INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
N.Touafek et al., Vol.4, No.4, 2014

Back Surface Recombination Effect on the Ultra-Thin CIGS Solar Cells by SCAPS

N. Touafek*[‡], R. Mahamdi**

*Department of Electronics, Faculty of engineering, University Constantine-1, B.P. 325 Route Ain El Bey Constantine 25017, Algeria.
**Department of Electronics, Faculty of Technology, Hadj Lakhdar University Batna, Avenue chahid Boukhlouf, Batna5000, Algeria.
(ntouafek@yahoo.fr, ra_mahamdi@yahoo.fr)

[‡] Corresponding Author; N. Touafek, University Constantine-1, B.P. 325 Route Ain El Bey Constantine 25017, Algeria, Tel: +213 91400637, e-mail: ntouafek@yahoo.fr

Received: 15.09.2014 Accepted: 07.11.2014

Abstract- The impact of the back surface recombination velocity (S_R) and the presence of the Electron Back Reflector (EBR) on the performance of CIGS solar cell when varying the absorber thickness from 0.3 to 2 µm is illustrated by the diverse results obtained by simulation using SCAPS. The variation of the EBR and S_R affects the thinner devices more than the thick ones. The gain in efficiency due to the reducing S_R is increased as the absorber thickness is reduced. The results revealed that for thin CIGS absorbent layer less than 1µm the efficiency increases by 1-3% depending on the thickness if the S_R is reduced to lower than 10^3 cm/s. This leads to enhance the V_{oc} and efficiency which become comparable to those obtained for standard devices (2µm). For high S_R the electron back reflector plays much more significant role and becomes beneficial. However the high band gap of EBR does not necessary result in high performance where the results show that 0.2 eV of EBR height is sufficient to enhance the performance. Independently to the absorber thickness the efficiency increased sharply, especially for thinner device, when an EBR with thickness around 5% corresponding of the total CIGS thickness was added at the back surface. The gain in efficiency increases as the thickness of the layers is reduced and reaches the same levels as the standard devices. As the thickness of EBR is increased, the reduction of J_{sc} is fairly recovered by the augmentation of V_{oc} which leads to a slight reduction in efficiency especially for thinner device.

Keywords—Cu(In,Ga)Se_2; Solar cell; Back Surface Velocity; EBR; SCAPS-1D.

1. Introduction

Thinning the absorber layer without adversely altering the solar cell performances remain the main goal of PV research [1, 2]. Reducing the thickness of the active layer solar cell is a promising technology which permits to save material, decrease the process time, the energy needed to produce the solar cell and therefore decreases the production cost. Cu(In,Ga)Se_2 is an excellent material for high-efficiency thin-film solar cells, it has high absorption coefficient ($10^5 cm^{-1}$) [3] which permits to 0.5 µm of the absorber to absorb most than 90 % of the incident photons. It can, therefore, reduce again the thickness of CIGS absorber layer, which makes it a promising material for the next generation thin film photovoltaic [4-5]. CIGS absorber today have a typical thickness of about 1.5-2 µm [6]. Various researches have reported the impact of the thickness of CIGS absorber layer less than 1µm on the cells parameters. The results show that as the thickness of the absorber is reduced the efficiency decreases. The experimental results [7, 8] revealed that the current density in thinner CIGS layers is lowered due to the reduction in absorption of sunlight. Besides, if the thickness is strongly reduced, the depletion region becomes very close to the back contact and therefore the recombination of electrons will increase and influence strongly the performance. In order to produce thin absorbers without significant losses in the cell, the risk for the carriers' recombination at the back surface must be mitigated. This risk can be minimized by passivating the CIGS back contact by:

- Building an electrical field (Electron Back Reflector (EBR)) into the material that bends the respective energy band such that the carriers are repelled from the interface keeping the photoelectrons away from the CIGS/Mo interface.
- Reduced back contacting area by combining a rear surface passivation layer and nano-sized local point contacts [9, 10].

The purpose of this work is to examine using SCAPS-1D [11] simulation package, the influence of the back surface velocity, as well as the effect of the height of EBR and its thickness on the performance of CIGS solar cell when the thickness of the active layer is reduced.

2. Device simulation details

2.1. CIGS Cell Structure

The sutructure of the CIGS PV cell considered in our simulation is depicted in Fig.1. It is consists of: substrate soda lime glass (SLG); a Molybdenum (Mo), to realize an ohmic back contact; a p-CIGS absorber layer; thin layer of which is usually intentionally made Cu-poor named the Surface Defect Layer (SDL); an n-type buffer layer; typically CdS [12]; an undoped ZnO layer namely a transparent conduction oxide (TCO), and an ZnO:Al transparent front contact that has the same parameters of i:ZnO except the doping concentration which equal to 10^{20} (cm^{-3}). Metallic Ni/Al contact grids complete the cell.

2.2. Numerical Modelling

The merit of the numerical methods is to test and predict the results and the influence of the process parameters on the device without fabrication. In this work, The CIGS solar cells are modeled using the latest version (3.0.0.2) of SCAPS [11,13,14] to study the effect of the variation of the back surface velocity and the introduction of the Electron Back Reflector (EBR) at the back contact on the electrical parameters solar cells for different thickness of absorber (CIGS). This numerical simulation programme, developed at the university of Gent [15], allows the definition of thin-film solar cell devices stacks of layers with a large set of parameters and solves for each point the fundamental solar cell equations: the Poisson equation and the continuity equations for electrons and holes . Definable parameters include the thickness, doping, defect and interface state densities and cross-sections, the optical absorption coefficient, the band-gap and the electron affinity. Furthermore, many of the properties can be specified as gradients of various forms. The Shockley-Read-Hall (SRH) model is used to describe the recombination currents in deep bulk levels. However, an extension of this model describes the defects at the interface [16]. All the bulk defects are at mid gap of the layers [17]. The parameters of cell are simulated under standard illumination AM1.5 and at temperature of 300 K. All electrical properties of SDL were chosen similar to the bulk except the band-gap, doping, and the carrier mobilities. Lower mobilities were chosen since this layer could be more disordered than the bulk material.

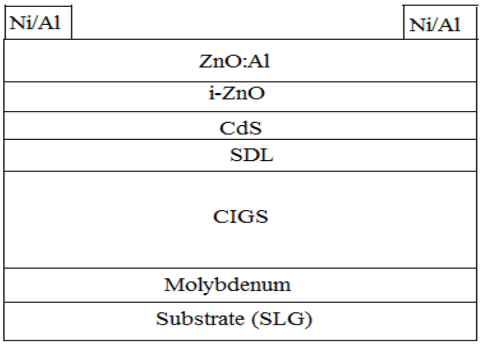

Fig. 1. Schematic structure of CIGS solar cells (layer thicknesses not to scale).

3. Results and Discussion

The current-voltage (J-V) results from simulation using the parameters given in table 1 with a back surface velocity equal 10^7 cm^2/s are compared with measurement data from [18] in the Fig.2. The results show that the measured JV curve is very well reproduced by the parameters model which validates our set of parameters as a baseline for simulating the effect of the S_R and the EBR on solar cell performance.

3.1. Effect of Variation of Back Surface Velocity

The recombination velocity at the CIGS/Mo interface has a typical value equal to 10^6 cm/s [10] which will enhance the recombination velocity S_R at the back surface. So, it is desirable to reduce the S_R which at the CIGS/substrate interface can be minimized at less than 10^2 cm/s using atomic-layer-deposited Al_2O_3 and CBD of CdS to generate nano-sized local rear point contacts [9, 10]. In the thin absorber layer compared to the thick ones the back contact and the depletion region become very close to each other which enhance the probability of the recombination carriers at the back contact. This explains the importance of the study of the effect of the S_R on the solar cell performance when

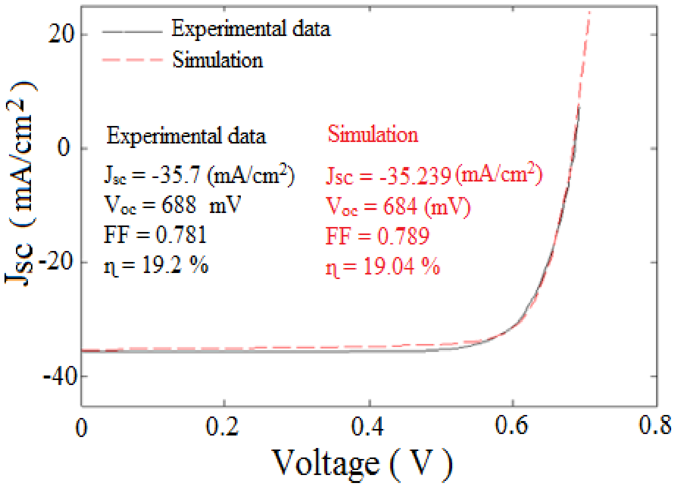

Fig. 2. Comparison between the (J-V) curves for the simulated and the reported experimental data[18].

Table 1. CIGS solar cell input parameter values used for this simulation.

Layer properties				
	CIGS	SDL	CdS	i: ZnO
W (µm)	2	0.015	0.05	0.2
Eg (eV)	1.15	1.3	2.4	3.3
χ (eV)	4.5	4.5	4.45	4.55
$\varepsilon/\varepsilon_0$	13.6	13.6	10	9
N_c (cm^{-3})	$2*10^{18}$	$2*10^{18}$	$1.3*10^{18}$	$3.1*10^{18}$
N_v (cm^{-3})	$1.5*10^{19}$	$1.5*10^{19}$	$9.1*10^{18}$	$1.8*10^{19}$
ν_n (cm/s)	$3.9*10^{7}$	$3.9*10^{7}$	$3.1*10^{7}$	$2.4*10^{7}$
ν_p (cm/s)	$1.4*10^{7}$	$1.4*10^{7}$	$1.6*10^{7}$	$1.3*10^{7}$
μ_n (cm^2/Vs)	100	10	72	100
μ_p (cm^2/Vs)	12.5	1.25	20	31
doping (1/ cm^{-3})	$1*10^{16}$ (a)	$1*10^{13}$ (a)	$5*10^{17}$ (d)	$1*10^{17}$ (d)
Bulk defects properties				
N (cm^{-3})	$1.1*10^{14}$ (d)	$1.1*10^{14}$ (d)	$5*10^{16}$ (a)	$1*10^{16}$ (a)
σ_n (cm^2)	10^{-13}	10^{-13}	10^{-15}	10^{-15}
σ_p (cm^2)	10^{-15}	10^{-15}	$5*10^{-13}$	$5*10^{-13}$
Interface properties				
	SDL/ CIGS	SDL/ CdS		
N (cm^{-3})	10^{11}	$3*10^{13}$		
σ_n (cm^2)	10^{-15}	10^{-15}		
σ_p (cm^2)	10^{-15}	10^{-15}		

varying the thickness of absorber from 0.3 to 2µm. The band gap of the absorber is kept constant equal 1.15 eV to exclude the rear surface passivation effects caused by the quasi-electrical field created by a G_a gradient. In Figure 3 we have reported the simulation results of the parameters efficiency, FF, V_{oc} and J_{sc} versus S_R for different thickness of the absorber. Initially, for standard back surface recombination $S_R = 10^7$ cm/s, all of the cell parameters are reduced when reducing the thickness of CIGS layer [19], which is mainly caused by: the absorption of light that starts to get incomplete and, in thinner layers, the high recombination at the CdS/CIGS interface due to the reduction of the bend bending that leads to shift the Fermi level towards mid-gap. Thus, the current density J_{sc} decreases. The thinner absorber layer is significantly affected by the S_R. The efficiency varies exponentially with decreasing S_R where the gain increases by about 1% to 3% depending on the thickness, and below $S_R=10^3$ cm/s the efficiency flattened out. However, for thick layer (beyond 1µm) no significant variation as function of S_R for all performance parameters, since 1.5 µm is enough to absorb all the solar spectrum incident photons [20]. Decreasing the back surface velocity improves the open circuit voltage, fill factor leading to an increase in the efficiency of the cell. The fact that V_{oc} and FF are significantly influenced by this parameter could be explained by the reduction of the recombination at the depletion region which becomes closer to the back surface and the drop of FF for thinner layer below 10^4 cm/s can be attributed to the increase in the series resistance. However, a no significant variation in short circuit current can be observed especially when the layers become lower than 0.5 µm. This is because most of the carriers are created in the CIGS Space Charge Region (SCR) and are collected by the drift field. The short circuit current increases by only about 0.5-1% shifting the thicknesses from 0.3 to 1 µm. When the thickness of the absorber is reduced, the effect of the S_R at the back surface becomes important, and at lower S_R the efficiency and V_{oc} for layers below 1 µm exceeded that of the thick ones.

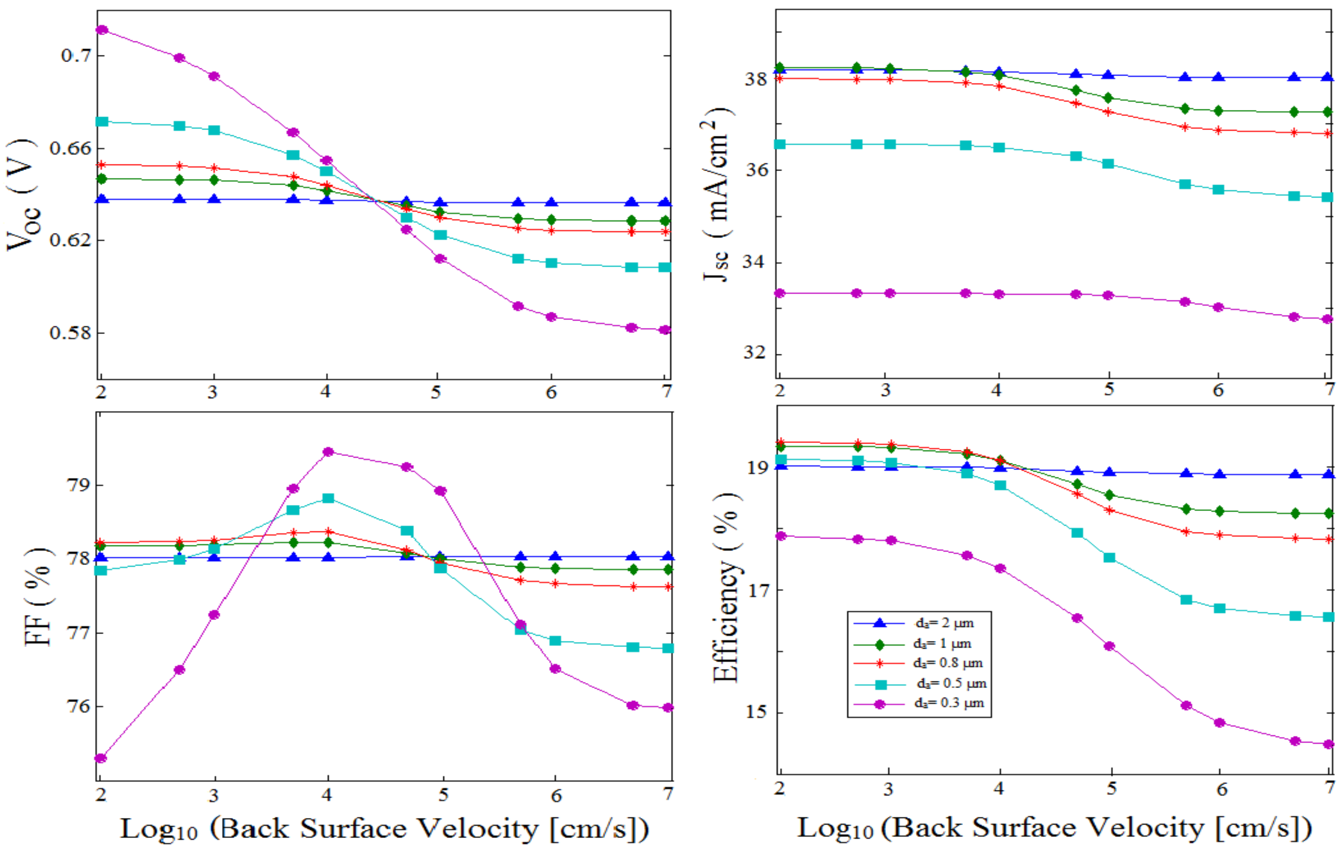

Fig. 3. The performance parameters variation of CIGS solar cell: as a function of CIGS absorber layer thickness and back surface recombination velocity.

3.2. Influence of the Characteristic Parameters of the EBR

In the CIGS solar cells, varying the Ga content leads to change the level of the conduction band and therefore the absorber band gap. To mitigate back-contact recombination for CIGS absorbers, a thin layer that has a band gap higher than the rest of the absorber was added towards the back of the absorber. This layer, referred to as electron-back reflector (EBR), reflects the electrons and keeps them away from the back contact. The difference between band gaps in the EBR layer and the rest of the absorber present the electron back reflector height. The influence of the height of EBR and its thickness denoted by W_{EBR}, added at the back surface, on the all performances of cell are studied.

3.2.1. Electron Back Reflector Height

We investigate the EBR height influence on the performance of the cell for different thickness of absorber. For this purpose, the height of elctron back reflector was varied by varying the band gap of the thin Ga-rich layer whose thickness is fixed at 15 % of the total thickness of the absorber. Figure 4 shows the role of both back-reflector height and back surface recombination velocity in determining the electrical parameters of cell for different thickness of absorber. We can see that the back-reflector height influence strongly the electrical parameters (V_{oc}, FF, and efficiency) especially for high back surface velocity. It is clear from the plot that the back reflector benefit is smaller when the S_R in CIGS solar cell is less than 10^3 cm/s. However, increasing the S_R the presence of the EBR becomes more significant which present an optimum value around 0.2 eV. Yet, further increases in the EBR height beyond this value do not improve the performance of the all thickness of CIGS absorber. For lower S_R, EBR is not beneficial for thinner layers due to the increase of the band gap in the SCR which enhance the V_{oc} and reduces the absorption in the absorber layer that leads to slightly reduction of J_{sc}. The back reflector benefit on the J_{sc} is smaller because in thinner layers the absorber is almost fully depleted. Therefore, the electrons generated close to the back contact will be collected by the electric-field that exists throughout the absorber. The EBR height reduces the effect of the S_R especially for thinner layers. The V_{oc} and efficiency follow the same trend with increasing EBR height. However, the FF presents an optimal value in the range 0.05 - 0.1 eV after which it drops down.

3.2.2. *Electron Back Reflector Layer Thickness*

The CIGS solar cell performance for different thickness versus thickness of the EBR (W_{EBR}) ranging from 0% to 50% corresponding of the total CIGS thickness is studied. The height of the EBR was fixed to 0.2 eV. The thickness of the

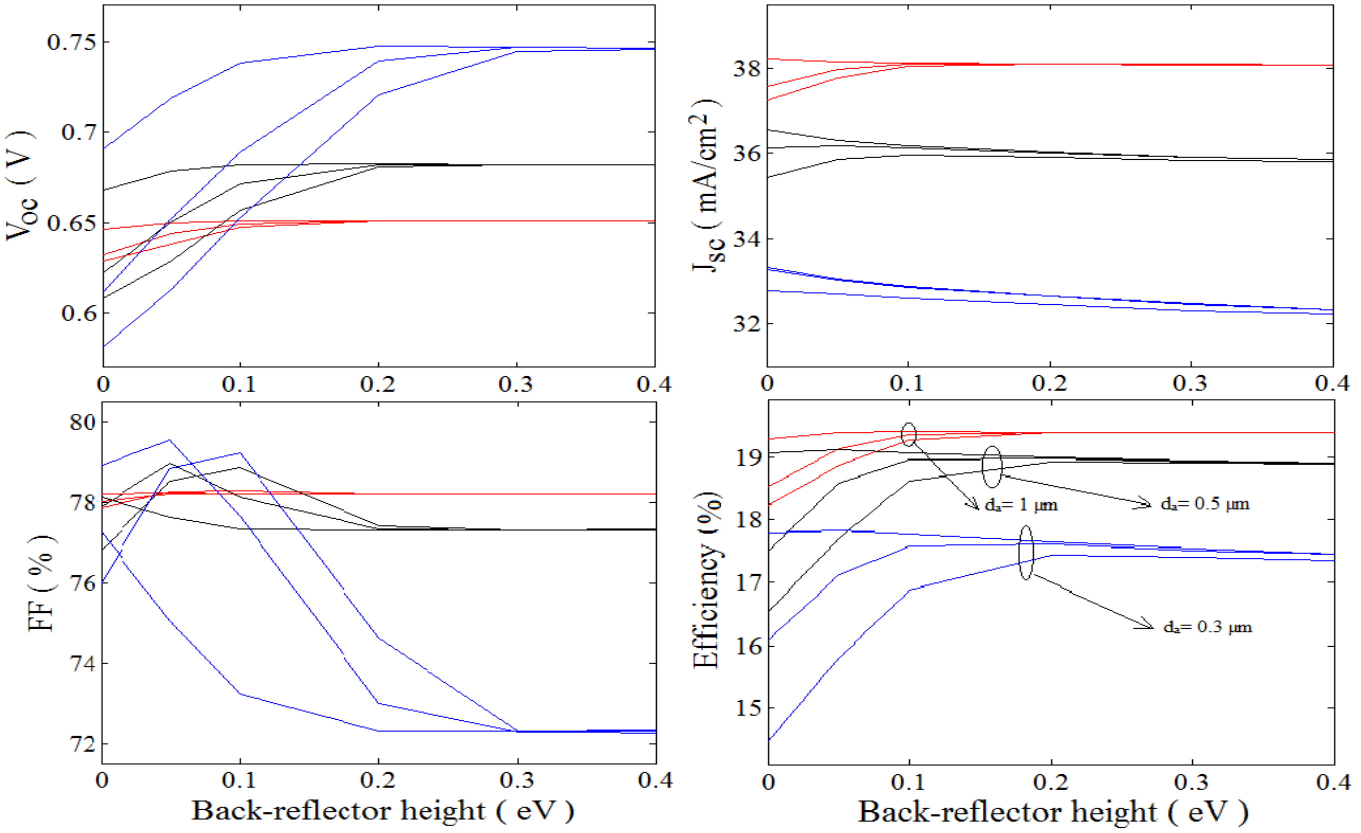

Fig. 4. The simulation results for different thickness, d_a=1µm (red lines), d_a=0.5µm (black lines), d_a=0.3µm (bleu lines). From top to bottom, the different solid lines correspond to S_R values of 10^3; 10^5; 10^7 cm/s.

active layer is varied from 0.3 to 2µm. The simulation results shown in Fig.5 indicate that the all parameters increased with increasing the W_{EBR}. However, as W_{EBR} continued to increase, all parameters except V_{oc} reach a maximum value at around 5% of the total CIGS thickness regardless of the thickness of the absorber layer. However, the peak value of efficiency depends on the absorber layer thickness; for example, for 0.3, 0.5 and 1 µm the efficiency is 3.1%, 2.5%, and 1.2% respectively. We also remark that the efficiency of thicknesses in 0.5-1µm can reaches the same level obtained for standard devices. Beyond this value (5%) increasing the EBR thickness further, up to 50%, the device performance is slightly reduced especially for thinner device, due to the reduction of absorption in the absorber layer caused by the high band gap of EBR. This reduction is not crucial because the drop in J_{sc} was recovered by the augmentation of V_{oc}. Our result is consistent with the experimental ones indicating that the optimum value of the EBR thickness is obtained at 30 s Ga evaporation time of EBR [21]. The performance of the thicker devices (beyond 1µm) is relatively independent of the W_{EBR} variations except for high values where an augmentation of the efficiency is shown due to the high band gap which leads to a reduction of the recombination at the bulk.

4. Conclusion

We presented the effect of variation of the back surface recombination velocity and the presence of the EBR at the back contact on the solar cell parameters when the absorber thickness varies from 0.3 to 2 µm using Capacitance Simulator in 1 Dimension SCAPS-1D. As the cells thickness is reduced the effect of the back surface recombination velocity becomes more important, because the photoelectrons generated occur close to the back-contact. At a thinner CIGS layer the improvement in efficiency, by reducing the S_R, is significant and the obtained values of V_{oc} and efficiency reach the same levels as for thick CIGS solar cells. The increase in V_{oc} and FF, explained by the reduction of the recombination at the SCR, is the reason for the gain in efficiency. However, no improvement in J_{sc} related to the reduction of back surface velocity was observed because most of the carriers are created in the CIGS depletion region and are collected by the drift field. Larger recombination velocities (S_R >10^4 cm/s) would require an EBR height at least 0.2 eV to enhance the solar cell performance. However, when decreasing S_R the effect of the EBR would be reduced. The beneficial effect of EBR height is increased with increasing the S_R when the thickness of the CIGS is reduced. Furthermore, the impact of the thickness of EBR on the performance of the cell was studied. The results show that the optimal EBR thickness (W_{EBR}), regardless of the CIGS thickness layer, is obtained around 5% of the total absorber thickness. For a thickness varies in the range of 0.5-1 µm the efficiency becomes comparable to this obtained for standard device (2 µm). Increasing W_{EBR} further, the performance reduced especially for thinner layers. Further, increases the absorber layer thickness, the electron back reflector becomes less influential.

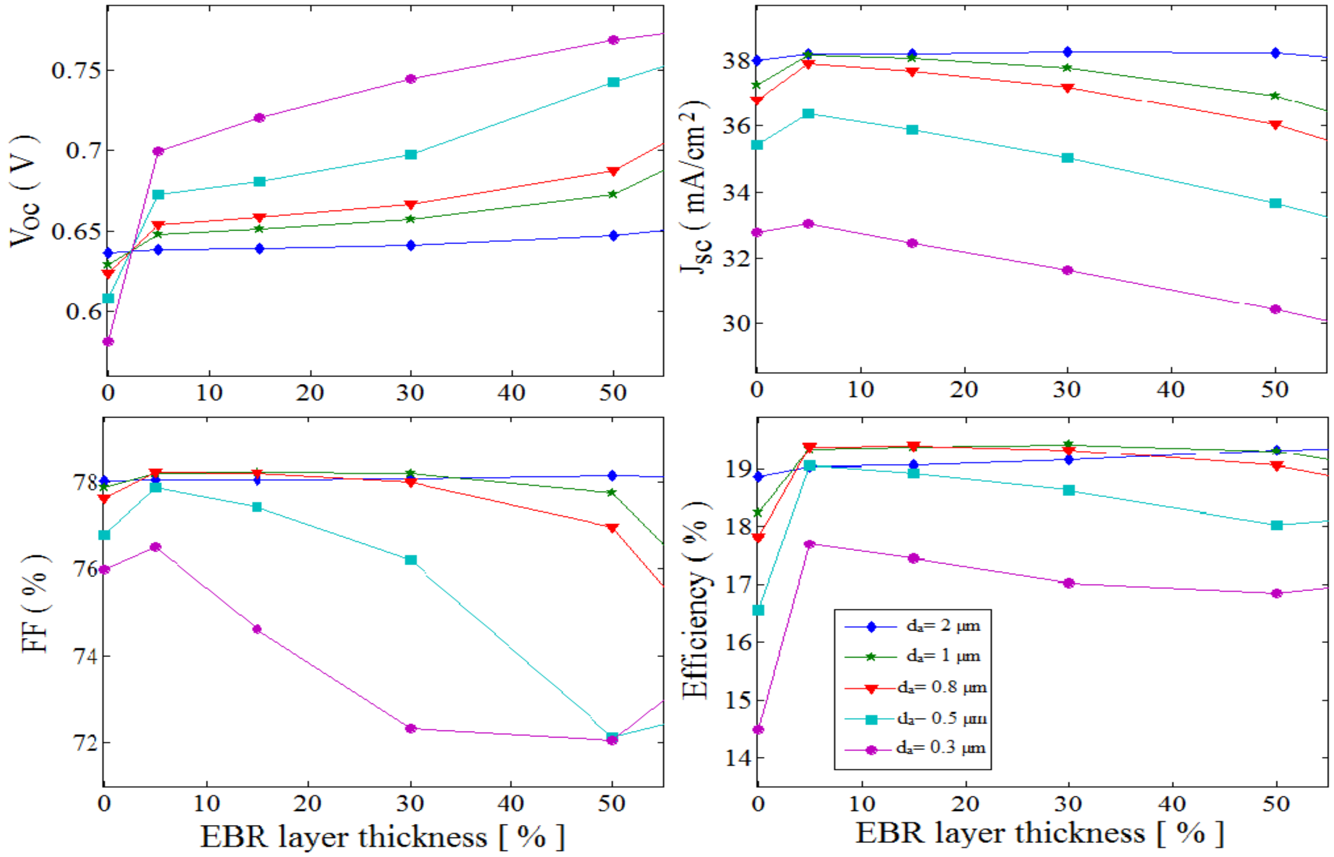

Fig. 5. The conversion efficiency as function of the EBR thickness variation for different thickness of absorber.

Acknowledgements

We acknowledge the use of SCAPS-1D program developed by Marc Burgelman and colleagues at the University of Gent in all the simulation presented in the paper.

References

[1] A. Luque and S. Hegedus, Handbook of Photovoltaic Energy Conversion and Engineering: John Wiley & Sons LTD, Chichester, West Sussex, England, 2003.

[2] R. Noufi and K. Zwiebel, “High-Efficiency CdTe and CIGS Thin-Film Solar Cells: Highlights and challenges”, The 4th World Conference Photovoltaic Energy Conversion. Hawaii, pp. 317-320, 7-12 May 2006.

[3] S.S. Viswanathan, C. IK-Ho, L. Chi-Woo. “Progress in electrodeposited absorber layer for $CuIn_{(1-x)}Ga_xSe_2$ (CIGS) solar cells”. Solar Energy. Vol. 85, pp. 2666-2678,2011.

[4] J. krc et al.”Optical and electrical modeling of $Cu(In,Ga)Se_2$ solar cells”. Optical and Quantum Electronics. vol. 38, pp. 1115-1123, 2006.

[5] A.Yamada et al.”Built-in potential and open circuit voltage of heterojunction $CuIn_{1-x}Ga_xSe_2$ solar cells”. Proc. Mater. Res. Soc. Symp. USA, vol. 865, pp. F5.19.1-F5.19.6, 2005.

[6] P. Chelvanathan, MI. Hossain, and N. Amin. “Performance analysis of copper-indium-gallium (CIGS) solar cells with various buffer layers by SCAPS”. Curr. Appl. Phys. vol. 10, No, 3, pp.387-391, 2010.

[7] O. Lundberg, M. Bodegard, J. Malmstrom, and M. Stolt. “Influence of the $Cu(In,Ga)Se_2$ thickness and Ga grading on solar cell performance”. Prog. Photovoltaics Res. Appl. vol.11, pp. 77–88 2003.

[8] Z. Jehl et al. “Thinning of CIGS solar cells: part II: cell characterizations”. Thin Solid Films. Vol. 519, pp. 7212–7215, 2011.

[9] B. Vermang, V. Fjallstrom, J. pettersson, P. Salomé, and M. Edoff. “Development of rear surface passivated $Cu(In,Ga)Se_2$ thin film solar cells with nano-sized local rear point contacts”. Solar Energy Materials and Solar cells. vol. 117, pp. 505-511, 2013.

[10] W.W. Hsu et al. “surface passivation of $Cu(In,Ga)Se_2$ using atomic layer deposited Al2O3”. Applied Physics Letters. Vol. 100, pp. 1-4, 2012.

[11] J. Petterson, C. Platzer-bjorkman, U. Zimmermann, and M. Edoff. “Baseline model of graded-absorber $Cu(In,Ga)Se_2$ solar cells applied to cells with $Zn_{1-x}Mg_xO$ buffer layers”. Thin Solid Films. vol. 519, pp.7476-7480, 2011.

[12] R. W. Miles, G. Zoppi, and I. Forbes. “Inorganic photovoltaic cells”. Mater today. vol. 10, No. 11, pp. 20-27, 2007.

[13] J.M. Burgelman. “Numerical modeling of intra-band tunneling for heterojunction solar cells in SCAPS”. Thin Solid Films. Vol. 515, pp. 6276-6279, 2007.

[14] H. Movla, D. Salami, S.V. Sadreddini. “Simulation analysis of the effect of defect density on the performance of p-i-n InGaN solar cell”. Applied Physics A. vol. 109, pp. 497-502, 2012.

[15] M. Burgelman, P. Nollet, S. Degrave. “Modeling polycrystalline semiconductor solar cells”. Thin Solid Films. Vol.361-362, pp. 527-532, 2000.

[16] S. J. Fonash. Solar Cell Device Physics, 2nd ed., USA, Academic Press (Elsevier), 2010.

[17] Metzger, K. Wyatt. “The potential and device physics of interdigitated thin-film solar cells”. Journal of Applied Physics. Vol. 103, No.9, pp.094515, 2008.

[18] A. O. Pudov. “Impact of secondary barriers on $CuIn_{1-x}Ga_xSe_2$ solar-cell operation” [Doctoral thesis].Colorado state University, 2005.

[19] Z. Jehl et al. “thinning of CIGS solar cells: Part II: cell characterizations”. Thin solid films. vol. 519, pp. 7212-7215, 2011.

[20] K. Orgassa. “Coherent Optical Analysis of the $ZnO/CdS/Cu(In,Ga)Se_2$ Thin Film Solar Cell” [Doctoral thesis]. University of Stuttgart, 2004.

[21] S.R. Seyrling, “Advanced Concepts for $Cu(In,Ga)Se_2$ Thin Film Solar Cells” [Doctoral thesis]. ETH ZURICH, 2011.