Towards High-Efficiency CZTSe Solar Cells Through the Optimization of the p-MoSe₂ Interfacial Layer

Mohamed Moustafa,¹* Tariq AlZoubi², Shadi Yasin¹, Ziad Abu Waar³, and Ahmad Moghrabi²

¹Department of Physics, School of Sciences and Engineering, The American University in Cairo, New Cairo, Egypt.
²College of Engineering and Technology, American University of the Middle East, Egaila, Kuwait.

* Corresponding author: mohamed.orabi@aucegypt.edu

Abstract. This paper reports the impact of the p-MoSe₂ transition metal dichalcogenide as an interfacial layer between the CZTSe absorber and Mo back contact in the CZTSe solar cells. Here, the solar cell capacitance simulator (SCAPS-1D) is employed. The I-V characteristic demonstrated a higher slope in comparison to CZTSe solar cell without considering the interfacial layer. The results show that the p-MoSe₂ layer benefits the CZTSe/Mo hetero contact by mediating the quasi-ohmic back contact of the CZTSe solar cell. Accordingly, the conversion efficiency improves from 16.17 % to 23.47 %. To investigate the effect of the p-MoSe₂ layer, various performance parameters such as open-circuit voltage (V_{oc}), short circuit current (J_{sc}), fill factor FF, and efficiency η were explored at a wide range of thicknesses, bandgap energies, and the carrier concentration. The results revealed that a thickness of the interfacial layer less than 70 nm would cause deterioration of overall cell performance. This is because a low thickness of p-MoSe₂ creates high barriers at the CZTS/p-MoSe₂ and p-MoSe₂/Mo interfaces, which impedes the drift process of photogenerated holes. Additionally, increasing the acceptor carrier concentration doping (N_A) above 10^{17} cm^{-3} results in an improved cell performance due to the enhanced band alignment at the back contact. The obtained values of the V_{oc} and J_{sc} are 0.74 V and 42.6 mA/cm², respectively.

1. Introduction

Cu₂ZnSnSe₄ (CZTSe) kesterite-structured semiconductors are drawing considerable attention recently as active layers of thin-film solar cells. They are considered promising candidates for photovoltaic devices and fabrications, among other thin-film solar cells, such as those based on polycrystalline cadmium telluride (CdTe), copper indium diselenide (CIS), and copper indium gallium diselenide (CIGS). This is due to the remarkable characteristics of the CZTSe. They are environmentally friendly since the materials consist of earth-abundant, non-toxic compounds such as copper, zinc, tin and sulfur, encouraging the mass production of photovoltaic devices contrary to CdTe or CIGS semiconductors [1]. The material CZTSe is a quaternary semiconductor associated with two different crystal structures, stannite and kesterite. The later structure shows more stability than the former one. These materials possess outstanding photovoltaic properties, such as useful bandgap energy values (E_g), various from 1.4 eV to 1.9 eV, and a high absorption coefficient of ~10⁷ cm⁻¹ [2–5]. During the last few years, many theoretical and experimental studies have investigated and improved solar cell efficiency using the CZTSe absorber layer [5–8]. A high power conversion efficiency of CZTSe solar cells was reported at 12.6 % for fabricated solar cells utilizing a spin-coating process and using the CdS as a buffer layer [9].
In the CZTSe based thin-film solar cells, Mo is a widely used material as a back contact, with a work function value of about 4.75 eV. It has been observed experimentally that a MoSe$_2$ interface layer is unintentionally formed between the CZTSe absorber and Mo back contact. This can result from the selenization process of the Mo electrode or can be caused by the reaction between the Mo electrode and the CZTSe absorber precursor during the sulfurization of the CZTSe absorber at high temperatures. For example, previous experimental work investigated the control of an interfacial MoSe$_2$ layer in CZTSe thin-film solar cells by introducing an appropriate S/Se partial pressure throughout the annealing process with a TiN diffusion barrier [3]. The thickness of the interfacial MoSe$_2$ layers is found to depend on the physical and chemical conditions employed in the deposition of the Mo layer. Schnabel et al. [10] discussed the thickness of the interfacial layer adding more sulfur into solution-processed CZGSSe layers by supplying Se and considerable amounts of GeSe while annealing process at the high temperature. Similarly, the vital role of the MoSe$_2$ has been studied by numerical analysis of Mo back contact in Se-containing CZTSe devices [11]. Furthermore, it has also been found in other CIGS solar cells that MoSe$_2$ mediates an ohmic contact with Mo back contact rather than the Schottky-type one [12].

The MoSe$_2$ interfacial layer belongs to group VI of the layered transition metal dichalcogenides (TMDCs). TMDCs, which are characterized by their layer structure, have attracted significant attention for various potential applications, such as low-dimensional electronic, optical, and photovoltaic devices [13]. These materials exhibit unique physical and structural properties due to their 2D character. The material is composed of Se-Mo-Se atomic layer where a strong in-plane covalent bonding exists, whereas the sheets are bonded together by weak Van-der-Waals forces coupling [14,15]. MoSe$_2$ has suitable bandgap values ranging from 1.0 eV to 1.7 eV as it can be tunable, associated with high hole mobility. Many researchers have studied and reported on the electronic properties of both calculations and experimentally of several TMDC materials, using different approaches and methods [14–16].

This study presents and discusses the effects of p-MoSe$_2$ TMDC as an interfacial layer between Mo back contact and CZTSe absorber by using the SCAPS-1D numerical analysis. The I-V characteristic is reported with the insertion of the MoSe$_2$. The solar cell performance parameters such as open-circuit voltage $V_{oc}$, short circuit current density $J_{sc}$, fill factor FF, and the conversion efficiency $\eta$ are presented. The basic parameters are studied as a function of the bandgap values, the thickness, and the acceptor carrier concentration ($N_A$) of the MoSe$_2$ interfacial layer. A good understanding of the CZTSe properties will make it easier to design suitable solar cell and for potential further development.

2. Materials and methods

SCAPS-1D, a solar cell simulation package, has been developed at the University of Gent [17, 18]. It is a computer-based tool adapted for the analyses of homo- and hetero-junctions, multi-junctions and Schottky barrier photovoltaic devices. It has been effectively employed to simulate different solar cells, e.g., Perovskite, CIGS, and CdTe based solar cells [19–22]. SCAPS calculates the steady-state band diagram, recombination profile, and carrier transport based on the Poisson equation jointly with hole and electron continuity equations. It has been modelled under standard testing conditions of AM 1.5 light spectrum, a 1000 (W/m$^2$) light intensity, and operating temperature of 300 K. This can describe a solar cell as a series of layers with various characteristics, such as absorber and buffer layer thickness, energy bandgap, and doping densities and other input materials, and device parameters. Fig. 1 illustrates the schematic diagram of the used CZTSe solar cell. The structure starts with the soda-lime glass substrate. A thin p-MoSe$_2$ interfacial layer The next layer is the CZTSe absorber layer. The buffer layer is n-type CdS with a thickness of 0.2 µm, and the window layer is Al-doped ZnO of 0.1 µm thickness. The MoSe$_2$ is a layered semiconductor that can exist in both n- and p-type with a net carrier concentration of about $10^{18}$ cm$^{-3}$ and Hall mobilities $\sim$150 cm$^2$/Vs at 300 K. The various material properties embedded for the current numerical analysis are collected in Table 1 [23–26]. The input values, thickness, and energy bandgap of the MoSe$_2$ layer have been changed from 10 nm to 300 nm and from 1.0 eV to 1.45 eV. Additionally, the carrier concentration of the p-MoSe$_2$ is varied from $1 \times 10^{15}$ cm$^{-3}$ to $1 \times 10^{19}$ cm$^{-3}$ to accentuate its effect on the performance of the CZTSe thin-film solar cells. In this study, the defect-free layers are assumed. The possible recombination and interfaces of Cds/CZTSe, the narrowing of the CZTSe bandgap, and short diffusion length phenomena are not considered in the present simulation.
**Figure 1.** Schematic diagram of CZTSe solar cell structure based on MoSe₂ interfacial layer

**Table 1.** The proposed model's materials parameters incorporated into SCAPS simulations at 300 K, from [23-26].

| Parameter/ Layer function | p-MoSe₂ Interfacial | p-CZTSe Absorber | n-CdS Buffer | n-ZnO:Al Window |
|---------------------------|----------------------|------------------|---------------|-----------------|
| Thickness [µm]            | 0.01 – 0.3           | 1                | 0.2           | 0.1             |
| εₑ [cm³/Vs]              | 8.76                 | 13.6             | 10            | 9               |
| μₑ [cm³/Vs]              | 100                  | 100              | 100           | 100             |
| Nₛ [cm⁻³]                | 10¹² – 10¹⁹          | 10¹⁸             | 0             | 0               |
| N₀ [cm⁻³]                | 0                    | 0                | 10¹⁸          | 5 x10¹⁸         |
| E_g [eV]                  | 1.0 – 1.45           | 1.05             | 1.3 – 1.9    | 3.3             |
| Nᵥₛ [cm⁻³]               | 2.8 x10¹⁹           | 2.2 x10¹⁸        | 2.2 x10¹⁸    | 2.2 x10¹⁸       |
| Nᵥ₀ [cm⁻³]               | 2.65 x10¹⁹          | 1.8 x10¹⁹        | 1.8 x10¹⁹    | 1.8 x10¹⁹       |
| vₑₛ [cm/s]               | 1 x10⁷              | 1 x10⁷           | 1 x10⁷       | 1 x10⁷          |
| vₑ₀ [cm/s]               | 1 x10⁷              | 1 x10⁷           | 1 x10⁷       | 1 x10⁷          |
| χ [eV]                   | 4.12                 | 4.35             | 4.2           | 4.65            |
| Defect type*             | SD                   | SD               | SA            | SA              |
| Defect density [cm⁻³]    | 10¹⁵                 | 10¹⁵             | 10¹⁴          | 10¹⁴            |

* N: Neutral, SD: Single Donor, SA: Single Acceptor

**Table 2.** The initial photovoltaic performance parameters of the CZTSe before and after the insertion of the p-MoSe₂.

| Photovoltaic Performance parameter | Without p-MoSe₂ | With p-MoSe₂ |
|-----------------------------------|----------------|--------------|
| PCE [%]                           | 16.17          | 23.47        |
| Jₑ [mA/cm²]                       | 37.99          | 42.6         |
| Vₑ [V]                            | 0.56           | 0.74         |
| FF [%]                            | 75.32          | 78.42        |
3. Results and discussion

Fig. 2 illustrates the simulated J–V characteristics and the quantum efficiency of the CZTSe based solar cell. The simulations are carried out with (red curve) and without (blue curve) the insertion of the interfacial MoSe$_2$ layer. The typical reported MoSe$_2$ thickness of 100 nm, a bandgap value of 1.05 eV and acceptor carrier concentration doping ($N_a$) $10^{18}$ cm$^{-3}$, are used. In this study, the most common experimental CZTSe absorber layer thickness of 1000 nm was used. The results show that the insertion of p-MoSe$_2$ directly impacts the J–V curve, i.e., giving higher steepness, which reveals a more ohmic contact feature. The slope ($\Delta I/\Delta V$) at the forward-current region with the MoSe$_2$ is higher than that without MoSe$_2$. This implies that the MoSe$_2$ layer at the CZTSe/Mo interface improves the CZTSe/Mo heterojunction interface, modifying it from Schottky-type contact to the favourable ohmic-type contact. The solar cell without and with the MoSe$_2$ layer showed a conversion efficiency of 16.17% and 23.47%, respectively, at moderate interface layer doping level $\sim 10^{18}$ cm$^{-3}$. Additionally, the solar cell made from Mo-CZTSe standard structure with the MoSe$_2$ layer revealed a marked increase of $J_{sc}$ with a value of 42.6 mA/cm$^2$. The device simulation results are listed in Table 2. The obtained results could be discussed based on the earlier theoretical and experimental studies concerned with the solar cell device performances using various TMDC semiconductors as an interfacial layer. By inserting the interfacial layer, the contacts are more ohmic, leading to high surface recombination velocities of about 10$^7$ cm/s [27]. These high holes recombination velocity at the MoSe$_2$/Mo contact is found to enhance the photovoltaic parameters of the solar cells. The $V_{oc}$ values are estimated by:

$$ V_{oc} = n k T / q \left[ \ln \left( J_{ph} / J_o + 1 \right) \right] $$

(1)

Where $J_{ph}$ is the photogenerated current density and $J_o$ represents the reverse saturation current density. $n$ is the ideality factor, $k$ and $T$ are the Boltzmann’s constant and absolute temperature, respectively. The high holes recombination velocity at the MoSe$_2$/Mo interface lets a high value of the recombination current, which leads to a decrease in the $J_o$ composed of electrons. According to equation (1), CZTSe solar cells’ photovoltaic properties can be enhanced by the suitable recombination velocity of the MoSe$_2$/Mo interface. The associated high holes recombination velocity might be due to a surface layer created between the absorber and buffer layers, called ordered vacancy or ordered defect compound (OVC/ODC). This ODC layer owns an n-type electrical conductivity characteristic [28]. This layer increases the absorber bandgap at the buffer absorber interface by downshifting the VBM to the Fermi level and reduces the interface recombination rate accordingly. The Quantum Efficiency (QE) of CZTSe solar cells with and without the interfacial layer is shown in Fig. 2 (b). It is used to look at the influence of the bandgap on carrier collection. The discrepancies observed in the short and long-wavelength are correlated to the absorber layer’s bandgap and the device structure and
its window layers. It is to note that from Fig. 2, an enhancement of QE from 68.1% to 89.7% was observed at longer wavelengths in 450 nm to 1250 nm.

In order to elucidate the effect of the bandgap values of the p-MoSe₂ layer on the solar cell performance, its values were varied from 1.0 eV to 1.45 eV, the thickness of the CdS buffer layer and absorber layer was set to 200 nm and 2000 nm, respectively. The thickness of the introduced MoSe₂ interfacial layer is 100 nm. The doping level is selected to be high at $10^{18} \text{cm}^{-3}$. Fig. 3 from (a) to (d) represents the obtained solar cell photovoltaic parameters, the $\eta$, $J_{sc}$, $V_{oc}$ and FF, respectively, as a function of the bandgap of the p-MoSe₂ layer. The simulation results show an improvement of the solar cell overall performance in the range from 1.0 eV to 1.3 eV. For instance, the $J_{sc}$ and the $V_{oc}$ increase from almost 38.9 mA/cm² to 42.6 mA/cm² and from 0.62 V to 0.74 V as the bandgap value increases from 1.0 eV to 1.3 eV, respectively. Afterwards, both the current density and the $V_{oc}$ saturate to a bandgap value of 1.45 eV. The optimum values obtained are conversion efficiency of 24.47%, $J_{sc}$ of 42.6 mA/cm², $V_{oc}$ of 0.74 and FF of 78.42%. The results can be interpreted referring to the band alignment and offset at p-MoSe₂/CZTSe heterojunction and the contact potential $qV_o$ of the Mo/MoSe₂ metal-semiconductor junction. The $qV_o$ parameter determines how easy the holes can transport from the valence band of p-MoSe₂ to Mo metal. $\Delta E_v$ is the valence band offset (VBO), defined as the difference in the valance band maximums. When the bandgap energy increases, the $\Delta E_v$ decreases, which assist the hole transport, and as a result, the hampered holes will be transported due to the lowering of the $\Delta E_v$. Reduction of this prohibition of the impeded holes helps to improve the $V_{oc}$, and hence $J_{sc}$ does. The significant impact was assumed to be due to the decrease of $\Delta E_v$, where the dominant carrier type is holes with high concentration. In other words, the insertion of the layer has been found to lead to the formation of the so-called type II heterojunction [29]. At type II, the CB of the absorber is higher than that of the buffer layer forming a cliff-like band alignment. The high concentration of the holes near the semiconductor junction would increase the possibility of interface recombinations. Therefore, it has been shown that such a heterojunction structure is favourable for efficient charge separation [29, 30].

Fig. 4 demonstrates the solar cell performance parameters versus the interfacial layer acceptor carrier concentration ($N_A$) (x-axis) and thickness (y-axis). The doping level was tuned in the range from...
1×10^{12} \text{ cm}^{-3} \text{ to } 1\times 10^{18} \text{ cm}^{-3}, \text{ while the thickness varied from } 10 \text{ nm to } 300 \text{ nm, respectively. As observed from the contour plot, the behaviour is almost constant for doping levels up to } 1\times 10^{16} \text{ cm}^{-3}. \text{ However, above } 1\times 10^{17} \text{ cm}^{-3}, \text{ an increase in the carrier concentration increases all parameters.}

Regarding the interfacial layer thickness, the solar cell performance enhances for MoSe$_2$ thickness up to 70 nm. The $V_{oc}$ is slightly improved from 0.65 V at 10 nm to 0.72 V, and the efficiency reaches almost 24.12% at a thickness of 70 nm. The fill factor remains almost flat at a value of 79%. According to simulated results presented in Fig. 4, the device performance is independent of the MoSe$_2$ layer thickness at a higher doping level above $1\times 10^{17} \text{ cm}^{-3}$. As the doping level decreases below $1\times 10^{17} \text{ cm}^{-3}$, the device output performance parameters become more dependent on the MoSe$_2$ layer for thicknesses greater than 70 nm. However, the effect of the MoSe$_2$ layer thickness is minor. For example, at a heavy MoSe$_2$ doping level of $10^{18} \text{ cm}^{-3}$, the device conversion efficiency increases from 25.19% to 25.4% as the MoSe$_2$ layer thickness increases from 70 nm to 300 nm. A thinner p-MoSe$_2$ layer causes lower shunt resistance, evident from the lower $V_{oc}$ values, and high barriers can exist at the CZTSe/p-MoSe$_2$ interface and p-MoSe$_2$/Mo interface. These barriers impede the drift of the photogenerated holes. Increasing the thickness of the interfacial layer leads to an increase in the optical absorption, which reveals a higher photogenerated charge carrier, leading to better CZTSe solar cells photovoltaic parameters. We can promote the results by looking at the studied CZTSe thin-film solar cell’s band diagram. Many photogenerated carriers recombine at the back contact, and fewer photogenerated electrons can contribute to the quantum efficiency, for the case of thin absorber layers and interfacial. With an increase in the layer thickness, the back-contact recombination current reduces, and consequently, the cell’s performance increases. Moreover, it has been noted that the MoSe$_2$ layer forms a back-surface field for the photogenerated electrons [31]. This produces a contact for holes with low resistivity simultaneously. The back-field causes a reduction in back-contact recombination and, that is why it improves the performance. The relationship between the back-surface field and the recombination rate at the back contact was reported experimentally in, e.g. [32]. Insertion of a layer with a similar conductivity type like the absorber between the back contact and the absorber generates a potential barrier that helps confine the minority carrier in the absorber. Nevertheless, after a specific thickness of p-MoSe$_2$ above 70 nm, the bandgap of p-MoSe$_2$ remains the same without changes. The barrier heights at the CZTS/p-MoSe$_2$ interface and p- MoSe$_2$/Mo interface remain constant. The high absorption causes the generation of more electron-hole pairs in the device, leads to an increase of the current density ($J_{sc}$) at thicker interfacial layers.
Figure 4. (Color online) contour graphs of the simulated parameters versus the doping density of MoSe$_2$ in the range of (10$^{12}$ to 10$^{18}$ cm$^{-3}$) and the thickness of MoSe$_2$ ranging from 10 nm to 300 nm.

We turn our attention now to discuss the performance parameters versus the p-MoSe$_2$ density of carrier concentration. Referring to Fig. 4, it shows that up to N$_A$ of 1×10$^{17}$ cm$^{-3}$, the behaviour is almost constant. However, above 1×10$^{17}$ cm$^{-3}$, one observes enhancement of the studied parameters. This is because that when the majority and minority carriers have similar type in adjacent layers of p-CZTSe and p-MoSe$_2$ as an isotype junction, the effect of N$_A$ is not that dramatic for moderate doping. The obtained results are discussed and interpreted from the interface properties standpoint. As the Mo metal and the MoSe$_2$ are brought in contact, the bands of MoSe$_2$ bend in such a way that the Fermi levels equilibrate. During the stage of contact formation, the conduction and valence bands of the MoSe$_2$ bend to reach an equilibrium state between the metal Fermi level and the MoSe$_2$ potential. Changing the MoSe$_2$ carrier concentration affects the band alignment at the Mo/MoSe$_2$ junction on the one hand and the MoSe$_2$/CZTSe junction. As known, back contact barrier height $\Delta E_c$ and $\Delta E_v$ parameters are considered almost constant no matter the variation in the carrier concentration of p-MoSe$_2$. As a result, the device performance can be assumed to depend on the equilibrium contact potential q$V_o$ and back built-in voltage (q$V_b$) parameters. In general, for Mo/p-MoSe$_2$/CZTSe band alignment, lower negative q$V_b$ and lower q$V_o$ are desirable for hole transport across the surface valence band of CZTSe to valence band p-MoSe$_2$ and from valence band of p-MoSe$_2$ to Mo metal. An increase in N$_A$ results in lower negative q$V_b$ parameters for p-type MoSe$_2$. Increase of N$_A$ in p-MoSe$_2$ results in comparatively beneficial band bending for both CB (E$_c$) and VB (E$_v$) after the junction is formed. Besides, the direction and level of band bending are a metal work function-dependent parameter relative to the Fermi level of the semiconductor. Thus, the increase in the doping level will result in Fermi level-pinning effect. It has been found that when the Fermi level is highly pinned, the best solar cell is formed. The low Fermi level pinning results in a minor band bending of the device and poor performance. As the N$_A$ increases, the Fermi level shifts downwards, resulting in much easiness for the hole flow from CZTSe to MoSe$_2$. It also strengthens the electron flow inhibition from CZTSe to MoSe$_2$, causing a reduction of the carrier recombination at back contact. Hence, higher N$_A$ results in higher $V_{oc}$ due to the favourable band alignment at the back contact.
4. Conclusions
The impact of the p-MoSe₂ interfacial layer on the performance of CZTSe thin-film solar cells was numerically investigated using SCAPS. The results show that the formation of the MoSe₂ layer between the absorber and Mo back contact results in a significant improvement of the overall performance of the CZTSe based solar cell compared to the conventional CZTSe structure. A p-type MoSe₂ layer in CZTSe devices found to facilitate ohmic-contact development, reducing the series resistance. The overall conversion efficiency was observed to increase with the bandgap reaching an optimum value of 25.19 % at Eg of 1.32 eV with high doping level up to 1×10¹⁸ cm⁻³. The results demonstrated that to maintain a remarkable overall performance of the solar cell, the thickness of the interfacial layer should be not less than 100 nm. This is to avoid the effect of the back-contact recombination. Additionally, increasing the doping concentration of the layer above 1×10¹⁷ cm⁻³ improves the cell performance due to the enhanced band alignment at Mo/MoSe₂ and MoSe₂/CZTSe junctions. The results obtained reveal the advantages of using p-MoSe₂ as an interfacial layer in CZTSe solar cells, presenting an alternative approach to boost the output performance of CZTSe solar cell devices.

5. References
[1] K. Gunavathy, V. Parthibaraj, C. Rangasami, K. Tamilarasan, South Asian J. Eng. Technol. 2 (2016)
[2] H. Katagiri, K. Saitoh, T. Washio, H. Shinhara, T. Kurumadani, S. Miyajima, PVSEC 11 Part I, 65 (2001)
[3] B. Shin, Y. Zhu, N. A. Bojarczuk, S. Jay Chey, S. Guha, Appl. Phys. Lett. 101 053903 (2012)
[4] K. Ito, T. Nakazawa, Jpn. J. Appl. Phys. 27 (1988)
[5] H. Katagiri, K. Jimbo, S. Yamada, T. Kamimura, W. S. Maw, T. Fukano, T. Ito, T. Motohiro, Appl. Phys. Express, I (2008)
[6] B. Shin, N.A. Bojarczuk, S. Guha, Appl. Phys. Lett. 102 (2013)
[7] C. Yan, J. Huang, K. Sun, S. Johnston, Y. Zhang, H. Sun, A. Pu, M. He, F. Liu, K. Eder, L. Yang, J. M. Cairney, N. J. Ekins-Daukes, Z. Hameiri, J. A. Stride, S. Chen, M. A. Green, X. Hao, Nat. Energy, 3 (2018)
[8] W. Wang, G. Chen, H. Cai, B. Chen, L. Yao, M. Yang, S. Chen, Z. Huang, J. Mater. Chem. A. 6 (2018)
[9] W. Wang, M.T. Winkler, O. Gunawan, T. Gokmen, T. K. Todorov, Y. Zhu, D. B. Mitzi, Adv. Energy Mater. 4 (2014)
[10] S. Schnabel, M. Seboui, E. Ahlswede, Energies. 10 (2017).
[11] D. Cozza, C. M. Ruiz, D. Duché, J. J. Simon, L. Escoubas, IEEE J. Photovolt. 6 (2016)
[12] D. Abou-Ras, G. Kostorz, D. Bremaud, M. Kälin, F. V. Kurdesau, A. N. Tiwari, M. Döbeli, Thin Solid Films 480-481 (2005)
[13] D. J. Late, C. S. Rout, D. Chakravarty, S. Ratha, Can. Chem. Trans. 3 (2015)
[14] T. Böker, R. Severin, A. Müller, C. Janowitz, R. Manzke, D. Voß, P. Krüger, A. Mazur, J. Pollmann, Phys. Rev. B. 64 (2001)
[15] M. Moustafa, A. Ghafari, A. Paulheim, C. Janowitz, R. Manzke, 12th Int. Conf. Electron. Spectrosc. Struct. ICESS-12. 189 (2013)
[16] M. Moustafa, A. Paulheim, M. Mohamed, C. Janowitz, R. Manzke, Appl. Surf. Sci. 366 (2016)
[17] M. Burgelman, K. Decock, S. Khelifi, A. Abass, Thin Solid Films. 535 (2013)
[18] M. Burgelman, P. Nollet, S. Degreve, Thin Solid Films, 361-362, (2000)
[19] M. Moustafa, T. Alzoubi, Mod. Phys. Lett. B. 32 (2018)
[20] M. Moustafa, T. AlZoubi, Optik. 170 (2018)
[21] S. Yasin, T. Al Zoubi, M. Moustafa, Optik. 229 (2021)
[22] T. Alzoubi, M. Moustafa, Mod. Phys. Lett. B. 34 (2020)
[23] S. Enayati Maklavani, S. Mohammadnejad, Opt. Quantum Electron. 52 (2020)
[24] M. T. Ferdaous, S. A. Shahahmadi, P. Chelvanathan, Md. Akhtaruzzaman, F. H. Alharbi, K. Sopian, S. K. Tiong, N. Amin, Sol. Energy. 178 (2019)
[25] T. Al Zoubi, M. Moustafa, G. Laouini, S. Yasin, 10th Int. Conf. Key Eng. Mater. 33 (2020)
[26] H. J. Gu, J.-H. Yang, S. Y. Chen, H. J. Xiang, X.G. Gong, APL Mater. 7 (2019)
[27] R. J. Matson, O. Jamjoum, A. D. Buonaquisti, P. E. Russell, L. L. Kazmerski, P. Sheldon, R. K., Sol. Cells. 11 (1984)
[28] I. M. Dharmadasa, J. D. Bunning, A. P. Samantilleke, T. Shen, Sol. Energy Mater. Sol. Cells. 86 (2005)
[29] K. Jiao, C. Duan, X. Wu, J. Chen, Y. Wang, Y. Chen, Phys. Chem. Chem. Phys. 17 (2015)
[30] D. Gross, I. Mora-Seró, T. Dittrich, A. Belaidi, C. Mauser, A.J. Houtepen, E.D. Como, A.L. Rogach, J. Feldmann, J. Am. Chem. Soc. 132 (2010)
[31] H. W. Schock, U. Rau, Int. Conf. Defects Semicond. 308–310 (2001)
[32] J. Guillemoles, P. Cowache, A. Lusson, K. Fezzaa, F. Boisivon, J. Vedel, D. Lincot, J. Appl. Phys. 79 (1996)