

RESEARCH ARTICLE

Optimization of Metal Semiconductor Junctions and $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ Heterojunction in a Thin Film Solar Cell

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ABSTRACT: Kesterite materials, like $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$, are one of the foremost materials as an absorber layer in thin-film solar cells due to their adaptable bandgap and high absorption coefficient above 10^4 cm^{-1} . Both the electron and hole transport layers in a solar cell are crucial for transferring electrons and holes to their respective contacts. In this work, we have analyzed the metal semiconductor junctions (both front and back contacts) and optimized the $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ heterojunction of a $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$ based solar cell to diminish the recombination losses of the cell, concentrating on their energy band alignment, carrier transport mechanism, and interface defect impacts. Through simulation and analytical modelling, we explored the nature of the contact (ohmic or Schottky) that is censoriously governed by the metal's work function relative to the semiconductor's electron affinity, influencing charge injection and barrier formation. We evaluated how electron (σ_n) and hole (σ_p) capture cross sections, along with interface defect density (N_t), influence recombination dynamics at the interface and affect the device efficiency. These findings emphasize the importance of the choice of contact materials, interface treatment, and band alignment strategies to diminish recombination losses and maximize the power conversion efficiency. This analysis and optimization provided the maximum efficiency (η) of 33.15% with a V_{oc} of 1.15 V, a J_{sc} of 31.116 mA/cm^2 , and an FF of 89.39%.

Keywords: $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$, Thin film solar cell, Metal semiconductor junction, Heterojunction.

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1. INTRODUCTION

The p-type absorber layer $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$ consists of copper (Cu), zinc (Zn), tin (Sn), sulphur (S), and selenium (Se) [1, 2], which are plentiful on earth and non-poisonous materials [3-5]. It is a potential and emerging candidate for the photovoltaic (PV) solar cell due to an adjustable band gap from 1 eV to 1.5 eV [6-8] and a high photon absorption coefficient (greater than 10^4 cm^{-1}) [9, 10]. $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) is a low-cost alternative [11] to (CIGS) and CdTe-based solar cells since the elements such as indium (In) and gallium (Ga) are expensive, infrequent, and poisonous [12, 13]. In

heterojunction cell structure, a ternary II-VI semiconductor compound, $\text{Zn}_y\text{Cd}_{1-y}\text{S}$ (Zinc cadmium sulfide) [14, 15], is a decent candidate in the field of optoelectronic devices and is broadly used as a window layer because of its expanse and adjustable band gap of 2.40 eV (CdS) to 3.6 eV (ZnS) [16-18]. Its lattice parameters, as well as its optical and electrical properties can be varied depending on the Zn content (y) [19]. However, CZTS-based solar cells suffer from several aspects, such as grain boundaries (GBs) defects, recombination losses in the junctions of the solar cell, less efficient of electron and hole transfer in the electron transport layer (ETL) and hole transport layer (HTL), and lattice mismatch (LM) in the $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ heterojunction. Several forms of defects in the absorber layer generate trap states as an outcome of increasing the recombination losses in the cell and diminishing the performance of the solar cell (SC) [20]. In order to explicate the deprived performance of the solar cell, a detailed investigation of the loss mechanism is

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necessary. To improve the power conversion efficiency (PCE) of the CZTS-based solar cell, it is important to investigate the ETL and HTL and their junction recombination. Additionally, recombination losses and LM of the $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ heterojunction also need to be investigated for the better performance of the modified solar cell. Therefore, a comprehensive investigation on the metal semiconductor (MS) junctions and which window layer ($\text{Zn}_y\text{Cd}_{1-y}\text{S}$, ZnS , and CdS) creates the best heterojunction with absorber layer $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$ that reduces the LM has been conducted in this work for better performance. In a thin-film solar cell, the metal-semiconductor junction serves as a monumental interface since charge injection, extraction efficiency, and overall device performance largely depend on it. The band bending near the interface and formation of interface potential due to the Fermi level differences [21], which modifies the carrier transport characteristics when a metal and a semiconductor (p-type or n-type) are brought into contact. The metal and n-type semiconductor like SnO_2 interface often gives rise to a Schottky barrier that obstructs electron movement unless the metal work function is adequately low. Conversely, in a p-type semiconductor like MoS_2 , where the majority carriers are holes, the formation of Schottky or ohmic contact depends on whether the metal work function is higher than that of the semiconductor. MoS_2 can be used as both p-type and n-type material based on the sulphur vacancies, doping level, chemical treatment or phase engineering [22-24]. In its p-type forms, MoS_2 exhibits an efficient hole transport characteristic, creating ohmic contact with the higher metal work function (e.g., $\text{Pt}/\text{Au}/\text{Ni}$). SnO_2 is widely utilized as a transparent conducting oxide (TCO) and ETL in solar cells due to its wide band gap and strong n-type conductivity [19]. Proper layer optimization of SnO_2 , including carrier concentration, band gap, and electron affinity (χ) creates an ohmic contact with front contact metals instead of a Schottky contact, which is crucial for facilitating electron extraction and reducing the recombination of the device. A recent SCAPS-1D simulation by Merzouk et al. compared the window layer in a CZTS solar cell, specifically CdS versus ZnS [25]. It demonstrated the performance ($\eta = 16.29\%$, $V_{oc} = 0.70$, $J_{sc} = 28.41 \text{ mA}/\text{cm}^2$, and $\text{FF} = 83.42\%$) of a solar cell for the ZnS instead of CdS . However, the use of molybdenum (Mo) with CZTS without incorporating a proper back surface field (BSF) layer often results in the formation of a Schottky barrier at the back contact instead of an ohmic contact. This barrier reduces the device's open-circuit voltage (V_{oc}) and fill factor (FF) by increasing interfacial recombination and impeding effective carrier transport. To overcome this drawback, it is important to investigate the window layer and BSF to improve the band alignment, suppress recombination, and enhance overall device efficiency. Incorporation of the transition metal dichalcogenides (TMDs) material like MoS_2 , WS_2 , MoSe_2 , and WSe_2 reduces the series resistance (R_s) in the BSF since they create an ohmic contact with the back contact metal platinum (Pt) during the investigation. In this work, we mainly focused on the MoS_2 as a BSF and investigated the effect of the interface of Pt/MoS_2 for various band gaps (E_g),

acceptor carrier concentrations (N_A), and electron affinities (EA) values in the MoS_2 layer [26]. Additionally, we analyzed the properties of WS_2 , MoSe_2 , and WSe_2 to investigate the performance of the solar cell [27-29]. Moreover, we have studied the variation of the band gaps (E_g) and donor carrier concentrations (N_D) of the TCO (SnO_2), and Al/SnO_2 interface in the cell to analyse the recombination losses of the device. The key outcome of this study is to investigate the recombination losses of metal semiconductor junctions and $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ heterojunction of a thin-film solar cell for better performance.

2. METHODOLOGY AND LAYER PROPERTIES

In this numerical study, a solar cell capacitance software called SCAPS-1D [30] is used to simulate the effect of BSF, TCO layer, and $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ heterojunction of $\text{Pt}/\text{MoS}_2/\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}/\text{Zn}_2\text{SnO}_4/\text{SnO}_2/\text{Al}$ structured solar cell. This software was developed at the Department of Electronics and Information Systems (ELIS) at the University of Ghent, numerically solves the Poisson, continuity, and carrier transport equations to characterize the solar cell devices, which are given below [31-33].

Poisson equation:

$$d^2\psi(x)/dx^2 = -q/\epsilon[p(x)-n(x)+N_D^+(x)-N_A^-(x)+p_t(x)-n_t(x)] \quad (1)$$

Continuity equations:

$$dn(x)/dt = 1/q \cdot dJ_n(x)/dx + G_n(x) - R_n(x) \text{ for electron} \quad (2)$$

$$dp(x)/dt = -1/q \cdot dJ_p(x)/dx + G_p(x) - R_p(x) \text{ for hole} \quad (3)$$

Carrier transport equations:

$$J_n(x) = q\mu_n n(x) d\psi(x)/dx + qD_n dn(x)/dx \text{ for electron} \quad (4)$$

$$J_p(x) = q\mu_p p(x) d\psi(x)/dx - qD_p dp(x)/dx \text{ for hole} \quad (5)$$

where $\psi(x)$, q , ϵ , $p(x)$, $n(x)$, $N_D^+(x)$, $N_A^-(x)$, $J_n(x)$, $J_p(x)$, $G_n(x)$, $G_p(x)$, $R_n(x)$, $R_p(x)$, μ_n , μ_p , D_n , D_p , n_t , and p_t are the Electrostatic potential, elementary charge, permittivity of the material, concentrations, ionized donor and acceptor concentrations, current densities, generation rates, recombination rates, mobilities, diffusion coefficients, and trapped concentration for electrons and holes.

Incorporation of the interfacial layer, MoS_2 , significantly stimulates the electronic band alignment at the Pt/MoS_2 metal semiconductor junction and the $\text{MoS}_2/\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$ heterojunction. In this work, we initially explored the effect of the MoS_2 by varying the band gaps from 1.2 eV to 1.4 eV, electron affinities (χ) from 4.0 eV to 4.2 eV, and the carrier concentrations from 10^{19} cm^{-3} to 10^{21} cm^{-3} [24, 34]. We perceive how these properties influence the band alignment, charge transport, recombination mechanism, and the overall efficiency of the

device.

The interfacial electronic characteristics, including barrier height at the back contact with respect to the conduction band edge (Φ_{Bn}), the barrier height relative to the valence band edge (Φ_{Bp}), equilibrium contact potential (qV_o), conduction band offset (CBO), valence band offset (VBO), and built-in voltage (qV_{biback}) were determined using the following equations [24]:

$$\Phi_{\text{Bn}} = \Phi_m - \chi_s \quad (6)$$

$$\Phi_{\text{Bp}} = E_g - \Phi_{\text{Bn}} \quad (7)$$

$$qV_o = \Phi_m - \Phi_s; \text{ for n-type semiconductor/metal junction} \quad (8)$$

$$qV_o = \Phi_s - \Phi_m; \text{ for p-type semiconductor/metal junction} \quad (9)$$

$$\text{CBO} = \chi_{\text{CZTSxSe1-x}} - \chi_{\text{MoS2}} \quad (10)$$

$$\text{VBO} = (\chi + E_g)_{\text{MoS2}} - (\chi + E_g)_{\text{CZTSxSe1-x}} \quad (11)$$

$$qV_{\text{biback}} = \Phi_{\text{MoS2}} - \Phi_{\text{CZTSxSe1-x}} \quad (12)$$

where Φ_m is the work function of the metal and Φ_s is the work function of the semiconductor. The value of Φ_s for the both n and p type was determined by the following equations:

$$\Phi_s = \chi_s + (kT \ln N_c / N_D); \text{ for n-type semiconductor} \quad (13)$$

$$\Phi_s = \chi_s + E_g - (kT \ln N_v / N_A); \text{ for p-type semiconductor} \quad (14)$$

Where T , N_c , N_v , q , k , N_A , and N_D are temperature, effective density states in the conduction band, effective density of the valence band, electron charge, Boltzmann constant, and acceptor and donor concentration for the n-type and p-type semiconductor, respectively. There are two types of contacts, called Ohmic and Schottky can be formed depending on the value of work function (Φ) of the metal and semiconductor. For the Pt/p-MoS₂ junction, Schottky contact generates the potential barrier, denoted as qV_o , which is the cause of disrupts the hole transport from the semiconductor valence band to the metal. However, we have explored Pt/MoS₂ by varying the values of carrier contraction and work function of the metal using equations (9), (13) and (14) and detected that the Ohmic contact provides us the better performance than the Schottky contact. We also do the same analysis for the Al/n-SnO₂ junction and identified the optimum values that are broadly discussed in the results and discussion section. In this work, we have used lower metal work function in the front contact and higher metal work function in the back contact to form the Ohmic contact and achieve the better performance of the device. We used SnO₂ and MoS₂ as a TCO and BSF layer respectively and investigated their behaviour in the interfaces with contact metals, focusing on their role of controlling charge carrier injection and extraction.

We have studied about the structural properties of the absorber layer ($\text{CZTS}_x\text{Se}_{1-x}$)₄ and window layer ($\text{Zn}_y\text{Cd}_{1-y}\text{S}$)

and numerically analysed the lattice parameters of both layers [35]. The values of the lattice constant (**a**) depending on the value of the mole fraction x were determined by Vegard's law [36-39].

$$a_{\text{ZnyCd1-yS}} = x a_{\text{ZnS}} + (1-x) a_{\text{CdS}} \quad (15)$$

$$a_{\text{CZTSxSe1-x}} = x a_{\text{CZTS}} + (1-x) a_{\text{CZTSe}} \quad (16)$$

$$\text{Lattice mismatch (LM) \%} = (a_{\text{window}} - a_{\text{absorber}}) / a_{\text{absorber}} \quad (17)$$

Here '**a**' denotes the lattice parameter of the corresponding materials while a_{window} and a_{absorber} refer precisely to the lattice parameter of the window and absorber layer respectively. The intention of the analysis is to determine the LM using equation (17) in the heterojunction of $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ and find out the best lattice structure of both the window and absorber layers of the device. To appraise the interfacial band alignment of the proposed solar cell structure, the CBO and VBO were determined using Anderson's electron affinity rule. This scrutiny was crucial to determine whether the band alignments shaped a spike, cliff, or flat junction, which directly affected device performance metrics such as open circuit voltage (V_{oc}) and short circuit current (J_{sc}). We investigated how CBO and VBO affect the ETL and HTL to transfer the electrons and holes in the front and left contact of the solar cell and explained it in section 3.1 of this research.

In this simulation, the series resistance (R_s) was assumed to be $0 \Omega \cdot \text{cm}^2$, while the shunt resistance (R_{sh}) was set to $0.5 \text{ M}\Omega \cdot \text{cm}^2$, under standard practices in the SCAPS-1D modelling. The device was simulated under a constant operating temperature of 300 K. Illumination was applied through the front contact (n-SnO₂) using the AM 1.5G solar spectrum [40], representing standard terrestrial conditions. All applicable electrical and optical properties exploited in this study are expansively listed in Tables 1, 2, and 3. The thermal velocities for both electrons and holes were homogeneously taken as 10^7 cm/s across all layers.

We considered two different interfacial layers, such as BSF/absorber and absorber/window, and their interfacial parameters, like defect type, which was single acceptor and donor for n-type and p-type, respectively. Electron and hole capture cross sections were $1 \times 10^{-19} \text{ cm}^2$ for both interfaces. The optical properties of the TCO layer were modelled by setting the reflectance (R) and transmittance (T) values to 0.1 and 0.9, respectively. Additionally, the electron and hole capture cross sections in the absorber, BSF, and window layers were each set to 10^{-15} cm^2 , resulting in subsequent steadiness in recombination modelling.

3. RESULTS AND DISCUSSION

3.1. Optimization of $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ heterojunction of the modified cell structure

We have studied the lattice constants of both the window and

absorber layer of the modified solar cell of $\text{Pt}/\text{MoS}_2/\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}/\text{Zn}_2\text{SnO}_4/\text{SnO}_2/\text{Al}$ structure, and selected these values based on the reported experimental and theoretical data. For the quaternary absorber layer $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$, the lattice parameter ‘a’ was assumed to vary between 5.431 Å for pure CZTS ($x=1$) and 5.685 Å for pure CZTSe ($x=0$) [37] according to equation (16), and those values were included in Table 2. For the window layer

$\text{Zn}_y\text{Cd}_{1-y}\text{S}$ lattice parameter ‘a’ was 5.406 Å ($y=1$) for ZnS and 5.842 Å ($y=0$) for CdS [39]. Lattice parameters of the $\text{Zn}_y\text{Cd}_{1-y}\text{S}$ layer for different Zn compositions (y) have been calculated based on equation (15) and listed in Table 3. These values were used to analyse the LM and interface behaviour of the heterojunction of $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$, which is a vital factor manipulating interface defect density and carrier recombination.

Table 1. Material properties of each layer in SCAPS-1D simulation.

Parameters	SnO_2	Zn_2SnO_4	$\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ ($x=0.7$)	$\text{Zn}_y\text{Cd}_{1-y}\text{S}$ ($x=0.6$)	$\text{MoS}_2/\text{MoSe}_2/\text{WS}_2/\text{WSe}_2$
W (nm)	50	50	1000	50	100
E_g (eV)	3.6	3.35	1.365	3.07	1.2/1.45/1.29/1.55
χ (eV)	4.5	4.5	4.0	4.14	4.0/4.05/4.05/4.03
ϵ/ϵ_0	9	9	13.6	9.3	13.6/11.9/13.6/13.8
N_c (cm^{-3})	2.2×10^{18}	2×10^{18}	2.2×10^{18}	2.1×10^{18}	$2.2 \times 10^{18}/2.8 \times 10^{19}/2.2 \times 10^{18}/1.4 \times 10^{19}$
N_v (cm^{-3})	1.8×10^{19}	1.5×10^{19}	1.8×10^{19}	1.7×10^{19}	$1.8 \times 10^{19}/2.65 \times 10^{19}/1.8 \times 10^{19}/8.3 \times 10^{18}$
μ_e (cm^2/Vs)	100	32	100	65	100/1450/100/30
μ_p (cm^2/Vs)	25	03	25	15	25/50/100/30
n, p (cm^{-3})	10^{17}	10^{19}	10^{19}	2.5×10^{15}	10^{21}
N_t (cm^{-3})	-	-	10^{14}	10^{14}	10^{14}
Defect type	-	-	Single donor	Single acceptor	Single donor

Note: Where, W, E_g , χ , ϵ/ϵ_0 , N_c , N_v , μ_e , μ_p , n, p, and N_t are the layer thickness, band gap, electron affinity, permittivity, CB effective density of states, VB effective density of states, electron mobility, hole mobility, shallow uniform (donor/acceptor) density, and defect density of each layer.

Table 2. Variations of stoichiometry, lattice parameters, and band gap for sulfur content (x) of $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$.

Composition (x)	Bandgap (eV)	Stoichiometry	Lattice parameter(a) (Å)
x = 0.4	1.2168	$\text{Cu}_2\text{ZnSnS}_{1.6}\text{Se}_{2.4}$	5.5834
x = 0.5	1.2675	$\text{Cu}_2\text{ZnSnS}_2\text{Se}_2$	5.558
x = 0.6	1.3168	$\text{Cu}_2\text{ZnSnS}_{2.4}\text{Se}_{1.6}$	5.5326
x = 0.7	1.3647	$\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$	5.5072
x = 0.8	1.4112	$\text{Cu}_2\text{ZnSnS}_{3.2}\text{Se}_{0.8}$	5.4818
x = 0.9	1.4563	$\text{Cu}_2\text{ZnSnS}_{3.6}\text{Se}_{0.4}$	5.4564

Table 3. Material properties of $\text{Zn}_y\text{Cd}_{1-y}\text{S}$ for different Zn compositions (y).

Parameter	y=0.1	y=0.2	y=0.3	y=0.5	y=0.6	y=0.8
μ_e (cm^2/Vs)	95	85	75	70	65	60
μ_p (cm^2/Vs)	35	30	25	20	15	10
n, p (cm^{-3})	2.5×10^{16}	1.7×10^{16}	1.6×10^{16}	4.1×10^{15}	2.5×10^{15}	1.7×10^{15}
E_g (eV)	2.55	2.58	2.64	2.70	3.07	3.33
χ (eV)	4.44	4.38	4.32	4.26	4.14	4.02
Lattice parameter (a), Å	5.7984	5.7548	5.7112	5.624	5.5804	5.4932

The output parameters of the solar cell, including open circuit voltage (V_{oc}), short circuit current (J_{sc}), fill factor (FF) & efficiency (η), and interfacing factors such as CBO & VBO, and LM between the absorber & window layers are presented in Table 4 for the various heterojunctions based on the x and y values of the absorber and window layers. A significantly high efficiency (33.15%) was observed for cell 3 of heterojunction $\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$ due to the CBO of -0.04 eV, VBO of -1.745 eV, and a low lattice mismatch (1.33%) of the cell. A very small cliff of -0.04 eV (nearly flat band alignment) is ideal for minimizing electron recombination at the interface. It is decent for efficient electron transport from the absorber layer into the window layer without forming a barrier or extreme recombination losses. On the other hand, a larger negative VBO of -1.745 eV indicates that the valence band of the absorber is much higher than that of the window layer. This creates a strong barrier for hole injection into the window layer, which is beneficial because holes should be collected at the back contact rather than at the window layer. A low lattice mismatch of 1.33% between the absorber and the window layers indicates that their crystal structures are closely aligned. This minimizes the formation of misfit dislocations and interface defects, which are significant sources of carrier recombination. As a result, the quality of the heterojunction interface is improved, leading to enhanced carrier separation and transport.

The efficiency drops to 31.83% in cell 4, although CBO is slightly positive (+0.08 eV). A negative LM (-0.25%) in this heterojunction means that the window layer lattice constant is smaller than the absorber layer, leading to compressive strain at the interface. Even though -0.25% is small, compressive strain can still introduce misfit dislocations and interface defects. As a result of these interface defects acting as recombination centres, the electron-hole pair losses arise in the heterojunction.

We have also simulated for CdS and ZnS as a window layer [32, 41], and only included the parameters for the CdS in Table 4 because we found a convergence failure for the ZnS. The efficiency has slightly gone down for the CdS because it creates a larger negative cliff of -0.3 eV, which increases the recombination loss in the interface due to unfavourable band alignment. CdS has a relatively large lattice constant (5.842 Å) and forms a very high lattice mismatch of 6.08% with the layer $\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$. This leads to the introduction of interface dislocations, crystal strain, and defect states that act as recombination centres. We simulated and calculated all of the theoretically possible combinations for the $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4$ absorber and $\text{Zn}_y\text{Cd}_{1-y}\text{S}$ window layers data that are listed in Tables 2 and 3, and we included only the best heterojunctions in Table 4. We found the highest efficiency, which is above 33% for cells 2 and 3, and the other cell efficiencies were lower than 33%. During this investigation, other layer properties are detailed in Table 1. This investigation reveals that the collective optimization of CBO, VBO, and lattice mismatch is crucial for exploiting the cell performance. The best results were accomplished when CBO was near zero and slightly negative,

and VBO was large and negative to facilitate hole blocking. Additionally, the lattice mismatch was minimized to below 2%. The heterojunction band alignment diagram of the window layer and absorber layer with CBO and VBO values of four particular distinct combinations of the cells 3, 4, 7, & 10 is displayed in Figure 1. After this investigation, it is evident that the use of $\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}$, and $\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$ as window and absorber layers provided the best performance as compared to the other compositions of the corresponding layers.

3.2. Optimization of the metal semiconductor junctions

It is vital to optimize the metal-semiconductor junction of a solar cell to make sure that charge carriers are extracted efficiently, the band alignment is optimized, the interfacial recombination loss is low, and the device stability is increased. In this work, we investigated both the front and back contacts by varying the layer properties of ETL and HTL materials and for different contact metals in the simulated solar cell structure of $\text{MoS}_2/\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}/\text{Zn}_2\text{SnO}_4/\text{SnO}_2$. Each of the metal semiconductor junctions has been explored in the following two sub-sections of 3.2.1 and 3.2.2.

3.2.1. Analysis of back contact metals (Pt/Au/Mo/Al) and TMDs interfacial layer on proposed solar cell performance

A simulated solar cell structure of $\text{Mo}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}/\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}/\text{Zn}_2\text{SnO}_4/\text{SnO}_2/\text{Al}$, without a BSF provided a lower performance ($V_{oc} = 0.67$ V, $J_{sc} = 24.54$ mA/cm², FF = 83.65%, and $\eta = 13.96\%$) as compared to the cell structure of assimilation of a BSF of MoS_2 . We obtained this lower result due to the larger work function of $\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$, $\Phi_{\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}} > \Phi_{\text{Mo}}$, which created a positive back contact barrier, Φ_{Bp} of 0.8647 eV, and contact potential, qV_o of 0.85 eV, and this exhibited Schottky contact, which causes recombination losses in the back contact of the cell. Consequently, this leads to a reduction in the V_{oc} , J_{sc} , FF, and conversion efficiency (η) of the simulated solar cell. To achieve higher performance, we have used metal contacts, platinum and gold (Pt/Au) of higher work function (Φ), and incorporated a back surface field of bulk p- MoS_2 . In this work, we varied the band gaps from 1.2 eV to 1.4 eV, acceptor carrier concentrations (N_A) from 10^{19} cm⁻³ to 10^{21} cm⁻³, electron affinities from 4.0 eV to 4.2 eV of bulk p- MoS_2 and listed all of the interface electronic parameters in Table 5 for the metal semiconductor junction of Pt/ MoS_2 . It is to be noted that, in this simulation, we have primarily omitted band-to-band (radiative) recombination by setting the radiative recombination coefficient to zero. A positive qV_o is responsible for a Schottky-type contact designating an energy barrier that hampers carrier flow, whereas a negative value of qV_o is distinctive of an ohmic contact, endorsing competent carrier transport [24].

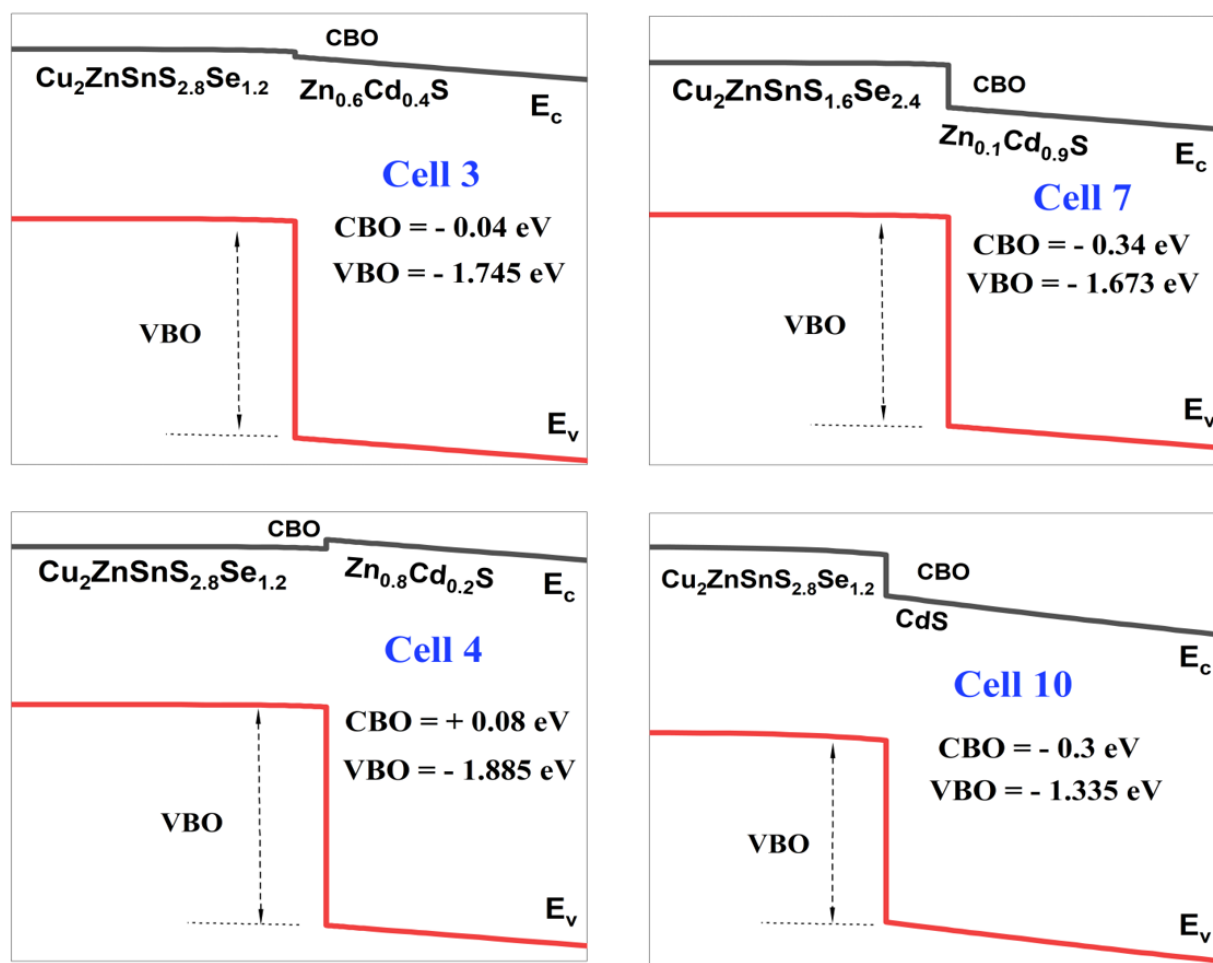


Fig. 1. Heterojunctions band alignments between the absorber and window layer with CBO and VBO values of cells 3, 4, 7, and 10.

Table 4. Output parameters performance of $\text{Cu}_2\text{ZnSn}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ heterojunction for the variation of x & y values in absorber and window layer respectively.

Cells	Heterojunctions	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	PCE (%)	CBO (eV)	VBO (eV)	LM (%)
1	$\text{Zn}_{0.3}\text{Cd}_{0.7}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$	1.1511	32.115	89.26	33.00	-0.22	-1.495	3.70
2	$\text{Zn}_{0.5}\text{Cd}_{0.5}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$	1.1540	32.115	89.43	33.14	-0.16	-1.495	2.12
3	$\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$	1.1546	32.116	89.39	33.15	-0.04	-1.745	1.33
4	$\text{Zn}_{0.8}\text{Cd}_{0.2}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$	1.1552	32.105	85.82	31.83	0.08	-1.885	-0.25
5	$\text{Zn}_{0.5}\text{Cd}_{0.5}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.4}\text{Se}_{1.6}$	1.1169	32.785	89.16	32.65	-0.16	-1.543	1.65
6	$\text{Zn}_{0.5}\text{Cd}_{0.5}\text{S}/\text{Cu}_2\text{ZnSnS}_{1.6}\text{Se}_{2.4}$	1.0214	34.782	88.32	31.38	-0.16	-1.643	0.73
7	$\text{Zn}_{0.1}\text{Cd}_{0.9}\text{S}/\text{Cu}_2\text{ZnSnS}_{1.6}\text{Se}_{2.4}$	0.9711	34.781	83.78	28.30	-0.34	-1.673	3.85
8	$\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}/\text{Cu}_2\text{ZnSnS}_{3.6}\text{Se}_{0.4}$	1.1800	30.036	89.43	31.70	-0.04	-1.654	2.27
9	$\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}/\text{Cu}_2\text{ZnSnS}_{3.2}\text{Se}_{0.8}$	1.1733	31.126	89.47	32.68	-0.04	-1.699	1.80
10	$\text{CdS}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$	1.1381	32.192	87.42	32.03	-0.30	-1.335	6.08

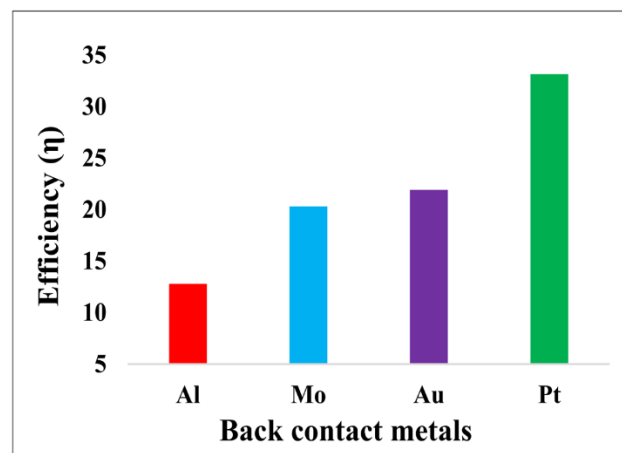
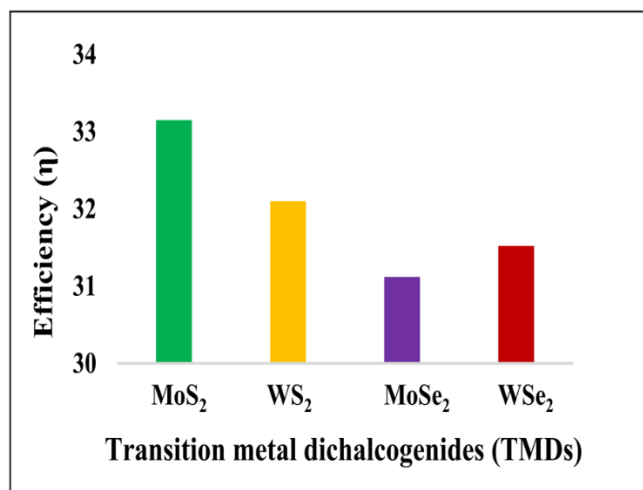
Table 5. Calculated interface parameters of Pt/MoS₂ for various E_g , N_A and EA values in MoS₂ layer.

MoS ₂	N _A (cm ⁻³)	10 ¹⁹			10 ²⁰			10 ²¹		
layer	E _g (eV)	PCE (%)	qV _o (eV)	Φ _{Bp} (eV)	PCE (%)	qV _o (eV)	Φ _{Bp} (eV)	PCE (%)	qV _o (eV)	Φ _{Bp} (eV)
EA:4.0	1.2	29.10	-0.4652	-0.45	31.81	-0.4056	-0.45	33.15	-0.3459	-0.45
	1.3	31.44	-0.3652	-0.35	31.99	-0.3056	-0.35	32.08	-0.2459	-0.35
	1.4	31.54	-0.2652	-0.25	31.55	-0.2056	-0.25	31.56	-0.1459	-0.25
EA:4.1	1.2	29.12	-0.3652	-0.35	31.81	-0.3056	-0.35	33.02	-0.2459	-0.35
	1.3	31.32	-0.2652	-0.25	31.77	-0.2056	-0.25	31.82	-0.1459	-0.25
	1.4	31.29	-0.1652	-0.15	31.30	-0.1056	-0.15	31.31	-0.0459	-0.15
EA:4.2	1.2	28.51	-0.2652	-0.25	30.23	-0.2056	-0.25	30.56	-0.1459	-0.25
	1.3	29.26	-0.1652	-0.15	29.32	-0.1056	-0.15	29.37	-0.0459	-0.15
	1.4	28.90	-0.0652	-0.05	29.12	-0.0056	-0.05	30.04	0.0541	-0.05

At a lower value of N_A ($=10^{19} \text{ cm}^{-3}$), the MoS₂ layer provided an efficient ohmic contact by minimizing the hole injection barrier, Φ_{Bp} ($= -0.45 \text{ eV}$), and maximizing the contact potential qV_o ($= -0.4652 \text{ eV}$). However, we found the highest efficiency (33.15%) for the higher value of carrier concentration (N_A) of 10^{21} cm^{-3} . This was accomplished for a less negative value of qV_o (-0.3459 V) where the contact barrier (Φ_{Bp}) was the same for both combinations of ($E_g = 1.2 \text{ eV}$, $EA = 4.0 \text{ eV}$, $N_A = 10^{21} \text{ cm}^{-3}$) and ($E_g = 1.2 \text{ eV}$, $EA = 4.0 \text{ eV}$, $N_A = 10^{19} \text{ cm}^{-3}$). This is because a high level of doping significantly increases the conductivity of the MoS₂ layer, thereby reducing series resistance for the formation of an ohmic contact. This improvement enhances the FF and facilitates quicker carrier extraction before recombination happens. Additionally, doping upsurges the electric field strength in the depletion region, improving the built-in potential and increasing carrier separation. From Table 5, it is clear that qV_o became less negative, indicating a weaker built-in potential, and also showed fewer negative values of Φ_{Bp} from -0.45 eV to -0.05 eV for increasing the EA values of the MoS₂ layer. Therefore, the higher value of the electron affinity reduces the hole transport efficiency at the Pt/MoS₂ interface, resulting in lower efficiency. It is also exhibited in Table 5 that the efficiency is slightly decreasing for the increasing bandgap of the MoS₂ layer when we set a higher value of N_A and EA to 4.0 eV . The configuration ($E_g = 1.2 \text{ eV}$, $EA = 4.0 \text{ eV}$, and $N_A = 10^{21} \text{ cm}^{-3}$) provided the best numerical performance when considering the high doping concentration and omitting the effect of band-to-band recombination during the simulation in SCAPS 1D software. This performance has slightly decreased when we consider the band-to-band recombination parameters (radiative and Auger). However, after this analysis, it is clear that an optimized p-type MoS₂ layer with lower E_g and EA is beneficial for back contact passivation in CZT($\text{S}_x\text{Se}_{1-x}$)₄ based thin film solar cells.

Figure 2 represents the efficiency performance for the back contact metals, aluminum, molybdenum, gold, and platinum (Al/Mo/Au/Pt), and from this figure it is evident that Pt provided the higher efficiency (33.15%) and formed a perfect ohmic contact with p-MoS₂ due to the high value of the metal work function of Pt [42]. All other metals

(Al/Mo/Au) created Schottky contact with the p-MoS₂, resulting in reduced efficiency for those metals. The graphical representation of efficiencies for the different TMDs is shown in Figure 3.

**Fig. 2.** Efficiency performance for the back contact metals (Al/Mo/Au/Pt).**Fig. 3.** Representation of efficiency performance for the TMDs.

It is evident that MoS_2 demonstrates better performance (33.15% efficiency) than the other TMDs, WS_2 , MoSe_2 , and WSe_2 . During this investigation, Pt has been used as a back contact metal, and it is found that only MoS_2 formed a perfect ohmic contact with Pt, ensuring minimal carrier recombination at the interface and endorsing efficient hole extraction. In contrast, WS_2 exhibited slightly low efficiency (32.10%) because of the formation of a weak ohmic contact with the Pt metal. The efficiency of both WSe_2 (31.52%) and MoSe_2 (31.12%) interfacial layers has decreased due to the formation of a weak Schottky contact with the back contact metal Pt. All of the layer properties of the BSFs are recorded in Table 1, and after this investigation, it is evident that MoS_2 with high carrier concentration (N_A) provides better performance than the other TMDs.

3.2.2. Analysis of front contact metals (Al/Mo/Au/Ni) and n- SnO_2 interfacial layer on proposed solar cell performance

We also inspected the performance of SnO_2 as a TCO layer with different front contact metals of aluminum, gold, molybdenum, and nickel (Al/Au/Mo/Ni) [43, 44]. In this section, we set the donor concentration (N_D) to a moderate value of 10^{17} cm^{-3} , and varied the band gaps of SnO_2 for 2.5 eV, 3.0 eV, and 3.6 eV. The results revealed a prominent disparity in the quantum efficacy spectra, especially in the short wavelength region (UV-visible range), but no significant change in the overall efficiency of the device was observed for the Al/ SnO_2 interfacial layer. Figure 4 is the variation in the quantum efficiency (QE) curve for the band gaps of 3.6 eV, 3.0 eV, and 2.5 eV of SnO_2 .

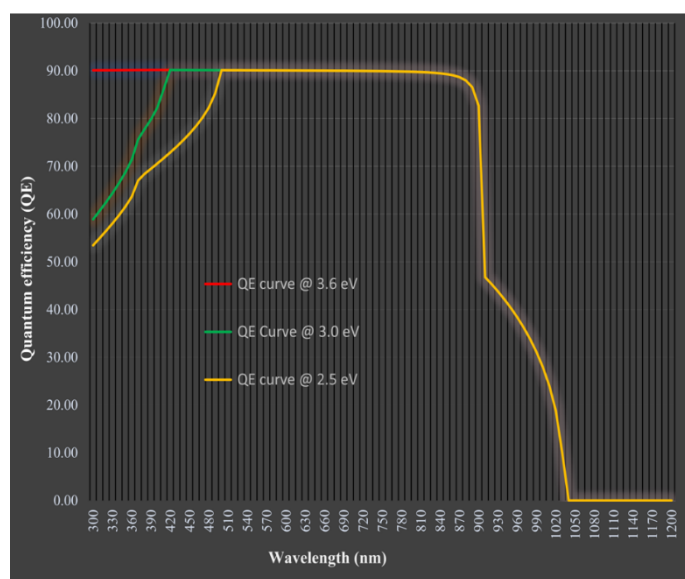


Fig. 4. Effect of band gap of the TCO layer SnO_2 in shorter wavelength of the QE curve.

From this figure, it is seen that there is a significant variation

in the shorter wavelength region (around 300 nm to 500 nm) of the curves. A wide band gap (3.6 eV) ensures transparency in the visible and near UV range by avoiding absorption of incoming photons [45, 46]. If E_g is too low (2.5 eV), TCO absorbs visible light, reducing transparency and QE in the short wavelength region.

Figure 5 shows the efficiency performance for the different front contact metals (Al/Mo/Au/Ni) with the n-type TCO layer SnO_2 . In this study, we investigated the impact of the metal work function of the front contact metals in the (Al/Mo/Au/Ni)- SnO_2 interfacial layer of the simulated solar cell, while keeping the doping concentration (N_D) and band-gap constant. The results revealed that the metal with a lower work function, especially for Al and Mo ($\Phi_{\text{Al}} = 4.28 \text{ eV}$ and $\Phi_{\text{Mo}} = 4.60 \text{ eV}$), formed an ohmic contact, which facilitates efficient electron extraction with the TCO layer of n- SnO_2 and provided the higher conversion efficiencies as compared to the higher value of metal work function ($\Phi \geq 5.0 \text{ eV}$). This reduced contact resistance and minimized recombination losses at the front interface, thereby improving the FF and J_{sc} . For the metals Ni and Au, whose work function is higher than 5 eV, a barrier was formed with an n-type SnO_2 layer, reducing charge carrier collection in the front contact as a result of a decrease in efficiency, and these two metals increase the series resistance and influence optical losses due to the reflection and shadowing.

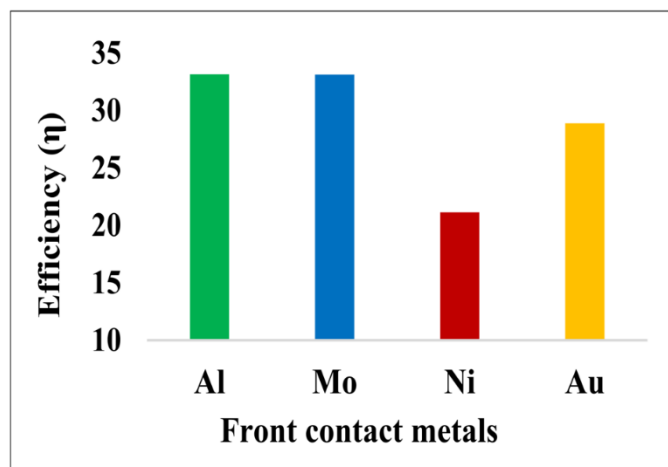


Fig. 5. Efficiency performance for the different front contacts materials (Al/Mo/Ni/Au) with n- SnO_2 .

3.3. Analysis of the $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ and $\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ interfaces parameters on the modified device performance

In this work, we have introduced two different interfaces of $\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ and $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ and investigated the device performance for these two interfaces. For both configurations, we analyzed the impact of both electron and hole capture cross sections (σ_n and σ_p) and also the total density (N_t) of each interface, which unswervingly stimulates the recombination losses and carrier lifetime within the device [47].

Figure 6 represents the efficiency performance for electrons (σ_n) and holes (σ_p) capture cross-section values at two different interfaces: $\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ (first interface) and $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ (second interface). We have varied the capture cross-sections (electrons & holes) values over a wide range of $1 \times 10^{-15} \text{ cm}^2$ to $1 \times 10^{-20} \text{ cm}^2$. In the first interface, $\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ plays a critical role in governing recombination losses. The efficiency of the device is significantly increased from 26.34% at $1 \times 10^{-15} \text{ cm}^2$ to over 33.15% at $1 \times 10^{-19} \text{ cm}^2$ as the capture cross section of electrons values of this interface was decreased, which is shown in the green line of Figure 6. Similarly, there was a minor variation of the efficiency with the variation of the capture cross section of electrons values in the second interface of $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$. In this interface, the efficiency was largely stable with only a slight increase as the cross-section decreased, indicating better innate passivation or lower recombination synergy at the second interface, as indicated by the blue line in Figure 6. Furthermore, there are no significant changes in the efficiency (orange colour line) of the device when varying the σ_p for both $\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ and $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$ interfaces. This indicated that the recombination at the interfaces is primarily governed by the electron capture processes. In this investigation, the interface defect energy level (E_t) was set to 0.6 eV for both interfaces above the valence band maximum, placing the defect states very close to the mid-gap of the $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ absorber. It is to be noted that during this investigation, total defect densities of each interface were set to 10^{10} cm^{-2} , and capture cross-sections (electrons and holes) values were 10^{-19} cm^2 while varying other interfaces.

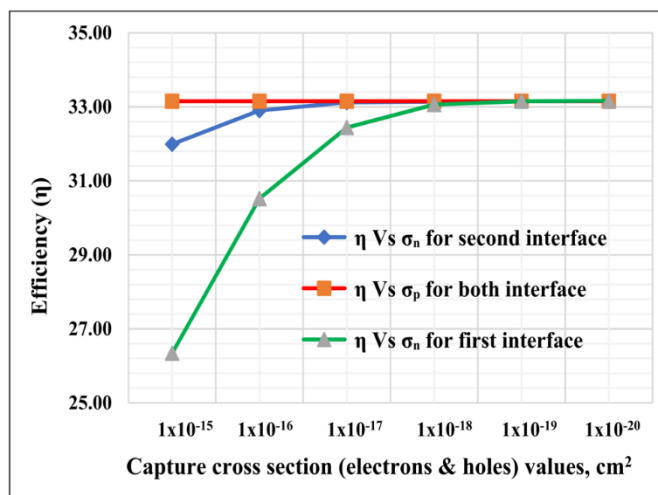


Fig. 6. Graphical representation of the device efficiency for the variation of electrons and holes capture cross sections values of the interfaces $\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ and $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$.

We further analysed the impact of the total interface defect density (N_t) on the device performance for both the first interface ($\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$) and second interface

($\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$) as shown in Figure 7. This investigation shows a negative correlation between N_t and efficiency (η). A reliable decline in efficiency was detected with increasing N_t values, primarily due to the augment in non-radiative recombination via trap aided Shockley–Read–Hall (SRH) processes [48]. As a result, it reduced the J_{sc} and lowered the V_{oc} , and an overall drop in the efficiency. High defect density also shortens the carrier lifetime (τ), causing recombination before reaching the junction and lowering the charge collection. The efficiency of the first interface drops significantly from 33.15% to 26.33% whereas the efficiency of the second interface shows a smaller decrease from 33.15% to 31.97% when the N_t values have been increased from 10^{10} cm^{-2} to 10^{14} cm^{-2} . Because if the high defect density exists in the rear contact, it acts as a strong recombination centre for electrons before they can be collected. This directly reduced the J_{sc} and efficiency (η). So, the rear interface is more serious in terms of defect tolerance. Devices with high N_t at the MoS_2 interface exhibited a stronger decline in efficiency due to their closer involvement with carrier gathering pathways and less favourable band alignment.

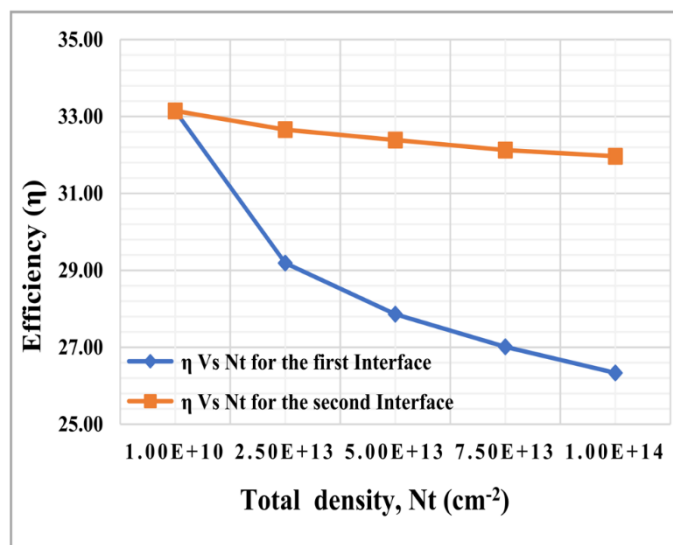


Fig. 7. Impact of the total interface defect density (N_t) on the device performance for both interfaces, $\text{MoS}_2/\text{CZT}(\text{S}_x\text{Se}_{1-x})_4$ and $\text{CZT}(\text{S}_x\text{Se}_{1-x})_4/\text{Zn}_y\text{Cd}_{1-y}\text{S}$.

3.4. Analysis of J-V curve and band diagram of the proposed device structure

In this work, we have chosen a window layer of $\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}$ of 50 nm thickness, an absorber layer of $\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$ (1 μm), and all of the data that are used for the different layers are listed in Table 1. The band diagram of the entire device structure is shown in Figure 8, revealing an optimized conduction band alignment for the $\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}$ window layer and $\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$ absorber layer, with a small negative cliff of -0.04 eV. The MoS_2 layer acts as a BSF, and it creates an ohmic contact with the back contact Pt, improving the hole collection and hence enhancing efficiency.

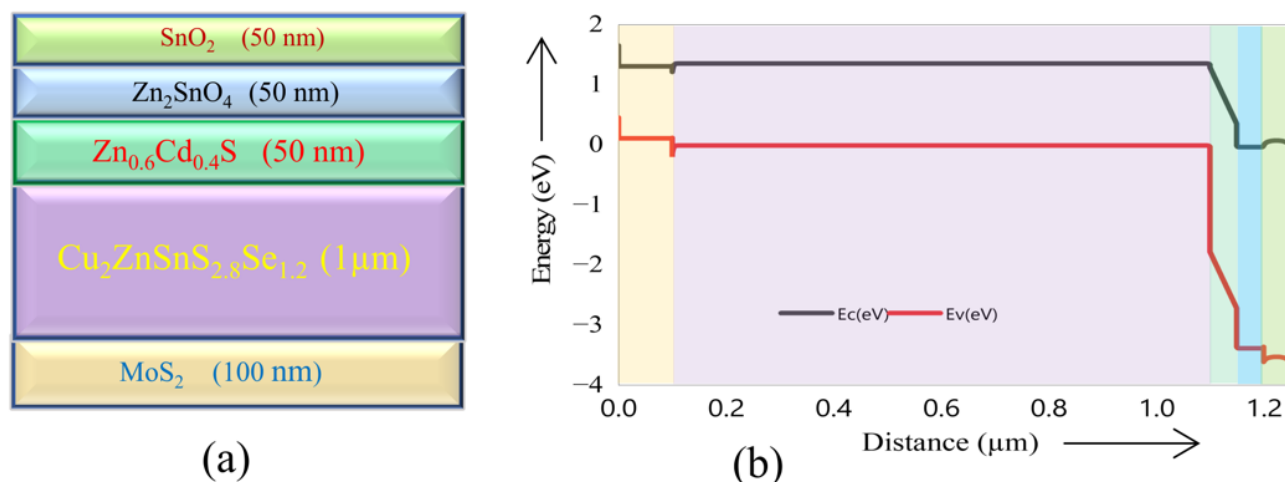


Fig. 8. (a) Device structure of the simulated solar cell and (b) band diagram of the entire solar cell.

To scrutinize the photovoltaic performance of the simulated solar cell structure, we investigated the J-V characteristic curves for four different heterojunctions between the window layer and absorber layer of cells (Table 4) 3, 4, 7, and 10, which is shown in Figure 9.

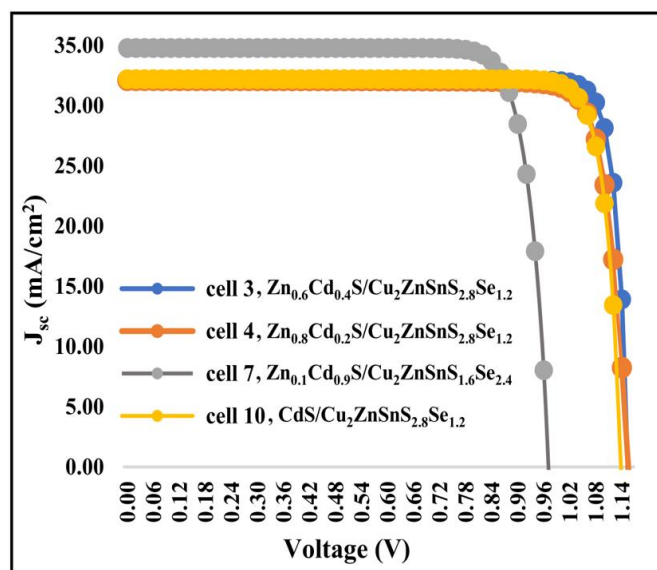


Fig. 9. J-V characteristics curves for the different heterojunctions of cells 3, 4, 7, and 10.

We only mentioned four simulated heterojunctions out of the ten simulated structures to understand the effect of J-V characteristic curves. It has been found that the maximum V_{oc} of 1.15 V, FF of 89.39% and the highest power conversion efficiency of 33.15% for cell 3 of the modified device structure $\text{SnO}_2/\text{Zn}_2\text{SnO}_4/\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}/\text{MoS}_2$, that is the blue line in Figure 9. The J_{sc} was 31.116 mA/cm², which was slightly lower than that of cells 6 and 7, but the conversion efficiency was comparatively low for these cells

because of unfavourable band alignment between the window layer and absorber layer. Similarly, for the pure CdS window layer of cell 10 (indicated by the yellow line), the efficiency was decreased due to the unfavourable band alignment of the heterostructure of CdS/ $\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$. In both cases, they created a negative cliff of -0.34 eV and -0.3 eV, which increased the recombination loss in the heterojunction of the device. However, we have explored several heterostructures of the simulated solar cell and depicted only four particular cells (3, 4, 7, and 10) to examine the effect of the window layer in the simulated solar cell. These findings helped us to select an optimized window layer and absorber layer, which combination provides the favourable band alignment and an optimized heterostructure to reduce the recombination loss in the device.

4. CONCLUSION

In this work, a detailed numerical simulation and analysis of a $\text{SnO}_2/\text{Zn}_2\text{SnO}_4/\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}/\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}/\text{MoS}_2$ modified solar cell structure was accomplished using SCAPS-1D software. The impact of the window layer and absorber layer for different material's compositions (y & x) in their respective layers was examined as well as heterojunctions of the device structure with superior attention to the CBO/VBO. The simulation results revealed that the incorporation of $\text{Zn}_{0.6}\text{Cd}_{0.4}\text{S}$ instead of CdS or ZnS provided a favourable band alignment with $\text{Cu}_2\text{ZnSnS}_{2.8}\text{Se}_{1.2}$ absorber layer. On the other hand, the use of the MoS_2 layer in BSF formed an ohmic contact with the back contact metal (Pt), ensured efficient hole extraction, significantly enhanced the overall efficiency of the device, and this material provided better performance than the other TMDs. The optimized solar cell structure exhibited a maximum efficiency of 33.15 % with a V_{oc} of 1.15 V, FF of 89.39 % and J_{sc} of 31.116 mA/cm². The findings of this research highlighted the optimization of the metal-semiconductor junctions, complimentary heterojunction, and highly favourable band alignment of the entire structure to improve the performance of the modified

solar cell. Future research will be concentrated on fabricating the simulated device structure and optimizing doping profiles using an AI-driven technique.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Availability of data and material

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally to this work.

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