East European Journal of Physics. **4.** 145-152 (2022)
DOI:10.26565/2312-4334-2022-4-14 ISSN 2312-4334

STUDY OF CIGS PSEUDO-HOMOJUNCTION THIN FILM SOLAR CELL USING SCAPS-1D†

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Received August 22, 2022; revised September 9, 2022; accepted September 15, 2022

The present modelling study reports the performance of defected CIGS pseudo-homojunction thin film solar cell (P-HTFSC) and determines its optimum parameters for high performance using the Scaps-1D software under the AM1.5 illumination and the operating temperature of 300 K. To focus the discussion on the optimal parameters (thickness, doping concentrations, deep/interface defect concentrations and bandgap) for the ZnO, CdS, ODC and CIGS thin film layers, cross sectional (1D) simulations have been performed on the ZnO/CdS/ODC/CIGS P-HTFSC device for obtaining its optimal structure that confers high light-into-electricity conversion efficiency. The four light J-V characteristics (short-circuit current: J_{SC}, open-circuit voltage: V_{OC}, fill factor: FF and conversion efficiency: η) have been used as indicators to evaluate the device performances. Simulation outcomes have proved that for a best performance for CIGS P-HTFSC device, the optimal thickness for CIGS and ODC layers should be small than 2 μm and few nm, respectively, while the optimal defect concentration within the layer should be 10^{13} cm^{-3} and between 10^{13} cm^{-3}-10^{18} cm^{-3}, respectively.
Keywords: CIGS, ODC, Pseudo-homojunction, J-V characteristics, Scaps-1D.
PACS: 02.60.Pn, 85.60.−q, 84.60.Jt, 79.60.Dp, 72.40.+w, 73.63.−b, 68.55.Ln

In recent decades, hiring photovoltaic devices in human being daily life has known an upward trend worldwide; especially in countries that have acquired photovoltaic technology and have use it to solve the problems associated with the dominance of fossil fuels on their growth and to prevent climate change as well. Generally, three generations have been developed and distinguished on the basis of used materials as active layers in photovoltaic device. CIGS, the abbreviation for copper indium gallium selenide materials are considered excellent active layers for the second generation, namely thin film solar cells (TFSC) that take into account the use of small amounts of raw materials that can be easily processed with little of time and energy [1-2]. Regardless of the material composition, the current record efficiency of CIGS thin film solar cell reaches 23.3 % achieved by National Renewable Energy Laboratory (NREL) under AM1.5 spectrum (1000 W/m^2) at temperature of 25° [3]. This record efficiency stays away by more than five-ones from the theoretical limit efficiency of CIGS solar cells that estimated between 28-30% [4]. Such theoretical limit is due to the optimal bandgap of CIGS semiconductor materials that ranges between 1.0-1.7 eV [1-2]. In addition, it was found that, since CIGS materials have high optical absorption coefficient, they absorb light strongly through thin layers not exceeding few (~2) micrometers and thus generate high currents and voltages. At the same time, the few nanometers of the few micrometers of CIGS layer at n-buffer/p-CIGS interface are highly defected region because of the Cu leakage towards the CIGS material and thus this part of the CIGS transforms from p-type to n-type and is named by the Ordered-Defect-Compound (ODC) part and, for example, is a compound of $CuIn_3Se_5$ or $CuIn_5Se_8$ or $Cu_2In_4Se_7$, etc [1,2]. Therefore, the junction formed between the ODC layer and the CIGS layer is an accidental junction that occurs during the fabrication process and is named the ODC/CIGS pseudo-homojunction. To study the impact of the work function on the overall performance of the superstrate CIGS TFSC, Bouchama et al. [5] inserted a significant n-type ODC layer between the In_2Se_3 and CIGS layers. At the end of the study, they obtained an outstanding efficiency of 20.18%. When photovoltaic community looks at the diversity of features that distinguish the CIGS material among others, they discover that CIGS still needs to more development to make the performance of CIGS solar cells more perfect and challenging to other photovoltaic devices in terms of large-scale manufacturing. Therefore, they have used software tools (AMPS-1D [5], SILVACO-TCAD [6], etc) that were developed in parallel with the development of solar cell devices to facilitate and streamline the manufacturing procedure.

The present article targets and analyses the light-to-electricity conversion performance of ZnO/CdS/ODC/CIGS pseudo-homojunction thin film solar cell (P-HTFSC) using a computer simulator named Solar Cell Capacitance Simulator (Scaps-1D) [7]. This leads to assess the performance of targeted device through the current density-voltage

† ***Cite as***: S. Boudour, I. Bouchama, S. Laidoudi, W. Bedjaoui, L. Lamiri, O. Belgherbi, and S. Aziez, East Eur. J. Phys. **4**, 145 (2022), https://doi.org/10.26565/2312-4334-2022-4-14

(J-V) characteristics, which consisted of short-circuit current (J_{SC}), open-circuit voltage (V_{OC}), fill factor (FF) and power conversion efficiency (η), against input settings, which includes the thickness, acceptor/donor concentration, interface/bulk defect and band gap of different device layers (ZnO or CdS or ODC or CIGS). As a result, the outcome of this study may be an optimized device that ensures to achieve the highly efficiency/cost ratio.

DEVICE AND SIMILATION TOOL

The following Figure 1(a) schemes the structure of the CIGS P-HTFSC, which is composed from the top to the bottom of: an aluminium (Al) metal fingers as an ohmic contact from the front side of the device; a zinc oxide (ZnO) thin film as a transparent conducting oxide (TCO) window layer; a cadmium sulphide (CdS) thin film as a buffer layer; an ordered defect compounds (ODC) layer, a copper indium gallium selenide (CIGS) thin film as an absorber layer; a molybdenum (Mo) metal as an ohmic back contact coated on the glass substrate.

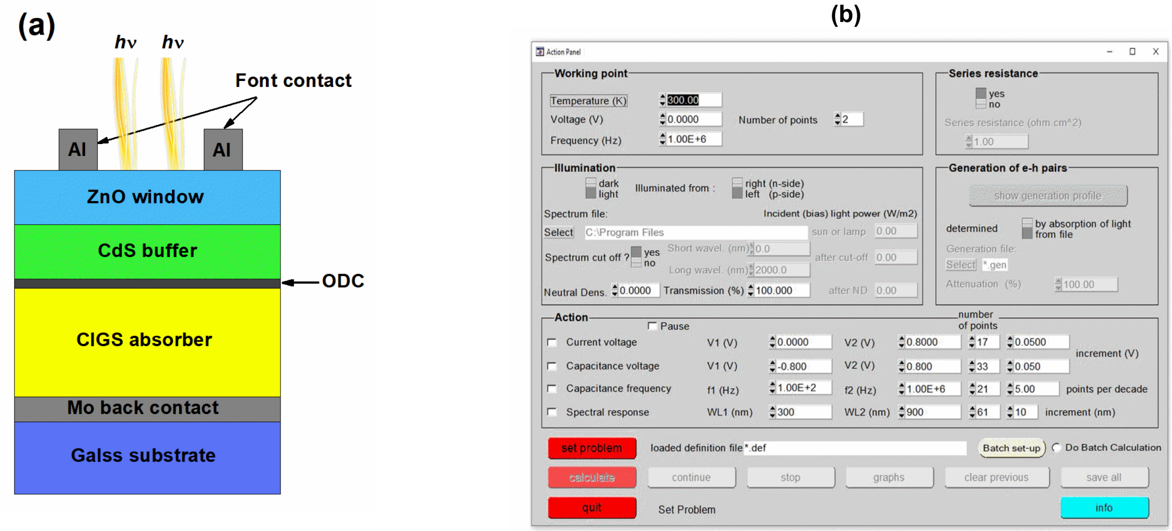

Figure 1. (a) Scheme of CIGS P-HTFSC Structure & (b) Scaps-1D graphical interface

In order to better address and analyse the light-to-electricity conversion efficiency of targeted device presented by Figure 1(a), Scaps-1D will be used as simulator tool [7]. This simulating tool resolves the dipolar problems in one dimension across layers of semiconducting devices by governing the equations of Poisson and electron/hole continuity. Moreover, it is featured by an easy graphical interface, as shown in Figure 1(b) that allows inputting and varying, either individually or collectively, the different properties of each layer, for example, thickness, bandgap energy, and donor/acceptor/defect concentrations. In addition, SCAPS-1D is equipped by different solar irradiation spectra, for example, the AM1.5 spectrum which will be used to radiate an incident power of 100mW/cm^2 towards the targeted device, while the reflection will be ignored during all simulation processes, meanwhile the operating temperature will be in contrast fixed at 300 K. While, each row in the Table 1 represents electrical and optical settings for a semiconducting layer in the proposed device shown in Figure 1(a), Table 2 represents the defect settings for CIGS layer.

Table 1. Settings for ZnO, CdS and CIGS layers used in SCAPS-1D simulation

Parameter	Symbol (unit)	ZnO	CdS	CIGS
Thickness	w (μm)	0.01 ~ 0.3	0.04 ~ 1	0.2 ~ 15
Dielectric constant	$\varepsilon/\varepsilon_0$	10	10	10
Electron affinity	χ_e (eV)	4.6	4.3	4.5
Electron mobility	μ_n (cm^{2}V^{-1}s^{-1})	100	100	100
Hole mobility	μ_p (cm^{2}V^{-1}s^{-1})	25	25	25
Bandgap	E_g (eV)	3.3	2.45	1.01 ~ 1.56
Donor / Acceptor concentration	N_d / N_a (cm^{-3})	10^{12} ~ 4 × 10^{21}	10^{12} ~ 4 × 10^{21}	10^{12} ~ 10^{22}
Effective density of states in CB	N_c (cm^{-3})	4 × 10^{18}	2 × 10^{18}	2 × 10^{18}
Effective density of states in VB	N_v (cm^{-3})	9 × 10^{18}	1.5 × 10^{19}	2 × 10^{18}

Table 2. Defect settings for CIGS absorber layer

Parameter	Symbol (unit)	Value
Defect density	N_t (cm^{-3})	1 × 10^{13}
Standard deviation	(eV)	0.1
Electron cross-section	(cm^2)	5.3 × 10^{-13}
Hole cross-section	(cm^2)	5 × 10^{-15}

RESULTS AND DISCUSSION

Optimal Thickness of CIGS Absorber Layer

The photovoltaic community has long sought an increased focus on thin film technology, which fulfils the criterions of high photon absorption and low quantity materials to improve the cost-efficiency ratio of the solar cell devices. Based on this approach, Figure 2 summarizes the evolution of J-V characteristics against the change in thickness of the CIGS absorber layer from 0.2 µm to 15 µm, starting with small steps of 0.2 µm to 0.5 µm to 1 µm as the CIGS layer thickness is increased; the important thing is that sharp increase was observed at first 2 µm of thickness in both J_{SC}, V_{OC}, FF and efficiency (η), which take almost unchanged value along the remaining 13 µm.

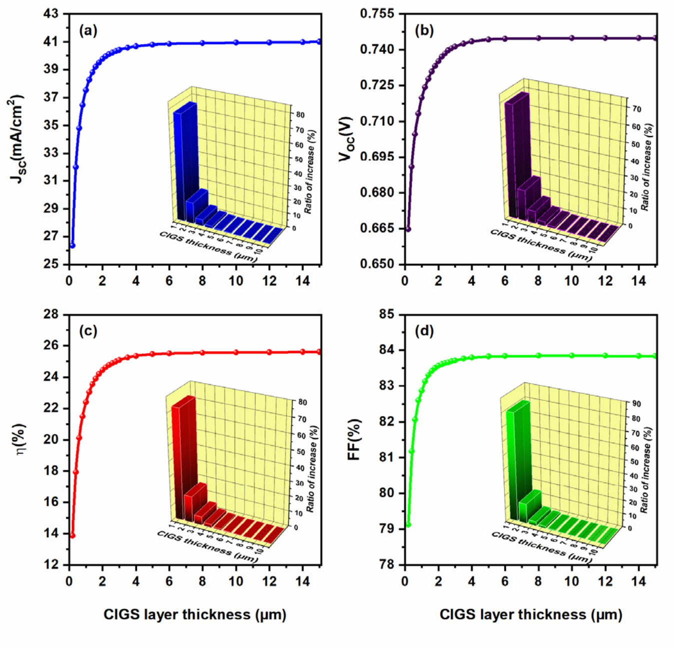

Figure 2. J-V characteristics versus thickness of CIGS absorber layer

Hence, at 2 µm, both J_{SC}, V_{OC}, FF and efficiency achieved 39.75 mA/cm^2, 0.73 V, 83.56 %, and 24.43 %, respectively, while at 15 µm they achieved 40.98 mA/cm^2, 0.74 V, 83.83 %, and 25.59 %, respectively. As a result, the convergence of the obtained values of J-V characteristics at 2 µm and 15 µm emphasized that a few µm of CIGS layer are sufficient for an absorber layer in a solar cell device to absorb the penetrating photons to the fullest. This was also supported by the included inset histograms in Figure 2, which emphasized that an approximately 2 µm of CIGS thin layer is necessary and sufficient to perform best cost-efficiency ratio. This sufficiency at 2 µm thickness is due to the high absorption coefficient (10^5 cm^{-1}) of CIGS material in the fundamental region of solar spectrum [8], where the absorbed energy of photons is responsible to generate hole-electron pairs, which will be separated by the space charge region (SCR) that is formed due to the metallurgical junction between parts of p-CIGS layer and n-CdS layer. Subsequently, the CIGS layer offers the bulk which through it will journey the separated holes to the back contact (Mo), while the electrons will journey through the buffer (CdS) to the window (ZnO) to the front contact (Al). The performed simulations subject to the conditions listed in Table 1 and 2 have proved that the extravagance of using 15 µm of the CIGS material for absorber layer will rise the manufacturing cost compared to the improvements it can achieve in the performance of the solar cell device, and sufficiency of using 2 µm or a little less of a CIGS absorber layer gives to ZnO/CdS/ODC/CIGS P-HTFSC the ability to perform an efficiency of about 24.43%.

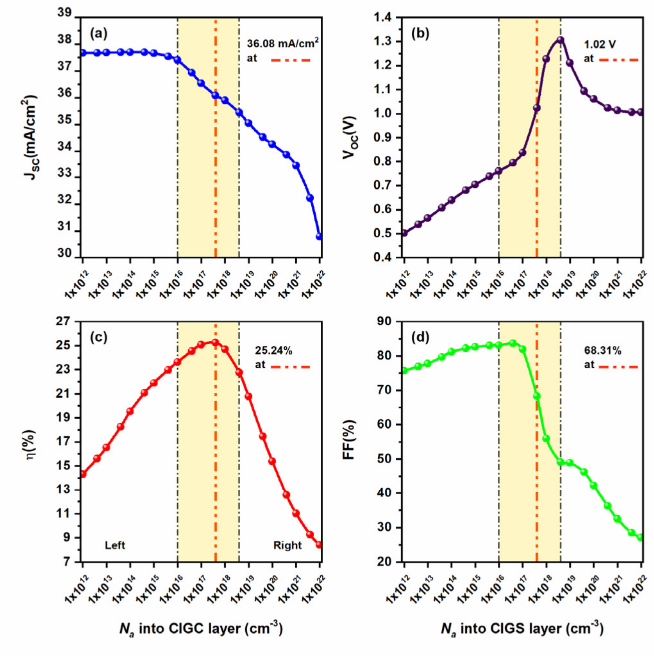

Figure 3 J-V characteristics versus acceptor concentration N_a into CIGS absorber layer

Optimal Acceptor Concentration into CIGS Absorber Layer

Figure 3 summarizes the evolution of J-V characteristics against the change in acceptor concentration (N_a) within CIGS absorber layer from 10^{12} cm^{-3} to 10^{22} cm^{-3}; the important thing is that the efficiency reaches its maximum value of 25.24% at 4×10^{17} cm^{-3} of acceptor concentrations into CIGS absorber layer that it was coincided with the achievements of 36.08 mA/cm^2, 1.02 V and 68.31% for both J_{SC}, V_{OC} and FF, respectively, as shown by the intersections of the dashed orange lines with the curves in Figure 3. However, the efficiency experienced weak or deteriorated behaviour on the right and left of the orange dashed line (at $N_a = 4\times10^{17}$ cm^{-3} in Figure 3) due to the deterioration of the V_{OC} at lower acceptor concentration (left of N_a) and the deterioration of both J_{SC}, V_{OC} and FF at higher acceptor concentration (right of N_a). The deterioration of the V_{OC} at higher acceptor concentration is due to an increase in recombination rate at rear surface of CIGS absorber layer. While the highly J_{SC} at low acceptor concentration is induced by the high carrier mobility and high carrier life time, which induce good collection of the photo-generated carriers, the drop of the J_{SC} at higher acceptor concentration is attributed to the increase of recombination rate of the photo-generated charge carriers that takes place within the CIGS bulk. As a result, in order to obtain best performance in term of efficiency (25.24%) for ZnO/CdS/ODC/CIGS P-HTFSC, the optimum acceptor concentration within CIGS absorber layer should be around $N_a = 4 \times 10^{17}$ cm^{-3}, which is slightly larger than what was mentioned by the experimental studies in both Lee et al [9] and Yüksel et al [10].

Optimal Bandgap of CIGS Absorber Layer

$CuIn_{1-x}Ga_xSe_2$ (CIGS: copper, indium, gallium and diselenide) materials are I-III-VI semiconducting alloys that mutate from $CuInSe_2$ (CIS: x=0) alloy to $CuGaSe_2$ (CGS: x=1) alloy according to x value (0 ~ 1) of Ga, as documented in Table 3.

Table 3. CIGS alloys and their bandgap energies

x concentration	Bandgap energy, E_g (eV)	$CuIn_xGa_{1-x}Se_2$
x = 0	1.01	$CuGaSe_2$
x = 0.31	1.176	$CuIn_{0.31}Ga_{0.69}Se_2$
x = 0.45	1.260	$CuIn_{0.45}Ga_{0.55}Se_2$
x = 0.66	1.398	$CuIn_{0.66}Ga_{0.34}Se_2$
x = 1	1.65	$CuInSe_2$

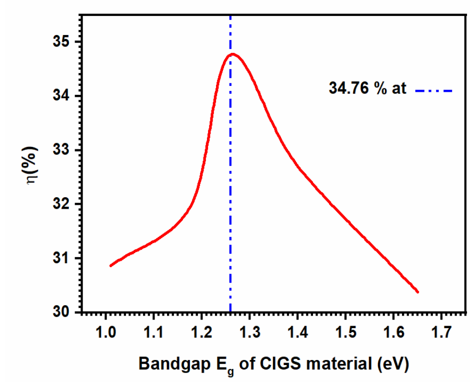

Figure 4. Efficiency (η) for ZnO/CdS/ODC/CIGS P-HTFSC versus bandgap (E_g) of CIGS material

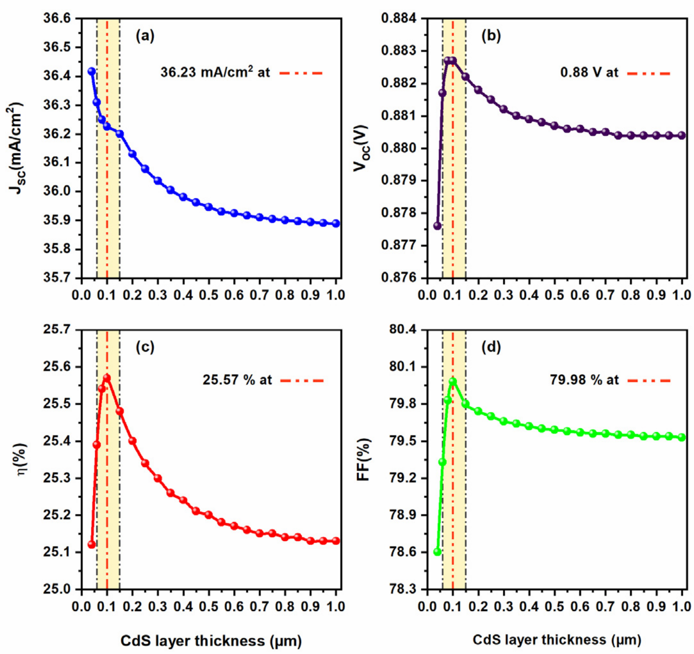

Figure 5. J-V characteristics versus thickness of CdS buffer layer

This wide range of x value means that the CIGS alloys can be tuned in terms of stability and miscibility of the embedded materials, therefore, tuning the optical bandgap energy (E_g) of CIGS alloys over a wide range (1.01 eV ~ 1.65 eV) is possible and sometimes even demanded (see Table 3). As mentioned in the literature, the bandgap of CIGS material is a direct optical feature, which allows to strongly absorbing the photons of fundamental range of the solar spectrum [4].

Figure 4 summarizes the evolution of power conversion efficiency (η) for ZnO/CdS/ODC/CIGS TFSC against the change in bandgap energy of CIGS absorber layer from 1.01 eV to 1.65 eV; the important thing is that the efficiency reaches its maximum value of 34.76% at 1.26 eV of bandgap energy as shown by the intersection of the dashed blue line with the curve in Figure 4. As a result, in order to obtain best performance in term of efficiency (34.76%) for ZnO/CdS/ODC/CIGS P-HTFSC, the optimum bandgap energy for CIGS absorber layer should be around 1.26 eV, which corresponds the x of 0.45 for Ga content.

Optimal Thickness of CdS Buffer Layer

Figure 5 summarizes the evolution of JV characteristics against the change in the thickness of the CdS buffer layer from 40 nm to 1 μm starting with small steps of 20 nm (at first 80 nm) to 50 nm as the CdS layer thickness is increased; the important thing is that while the performances in both J_{SC}, V_{OC}, FF and efficiency were low or deteriorated at thicknesses less than 80 nm and more than 100 nm, they were excellent and even improvements were achieved at thicknesses over 80 nm and less than 100 nm, as shown by the curves outlined in the yellow areas in Figure 5.

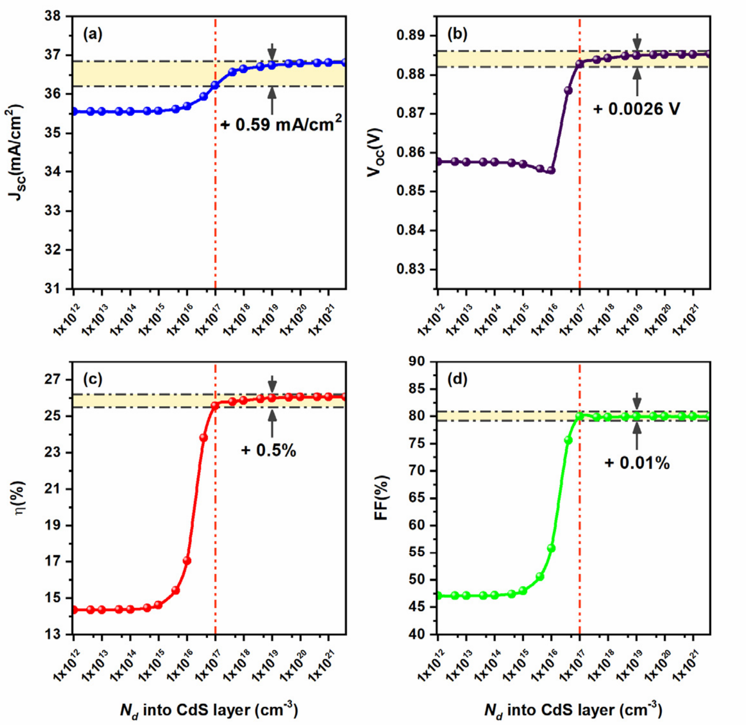

Figure 6. J-V characteristics versus donor concentration N_d into CdS buffer layer

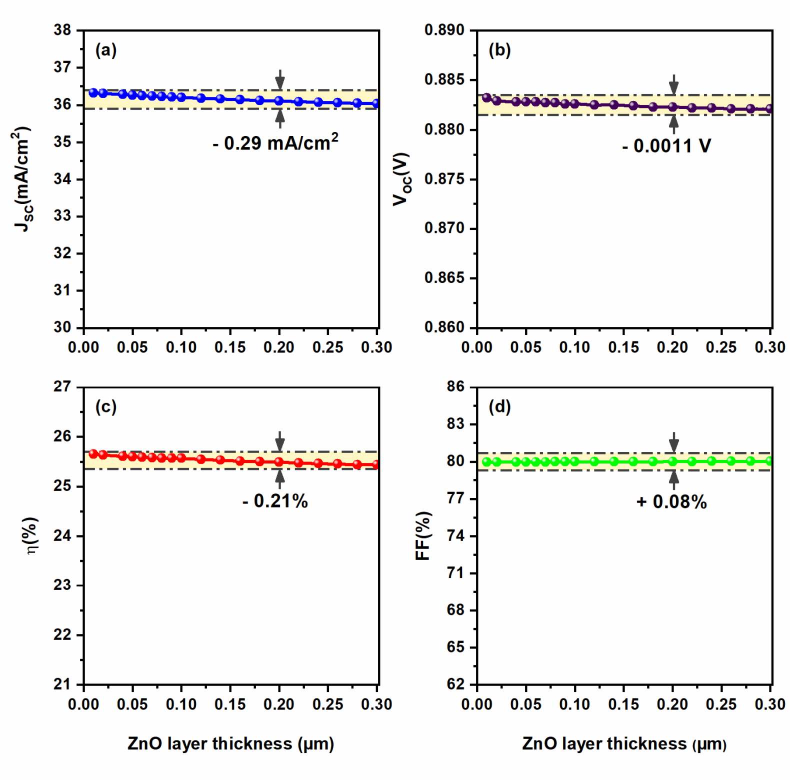

Figure 7. J-V characteristics versus thickness of ZnO window layer

While the poor efficiency of CIGS solar cell with a CdS buffer layer of some only tens of nanometres thick (<80 nm) is due to V_{OC} and FF deteriorations, which are attributed to the low bandgap of CdS material that cause an excessive absorption of photons in the blue wavelength range [11], the poor efficiency of CIGS solar cell with a CdS buffer layer of thickness over than 100 nm is due to J_{SC}, V_{OC} and FF deteriorations, which are attributed to the high recombination rate of charge carrier during its journey through CdS buffer layer. As a result, a sufficiency of using 100 nm or a little less of a CdS buffer layer gives to ZnO/CdS/ODC/CIGS P-HTFSC the ability to perform high J_{SC}, V_{OS}, FF and efficiency of 36.23 mA/cm^2, 0.88 V, 79.98 % and 25.57 %, respectively.

Optimal Donor Concentration into CdS Buffer Layer

Figure 6 summarizes the evolution of J-V characteristics against the change in donor concentration (N_d) within CdS buffer layer from 1×10^{12} cm^{-3} to 4×10^{21} cm^{-3}; the important thing is that the efficiency reaches its optimum value of 25.57% at 1×10^{17} cm^{-3} of donor concentration into CdS buffer layer that it was coincided with the achievements of 36.23 mA/cm^2, 0.88 V and 79.98% for both J_{SC}, V_{OC} and FF, respectively, as depicted by the intersections of the dashed orange lines with the curves shown in Figure 6. The sharp increase in all J-V characteristics at 1×10^{17} cm^{-3} of donor concentration is attributed to increase in collection rate of minority carrier charge. The slight increases of 0.59 mA/cm^2, 2.6 mV, 0.01% and 0.5% in both J_{SC}, V_{OC}, FF and efficiency, respectively, despite the big jump in donor concentration from 1×10^{17} cm^{-3} to 4×10^{21} cm^{-3} confirm that the 1×10^{17} cm^{-3} concentration is the optimum donor concentration for CdS material to be a highly performant buffer layer for the ZnO/CdS/ODC/CIGS P-HTFSC. This optimized concentration means that the CdS buffer layer do not need to reaches its effective density of states (2×10^{18} cm^{-3}) to do best performance.

Optimal Thickness of ZnO

Window Layer. Figure 7 summarizes the evolution of JV characteristics against the change in the thickness of the ZnO window layer from 10 nm to 300 nm starting with small steps of 10 nm to 20 nm as the ZnO layer thickness is increased; the important thing is that there was no significant change in all J-V characteristics performances, as shown by the curves outlined in the yellow areas in Figure 7, where small decreases of 0.29 mA/cm^2, 1.1 mV, 0.08% and 0.21% were recorded in both J_{SC}, V_{OS}, FF and efficiency, respectively.

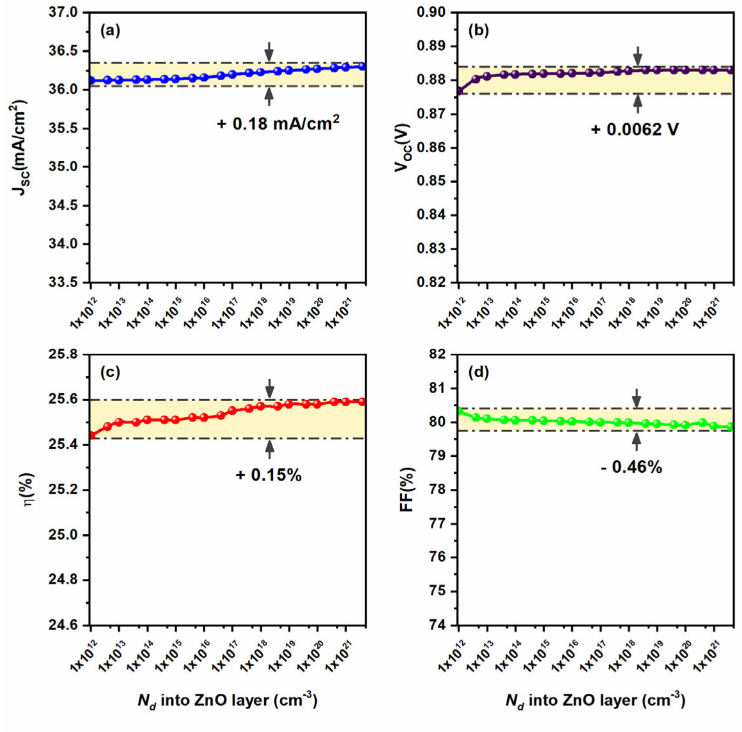

Figure 8. J-V characteristics versus donor concentration N_d into ZnO window layer

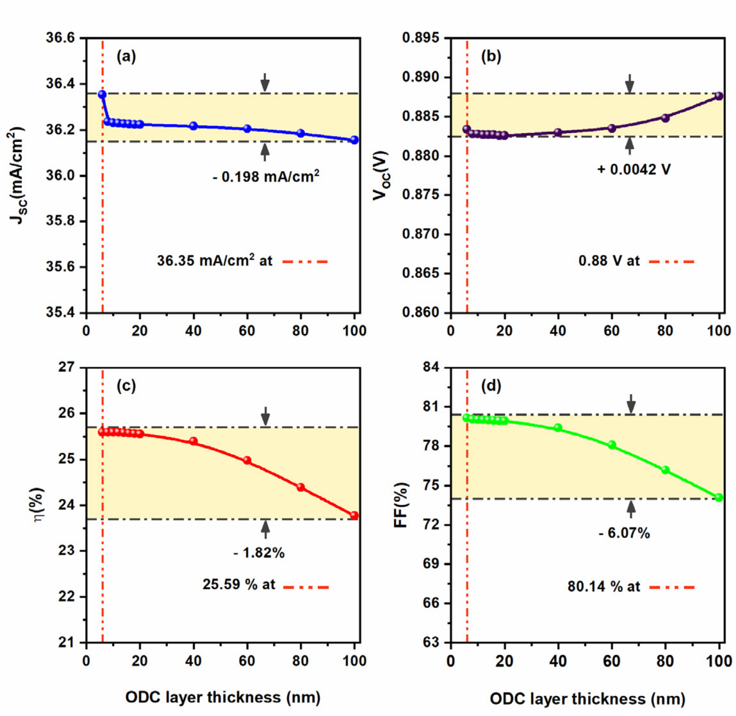

Figure .9 J-V characteristics versus thickness of OCD layer

This slight decrease is attributed to the wide optical bandgap (3.3 eV) of the ZnO material that prevents the absorption of photons that have less energy than their bandgap. As a result, a sufficiency of using few manometers of a ZnO layer gives to ZnO/CdS/ODC/CIGS P-HTFSC the ability to perform high J_{SC}, V_{OS}, FF and efficiency of about 36.32 mA/cm^2, 0.88 V, 80% and 25.65%, respectively.

Optimal Donor Concentration into ZnO Window Layer

Figure 8 summarizes the evolution of J-V characteristics against the change in donor concentration (N_d) within ZnO window layer from 1×10^{12} cm^{-3} to 4×10^{21} cm^{-3}; the important thing is that there was slight changes of +0.18 mA/cm^2, +6.2 mV, -0.46% and +0.15% in both J_{SC}, V_{OC}, FF and efficiency, respectively, despite the high increase in donor concentration within ZnO window layer. Based on what summarized in Figure 8 that both J_{SC}, V_{OC}, FF and efficiency achieved 36.25 mA/cm^2, 0.88 V, 79.94%, 25.58%, respectively, at 10^{19} cm^{-3} of donor concentration and based on what is mentioned in the literature that the elaborated ZnO thin films are semiconductors with stoichiometry controlled carrier concentration ranging from 10^{16} cm^{-3} to 10^{21} cm^{-3} [12], the 10^{19} cm^{-3} is the optimum donor concentration within ZnO window layer that gives the best performance for ZnO/CdS/ODC/CIGS P-HTFSC.

Optimal Thickness of ODC Layer

While Section (3.1.) has studied the effect of the overall thickness of the CIGS material used inside the solar cell structure, this section will study the effect of the last few nanometres of the CIGS layer near the CdS/CIGS interface side. Figure 9 summarizes the evolution of J-V characteristics against the change in thickness of ODC layer from 6 nm to 100 nm; the important thing is that there were small changes of +0.198 mA/cm^2, +4.2 mV, -6.07% and -1.82% in both J_{SC}, V_{OC}, FF and efficiency, respectively. The negative changes in JSC and hence efficiency (Figure 9) is may be due to the increase in recombination rate at the CIGS/CdS interface due to the inadequacy of passivation effect of the ODC layer.

Study of Defects in CIGS Pseudo-Homojunction Structure

Effect of defect Concentration into CIGS Absorber Layer. Figure 10 summarizes the evolution of J-V characteristics against the change in defect concentration N_t into CIGS absorber layer from the concentration

10^{13} cm^{-3} to the concentration 4×10^{17} cm^{-3}, which represents the optimum acceptor concentration for the CIGS pseudo-homojunction cell; the important thing is that the efficiency achieved its maximum value of 25.57% at 10^{13} cm^{-3} of defect concentration into CIGS absorber layer that it was coincided with the achievements of 36.23 mA/cm^2, 0.88 V and 79.98% for both J_{SC}, V_{OC} and FF, respectively. However, both J_{SC}, V_{OC}, FF and efficiency began to deteriorate once the defect concentration began to decrease, reaching their lowest levels of 9.57 mA/cm^2, 0.53 V, 43.37% and 2.19%, respectively, once the defect concentration reaches 4×10^{17} cm^{-3}. This J-V deterioration behaviour is attributed to the reduction in generated carrier journeying through the bulk of the CIGS absorber layer because of the high defect concentration within it, which means that for the CIGS pseudo-homojunction cell to perform well, the defect concentration must be lowered to 10^{13} cm^{-3}.

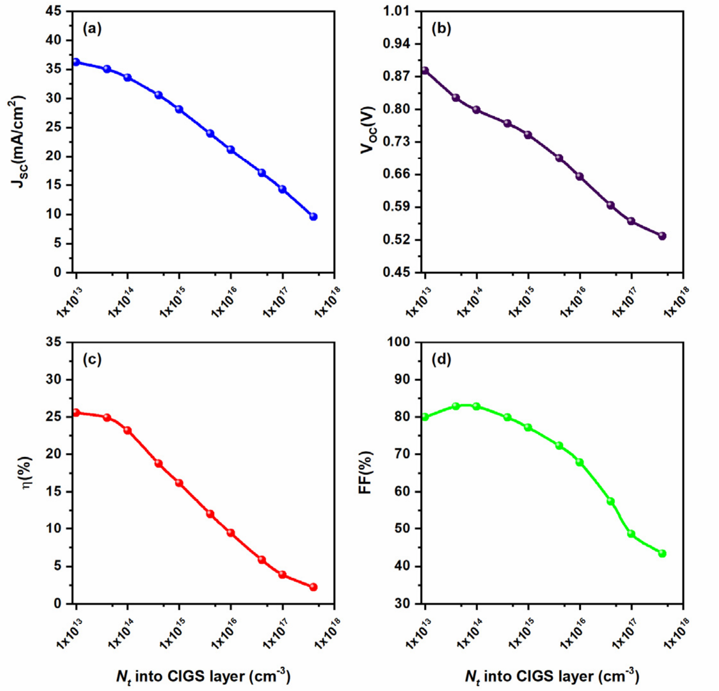

Figure 10. J-V characteristics versus defect concentration N_t into CIGS absorber layer

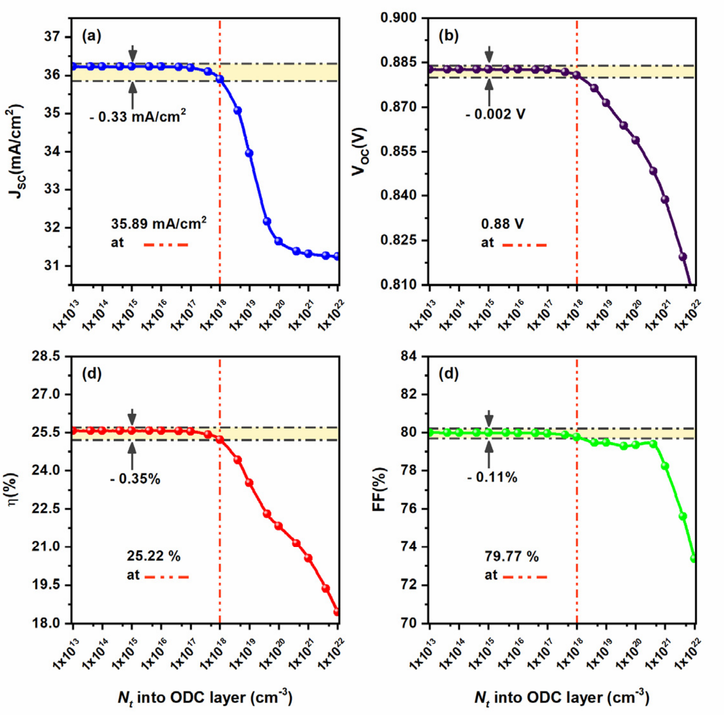

Figure 11. J-V characteristics versus defect concentration N_t into OCD layer

Effect of defect concentration into ODC Layer. Figure 11 summarizes the evolution of J-V characteristics against the change in defect concentration N_t within ODC layer from 10^{13} cm^{-3} to 10^{22} cm^{-3}; the important thing is that while increasing defect concentration from 10^{13} cm^{-3} to 10^{18} cm^{-3} there was slight decreases of 0.33 mA/cm^2, 2 mV, 0.11% and 0.35% in both J_{SC}, V_{OC}, FF and efficiency, respectively. After achieving considerable values of 35.89 mA/cm^2, 0.88 V, 79.77% and 25.22% (Figure 11) in both J_{SC}, V_{OC}, FF and efficiency, respectively, at defect concentration of 10^{18} cm^{-3}, all characteristics experienced deterioration down to their minimum values 10^{22} cm^{-3} of defect concentration. As a result, limiting the defect concentration 10^{13} cm^{-3} to 10^{18} cm^{-3} within the ODC layer leads the ZnO/CdS/ODC/CIGS P-HTFSC device to the best performance.

CONCLUSIONS

Through the present simulation study, the feasibility of CIGS material for thin film solar cell device has been investigated through numerical simulation using Scaps-1D software. CdS/CIGS heterojunction and ODC/CIGS pseudo-homojunction have been systematically investigated, and the influences of bandgap, thickness, carrier concentration, defect concentration and the performance of layers within the ZnO/CdS/ODC/CIGS P-HTFSC device have been discussed in more details. It was found that for a CdS/CIGS heterojunction, an efficiency of 25.57% can be obtained, with a CIGS layer at 4×10^{17} cm^{-3} of acceptor concentrations, 10^{13} cm^{-3} of defect concentration and 2 µm of thickness. And if an ODC layer is considered at the CdS/CIGS interface to form a new ODC/CIGS pseudo-homojunction, an efficiency of 25.22% can be obtained, with an ODC layer of 1013-1018 cm^{-3} of defect concentration and 100 nm of thickness. These results-out performances are very promising for further improvements for CIGS thin film solar cell.

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Credit author statement. Samah Boudour: Conceptualization, Methodology, Data curation, Original draft preparation Writing, Editing. Idris Bouchama: Data curation, Editing, Supervision.

Acknowledgments
The authors show recognition to the scientists, at the Department of Electronics and Information Systems (ELIS) of the University of Gent, Belgium, that developed the freely SCAPS-1D simulator.

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ДОСЛІДЖЕННЯ ПСЕВДОГОМОПЕРЕХОДУ CIGS ТОНКОПЛІВКОВОГО СОНЯЧНОГО ЕЛЕМЕНТА З ВИКОРИСТАННЯМ SCAPS-1D

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У цьому дослідженні повідомляється про моделювання продуктивності пошкодженої псевдогомоперехідної тонкоплівкової сонячної батареї CIGS (P-HTFSC) і визначаються її оптимальні параметри для високої продуктивності за допомогою програмного забезпечення SCAPS-1D при освітленні AM1.5 і робочій температурі 300 K. Щоб зосередити дискусію на оптимальних параметрах (товщині, концентраціях легування, концентраціях дефектів на глибині/інтерфейсі та ширині забороненої зони) для тонкоплівкових шарів ZnO, CdS, ODC та CIGS, було виконано моделювання поперечного перерізу (1D) на ZnO/CdS/ Пристрій ODC/CIGS P-HTFSC для отримання оптимальної структури, яка забезпечує високу ефективність перетворення світла в електрику. Чотири світлові характеристики J-V (струм короткого замикання: JSC, напруга холостого ходу: VOC, коефіцієнт заповнення: FF та ефективність перетворення: η) використовувалися як індикатори для оцінки характеристик пристрою. Результати моделювання показали, що для найкращої продуктивності пристрою CIGS P-HTFSC оптимальна товщина шарів CIGS і ODC повинна бути відповідно меншою за 2 мкм і декілька нм, тоді як оптимальна концентрація дефектів у шарі повинна становити 10^{13} cm^{-3}-10^{18} cm^{-3}, відповідно.

Ключові слова: CIGS, ODC, псевдогомоперехід, J-V характеристики, SCAPS-1D.