Simulation Study on the Effects of Changing Band gap on Solar Cell Parameters

By

Mostofa Amir Rifat (2012-2-80-044)

And

Mohammad Imtiaz Morshed Khan (2012-2-80-051)

Submitted to the

Department of Electrical and Electronic Engineering

Faculty of Sciences and Engineering

East West University

In partial fulfillment of the requirements for the degree of

Bachelor of Science in Electrical and Electronic Engineering

(B.Sc. in EEE)

Spring, 2016

Approved By

Thesis Advisor	**Department Chairperson**
Dr. Khairul Alam	**Dr. Mohammed Mazharul Islam**
Professor	**Assistant Professor**

Abstract

Solar cell is treated as a wonderful source of renewable energy. Researchers are much interested in this source of renewable energy because of being environment friendly. Solar cell technology is much advance and day by day it is being enriched. In this thesis, we study the numerical analysis of solar cell parameters; such as open circuit voltage, short circuit current, maximum power, fill factor, and external quantum efficiency as a function of observer layer band gap. These parameters are known as basic parameters of a solar cell. In this thesis, band gap of absorber layer of a solar cell structure is selected to be varied, and the impacts of varying band gap on the basic solar cell parameters are presented. ATLAS SILVACO is used to construct and simulate the CIGS solar cell structure. Standard AM1.5 spectrum for incident photon is used for this analysis. The characteristic of external quantum efficiency with respect to input photon wavelength is also studied for different band gap of absorber layer. MATLAB is used to plot different characteristics of desired study.

Acknowledgement

This thesis is nothing but the outcome of works done for eight months. In the meantime, we are supported by many people. This is the time to express our gratitude to everyone.

At first, we want to thank our thesis supervisor Dr. Khairul Alam, Professor of Department of Electrical and Electronic Engineering of East West University for his affectionate guidance, innovative suggestion from the very beginning to the end of this task. Without his support it was next to impossible for us to reach in the current stage with this thesis. We owe him lots of gratitude for guiding us with friendly behavior.

We want to thank our honorable teacher Dr. Anisul Haque, Professor of Department of Electrical and Electronic Engineering of East West University for supporting us with his profound knowledge through this study period on semiconductor materials. From the very beginning of this journey, his constructive suggestions helped us to learn about semiconductor materials and the basic properties of those. Special thanks also go to our department chair person Dr. Mohammed Mazharul Islam. We further thank to Dr. Mohammad Mojammel Al Hakim to encourage us to do research and use ATLAS SILVACO as a simulation tool. Finally we want to thank our family for support us all the way of this study, as well as thank to our entire friends and classmates for support us mentally.

Authorization

We hereby declare that we are the sole author of this thesis. We authorize East West University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

Mostofa Amir Rifat	Mohammad Imtiaz Morshed Khan
(SID: 2012-2-80-044)	(SID: 2012-2-80-051)

We further authorize East West University to reproduce this thesis by photocopy or other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Mostofa Amir Rifat	Mohammad Imtiaz Morshed Khan
(SID: 2012-2-80-044)	(SID: 2012-2-80-051)

Contents

List of Figures

Chapter 1: Introduction

One of the major problems of this century is limitation of fossil fuels. So, it is high time to search for new sources of renewable energy. Since the modern age is blessed with numerous technologies, there is enough scope to think and implement new concepts related to renewable energy. Among different types of renewable source of energies, solar energy is very popular. Solar energy is the principle source of all energies. The technology through which it is possible to use solar energy to get electrical energy is called photovoltaic technology.

Photovoltaic or solar cell technology is nothing new concept. It is widely used and being implemented in different sectors and different places. The cell which is designed to convert photo energy into electrical energy is called solar cell. The basic idea of solar cell is very similar to a simple p-n junction. This p-n junction should be of proper semiconductor materials having good optoelectronic properties.

Photovoltaic (PV) technology can be categorized under different generations. The first generation PV technology was based on using crystalline silicon, which were bulky in size. Second generation PV technology was based on thin film cells, which were prepared using cheaper technology. The final PV technology is based on III-V semiconductor materials, which are known as multi junction cells.

There are many positive perspectives of photovoltaic power plants. This type of power plant is good for environment because of being pollution free and noise free because of not having any rotational parts. Since there is no mechanical component in photovoltaic energy generation plants, the maintenance is also easier than other fossil fuel based power stations. The transmission and distribution processes are also simpler than others. These are the main reasons of photovoltaic technology being more preferable than other renewable energy sources.

To get excellent efficiency, solar cells should be made of pure materials. Not only optimum band gap, but also purity of materials is responsible for high efficiency of solar cell. The defects in materials results in unnecessary recombination of charge carriers, which leads to decrease in solar cell efficiency.

1.1 Objective

Silicon is used very largely in photovoltaic technology. The reason is nothing but having high efficiency and availability. There are some barriers of cost and slow grow process in using silicon in photovoltaic technology. Actually to have good efficiency of silicon solar cell, the thickness of silicon layer should be much thicker, which results in high cost. The growing process of silicon layer is quite slower. So, different manufacturing companies are interested in applying different materials which can be more efficient. The recent approach towards the development of photovoltaic technology is to use hetero junction, tandem, multiple junction solar cells using materials of different band gap. Recently many researches are going to implement and develop organic solar cells also.

The main objective of this thesis is to study different parameters of solar cell, such as open circuit voltage, short circuit current, maximum power, fill factor, external quantum efficiency, and efficiency. In this purpose, realistic material Cu (In, Ga)Se2 (CIGS) is studied to see the responses by taking different values of composition of the materials in CIGS. ATLAS is used to model solar cells. CIGS was used to study the variation of the parameters of solar cell with the variation of band gap by using different value of material composition. Necessary data are taken from ATLAS simulation. MATLAB is also used to obtain required plots using simulated data of ATLAS. According to the analysis of those data, band gap effects on solar cell performance metrics are concluded.

1.2 Literature Review

Toberer *et al*. [1] suggested that open circuit voltage should be an indicator of material quality. They presented the dependence of open circuit voltage on band gap. They used a step-edge absorption model to show that the photo voltage increases and photocurrent decreases systematically with increasing band gap. They also discussed the effect of changing thickness in increasing efficiency. They studied upon base thickness of 1μm and 3μm using conventional epitaxial growth and processing techniques, but without antireflection coating. Next, they used antireflection coating to study the behavior of External Quantum Efficiency (EQE). Their study was the inspiration of this thesis. Next, our attraction on CIGS was drawn by the work of J. Krc and co-workers [2] on optical and electrical modeling of CIGS solar cells. They studied on thin-film CIGS solar cell. For optical simulations of the structure, they performed experimentally determined complex refractive indices of the real layers because of lateral

dimensions of thin film solar cells being much larger than the thickness of the structure. The optical simulator Sun Shine [3, 4] and the electrical simulator Aspin [5, 6] were used to simulate optical and electrical properties and characteristics of the thin CIGS solar cell in their study. In their study, EQE and other parameters were found. From the work of Samaneh Sharbati and James R. Sites [7] the performance analysis of solar cells was done for Zn(O, S)/ Cu(In,Ga)Se2 hetero junction. The individual electron affinities and band gaps were controlled and variation in result was studied. They showed that with the increase in band gap of CIGS, open circuit voltage increased. Another work by Mustafa M. A. Hussein and co-workers [8] on ITO/CdTe/Al_2O_3/Si/Au Thin Film Solar Cell showed the electrical properties including I-V curve with respect to the layer thickness ofAl_2O_3.They proposed maximum value of quantum efficiency and fill factor at thickness of 1.7 nm. I-V characteristics are measured by KEITHLEY computerized system. The contact wires are soldered to each layer of samples by indium alloy soldering. This type of soldering ensures good contacts, and low temperature keeps the structural properties of films unchanged. The fill factor and efficiency are calculated from I-V characteristics for different thickness of Al_2O_3 layer. They declared Gold as back contact and ITO as front contact for their hetero junction structure. According to these reviews, we become interested in this simulation study. Our intension is to vary the band gap of CIGS layer of a solar cell to observe the resultant variations in open circuit voltage, short circuit current, maximum power, fill factor, and external quantum efficiency.

1.3 Motivation

Open circuit voltage is a performance indicator of solar cell. Open circuit voltage is the maximum voltage that is found from the solar cell when no current flows through the external circuit. Open circuit voltage depends on the photo generated current density, and increases with increase in band gap of solar cell materials [9]. Another important solar cell parameter is short circuit current. The current which flows through the external circuit when two electrodes of the solar cell are shorted is called short circuit current. This is dependent on the incident photon flux and the solar cell area. So, to represent the area independent solar cell parameter, short circuit current density is also presented. The maximum current delivered from the solar cell also depends on optical properties of solar cell materials; such as: absorption in the absorption layer and reflection of the material. Generally, short circuit current decreases with the increase in band gap of solar cell materials [10]. From the I-V characteristics of a solar cell, maximum power of a solar cell can be found. The peak point of the P-V curve of a solar cell indicates the

maximum power delivered by a solar cell. From this theoretical study, we are interested in the numerical analysis of solar cell parameters by varying the band gap of the absorber material. In this purpose, ATLAS SILVACO is used to simulate a solar cell structure for different band gap.

1.4 Thesis Outline

- In chapter 1, introduction of photovoltaic technology as an alternative renewable energy is done and the categories of this technology and the current perspective of this technology are presented. Then the objective of this thesis is revealed along with the literature review and motivation part.
- In chapter 2, different models and methods of ATLAS is presented as a tool of this analysis.
- In chapter 3, the result of this study is presented. The effect of changing band gap on solar cell parameters such as open circuit voltage, short circuit current, maximum power, fill factor, and external quantum efficiency are presented.
- Finally, the findings are concluded in chapter 4.

Chapter 2: Basic of Solar Cell and Simulation Setup Using ATLAS SILVACO

For this thesis on impacts of changing bang gap on solar cell parameters, ATLAS SILVACO is used. In this chapter, a brief overview on solar cell will be presented, and then the simulation strategy of solar cell in SILVACO is going to be revealed.

2.1 Brief Review on Solar cell

Basically solar cell is nothing but a p-n junction. The basic building block of a solar cell is simple p-n junction. In p-type semiconductor the density gradient of hole is greater than the density gradient of hole in n-type semiconductor. As a result, holes are diffused from p-type to n-type semiconductor. Similarly, electron density gradient is larger in n-type semiconductor than the electron density gradient in p-type semiconductor, so electrons are diffused from the n-type semiconductor to p-type semiconductor. As a result, near the junction of the semiconductors, a depletion region is created; and the n-type semiconductor near the junction becomes positively charged and the p-type semiconductor near the junction becomes negatively charged. Due to the creation of the depletion region in the contact of oppositely doped semiconductors, an electric field is created, and the direction of the electric field is from the positively charged part of depletion region to the negatively charged part of the depletion region. This electric field removes the charge carriers from the oppositely doped regions, and this process is called drift. The electric field at the depletion region forces the minority charge carriers in the p-type region, the electrons to move to the n-region, and the minority charge carriers in the n-type region, the holes to move to the p-region. Doing this, the electric field prevents the further diffusion of the charge carriers. So, the diffusion process tends to the increase the charge area in the diffusion region, and the electric field tends to retain the carrier diffusion and prevents flow of current. Due to the creation of depletion region, a potential barriers is emerged which counteracts the diffusion of the electrons from the n-type region to the p-type region. This potential barrier is also called built in voltage, which is represented as V_{bi}. This potential barrier can be varied by applying bias voltage.

Now, let us concentrate on the structure of a solar cell. A simple structure of solar cell consists of a transparent conductive oxide (TCO) on top, after that p-n junction of semiconductor material is used to separate the light excited charge carriers and a front metal contact and a

back metal contact is used. When light falls on top, photons pass through the TCO layer since the band gap of the TCO material is very high than the energy of light photon. Then the photons energize the charge carriers; holes and electrons, which results in excess carrier generation in p-n regions, and the charge carriers diffuse through the depletion region. If the back contacts are connected to a load, charge carriers will flow through the load, and that is how we get electricity from a solar cell.

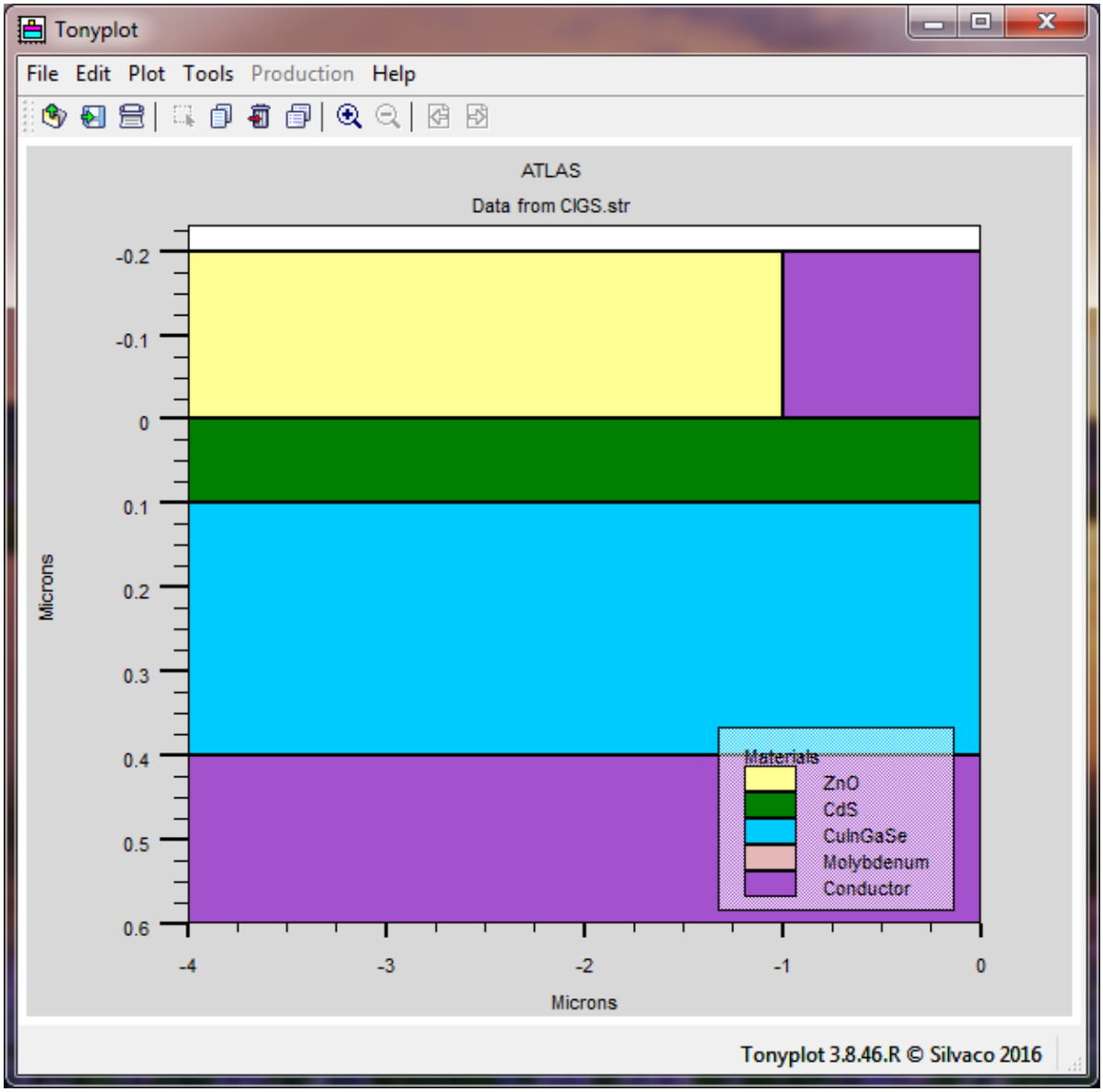

Figure 2.1: A basic solar cell structure (snap shot from TONYPLOT of ATLAS SILVACO)

In this particular sample of solar cell presented in figure: 2.1, Zinc Oxide (ZnO) was doped with Aluminum (Al) to form TCO. Cadmium Sulphide (CdS) layer was n-type doped, while

Copper Indium Galium Selenide (CIGS) was p-type doped. At top rightmost corner, front contact metal was used and at the bottom of the structure back contact metal was used.

2.2 Simulation Setup with SILVACO

2.2.1 Overview

In this thesis, ATLAS SILVACO is used to simulate a solar cell structure having CdS as n-type material, CIGS as p-type material, TCO layer, and two contacts. In this step, the composition of materials in CIGS alloy is varied to vary the band gap of CIGS. The variations in solar cell parameters with respect to the change in band gap are studied. The commands used in ATLAS SILVACO are presented below:

2.2.2 Statements Used to Model Structures

Solar cell simulation is done in ATLAS SILVACO through a text input run time environment, called DeckBuild, in which different cell parameters and composition were defined.

Set

Set statement is used to define value of a variable for using and substituting into Atlas syntax. Set was used to define a numerical value in a variable. For example:

```
SET Lm = 0.4
```

Here, the numerical value 0.4 was defined inside a variable Lm.

Mesh

The grid is made of horizontal and vertical lines with some distances which can be defined by the user. Using mesh, the physical area of the structure is bounded by the creation of a number of triangles in which simulation takes place. For example:

```
y.mesh loc=-$Lm spac=0.01

x.mesh loc=-$T spac=0.1
```

Here, vertical and horizontal division of mesh is defined with user defined location value and spacing.

Region

Using “region” statement, the total structure and mesh is divided into areas. Each area is then declared having a specific material from the ATLAS library. For example:

```
region number=1 y.min=-$Lm y.max=0 x.min=-$T x.max=0 material=ZNO
```

Here, a region is defined with number 1 and a particular material is declared for this region.

Electrode

This statement is used for the specification and naming of electrodes in the mesh or region defined before. For example:

```
electrode y.min=-$Lm y.max=0 x.min=-$T1 x.max=0 name=cathode
electrode y.min=$L3  y.max=$L4 x.min=-$T x.max=0 name=anode
```

Here, two electrodes: cathode and anode were declared in two predefined regions.

Doping

The specification of the doping concentration of the materials is done using “doping” statement. For example:

```
doping y.min=0 y.max=$L1 x.min=-$T x.max=0 n.type conc=$NN uniform
```

In this command, the material is uniformly n type doped having user defined concentration in a predefined mesh.

Material

Using “material”, different properties and physical parameters of previously defined and doped regions are selected from the ATLAS database. For example:

```
material mat=CIGS PERMITTIVITY=13.6 AFFINITY=3.89 MUN=300 MUP=30 \
NC300=2.2e18 NV300=1.8e19
```

Here, the material CIGS was used whose dielectric permittivity is 13.6 F/m, electric affinity is 3.89 eV, low field electron mobility is 300 cm^2/Vs, low field hole mobility is 30 cm^2/Vs, conduction band effective density-of-states at 300 K is 2.2×10^{18} cm^{-3}, and valence band effective density-of-states at 300 K is 1.8×10^{19} cm^{-3}.

Model

Using "model" statement, specified and required physical model is declared for simulating the structure. The physical models are divided into five classes: mobility, recombination, carrier statistics, impact ionization, and tunneling.

models srh temperature=318 bound.trap print

In this thesis, Shockley-Read-Hall (SRH) recombination model was used. The theory of photon transition in the presence of defect within the forbidden gap of the semiconductor was first derived by Shockley and Read and then by Hall. The SRH recombination is modeled as below:

$$R_{SRH} = \frac{pn - n_{ie}^2}{TAUP0[n + n_{ie}\exp(\frac{ETRAP}{kT_L})] + TAUN0[p + n_{ie}\exp(\frac{-ETRAP}{kT_L})]}$$

Here, ETRAP is the difference between the trap energy level and the intrinsic Fermi level, T_L is the lattice parameter in degree kelvin, and TAUN0 and TAUP0 are the electron and hole lifetimes. Using "srh" parameter of the model statement, this recombination model is declared.

Beam

Using "beam" statement, optical beam is declared. For example:

beam num=1 AM1.5 wavel.start=0.3 wavel.end=1.2 wavel.num=50

Here, one beam is defined, and the AM1.5 spectrum is used and the range of wavelength is also defined to simulate the solar cell defined earlier.

Log

Using this statement, a log file is opened. A particular name of the log file should be given.

log outfile="iv035.log"

Here, a log file whose name is "iv.log" is opened.

Solve

This statement follows a statement and further a solution is performed for some user defined bias points.

solve vanode=0 name=anode vstep=0.01 vfinal=1

Here, the simulation is performed for anode voltage range. The difference between each bias point is 0.01 volt. The results are saved in the log file declared earlier.

Tonyplot

This command is used to see the plot of log file and structure file. Structure file saves the structure of the cell defined earlier. For example:

tonyplot iv035.log

Here, this statement is used to see the plot of the desired log file.

The code used for CIGS solar cell simulation is presented below:

Code:

```
go atlas
mesh

#Device Dimension
SET Lm = 0.4
SET L1 = 0.04
SET L2 = 3
SET M = 0.35
SET T = 4
SET T1 = 1
SET L3 =$L1+$L2
SET L4 =$L1+$L2+$M

#Grid Spacing
SET dx = 0.05
SET dy = 0.05

#Doping Concentration
SET NP = 1*1e16
SET NN = 1*1e18
SET NL = 5*1e17
SET x_comp = 0.35
```

```
y.mesh loc=-$Lm spac=0.01
y.mesh loc=0 spac=0.01
y.mesh loc=$L1 spac=0.1
y.mesh loc=$L3  spac=0.01
y.mesh loc=$L4 spac=0.01


x.mesh loc=-$T spac=0.1
x.mesh loc=0 spac=0.1
x.mesh loc=-$T1 spac=$dy



region   number=1   y.min=-$Lm   y.max=0   x.min=-$T   x.max=0
material=ZNO
region number=2 y.min=0 y.max=$L1 x.min=-$T x.max=0 material=CdS
region   number=3   y.min=$L1   y.max=$L3   x.min=-$T   x.max=0
material=CIGS x.comp=$x_comp
region   number=4   y.min=$L3     y.max=$L4   x.min=-$T   x.max=0
material=Molibdinum

electrode y.min=-$Lm y.max=0 x.min=-$T1 x.max=0 name=cathode
electrode y.min=$L3  y.max=$L4 x.min=-$T x.max=0 name=anode

doping  y.min=0  y.max=$L1  x.min=-$T  x.max=0  n.type  conc=$NN
uniform
doping y.min=$L1  y.max=$L3 x.min=-$T  x.max=0  p.type  conc=$NP
uniform
doping  y.min=-$Lm  y.max=0  x.min=-$T  x.max=0  n.type  conc=$NL
uniform

## MATERIAL PROPERTIES ##
material   TAUN=1e-7   TAUP=1e-7   COPT=1.5e-10   AUGN=8.3e-32
AUGP=1.8e-31

# ZnO
material  mat=ZnO  EG300=3.3  PERMITTIVITY=9  AFFINITY=4  MUN=50
MUP=5 \
            NC300=2.2e18 NV300=1.8e19 resistivity=480
# Cds
material mat=CdS EG300=2.4 PERMITTIVITY=10 AFFINITY=3.75 MUN=10
MUP=1 \
       NC300=2.2e18 NV300=1.8e19
Material          material=CdS          indx.real=solarex05_0.n
indx.imag=solarex05_0.k
out.index=solarex05_0

# CIGS
material  mat=CIGS  PERMITTIVITY=13.6  AFFINITY=3.89  MUN=300
MUP=30 \
            NC300=2.2e18 NV300=1.8e19
```

```
out.index=solarex05_1

# Molibdinum
material mat=Molibdinum resistivity=120

models srh temperature=318 bound.trap print
output opt.intens band.param con.band val.band


## PLOTS
# Plot structure
Struct outfile=CIGS.str
Tonyplot CIGS.str

## SOLVING I-V CURVE ##
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 OUTFILE="IV035.LOG"
SOLVE VANODE=0 NAME=ANODE VSTEP=0.01 VFINAL=0.3
SOLVE NAME=ANODE VSTEP=0.01 VFINAL=0.8
TONYPLOT IV035.LOG
solar iw=eqe035.log min.wave=0.3 max.wave=1.2 step.wave=0.01
tonyplot eqe035.log
quit
```

Chapter 3: Result and Analysis

Semiconductor band gap is one of the key factors that influences losses and hence the conversion efficiency of a solar cell. To see the band gap influence on a solar cell parameters such as open circuit voltage, short circuit current and fill factor, we simulate a solar cell structure using SILVACO simulation package with CIGS as the absorbing layer. The solar cell structure has Cadmium Sulfide (CdS) as n-type material, Copper Indium Gallium Selenide: $CuIn_xGa_{1-x}Se_2$ (CIGS) as p-type material, transparent conductive oxide (TCO) layer, and Molybdenum contacts. The composition of materials in CIGS alloy was varied to vary the band gap of CIGS.

To simulate a solar cell structure having Cadmium sulfide (CdS) as n-type material, Copper Indium Gallium Selenide (CIGS) as p-type material, Transparent Conductive Oxide (TCO) layer, and Molybdenum contacts, the following structure, Fig. 3.1 was used in ATLAS SILVACO.

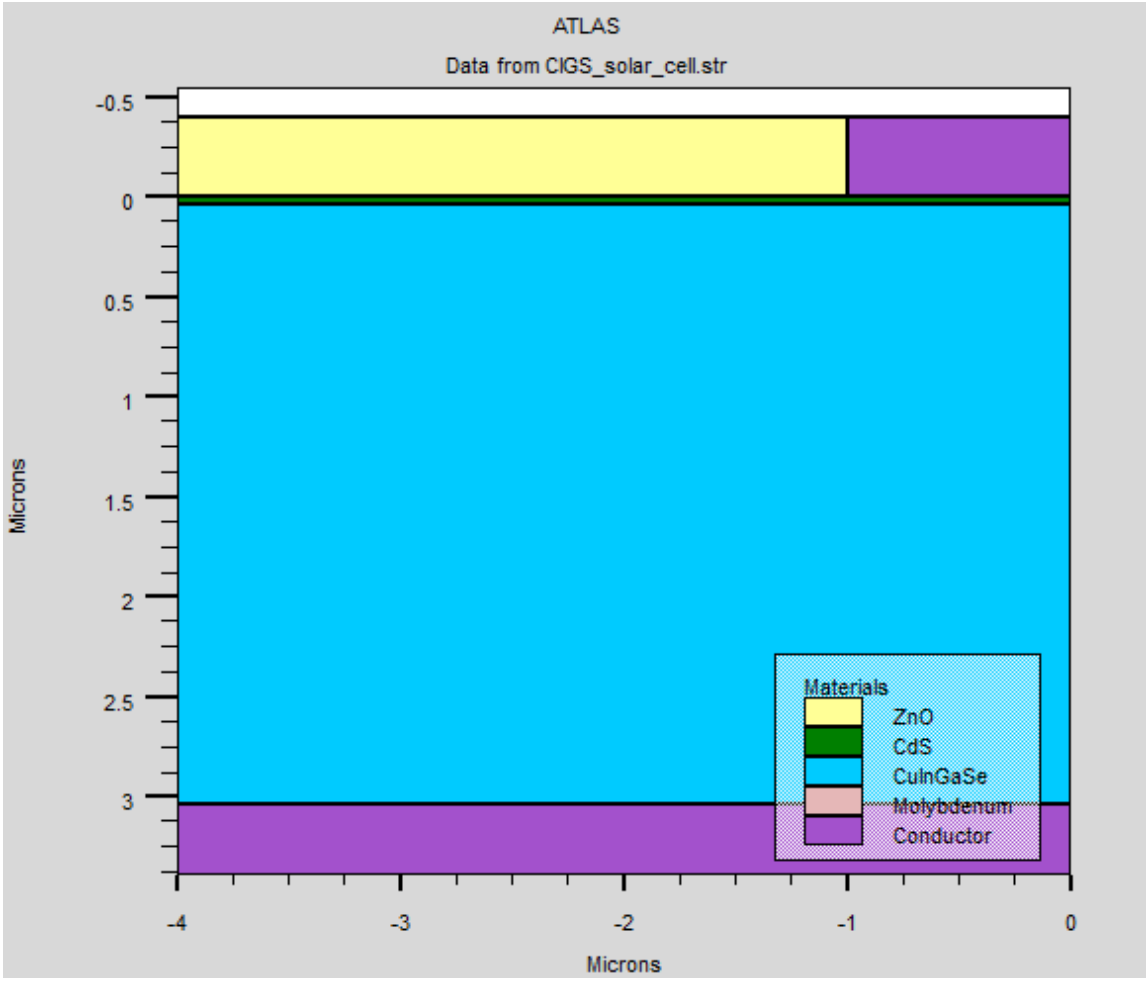

Figure 3.1: A CIGS solar cell structure

In this structure, the width of TCO is0.4 micron, the width of n type CdS is 0.04 microns, the width of p type CIGS is 3 micron, the width of the front contact is 0.4 micron and back contact is 0.35 micron.

The structure is simulated under different grid in different layer. TCO layer has space of 0.01 microns at y axis, and 0.1 microns at x axis. Front contact has space of 0.01 microns at y axis, and 0.05 microns at x axis. The space for n type CdS is 0.01 micron at y axis and 0.1 micron at x axis. The space for p type CIGS is 0.1 micron at y axis and 0.1 micron at x axis. The space for molybdenum back contact is 0.01 micron at y axis and 0.1 micron at x axis. The doping concentration of p type region and n type region is taken 1×10^{16} cm^{-3} and 1×10^{18} cm^{-3} respectively, and the doping concentration of ZnO is $5 \times 10^{17} cm^{-3}$.The finite element mesh grids are shown in Fig. 3.2.

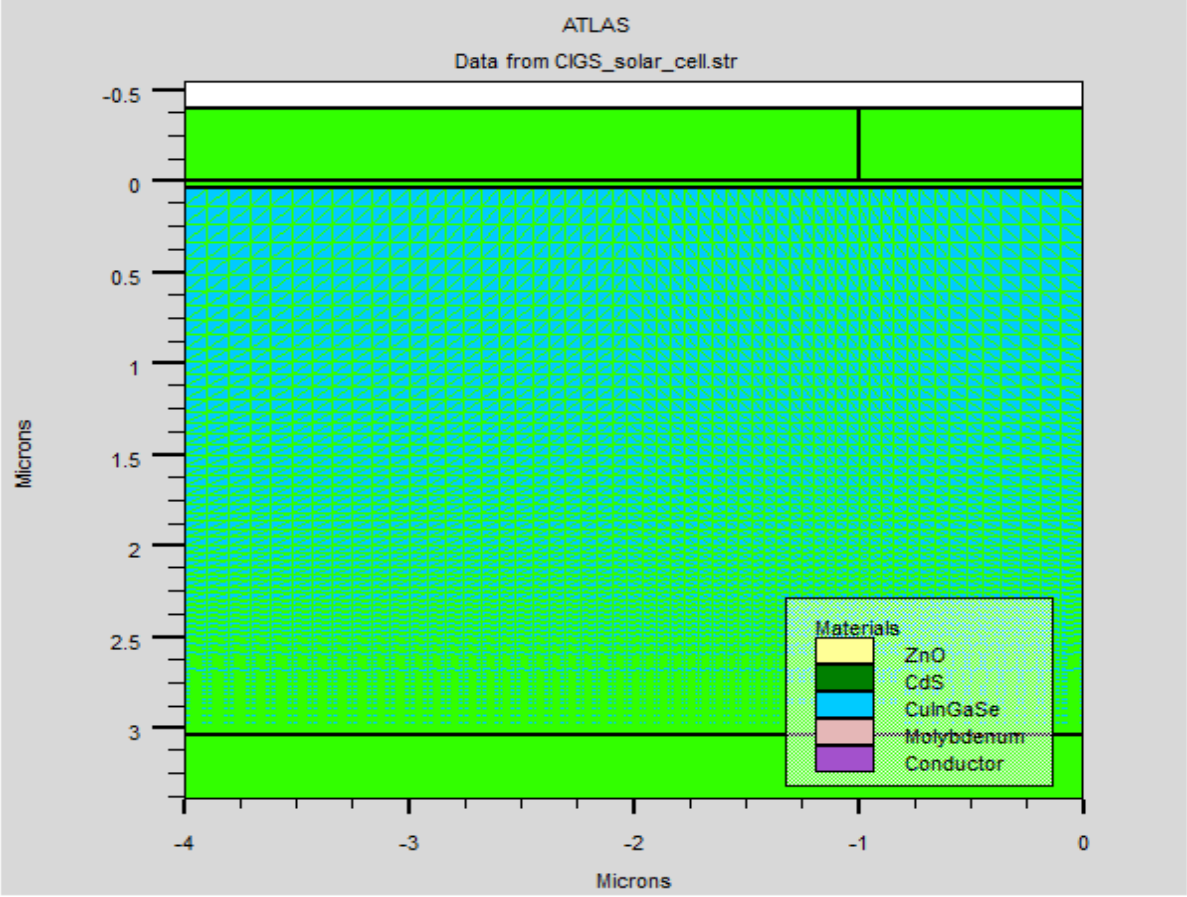

Figure 3.2: Mesh specification of solar cell structure

The band gap of CIGS, $CuIn_xGa_{1-x}Se_2$ varies from 1.01 eV to 1.67 eV as shown in figure 3.3 when the x composition is changed from 0 to 1. The band gap of CIGS is related to the x composition according to the following equation [11]:

$$E_g(x) = 1.01 + 0.42x + 0.24x^2$$

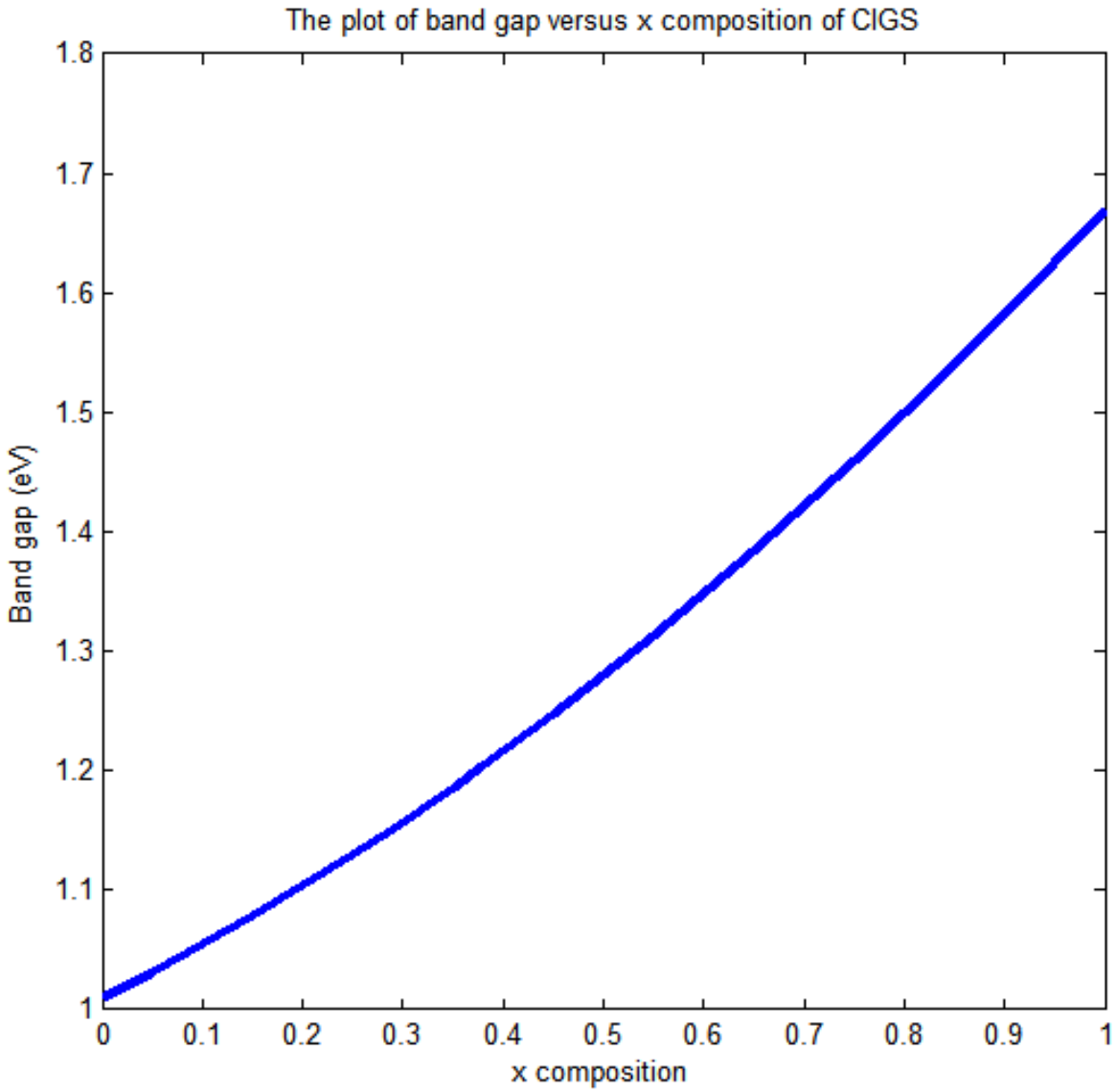

Figure 3.3: Band gap versus x composition for CIGS

For the variation of x composition, difference in J-V characteristics are shown in figure 3.4.

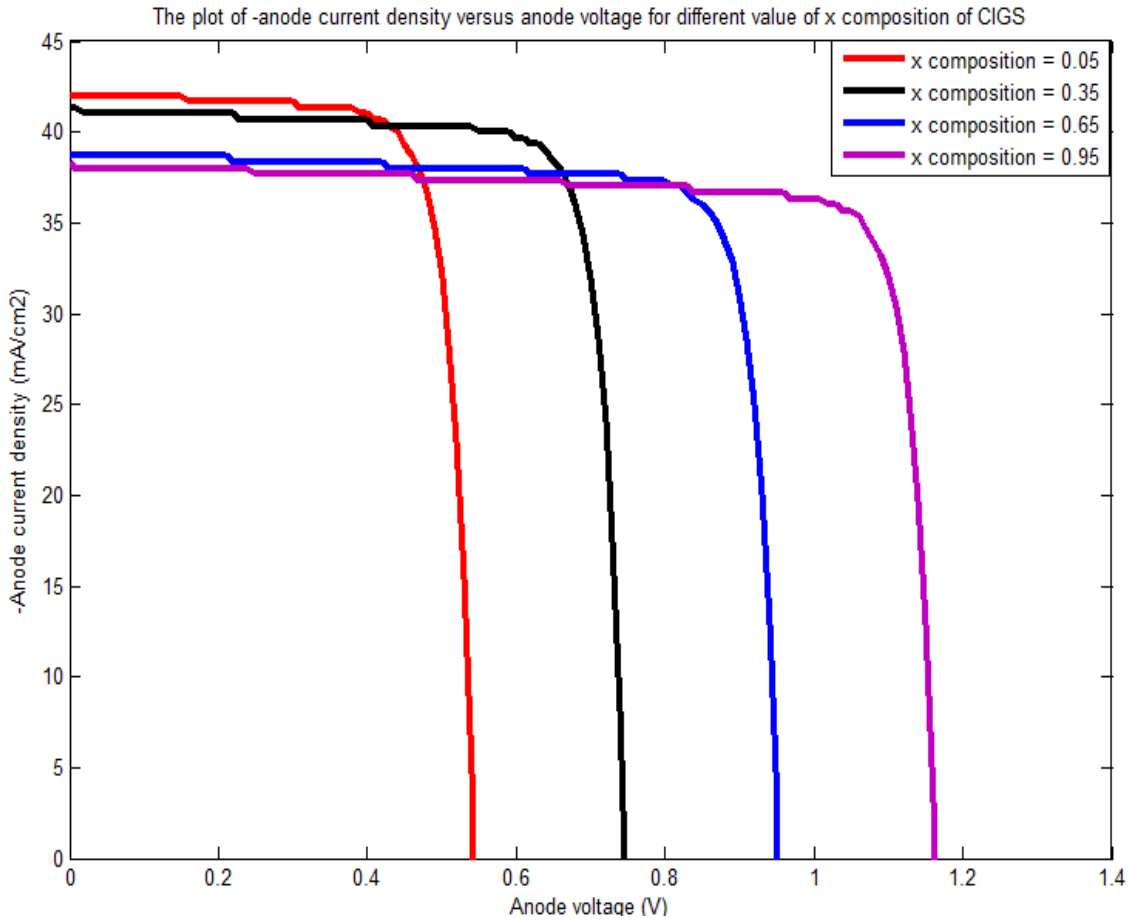

Figure 3.4: Anode current density versus anode voltage characteristics for different x composition of CIGS solar cell

Clearly, the J-V changes, especially the open circuit voltage and short circuit current with x-composition, that is with band gap. Different parameters of solar cells such as open circuit voltage (V_{oc}), short circuit current density (J_{sc}), maximum power (P_m), fill factor (FF), external quantum efficiency (EQE) are studied. Those are presented below.

3.1 Open Circuit Voltage Analysis

From our simulation, the following profile of open circuit voltage was found with changing x composition of CIGS. In figure 3.5, it is clear that open circuit voltage increases with the increase in x composition of CIGS material. The variation of open circuit voltage is almost linear with x-composition. The open circuit voltage can be written as

$$V_{oc} = \frac{K_B T}{q} \ln\left(\frac{J_{sc}}{J_0} + 1\right)$$

With band gap, J_0 changes significantly compared to the change in J_{sc}. J_0decreases almost exponentially with band gap, which results in a linear change in V_{oc}.

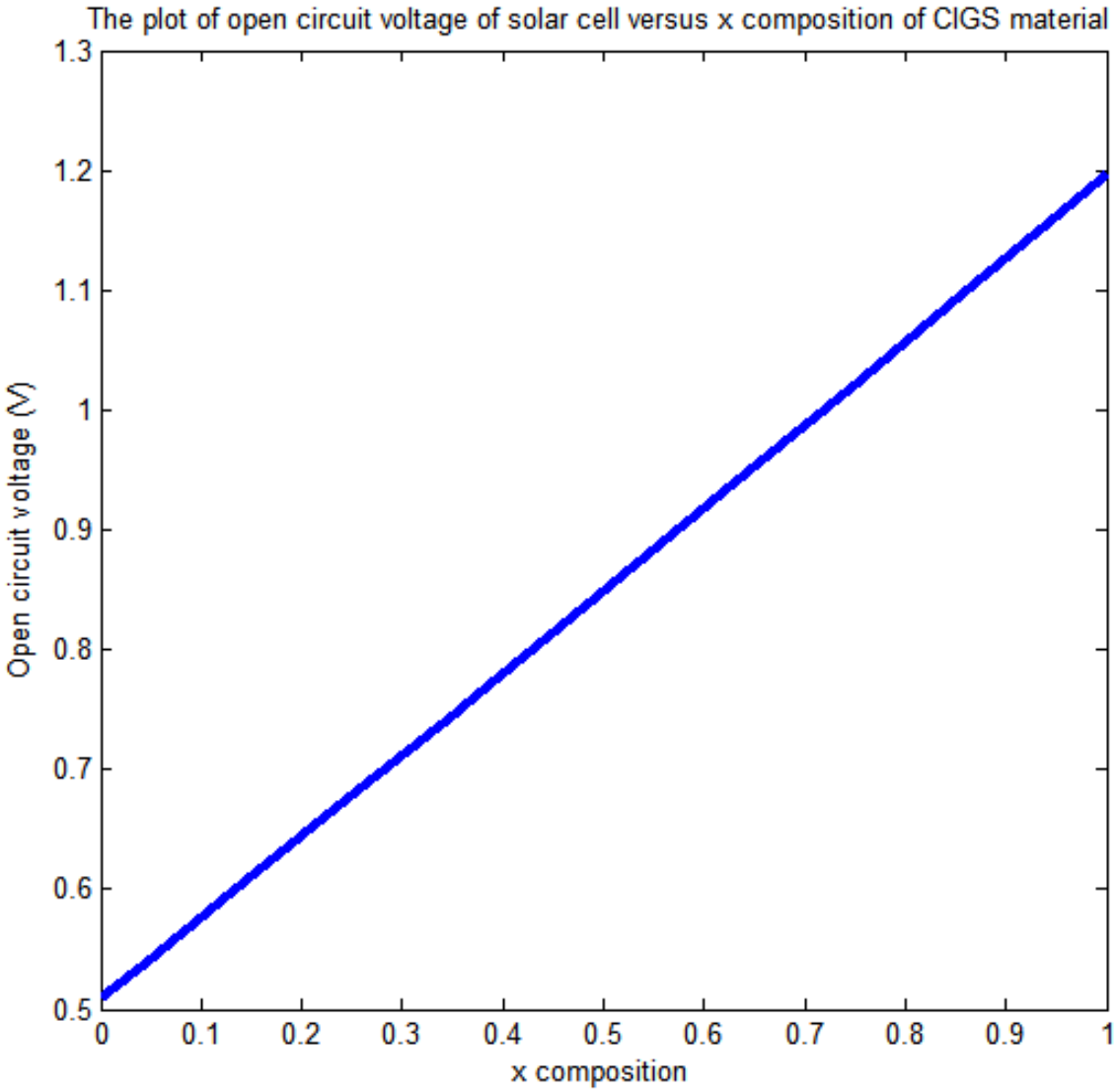

Figure 3.5: Open Circuit Voltage versus x composition for CIGS solar cell

3.2 Short Circuit Current Analysis

According to simulation, the profile of short circuit current density with respect to the x composition of CIGS material is resented in the following figure 3.6.

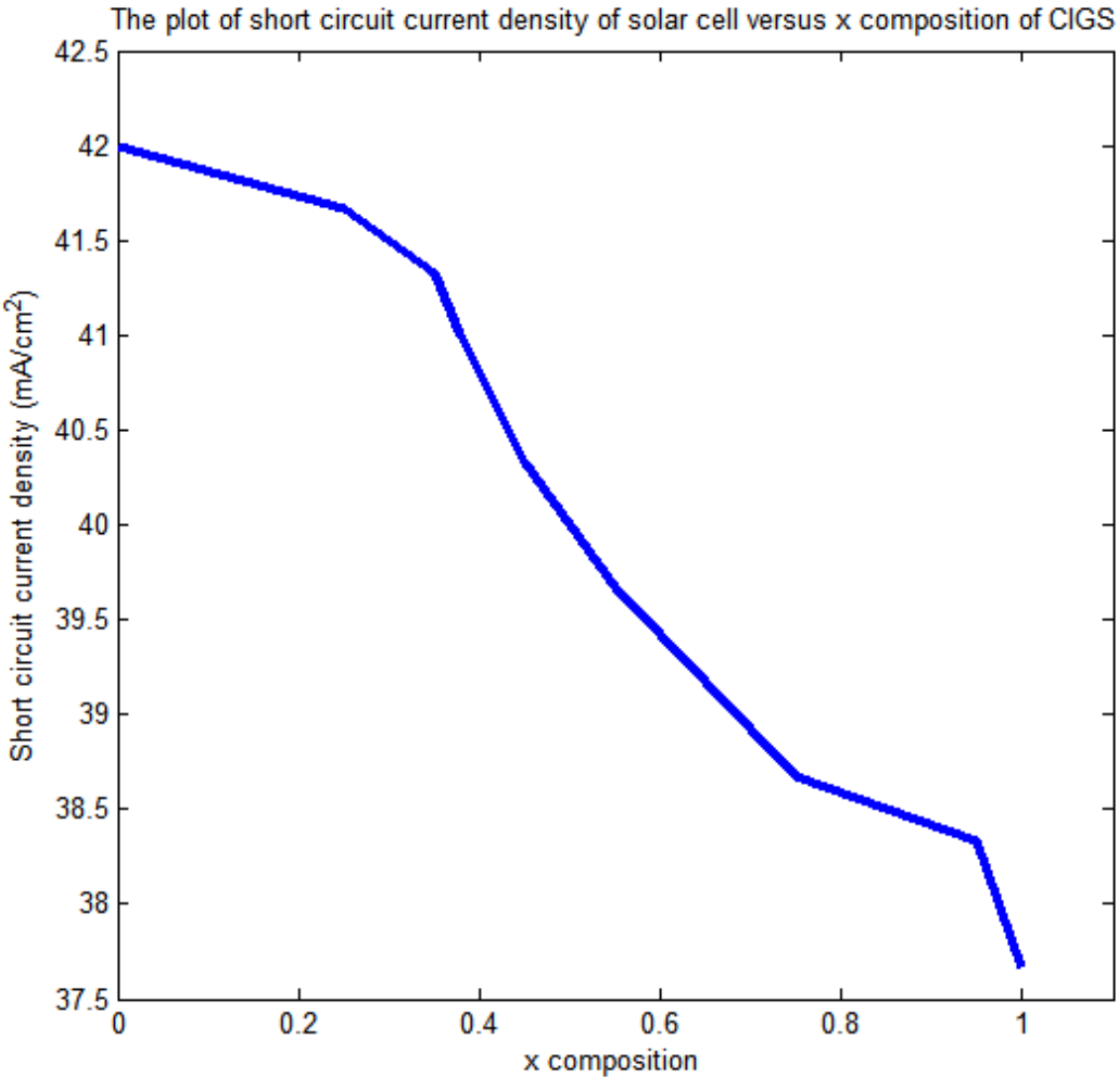

Figure 3.6: Short Circuit Current Density versus x composition for CIGS solar cell

According to the figure presented above, short circuit current of the CIGS solar cell is decreased with increasing x composition of the CIGS material, and the change does not follow any particular relationship. The current density changes from 42 mA/cm^2 to 37.6 mA/cm^2 when the x-composition is varied from 0 to 1.

3.3 Maximum Power Analysis

The maximum power is the multiplication of maximum voltage and maximum current. This is found from the peak point of P-V curve, shown in figure 3.7:

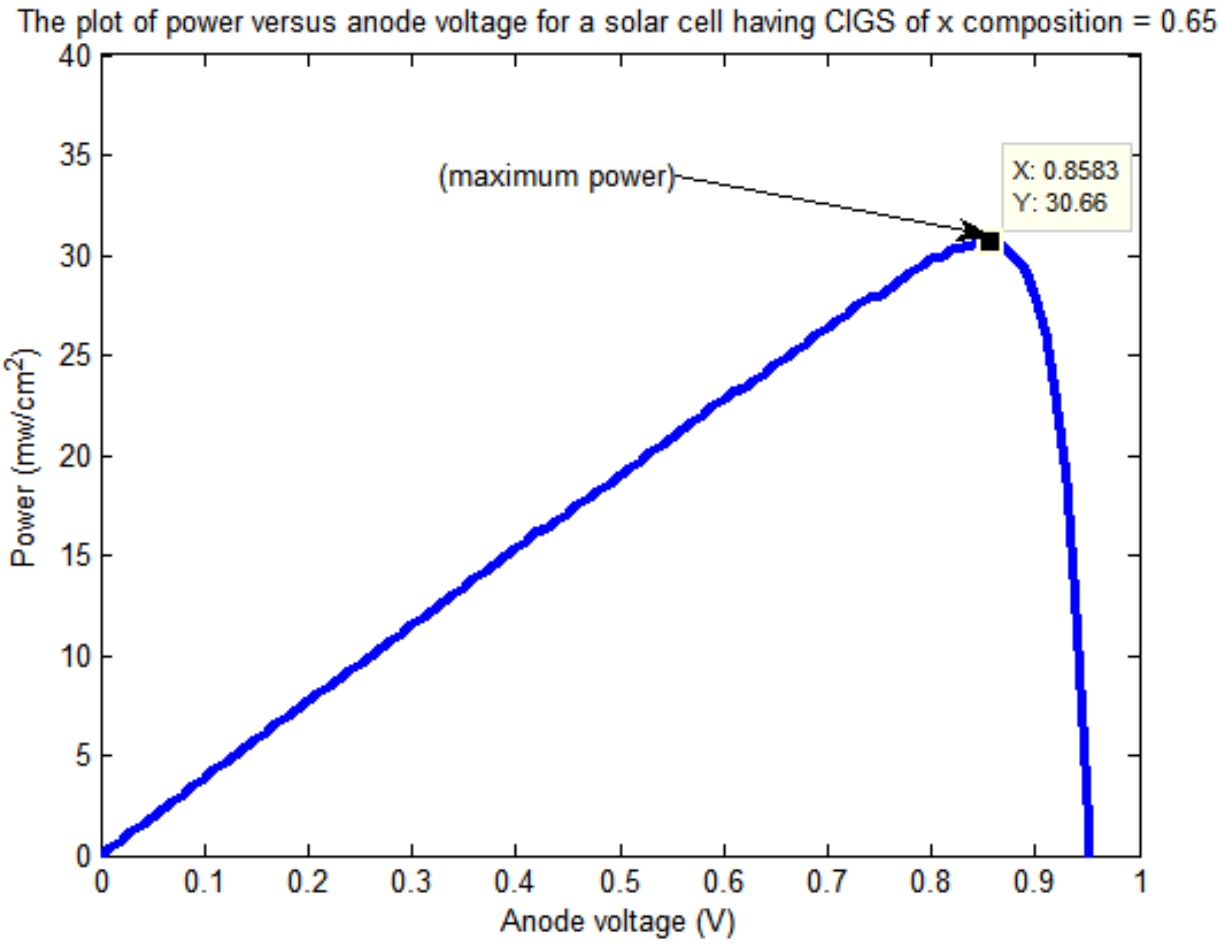

Figure 3.7: Maximum power obtained from power versus anode voltage for x composition = 0.65 for a CIGS solar cell

For different value of x composition, simulation is done. From P-V curves for each x composition, maximum power is found. Finally, the maximum power profile is found as shown below in figure 3.8:

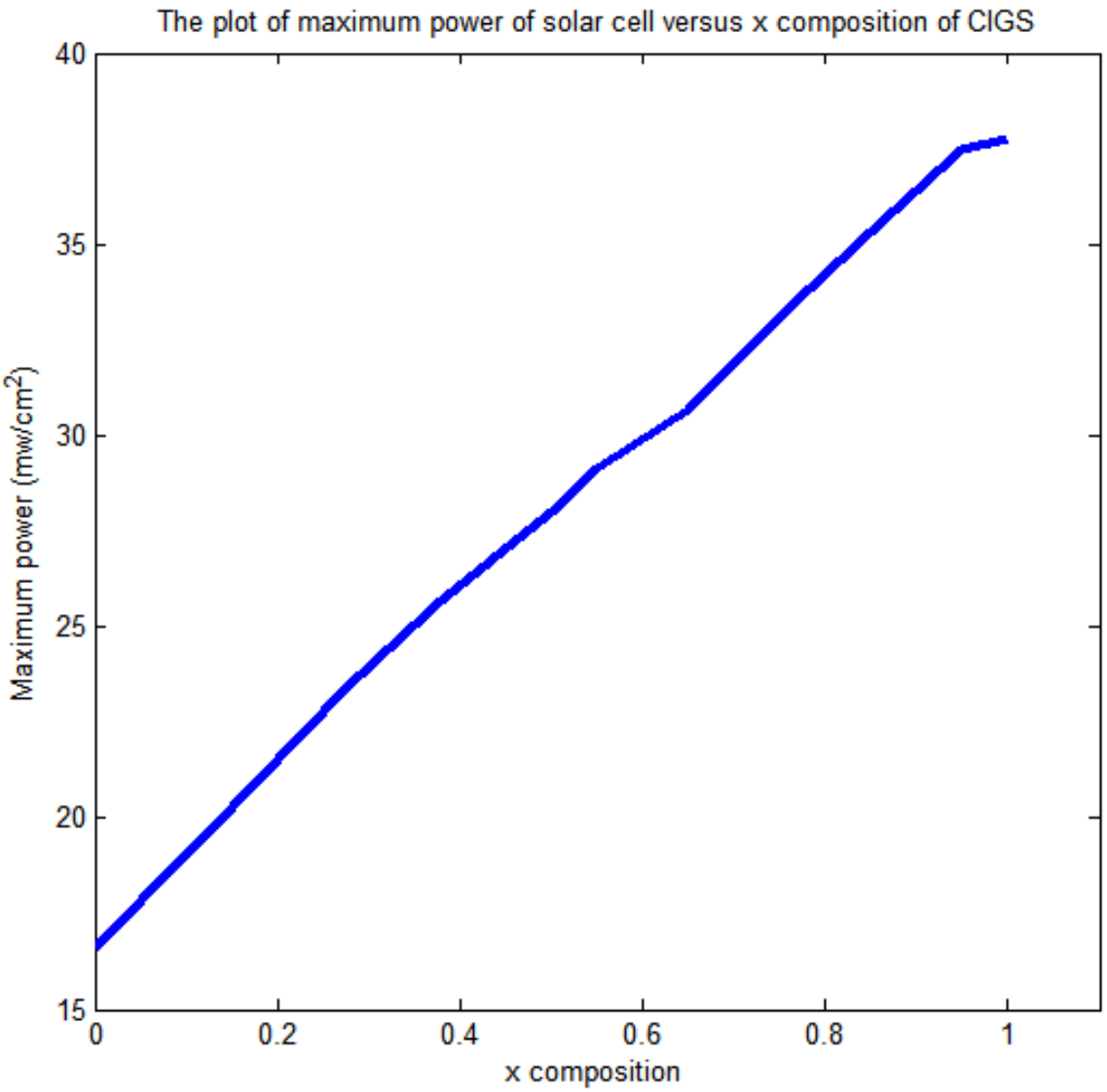

Figure 3.8: Maximum power versus x composition for CIGS solar cell

From the simulation result, it is clear that with the increase in x composition of the CIGS material, the maximum power of CIGS solar cell increases. Theoretically, the maximum power increase with band gap, peaks and then decreases. The peak occurs at a band gap value of 1.67 eV. With x-composition, the band gap of CIGS changes from 1.01 to 1.67 eV, that is, the band gap does not exceed the optimum value, and therefore, we do not see a decline nature in maximum power.

3.4 Fill Factor Analysis

The fill factor profile is quite interesting for this CIGS solar cell. The profile is shown in figure 3.9:

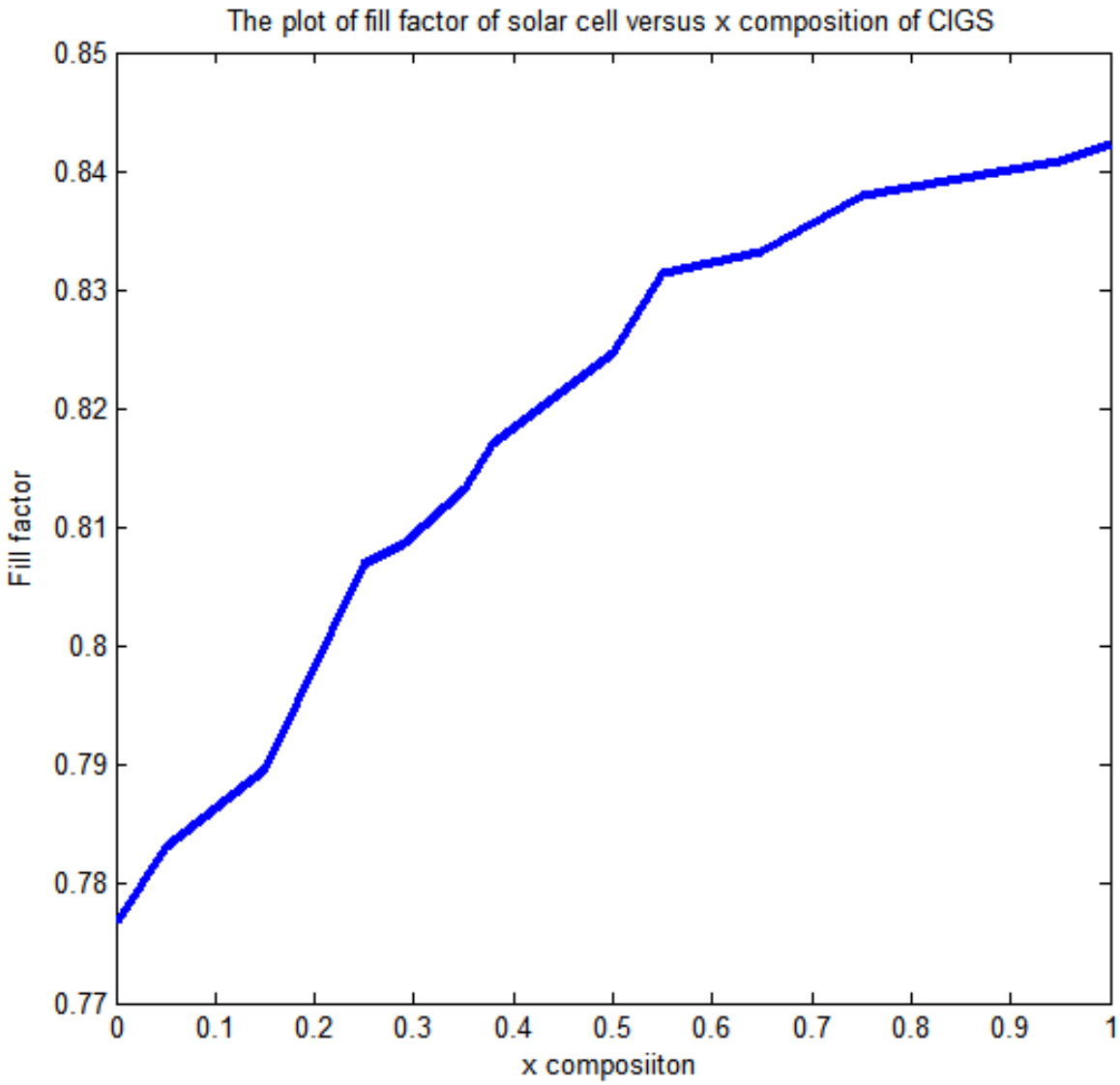

Figure 3.9: Fill factor versus x composition for CIGS solar cell

The fill factor is known to increase with open circuit voltage. As the V_{oc} increases with x-composition, so does the fill factor. However, when the V_{oc} change from 0.51 V to 1.2 V, the fill factor change from 0.778 to 0.841. In other word, the change in fill factor is not significant compare to the change in V_{oc}.

3.5 External Quantum Efficiency Analysis

External Quantum Efficiency (EQE) was studied for a range of optical wavelength from 0.3 micron to 2.5 micron.

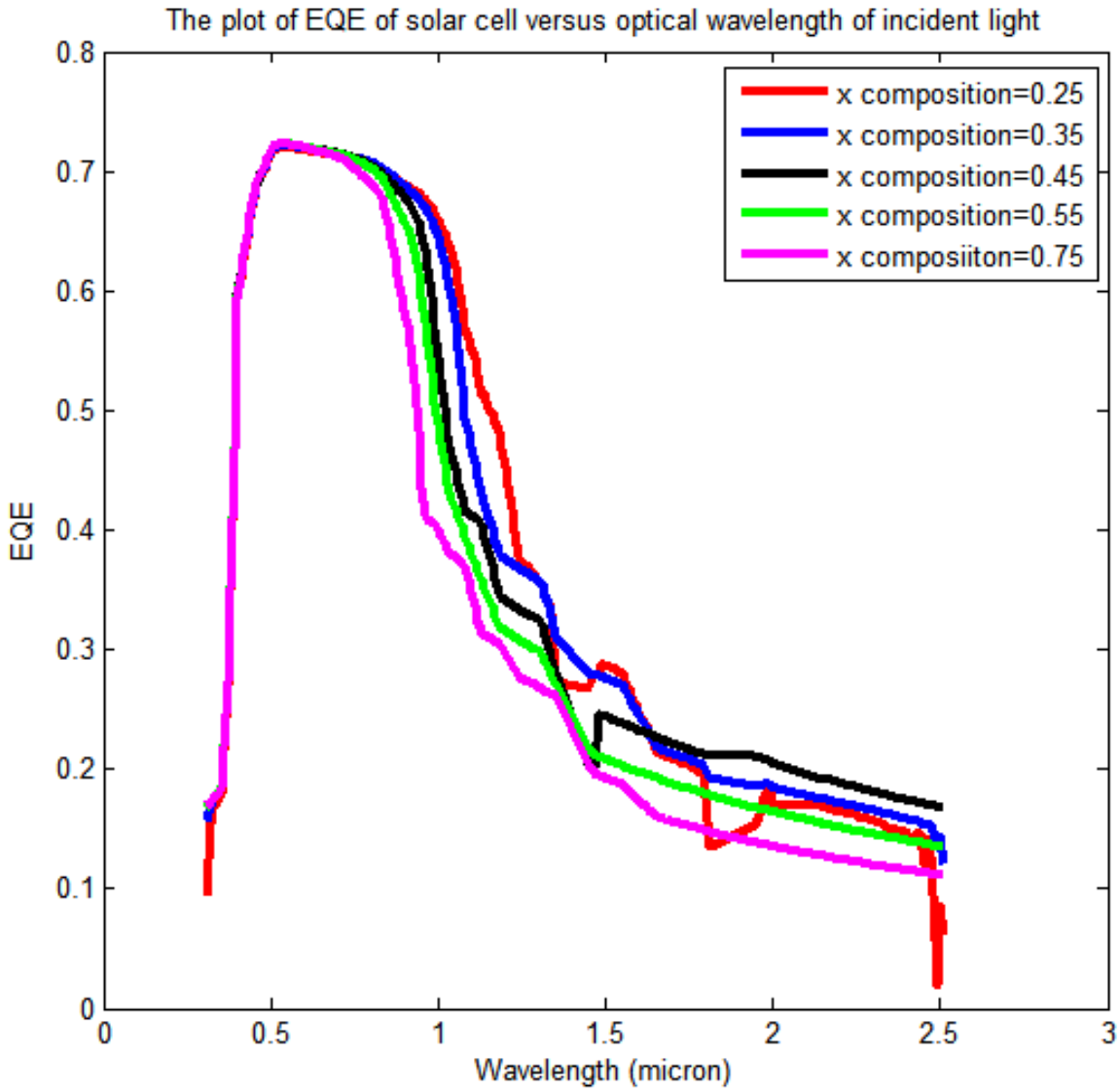

Figure 3.10: External Quantum Efficiency (EQE) versus optical wavelength of CIGS solar cell for five different value of x-composition

Figure 3.10 represents different EQE versus optical wavelength characteristics for different x composition values. From this characteristic, it is clear that the cell with lower x composition can be used for longer range of optical wavelength. So, the design of an efficient solar cell over a long range of optical wavelength of incident photon on the surface should consist of CIGS ($CuIn_xGa_{(1-x)}Se_2$) layer having smaller x composition.

The equation of photon energy:

$$E_{ph} = \frac{1.24}{Optical\ wavelength}$$

With the increase in optical wavelength, the energy of photon decreases. Photon having energy less than the band gap of the absorption layer of solar cell will not be absorbed. So, the EQE at longer wavelength becomes zero as the CIGS absorber layer becomes transparent to the incident photons. At small wave length, the photo generated electrons go to excited energy level, and then come to the conduction band edge by thermalization. This thermal loss reduces EQE at short wave length.

Chapter 4: Conclusion

This thesis can be concluded as a numerical study on the effects of changing band gap on solar cell parameters. ATLAS SILVACO is used to create a solar cell structure having the width of TCO is 0.4 micron, the width of n type CdS is 0.04 microns, the width of p type CIGS is 3 micron, the width of the front contact is 0.4 micron and back contact is 0.35 micron. This structure is simulated for different x composition of the CIGS layer under AM1.5 spectrum illumination. Then open circuit voltage, short circuit current, maximum power, fill factor, and external quantum efficiency are plotted to see the variations of these parameters with variation of band gap. It is seen that, open circuit voltage increases with increase in x composition of CIGS; short circuit current decreases with increase in x composition of CIGS; maximum power should increase, reach at a peak and then decrease; but in this study the range of band gap of CIGS, $CuIn_xGa_{1-x}Se_2$ varies from 1.01 eV to 1.67 eV when the x composition is changed from 0 to 1; which is not enough to see that characteristics. Fill factor also increased with increase in x composition; but this change is not as significant as open circuit voltage. The external quantum efficiency is found for different x composition of CIGS layer, where flatter upper peak is found for smaller x composition. It indicates that cell with lower x composition can be used for longer range of optical wavelength. In this study, instead of CIGS other alloy can be used to see a large range of variation in band gap with variation in x composition. Doing that, better response of maximum power can be obtained for different x composition.

References

[1]: S. Eric Toberer, C. Tamboli Adele, S. Myles, and K. Sarah, "Analysis of Solar Cell Quality Using Voltage Matrics", *Conference Paper,* NREL/CP-5200-54120, June 2012

[2]: J. Krc, G. Cernivec, A. Campa, J. Malmström, M. Edoff, F. Smole, and M. Topic, "Optical and electrical modeling of Cu(In,GA)Se_2 solar cells", *optical and quantum electronics*, vol. 38, PP. 1115-1123, 2006

[3]: J. Krc, PhD Thesis, University of Ljubljana, 2002

[4]: J. Krc, F. Smole and M. Topic, "*Prog. Photovolt., Res. Appl."*vol. 11**,** PP. 15, 2003

[5]: M. Topic, F. Smole and J. Furlan, *J. Appl. Phys.* vol. 79, PP. 8537, 1996

[6]: G. Cernivec, J. Krc, F. Smole and M. Topic, *Thin solid films*, vol. 60, PP. 511–512, 2006

[7]: S. Sharbati and R. Sites James, "Impact of the Band Offset for n-Zn(O,S)/p-Cu(In,Ga)Se2 Solar Cells", *IEEE Journal of photovoltaics*, vol. 4, PP. 2, 2014

[8]: M. A. Hussein Mustafa, M. Abdullah Manal, R. Saleh Wasan and A. Aadem Kadhim, "I-V Characteristics of ITO/CdTe/Al2O3/Si/Au Thin Film Solar Cell", *International Journal of Current Engineering and Technology*, E-ISSN 2277 – 4106, P-ISSN 2347 – 5161 ©2014 INPRESSCO® , All Rights Reserved, Available at http://inpressco.com/category/ijcet

[9]: Online available:http://www.pveducation.org/pvcdrom/solar-cell-operation/open-circuit-voltage

[10]: Online available:http://www.pveducation.org/pvcdrom/solar-cell-operation/short-circuit-current

[11]: S. Sharbati and R. Sites James, "Impact of the Band Offset for n-Zn(O,S)/p-Cu(In,Ga)Se2 Solar Cells", *IEEE Journal of photovoltaics*, vol. 4, PP. 2, 2014