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Project Report

"Simulation study of high conversion efficiency of CdS/CIGS solar cell"

Submitted by

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Declaration

We hereby declare that we have completed project on the topic entitled "**Simulation study of high conversion efficiency of CdS/CIGS solar cell**" as well as prepared as research report to the department of Electronics and Communications Engineering, East West University in partial fulfillment of the requirement for the degree of B.Sc. in Electronics and Telecommunications Engineering, under the course "Research/Internship (ETE 498)".

We further assert that this report in question is based on our original exertion having never been produced fully and/or partially anywhere for any requirement.

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Acceptance

This research report presented to the Department of Electronics and Communications Engineering, East West University is submitted in partial fulfillment of the requirement for the degree of B. Sc. In Electronics and Telecommunications Engineering, under complete supervision of the undersigned.

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Professor

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Acknowledgement

First and foremost with all our heartiest devotion we are grateful to almighty Allah for blessing us with such opportunity of learning and ability to successfully complete the task.

A special thanks with honor to our supervisor M. Mofazzal Hossain who was kind enough to allocate his valuable time to provide us with his humble guidance, motivating thought and encouragement.

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Abstract

A high efficiency CIGS/CdS solar cell is designed including an intrinsic CIGS layer and a highly doped CIGS as a Graded p-type layer. The designed cell is simulated using industrial grade software SILVACO. With the combination of TCO layer (ZnO), CdS window layer, CIGS Intrinsic layer, the higher conversion efficiency is achieved which is about 20.94%. After introducing graded p-type layer efficiency increased by great extent. In addition to this, with the increase of thickness of intrinsic layer efficiency also increased. At AM 1.5 solar radiation, the proposed cell structure had a V_{oc} of 0.726V, a J_{sc} of 57.72mAcm^{-2}, a maximum power is 35.27mW/cm^2 and a fill factor of 84%, corresponding to an overall efficiency of 29.69%.

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Chapter 1
Introduction

1.1 Solar Energy

The solar energy is known as the light energy which is emitted by the sun. Solar energy maintains life on earth. It is also increasing commonly that this energy is converted and used as an alternative to fossil fuels. Solar energy can be implemented by using a range of technologies such as solar thermal electricity. It is considered an environmentally friendly source of energy because it comes directly from the sun, it does not relate to the burning of fossil fuels. The primary limitation of solar energy is that it is not always available and methods of storage and stop-gap are required for when it is cloudy or raining outside [1].

Energy is the ability to do work and 'solar' is a Latin word for the sun. So we can define solar energy as energy obtained from the sun. We can use this energy for us in many ways from heating water to living spaces within our homes to generate electrical energy. Solar energy is a type of radiant energy, so named for the vibration particles 'radiating' from the sun. Solar energy is also called solar radiation for this reason. Solar energy also does other kinds of work indirectly. Plants use the sun's energy through the process of photosynthesis to grow and more indirectly. The sun is such an important part of life on Earth that it's not surprising that so many end-of-the world science fiction movies related with the sun not doing its job properly.

Solar energy is important to support life on earth, it helps to grow our food, light our days, influence weather patterns, provide heat and can be used to generate solar electricity man-made devices such as solar panels or solar cells in order to provide a source of clean and low cost renewable energy. Solar energy technologies are becoming more advanced. Photons contained in this solar radiation makes the generation of electricity from the sun rays. Solar energy is also responsible for wind energy, as wind patterns are very much influenced by the sun. Also, the sun is responsible for heating the ground beneath our feet to a significant degree to support the use of geothermal, ground source heat pumps [2].

1.2 Potential and Importance of Solar Energy

The potential of solar energy is almost limitless. The International Energy Agency announced in 2011 that solar energy technologies have the potential to provide one third of the world's energy by 2060, given that the world leaders commit to limiting climate change. Of course, the total solar energy potential is so much bigger that only a small fraction of totally available solar energy would be enough to satisfy global energy demand.

The main reason why solar energy still hasn't become the most important energy source on our planet is because solar power technologies still cannot find the balance of cost with fossil fuels. The good news is that solar energy industry is one of the fastest growing industries in the world. However, even it is increasing in the rapid growth, solar energy industry will still require time to achieve technological maturity that means fossil fuels will likely remain top energy sources for foreseeable future. Solar energy is the most abundant form of renewable energy available in our planet. Wind energy is also a form of solar energy, and only geothermal and tidal are renewable energy sources that do not derive their energy from the Sun. This means that implementing solar energy has enormous future potential, not only in electricity generation and heating but also for many other industrial processes as well as for the development of solar powered vehicles.

Solar energy is almost limitless source of energy but this doesn't make it a perfect source of energy. This isn't only because solar sector still lacks cost parity with fossil fuels but also because of continuity issue. We can define it as the intermittency of the renewable energy or solar energy. The intermittency of solar energy means that solar energy isn't available all the time and requires efficient energy storage solution to ensure continuous reliability of delivery. Using more solar energy instead of staying with fossil fuels would do wonders for our environment, it would slow the impact of climate change, reduce air pollution, and give many animals and plants species enough time to adapt with the changes in climate, thus preventing future biodiversity loss. Solar energy also has the ability to improve our future energy security by reducing the need for expensive foreign fuel import. Solar energy is there, free to use, as we know nobody owns the sun. Improving economics of the solar power technologies is the only thing that stands between us and clean energy future [3].

1.3 Generation of Solar Energy

Electricity generation in a solar plant occurs in two stages. First the heat energy from the sun is captured and the energy is used to heat a working fluid which is then used in a second energy transformation stage to generate the electricity. The thermal energy comes from the suns radiation and not from the air. As we know the temperature of air will usually be much lower than the temperature of the working fluid. The actual operating temperature is reached by the working fluid and the temperature will depend on the rate at which the thermal energy is being extracted by the working fluid and delivered to the electricity generating system. A solar power plant usually has a system of mirrors to concentrate the sunlight on to an absorber, the absorbed energy then being used to power a heat engine which in turn drives a rotary generator. In large scale systems, the heat engine is usually a turbine which is driven by steam or other vaporous working fluid [4].

Solar power generating systems absorb sunlight and convert it into electricity that we can use. The sun sends about 42 trillion kilocalories of energy to the Earth per second. If we could convert 100% of this solar energy into electricity, we could create one year's worth of power for the entire planet in a single hour. Solar energy is the most powerful of all renewable energy resources. The Earth's reserves fossil fuels such as petroleum and coal. Eventually it may be depleted. Moreover, burning these fossil fuels create carbon dioxide emissions, which are very much responsible to climate change. In contrast, as long as the sun exists, we can use its energy here on Earth. And because solar power emits no carbon dioxide, it is an effective solution to natural resource depletion and climate change problems that are becoming more serious every year.

1.4 Advantages of Solar Energy

Renewable Energy Source: Solar energy is a truly renewable energy source. It can be harnessed in all areas of the world and it is available every day we cannot run out of solar energy, unlike some of the other sources of energy. Solar energy will be available as long as we have the sun, therefore sunlight will be available to us for at least 5 billion years, when according to scientists the sun is going to die.

Reduces Electricity Bills: Since you will be meeting some of your energy needs with the electricity. When your solar system has generated, your electricity bills will drop. How much you save bill will be dependent on the size of the solar system and your electricity or heat usage. Moreover, not only you will be the electricity bill, but also if you generate more electricity than you use, the remaining will be exported back to the grid and you will receive bonus payments for that amount (considering that your solar panel system is connected to the grid). Savings can further grow if you sell excess electricity at high rates during the day and then buy electricity from the grid during the evening when the rates are lower.

Diverse Application: Solar energy can be used for diverse purposes. You can generate electricity (photovoltaic) or heat (solar thermal). Solar energy can be used to produce electricity in areas without access to the energy grid, to distill water in regions with limited clean water supplies and to power satellites in space. Solar energy can also be integrated in the materials used for buildings. A few days ago Sharp introduced transparent solar energy windows.

Low Maintenance Costs: Solar energy systems generally don't require a lot of maintenance. You only need to keep them relatively clean, so cleaning them a couple of times per year will do the job. Most reliable solar panel manufacturers give 20-25 years warranty. Also, as there are no moving parts, there is no wear and tear. Usually The inverter is the only part that needs to change after 5-10 years because it is continuously working to convert solar energy into electricity (solar PV) and heat (solar thermal). So, after covering the initial cost of the solar system, you can expect very little spending on maintenance and repair work.

1.5 Disadvantages of Solar Energy

Cost: The initial cost for purchasing a solar system is fairly high. Although the UK government has introduced some schemes for encouraging the adoption of renewable energy sources. As example the feed in Tariff, you still have to cover the initial costs. This includes paying for solar panels, inverter, batteries, and wiring and for the installation. Nevertheless, solar technologies are constantly developing, so it is safe to assume that prices will go down in the future.

Weather Dependent: Although solar energy can still be collected during cloudy and rainy days, the efficiency of the solar system drops. Solar panels are dependent on sunlight to gather solar

energy effectively. Therefore, a few cloudy, rainy days can have a noticeable effect on the energy system. We should also take into calculation that solar energy cannot be collected during the night.

Solar Energy Storage is Expensive: Solar energy has to be used right away or it can be stored in large batteries. These batteries used in off-the grid solar systems that can be charged during the day so that the energy is used at night. This is good solution for using solar energy all day long but it is also quite expensive. In most cases it is smarter to use solar energy just during the day and take energy from the grid during the night. Luckily our energy demand is usually higher during the day so we can get most of it with solar energy.

Associated with pollution: Although pollution in solar energy systems is far less compared to other sources of energy. Solar energy can be related with pollution. Transportation and installation of solar systems have been associated with the emission of greenhouse gases. There are also some toxic materials and hazardous products used during the manufacturing process of solar photovoltaic and it can indirectly effect the environment. Nevertheless, solar energy pollutes far less than the other alternative energy sources.

1.6 Solar Cell

Solar cell can be defined as an electric cell that converts visible light into electrical energy. Solar cells are used as power supply component in calculators, satellites and other devices and used as a prime source of electricity in remote locations. It is also called photovoltaic cell. In general, a solar cell that includes both solar and non-solar sources of light (such as photons from incandescent bulbs) is derived as 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 research field related to solar cells is known as photovoltaic. Solar cells have many applications. In the past solar cells have been used in such areas where electrical power from the grid is unavailable, such as in remote area power systems, Earth orbiting satellites, consumer systems, e.g. handheld calculators or wrist watches, remote radio-telephones and water pumping applications. Solar cells are regarded as one of the key technologies towards a sustainable energy supply [5].

1.7 Generation of solar cell

Traditional solar cells are made from silicon, are currently the most efficient solar cells available for residential use and around 80+ percent of all the solar panels sold around the world. Generally silicon based solar cells are more efficient and longer lasting than non silicon based cells. However, they are more at risk to lose some of their efficiency at higher temperatures (hot sunny days), than thin-film solar cells.

1.7.1 Mono-crystalline Silicon Cells: The oldest solar cell technology and still the most popular and efficient are solar cells made from thin wafers of silicon. These are called mono-crystalline solar cells because the cells are sliced from large single crystals that have been difficult to grow carefully under controlled conditions. Typically, the cells are a few inches across and a number of cells are laid out in a grid to create a panel. Relative to the other types of cells, they have a higher efficiency (up to 24.2%) that means we will obtain more electricity from a given area of panel. This is useful if we only have a limited area for mounting our panels or want to keep the installation small for aesthetic reasons. Implementing large crystals of pure silicon is a difficult and very energy-intensive process. So, the production costs for this type of panel is very high from all the solar panel types, we can say that from our past experience. Though production methods have improved and prices for raw silicon as well as to build panels from mono-crystalline solar cells. These solar cells are partly driven by competition as other types of panel have been produced. Another issue about panels made from mono-crystalline silicon cells is that they lose their efficiency as the temperature increases about 25°C. So they have to be installed in such a way that air can circulate over and under the panels to improve their efficiency.

1.7.2 Polycrystalline Silicon Cells: It is cheaper to produce silicon wafers in molds from multiple silicon crystals rather than from a single crystal and the conditions for growing do not need critical controlled conditions. In this form, a number of interlocking silicon crystals grows together. Panels based on these cells are cheaper per unit area than mono-crystalline panels - but they are also slightly less efficient (up to 19.3%).

1.7.3 Amorphous Silicon Cells: You probably never thought about it before, but most solar cells used in calculators and many small electronic devices that are made from amorphous

silicon cells. Instead of growing silicon crystals as is done in making the two previous types of solar cells, silicon is deposited in a very thin layer on to a backing substrate – such as metal, glass or even plastic. Sometimes several layers of silicon, doped in slightly different ways to respond to different wavelengths of light, are laid on top of one another to improve the efficiency. The production methods are complex, but less energy intensive than crystalline panels, and prices have been coming down as panels are mass-produced using this process .One advantage of using very thin layers of silicon is that the panels can be made flexible. The disadvantage of amorphous panels is that they are much less efficient per unit area (up to 10%) and are generally not suitable for roof installations you would typically need nearly double the panel area for the same power output. Having said that, for a given power rating, they do perform better at low light levels than crystalline panels - which is worth having on a dismal winter's day, and are less likely to lose their efficiency as the temperature climbs. However, there flexibility makes them an excellent choice for use in making building integrated PV (e.g., roofing shingles), for use on curved surfaces, or even attached to a flexible backing sheet so that they can even be rolled up and used when going camping / backpacking, or put away when they are not needed.

1.7.4 Hybrid Silicon Cells: The recent turning point in the industry is the emergence of hybrid silicon cells. Several companies are now investigating about the ways of combining different materials to make solar cells with better efficiency, longer life, and at lower costs. Recently, Sanyo introduced a hybrid HIT cell where a layer of amorphous silicon is deposited on top of single crystal wafers. The result is an efficient solar cell that performs well in indirect light and loses less efficiency as the temperature climbs.

1.7.5 Second Generation Solar Cells: Second-generation solar cells are usually called thin-film solar cells because when they are made from layers of semiconductor materials only a few micrometers thick. That's the difference between crystalline silicon based cells and thin film solar cells. Since the process of manufacturing is at lower cost and the combination of using material become less, it allows the manufacturer of solar panels to produce the solar panels from this type of technology and sell panels at much lower cost. There are basically three types of solar cells that are considered in this category, amorphous silicon (mentioned above) and rest of the two are made from non-silicon materials that are cadmium telluride

(CdTe) and copper indium gallium selenide (CIGS). Together they accounted for around 16.8% of the panels sold in 2009.First Solar, the number one producer and seller of solar panels in the world currently makes their solar cells using cadmium telluride. The big appeal of these type of solar cells is that they are inexpensive (currently below $1.00 / watt to produce and heading towards $0.70 / watt). However, as we discuss in the accompanying articles about cadmium telluride (CdTe) and First Solar – there are some concerns about this technology. Venture capitalists love CIGS solar cells (or at least used to – as they have invested over $2.3 billion into companies developing these cells but have yet to see them be a commercial success) – as they have been able to reach efficiency levels of 20% in the laboratory. Unfortunately it has turned out to be much more difficult to produce CIGS solar cells in mass quantities at competitive prices with anywhere near than efficiency level, so the jury is still out on this technology. New Recently a Company based in Idaho has come up with a thin-film mono-crystalline solar cell – that uses about 20% of the crystalline silicon in current silicon based cells and has number of advantages.

1.7.6 Third Generation Solar Cells: Currently there is a lot of solar research going on in what is being referred to in the in the industry as Third-generation solar cells. In fact according to the number of patents filed last year in the United States – solar research ranks second only to research in the area of fuel cells. This new generation of solar cells are being made from variety of new materials besides silicon, including nanotubes, silicon wires, solar inks using conventional printing press technologies, organic dyes, and conductive plastics. The goal of course is to improve on the solar cells already commercially available – by making solar energy more efficient over a wider band of solar energy (e.g., including infrared), less expensive so it can be used by more and more people, and to develop more and different uses. Currently, most of the work on third generation solar cells is being done in the laboratory and being developed by new companies and for the most part is not commercially available [6].

1.8 How does Solar Cell Work?

When the cell is illuminated, the photons having energy greater or equal to the energy band gap of the semiconductor may be absorbed by the bound electrons and cause the formation of an electron-hole pair, which is immediately separated due to the internal electrostatic field. A solar cell cannot convert the entire amount of solar radiation received on its surface into electrical energy. A part of the radiation is reflected from the surface of the cell and diffused back into the environment. Afterwards, from the radiation that penetrates the semiconductor, those photons having energy smaller than the energy band gap cannot be absorbed. For these photons, the cell behaves like a transparent body. This pattern is shown in figure below:
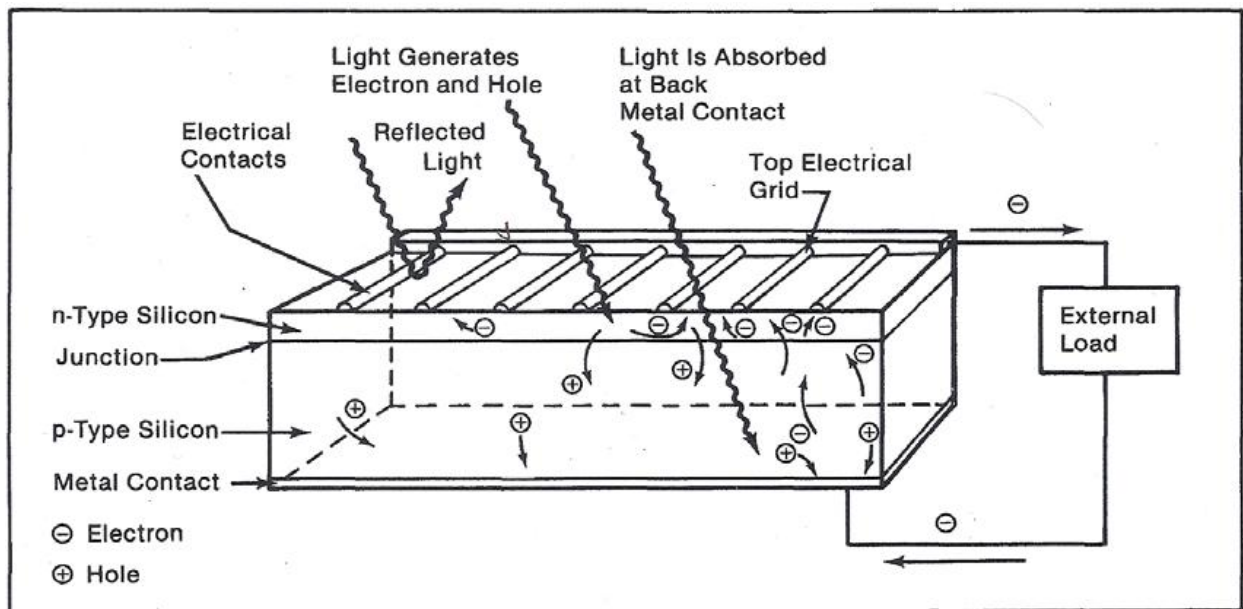

Figure 1.1: Light incident on a cell [7].

Shorting the terminals of the device, the extra electrons of the n-region move through the external circuit to counteract the additional holes in the p-region. The current due to this flow of excited carriers is called photocurrent, (where L stands for light) depicted in figure below:
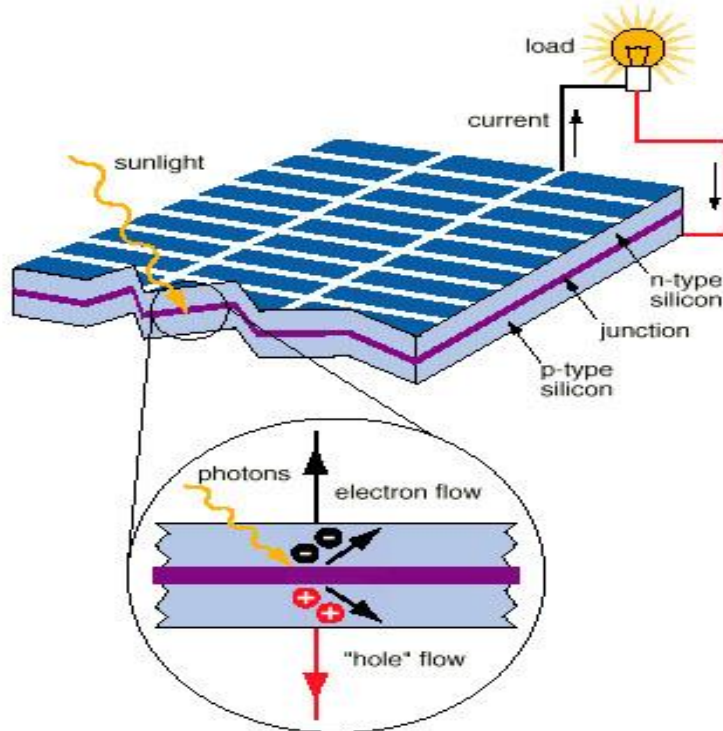
Figure 1.2: The PV effect in a solar cell [7].

In an ideal PV cell under illumination, the short-circuit current is equal to the produced photocurrent since the load resistance is zero, causing the voltage to also be zero. If a load resistance is connected to the circuit, the photocurrent causes the creation of a voltage in the cell, which forward-biases the p–n junction and reduces its potential as well as the infusion of minority carriers and their diffusion, just as would happen in a normal diode. Therefore, due to the forward-bias voltage, a forward-bias current, which opposes the photocurrent, will be present. This is given by,

$$I_F = I_o \ (e^{eV/\eta kT} -1) \tag{1.1}$$

where is the reverse saturation current and the quality factor which ranges from one to two. The resulting net p-n junction current I is

$$I = I_L - I_F = I_{sc} - I_o \ (e^{eV/\eta kT} -1) \tag{1.2}$$

1.9 CIGS solar cell

Copper indium gallium selenide solar cell is known as CIGS (CIGS cell, sometimes CI(G)S or CIS cell) solar cell in short that is 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 back to collect current. The material has a high absorption coefficient and strongly absorbs sunlight. CIGS layers are very thin to be flexible. It allows to deposit on the flexible substrate. CIGS has an exceptionally high absorption coefficient more than 10^5/cm for 1.5eV. CIGS solar cells have the efficiency around 20% that have been claimed by the National Energy Laboratory (NREL)[8].Copper indium diselenide (CIS) is a p-type multi-crystalline semiconductor with high optical absorption coefficient. For thin film solar cell applications this compound is used in a heterojunction structure, commonly with a very thin n-type cadmium sulfide layer. The optimal band gap for a single-junction solar cell with respect to the solar spectrum is around 1.4 eV . Pure CuInSe2 has a band gap of 1.04 eV. To increase the band gap, indium can be partially replaced by gallium, thus obtaining copper indium gallium selenide (CIGS). An indium to gallium ratio of 20–40% will result in a band gap of approximately 1.1–1.2 eV which has been shown empirically to give the best cell results. The band gap of pure $CuGaSe_2$(CGS) is 1.67 eV. A further degree of freedom is achieved by the partial substitution of Se_2 for S_2 (CIGS). The direct band gap and the high absorption coefficient of CIGS relaxes the requirements on minority carrier lifetime and facilitates thinner absorber layers since the photo-excited carriers are generated close to the depletion region. This makes CIGS a suitable compound for thin film solar cells. CIGS thin film solar cells have been fabricated by several research groups at over 15% efficiency, and the efficiency record obtained for a small laboratory cell is as high as 18.8%. Laboratory mini-modules have reached 16.6%efficiency. In terms of stability, CIGS solar cells do not have the problem of light-induced degradation. On the contrary, they tend to exhibit a slight increase in open circuit voltage and in efficiency during the first hours of operation. CIGS devices have shown promising results in outdoor long-term performance tests but at the same time they are more sensitive than for example crystalline silicon solar cells to hot and humid environments. $Cu(In,Ga)Se_2$ is considered to be one of the most promising materials for large-scale fabrication of low-cost high-efficiency thin film solar cells, and as device results are approaching two of the important milestones on the route to commercialization – the 15% efficient module and the 20% cell –

several research institutes have announced their plans for CIGS production lines. The first, and so far the only, commercial CIGS module was released in 1998 by Siemens Solar Industries, but the US-based production is still on a limited scale. It is expected that CIGS modules in mass production will be substantially cheaper than wafer-based crystalline silicon modules. Module production costs of less than1 USD per watt peak is commonly forecasted. Much of the current research activities in the CIGS field are directed towards manufacturability issues such as technology scale up, module design, packaging, and long-term stability. Other potential research topics are the possibilities to reduce the amount of indium used, and to remove or to find a less hazardous replacement of the thin cadmium sulfide layer.

The benefits of CIGS solar cells include:

- **High absorption**: This direct-band gap material can absorb a significant portion of the solar spectrum, enabling it to achieve the highest efficiency of any thin-film technology.
- **Tandem design**: A tunable band gap allows the possibility of tandem CIGS devices.
- **Protective buffer layer**: The grain boundaries form an inherent buffer layer, preventing surface recombination and allowing for films with grain sizes of less than 1 micrometer to be used in device fabrication.

1.10 Objective and scope of this thesis:

Polycrystalline thin film solar cells made from CuInSe2 (CIS) alloys have begun to fulfill the promise of low-cost, power generation from non-polluting, clean energy sources. The efficiency of laboratory scale solar cells is now well over 19%, and that of commercial modules is around 13%. These are shocking milestones when we take into account the inadequate knowledge-base. The task at hand is still the need to correlate the properties of the absorbers and junction formation processes to the properties of the solar cells. In this thesis work, we studied the efficiency of CIGS solar cell varying the thickness of intrinsic layer using the industry standard simulation package SILVACO [9].

1.11 Organization of the thesis:

Our thesis report has several chapters which described the whole work. In chapter 1 we discussed the introduction of this thesis along with the objective, and organization of the paper.

In chapter 2 we make a short description about our models and methods which are incorporated in our program.

In chapter 3, we discuss our results which we obtained from our work.

Finally in chapter 4 make a conclusion of our thesis work.

Chapter 2

Simulation Models and Methods

The major objectives of numerical modeling and simulation in solar cell research are testing the validity of proposed physical structures, geometry on cell performance and fitting of modeling output to experimental results. Any numerical program capable of solving the basic semiconductor equations could be used for modeling thin film solar cells.

This research is physically-based solar cell model using the general-purpose ATLAS device simulator by Silvaco International [9]. Here, the electrical characteristics of a solar cell based on virtual fabrication of its physical structure, allowing for direct manipulation of materials, dimensions and doping. In addition, our model has the ability to accurately simulate more advanced solar cell design features Available outputs include efficiency, open circuit voltage, current density, fill factor. The operation of the ATLAS software is described in detail and our model is applied to known single junction cell designs. The results of the solar cell simulation in ATLAS are compared and shown to be similar to published experimental results.

2.1 Models

In our project we used the following models of SILVACO software package

Models srh conmob fermi ni.fermi bgn optr auger

2.1.1 Concentration Dependent Mobility (CONMOB)

CONMOB specifies that a concentration dependent mobility model be used for silicon and gallium arsenide. This model is a doping versus mobility table valid for 300K only.

2.1.2 Shockley-Read-Hall (SRH) Recombination

The Shockley-Read-Hall recombination is modeled as follows:

$$R_{SRH} = \frac{pn - n_{ie}^2}{TAUPO\left[n + n_{ie}\exp\left(\frac{ETRAP}{kT_L}\right)\right] + TAUNO\left[p + n_{ie}\exp\left(\frac{-ETRAP}{kT_L}\right)\right]} \qquad \textbf{[2.1]}$$

Where,

ETRAP = Thedifference between the trap energy level and the intrinsic Fermi level

TAUN0 = The electron lifetimes

TAUP0 = The hole lifetimes.

This model is activated by using the SRH parameter of the MODELS statement. The electron and hole lifetime parameters, TAUN0 and TAUP0, are user-definable in the MATERIAL statement. The default values for carrier lifetimes are shown in Table 2.1. Materials other than silicon will have different defaults.

Table 2.1 Parameter

Statement	Parameter	Default	Units
MATERIAL	ETRAP	0	eV
MATERIAL	TAUNO	1×10^{-7}	s
MATERIAL	TAUPO	1×10^{-7}	s

The constant carrier lifetimes that are used in the SRH recombination model above can be made a function of impurity concentration using the following equation:

$$R_{SRH} = \frac{pn - n_{ie}^2}{\tau_p \left[n + n_{ie} \exp\left(\frac{ETRAP}{kT_L}\right) \right] + \tau_n \left[p + n_{ie} \exp\left(\frac{-ETRAP}{kT_L}\right) \right]}$$ **[2.2]**

Where,

$$\tau_n = \frac{TAUNO}{AN + BN\left(\frac{N_{total}}{NSRHN}\right) + CN\left(\frac{N_{total}}{NSRHN}\right)^{EN}}$$ **[2.3]**

$$\tau_p = \frac{TAUPO}{AP + BP\left(\frac{N_{total}}{NSRHN}\right) + CN\left(\frac{N_{total}}{NSRHN}\right)^{EP}}$$ **[2.4]**

Here,

N = The local impurity concentration.

The TAUN0, TAUP0, NSRHN, and NSRHP parameters can be defined on the MATERIAL statement.

Table 2.2 Material properties parameters

Statement	Parameter	Default	Units
MATERIAL	TAUNO	1	S
MATERIAL	NSRHN	-1×10^3	cm^{-3}
MATERIAL	TAUPO	1	s
MATERIAL	NSRHP	-1×10^3	cm^{-3}
MATERIAL	AN	1	
MATERIAL	AP	1	
MATERIAL	BN	0	
MATERIAL	EP	0	

2.1.3 Fermi-Dirac (FERMI)

Fermi-Dirac reduced carrier concentrations in heavily doped regions**.** Electrons in thermal equilibrium at temperature T_L with a semiconductor lattice obey Fermi-Dirac statistics. That is the probability $f(\varepsilon)$ that an available electron state with energy ε is occupied by an electron is:

$$f(\varepsilon) = \frac{1}{1 + \exp\left(\frac{\varepsilon - E_F}{kT_L}\right)} \qquad \text{[2.5]}$$

Where,

$E_{F =}$ A spatially independent reference energy known as the Fermi level

$k =$ is Boltzmann's constant.

If $\varepsilon - E_F >> kT_L$, then the above equation can be express as,

$$f(\varepsilon) = \exp\left(\frac{\varepsilon - E_F}{kT_L}\right) \qquad \text{[2.6]}$$

2.1.4 Auger Recombination

Auger recombination occurs through a three particle transition whereby a mobile carrier is either captured or emitted. It is important at high current densities. The underlying physics for such processes is unclear and normally a more qualitative understanding is sufficient.

Auger Recombination is commonly modeled using the expression:

$$R_{Auger} = AUGN\ (pn^2 - nn^2_{ie}) + AUGP\ (np^2 - pn^2_{ie}) \tag{2.7}$$

Where the model parameters AUGN and AUGP are user-definable in the MATERIAL statement.

Table 2.3 Parameter for Equation [2.7]

Statement	Parameter	Value	Units
MATERIAL	AUGN	0	cm^6/s
MATERIAL	AUGP	0	cm^6/s

2.1.5 Bandgap Narrowing (BGN)

In the presence of heavy doping, greater than $10^{18} cm^{-3}$, experimental work has shown that the pn product in silicon becomes doping dependent. As the doping level increases, a decrease in the bandgap separation occurs, where the conduction band is lowered by approximately the same amount as the valence band is raised. In ATLAS this is simulated by a spatially varying intrinsic concentration n_{ie} defined according to equation

$$n^2_{ie} = n^2_i \exp(\frac{\Delta Eg}{kT}) \tag{2.8}$$

Band gap narrowing effects in ATLAS are enabled by specifying the BGN parameter of the MODELS statement. These effects may be described by an analytic expression relating to the variation in ban dgap, ΔEg, to the doping concentration, N. The expression used in ATLAS is from Slot boom and de Graaf:

$$\Delta Eg = BGN.E\left\{ ln\frac{N}{BGN.N} + \left[\left(ln\frac{N}{BGN.N} \right)^2 + BGN.C \right]^{\frac{1}{2}} \right\} \tag{2.9}$$

We can specify the BGN.E, BGN.N, and BGN.C parameters in the MATERIAL statement. The default values from Slot boom and Klaassen are shown in Table 2.3.

Table 2.3 Parameters for Bandgap Narrowing Model

Statement	Parameter	Values	Unit
MATERIAL	BGN.E	0.009	eV
MATERIAL	BGN.N	1×10^{17}	cm^{-3}
MATERIAL	BGN.C	0.5	-

2.1.6 Optical Generation/Radiative Recombination

OPTR selects the optical recombination model. When this parameter is specified, the COPT parameter of the MATERIAL statement should be specified. The next physical mechanisms we have to consider for generation/recombination are photon transition. There are two partial processes involved. For radiative recombination, an electron loses energy on the order of the band gap and moves from the conduction band to the valence band. For optical generation, an electron moves from the valence band to the conduction. In silicon, band to band generation/recombination is insignificant. This effect, however, is important for narrow gap semiconductors and semiconductors whose specific band structure allows direct transitions. By assuming a capture rate CcOPT and an emission rate CeOTP, the involved partial processes can be written as:

$$R_{np}^{OPT} = C_c^{OPT}{}_{np}$$
[2.10]

for recombination and

$$G_{np}^{OPT} = C_e^{OPT}$$
[2.11]

for generation

These rates must be equal in thermal equilibrium so that

$$C_{np}^{OPT} = C_c^{OPT} n_{ie}^2$$
[2.12]

The total band to band generation/recombination is the difference of the partial rates, which equates to

$$R_{np}^{OPT} = C_c^{OPT}(np - n_{ie}^2)$$ **[2.13]**

In ATLAS, COPT is used express C_c^{OPT} and can be defined away from default values on the materials statement or implemented using a C-Interpreter routine. To turn on the optical recombination/ generation model, define the OPTR keyword on the MODELS statement.

2.2 Simulating Photodetectors

This section describes techniques simulate photo detectors. This section applies to the simulation of the following devices: p-n and p-i-n photodiodes, avalanche photodiodes, Schottky photo detectors, CCDs, MSMs, photoconductors, optical FETs and optically triggered power devices.

2.2.1 Defining Optical Sources

We can define up to ten optical sources. Optical sources are described by using the BEAM statement. All BEAM statements must appear somewhere after the MESH, REGION, DOPING, and ELECTRODE statements and before any SOLVE statement. The parameters in the BEAM statement describe a single optical source.

The NUM parameter is used to uniquely identify one optical source. Values between 1 and 10 are valid for the NUM parameter. Optical sources are subsequently referred to by the value of their NUM parameter. The ANGLE parameter specifies the angle of the direction of propagation of the beam with respect to the device coordinate system. ANGLE=90 specifies vertical (normal) illumination from above.

The optical source can be either monochromatic or multispectral. For monochromatic sources, we can use the WAVELENGTH parameter to assign the optical wavelength. WAVELENGTH uses the unit microns to be more consistent with the rest of ATLAS. For multispectral sources, spectral intensity is described in an external ASCII file indicated by the POWER.FILE parameter. This is a text file that contains a list of pairs defining wavelength and spectral intensity. The first line of the file gives the integer number of wavelength-intensity pairs in the file. An example of such a file is shown below.

This example specifies that there are four samples and that at a wavelength of 0.4 μm, the intensity is 0.5 Watts per square cm per μm of wavelength, and so on. With multispectral sources, specify a discretization of the interpolated information. Values must be specified for the WAVEL.START, WAVEL.END, and WAVEL.NUM parameters. These values specify the starting and ending wavelengths and the number of wavelengths to sample. LUMINOUS uses wavelengths at equal intervals over a specified range of wavelengths. LUMINOUS performs an independent ray trace at each of the sample wavelengths. For example:

WAVEL.START=0.4 WAVEL.END=0.6 WAVEL.NUM=2

Causes ray traces at wavelengths of 0.45 and 0.55. LUMINOUS obtains the intensity associated with each sample by integrating the values of the spectral intensity file using a piece wise linear approximation. Each integral is performed over the range between successive midpoints. In the preceding example, the integration for the sample at 0.45 would be performed over the range of 0.4 to 0.5.

For a multispectral source, the generation rate is given by:

$$G = \eta_0 \int_{WAVEL.START}^{WAVEL.END} \frac{P(\lambda)L\lambda}{hc} \alpha e^{-\alpha y} d\lambda \qquad \textbf{[2.14]}$$

Where,

η_0 = The internal quantum efficiency.

$P(\lambda)$ = The power spectral density of the source.

L = A factor representing the cumulative loss due to reflections, transmissions, and absorption over the ray path.

λ = The wavelength.

h = Planck's constant.

c = The speed of light.

α = The absorption coefficient

y = The depth of the device, where x,y forms the two-dimensional mesh.

WAVEL.START= The starting of spectral limits specified on the BEAM statement

WAVEL.END = The ending of spectral limits specified on the BEAM statement.

The source photocurrent is given by:

$$I_S = q\frac{Bn}{hc} W \int_{WAVEL.START}^{WAVEL.END} P(\lambda)\lambda d\lambda \qquad \text{[2.15]}$$

Where,

P(λ) = The power spectral density of the source.

The other parameters have the same definition as in Equation

The available photo current is given by:

$$I_A = q\frac{Bn}{hc} \sum_{i=1}^{Nr} Wr \int_0^{Xi} \int_{WAVEL.START}^{WAVEL.END} P(\lambda) \, \alpha_i e^{-\alpha_i Y} P_i dy d\lambda \qquad \text{[2.16]}$$

where

P(λ) = The power spectral density of the source.

The other parameters have the same definition as in Equation.

LUMINOUS allows you to choose the units of spectral intensity in an input spectrum file. By default, the units of spectral intensity in the POWER.FILE are W/cm^2. In this case, LUMINOUS carries out the integration. If the units of spectral intensity in the POWER.FILE are W/cm2, then you need to use the flag INTEGRATE on the BEAM statement. In this case, each value P(λ) in the second column of the file is a total intensity for a corresponding spectral interval. Integrals over spectrum are reduced to summations of P(λ) values. In both cases, LUMINOUS treats the subsequently specified value of B on the SOLVE statement as a unit less multiplier or scale factor for intensity.

One of the simpler tasks in characterizing a photo detector design is to measure DC detection efficiency. This will be done typically as a function of bias voltage, optical intensity, or

wavelength. Each of these analyses can be performed using the SOLVE statement. The Bn parameter can be used to set the optical intensity of the optical sources described in the previous section. The following example illustrates obtaining a solution with a specified optical intensity:

SOLVE B1=1.0

This specifies that a solution is to be obtained for an optical intensity in the beam numbered "1" of 1.0 Watt/cm^2. If this were the first SOLVE statement specified, the ray trace in LUMINOUS would be initiated. At the start of the solution, the optical intensities of each optical source with a positive intensity is printed. In addition, the available photocurrent and source photocurrent are printed.

The available photocurrent divided by the source photocurrent is a measure of the external quantum efficiency of the detector. The calculated terminal current can be divided by the source or available photocurrents are used to evaluate the internal quantum efficiency of the device. To obtain V_{OC} and I_{SC} for a solar cell, first define the illumination conditions. This should be done as discussed above in describing multi-spectral sources. The short circuit current is obtained by defining the contacts as voltage dependent contacts (default) and obtaining a solution with the device under zero bias with illumination. This can typically be done as a first step by the following input statement, for example:

SOLVE B1=1

In this statement, it's assumed the source, B1, has been already defined and the intensity is expected in the actual device. When you obtain a solution, the terminal currents represent the short circuit current. The open circuit voltage is obtained by defining one or more of the contacts as current controlled. This is done using the CONTACT statement. For example:

CONTACT NAME=anode

The response of photo detectors to angle of incidence can be obtained in a manner analogous to the method used to obtain spectral response. In this case, the ANGLE parameter of the SOLVE statement specifies an angle added to the value of the BEAM parameter PHI (ANGLE). This allows collection of response versus angle. The following examples statements demonstrate the syntax.

SOLVE B1=1 ANGLE=0

Equivalently, you may find it more convenient to specify an angle ramp. To specify a ramp of angle, you should assign the BEAM parameter to the beam index of the optical source to be ramped. Also, you should specify the initial angle with the ANGLE parameter, the final angle with the AFINAL parameter, and the angle step size with the ASTEP parameter as illustrated in the following.

SOLVE B1=1 BEAM=1 ANGLE=0.0 ASTEP=10.0 AFINAL=60.0

This is completely analogous to the seven statements described above.

Luminous 2D provide flexible means for defining multispectral sources. In addition, you can directly access built-in public domain solar spectra for am0 and am1.5 conditions by specifying AM0 or AM1.5 on the BEAM statement. These spectra consist of numerous samples.

The following is an example of how you might define the BEAM statement for analysis of am1.5 conditions with sub sampling.

BEAM NUM=1 AM1.5 WAVEL.START=0.3 WAVEL.END=1.0 WAVEL.NUM=50

Here, we are choosing to simulate am1.5 conditions sampled between 0.3 microns and 1.0 microns at 50 samples. We do not have to worry about sampling the many peaks and valleys in the solar spectrum as it is automatically integrated into each subsample. The sub sampling effects only the number of wavelengths for which the propagation model is calculated not the integrated intensity. Ray tracing is the principal propagation model for cases where we are not concerned about interference or diffraction effects in the bulk of the device. This is most useful for relatively thick bulk devices, such as crystalline silicon devices. It is useful for planar or textured devices. For textured devices, the texturing must be described explicitly in the device structure. The following gives an example of the specification of ray tracing for the optical propagation model for Luminous.

BEAM NUM=1 AM1.5 WAVEL.START=0.3 WAVEL.END=1.0 WAVEL.NUM=50

In this case, we will perform 50 ray traces. The omission of other model keywords, such as TR.MATRIX, FDTD, or BPM, signifies that ray tracing will be performed.

For Luminous, the algorithm automatically traces exactly the right number of rays to completely resolve all discontinuities at the surface and deep into the device. Here, we will describe how to extract the most common figures of merit for solar cells. These extraction methods are solution strategies placed in your input deck after defining the device structure, physical models, and the optical source as described in the previous section.

Typically, the first step in solar analysis is to illuminate the device. You can turn on the illumination by assigning the beam intensity on a SOLVE statement as follows:

SOLVE B1=1.0

Here, we assign a value of one "sun" to the intensity of the optical source indexed as number

"1" (B1).

As we had assigned AM1.5 on the BEAM statement, this corresponds to standard test conditions. In some cases, we may encounter convergence difficulties and may need to ramp the light intensity as shown in the following:

SOLVE B1=1.0

You may also choose to assign the beam intensity to a value greater than one to simulate solar concentrator effects. Since we have not yet assigned any bias voltages, the current in the run time output corresponds to the short circuit current (Isc).

2.2.2 Air mass

Air mass is a measure of how much atmosphere the sun's rays have to pass through on their way to the surface of the earth. Since particles in the atmosphere absorb and scatter light rays, the more atmosphere solar radiation passes through on its way to us, the less solar energy we can expect to get. Air Mass is a measure of the amount of atmosphere the Sun's rays have to pass through. Air mass is abbreviated to AM where the following notation is used: AM1 is the amount of atmosphere the Sun's rays have to pass through when the Sun is directly overhead. This is the lowest possible AM value. In the example above where we had the Sun at 45° above the horizon, we write that we have AM1.41.As the Sun moves closer to the horizon, the amount

of air mass that it's rays have to pass through starts to rapidly increase. Here is a table of air mass for some values of solar zenith angle:

Table2.4: Different air mass ratio for different angle.

SEA	Air Mass
90°	AM1
60°	AM1.15
45°	AM1.41
30°	AM2
20°	AM2.92
15°	AM3.86

The "standard" for testing. The air mass coefficient is defined in proportion to the cosine of the zenith angle (z): the angle between the beam from the Sun and the normal vector pointing directly up to the zenith of the sky (normal to the horizontal surface).

AM=1/cos(z) [simple, parallel plate]

One needs:

- The day number (N),
- The declination (δ),
- The hour angle (ω), and
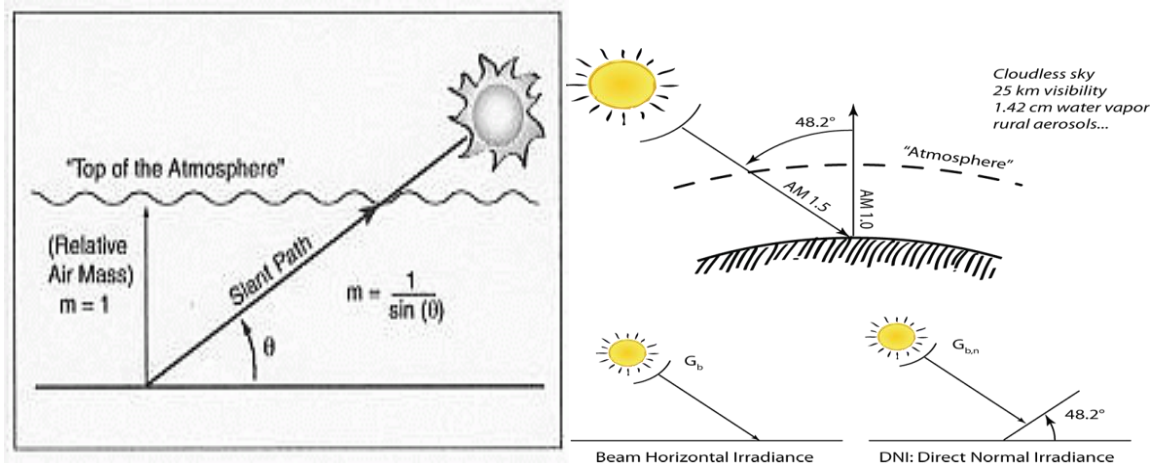- The local latitude (ϕ) to calculate the zenith angle.

Figure 2.1: Air mass ratio [10]

Once we get below a solar elevation angle of around 15-20°, this simple trigonometrical estimation of air mass becomes increasingly inaccurate since it ignores the curvature of the Earth. As the Sun get's closer to the horizon, the following equation can be used:

$$AM = \frac{1}{cosz + 0.50572\,(96.07995 - z)^{-1.6364}}$$
[2.17]

Where z is (90 - solar zenith angle).

If the atmosphere is treated as a simple spherical shell, the above equation can be simplified to:

$$AM = \sqrt{(rcosz)^2 + 2r + 1} - rcosz$$
[2.18]

Where again z is $(90 - solarzenithangle)$, and r is the ratio the radius of the Earth (approx 6371km) to the depth of the atmosphere (9km since we can ignore the effect of the very thin atmosphere above that height without losing much accuracy). Therefore the value of r is approximately 708.Using either of these equations, we see (approximately) that with an SEA of 10° we have AM5, at 5° we have AM10, at 2° we have AM20, and at 0° we have AM38. Therefore, when the Sun is say 2° above the horizon, the sunlight has to travel through 20 times more air mass than when the Sun is directly overhead.

Chapter 3

Simulation Results and Discussion

3.1 Proposed Solar Cell

As we all know from the above conversation solar cell have different layers such as font and back contact ,Transparent Conductive Oxide (TCO) layer, Window layer, Intrinsic layer, Absorber layer and BSF layer. As far concern about our solar cell we use Aluminium(Al) at the font contact, CdS at the window layer define as n-CdS, CIGS at the both intrinsic and absorber layer define as i-CIGS and P-CIGS and for the BSF layer we also use CIGS define as p-CIGS and molybdenum(Mo) at the back contact. After simulating by Silvaco software [9] we get our desired solar cell:
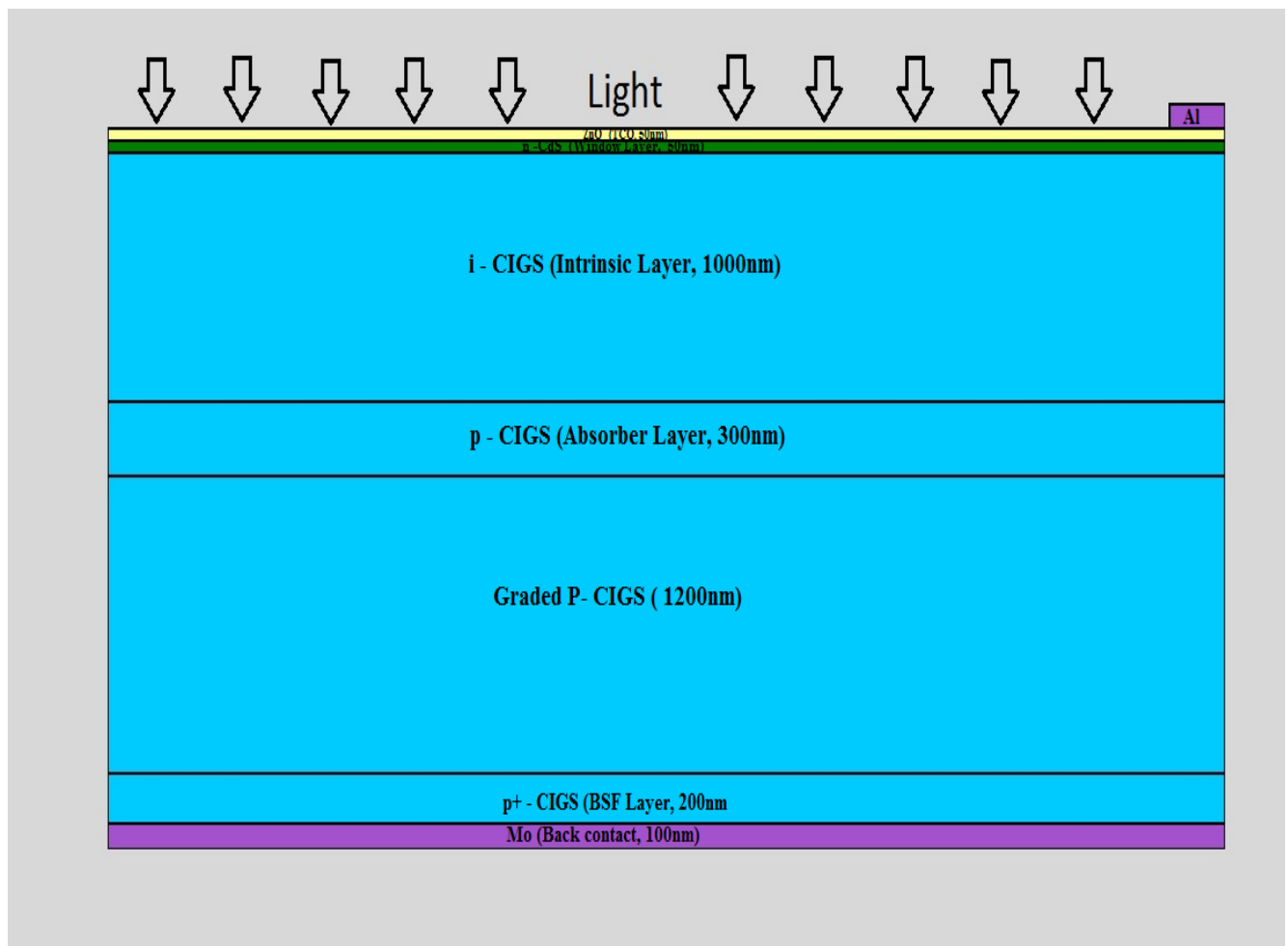

Figure 3.1: Proposed CdS/CIGS Solar Cell

3.2 Parameters of Different Layers

Parameters that are used in this project analysis for different layer and material are given as follow:

Table-3.1: TCO Layer Parameters

No	Parameters	Value
1	Layer	TCO
2	Type	ZnO
3	Thickness (nm)	50
4	Eg(eV)	3.37
5	EPS	8.49
6	Nc (per cc)	2.2×10^{18}
7	Nv (per cc)	1.8×10^{19}
8	ni (per cc)	3.11×10^{-10}

Table-3.3: Intrinsic Layer Parameters

No	Parameters	Value
1	Layer	Intrinsic
2	Type	CIGS
3	Thickness (nm)	100
4	Eg(eV)	1.07
5	EPS	13.6
6	Nc (per cc)	2.2×10^{18}
7	Nv (per cc)	1.8×10^{19}
8	ni (per cc)	6.57×10^{9}

Table-3.4: n Layer Parameters

No	Parameters	Value
1	Layer	n-type
2	Type	CdS
3	Thickness (nm)	50
4	Eg(eV)	2.48
5	EPS	10
6	Nc (per cc)	2.41×10^{18}
7	Nv (per cc)	2.57×10^{19}
8	ni (per cc)	0.0116

Table-3.5: p Layer Parameters

No	Parameters	Value
1	Layer	p-type
2	Type	CIGS
3	Thickness (nm)	1000
4	Eg(eV)	1.07
5	EPS	13.6
6	Nc (per cc)	2.2×10^{18}
7	Nv (per cc)	1.8×10^{19}
8	ni (per cc)	6.57×10^{9}

3.3 TCO Layer

A TCO is used as a front contact in order to create the heterojunction with the absorber and to gain as much photocurrent as possible from the solar panel with increasing the energy gap of the window layer. This layer should allow the largest possible percentage of photons to reach the absorber layer and is required for good conductivity and high transmittance in visible light. Conductivity depends on the concentration and mobility of charge carriers, and its increase is usually achieved after mixing with elements such as Al. However, increasing the concentration of impurities using alloys leads to the reduction of the permeability of films at long wavelengths. Therefore, an increase in the mobility of carriers should be performed primarily by improvement of the film's crystalline. However, ZnO is considered the most competitive in cost and properties. Typically, these applications use electrode materials that have greater than 80% transmittance of incident light as well as electrical conductivities higher than 103 S/cm for efficient carrier transport. In general, TCOs for use as thin-film electrodes in solar cells should have a minimum carrier concentration on the order of 10^{20} cm^{-3} for low resistivity and a bandgap greater than 3.2 eV to avoid absorption of light over most of the solar spectra. Mobility in these films is typically limited by ionized impurity scattering due to the large amount of ionized donors in the order of 40 cm^2/(V·s) for the best performing TCOs.

A good TCO has a large enough band gap to allow a majority of photons to reach the absorber layer. It is also critical that the TCO has a low resistivity to reduce recombination losses. This material boasts a low resistivity of ~$10^{-4}\Omega\cdot$cm and a transmittance of greater than 80%. In common CIGS cells, zinc oxide (ZnO) is used for the TCO. ZnO has a band gap of 3.3 eV

To date, the industry standard in TCOs is ITO, or tin-doped indium-oxide. ITO has the drawback of being expensive. Indium, the film's primary metal, is rare (6000 metric tons worldwide in 2006), and its price fluctuates due to market demand (over $800 per kg in 2006). For this reason, doped binary compounds such as aluminum-doped zinc-oxide (AZO) and indium-doped cadmium-oxide have been proposed as alternative materials. AZO is composed of aluminum and zinc, two common and inexpensive materials, while indium-doped cadmium oxide only uses indium in low concentrations. In PV technology, except from ZnO many different TCOs have been used as transparent windows of the cell. These are the indium– tin oxide (ITO), the indium–gallium oxide (IGO) and SnO2.

3.4 Intrinsic Layer

PIN photodiodes are used in fiber optic network cards and switches. As a photo detector, the PIN diode is reverse biased. Under reverse bias, the diode ordinarily does not conduct (save a small dark current or leakage). When a photon of sufficient energy enters the depletion region of the diode, it creates an electron-hole pair. The reverse bias field sweeps the carriers out of the region creating a current. Some detectors can use avalanche multiplication. The same mechanism applies to the PIN structure, or p-i-n junction, of a solar cell. In this case, the advantage of using a PIN structure over conventional semiconductor p–n junction is the better long wavelength response of the former. In case of long wavelength irradiation, photons penetrate deep into the cell. But only those electron-hole pairs generated in and near the depletion region contribute to current generation. The depletion region of a PIN structure extends across the intrinsic region, deep into the device. This wider depletion width enables electron-hole pair generation deep within the device. This increases the quantum efficiency of the cell.

Table 3.1: I- layer scaling study of CdS/CIGS solar cell, for all cases TCO layer = 50nm, front contact and back contact= 100nm, CdS=50nm, CIGS=1um, BSF = 200nm, TCO doping=10^{20}cm^{-3}, **n-type doping=10^{17}cm^{-3}, p-type doping=10^{18}cm^{-3}, BSF doping=10^{19}cm^{-3}.**

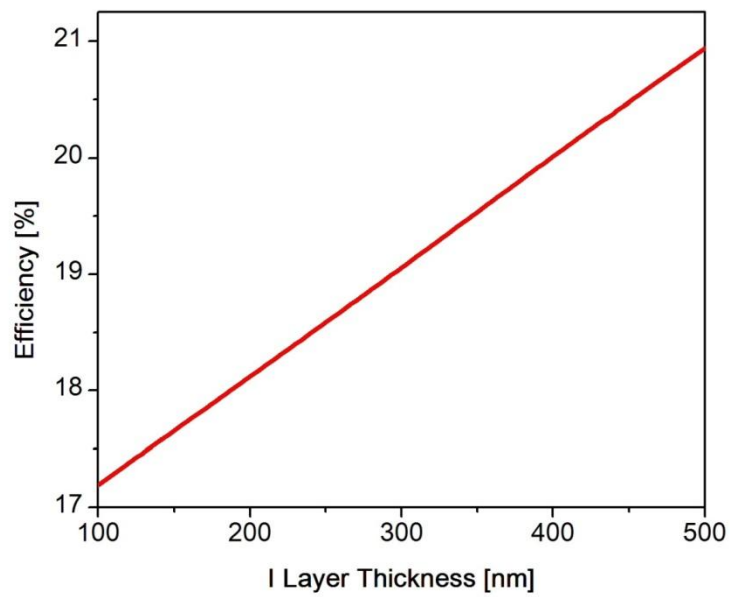| I- layers	Voc (V)	Jsc (mA/cm2)	Pmax (mW/cm2)	FF (%)	Efficiency (%)
I- layer = 100nm	0.71	34.12	20.40	84	17.19
I- layer = 200nm	0.712	36.03	21.56	84	18.12
I- layer = 300nm	0.713	37.89	22.68	84	19.05
I- layer = 400nm	0.714	39.65	23.81	84	20.02
I- layer = 500nm	0.715	41.47	24.92	84	20.94

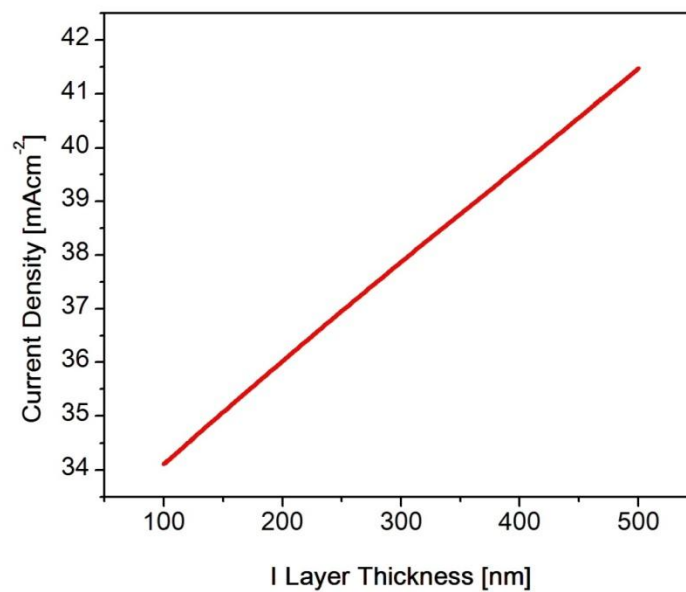**Fig 3.1**: Efficiency vs. I Layer Thickness

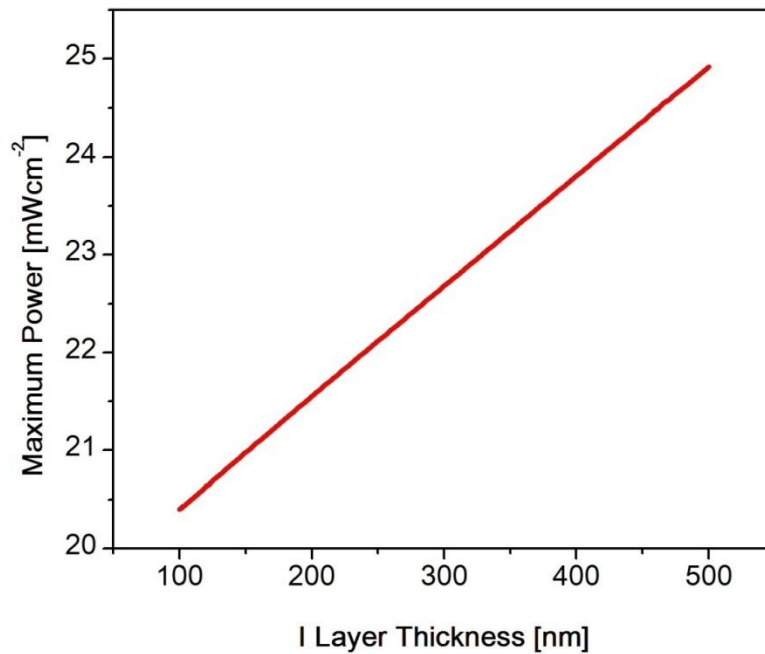**Fig 3.2**: Current density vs. I Layer Thickness

Fig 3.3: Maximum Power vs. I Layer Thickness

The above three figures shows the efficiency, maximum power and current density versus I-layer thickness. We find that the efficiency, maximum power and current density are linearly increases with increasing intrinsic layer thickness. Here we use variation in the thickness of I-layer and apply doping density 10^{17}, 10^{18}, 10^{19} respectively at n-type, P-type and BSF layer. Finally we get the efficiency 20.94% at 500nm thickness of I-layer. At the back and font contact we use 100nm and for BSF 200nm.

Table 3.2: I- layer scaling study of CdS/CIGS solar cell, for all cases TCO layer = 50nm, front contact and back contact= 100nm, CdS=50nm, CIGS=1.5um, BSF = 200nm, TCO doping=10^{20}cm^{-3}, **n-type doping=10^{17}cm^{-3}, p-type doping=10^{17} - 10^{18} cm^{-3}, BSF doping=10^{19}cm^{-3}**.

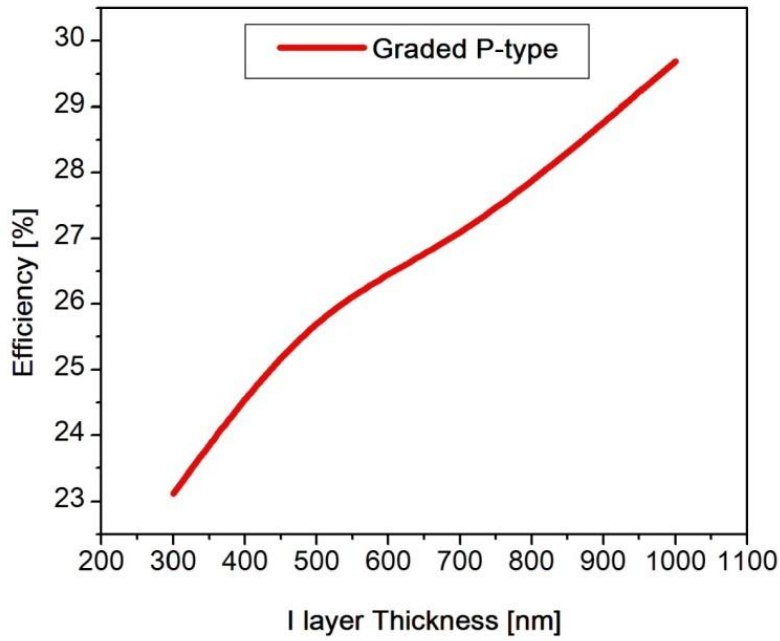| Graded P-type CIGS	I-layers (nm)	Voc (V)	Jsc (mA/cm2)	Pmax (mW/cm2)	FF (%)	Efficiency (%)
P-CIGS (300_{17} + 1200_{18})	300	0.720	45.35	27.48	84	23.12
	500	0.730	50.23	30.89	84	26.04
	700	0.724	52.44	31.95	84	26.89
	1000	0.726	57.72	35.27	84	29.69

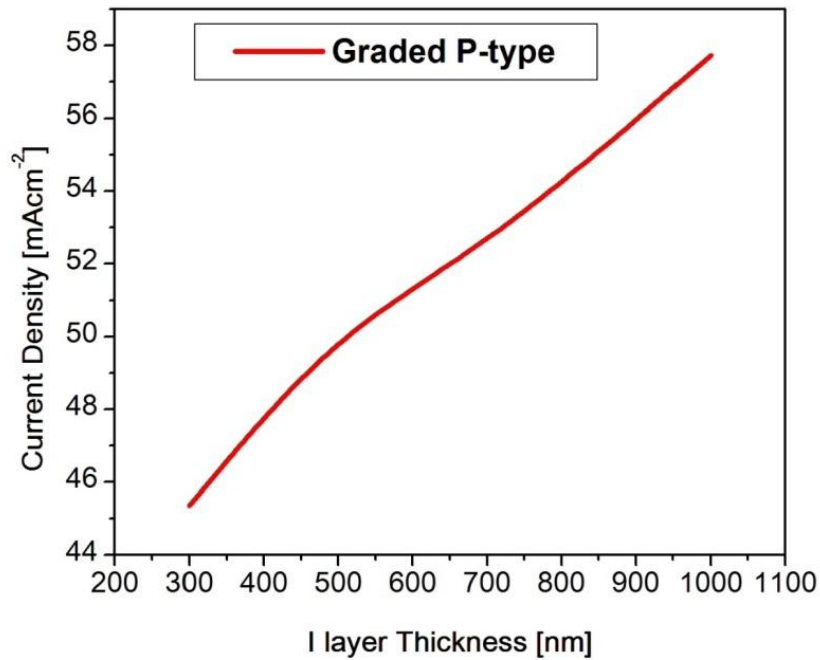**Fig 3.4:** Efficiency vs. I-Layer Thickness

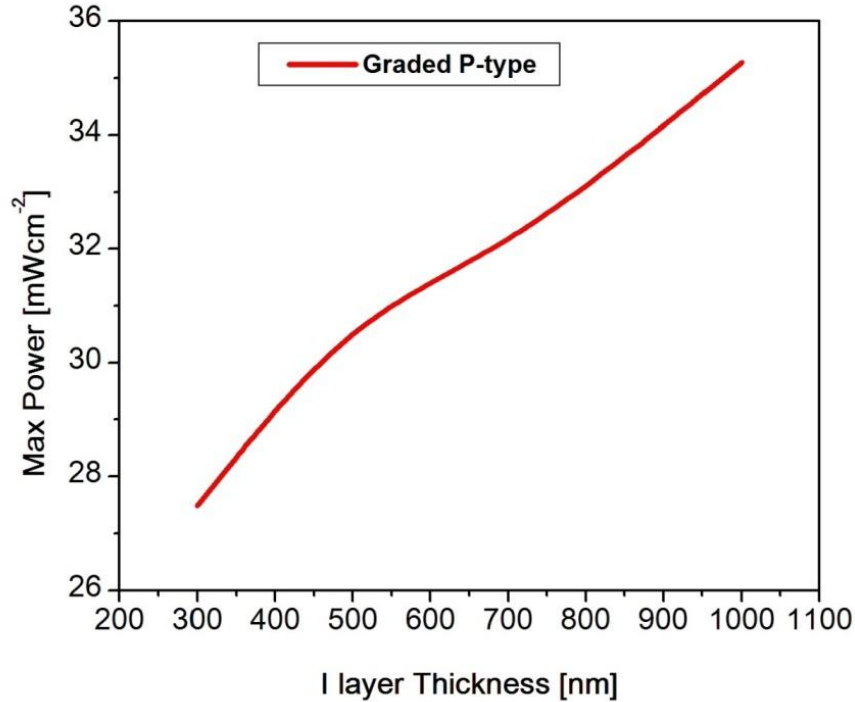**Fig 3.5**: Current Density vs.I Layer Thickness

Fig 3.6: Maximum Power vs.I Layer Thickness

As mentioned above figures show the almost linearly nature of efficiency ,current density and maximum power with respect to I-layer thickness in nm for graded P-type CIGS. Here we use different thickness of I-layer and apply doping density 10^{17}, 10^{18}, 10^{19} respectively at n-type, P-type and BSF layer. As a result we get the efficiency 29.69% at 1000nm thickness of I-layer. The thickness of font contact and back contact is 100nm and BSF layer is 200nm.

Table 3.3: Graded CIGS/CdS solar cell, for all cases TCO layer = 50nm, front contact and back contact= 100nm, CdS=50nm, BSF = 200nm, TCO doping=10^{20}cm^{-3}, **n-type doping=10^{17}cm^{-3}p-type doping=10^{16} - 10^{18}cm^{-3}, BSF doping=10^{19}cm^{-3}**.

	Graded	Voc (V)	Jsc (mA/cm2)	Pmax (mW/cm2)	FF (%)	Efficiency (%)
P-CIGS	$300_{17} + 1200_{18}$	0.721	50.22	30.9	85.3	26.3
	$500_{17} + 1000_{18}$	0.721	50.07	30.4	84	25.58
	$500_{16} + 1000_{18}$	0.721	49.69	30.16	84	25.4
	$500_{17} + 500_{18}$	0.721	42.68	25.66	83	21.4
	$400_{17} + 600_{18}$	0.721	42.65	25.61	83	21.323

In graded CIGS/CdS Solar cell, we have used different layers like TCO layer, Window layer, Intrinsic layer, BSF layer, Absorber layer, Back contact. In TCO layer, we have used ZnO with thickness 50nm. The doping density we used in the TCO layer is 10^{20} cm^{-3}. CdS is used in window layer with 50nm thickness and doping concentration is 10^{17} cm^{-3}. Here Intrinsic layer thickness is 1000nm and doping concentration is 2e14 cm^{-3}. In graded p-type layer, the doping concentration is considered as 10^{16} to 10^{18} cm^{-3}. In order to change the thickness of the layer, we get the different value of the Current density, maximum power and efficiency, shown in the above Table 3.3. Here the highest efficiency is 26.3%.

Chapter 4

Conclusion

In this project we designed and simulated a CdS/CIGS high efficiency solar cell using SILVACO. It is found that the efficiency of the solar is increased linearly by increasing the thickness of the intrinsic layer. Our proposed solar cell is designed with thickness of BSF layer p+ CIGS 200nm, Intrinsic layer CIGS 1000nm, TCO ZnO 50nm. Output of the cell efficiency is about 29.69%, fill factor 84%, maximum power 35.27 mWcm^{-2}, current density 57.72 mAcm^{-2}, and open circuit voltage 0.726V.

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[10]https://www.google.com.bd/search?q=pic+of+air+mass+of+solar+cell&biw=1366&bih=657 &tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjC45yk9OvQAhUHpI8KHXJ6CdkQs AQIFw#imgrc=ayuwOLN3kiL7RM%3A (4:30pm, 11 Dec. 2016)

Appendix A

Silvaco Code:

```
go atlas
mesh
y.meshloc=-.2 spac=.2
y.meshloc=-.1 spac=.2
y.meshloc=-.05 spac=.25
y.meshloc=0 spac=.25
y.meshloc=1 spac=.25
y.meshloc=1.3 spac=.25
y.meshloc=2.5 spac=.2
y.meshloc=2.7 spac=.2
y.meshloc=2.8 spac=.2
x.meshloc=-2 spac=.15
x.meshloc=-.1 spac=.15
x.meshloc=0 spac=.15


region number=1 y.min=-.2 y.max=-.1 x.min=-2 x.max=-.1 material=Air
region number=2 y.min=-.2 y.max=-.1 x.min=-.1 x.max=0
material=aluminum
region number=3 y.min=-.1 y.max=-.05 x.min=-2 x.max=0 material=ZnO
region number=4 y.min=-.05 y.max=0 x.min=-2 x.max=0 material=CdS
region number=5 y.min=0 y.max=1 x.min=-2 x.max=0 material=CIGS
region number=6 y.min=1 y.max=1.3 x.min=-2 x.max=0 material=CIGS
region number=7 y.min=1.3 y.max=2.5 x.min=-2 x.max=0 material=CIGS
region number=8 y.min=2.5 y.max=2.7 x.min=-2 x.max=0 material=CIGS
region number=9 y.min=2.7 y.max=2.8 x.min=-2 x.max=0
material=Molybdenum
electrode name=cathode y.min=-.2 y.max=-.1 x.min=-.1 x.max=0
electrode name=anode y.min=2.7 y.max=2.8 x.min=-2 x.max=0
dopingy.min=-.1 y.max=-.05 x.min=-2 x.max=0 n.typeconc=1e20 uniform
dopingy.min=-.05 y.max=0 x.min=-2 x.max=0 n.typeconc=1e17 uniform
dopingy.min=0 y.max=1 x.min=-2 x.max=0 p.typeconc=2e14 uniform
dopingy.min=1 y.max=1.3 x.min=-2 x.max=0 p.typeconc=1e17 uniform
dopingy.min=1.3 y.max=2.5 x.min=-2 x.max=0 p.typeconc=1e18 uniform
dopingy.min=2.5 y.max=2.7 x.min=-2 x.max=0 p.typeconc=1e19 uniform

modelssrhconmob fermi ni.fermibgnoptr auger
outputcon.bandval.bandband.parame.mobh.mob opt.int
BEAM NUM=1 AM1.5 WAVEL.START=0.3 WAVEL.END=1.2 WAVEL.NUM=50

SOLVE B1=1 BEAM=1 ANGLE=0.0 ASTEP=10.0 AFINAL=60.0

log outf=CdS_&_CIGS_I_layer_300nm_graded_1200nm_1000nm_new.log


solve name=anode vanode=0 vstep=0.001 vfinal=.80
log off
```

```
saveoutf=CdS_&_CIGS_I_layer_300nm_graded_1200nm_1000nm_new.str


tonyplot CdS_&_CIGS_I_layer_300nm_graded_1200nm_1000nm_new.log
tonyplot CdS_&_CIGS_I_layer_300nm_graded_1200nm_1000nm_new.str

quit
```