Recital Investigation of Heterojunction Thin Film Gallium Nitride/Polysilion Solar Cell and its Optimization

Muhammad Saad[1], Abdul Sattar Malik[1], Zahra Noor[2], Adil Salman[3]

[1]Department of Electrical Engineering, Bahauddin Zakriya University, Multan, Pakistan, [2]College of Electrical and Mechanical Engineering, NUST Rawalpindi, Pakistan, [3]University of Dublin, Ireland

Abstract

Conversion of solar energy into electricity by a solar cell substantively depend on properties of materials and design of solar cell. Heterojunction solar cells are gaining attention due to their high efficiencies. For the very purpose, a heterojunction thin film Gallium Nitride/polysilicon solar cell is simulated and optimized in Silvaco Atlas, which is a two dimensional device design simulation software. The intrinsic layer of solar cell is probed to enhance the efficiency of solar cell. Electrical and optical characteristics of solar cells are investigated by changing the thickness of intrinsic layer. The investigation is based on model parameters such as bandgap energy, material thickness and doping concentration of solar cell. Intrinsic layer is varied to obtain the maximum possible output from the proposed Gallium Nitride/polysilicon solar cell.The optical losses such as ultraviolet light immersion by transparent conductive oxide (TCO) layer is minimized by optimizing the thickness of TCO. The conversion efficiency of as high as 26.67% can be obtained by optimizing model parameters. Open circuit voltage Voc of 0.789V, short circuit density Jsc of 52.66 mA/cm2, Fill factor of 73.9% is achieved by a small area of 14.8 μm^2. The result of simulation suggest that proposed Gallium Nitride/polysilicon solar cell will prove to be a potential candidate for high performance and higher efficiency applications of photovoltaic.

Key words: Heterojunction; Thin film; Intrinsic layer; Transparent Conductive Oxide; Simulation

INTRODUCTION

Thin film solar cells are gaining attention day by day, not only due their portability but they also are less hefty (Chopra et al., 1983). Thin film solar cell technology is made by depositing one or more layers of thin film on a substrate. There are many types of substrates used for thin film solar cell such as glass, plastic and metal (Berman and Elliot,1985).Thin film solar cell belongs to second generation of solar cell and they have less thickness of film as compared to their thin film rivals, the first generation crystalline solar cell that are that are made up of wafer with thickness varies from few micrometer to 200 micrometer (Kuo-Hung, 2010). Though thin film technology is economical, but they have low conversion efficiencies as compared to crystalline solar cell. However with advancement of fabrication techniques, thin film solar cells are capturing the market share with their pros of truncated cost and comparatively extraordinary efficiency. Thin film technology beating silicon cells in term of market share (Brad Mattson, 2014) as shown in the figure 1.Thin film solar cells are light weight, economical and are very malleable (Shin et al., 2013). A thin film solar cell consist of different layers as shown in figure 2.Edifice of solar cell shows that it consist of many layers. Solar cells with thin film characteristics are characterized according to the nature and properties of materials. Thin film solar cells have many types such homojunction, heterojunction, single junction and dual junction. Heterojunction thin film solar cells have the highest conversion efficiency till date (Taguchi et al., 2014).

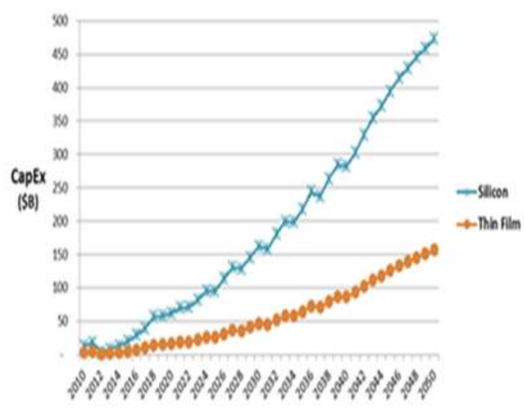

Figure 1: Thin film technology comparison with silicon[1]

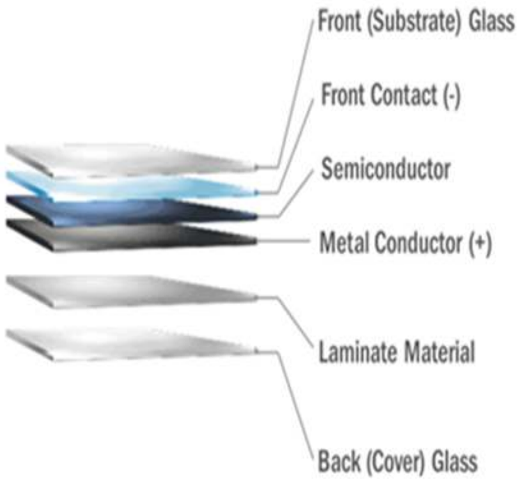

Figure 2: Thin film solar cell and its constituent's layers

In this paper, we proposed a heterojunction Gallium Nitride/polysilicon thin film solar cell. Gallium Nitride is an exotic semi-conductor material having a wide bandgap. High band gap energy of Gallium Nitride made it conceivable to achieve higher transformation efficiency. Gallium Nitride is used as a window layer to receive maximum amount of high energy photons. After defining the dimensions of solar cell, we optimized the intrinsic layer of the solar cell and then investigate and optimized it according to doping level. An efficiency greater than 26% is achieved by optimization of proposed solar cell. The electrical and optical parameters of the solar cell are calculated. The V-I characteristics of solar cell is obtained for all model design to optimize the solar cell. The design achieved maximum efficiency of 26.67% with open circuit voltage of 0.789V, short circuit current density of 52.66 mA/cm^2, and fill factor of 73.9%.

The proposed Gallium Nitride/polysilicon solar cell is simulated in Silvaco Atlas which is a virtual wafer fabrication (VWF) tool. Atlas is the module of the Silvaco software package which is used to design and simulate the numerical solution of the solar cell without costly split-lot experiments. Silvaco Atlas is also used to simulate various semiconductor devices such as bipolar junction transistors, field effect transistors, light emitting diodes and solar cells. Silvaco Atlas has ability to simulate solar cell in three dimensions but in our work we use two dimensional modelling of solar cell. Silvaco Atlas is widely used for novel device designing (Silvaco, 2015).

Analysis of solar cell

In this paper, our solar cell is designed by stacking layers of thin films of gallium nitride and polysilicon. An n+/-i-/p+ solar cell is proposed. The transparent conducting oxide(TCO) used for solar cell is zinc oxide. Zinc oxide is highly conductive and is transparent to high energy photons (Ellmer et al., 2007). Due to this reason zinc oxide is deposited on the solar cell as a top layer. The electrodes are made up of Aluminum. Aluminum is a ductile material and is third most copious element in earth's scab (Sam Davyson). It exhibit low density and has ability to resist corrosion. Thus Aluminum as an electrode material is selected in order to diminish the cost of electrode. The heterojunction is made between n type gallium nitride and p type polysilicon. Gallium nitride has high bandgap energy of 3.4 eV (Davis, R. F. et al., 1988) and is used as a window layer to absorb photons, having energy greater than or equal to 3.4 eV. The basic solar cell structure with dimension is shown in figure 3.

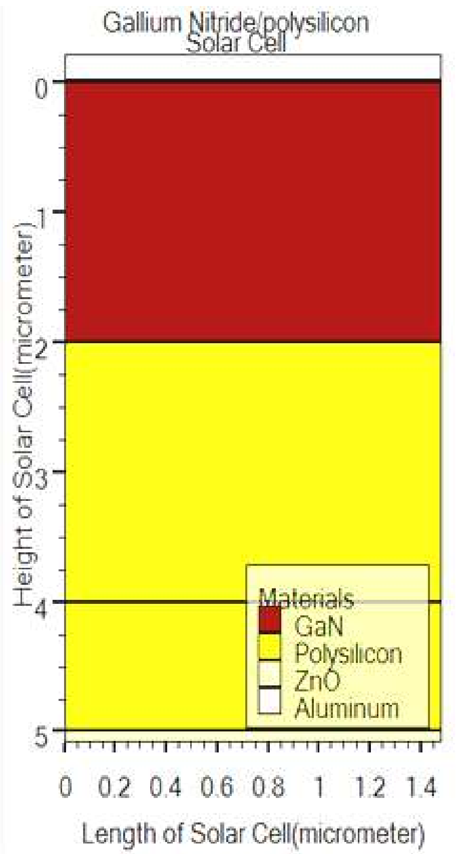

Figure 3: Dimensions of proposed Gallium Nitrdie /Polysilicon Solar Cell

The doping levels and thickness of each layer is given in table I. The bandgap diagram of solar cell is given in figure 4.

Table 1: Basic parameters of Gallium Nitride /polysilicon solar cell

Layers	n-GaN	i-p/Si	p-p/Si
Dimensions	2μm	Variable	1 μm
Bandgap Energy	3.4 eV	1.5 eV	1.5 eV
Doping Level	1 X $10^{19}/cm^3$	1X $10^{16}/cm^3$	1 X 10^{19} $/cm^3$

Silvaco Atlas which is a 2D simulation software was used as simulation and modelling software for solar cell and is used in investigation and performance analysis of intrinsic layer of our proposed solar cell. The performance of the proposed Gallium Nitride/polysilicon solar cell is evaluated on the basis of design. The proposed design for the proposed solar cell is investigated both in term of electrical and numerical parameters. Silvaco Atlas estimates the mechanism of carrier transport on the basis of coupled equations such as Poisson equation and electron and hole equations[Michael et al., 2005].Shockley Read Hall equation is used to calculate recombination current. AM 1.5 spectrum is used as an incident power on the solar cell. AM 1.5 spectrum has power density of 100 milliWatt/cm^2 (Green, M. A. et al., 2015). In our simulation, we used constant parameters for Zinc Oxide conductors. Simulations are carried out at room temperature.

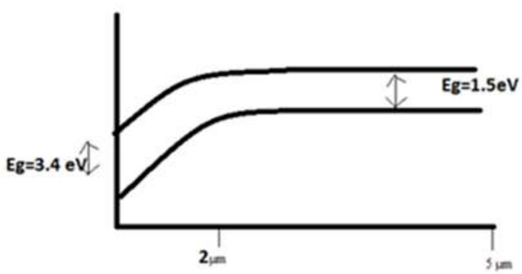

Figure 4: Bandgap diagram of Gallium Nitride /polysilicon solar cell

Four major parameter are calculated for Gallium Nitride/polysilicon solar cell to evaluate the performance of solar cell (Chan, D. S., & Phang, et al., 1987). The four parameter are as follow.

a) Open Circuit Voltage
b) Short Circuit Current Density
c) Fill Factor
d) Efficiency

Maximum voltage available at the output terminal of solar cell when no load is connected to solar cell is called as open circuit voltage. Calculation of open circuit voltage of solar cell is given by equation:

$$V_{oc} = (KT/q)\ ln(1 + Iph/Io) \quad (1)$$

Where,
K=Boltzmann constant
q= Charge on electron
I_{ph}=Photo current of solar cell
I_0=Dark current

Maximum power point tracking is the term used to track all-out solar cell's power.

Maximum power is premeditated by using current and voltage sensors. Maximum power of solar cell is given by following equation:

$$Pmax=Imax.Vmax. \quad (2)$$

Where,
I_{max}= Maximum Current of Solar cell
V_{max}=Maximum Voltage of Solar cell

The short circuit current of the solar cell is the maximum current which is available when both output terminal of solar cell are short. Short circuit current of the solar cell is given by:

$$I = Iph - Io\ (e\ \hat{}(qv/KT) - 1) \quad (3)$$

Where,
K=Boltzmann constant
q= Electronic charge
I_{ph}=Photo current of solar cell
I_0=Dark current
T= Room temperature

Fill factor is the maximum obtainable power of the solar cell to the product of short circuit current and open circuit voltage. In commercial solar cell fill factor should be greater than 0.7[He, et al., 2011]. Advantage of having higher fill factor is that the solar cell have high shunt resistance and low series resistance.

$$FF = (Vmpp.Impp)/(Voc.Isc) \quad (4)$$

Solar cell efficiency is the most imperative and the most crucial parameter. Proportion of energy output from the solar cell to the input energy from the incident light is called as efficiency. Efficiency of the solar cell hinge on spectrum, temperature and intensity of the incident photons. In our proposed solar cell efficiency is measured on AM1.5 spectrum and at room temperature of 25^o C. Solar cell's efficiency is given by:

$$\eta = Voc\ Isc\ FF/Pin \quad (5)$$

Where,
V_{oc}=Open-circuit voltage
I_{sc}=Short-circuit current; and
FF=Fill factor
η=Efficiency

Simulation of solar cell and optimization of intrinsic region

Figure 5 shows the investigation of solar cell with and without intrinsic layer. The intrinsic layer is made up of polysilicon. The behavior of photocurrent clearly shows that introduction of intrinsic layer have a foremost impact on it. The cell with intrinsic layer have high value of photocurrent. The forward current in Gallium Nitride/polysilicon solar cell is dominated by drift carrier mechanism. The insertion of intrinsic layer, improve the light capturing ability of the solar cell. The solar cell model with dimensions given in table 1 have open circuit voltage of 0.701 V, short circuit current density of 29.889 mA/cm^2 , fill factor of 77.9% and efficiency of 17.5%.

In our methodology the solar cell is optimized by a) Increasing the thickness of intrinsic layer so that charge carriers are generated and can be transported by drift mechanism b) Reducing the drift length of the solar cell to the diffusion length of the solar cell, which can causes increase in drift process c) Changing the doping level of the solar cell according to the design of the solar cell. Thus all three parameter are taken into account in order to optimize the solar cell. Solar cell must have low carrier recombination rate at the top surface to increase the overall efficiency.

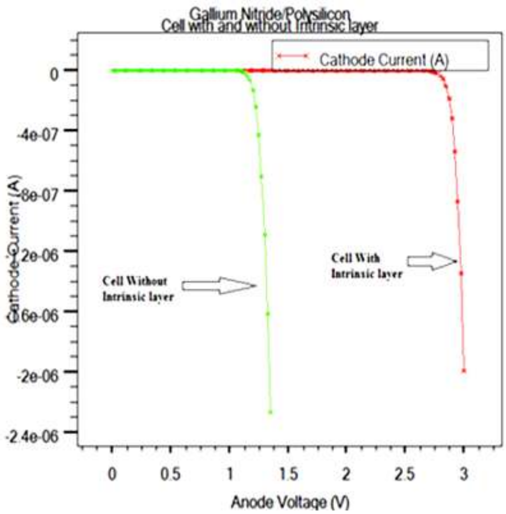

Figure 5: Investigation of Gallium Nitride/polysilicon solar cell with and without intrinsic layer

Drift field throughout the intrinsic layer causes decrease in recombination of charge carrier. The doping concentration has direct influence on the recital of the solar cell. As we increased the doping concentration a decreases in recombination rate was observed. Moreover increase in doping concentration decreased the series resistance of solar cell. The complete solar cell model is given in table 2. The defects in polysilicon solar cell is given in table 3.

RESULTS AND DISCUSSION

The simulation of Gallium Nitride/Polysilicon solar cell with variable intrinsic layer is performed and investigated. The performance of proposed solar cell influenced directly by mole fraction of gallium and nitride in GaN alloy. Results are compared with basic simulated Gallium Nitride/polysilicon solar cell having 17.5% efficiency. Increase in the thickness of intrinsic layer to 3µm and optimization of doping concentration of the intrinsic layer accordingly, will increase the efficiency of solar cell to 23.88%. As we know that open circuit voltage is direct function of the bandgap energy. So, high bandgap energy of Gallium Nitride will result in increased open circuit voltage. The doping level of donor and acceptor has to be optimized for reduction in recombination and static electric field that interrupts the flow of free charge carriers. When intrinsic layer thickness is maintain at 3µm, the doping level for donor concentration N_D is 2.9 X 10^{19} cm^{-3}and acceptor concentration N_A is 3.2 X 10^{19} cm^{-3}. The doping level of intrinsic layer is 1.8 X 10^{17} cm^{-3}.

The thicker absorb layer can able to absorb high energy photon. Increase in thickness will increase the output characteristics of device, such as open circuit voltage, short circuit current and efficiency of solar cell. Though increase in thickness of intrinsic layer can cause increase in photons absorptions, however it can increase the electrical losses in solar cell. The open circuit voltage will decrease by increase in thickness of intrinsic layer to certain limit but by adjusting doping level will cause increase in open circuit voltage as shown in table IV. Open circuit voltage with layer of intrinsic layer thickness is given in figure. The open circuit voltage has an optimum value of 789 mV between 5 and 6 µm of intrinsic layer as shown in figure 6. Further increase in intrinsic layer did not affect the open circuit voltage. Increase in thickness layer will stabilize the output from solar cell. All results are tabulated in table 4.

Short circuit current density upsurges with escalation in thickness of layer. The intrinsic layer have acceptor concentration of 1X10^{16} cm^{-3}.Thus the transport mechanism in intrinsic layer is diffusion dominated rather than drift in the intrinsic layer. As the thickness of layer varies from 3 µm to 7 µm the doping concentration also varies from 1X10^{16} cm^{-3} to 2X10^{18} cm^{-3}.Thickness of intrinsic layer with short circuit current density is given in figure 7.

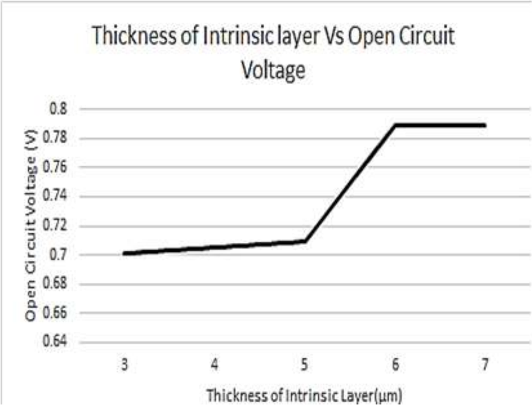

Figure 6: Graph between thickness of intrinsic layer and open circuit voltage

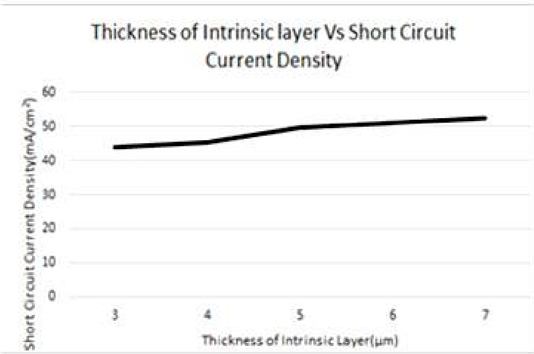

Figure 7: Graph between thickness of intrinsic layer and short circuit current density

Practical solar cells have fill factor greater than 0.7 (He, et al., 2011). In our solar cell as we increased the thickness of intrinsic layer, fill factor starts decreasing. This decrease in fill factor is due to diffusion carrier length. Diffusion carrier length is the distance from generation of photon to the length they combine. Diffusion length strongly dependent of recombination. In our simulation we used Shockley Read Hall (SRH) recombination which is the most dominant phenomena in solar cell. Increase in intrinsic layer thickness will cause increase in diffusion length but as doping of solar cell should also be optimized, so there should increase charge carrier. Increased in charge carrier concentration caused decrease in diffusion length, which decreases the fill factor of our solar. A point came where further increase in intrinsic layer do not have protruding impact on fill factor. Thickness of intrinsic layer with fill factor of the solar cell is given in figure 8.

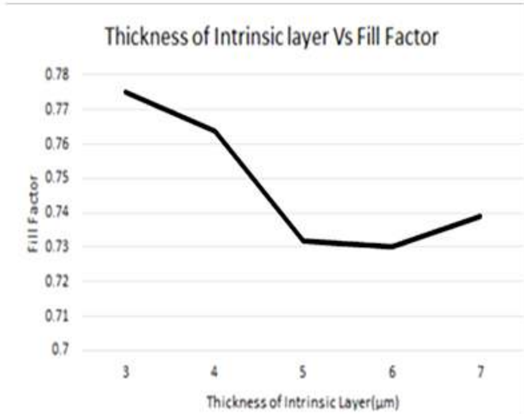

Figure 8: Graph between thickness of intrinsic layer and fill factor

Solar cell efficiency is the most important parameter used to compare solar cell with one another. Efficiency unswervingly, depend on open circuit voltage, short circuit current and fill factor. For AM1.5 spectrum with input power of 100mW/cm^2 the thickness of intrinsic layer with efficiency of the solar cell is given in figure 9.

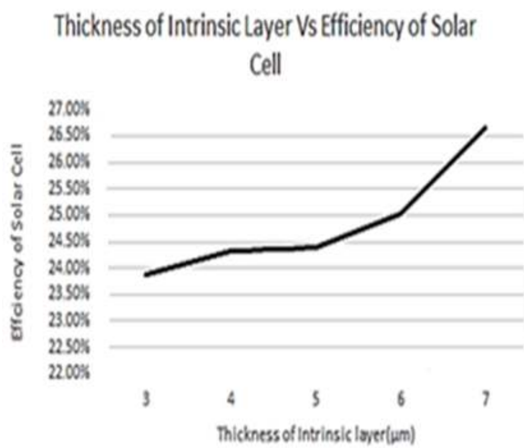

Figure 9: Graph between thickness of intrinsic layer and efficiency of solar cell

CONCLUSION

A heterojunction thin film solar cell is designed and optimized by using Gallium Nitride as a window material and polysilicon as an intrinsic and base material. In our paper, development of design is based on thickness of intrinsic layer and doping concentration. However other parameters such as recombination rate, permittivity, affinity, lattice constant and holes and electron states are also used to appraise the performance of our proposed solar cell. Simulation of our proposed solar cell shows promising results. Our Gallium Nitride/polysilicon solar cell have maximum\efficiency of 23.88% with a small area of 6 µm X 1.48 µm. As we further increased the thickness of intrinsic layer of solar cell, efficiency of solar cell increases. With 7 µm thickness of intrinsic layer and an area of 11 µm X 1.48 µm, maximum efficiency of the solar cell is achieved which is 26.67%. achieved which is 26.67%. We hope that development of proposed solar cell will benefit mankind with its supreme productivity.

Table 2: Model of Gallium Nitride/polysilicon Solar cell

Material	n-GaN	i-p/Si	p-p/Si
Electron Mobility	-	600	200
Hole Mobility	-	100	300
Conduction band density at 300K	-	$1x10^{20}$ /cm³	$1x10^{20}$ /cm³
Conduction band density at 300K	-	$1x10^{20}$ /cm³	$1x10^{20}$ /cm³
Minority carrier lifetimes for Electrons	-	$1x10^{-6}$s	$1x10^{-7}$s
Minority carrier lifetimes for Holes	-	$0.1x10^{-6}$s	$0.1x10^{-6}$s
Bandgap Energy	3.4eV	1.5eV	15Ev

Table 3: Defects induced in polysilicon crystal

Polysilicon	
Acceptor-like states in the tail distribution at the conduction band edge	$1x10^{21}$ cm³/eV
Donor-like states in the tail distribution at the conduction band edge	$1x10^{21}$ cm³/eV
Decay energy for the tail distribution of acceptor-like states	0.033 eV
Decay energy for the tail distribution of donor-like states	0.049 eV
Density of acceptor-like states in a Gaussian distribution	$1.5x10^{15}$cm³/eV
Density of donor-like states in a Gaussian distribution	$1.5x10^{15}$cm³/eV
Energy that corresponds to the Gaussian distribution peak for acceptor-like states	0.62 eV
Energy that corresponds to the Gaussian distribution peak for donor-like states	0.78 eV
Gaussian distribution of acceptor-like states for a characteristic decay energy	0.15 eV
Gaussian distribution of donor-like states for a characteristic decay energy	0.15 eV

Table 4: Results of simulated Gallium Nitride / polysilicon solar cell

Thickness of intrinsic layer	Current density	Fill Factor	Voc	Efficiency
3µm	43.87 mA/cm²	0.775	0.701V	23.88%
4 µm	45.45 mA/cm²	0.764	0.705V	24.33%
5 µm	49.66 mA/cm²	0.732	0.709V	24.39%
6 µm	51.12 mA/cm²	0.730	0.789V	25.02%
7 µm	52.66 mA/cm²	0.739	0.789 V	26.67%

REFERENCES

- Chopra KL and Das SR. (1983). Why Thin Film Solar Cells. *Springer.*1-18
- Berman, Elliot. (1985). Thin film solar cell substrate. *US Patent.*1-4
- Kuo-Hung SHEN. (2010). Thin-film solar cell. *Patent Application Publication*. 1-10
- Shin B, Gunawan O, Zhu Y, Bojarczuk NA, Chey SJ and Guha S. (2013).Thin film solar cell with 8.4% power conversion efficiency using an earth abundant Cu2ZnSnS4 absorber. *Progress in Photovoltaics: Research and Applications*. 21(1): 72-76.
- Taguchi, Mikio, Yano A, Tohoda S, Matsuyama K, NakamuraY, Nishiwaki T, Fujita K and Maruyama E. (2014). 24.7% record efficiency HIT solar cell on thin silicon wafer. *Photovoltaics, IEEE Journal.* 4(1): 96-99.
- Silvaco TCAD. (2015).Manuals, Atlas, Silvaco International, Co.
- Davis RF, Sitar Z, Williams BE, Kong HS, Kim HJ, Palmour JW and Carter CH. (1988). Critical evaluation of the status of the areas for future research regarding the wide band gap semiconductors diamond, gallium nitride and silicon carbide. *Materials Science and Engineering.*(1): 77-104.
- Green MA, Emery K, Hishikawa Y, Warta W and Dunlop ED. (2015). Solar cell efficiency Tables. *Progress in photovoltaics: research and applications.* 24:3–11.
- Chan DS and Phang JC. (1987). Analytical Methods for the Extraction of Solar-cell Singleand Double-diode Model Parameters from Iv Characteristics.

- He Z, Zhong C, Huang X, Wong WY, Wu H, Chen L and Cao Y. (2011). Simultaneous enhancement of open circuit voltage, short circuit current density and fill factor in polymer solar cells. *Advanced Materials.* 23(40): 4636-4643

- Ellmer K, Klein A and Rech B. (2007). Transparent conductive zinc oxide: basics and applications in thin film solar cells. *Springer Science & Business Media*. 104:1-33

- Michael S, Bates AD and Green MS. (2005). Silvaco ATLAS as a solar cell modeling tool. In Photovoltaic Specialists Conference, Conference Record of the Thirty-first IEEE. 719-721.