Acta Scientific Applied Physics

Volume 1 Issue 2 February 2020

Review Article

Determination of the Effect of Layer Thickness on the Efficiency of Cigs-Based Solar Cells Using Scaps-1d

Hayat M[1], Babaji G[1], Mansur Said[2]* and A B Ahmed[3]

[1]Department of Physics, Bayero University, Kano, Nigeria

[2]Department of Physics, Yusuf Maitama Sule University, Kano, Nigeria

[3]Department of Physics, Gombe State University, Gombe, Nigeria

***Corresponding Author:** Mansur Said, Department of Physics, Yusuf Maitama Sule University, Kano, Nigeria.

Received: December 23, 2019

Published: February 12, 2020

Abstract

Most state-of-art CIGS based solar cells employs CdS as buffer layer. However, due to its toxic nature, there is need for searching possible alternatives. In this work, the performance of the CIGS solar cells was simulated using SCAPS-1D software. Photovoltaic parameters of CIGS solar cells using different buffer layer materials; CdS, ZnS, ZnO, ZnSe and InS were simulated. The optimized thickness of buffer and absorber layers was found to be 0.02µm and 0.75µm respectively for the selected ZnO buffer layer. Also, for the optimized cell, the V_{oc}, J_{sc}, FF, and efficiency were found to be 0.8842V, 34.3739mA/cm2, 80.63% and 24.51% respectively. Finally it was found that ZnO can be a good material that can substitute the toxic CdS element for the production of solar cell and promise high efficiency.

Keywords: Buffer layer, CIGS, efficiency, FF, J_{sc}, Photovoltaic, V_{oc}

Introduction

It is now generally believe that there is the need for other source of energy apart from the conventional fossil and nuclear energy. The main drawback of the use of these sources is that they are exhaustible and contribute to the pollution of the environment. Hence, the necessity to use renewable energy sources. Solar energy occupies an important place because it is available everywhere. The light from the sun is a non-vanishing renewable source of energy which is free from environmental pollution and noise [1].

Thin film solar cells are introduced and developed as the second generation of solar cells to provide high production capacity at lower energy and material consumption [2]. Main motivations for the growth of thin film photovoltaic are their Potential for high-speed manufacturing and minimum material requirements that lead to cost reduction [3].

Copper Indium Gallium di Selenide (CIGS) is today by far the most efficient thin film solar cell technology. However, recent achievements are based on a long history of research and technological development. CuInSe2 material was synthesized for the first time by Hahn in 1953 and proposed as a photovoltaic material in 1974. In the years 1983-1984, Boeing Corp. reported efficiencies in excess of 10% from thin film CIGS. The CIGS performance has been improved significantly over the past decades. Among thin film solar cells, the CIGS has the highest efficiency of over 20% (22.3% for a cell with glass substrate and 20.4% for a cell with polyimide foil substrates), which was recently published by US National Renewable Energy Laboratory NREL, shows the best researched solar cell efficiencies that have been reported so far [4].

Furthermore, different conversion efficiencies of CIGS cells are mentioned in the literature [2,5]. By changing the material of the buffer layer, the most efficient CIGS/CdS thin film solar cell with a flexible polymer has achieved 20.4% efficiency [6]. The efficiency improvement from 20.4% to over 22% [7] are found by different research groups. All these efficiency records were obtained from CIGS solar cells with the CdS buffer layer. Despite the high efficiency level of the CIGS/CdS buffer layers the development of Cd-free buffer layers is one of the main objectives in the field of CIGS thin film solar cells. This is mainly because of the toxicity of CdS.

In this work, the performance of CIGS solar cell using different materials as buffer layer was studied. The effect of layer thickness on the efficiency of CIGS-based solar cells was determined using SCAPS-1D. The J-V characteristic was calculated under different buffer layer materials (CdS, Cd-free buffer layers). The purpose is to find a replacement of CdS by Cd-free buffer layer (i.e Zinc-based and Indium-based). The objective of this research is to investigate the effect of different buffer layers on the performance of the CIGS solar cell, the effect of thicknesses of absorber layer and buffer layer on the photovoltaic parameters, the effect of temperature on the performance of the solar cell.

Theoretical Background

The parameters obtained from the I-V characteristics that are use to characterize the output of solar cells are short circuit current (I_{sc}), short circuit current density (J_{sc}), open circuit voltage (V_{oc}), maximum power point (P_{max}), current at maximum power point (Imax), voltage at maximum power point (V_{ma}x), fill factor (FF), conversion efficiency (ŋ), series resistance (R_s), and shunt resistance (R_{sh}).

The short circuit current (I_{sc}) is the current through the solar cell when the voltage across the solar cell is zero. The open circuit voltage (V_{oc}) is the voltage across the solar cell when the current through the solar cell is zero. The maximum power point (P_{max}) is the condition under which the solar cell generates its maximum power; the current and voltage are defined as Imaxand V_{max} respectively. The fill factor (FF) is defined as the ratio of P_{max} divided by the product of V_{oc} and I_{sc}. The conversion efficiency is defined as the ratio of P_{max} to the product of the input light irradiance (E) and the surface area of the solar cell (A).

$$I = I_o\left(1 - e^{\frac{qV}{KT}}\right) + I_L \quad (1)$$

$$V_{oc} = \frac{KT}{q}\left(In\frac{I_{sc}}{I_0}\right) \quad (2)$$

$$FF = \frac{P_{max}}{V_{oc}\times I_{sc}} = \frac{V_{max}\times I_{max}}{V_{oc}\times I_{sc}} \quad (3)$$

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{max}\times I_{max}}{E\times A} = \frac{\overline{V_{oc}}\times I_{sc}\times FF}{E\times A} \quad (4)$$

Governing Equations of SCAPS

SCAPS-1D is a one-dimensional solar cell device simulator, developed at Electronics and Information Systems (ELIS), University of Gent, Belgium by Burgelman., *et al.* [8]. SCAPS is freely available to the PV research community. The user can describe a solar cell as a stack of up to seven layers with different properties, such as thickness, optical absorption, doping, defect densities and defect distribution. It is then possible to simulate a number of common measurements: I-V, C-V, C-f, QE (Mandadapu., *et al*. 2017).

SCAPS is capable of solving the basic semiconductor equations, the Poisson equation and the continuity equations for electrons and holes:

$$\frac{d^2}{dx^2}\Psi(x) = \frac{e}{\varepsilon_0\varepsilon_r}\left(p(x) - n(x) + N_D - N_A + \rho_P - \rho_n\right) \quad (5)$$

Where Ψ is electrostatic potential, e is electrical charge, ε_r is relative and ε_0 is the vacuum permittivity, p and n are hole and electron concentrations, N_D is charged impurities of donor and N_A is acceptor type, ρ_p and ρ_n are holes and electrons distribution, respectively. The continuity equations for electrons and holes are:

$$\frac{dj_n}{dx} = G - R \quad (6)$$

$$\frac{dj_p}{dx} = G - R \quad (7)$$

where, j_n=Electron Current Density, j_p=Hole Current Density, G= Recombination Rate, R= Generation Rate. Carrier transport in semiconductors occurs by drift and diffusion and can be expressed by the equations:

$$J_n = D_n\frac{d_n}{dx} + \mu_n n\frac{d\emptyset}{dx} \quad (8)$$

$$J_p = D_p\frac{d_p}{dx} + \mu_p p\frac{d\emptyset}{dx} \quad (9)$$

SCAPS calculates solution of the basic semi-conductor equations in one dimension and in steady state conditions [9].

Procedure

SCAPS is primarily designed to simulate CIGS and CdTe-based thin film solar cell devices. The user can obtain results in the form of I-V, C-V, C-f and Q(λ) characteristics, band diagrams, electric field, carrier densities and partial recombination currents. The user sets parameters of materials and an operating points; temperature, voltage, frequency and illumination condition. Device is represented as a stack of layers, up to 7 semiconductor layers with specified properties. Separate entries for interface parameters and two additional layers for front and back contacts were to be set [8]. Figure 1 shows the steps in the simulation process.

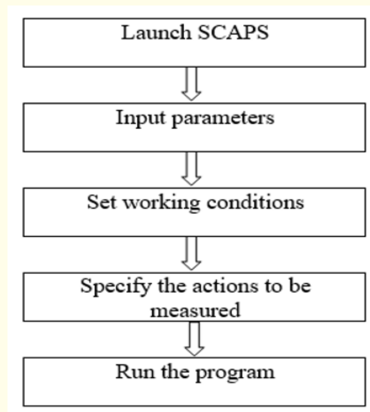

Figure 1: SCAPS working procedure.

A CIGS-based solar cell structure consists of a p-type absorber layer, an n-type buffer layer made of ZnO and window layer made of n-ZnO: Al. The TCO window layer that is used in this simulation is aluminum doped zinc oxide (ZnO: Al) deposited on the top of Zinc Oxide which serves as a buffer layer.

Each layer has its own parameters (band gap, permittivity, electron affinity etc.) which should be specified inside the SCAPS software as inputs before execution. The parameters of materials used for the specific layers are extracted from literature.

The simulations are conducted by specifying the materiel parameters in each defined layer of the device structures as the input parameters. Within the reasonable ranges, the material parameters selected from the reported literature for all the layers are shown in Table 1 and Table 2. In order to study the influence of thickness on the performances of the CIGS solar cells, we have proceeded layer by layer in such a way that the thickness of two layers are kept unchanged and those of the third layer are varied. This has allowed us to attain solar cells with high efficiencies. The J-V characteristic was simulated with the AM1.5 illumination conditions (100mW/cm^2). The simulation started by changing the thickness of the absorber layer from 1 to 5μm and the thickness buffer layer was changed from 0.01μm to 0.10μm, and the variation of the cell performance has been reviewed. The open-circuit voltage (Voc), short circuit current density (Jsc), fill factor (FF), efficiency (η) is calculated by the software.

Parameters	CIGS [7]	nZnO: Al [10]	CdS [7]	ZnO [11]	ZnSe [11]	In_2S_3 [12]	ZnS [13]
Eg(eV)	1.5	3.3	2.4	3.3	2.7	2.5	3.3
ϵ_r	13.6	9	10	10	10	13.5	10
X(eV)	4.5	4.65	4.2	4.6	4.09	4.25	4.7
$\mu n(cm^2V^{-1}s^{-1})$	100	100	100	100	50	400	50
$\mu p(cm^2V^{-1}s^{-1})$	25	25	25	30	20	210	20
$NC(cm^{-3})$	2.2e18	2.2e18	1.5e18	1.5e18	1.5e18	1.5e18	1.5e18
$NV(cm^{-3})$	1.8e19	1.8e19	1.8e19	1.8e19	1.8e19	1.8e19	1.8e19
Vt(cm/s)	1e7	1e7	1e7	1e7	1e7	1e7	1e7
Vt(cm/s)	1e7	1e7	1e7	1e7	1e7	1e7	1e7

Table 1: Parameters of materials at 300K.

Properties	CIGS	n-ZnO: Al	CdS	ZnO	ZnSe	In_2S_3	ZnS
NGA, NGD (cm^3)	1.772E+15	1.772E+18	1.772E+16	1.772E+16	1.772E+16	1.772E+16	1.772E+16
EGA, EGD (eV)	0.6	1.65	1.2	1.2	1.2	1.2	1.2
WGA, WGD (eV)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
σ_n (cm^2)	1.0E-13	1.0E-12	1.0E-13	1.0E-13	1.0E-13	1.0E-13	1.0E-13
σ_p (cm^2)	1.0E-15	1.0E-12	1.0E-13	1.0E-13	1.0E-13	1.0E-13	1.0E-13

Table 2: Gaussian defect states.

The parameters used for simulations of a standard CIGS-based solar cell are summarized in table 1.

Results and Discussion

Performance of the CIGS using different materials as buffer layer

Figure 2 shows the simulated J-V characteristics at AM1.5 illumination conditions (100mW/cm^2) for different buffer layer. Table 3 includes all the photovoltaic parameters (I_{sc}, V_{oc}, ŋ and FF) of the CIGS-based solar cell with different buffer layer. From the Figure, it was found that the solar cells with ZnO as buffer layer gives high conversion efficiency. As for the solar cell with ZnSe buffer layer had the least conversion efficiency. This is because ZnO have wider band gap than that of CdS and higher efficiency than that of the CdS based cell.

	CdS Buffer Layer	InS Buffer Layer	ZnO Buffer Layer	ZnSe Buffer Layer	ZnS Buffer Layer
V_{OC}(V)	0.9083	0.9080	0.9094	0.9097	0.9128
J_{SC}(mA/cm^2)	27.86	27.65	27.86	27.86	27.83
F_F(%)	85.82	85.96	85.86	81.10	85.32
Ŋ(%)	21.72	21.58	21.75	20.56	21.67

Table 3: The photovoltaic parameters for the CIGS-based solar cell for different buffer layer.

Effect of variation in absorber layer thickness (with ZnO as Buffer Layer)

From Figure 3(a) show there is rapid increase in the V_{oc} for a thickness between 0.5 - 1.25µm and then remains almost constant.

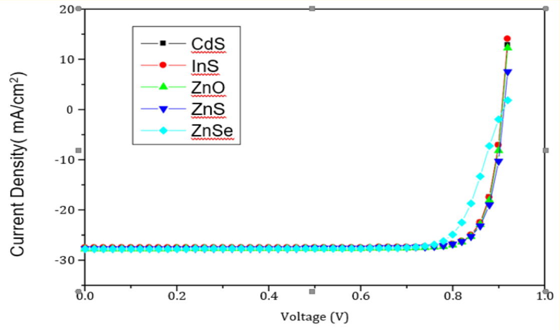

Figure 2: J-V characteristics of cells with different buffer layers.

This is due to the fact that 0.8854V may be the highest pick voltage attained before it falls into saturation level as expected. Similar behavior was also observed in Figure 3(b) for J_{sc}. This shows that the voltage and current are proportional to each other with respect to thickness.

Figure 3(c) shows the result of Fill Factor against thickness. The fill factor as in equation (2) depend inversely on V_{oc} and J_{sc} as such one can expect as V_{oc} and J_{sc} reach highest pick point, the fill factor will decrease and as V_{oc} and J_{sc} reaches saturation level also fill factor remains constant at every thickness.

Figure 3(d) shows the efficiency against thickness of absorber (CIGS) layer and it was found that the highest efficiency obtained is 24.51% at a thickness of 0.75µm. This efficiency was found to be higher than the finding of [11] which was 23.67% and lower than the value obtained by [13] which was 28.66%.

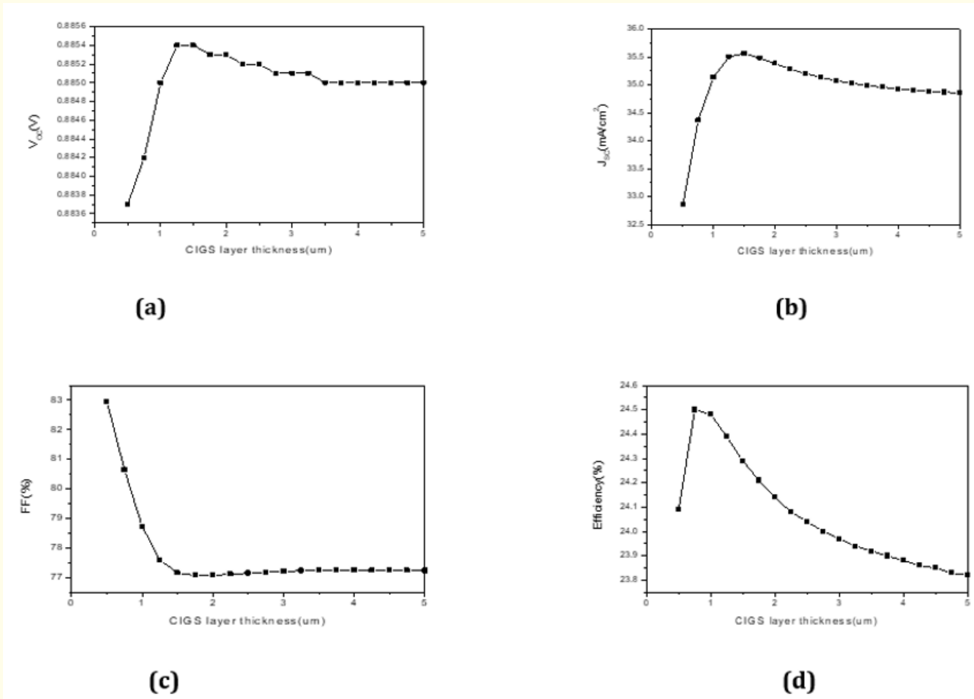

Figure 3: Variation of (a) V_{oc} (b) J_{sc} (c) FF and (d) Efficiency as a function of CIGS layer thickness.

Effect of variation in Buffer Layer (ZnO) Thickness

Figure 4(a) shows that the open circuit voltage (V_{oc}) remains constant on changing the buffer layer thickness. The short circuit current density decreases with increase in buffer layer thickness. From Figure 4(d) shows that the efficiency initially started to increase and then decreases from 0.02µm on increasing the thickness. These observations have good agreement with earlier reported work by Heriche., *et al.* [14]. This is due to the fact that with thinner buffer layer most of the generated carriers are collected. When the thickness increases the photons of short wavelengths are absorbed at further distance between the window and the absorber junction [5]. Though the buffer layer is characterized by defect states which act as recombination centers reduce the lifetime carriers and consequently the photogenerated carriers created on the absorber recombine before reaching the window layer. Therefore there is a drop of efficiency with increase in the buffer layer thickness. Therefore the optimized thickness of the buffer layer is 0.02µm.

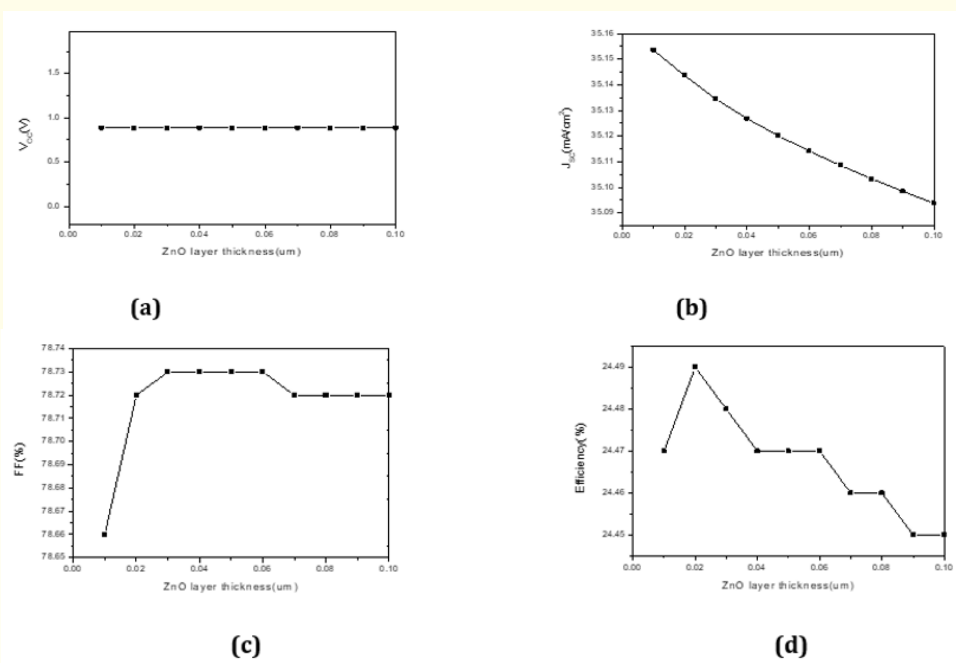

Figure 4: Variation of (a) V_{oc} (b) J_{sc} (c) FF and (d) Efficiency as a function of ZnO layer thickness.

Effect of temperature

Operating temperature plays a vital role in the performance of the solar cells. The temperature dependence of photovoltaic parameters of cell CIGS is studied in the temperature range (260-360K) under a constant illumination (1000W/m2). It was found that the overall efficiency in case of ZnO buffered cells is severely affected by the operating temperature. At higher temperature, parameters such as the electron and hole mobility, carrier concentrations and band gaps of the materials would be affected in a manner that result in lower efficiency of the cells. This can be explained by majority charge carriers recombination in the space charge region.

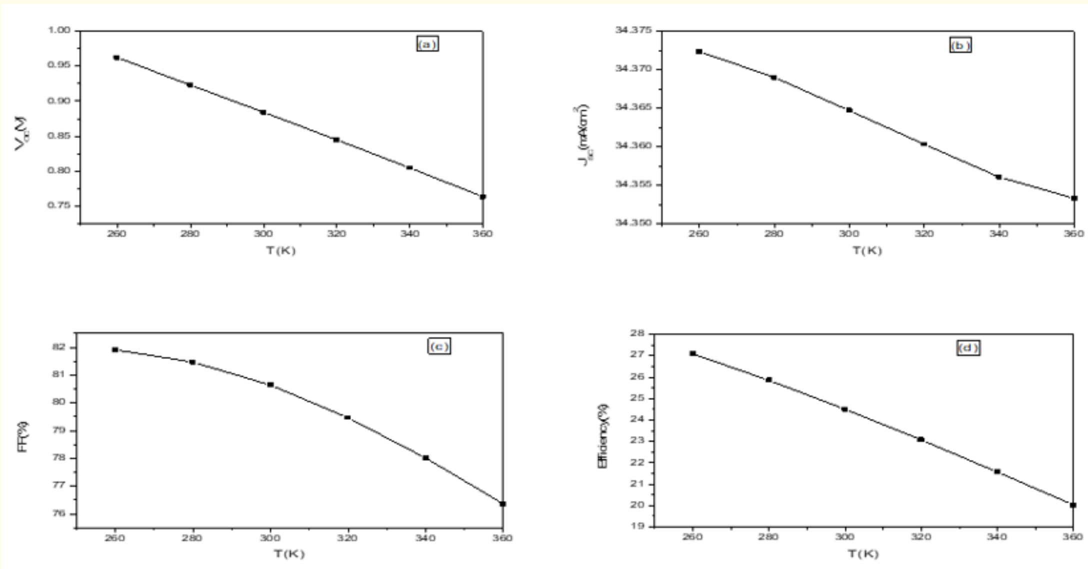

Figure 5: Effect of temperature on photovoltaic parameters of cell CIGS: (a) Voc, (b) Jsc, (c) FF and (d) Efficiency with ZnO as buffer layer.

Conclusion

In this work, the performance of the CIGS-based solar cells was investigated. It was found that ZnO can be used as alternative material to CdS. It was also demonstrated that the variation in the thicknesses of the absorber and buffer layers as well as the temperature affect the conversion efficiency. Photovoltaic parameters of CIGS: open circuit voltage (V_{oc}), short circuit current density (J_{sc}), Fill Factor (FF) and efficiency (ŋ) are 0.8842V, 34.3739mA/cm^2, 80.63% and 24.51% respectively. With this properties obtained it is recommended that ZnO buffer layer can be a good substitute to these CdS.

Bibliography

1. Sharma S., *et al*. "Solar cells: In Research and Applications- A Review". *Material Science and Application* 6 (2015): 1145-1155.
2. Poortmans J and Arkhipov V. "Thin film solar cells: fabrication, characterization and applications". John Wiley and Sons, West Sussex, England 5 (2006).
3. Arnulf JW. "Progress in chalcopyrite compound semiconductor research for photovoltaic applications and transfer of results into actual solar cell production". *Solar Energy Materials and Solar Cells* 95 (2011): 1509 -1517.
4. Kazmerski LL. "Best research solar cell efficiencies" (2016).
5. Chelvanathan P., *et al*. "Performance analysis of copper-indium gallium diselenide (CIGS) solar cells with various buffer layers by SCAPS". *Current Applied Physics* 10 (2010): S387-S391.
6. Lindahl J., *et al*. "In line Cu (In,Ga)Se2 Co-evaporation for high efficiency solar cells and modules". IEEEJ *Photovoltaics* 3 (2013): 1100-1105.
7. Mostefaoui M., *et al*. "Simulation of High Efficiency CIGS solar cells with SCAPS-1D software". International conference on technology and materials for renewable energy, *Energy Procedia* 74 (2015): 736-744.
8. Burgelman M., *et al*. SCAPS manual version 3.3.06, Department of ELIS, University of Gent, Belgium (2016): 1-110.
9. Ouedraogo S., *et al*. "Numerical Analysis of Copper-Indium- Gallium-Diselinide-Based Solar Cells by SCAPS-1D". *International Journal of Photoenergy* 2 (2013): 1-9.
10. Oubda D., *et al*. "Numerical simulation of Cu (In,Ga)Se2 Solar cells performances". *Journal of Energy and Power Engineering* 9 (2015): 1047-1055.

11. Asaduzzaman Md., *et al*. "Non-Toxic Buffer Layers in Flexible Cu (In,Ga)Se2 Photovoltaic Cell Applications with Optimized Absorber Thickness". *International Journal of Photoenergy* (2017).

12. Khoshsirat N., *et al*. "Analysis of absorber layer properties effect on CIGS solar cell performance using SCAPS". *Optik – International Journal for Light and Electron Optics* 126 (2015): 681-686.

13. Feroz Ali., *et al*. "Numerical Simulation and Observation the Characteristics of CIGS Thin Film Solar Cell using SCAPS-1D". *American Journal of Engineering Research* (AJER) 7 (2018): 176-182.

14. Heriche H., *et al*. "High-efficiency CIGS Solar Cells with optimization of layers thickness and doping". *Optik-International Journal for Light and Electron Optics* (2016).