Efficiency enhancement of thin film solar cell by implementation of double-absorber and BSF layers: the effect of thickness and carrier concentration

Seyed Ashkan Moghadam Ziabari

Iran University of Science and Technology

Ali Abdolazadeh Ziabari (✉ ali.abd.ziabari@gmail.com)

Islamic Azad University of Lahijan <https://orcid.org/0000-0001-6229-5789>

S. Javad Mousavi

Islamic Azad University Rasht Branch

Research Article

Keywords: Thin film, BSF, CIGS, CZTSe, Thickness, Efficiency

Posted Date: February 23rd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1349949/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

A Back–Surface Field (BSF) CIGS multilayer solar cell structure is simulated by SCAPS–1D in which, a CZTSSe layer is added between BSF and CIGS layers as a second absorber layer. To achieve the best performance for the proposed structure, the thickness of different layers and the related carrier concentration varied. The 1 μm and 0.5 μm thickness for CZTSSe and CIGS leads to the best performance of the device. The optimum thickness for the rest of layers is also calculated. The effect of the carrier concentration on the performance of the proposed solar cell is also studied. After optimization, a solar cell with a privilege power conversion efficiency of 35.1% was achieved.

Introduction

Due to special features such as high–power conversion efficiency (PCE) and low deposition cost on large areas, thin film solar cells are very promising options for energy harvesting applications. In this regard, approaching a new structure to improve the power/cost ratio is always a strong purpose for scientists. Thus, various thin film materials such as CIGS, CIS, CZTS, CZTSe, and CdTe have been studied for the fabrication of solar cells [1–4]. $\text{Cu}_2\text{ZnSnS}_{4-x}\text{Se}_x$ (CZTSSe) semiconductor is an excellent candidate as absorbers for thin film solar cells. This material shows an appropriate direct bandgap of 1–1.4 eV that well fit the solar spectrum and can collect most of the incident photons. Besides, this compound is nontoxic and abundant in the earth crust. CZTSSe has a high absorption coefficient (more than 10^4 cm^{-1}). This material also has a tunable bandgap that is controlled by S and Se contents in the material [2, 3, 5–9, 22]. Copper–indium–gallium–diselenide (CIGS) based solar cells are well known for their special features such as high efficiency, easy fabrication process, low cost, very high durability and stability, flexibility and light weight. CIGS has a high absorption coefficient of 10^5 cm^{-1} in the visible solar spectrum and a direct bandgap that varies from 1.04 to 1.7 eV [10–13]. In the fabrication process of solar cells, using a back–surface field (BSF) layer is a solution to boost the efficiency of the solar cell. BSF layer causes a rear pushing force at the highly doped back side of the solar cell and leads to deflection of the minority carriers toward front depletion area. Hence, the BSF layer lowers the rear recombination of the solar cell, which accordingly improves the electrical characteristics of the solar cell. Lead sulfide (PbS) is a promising candidate as the BSF layer. It is low–cost and abundant with higher electron affinity and better absorption coefficient than materials such as SnS, Al_2O_3 and MoSe_2 BSF [5, 14, 15]. In this study, we regarded an experimental work on a single–junction CIGS solar cell as the baseline [10] and regenerated the results through the numerical simulation followed by adding a CZTSSe layer as the second absorber layer and manipulated the thickness of the layers to achieve the optimum efficiency.

Simulation And Analysis

Recently, simulation has been a great tool for optimizing and analyzing the performance of efficient solar cells. In this study, we operate solar cell capacitance simulator structures in 1 dimension (SCAPS–1D) which is a one–dimensional simulator tool for solar cell devices developed by ELIS, University of Gent,

and can be used freely by PV field researchers [16, 17]. SCAPS simulator can solve the Poisson and continuity equations of electron and holes. The equations are:

$$\left(\frac{d^2}{dx^2}\right) \Psi(x) = \frac{e}{\epsilon_0 \epsilon_r} p(x) - n(x) + N_D - N_A + \rho_p - \rho_n \quad (1)$$

$$\left(\frac{dJ_n}{dx}\right) = G - R \text{ and } \left(\frac{dJ_p}{dx}\right) = G - R \quad (2)$$

$$J_n = Dn \left(\frac{dn}{dx}\right) + \mu_n n \left(\frac{d\Phi}{dx}\right) \quad (3)$$

$$J_p = Dp \left(\frac{dp}{dx}\right) + \mu_p p \left(\frac{d\Phi}{dx}\right) \quad (4)$$

where $\Psi(x)$ is the electrostatic potential, e is electrical charge, ϵ_r is the relative and ϵ_0 is the vacuum permittivity, n and p are electron and hole concentrations, respectively, N_A is acceptor type and N_D is charged impurities of donor, ρ_n and ρ_p are electron and hole volume density, G is generation rate and R is recombination rate [18–20].

SCAPS–1D solves the above equations and calculates all point quasi–Fermi level and electrostatic potential for electrons and holes [21]. All the simulations are conducted under 1.5 AM solar spectrum and at the temperature of 300 K.

Table 1

Physical parameters of the proposed solar cell [7, 10, 13, 22] including d (thickness), bandgap (E_g), electron affinity (χ), dielectric constant (ϵ), conduction/valence band density of states (N_c/N_v), electron/hole mobility (μ_n/μ_h), thermal velocity of electron/hole (v_{thn}/v_{thp}) and donor/acceptor concentration (n/p).

Parameter	p-CIGS	n-CdS	i-ZnO	Al-ZnO	p-PbS	CZTSSe
d(μm)	1.5	0.05	0.05	0.2	0.15	1
E_g (eV)	1.3	2.4	3.4	3.4	1.4	1
χ (eV)	4.5	4.2	4.5	4.6	4.35	4.6
ϵ	13.6	10	9	9	10	13.6
N_c (m^{-3})	2.2×10^{18}	2.4×10^{18}	2×10^{18}	2×10^{18}	2×10^{18}	2.2×10^{18}
N_v (m^{-3})	1.8×10^{19}	2.6×10^{19}	1.8×10^{19}	1.8×10^{19}	2×10^{18}	1.8×10^{19}
μ_n (cm^2/Vs)	200	340	100	100	25	100
μ_p (cm^2/Vs)	100	50	25	25	100	25
v_{thn} (cm/s)	1.0×10^7	1.0×10^7	1.0×10^7	1.0×10^7	1.0×10^7	1.0×10^7
v_{thp} (cm/s)	1.0×10^7	1.0×10^7	1.0×10^7	1.0×10^7	1.0×10^7	1.0×10^7
n (cm^{-3})	0	1.1×10^{18}	1×10^{18}	1×10^{18}	0	0
p (cm^{-3})	5.1×10^{16}	0	0	0	5.5×10^{16}	1.5×10^{15}

Figure 1 shows our purposed double-absorber layer solar cell structure (Al/ITO/AZO/i-ZnO/CdS/CIGS/CZTSSe/PbS/Mo) with a p-type CIGS absorber layer, a p-type CZTSSe absorber layer and an n-type CdS buffer layer. A PbS layer as the BSF layer is added to the structure between the absorption layer and Mo back contact.

To verify the simulation process, results related to an experimental work [10] was simulated and the calculated values are summarized in Table 2. It is seen that the calculated values almost match the reported values [10].

Table 2

Photovoltaic parameters of the proposed solar cell with and without PbS layer in comparison with those reported in [10].

Parameters	V_{oc} (V)		J_{sc} (mA/cm ²)		FF (%)		η (%)	
	Ref [10]	This work	Ref [10]	This work	Ref [10]	This work	Ref [10]	This work
Without PbS	0.81	0.78	33.96	33.52	82.35	82.71	22.67	21.63
With PbS	0.83	0.81	35.22	35.84	82.29	83.90	24.22	24.23

Effect Of The Thickness Of Cztssse As The Second Absorber Layer On The Performance Of The Proposed Solar Cell

Initially, it is shown that by applying a PbS layer as BSF, recombination of the solar cell is decreased and, accordingly, efficiency is increased. By adding CZTSSe as a second absorber layer with the thickness of 0.1 μm to 4.5 μm , photovoltaic parameters are calculated. It is obvious that all photovoltaic parameters (V_{oc} , J_{sc} , FF and η) are increased. Although all parameters are increased, the increase of V_{oc} and FF is not considerable. Also, the significant change occurs in the thicknesses under 1 μm for CZTSSe layer. It is seen that the photovoltaic parameters for CZTSSe layer with 1 μm thickness are better than the other thickness values (Figs. 2 and 3). So, the thickness of 1 μm for CZTSSe layer is the optimal choice for the next step of simulation. Comparing this choice with Barman's optimum structure shows more than 4.5% increase in η .

Determination Of The Optimum Thickness Of Cigs Layer

After finding the optimum thickness of CZTSSe layer, the thickness of CIGS layer changed from 1 μm to 0.05 μm . Results showed an overall increase in photovoltaic parameters (Figs. 4 and 5) and the efficiency of the cell increased more than 3%. This trend can be linked to: a) the reduction of the series resistance of the cell stemming from shorter length of CIGS layer and b) decrease in recombination of the charge carriers travelling in shorter paths. For the next step of optimization, the structure with 0.05 μm CIGS layer is considered.

When we calculate the photovoltaic parameters for a structure with PbS, CIGS, CdS, ZnO and AZO of 0.05 μm thickness and CZTSSe of 1 μm thickness, V_{oc} (0.8336 V), J_{sc} (45.006305), FF (85.72%) and η (32.16%) are achieved. These values are very promising as compared to the initial values. The J–V characteristic along with the QE of this structure is shown in Figs. 6 and 7, respectively.

The Effect Of Carrier Concentration On The Performance Of The Proposed Solar Cell

Another key parameter that has a drastic effect on the performance of a solar cell is the carrier concentration of different layers. Initially, the variation of the carrier concentration of CIGS as the absorber layer of the cell is studied (Fig. 8). It is seen, as the carrier concentration varies from 10^{11} to 10^{16} cm^{-3} , J_{sc} and η increase, while V_{oc} and FF decrease. Meanwhile, when the carrier concentration of CZTSSe layer changes from 10^{14} to 10^{20} cm^{-3} , J_{sc} increases rapidly up to 10^{17} cm^{-3} followed by trivial increase above that (Fig. 9). Contrarily, the other parameters decreased in this range. This implies that, higher carrier concentration of the second absorber layer causes narrowing of the depletion zone leading to decrease of V_{oc} . Also, this can be due to the high recombination of the photo-generated carriers in the CZTSSe absorber layer.

With the optimum value of $1 \text{ }\mu\text{m}$ for thickness and 10^{17} cm^{-3} for carrier concentration of CZTSSe layer, the highest $\eta = 32.17\%$ is achieved.

The effect of carrier concentration of PbS (Fig. 10) and CdS layer (Fig. 11) on the performance of the proposed solar cell is also studied. It is seen that all output parameters of the cell increase with the carrier concentration of PbS layer up to 10^{17} cm^{-3} . Increasing of PV performance parameter with increasing carrier concentration implies the reduction of photo-generated charge carrier recombination. On the other hand, at high carrier concentration, the Fermi level of PbS at HTL (hole transport layer) shifted towards the valence band, thus forming a nearly ohmic contact with back-metal electrode caused the efficient collection of holes. For CdS layer, the carrier concentration is changed from 10^{16} to 10^{20} cm^{-3} . As it is clear from Fig. 11, except FF, the other output parameters increased by carrier concentration. The increase of the efficiency of the cell can be concerned to the better collection a photo generated electron on the optimized thickness of buffer layer. The optimum performance of the designed structure was achieved at $0.05 \text{ }\mu\text{m}$ thickness and $9 \times 10^{19} \text{ cm}^{-3}$ carrier concentration of CdS layer where $\eta = 35.1\%$. The corresponding V_{oc} , J_{sc} and FF is 0.89 V , 45.6 mA/cm^2 and 87% , respectively.

Conclusion

In summary, a thin film solar cell with double-absorber layer and BSF layer was proposed and the effect of the thickness of different layers and carrier concentration was studied. The optimum thickness for CZTSSe and CIGS layers were found 1 and 0.5 microns, respectively. Using a BSF layer improved the photovoltaic properties of the device drastically. The optimum carrier concentration of each layer was determined through optimization process. After determination of the optimum values, the final structure was simulated. Calculations revealed a privileged power conversion efficiency of 35.1% . This result makes our modeled structure as a promising candidate for thin film solar cells.

Declarations

Author declaration

[Instructions: Please check all applicable boxes and provide additional information as requested.]

1. Conflict of Interest

Potential conflict of interest exists:

We wish to draw the attention of the Editor to the following facts, which may be considered as potential conflicts of interest, and to significant financial contributions to this work:

The nature of potential conflict of interest is described below:

No conflict of interest exists.

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

2. Funding

- Funding was received for this work.

All of the sources of funding for the work described in this publication are acknowledged below:

[List funding sources and their role in study design, data analysis, and result interpretation]

- No funding was received for this work.

3. Intellectual Property

- We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

4. Research Ethics

- We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.
- IRB approval was obtained (required for studies and series of 3 or more cases)
- Written consent to publish potentially identifying information, such as details or the case and photographs, was obtained from the patient(s) or their legal guardian(s).

5. Authorship

The International Committee of Medical Journal Editors (ICMJE) recommends that authorship be based on the following four criteria:

1. Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
2. Drafting the work or revising it critically for important intellectual content; AND
3. Final approval of the version to be published; AND
4. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

All those designated as authors should meet all four criteria for authorship, and all who meet the four criteria should be identified as authors. For more information on authorship, please see <http://www.icmje.org/recommendations/browse/roles-and-responsibilities/defining-the-role-of-authors-and-contributors.html#two>.

- All listed authors meet the ICMJE criteria. We attest that all authors contributed significantly to the creation of this manuscript, each having fulfilled criteria as established by the ICMJE.
- One or more listed authors do(es) not meet the ICMJE criteria.

We believe these individuals should be listed as authors because:

[Please elaborate below] ☐

- We confirm that the manuscript has been read and approved by all named authors.
- We confirm that the order of authors listed in the manuscript has been approved by all named authors.

6. Contact with the Editorial Office

The Corresponding Author declared on the title page of the manuscript is:

Ali Abdolazadeh Ziabari

This author submitted this manuscript using his/her account in EVISE.

- We understand that this Corresponding Author is the sole contact for the Editorial process (including EVISE and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.
- We confirm that the email address shown below is accessible by the Corresponding Author, is the address to which Corresponding Author's EVISE account is linked, and has been configured to accept email from the editorial office of American Journal of Ophthalmology Case Reports:

- Someone other than the Corresponding Author declared above submitted this manuscript from his/her account in EVISE:

[Insert name below]

- We understand that this author is the sole contact for the Editorial process (including EVISE and direct communications with the office). He/she is responsible for communicating with the other authors, including the Corresponding Author, about progress, submissions of revisions and final approval of proofs.

Funding declaration

This study didn't use any fund.

Availability of data and material

All data are available whenever were asked.

Code availability

The code will be available whenever is asked.

Ethics approval

I, Ali Abdolazadeh Ziabari, corresponding author of the manuscript, submitted to the Journal of Computational Electronics for possible evaluation. With the submission of this manuscript I would like to undertake that the above mentioned manuscript has not been published elsewhere, accepted for publication elsewhere or under editorial review for publication elsewhere; and that my Institute's Islamic Azad University, Lahijan branch representative is fully aware of this submission.

Submitted manuscript is an original research article.

Sincerely Yours,

Ali Abdolazadeh Ziabari, PhD

Consent for publication

I, the undersigned, give my consent for the publication of identifiable details, which can include photographs and details within the text to be published in the above Journal and Article.

Dr. Ali Abdolazadeh Ziabari

Corresponding Author

References

1. Amiri, M., Eskandarian, A., Abdolazadeh, A., Ziabari: Performance enhancement of ultrathin graded $\text{Cu}(\text{InGa})\text{Se}_2$ solar cells through modification of the basic structure and adding antireflective layers. *J. Photon Energy* **10**(2), 024504 (2020)
2. Cherouana, A., Labbani, R.: 2018. Numerical simulation of CZTS solar cell with silicon back surface field. *Materials Today: Proceedings*, 5(5), pp.13795–13799
3. Tripathi, S., Lohia, P., Dwivedi, D.K.: Contribution to sustainable and environmentally friendly non-toxic CZTS solar cell with an innovative hybrid buffer layer. *Sol. Energy* **204**, 748–760 (2020)
4. Saha, U., Alam, M.K.: Boosting the efficiency of single junction kesterite solar cell using Ag mixed $\text{Cu}_2\text{ZnSnS}_4$ active layer. *RSC Adv.* **8**(9), 4905–4913 (2018)
5. Abderrezek, M., Djeghlal, M.E.: Contribution to improve the performances of $\text{Cu}_2\text{ZnSnS}_4$ thin-film solar cell via a back-surface field layer, 181, pp. 220–230. *Optik* (2019)
6. Kumar, A., Thakur, A.D.: 2018, September. Improvement of efficiency in CZTSSe solar cell by using back surface field. In *IOP Conference Series: Materials Science and Engineering* (Vol. 360, No. 1, p. 012027). IOP Publishing
7. Omrani, M.K., Minbashi, M., Memarian, N., Kim, D.H.: Improve the performance of CZTSSe solar cells by applying a SnS BSF layer. *Solid-State Electron.* **141**, 50–57 (2018)
8. Saha, U., Alam, M.K.: Boosting the efficiency of single junction kesterite solar cell using Ag mixed $\text{Cu}_2\text{ZnSnS}_4$ active layer. *RSC Adv.* **8**(9), 4905–4913 (2018)
9. Khattak, Y.H., Baig, F., Taura, H., Ullah, S., Marí, B., Beg, S., Ullah, H.: Effect of CZTSe BSF and minority carrier life time on the efficiency enhancement of CZTS kesterite solar cell. *Curr. Appl. Phys.* **18**(6), 633–641 (2018)
10. Barman, B., Kalita, P.K.: Influence of back surface field layer on enhancing the efficiency of CIGS solar cell. *Sol. Energy* **216**, 329–337 (2021)
11. Bouabdelli, M.W., Rogti, F., Maache, M., Rabehi, A.: Performance enhancement of CIGS thin-film solar cell. *Optik* **216**, 164948 (2020)
12. Sobayel, K., Shahinuzzaman, M., Amin, N., Karim, M.R., Dar, M.A., Gul, R., Alghoul, M.A., Sopian, K., Hasan, A.K.M., Akhtaruzzaman, M.: Efficiency enhancement of CIGS solar cell by WS_2 as window layer through numerical modelling tool, 207, pp. 479–485. *Solar Energy* (2020)
13. Panahi, F.S., Abbasi, S.R., Ghods, A., V. and Amirahmadi, M.: Analysis and improvement of CIGS solar cell efficiency using multiple absorber substances simultaneously. *J. Mater. Sci.: Mater. Electron.* **31**, 11527–11537 (2020)
14. Sharma, A., Yadav, R.S., Pandey, B.P.: Performance Analysis of PbS Colloidal Quantum Dot Solar Cell at Different Absorption Coefficient. *J. Energy Environ. Sustain.* **7**, 32–35 (2019)
15. Pandey, R., Khanna, A., Singh, K., Patel, S.K., Singh, H., Madan, J.: Device simulations: Toward the design of > 13% efficient PbS colloidal quantum dot solar cell. *Sol. Energy* **207**, 893–902 (2020)

16. Burgelman, M., Verschraegen, J., Degraeve, S., Nollet, P.: Modeling thin-film PV devices. Prog. Photovoltaics Res. Appl. **12**(2-3), 143–153 (2004)
17. Speirs, M.J., Balazs, D.M., Fang, H.–H., Lai, L.–H., Protesescu, L., Kovalenko, M.V., Loi, M.A.: Origin of the increased open circuit voltage in PbS–CdS core–shell quantum dot solar cells. J. Mater. Chem (2014)
18. Tariq, A., Moustafa, M.: Simulation analysis of functional MoSe₂ layer for ultrathin Cu(In, Ga)Se₂ solar cells architecture. Modern Phys. Lett. B (2019)
19. Wanda, M.D., Ou´edraogo, S., Tchoffo, F., Zougmor´e, F., Ndjaka, J.M.B.: 2016. Numerical investigations and analysis of Cu₂ZnSnS₄ based solar cells by SCAPS–1D. Int. J. Photoenergy 2016. <https://doi.org/10.1155/2016/2152018>. Article ID 2152018, 9 pages
20. Azizi, T., Toujeni, H., Karoui, M.B., Gharbi, R.: 2019, March. A comprehensive device modeling of solid state dye sensitized solar cell with SCAPS–1D. In 2019 19th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA) (pp. 336–340). IEEE
21. Kunal, C., Mahua, G.C., Samrat, P.: Numerical study of Cs₂TiX₆ (X = Br–, I–, F– and Cl–) based perovskite solar cell using SCAPS–1D device simulation. Sol. Energy **194**, 886–892 (2019)
22. Yang, K.J., Son, D.H., Sung, S.J., Sim, J.H., Kim, Y.I., Park, S.N., Jeon, D.H., Kim, J., Hwang, D.K., Jeon, C.W., Nam, D., Cheong, H., Kang, J.K., Kim, D.H.: A band–gap–graded CZTSSe solar cell with 12.3% efficiency. J. Mater. Chem. A **4**, 10151–10158 (2016)

Figures

Figure 1

Schematic diagram of the proposed solar cell

Figure 2

Variations of J_{sc} and V_{oc} of the proposed solar cell as a function of CZTSSe layer thickness.

Figure 3

Variations of FF and η of the proposed solar cell as a function of CZTSSe layer thickness.

Figure 4

Variation of J_{sc} and V_{oc} of the proposed solar cell with the thickness of CIGS layer.

Figure 5

Variation of FF and efficiency of the proposed solar cell with the thickness of CIGS layer.

Figure 6

The calculated J–V characteristic of the proposed structure with optimum thickness for CSTS_{Se} and CIGS layers.

Figure 7

The calculated QE of the proposed structure with optimum thickness for CZTSSe and CIGS layers.

Figure 8

Variation of photovoltaic parameters of the proposed solar cell with carrier concentration of CIGS absorber layer.

Figure 9

Variation of photovoltaic parameters of the proposed solar cell with carrier concentration of CZTSSe as the second absorber layer.

Figure 10

Variation of photovoltaic parameters of the proposed solar cell with carrier concentration of BSF layer.

Figure 11

Variation of photovoltaic parameters of the proposed solar cell with carrier concentration of CdS layer.