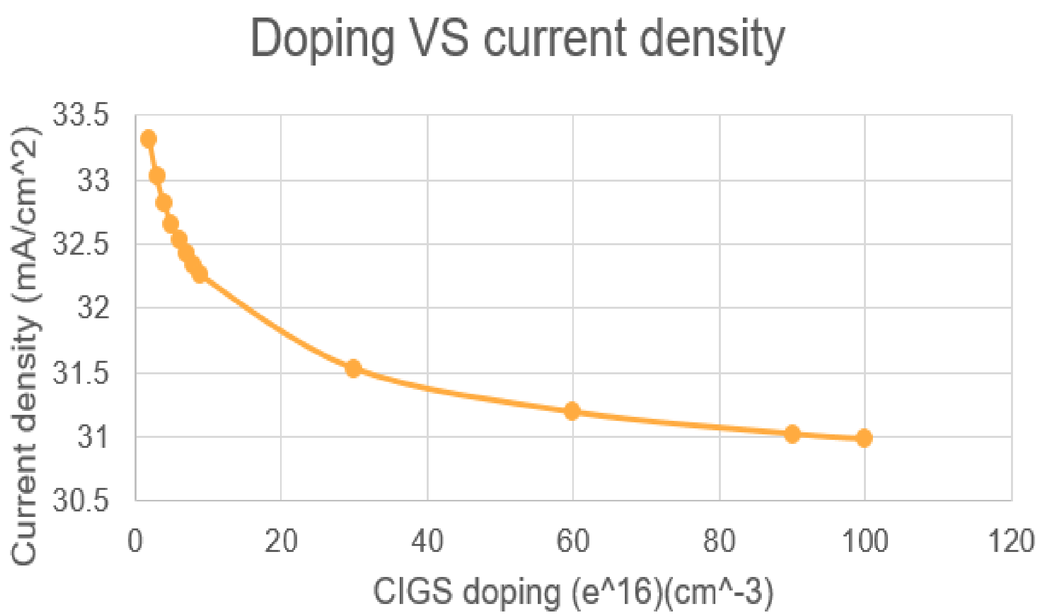
•This eventually will contribute to more electron-hole pair generation therefore increasing the open circuit voltage(Voc) and short circuit current(Jsc). An increase in Jsc and Voc will collectively increase the conversion efficiency of the solar cell.

•Meanwhile, a very thin absorber layer physically means the back contact and the depletion region are very close to each other which enhances the capturing of electrons by the back contact. This form of recombination process is detrimental to the cell performance as it affects both Voc and Jsc.

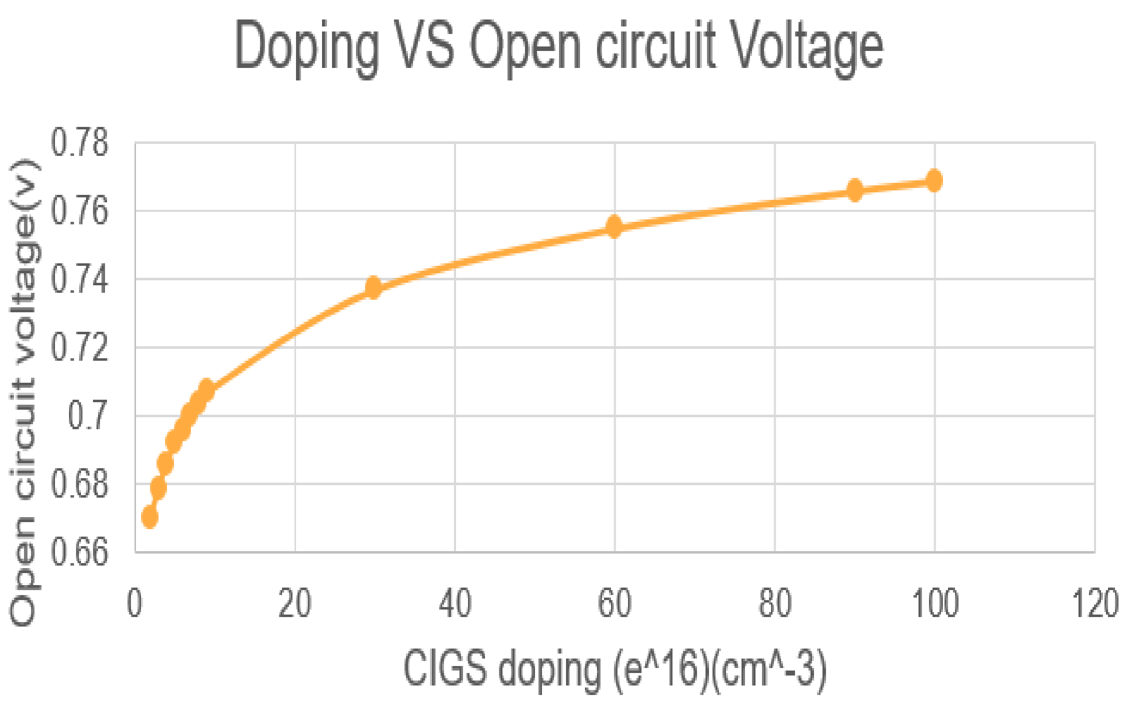
• After 2000nm all the values are getting saturated so I changed my initial thickness value from 3000nm to 2000nm by which we can decrease the material usage and have same efficiency.

4.6 Effect of Doping

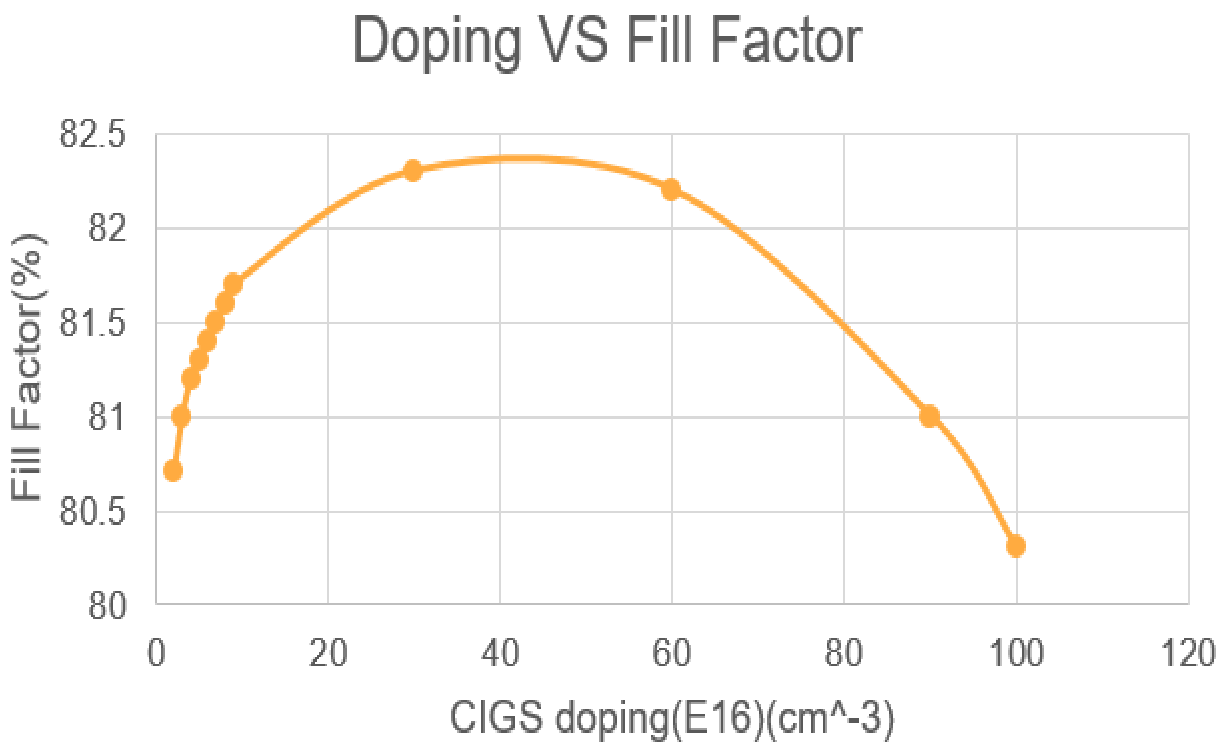
The doping of the CIGS absorber layer was varied from 1e^16 to 1e^18 (1/cm^3). By changing the doping value change in short circuit current density, open circuit voltage, fill factor and efficiency were observed.



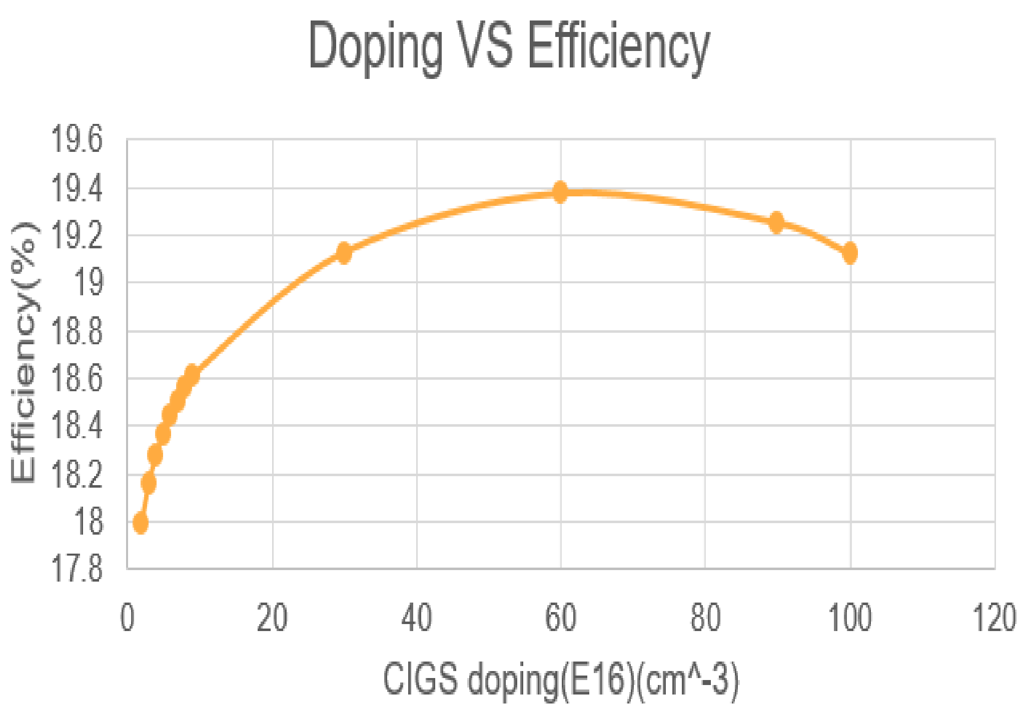
4.9 Short circuit current density verses Doping of CIGS material



4.10 Open circuit voltage verses Doping of CIGS material



4.11Fill Factor Verses Doping of CIGS material



4.12 Efficiency Verses Doping of CIGS material

Results and conclusions

• A higher doping level in CIGS layer will affect the mobility of charge carriers.

by increasing doping concentration mobility gets reduced.

•So, output current decreases with increasing doping concentration.

•But, open circuit voltage increases with increase in doping concentration by the following relation.

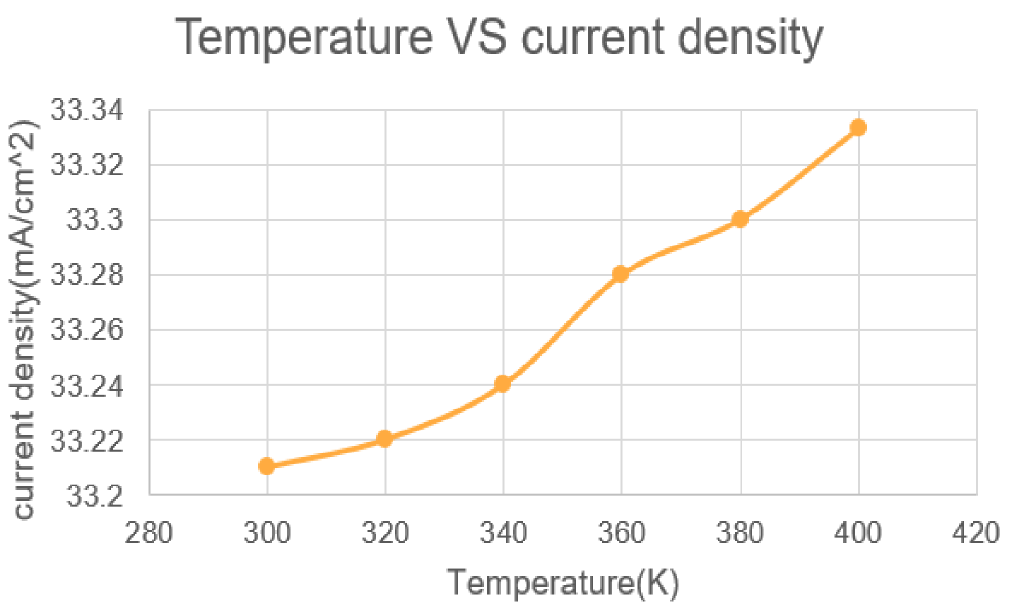
$$V_{OC} = \frac{kT}{q} \ln\left[\frac{(N_A + \Delta n)\Delta n}{n_i^2}\right]$$

•From the above results we can conclude that up to some values of doping concentration efficiency was increasing and after that value efficiency starts decreasing.

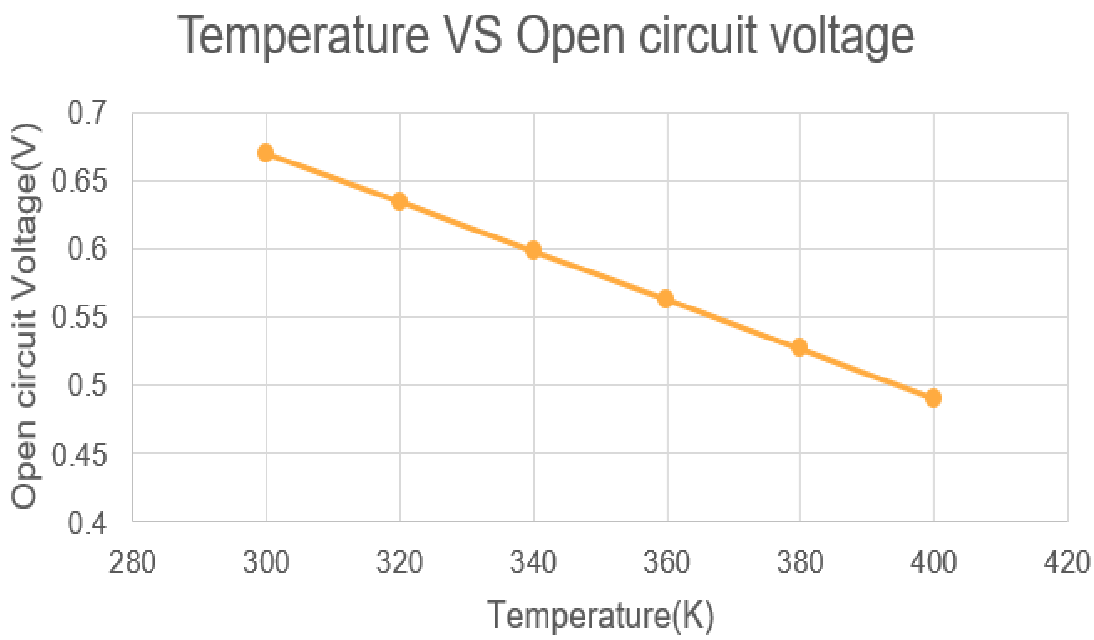
•From the above efficiency graph I have concluded optimal doping value as 6e^17(1/cm^3).

4.7 Effect of Temperature

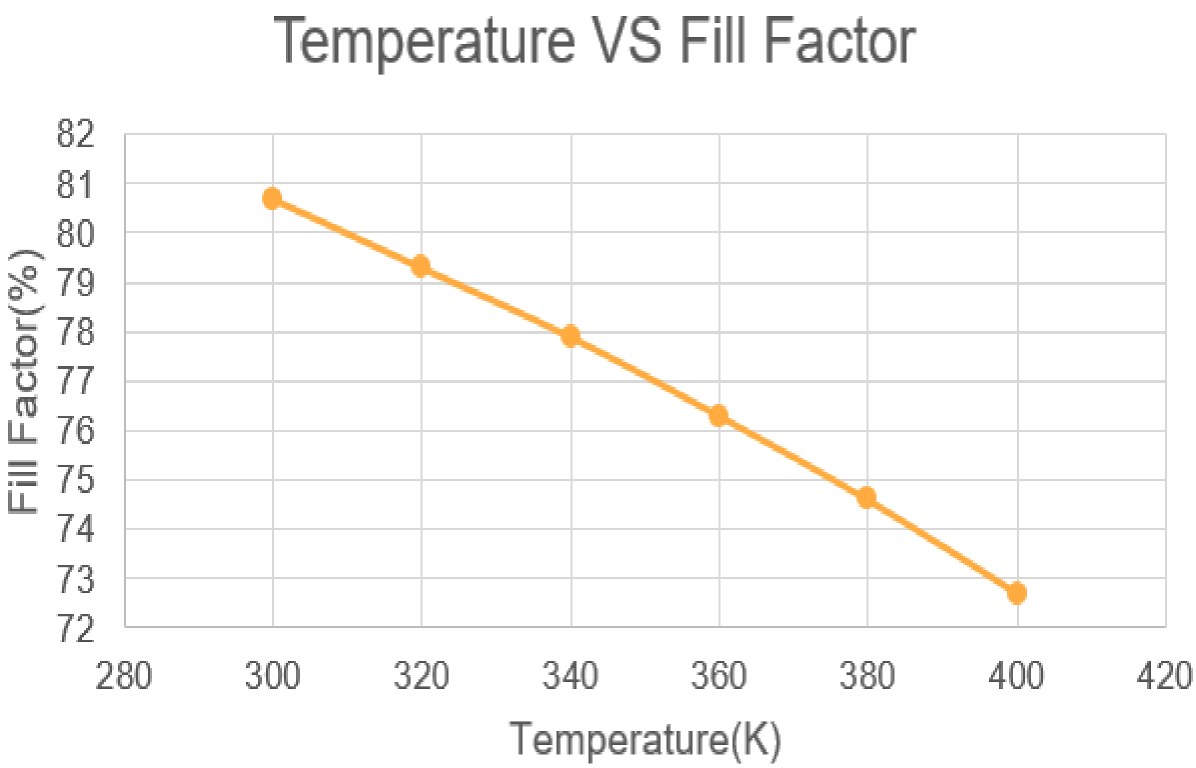
The temperature of the CIGS solar cell was varied from 300 K to 400K. By changing the temperature value change in short circuit current density, open circuit voltage, fill factor and efficiency were observed.



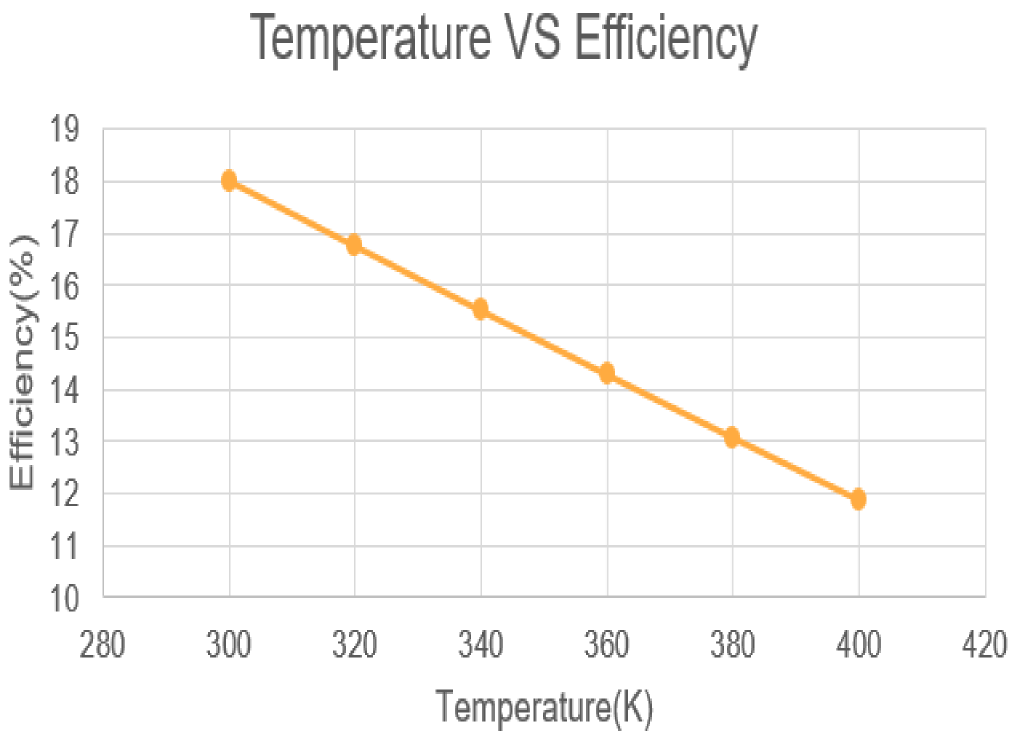
4.13 Short circuit current Verses temperature



4.14 Open circuit voltage Verses temperature



4.15 Fill Factor Verses temperature



4.16 Efficiency Verses temperature

Results and conclusions

•Increase in temperature reduces the band gap energy of absorber layer therefore it increases the absorption within this layer and therefore the short-circuit current increases.

•The open-circuit voltage decreases with temperature because of the temperature dependence of Io. The equation for Io from one side of a p-n junction is given by

$$V_{oc} \approx nV_t (\ln [I_{ph}/I_o])$$

$$I_o = qA (DNi^2/LN_d)$$

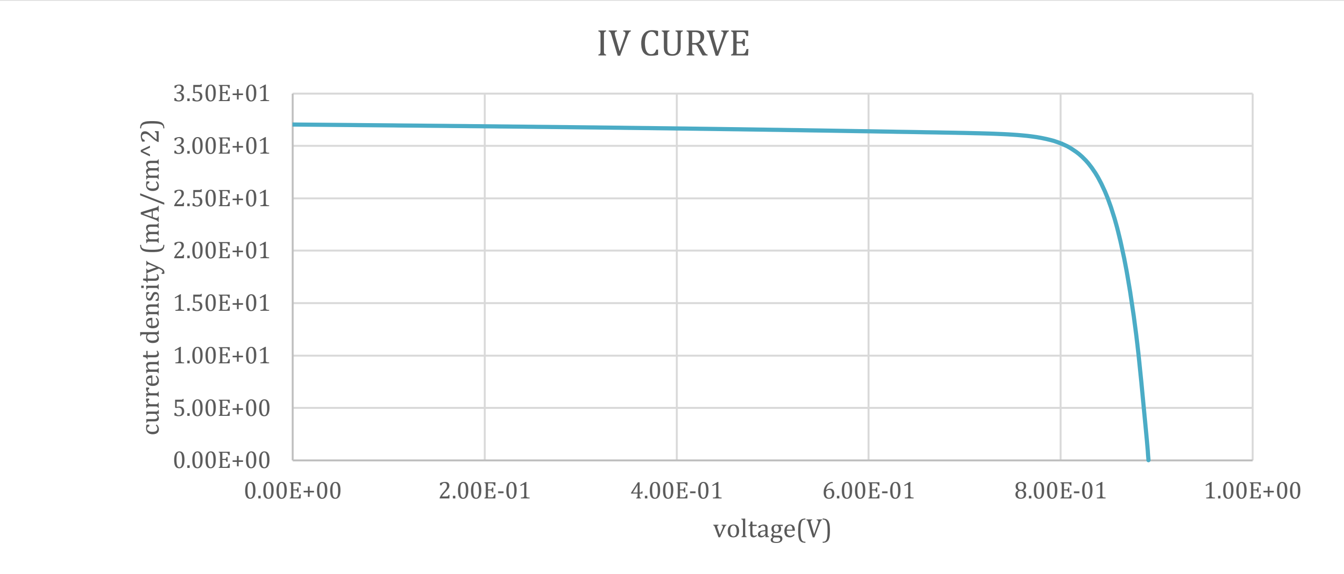
$$Ni^2 = BT^3 \exp(Ego/KT)$$

Where

q is the electronic charge
A is the area
D is the diffusivity of the minority carrier
L is the minority carrier diffusion length
N_d is the doping
N_i is the intrinsic carrier concentration
T is the temperature
Ego is the band gap linearly extrapolated to absolute zero and
B is a constant which is essentially independent of temperature
• Because of the more effect of decrease in Voc value, fill factor and efficiency got decreased with increase in temperature

Results after optimization

By taking the optimal values of bandgap, thickness, doping and temperature simulations were performed in AMPS 1D.



4.17 Simulation results with optimized values

Output values:

Current density(Jsc) =32.052 mA/cm^2

Open circuit voltage(Voc) = 0.892 V

Fill Factor(FF) = 84.7%

Efficiency(η) = 24.210%

Comparison of output parameters with default and optimized values

Output parameter	For default values	For optimized values
Jsc	33.295 mA/cm^2	32.052mA/cm^2
Voc	0.67 V	0.892V
FF	80.7%	84.7%
η	17.982%	24.210%

4.5 Comparison table

4.9 Module level Modelling

- **4.9.1 Solar cell modules**

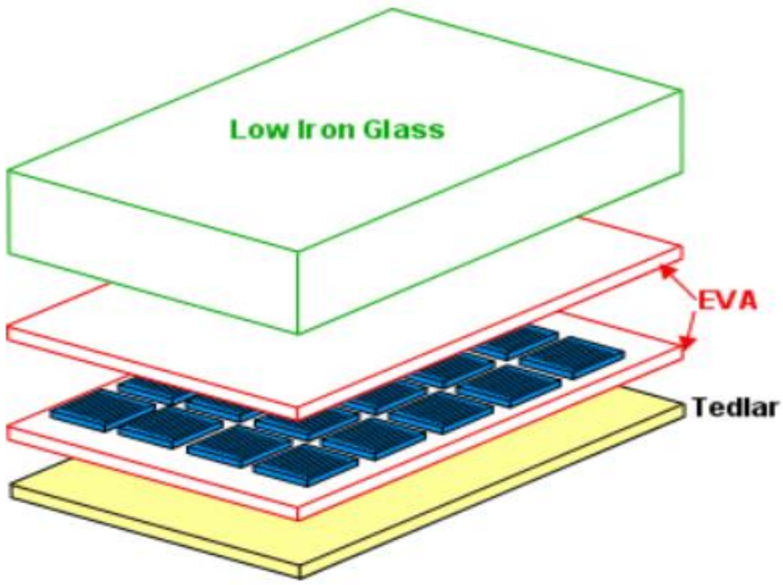
A PV module consists of a number of interconnected solar cells (typically 36 connected in series) encapsulated into a single, long-lasting, stable unit. The key purpose of encapsulating a set of electrically connected solar cells is to protect them and their interconnecting wires from the typically harsh environment in which they are used. For example, solar cells, since they are relatively thin, are prone to mechanical damage unless protected. In addition, the metal grid on the top surface of the solar cell and the wires interconnecting the individual solar cells may be corroded by water or water vapour. The two key functions of encapsulation are to prevent mechanical damage to the solar cells and to prevent water or water vapour from corroding the electrical contacts.

Many different types of PV modules exist and the module structure is often different for different types of solar cells or for different applications. For example, amorphous silicon solar cells are often encapsulated into a flexible array, while bulk silicon solar cells for remote power applications are usually rigid with glass front surfaces.

Module lifetimes and warranties on bulk silicon PV modules are over 20 years, indicating the robustness of an encapsulated PV module. A typical warranty will guarantee that the module produces 90% of its rated output for the first 10 years and 80% of its rated output up to 25 years. A third party reinsurance company ensures these warranties are valid in the event the manufacturer goes bankrupt.

- **4.9.2 Module structure**

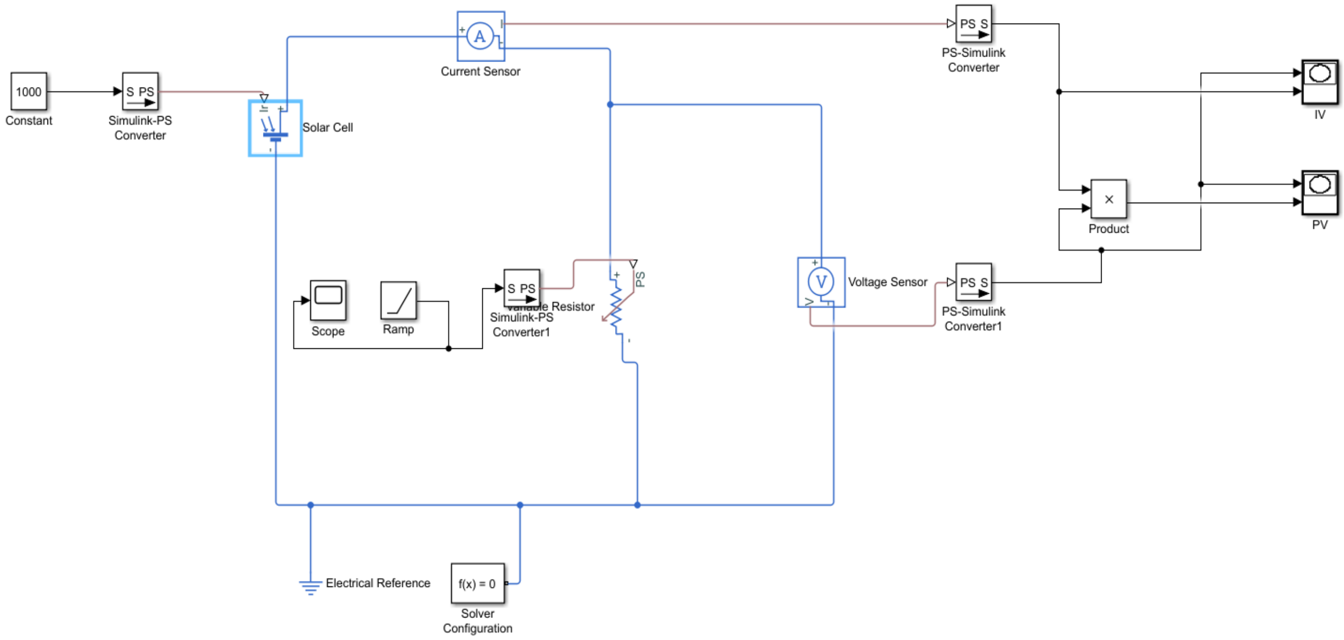
Most PV bulk silicon PV modules consist of a transparent top surface, an encapsulant, a rear layer and a frame around the outer edge. In most modules, the top surface is glass, the encapsulant is EVA (ethyl vinyl acetate) and the rear layer is Tedlar, as shown below.



4.18 Module structure

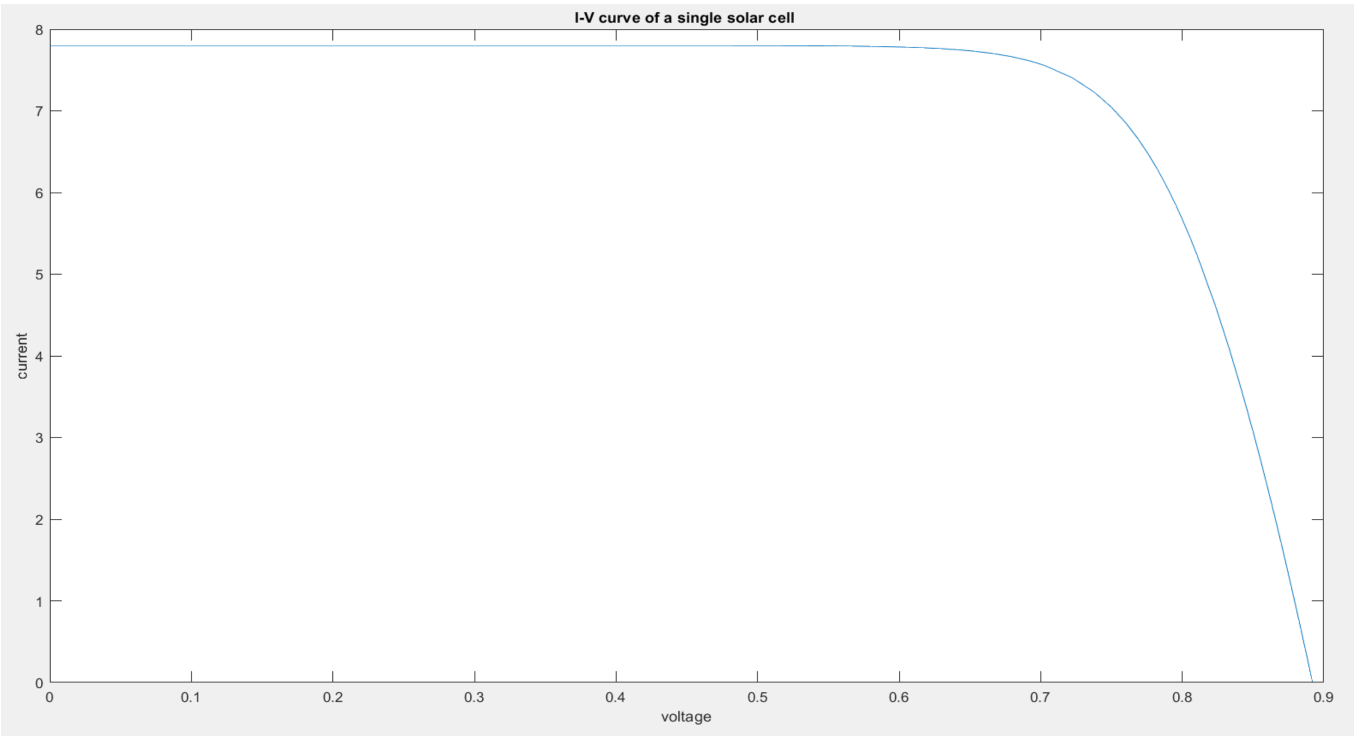
4.9.3 Matlab Simulink model

Simulated CIGS solar cell in AMPS 1D was a 1 dimensional structure. To study series and shunt losses at modular level I have taken the general dimensions of solar cell as 156mm* 156mm. I have multiplied the same area to short circuit current density of 1D CIGS solar cell to get short circuit current at cellular level. I have taken resistance per unit area of CIGS solar cell and multiplied with taken area to get series and shunt resistances. I have calculated short circuit current, open circuit voltage, series and shunt resistances and solar module is simulated to study the effect of series and shunt losses.



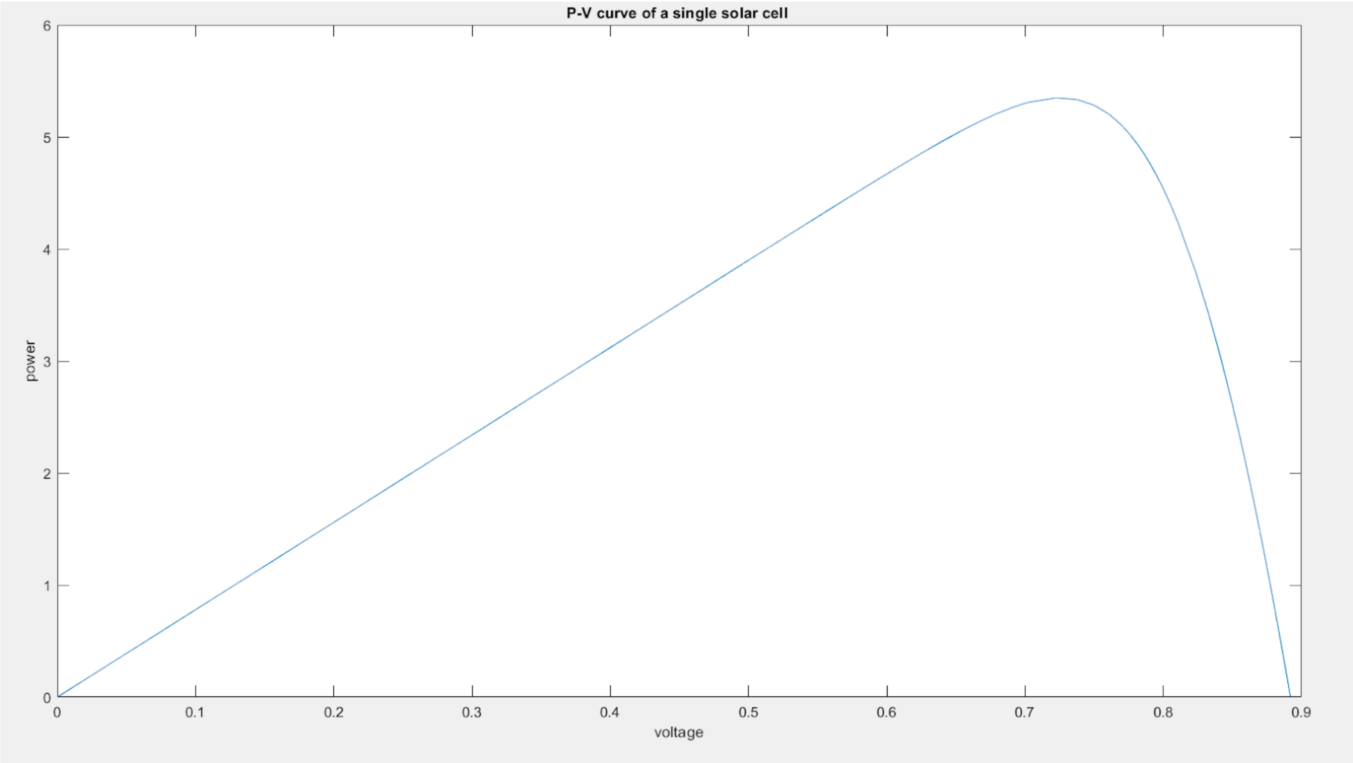
4.19 Single solar cell model in Simulink

I-V curve



4.20 I-V curve in Simulink

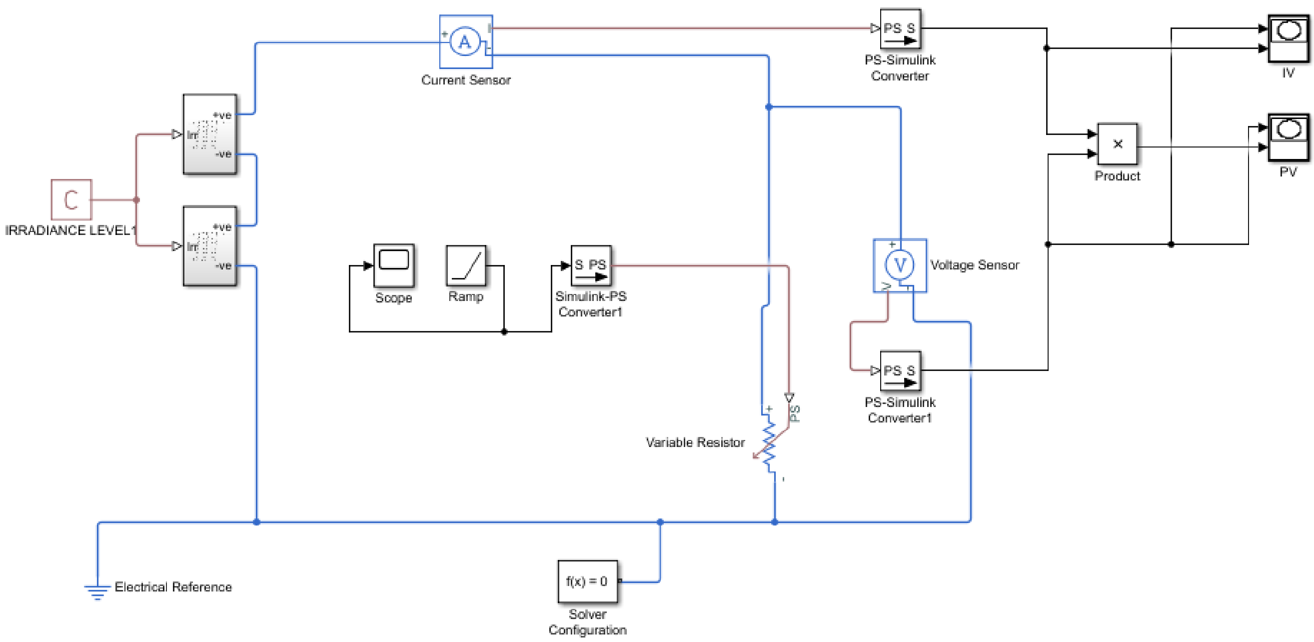
P-V Curve



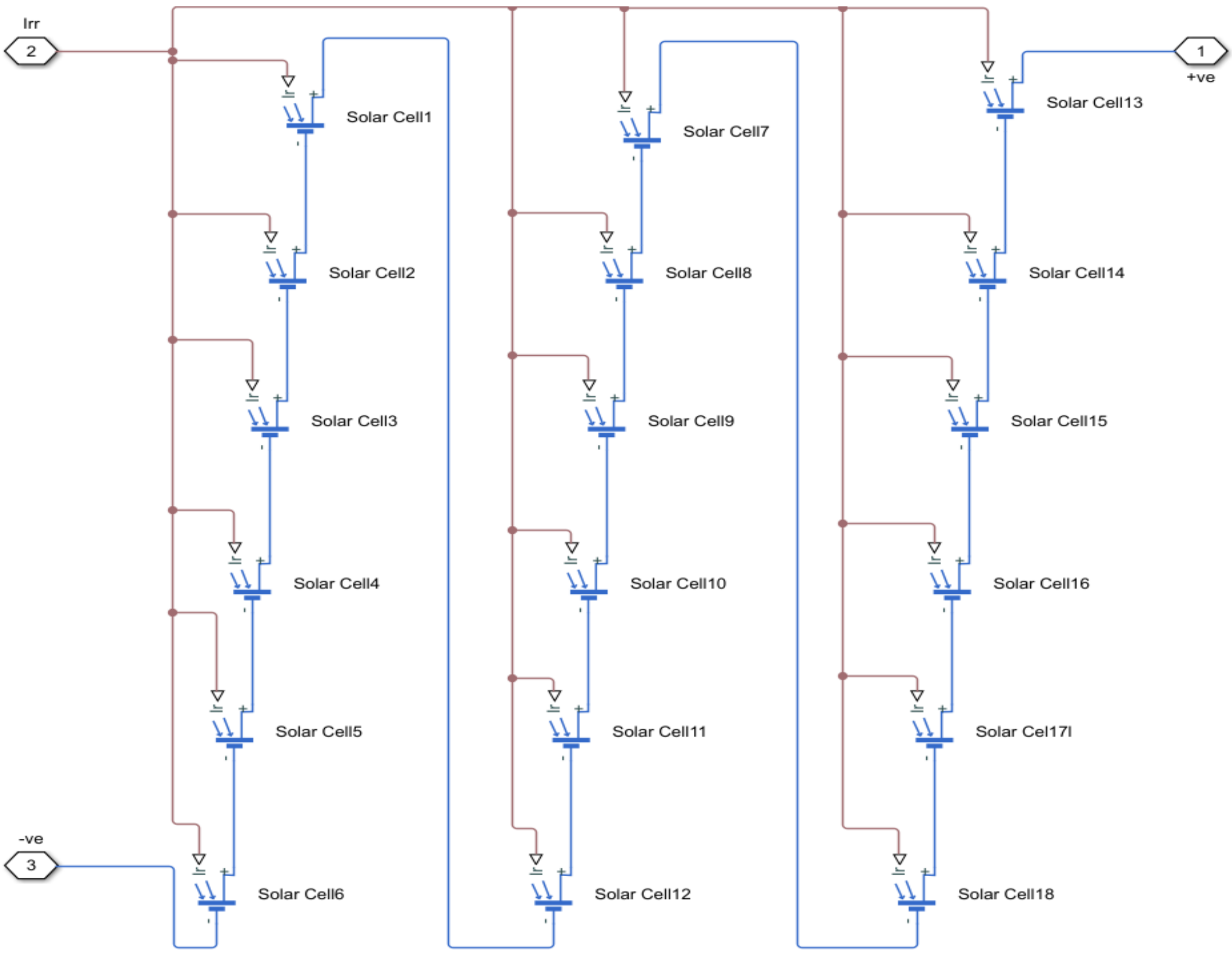
4.21 P-V curve in Simulink

4.9.4 Series connected solar cells

For the series connected solar cell module 36 solar cells are connected in series by using two mini modules each consisting of 18 cells. This structure was simulated in Matlab Simulink and output parameters were calculated to study series and shunt losses.

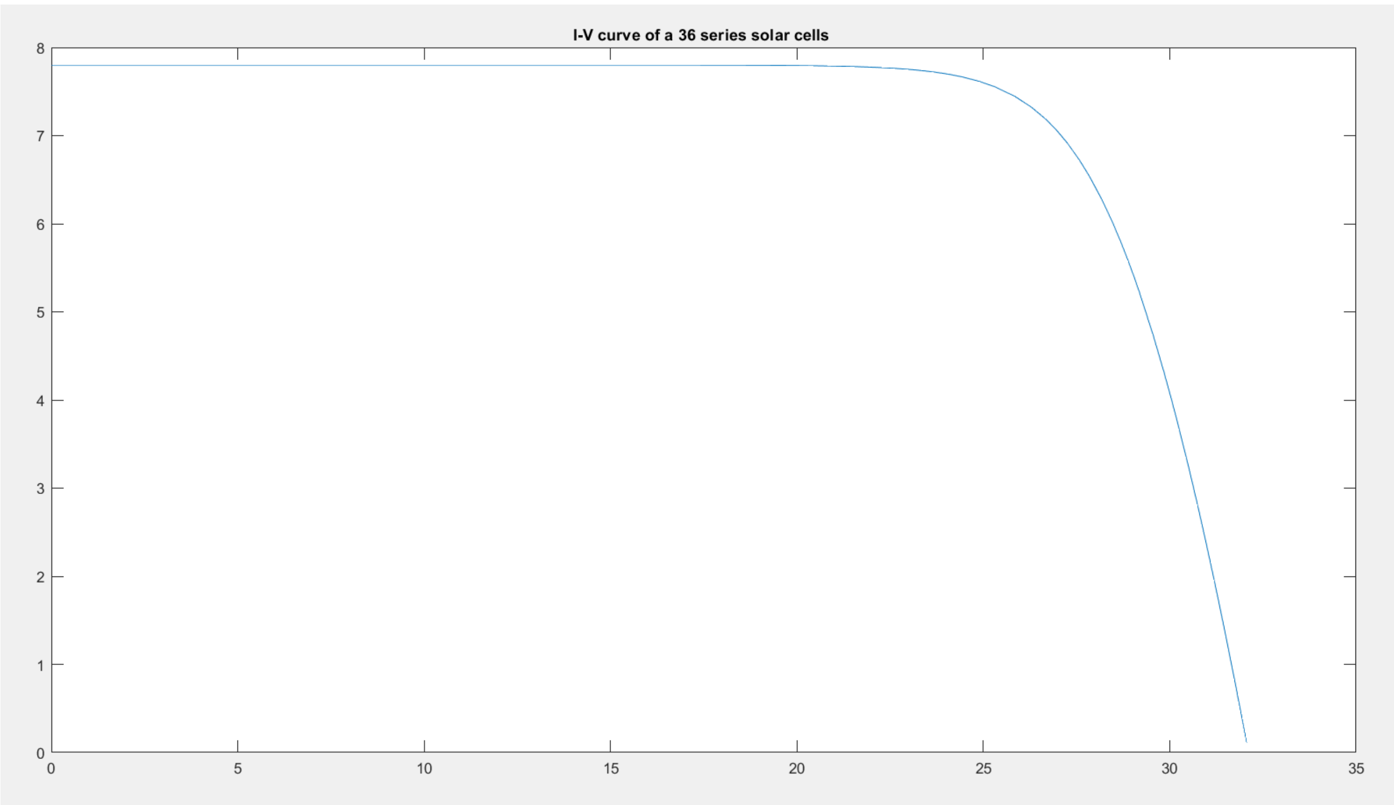


4.22 series connected solar cells



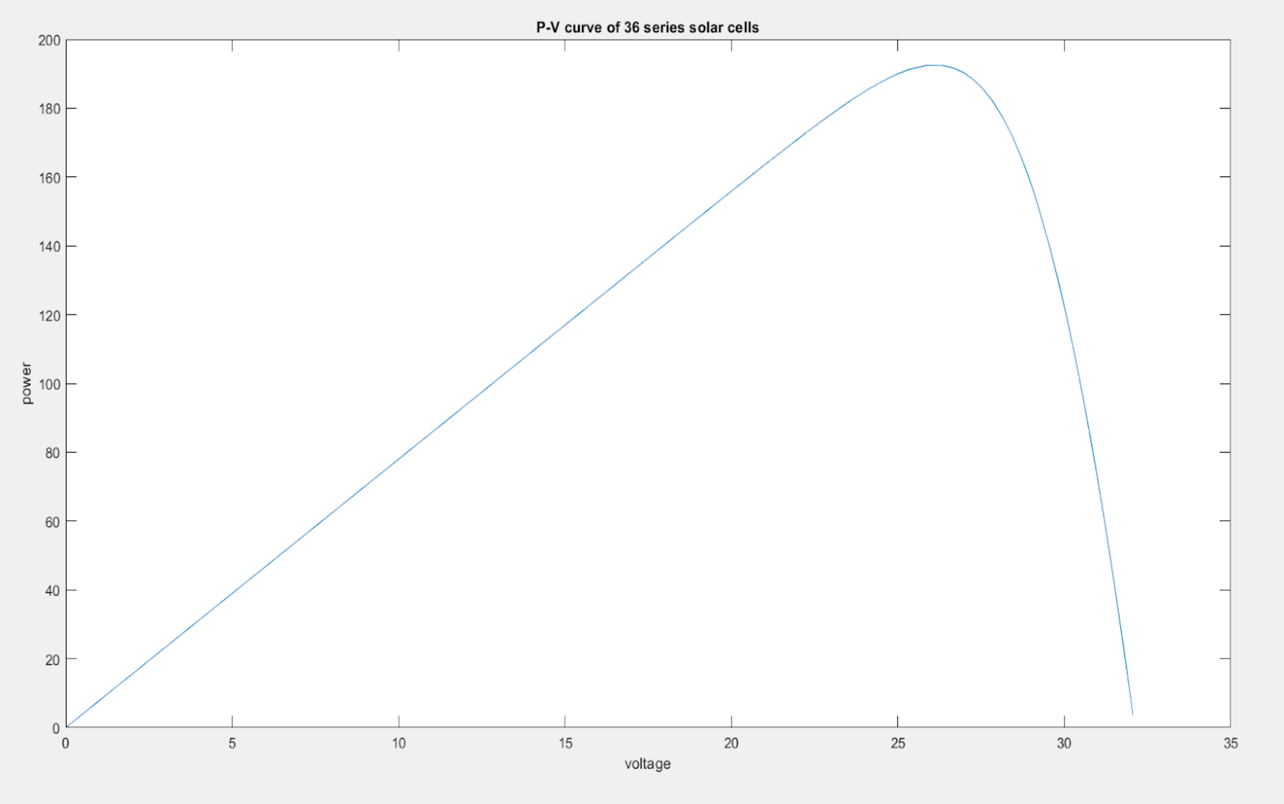
4.23 series mini module

I-V curve



4.24 I-V curve for series connected cells

P-V curve



4.25 P-V curve for series connected cells

Results of simulation for series connected cells

•Short Circuit Current (Isc) = 7.8A

•Open Circuit Voltage = 32.112 V

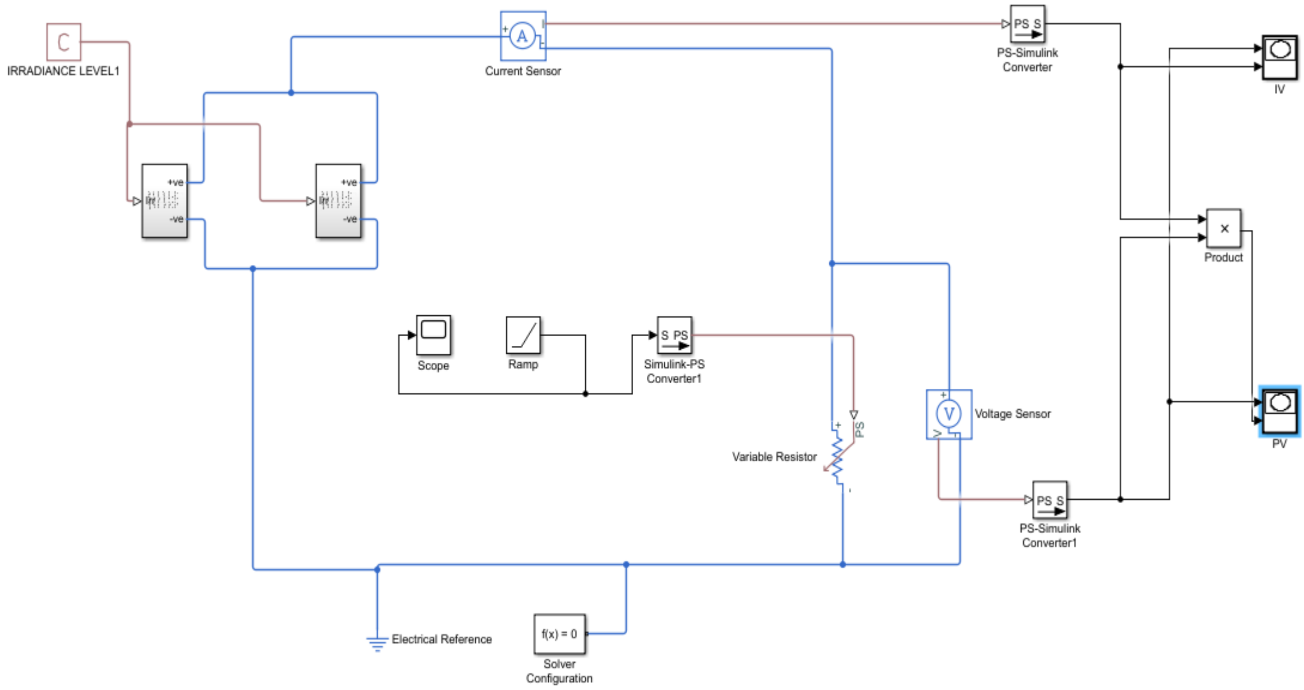
•Fill Factor = 79.34%

•Efficiency = 21.68%

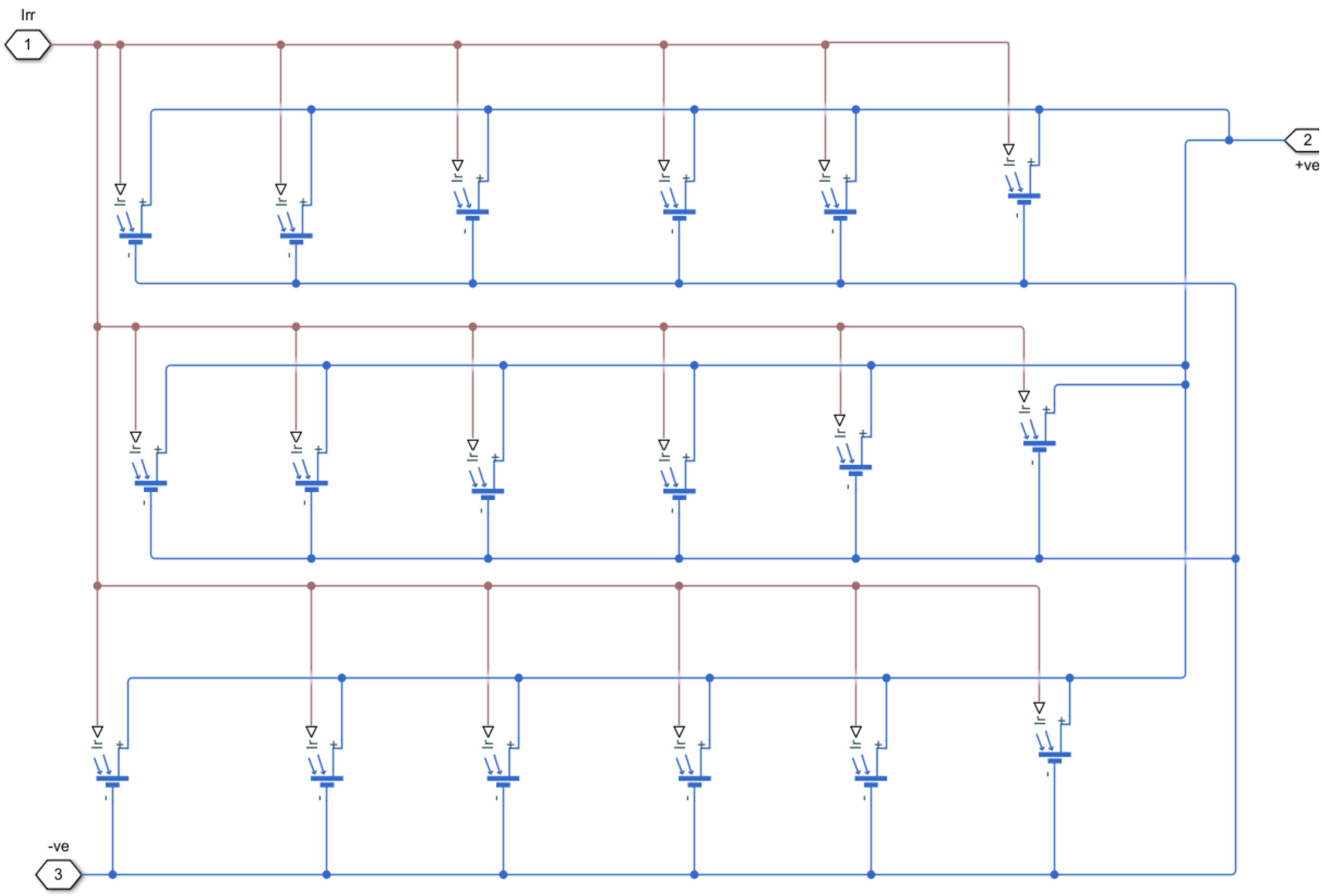
Generally, for series connected solar cells short circuit current should be same and open circuit voltage will become n times Voc, where n is the number of cells connected in series. But due to series and shunt losses we can see a decrease of 3% efficiency in series connected solar cells.

4.9.4 Parallel connected solar cells

For the parallel connected solar cell module 36 solar cells are connected in series by using two mini modules each consisting of 18 cells. This structure was simulated in Matlab Simulink and output parameters were calculated to study series and shunt losses.

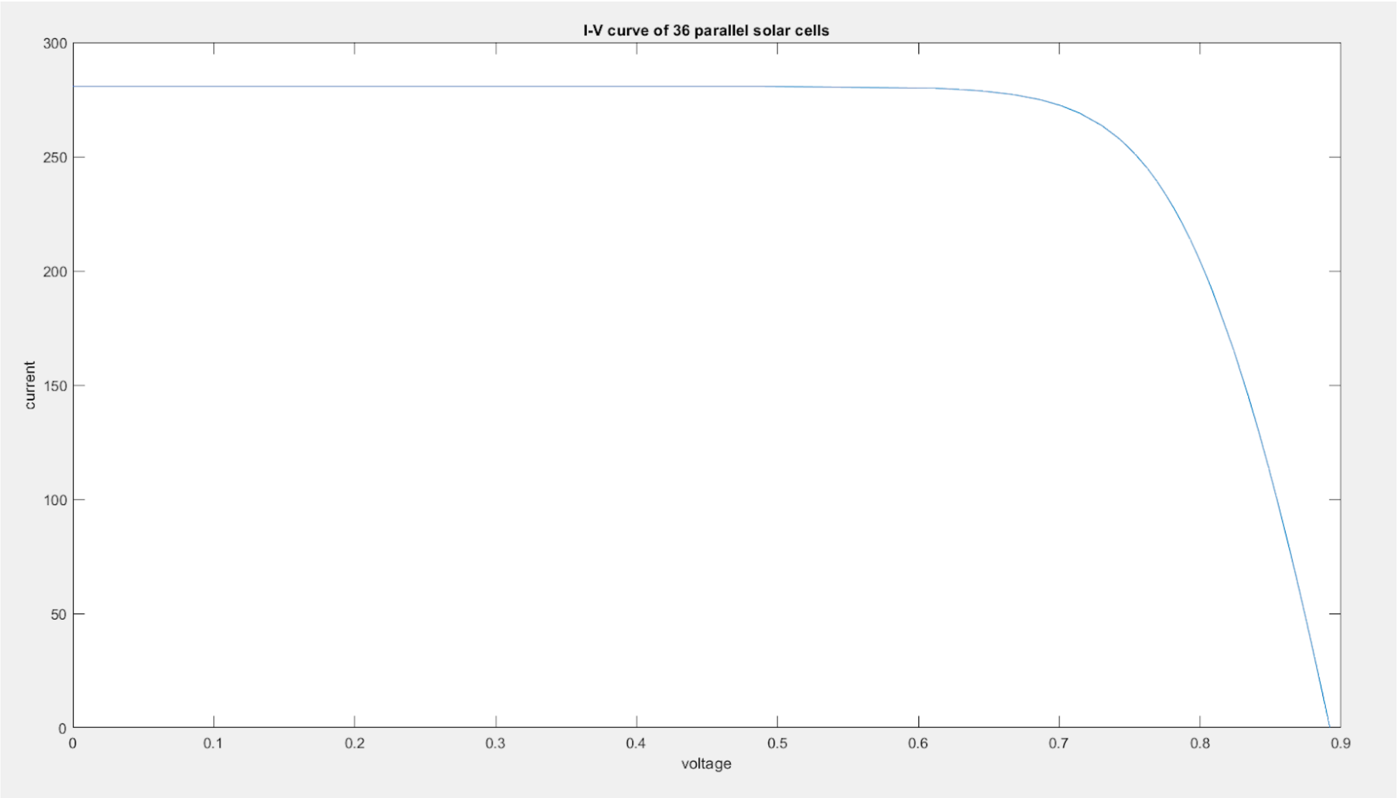


4.26 Parallel connected cells



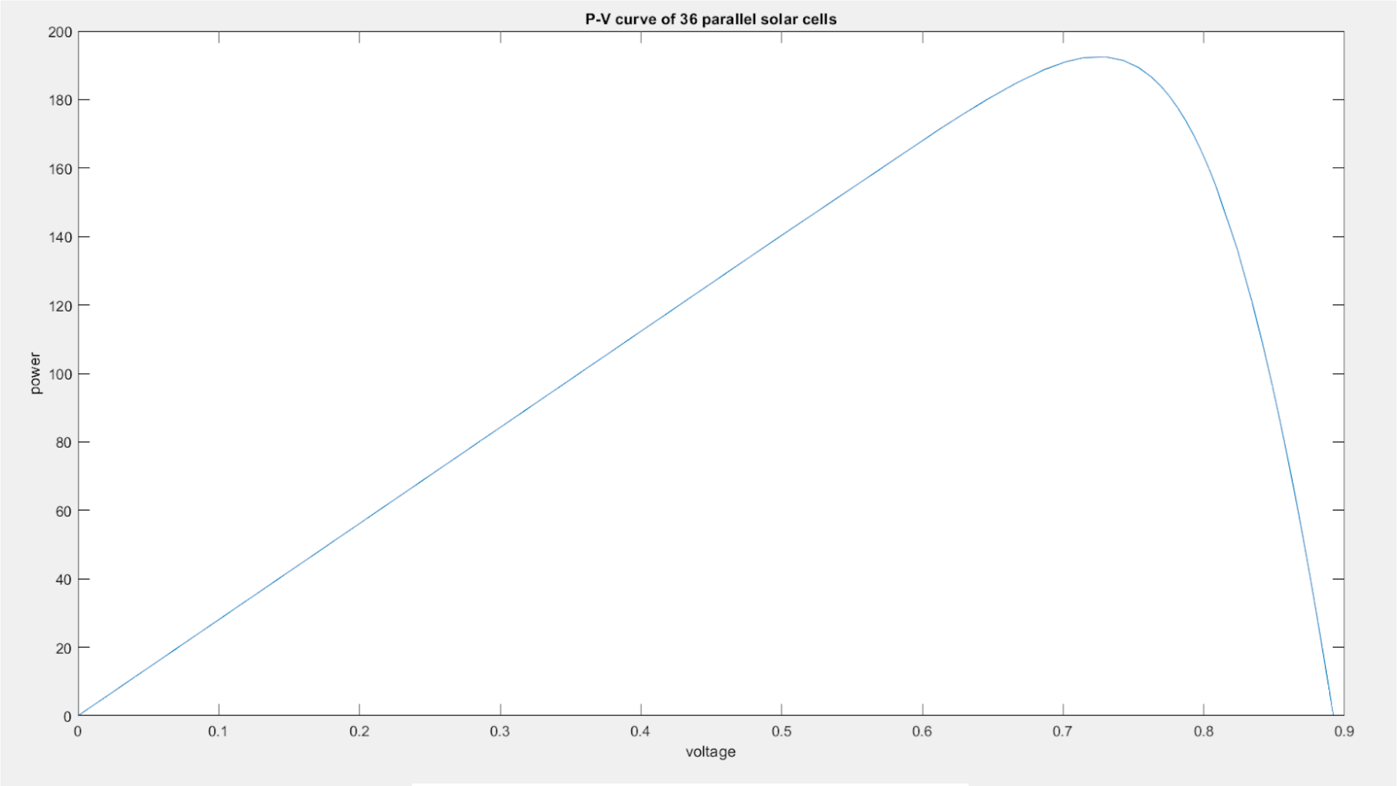
4.27 Parallel mini module

I-V Curve



4.28 I-V curve for parallel connected

P-V Curve



4.29 P-V Curve for parallel connected

Results of simulation for series connected cells

•Short Circuit Current (Isc) = 280.8A

•Open Circuit Voltage = 0.892 V

•Fill Factor = 78.91%

•Efficiency = 21.56%

Generally, for parallel connected solar cells open circuit voltage should be same and short circuit current will become n times Isc, where n is the number of cells connected in parallel. But due to series and shunt losses we can see a decrease of 3% efficiency in parallel connected solar cells.

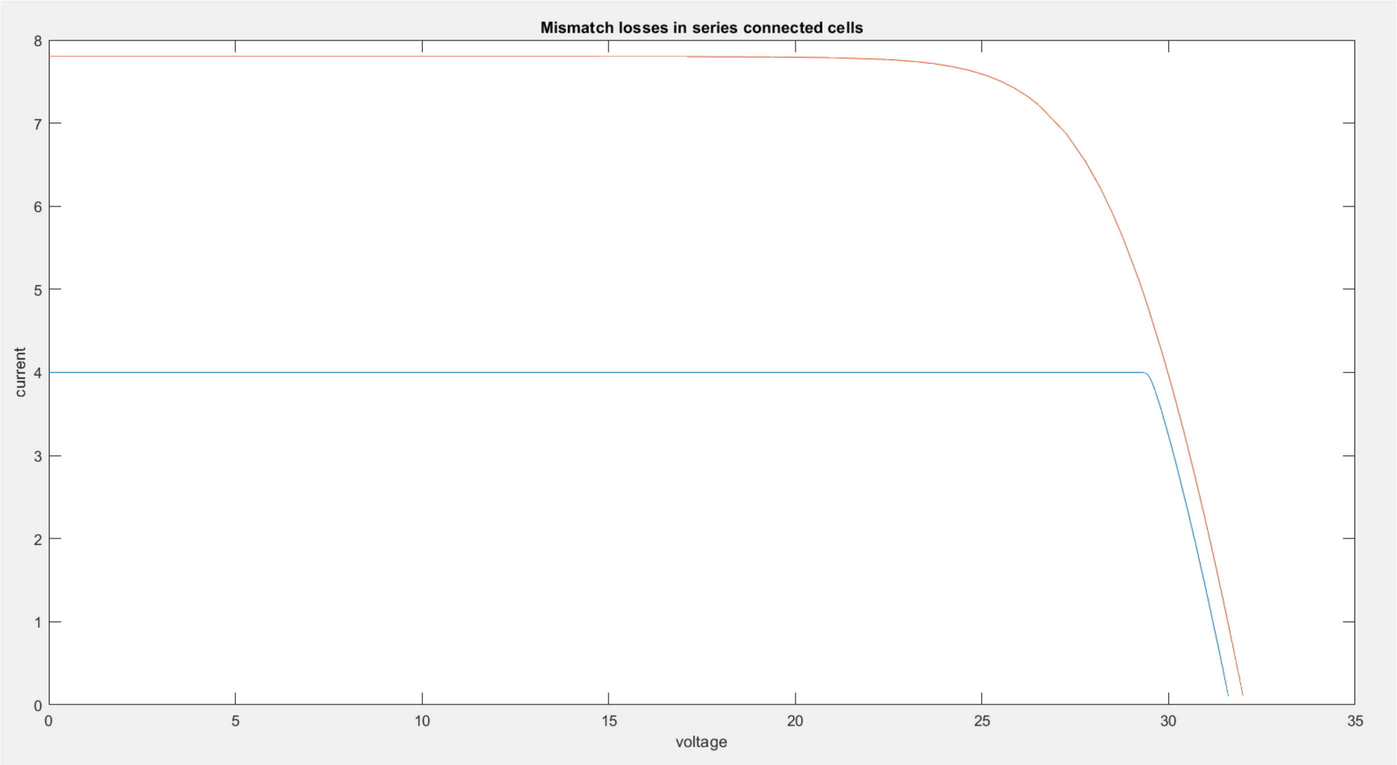
4.9.5 Mismatch losses

Mismatch losses are caused by the interconnection of solar cells or modules which do not have identical properties or which experience different conditions from one another. Mismatch losses are a serious problem in PV modules and arrays under some conditions because the output of the entire PV module under worst case conditions is determined by the solar cell with the lowest output. For example, when one solar cell is shaded while the remainder in the module are not, the power being generated by the "good" solar cells can be dissipated by the lower performance cell rather than powering the load. This in turn can lead to highly localised power dissipation and the resultant local heating may cause irreversible damage to the module. Shading of one region of a module compared to another is a major cause of mismatch in PV modules.

Mismatch losses in series connected cells

As most PV modules are series-connected, series mismatches are the most common type of mismatch encountered. Of the two simplest types of mismatch considered (mismatch in short-circuit current or in open-circuit voltage), a mismatch in the short-circuit current is more common, as it can easily be caused by shading part of the module. This type of mismatch is also the most severe. For two cells connected in series, the current through the two cells is the same. The total voltage produced is the sum of the individual cell voltages. Since the current must be the same, a mismatch in current means that the total current from the configuration is equal to the lowest current.

For mismatch losses simulation I have reduced Isc of single solar cell to 4 amps and Voc to 0.5 by the simulation results we can conclude that by changing short circuit current and open circuit voltage of a single solar cell, whole systems short circuit current was reduced to 4 amps from 7.8 amps and open circuit voltage is the sum of voltages across all the cells connected in series.



4.30 Mismatch losses in series connected cells

Chapter 5 Conclusions and Future scope

A numerical model of a CIGS solar cell which is based on the one-diode model and takes into account electrical, optical and geometrical parameters was derived. The model consists of a set of partial differential equations which can successfully be solved using AMPS 1D simulation software. Module level modelling and module level losses were studied using MATLAB Simulink. Solar cell modelling was done by changing different parameters like bandgap, thickness, doping and temperature and output was optimized by using modelled values of different parameters. An overall efficiency of 21.5% was achieved at the modular level

Buffer layer absorption represents one of the major losses in today's CIGS thin-film solar cells. Thinning of the CdS or replacing it with a higher band-gap material are possible alternatives. New materials are necessary for several reasons: (a) minimization of current losses by window and buffer absorption. (b) establishment of favorable band-offsets for wider-band-gap CIGS. (c) use as transparent front and back contacts in tandem devices. Several alternative buffer layers can be investigated, including Zn (OH, S), ZnSe, Zn (Se, OH), Zinc sulfide (ZnS) a possible replacement for II–VI semiconductor materials, is a direct wide band gap compound with a band gap energy of∼3.8 eV. Apart from all these factors the toxicity of cadmium is an environmental concern mitigated by the recycling of modules at the end of their life time.

References and Image sources

- Numerical Modelling of Ultra-Thin Cu (In, Ga) Se2 Solar Cells Now shad Amina, b, c, Puvaneswaran Chelvanathanb, M. Istiaque Hossaina, b and Kamaruzzaman Sopian Nowshad Amin et al. / Energy Procedia 15 (2012) 291 – 298
- Analytical modeling and simulation of CIGS solar cells A. Benmir and M.S. Aida / Energy Procedia 36 (2013) 618 – 627
- Photovoltaic module characteristics from CIGS solar cell modelling Antonino Parisi ; Luciano Curcio ; Vincenzo Rocca ; Salvatore Stivala ; Alfonso C. Cino ; Alessandro.
- Sylla, A., Touré, S. and Vilcot, J.-P. (2017) Numerical Modeling and Simulation of CIGS-Based Solar Cells with ZnS Buffer Layer. Open Journal of Modelling and Simulation, 5, 218-231.
- Jaymin Ray, Chetan Panchal, M S Desai, Urmesh Trivedi Simulation of CIGS thin film solar cells using AMPS-1D Journal of Nano- and Electronic Physics (2011)
- Numerical simulation of CIGS solar cell with ZnS buffer layer. Benslimane Hassane, Gani Abdennour, Dennai Benmoussa and Benslimane Abdelkader.
- www.wikipedia.com
- www.pveducation.org
- www.iopscience.iop.org
- www.researchgate.net
- www.sciencedirect.com
- www.hindawi.com
- Ieeexplore.ieee.org
- www.en.f-alpha.net
- http://www.samlexsolar.com/learning-center/solar-cell-module-array.aspx
- pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/diode-equivalent-circuit-models/
- www.researchgate.net/publication/316915102
- http://cpb.iphy.ac.cn/article/2016/1846/cpb_25_9_098402/cpb160865f1_hr
- https://www.sciencedaily.com/terms/solar_cell.html
- https://phys.org/news/2015-06-large-area-industrial-crystalline-silicon.html
- https://greenliving.lovetoknow.com/
- http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/cells_modules_arrays.html
- www.energysage.com/solar/101/monocrystalline-vs-polycrystalline-solar-panels/
- https://www.greenmatch.co.uk/blog/2015/06/advantages-and-disadvantages-of-solar-cells
- http://www.renxsol.com/faq/