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New ultra thin CIGS structure solar cells using SCAPS simulation program

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ABSTRACT

The present contribution reports on the performances of ultra thin chalcopyrite Cu (In,Ga) Se (CIGS) solar cells. An alternative ZnO/CdS/CIGS/Si structure has been proposed using solar cell capacitance simulator (SCAPS). The main idea behind this analysis is the improvement of the device efficiency using materials cheaper than conventional CIGS. For that purpose, a 1 μm of a new layer p-Si has been added. Various thicknesses of CIGS absorber layer ranging from 0.1 to 1 μm have been used. Our findings showed that the increase of the absorber layer thickness leads to the improvement of the performance of the new CIGS solar cells. It was found that the best structure must have a window layer ZnO, a buffer layer (CdS), an absorbent layer (CIGS) and a Si layer with thicknesses of 0.02, 0.05, 1 and 1 μm, respectively. Cells with these features give conversion efficiency of 21.3%. The present results showed that the new ultra thin CIGS solar cells structure has performance parameters that are comparable to those of the conventional ones with reduced cost.

Introduction

Materials for thin film solar cells are currently the subject of multiple researches in order to reach the highest ratio efficiency/cost. Solar cells based on chalcopyrite materials are distinguished by their thick absorbent layer not exceeding 2 μm, but sufficient to absorb the useful part of solar spectrum. This reduces the cost of the solar cells and retains an acceptable performance compared to cells based on silicon which requires an absorber layer with a thickness of 200 μm. Polycrystalline chalcopyrite $Cu(In,Ga)Se_2$ (CIGS) is a very promising material for thin film photovoltaics and offers a number of interesting advantages compared to the bulk silicon devices [1]. Because of its appropriate band gap and high absorption coefficient for solar radiation [2], CIGS thin film solar cell has achieved the highest conversion efficiency of 20.4% [3]. In a CIS/CIGS model, the absorber acts as a p-type doped region [4], whereas the quaternary system $Cu(In,Ga)Se_2$ (CIGS) allows the band gap of the semiconductor to be adjusted over a range of 1.04–1.67 eV by adding the gallium content into the CIS model. Huang et al. reported that the optimum CIGS band gap is about 1.16 eV [5]. The inconvenience of using CIGS materials is the high cost of indium and gallium constituents. This has affected the use of CIGS thin film solar cells. In order to overcome this short coming, people have thought to reduce the thickness of CIGS absorber layer leading thus to the reduction in the use of indium and gallium. Based on numerical modeling and using 1 μm of CIGS absorber layer thickness, Amin et al. [6] have achieved an efficiency of 17.26%. On the experimental side, Vermang et al. [7] have employed Si solar cell technology at Ångström Solar Centre in

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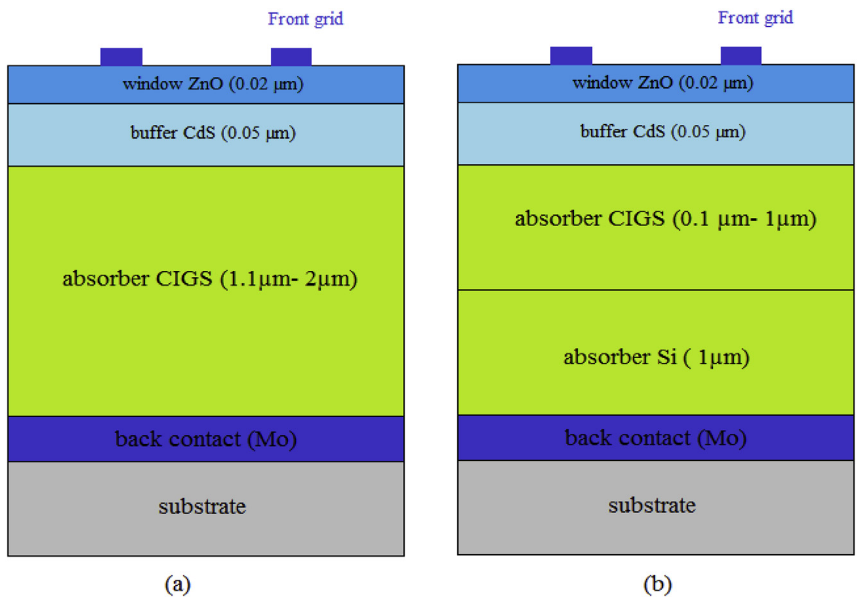

Fig. 1 – (a) Schematic view of CIGS solar cells (b) Schematic view of new ultra thin CIGS structure.

Sweden and increased the efficiency of ultra-thin $Cu(In,Ga)Se_2$ solar cells up to 13.5% using a CIGS absorber layer with a thickness of 0.385 μm. This efficiency is still remain smaller than those of conventional CIGS solar cells with an absorber layer thickness lying in the range 2.5–4 μm.

In the present work, an alternative structure of CIGS thin film solar cells is suggested. The one-dimensional SCAPS-1D simulator is used to analyze numerically the performances of the newly proposed ZnO/CdS/CIGS/Si thin film solar cells. We show how the device performance is affected by adding the new absorber layer of Si. We examine also the effect of operating temperature on both conventional and new ultra thin CIGS structures solar cells.

Device structure and simulation

In recent years, interests in numerical simulation have a great importance for the understanding and design of solar cells based on crystalline, polycrystalline and amorphous materials [8–11]. However, the major difficulty lies in the large number of parameters influencing the performance of thin film solar cells. SCAPS is a dimensional solar cell simulation program developed at the department of Electronics and Information Systems (ELIS) of the University of Gent, Belgium. Several researchers have contributed to its development: Alex Niemegeers, Marc Burgelman, Koen Decock, Johan Verschraegen, and Stefaan Degrave. A description of the program, and the algorithms it uses, can be found in the literature [12–17]. SCAPS is originally developed for cell structures of the $CuInSe_2$ and the CdTe family. Nevertheless, several extensions have improved its capabilities so that it is also applicable to crystalline solar cells (Si and GaAs family) and amorphous cells (a-Si and micromorphous Si) [12]. In the model, the absorber (CIGS) is a p-type [4], with a gap ranging from 1.00 to 1.70 eV, the junction is made between the $Cu(In,Ga)Se_2$ p-type and n-type CdS which has a gap of 2.45 eV and the window layer is formed from ZnO with a gap equal to 3.30 eV [18].

In the new structure we have added a new layer p-Si which has a gap of 1.12 eV. The effect of adding the new absorber layer on photovoltaic cell parameters has been examined using SCAPS computer software program [12]. Various thicknesses of CIGS absorber layer ranging from 1.10 to 2.0 μm have been used so as to investigate the performance of the new ultra thin CIGS structure solar cells. These solar cells consist of a Si and CIGS p-type as absorber layers with a thickness of 1 μm, deposited on molybdenum coated back glass substrate, an n-type buffer layer made of CdS with a thickness of 0.05 μm and a window layer that is made of n-ZnO with a thickness of 0.02 μm. A schematic view of the new cell structure is shown in Fig. 1(b).

The band alignment is one of the most important parameters that influences the current transport across the heterojunction and the performance of the solar cells. As a matter of fact, the band diagram of solar cells structure can be obtained by using SCAPS-1D software program. In this respect, the band diagram of the new ultra thin CIGS structure solar cells has been computed using SCAPS-1D code. Our results are displayed in Fig. 2. One can observe that there is a good band

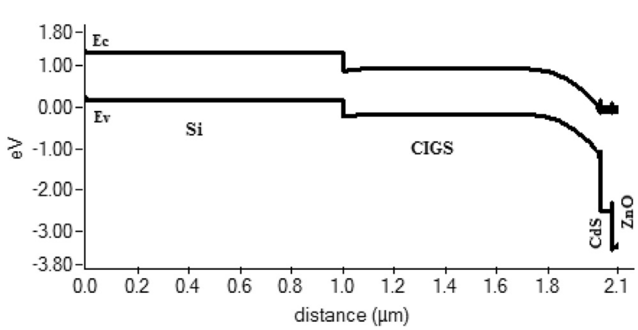

Fig. 2 – Band diagram for new ultra thin CIGS structure solar cells.

Table 1 – Physical parameters used in the simulation.

Parametres	n-ZnO	n-CdS	p-CIGS	p-Si
Bandgap, E_g (eV)	3.30	2.45	1.10	1.12
Electron affinity, X_e (eV)	4.60	4.40	4.50	4.05
Dielectric constant, ε_r	9	10	13.60	11.90
Density of states at conduction band, N_C (cm^{-3})	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}	2.8×10^{19}
Density of states at valence band, N_V (cm^{-3})	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	2.65×10^{19}
Electron mobility μ_n (cm^2/V_s)	100	100	100	1450
Hole mobility, μ_p (cm^2/V_s)	25	25	25	500
Electron and hole concentration, n, p (cm^{-3})	1×10^{20}	1×10^{20}	2×10^{6}	1×10^{20}
Defect density (cm^{-3})	1×10^{14}	1×10^{14}	1×10^{14}	1×10^{14}

alignment between Si and CIGS absorber layers. It should be noted that the defect is taken into account in each layer as well as in the interface between $Cu(In,Ga)Se_2$(CIGS) and Si. The defect density in each layer is taken to be 10^{14} cm^{-3}. CdS is normally used as a buffer. The semiconductor parameters of each layer used in the simulation are shown in Table 1.

Results and discussion

The SCAPS program has been used so as to simulate the behavior of ultra thin chalcopyrite Cu(In,Ga)Se (CIGS) solar cell with a reduction in the thickness of the absorbing layer

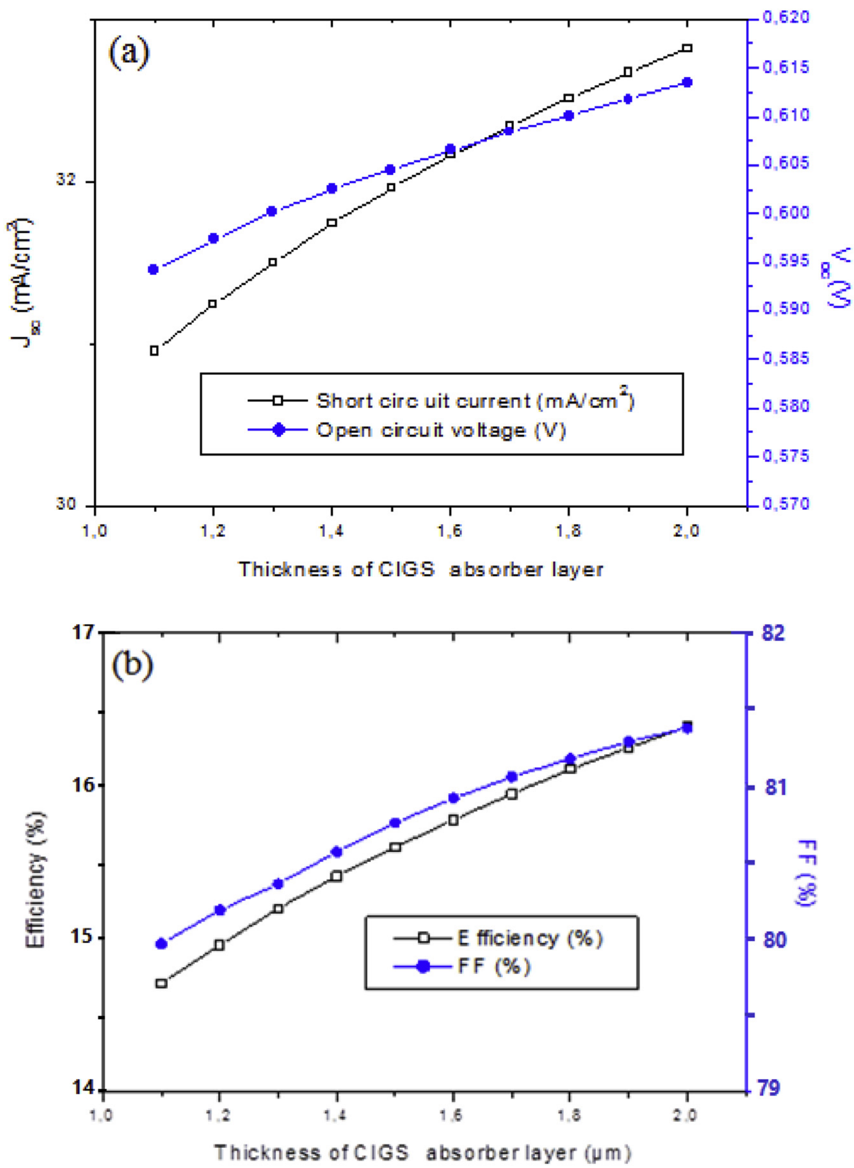

Fig. 3 – (a) Variation of J_{SC} and V_{OC}, (b) Variation of efficiency and FF as a function of CIGS thickness.

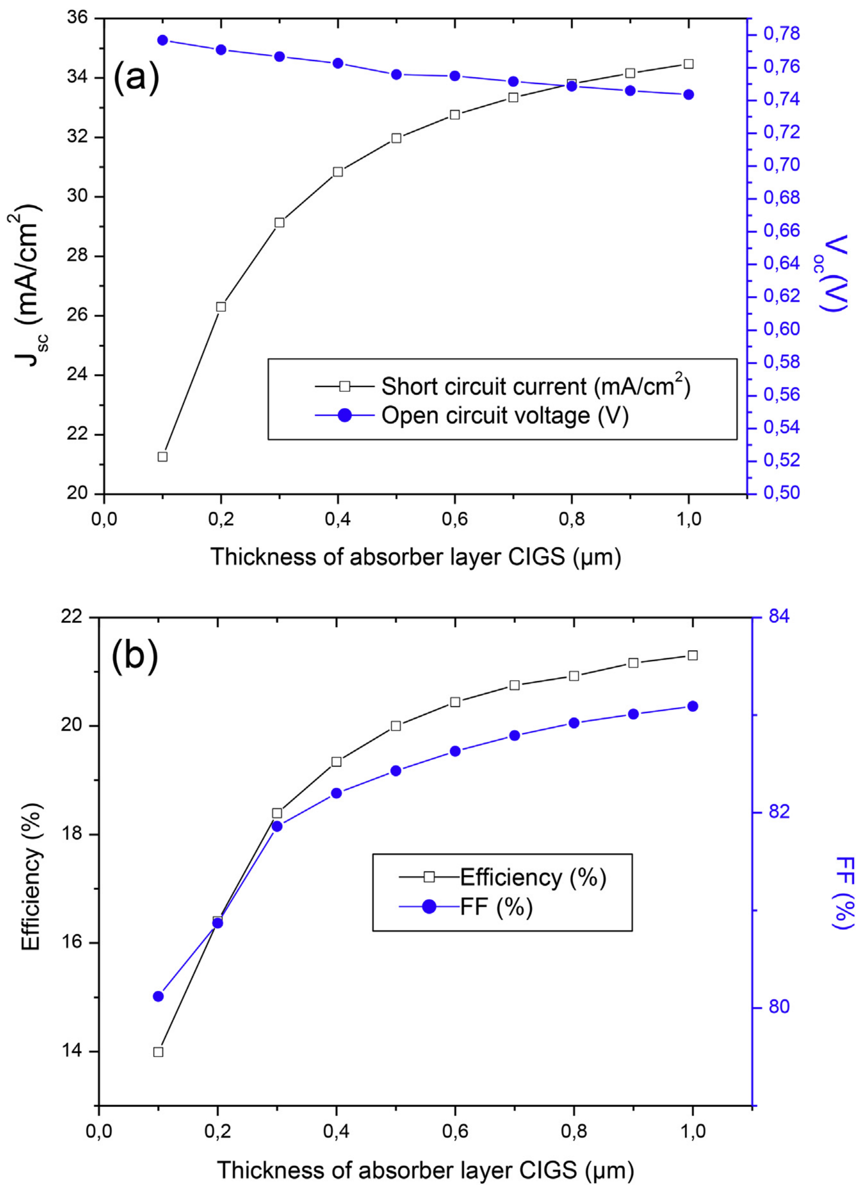

Fig. 4 – (a) Variation of J_{SC} and V_{OC}, (b) Variation of efficiency and FF as a function of new solar cell CIGS thickness.

Cu(In,Ga)Se and to show the effect of adding a new layer p-Si on the device performance. In both structures, we have investigated the influence of the thickness of CIGS layers on the photovoltaic cell parameters. The structure has been studied under solar spectrum AM 1.5 with an incident solar power of $P = 1000\ W/m^2$ and at a temperature of 300 K. The simulation of the photovoltaic parameters has been made considering a nul series and an infinitely large shunt resistances.

Table 2 – Comparison between performances of solar cells with and without Si.

PV performance parameters	Solar cell with Si layer (2 μm)	Solar cell without Si layer (2 μm)
Efficiency (%)	21.3	16.39
FF (%)	83.09	81.38
Jsc (mA/cm^2)	34.47	32.82
Voc (V)	0.7436	0.6135

Thickness optimization of CIGS absorber layer

The conventional ultra thin CIGS structure with CdS buffer layer has been checked in terms of CIGS absorber layer. Fig. 3 shows the effect of the thickness of Cu(In,Ga)Se absorber layer on the cell performance. In the present contribution, the thickness of the CIGS absorber layer was varied from 1.1 up to 2 μm using SCAPS (one dimensional solar cell simulation program). When the CIGS absorber layer thickness increases, a large number of photons are absorbed. This leads to an increase in the efficiency from 14.71% for a thickness of 1.1 μm to a 16.39% for a thickness of 2 μm with a fill factor (FF) of 81.38%, open circuit voltage (V_{OC}) of 0.6135 V and a short circuit current density (J_{SC}) of 32.83 mA/cm^2. Note that the values of Voc and Jsc are increased. It is also understood that both Voc and Jsc values will be reduced when the thickness of the absorber layer is reduced. This may be caused by the recombination process at the back contact of the solar cell. If the absorber layer thickness is reduced, the back contact will be very close to the depletion region [23].

Thickness optimization of CIGS absorber layer for new ultra thin CIGS structure solar cells

By adding 1 μm of the new layer Si of p-type, the efficiency has been increased from 16.39% for conventional ultra thin CIGS structure to 21.3% for the new structure. The main reason can be traced back to the increase of the thickness of the layer of p-type. According to Fig. 4, the cell efficiency increases when the absorbing layer is thicker. In this simulation, the thickness of the CIGS absorber layer was varied from 0.1 to 1 μm, while other input parameters are kept unchanged. Our findings showed that for a thickness of 1 μm, an efficiency of 21.3% has been achieved. This is primarily due to the fact that when the absorber layer is thicker, most of the photons can be absorbed and hence more electron–hole pairs are generated. This increases J_{SC} from 21.26 to 34.47 mA/cm^2 and decreases slightly V_{OC} from 0.7668 to 0.7436 V leading thus to the improvement of the efficiency. The performances of both solar cells with and without Si are summarized in Table 2. Considering the high cost of indium and gallium materials in CIGS solar cells [24,25], it would not be advisable to produce CIGS solar cells with very large absorber thickness. Thus, by reducing the thickness of CIGS solar cells, we reduce the use of indium and gallium materials which reduces the cost. Hence, a compromise between cell efficiency and cost is needed for mass production. Therefore, with our new ultra thin solar cells CIGS that use silicon which is cheaper compared to indium and gallium materials, a compromise between cost and efficiency can be achieved. This can help a lot in the development of industry and the manufacture of solar cells. The quantum efficiency is the ratio of the number of charge carriers passing through the external circuit to the number of incident carriers. For a given wavelength, the external quantum efficiency is equal to 1 if each photon generates a pair electron–hole. The effect of thicknesses of the CIGS layer on quantum efficiency of the cells in the new structure has also been analyzed. Fig. 5 displays the quantum efficiency (QE) of the solar cell structure (ZnO/CdS/CIGS/Si) with different CIGS layer thicknesses. Note that QE of CIGS/Si solar cell increases with increasing the absorber layer thickness. In fact, more photons are absorbed when the absorber layer thickness is increased [26].

Effects of operating temperature on ultra and new ultra thin CIGS structure solar cells

Among the most important things in the performance of the solar cells is the investigation of the effect of operating temperature on ultra thin CIGS structure. The study of the behavior of solar cells with temperature (T) is important since in terrestrial applications [19] they are generally exposed to temperatures ranging from 15 °C (288 K) to 50 °C (323 K) and to even higher temperatures in space and concentrator-systems [20]. The performance of a solar cell is influenced by temperature since its performance parameters, viz. Voc, Jsc, FF and efficiency are temperature dependent [21]. Fig. 6 shows the variation of both J_{SC} and V_{OC} as a function of temperature for both solar cells with and without Si layer. We observe that J_{SC} increases with increasing temperature. This is due to the reduction of the band-gap energy. As a result more photons will have enough energy to create electron–hole pairs. On the other hand, we note that V_{OC} decreases with raising temperature. The decrease of the V_{OC} with increasing temperature lies in the fact that V_{OC} depends directly on the saturation current which in turn decreases rapidly with increasing temperature. The efficiency of ultra thin CIGS structure solar cells is decreasing when the temperature is increased as

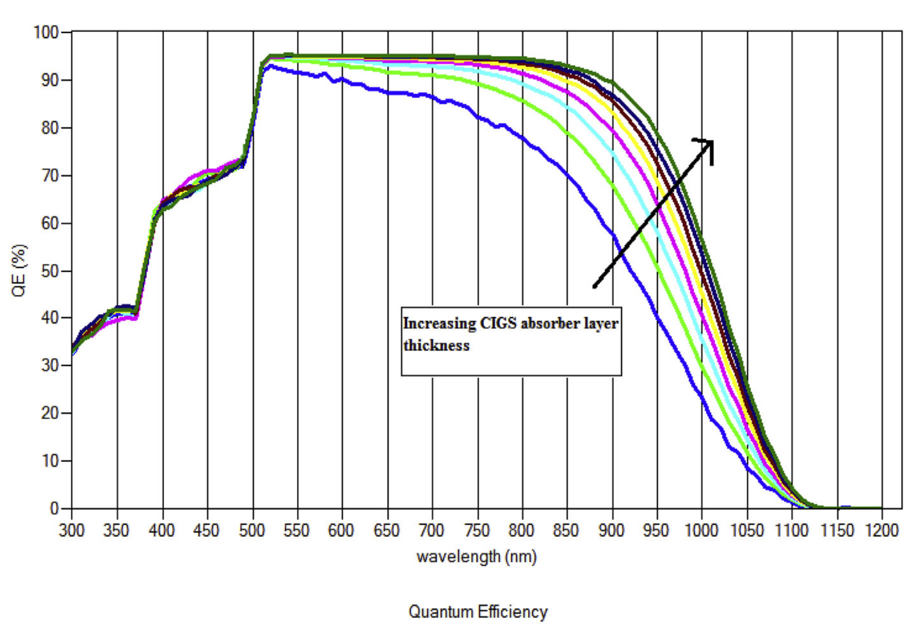

Fig. 5 – Spectral response of the new ultra thin CIGS structure solar cells with various thicknesses of CIGS absorber layers.

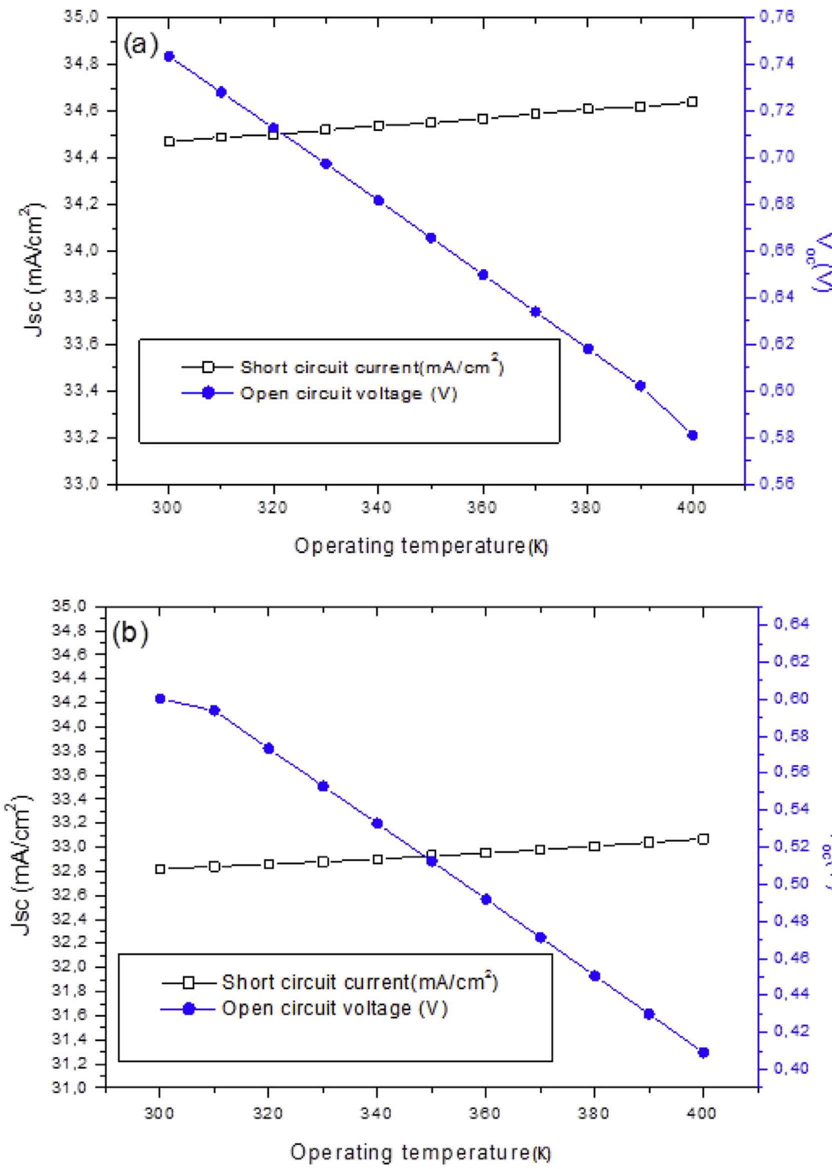

Fig. 6 – Variation of J_{SC} and V_{OC} as a function of operating temperature for (a) new ultra thin cell, (b) conventional ultra thin CIGS solar cells.

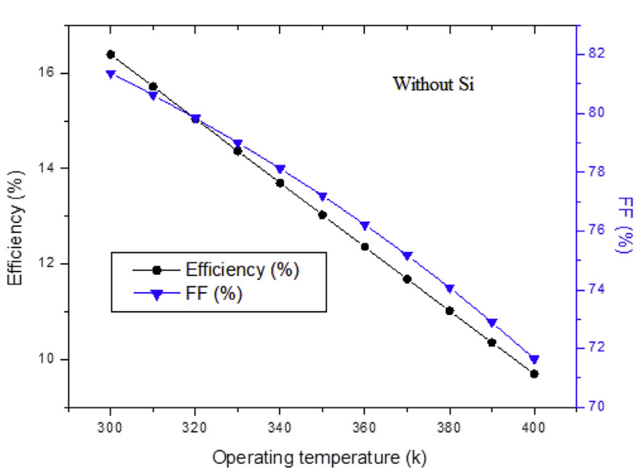

Fig. 7 – Ultra thin cell performance with various operating temperatures for CIGS cells.

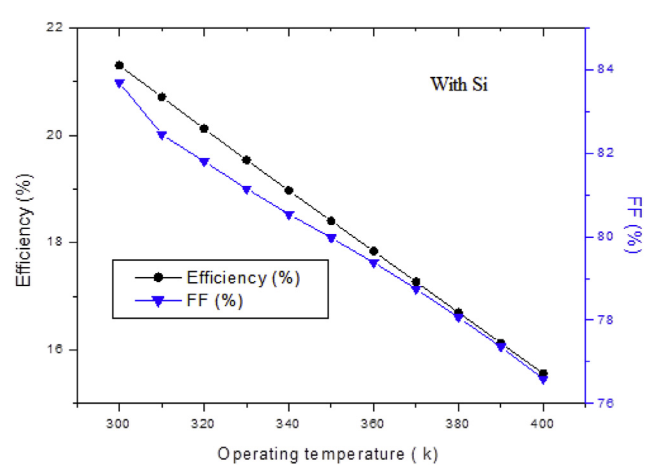

Fig. 8 – New ultra thin cell performance with various operating temperatures for CIGS cells.

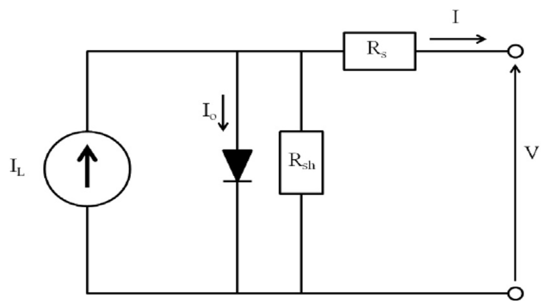

Fig. 9 – Equivalent circuit of an ideal cell under illumination [29].

displayed in Fig. 7. Similar trend can be seen for the new ultra thin CIGS solar structure from Fig. 8. At higher temperatures, parameters such as the electron and hole mobilities, carrier concentrations and band gaps of the materials would be affected which results in lower efficiency of the cells [22].

Table 3 – Comparison between efficiencies of solar cells with and without Si.

Rs (Ω cm^2)	Solar cell with Si layer (2 μm) (%)	Solar cell without Si layer (2 μm) (%)
0	21.3	16.39
1	20.23	15.45
2	19.17	14.52
3	18.12	13.61
4	17.08	12.70
5	16.06	11.88

Effect of series resistance (R_s) on solar cell device

SCAPS software program allows one to explore the effect of series and shunt resistances on solar cell device. The series resistance is due to the bulk resistance, the resistance of the metallic contacts of the front- and back surface and further circuit resistances from terminals and also from connections. The parallel resistance is caused by leakage currents. A p–n junction non-idealities and impurities near the junction causes

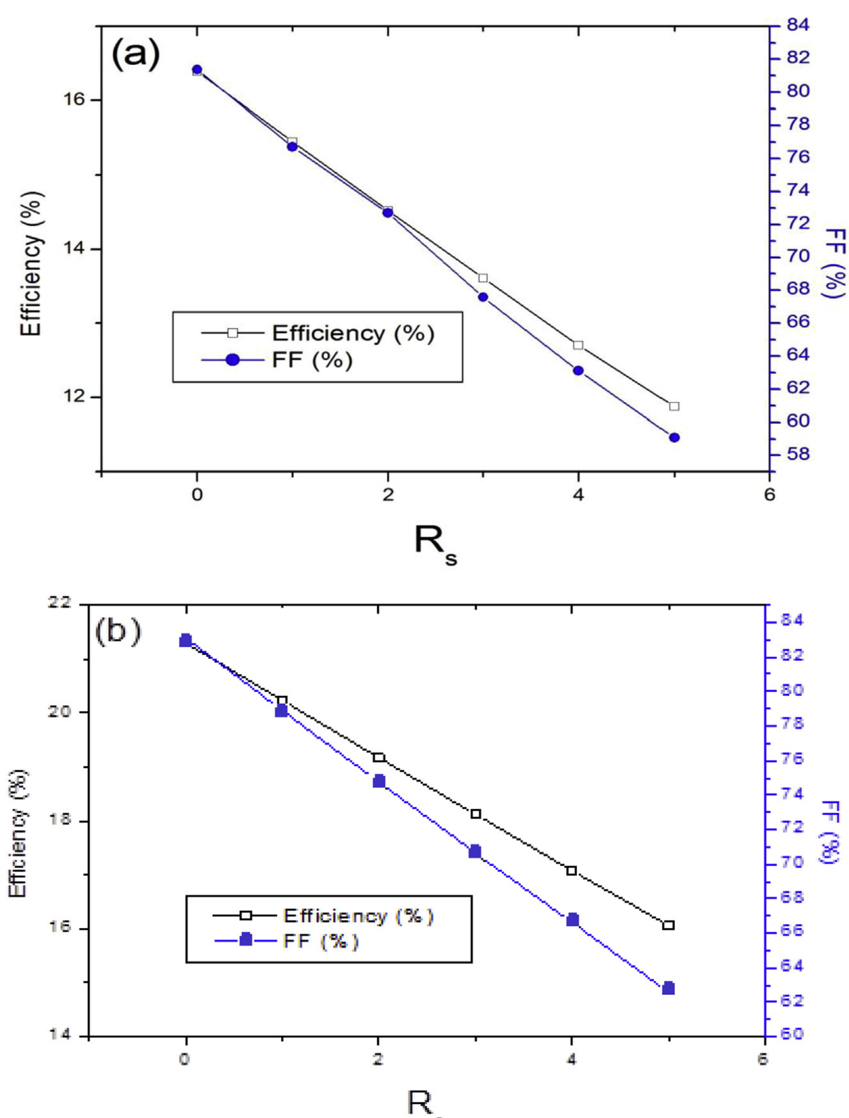

Fig. 10 – Efficiency as a function of series resistance (R_S) for (a) conventional ultra thin CIGS solar cells (b) new ultra thin cell.

partial shorting of the junction, particularly near the cell edges [27]. In order to reach the goal of obtaining high efficiency, it is better to obtain low series and high shunt resistances. Jsc and Voc are both affected. It is impossible to get a 100% FF. This is due to imperfect diode behavior of a solar cell, even if we can achieve a zero series resistance (Rs) and an infinitely large shunt resistance (Rsh) [28]. Using an equivalent circuit shown as a model of a solar cell (see Fig. 9) and including the Shockley diode (equation (1)), we can deduce an equation (2) which represents well the effects of resistive losses [29]. This equation is important for the understanding solar cells.

$$I = I_0 \left(e^{\frac{Vj}{n\,V_0}} - 1 \right) \tag{1}$$

where I is the current drawn from the cell, I_0 is the reverse saturation current, V_j is the voltage across the diode, V_0 is the thermal voltage, and n is the ideality factor.

$$I = I_L - I_0 \left(e^{\frac{q(V+IR_s)}{kT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \tag{2}$$

where I_L is the light induced current, R_S is the series resistance, k is the Boltzman constant, T is the temperature and q is the charge of the electron.

In order to see the effect of Rs on the solar cell parameters, such as FF and efficiency of both new and conventional CIGS solar cells under illumination, Rs has been varied between 0 and 5 Ω cm^2. Our results are illustrated in Fig. 10. Note that the efficiency of the new and conventional CIGS solar cells are affected rapidly by increasing the value of Rs. For conventional ultra thin CIGS solar cells and for values of 0 and 5 Ω cm^2, we get efficiencies of 16.39% and 11.88%, respectively. However, for a new ultra thin cell and for the same values of Rs, i.e. 0 and 5 Ω cm^2, we get efficiencies of 21.3% and 16.06%, respectively. This indicates that the increase of R_S affects significantly the efficiency and FF of both solar cells with and without Si. Table 3 shows the efficiencies as a function of R_S for solar cells with and without Si.

Conclusion

In summary, the addition of silicon absorber layer in Cu (In,Ga)Se (CIGS) solar cell, influences in a remarkable way on the characteristics and the electrical performance of the solar cell. The performance of CIGS solar cells has been improved as far as the absorber layer thickness is increased. It was found that a best structure must have a window layer of thickness of 0.02, a buffer layer (CdS) with a thickness of 0.05 and an absorbent layer which contains CIGS and a Si with thicknesses of 1 μm for each of them. Cells with these features give conversion efficiencies of 21.3%. Our study suggested a new ultra thin CIGS solar cells structure with Si which have performance parameters comparable to those of conventional CIGS solar cells (without Si), but with reduced cost.

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REFERENCES

[1] Movla H. Optimization of the CIGS based thin film solar cells: numerical simulation and analysis. Optik 2013;124:5871–3.
[2] Wada T, Hashimoto Y, Nishiwaki S, Satoh T, Hayashi S, Negami T, et al. High-efficiency CIGS solar cells with modified CIGS surface. Sol Energy Mater Sol Cells 2001;67:305–10.
[3] Khoshsirat N, Amziah Md Yunus N, Nizar Hamidona M, Shafie S, Amin N. Analysis of absorber layer properties effect on CIGS solar cell performance using SCAPS. Optik 2015;126:681–6.
[4] Pudov AO, Kanevce A, Al-Thani H, Sites JR, Hasoon FS. Secondary barriers in CdS–$CuIn_{1-x}Ga_xSe_2$ CdS–$CuIn_{1-x}Ga_xSe_2$ solar cells. J Appl Phys 2005;97:1063–9.
[5] Huang CH, Li SS, Anderson TJ. Device modeling and simulation of CIS-based solar cells. In: 29th IEEE photovoltaic specialist conference; 2002. p. 748–51.
[6] Amin N, Chelvanathan P, Istiaque Hossain M, Sopian K. Numerical modelling of ultra thin Cu(In,Ga)Se2 solar cells. Energy Procedia 2012;15:291–8.
[7] Vermang B, Timo Wätjen J, Fjällström V, Rostvall F, Edoff M, Kotipalli R, et al. Employing Si solar cell technology to increase efficiency of ultra-thin Cu(In,Ga)Se2 solar cells. Prog Photovolt Res Appl 2014;22:1023–9.
[8] Morales-Acevedo A, Hernández-Como N, Casados-Cruz G. Modeling solar cells: a method for improving their efficiency. Mater Sci Eng B 2012;177:1430–5.
[9] Aissat A, El beya M, Bestam R, Vilcot JP. Modeling and simulation of $Al_xGa_yIn_{1-x-y}As$/InP quaternary structure for photovoltaic. Int J Hydrogen Energy 2014;39:15287–91.
[10] Wang Dong Lin, Cui HuiJuan, Su Gang. Modeling method to enhance the conversion efficiency by optimizing light trapping structure in thin-film solar cells. Sol Energy 2015;120:505–13.
[11] Arbouz H, Aissat A, Vilcot JP. Modeling and optimization of CdS/$CuIn_{1-x}Ga_xSe_2$ structure for solar cells applications. Int J Hydrogen Energy 2016;41:20987–92.
[12] Burgelman M, Nollet P, Degrave S. Modelling polycrystalline semiconductor solar cells. Thin Solid Films 2000;361:527–32.
[13] Decock K, Khelifi S, Burgelman M. Modelling multivalent defects in thin film solar cells. Thin Solid Films 2011;519:7481–4.
[14] Burgelman M, Marlein J. Analysis of graded band gap solar cells with SCAPS. In: Proceedings of the 23rd European photovoltaic solar energy conference; 2008. p. 2151–5.
[15] Verschraegen J, Burgelman M. Numerical modeling of intra-band tunneling for heterojunction solar cells in SCAPS. Thin Solid Films 2007;515:6276–9.
[16] Degrave S, Burgelman M, Nollet P. Modelling of polycrystalline thin film solar cells: new features in SCAPS version 2.3. In: Proceedings of the 3rd world conference on photovoltaic energy conversion; 2003. p. 487–90.
[17] Niemegeers A, Burgelman M. Numerical modeling of ac-characteristics of CdTe and CIS solar cells. In: Proceedings of the 25th IEEE photovoltaic specialists conference; 1996. p. 901–4.
[18] Wagner S, Shay JL, Migliorato P, Kasper HM. CuInSe2/CdS heterojunction photovoltaic detectors. Appl Phys Lett 1974;25:434–5.
[19] Sze SM. Physics of semiconductor devices. New York: John Wiley &Sons; 1981.
[20] Landis G, Rafaelle R, Merritt D. High temperature solar cell development. In: 19th European photovoltaic science and engineering conference, Paris, France; June 7-11, 2004.
[21] Singh P, Singh SN, Lal M, Husain M. Temperature dependence of I–V characteristics and performance

parameters of silicon solar cell. Sol Energy Mater Sol Cells 2008;92:1611–6.

[22] Nakada T, Mizutani M. 18% efficiency Cd-free Cu(In,Ga)Se_2 thin film solar cells fabricated using chemical bath deposition (CBD)-ZnS buffer layers. Jpn J Appl Phys 2002;41:L165–7.

[23] Chelvanathan P, Hossain MI, Amin N. Performance analysis of Copper-Indium-gallium-diselenide (CIGS) solar cells with variais buffer layers by SCAPS. Curr Appl Phys 2010;10:5387–91.

[24] Tanaka K, Oonuki M, Moritake N, Uchiki H. Thin film solar cells prepared by non-vacuum processing. Sol Energy Mater Sol Cells 2009;93:583–7.

[25] Jimbo K, Kimura R, Kamimura T, Yamada S, Maw WS, Araki H, et al. Cu2ZnSnS4-type thin film solar cells using abundant materials. Thin Solid Films 2007;515:5997–9.

[26] Amin N, Sopian K, Konagai M. Numerical modeling of CdS/CdTe and CdS/CdTe/ZnTe solar cells as a function of CdTe thickness. Sol Energy Mater Sol Cells 2007;91:1202–8.

[27] Azzouzi G. Study of silicon solar cells performances using the impurity photovoltaic effect. Ph.D Thesis. Setif: Université Ferhat Abbas; 2012.

[28] Simya OK, Mahaboobbatcha A, Balachander K. A comparative study on the performance of Kesterite based thin film solar cells using SCAPS simulation program. Superlattices Microstruct 2015;82:248–61.

[29] Fink JE. Fine line metallization of silicon heterojunction solar cells via collimated aerosol beam direct write. Master of science. North Dakota State University of Agriculture and Applied Science; 2012.