

Numerical Investigation of Advanced Thin-Film Solar Cells Based on SnSe

A. LABIOD^{a,b} AND A. KHADIR^{a,c,*}

^aMaterials Science and Informatics Laboratory, Faculty of Exact Science and Computer Science, University of Djelfa, Cité 05 Juillet route Moudjbara, BP 3117, 17000 Djelfa, Algeria

^bFaculty of Science of Nature and Life, University of Djelfa, Cité 05 Juillet route Moudjbara, BP 3117, 17000 Djelfa, Algeria

^cLaboratory of Metallic and Semiconducting Materials, University of Biskra, BP 145 RP, 07000 Biskra, Algeria

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*e-mail: a.khadir@univ-djelfa.dz

Recently, there has been increased interest in tin selenide (SnSe) material elements in thin-film solar cells. This interest is due to its simple elemental composition, high absorption coefficients, and abundance, making it a cost-effective alternative to CdTe and Cu(In,Ga)(S,Se)₂ materials, which contain rare and expensive elements. Using the one-dimensional Solar Cell Capacitance Simulator software, we simulated a SnSe-based solar cell structure, namely glass/Mo/SnSe/CdS/*i*-ZnO/ZnO:Al, striving to attain greater power conversion efficiency. The initial model was created based on the model with 2.51% efficiency from previous experimental work. We then proposed replacing the toxic CdS with SnO₂ as a buffer layer material and optimizing the absorber and buffer parameters of the device. The optimization focused on thickness, metal work function, electron density of states, shallow acceptor density, radiative recombination, and series and shunt resistances. This optimization resulted in a conversion efficiency of 15.45%. Finally, a copper(I) thiocyanate (CuSCN) layer that helps to transport holes was proposed and then evaluated, leading to significant improvements in open-circuit voltage and fill factor and achieving a remarkable conversion efficiency of 19.68%.

topics: thin-film solar cell, SnSe, SnO₂, Solar Cell Capacitance Simulator (SCAPS)

1. Introduction

Thin-film solar cells (TFSCs) have gained recognition as a viable substitute for traditional photovoltaics (PV) based on silicon crystal systems, employing a variety of semiconductors and configurations [1–4]. In this context, absorber materials such as CdTe and Cu(In,Ga)(S,Se)₂ (CIGS) have undergone extensive research, achieving efficiency rates near 23% and being effectively incorporated into commercial PV modules [5–8]. Nevertheless, the extensive adoption of such PV technologies is hindered by the reliance on scarce elements (In, Ga, and Te) and toxic substances (Cd and Te).

The solar cell research community has shown significant interest over the past decade in kesterite-based materials, such as CZTS (Cu₂ZnSnS₄), CZTSe (Cu₂ZnSnSe₄), and CZTSSe (Cu₂ZnSn(S_xSe_{1-x})₄), due to their non-toxic nature, low cost, and abundance on Earth. These materials have an important absorption coefficient ($> 10^4 \text{ cm}^{-1}$) with a p-type conductivity and

have bandgaps closer to the optimal range for single-junction solar [9, 10]. Regrettably, defects, the emergence of secondary phases, and band-tailing issues constrain the power conversion efficiency (PCE) of kesterite materials [11].

Materials based on chalcogenide metals comprise elements abundant in the Earth, which makes them eco-friendly. They have appropriate optical bandgaps and high coefficients of absorption ($E_g = 1.0\text{--}1.5 \text{ eV}$). These attributes make them excellent candidates for materials that absorb light in future thin-film solar cells (TFSCs), particularly considering several terawatts of expected annual power growth [12]. As a result, sustained efforts have been directed towards improving solar cells with high efficiency based on metal chalcogenide absorbers in thin-film configurations, including Sb₂S₃, Sb₂Se₃, Sb₂(S,Se)₃, and various tin chalcogenides (SnX and SnX₂, such as SnS, SnS₂, SnSe, and SnSe₂) [12–18]. From the aforementioned materials, the focus is centered on Sn-X materials, which crystallize in hexagonal Sn-X₂, monoclinic Sn-X₂, and orthorhombic Sn-X [12].

Furthermore, SnS and SnSe are economically viable compounds within the Sn-X group, containing abundant terrestrial elements that are non-toxic and environmentally friendly. These characteristics make them promising candidates for future photovoltaic applications [15, 19].

SnSe, known for its robust electronic structures with pronounced anisotropy, showcases superior mobilities of hole and electron compared to SnS, primarily attributable to smaller effective masses in its first valence and conduction band valleys [20]. As a result, SnSe exhibits markedly higher electrical conductivities than SnS [21, 22]. Its structure imparts exceptional optical and electrical characteristics, ultra-low lattice thermal conductivity, and excellent thermoelectric performance [23]. These attributes have sparked increasing interest in SnSe for solar cell applications [20].

Various chemical and physical processing techniques have been developed to produce SnSe thin films, with the aim of enhancing the performance of SnSe-based devices [24, 25]. Over the years, many works have reported the development in the performance of thin-film solar cells based on SnSe with cell structure. Reddy et al. [26] reported the first configuration of a planar substrate (Mo/SnSe/CdS/TCO/Al) with a power conversion efficiency of 1.42%. Li et al. [27] described SnSe-based solar cells with a thickness of 1.3 μm , achieving a conversion efficiency of 1.02%. Beltrán-Bobadilla et al. [28] found that thicknesses above 1 μm do not enhance the efficiency of the devices. Nandi et al. [1] fabricated a device using the SnSe/CdS heterojunction, achieving a conversion efficiency of 2.51%. El-Rahman et al. [29] documented a power conversion efficiency of 6.44% for the device configuration Al/Si/SnSe/In. These previously recorded PCE values are significantly below the expected ones, which are predicted to be theoretically between 28 and 32% [30].

Alongside experimental research, there has been a swift increase in numerical studies focusing on tin selenide-based devices. Correspondingly, many investigations have been carried out to assess the performance of these devices. R.K. Yadav et al. [12] demonstrated a power conversion efficiency of 22.69% using a one-dimensional Solar Cell Capacitance Simulator (SCAPS-1D) with a glass/Mo/SnSe/CdS/*i*-ZnO/AZO/Al structure. Similarly, M. Kumar et al. [31] achieved a conversion efficiency of 27.7% with a device structure consisting of a substrate/back contact/SnSe/CdS/*i*-ZnO/ITO/front contact. These works open the doors and encourage numerical study on SnSe-based solar cells.

Cadmium sulfide (CdS) is the most commonly used material in the layer that transports electrons (ETL) in thin-film solar cells (TFSCs). However, it is considered a limiting factor owing to its band gap, which causes current losses in the short-wavelength part of the solar spectrum, and

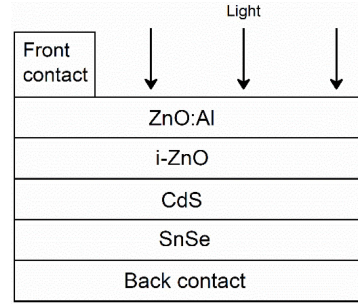


Fig. 1. Structure of the simulated SnSe-based solar cell.

because of concerns about cadmium contamination. Although there have been efforts to replace CdS with cadmium-free compounds, these alternatives have not yet achieved higher efficiency than CdS-based devices [32]. Also, the use of hole transport layers (HTL) is crucial for improving the efficiency of solar cells by lowering recombination losses and easing the transport of carriers to their intended destinations.

Given the limited studies on ETL and HTL in SnSe-based solar cells, this work proposes SnO₂ and NiO as ETL and HTL, respectively. The effects of these materials on SnSe-based solar cell performance are investigated numerically in this work.

2. Theory and models

Experimental processing of solar cells requires significant time and materials. As a result, numerical simulations based on physical principles have become widely adopted because they are more cost-effective and faster than traditional experimental methods [18]. Challenges in measuring information through experiments can be easily overcome using simulations. In this context, numerical simulations of the present work are performed using the one-dimensional (1D) SCAPS simulator [33]. The device geometry shown in Fig. 1 presents the proposed structure, which includes a front-contact/ZnO/*i*-ZnO/CdS/SnSe/back-contact/substrate arrangement. In this structure, the window, buffer, absorber, and back contact layers are composed of ZnO, CdS, SnSe, and molybdenum, respectively. A high-resistivity transparent conductive oxide *i*-ZnO layer is placed next to the CdS layer. This layer is topped with an Al-doped ZnO layer to collect and transport charges from the cell effectively. Table I displays the physical constants and variables related to each material employed in computations extracted from references [12, 17, 18, 31, 33–39]. These parameters are chosen based on theoretical foundations or values obtained from experiments reported in the literature.

Materials' parameters used in the simulation.

TABLE I

Parameter	Unit	ZnO:Al	<i>i</i> -ZnO	CdS	SnSe	SnO ₂	CuSCN
thickness	[nm]	400	80	70	400	70	50
E_g	[eV]	3.6	3.4	2.4	0.98	3.6	3.4
χ	[eV]	4.5	4.55	4.2	4.2	4.4	1.9
χ		9	9	10	12.5	9	10
N_C	[cm ⁻³]	2.2×10^{18}	2.2×10^{18}	2.8×10^{19}	5.3×10^{20}	4.36×10^{18}	1.7×10^{19}
N_V	[cm ⁻³]	1.8×10^{18}	1.8×10^{19}	2.8×10^{19}	1.1×10^{21}	2.52×10^{19}	2.5×10^{21}
$v_{th}(n, p)$	[cm/s]	10^7	10^7	10^7	10^7	10^7	10^7
μ_n	[cm ² /(V s)]	100	100	100	130	240	0.0001
μ_p	[cm ² /(V s)]	25	25	25	56.7	25	0.1
doping	[cm ⁻³]	10^{20}	10^{18}	5×10^{17}	$5.5 \times 10^{16}(p)$	10^{17}	10^{18}
N_t	[cm ⁻³]	3×10^{16}	10^{14}	10^{14}	10^{16}	10^{14}	10^{14}
RRC	[cm ³ s ⁻¹]	2.3×10^{-9}	2.3×10^{-9}	2.3×10^{-9}	2.3×10^{-9}	2.3×10^{-9}	10^{-9}
absorption coefficient		[34]	[34]	[35]	[36]	[38]	[39]

The SCAPS-1D program [33] includes features such as batch calculations and the ability to handle up to seven layers. SCAPS operates using the drift-diffusion model and solves both the Poisson equation and the continuity equations for electrons and holes. These equations are given as follows

$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{q}{\varepsilon} [p(x) - n(x) + N_D - N_A + p_t - n_t], \quad (1)$$

$$\frac{1}{q} \frac{dJ_n}{dx} = -G_{op}(x) + R(x), \quad (2)$$

$$\frac{1}{q} \frac{dJ_p}{dx} = G_{op}(x) - R(x), \quad (3)$$

where ϕ , ε_0 , and ε_r designate the electrostatic potential, vacuum, and relative permittivities, respectively; p and n are the hole and electron concentrations, respectively. The donor impurity and acceptor impurity are denoted with N_D and N_A , respectively. Generation (G) and recombination (R) rates are represented in the device, which is exposed to an AM1.5 spectrum with an incident power density of 100 mW/cm² at room temperature.

The solar cell J - V characteristics under illumination are the sum of the dark and the photo-generated currents densities [40]

$$J = J_L - J_S \left(e^{qV/(a k_B T)} - 1 \right), \quad (4)$$

$$J_S = q \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right) n_i^2 = C T^3 \exp \left(-\frac{E_g}{k_B T} \right), \quad (5)$$

where J_L represents the photo-generated current density, J_S is the diode reverse saturation current density, V is the terminal voltage, k_B is the Boltzmann constant, a is the ideality factor, T is the temperature in Kelvin, L_n and L_p are the diffusion lengths of minority carriers; C is a constant, which combines doping and material parameters; E_g is the energy band gap; n_i is the intrinsic carrier density.

Under the short-circuit condition ($V = 0$), the short-circuit current density equals the photo-generated current density.

The relation between the short-circuit current density and minority carrier diffusion length has the following expression

$$J_{SC} = q G (L_n + L_p), \quad (6)$$

where G denotes the electron-hole pair optical generation rates.

Under the open-circuit condition ($J = 0$), V in (4) becomes V_{OC} , i.e., the open-circuit voltage.

Thus, (4) becomes

$$V_{OC} = \frac{a k_B T}{q} \ln \left(\frac{J_{SC}}{J_S} + 1 \right). \quad (7)$$

The fill factor of a solar cell is given by

$$FF = \frac{J_m V_m}{J_{SC} V_{OC}}. \quad (8)$$

The efficiency of a solar cell can be determined as the maximum output power point with respect to incident power

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{V_{OC} J_{SC} FF}{P_{in}}, \quad (9)$$

where $P_{\max}$ is the maximum output power and P_{in} is the incident solar power.

3. Results and discussions

3.1. Simulation of the base structure

To validate the model against experimental results reported by [1], various parameters, namely, the electronic density of states in the conduction band (CB DOS) and in the valence band (VB DOS), series resistance (R_S), and shunt resistance (R_{SH}), in the proposed structure, were adjusted to achieve a precise match. The specific values identified for

an exact fit are $\text{CB DOS} = 5.3 \times 10^{20} \text{ cm}^{-3}$, $\text{VB DOS} = 1.1 \times 10^{21} \text{ cm}^{-3}$, $R_S = 1.69 \Omega \text{ cm}^2$, and $R_{SH} = 61 \Omega \text{ cm}^2$. The resultant J - V characteristics (the open-circuit voltage (V_{OC}), short-circuit voltage (J_{SC}), fill factor (FF), and power conversion efficiency (η)) are shown in Fig. 2. The electrical outputs obtained from the $J(V)$ characteristics are 0.198 V, 28.18 mA/cm^2 , 45.02%, and 2.51% for V_{OC} , J_{SC} , FF, and η , respectively. These results are very close to [1], which validates our model.

3.2. Effects of SnO_2 as electron transport layer (ETL)

After the model validation, the exploration of the non-toxic, Earth-abundant, and stable buffer material SnO_2 as a substitute for CdS was undertaken; the SnO_2 alloy, known for its wide bandgap, offered the advantage of transmitting short-wavelength photons. Secondly, optimizing some parameters, including absorber layer thickness, buffer layer thickness, metal work function, electronic density of states, acceptor density, coefficient of radiative recombination (RRC), series resistance, and shunt resistance, was done using the new SnO_2 buffer layer material.

The corresponding J - V outputs are shown in Fig. 2. The electrical outputs obtained from the $J(V)$ outputs corresponding to SnO_2 as ETL are 0.199 V, 25.50 mA/cm^2 , 45.74%, and 2.32%, for V_{OC} , J_{SC} , FF, and η , respectively.

3.2.1. SnSe and SnO_2 thickness effects

Optimizing the absorber and buffer layer thickness in photovoltaic devices is crucial for maximizing energy conversion efficiency. The material thickness of these layers affects absorption and electron-hole pair separation. Adjusting layer thickness impacts electron-hole pair generation, carrier travel distances, and recombination chances, influencing V_{OC} , J_{SC} , FF, and η . Hence, the thickness of SnSe and SnO_2 is varied from 0.2 to 1.4 μm and from 0.01 to 0.1 μm , respectively. The effect of SnSe and SnO_2 thickness on electrical outputs is illustrated in Figs. 3 and 4, respectively.

Figure 3 demonstrates that all electrical parameters increase with the thickness of SnSe , except for the fill factor (FF), which rises until 0.8 μm and then stabilizes. This indicates that thicknesses below 0.8 μm are inadequate for sufficient light absorption and result in low efficiency. Conversely, thicknesses exceeding 1.2 μm lead to longer travel paths for photo-generated carriers, increasing carrier recombination and causing only a slight improvement in efficiency. Thus, the optimal thickness for SnSe , balancing light absorption and

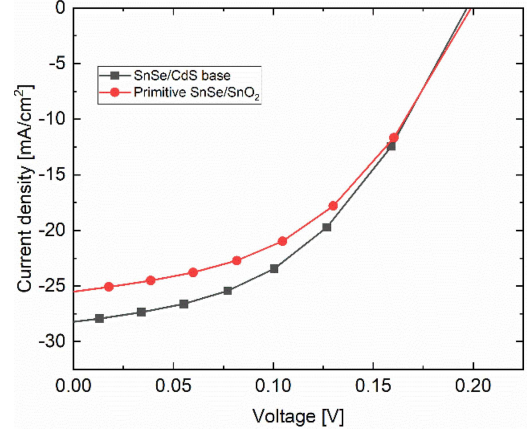


Fig. 2. The $J(V)$ characteristics of SnSe -based primitive solar cell using CdS (black line) and SnO_2 (red line) as ETL.

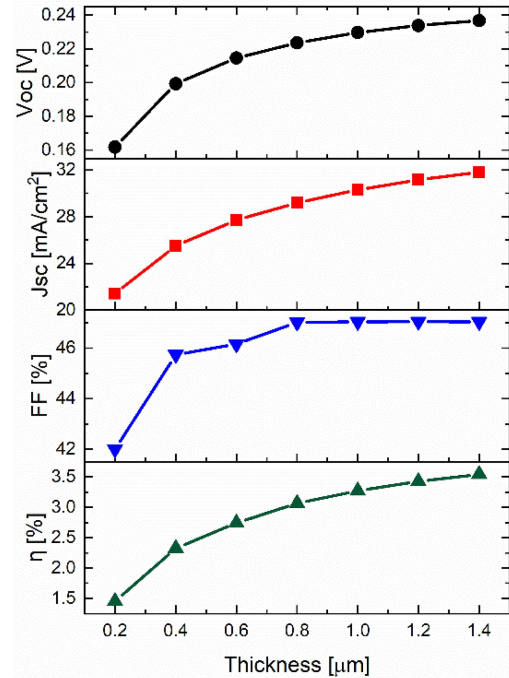


Fig. 3. Effect of SnSe thickness on electrical parameters.

carrier transport, falls between 0.8 μm and 1.2 μm . These findings align with those in [27]. Note that 0.8 μm SnSe thickness gives a conversion efficiency of 3.07%.

In Fig. 4, as the thickness of the SnO_2 increases, there is a noticeable decrease in the open-circuit voltage, short-circuit current, and overall conversion efficiency. Conversely, the fill factor initially decreases with increasing SnO_2 thickness but then starts to rise. In reality, a thicker buffer layer absorbs more photons, which results in a reduction in the number of photons that reach the absorber layer, causing a decrease in conversion efficiency.

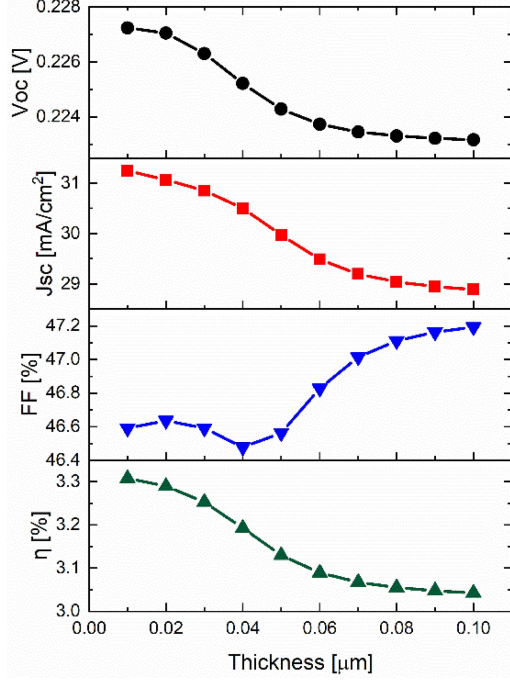


Fig. 4. Effect of SnO_2 thickness on electrical parameters.

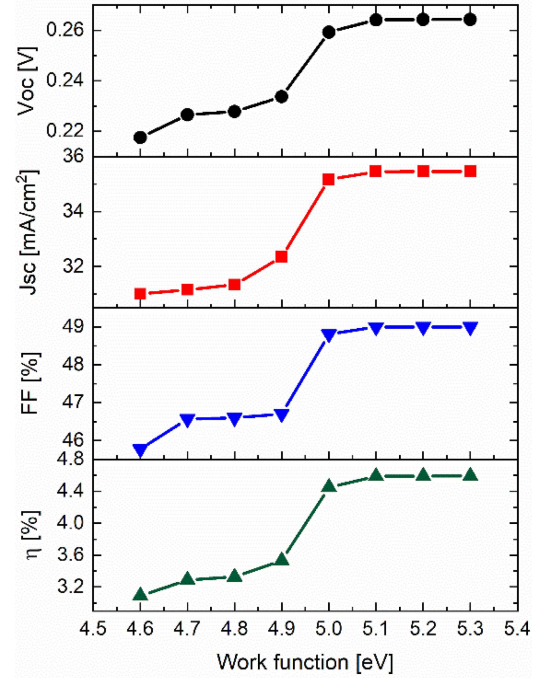


Fig. 5. Effect of metal work function on electrical parameters.

Therefore, it is preferable for the buffer layer to be thin to maximize the number of photons reaching the absorbent layer. The conversion efficiency peaks at 3.31% for a buffer layer thickness of 10 nm, which aligns with the findings in [41].

3.2.2. Effects of metal work function

The rear contact work function significantly affects the efficiency of solar cells. Hence, we examine how the rear contact work function affects the solar cell performance. For the studied SnSe-based solar cell, the work function is varied from 4.6 to 5.3 eV, as illustrated in Fig. 5. As can be seen, as the work function increases, all electrical parameters also rise. The parameters increase gradually from 4.6 to 4.9 eV and more significantly from 4.9 to 5 eV, after which they stabilize. Consequently, a work function of 5 eV is selected, resulting in a good conversion efficiency of 4.45%.

3.2.3. Electronic density of states effects

Understanding the electronic density of states (eDOS) is crucial for various semiconductor applications, such as optimizing and designing devices like solar cells. For this purpose, the conduction band (CB) DOS was varied from 10^6 to 10^{21} cm^{-3} , while the valence band (VB) DOS was varied from 10^{18}

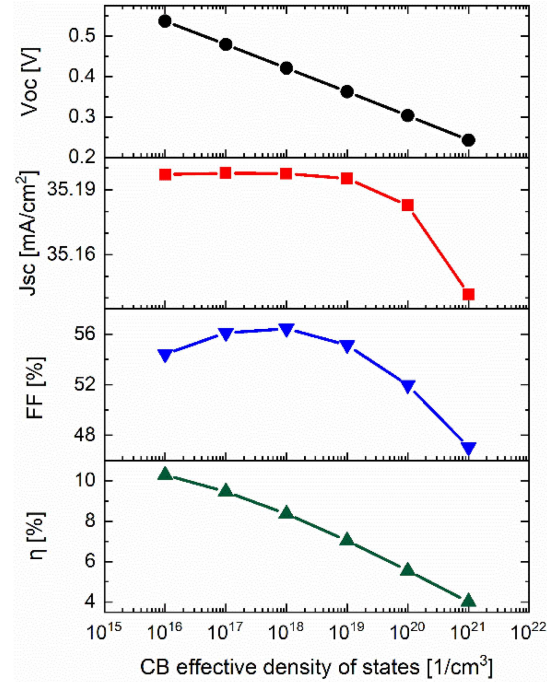


Fig. 6. Effect of CB DOS of SnSe on electrical parameters.

to 10^{22} cm^{-3} , and their effect on electrical outputs is depicted in Fig. 6 and 7. These figures reveal an inverse relationship between essential electrical parameters (V_{oc} , J_{sc} , FF, and η) and eDOS. For the CB DOS, as the concentration decreased from 10^{21} to 10^{16} cm^{-3} , the conversion efficiency improved

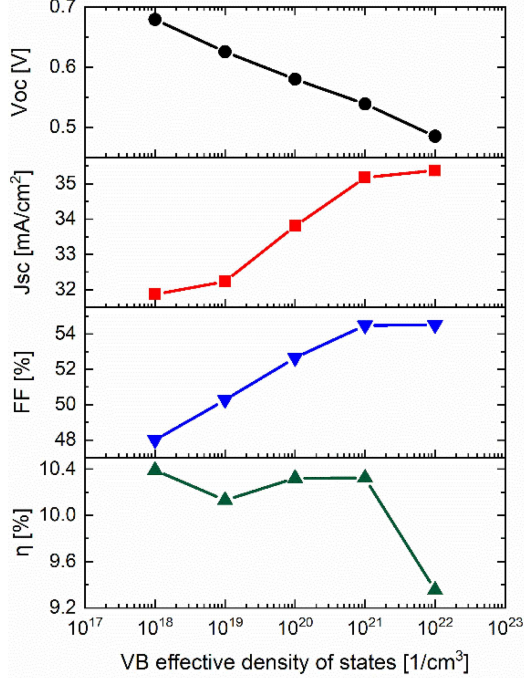


Fig. 7. Effect of VB DOS of SnSe on electrical parameters.

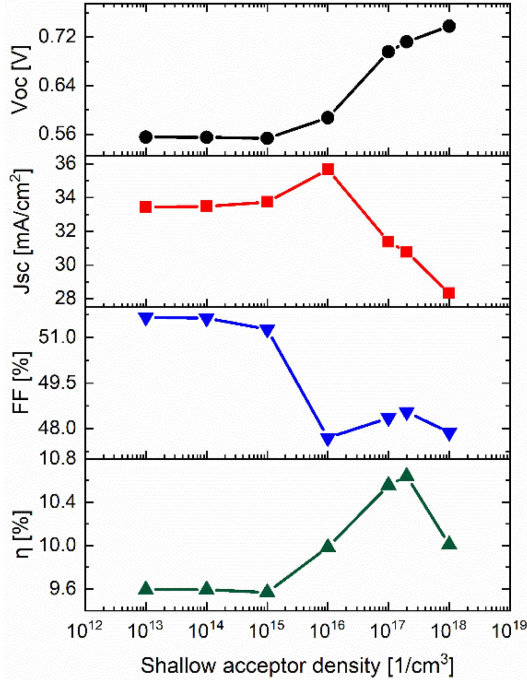


Fig. 8. Effect of shallow acceptor density on electrical parameters.

from 4.01% to 10.28%. Similarly, for the VB DOS, the efficiency increased from 9.35% to 10.39% as the concentration dropped from 10^{22} to 10^{18} cm^{-3} . These results suggest that lower eDOS values are more advantageous for optimal device performance, in line with previous studies [42].

3.2.4. Effects of shallow acceptor doping density

In a thin-film solar cell, the crucial region is the absorbent layer, where the majority of photons are anticipated to be absorbed. The doping concentration within this layer is a key factor that influences its performance. Therefore, the optimization of the acceptor dose in the absorber is essential. According to [43], the SnSe doping concentration is varied from 10^{13} to 10^{18} cm^{-3} , and its effects are shown in Fig. 8. The curves in this figure indicate that for concentrations from 10^{13} to 10^{15} cm^{-3} , the variation is minimal in electrical parameters. Between 10^{15} and 10^{16} cm^{-3} , the doping concentration increases, leading to rises in V_{OC} , J_{SC} , and η , while FF tends to decrease. Beyond 10^{16} cm^{-3} , J_{SC} begins to decline, the variation in FF remains negligible, and both V_{OC} and η continue to increase. In the case of η , it reaches a peak value of 10.64% at an acceptor doping concentration of 2×10^{17} cm^{-3} , after which it starts to decrease, in accordance with [44].

3.2.5. Effects of radiative recombination coefficient (RRC)

The radiative recombination coefficient measures the likelihood of radiative recombination happening per unit time and volume. In solar cells, reducing radiative recombination is essential for enhancing device efficiency. This is because radiative recombination is a loss mechanism: when electrons and holes recombine radiatively, the energy that could have generated electricity is instead emitted as light. Consequently, a lower radiative recombination coefficient is typically preferable for improving solar cell performance. Figure 9 demonstrates the changes in photovoltaic parameters relative to this coefficient in the studied SnSe-based solar cell. It is evident that at low values of RRC, the solar cell exhibits high electrical performance. This favorable performance persists up to a radiative recombination coefficient from 10^{-9} to 10^{-10} cm^{-3}/s , beyond which all parameters start to decline. So, values of RRC between 10^{-9} to 10^{-10} cm^{-3}/s are acceptable. We choose the value of 10^{-10} cm^{-3} for RRC, which gives a conversion efficiency of 10.97%.

3.2.6. Effects of series and shunt resistances

Series resistance (R_S) and shunt resistance (R_{SH}) significantly affect a solar cell's efficiency. Keeping series resistance low is crucial for achieving optimal efficiency, as higher values can reduce the short-circuit current density. The low experimental efficiency observed in SnSe-based thin-film

TABLE II

Electrical parameters of the primitive SnSe/SnO₂, optimized SnSe/SnO₂ without HTL, and optimized SnSe/SnO₂ with HTL.

Structure	η [%]	J_{SC} [mA/cm ²]	V_{OC} [V]	FF [%]
primitive SnSe/SnO ₂	2.32	25.50	0.199	45.74
optimized SnSe/SnO ₂ without HTL	15.45	31.88	0.732	66.19
optimized SnSe/SnO ₂ with HTL	19.68	36.65	0.779	68.90

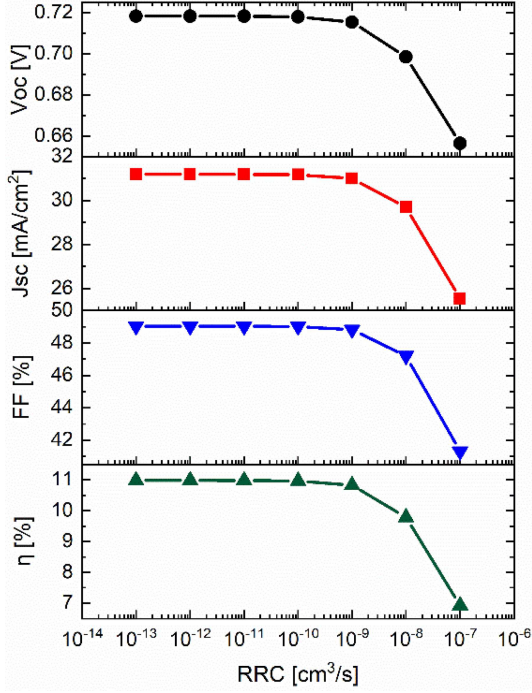


Fig. 9. Effect of RRC in SnSe on electrical parameters.

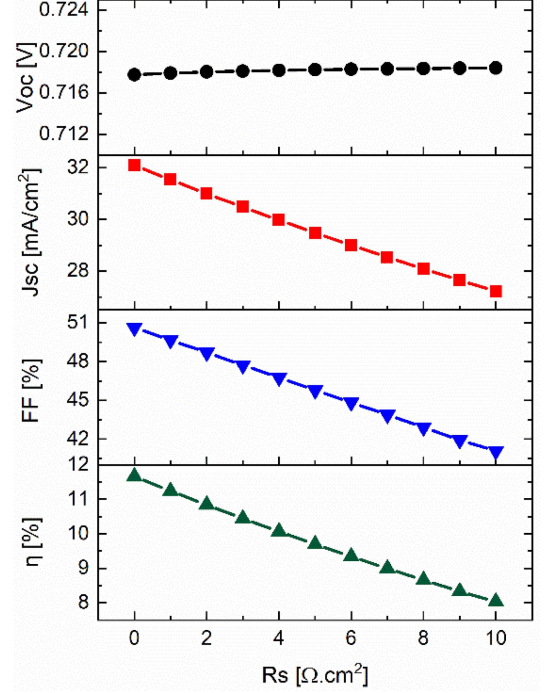


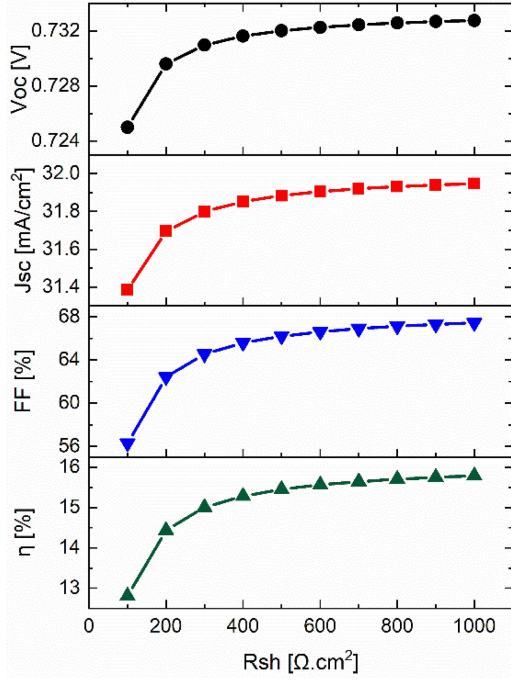
Fig. 10. Effect of R_S on electrical parameters.

solar cells is due to high series resistance and low shunt resistance [45]. Both types of resistance negatively impact solar cell efficiency and the fill factor.

To optimize R_S and R_{SH} in the studied SnSe-based solar cells, these resistances were adjusted within the ranges of 1–10 $\Omega \text{ cm}^2$ and 100–1000 $\Omega \text{ cm}^2$, respectively. Figures 10 and 11 illustrate the impact of R_S and R_{SH} on electrical parameters. The results show that both R_S and R_{SH} significantly influence solar cell efficiency. Specifically, lower shunt resistance values have a greater impact on the open-circuit voltage compared to series resistance, while J_{SC} is more sensitive to higher R_S values compared to R_{SH} . Additionally, variations in series resistance have a more significant effect on the fill factor than shunt resistance. Values of 2 $\Omega \text{ cm}^2$ for R_S and 500 $\Omega \text{ cm}^2$ for R_{SH} were selected as optimal, in line with [1, 45]. Such values for R_S and R_{SH} give an encouraging conversion efficiency of 15.45%.

3.3. Effects of CuSCN as hole transport layer (HTL)

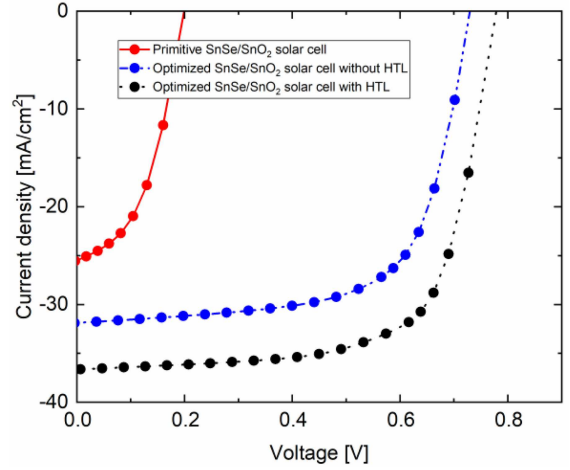
In solar cell devices, a hole transport layer facilitates the extraction of positive charges generated upon absorption of sunlight by the absorber material. This layer facilitates the movement of these positive charges (holes) to the rear contact, thereby preventing Fermi-level pinning that can arise from direct contact between the semiconductor and metal. By mitigating Fermi-level pinning, the HTL enhances the solar cell's efficiency [46]. As a third phase of the investigation, CuSCN is examined as a potential HTL for SnSe-based solar cells. Figure 12 illustrates the $J(V)$ characteristics of SnSe-based solar cells utilizing SnO₂ as the ETL before and after optimization, as well as those employing CuSCN as the HTL. The results demonstrate a significant improvement in the solar cell's performance with the use of CuSCN as the HTL.

Fig. 11. Effect of R_{SH} on electrical parameters.

The PCE of the SnSe-based solar cell with CuSCN as the HTL achieves an impressive 19.68% compared to 15.45% for the free HTL SnSe-based solar cell, and it is comparable to the results reported in [47]. Table II recapitulates the results of the three SnSe-based solar cells: primitive SnSe/SnO₂, optimized SnSe/SnO₂ without HTL, and optimized SnSe/SnO₂ with HTL.

4. Conclusions

This study involved a numerical analysis using the SCAPS-1D program to examine the performance of an anode/SnSe/CdS/*i*-ZnO/ZnO/cathode solar cell structure. Initially, various physical parameters of the primary SnSe, CdS, and ZnO layers were adjusted to align the simulated outcomes with experimentally demonstrated results. The simulated results closely matched the experimental ones, validating the model. Next, SnO₂ was proposed and investigated as a non-toxic buffer layer material to replace the toxic CdS. During the investigation, parameters such as thickness, metalwork function, electron density of states, shallow acceptor density, radiative recombination, and series and shunt resistances were optimized. The optimized values for SnSe, including a thickness of 0.8 μm , CB DOS of 10^{16} cm^{-3} , VB DOS of 10^{18} cm^{-3} , NA of $2 \times 10^{17} \text{ cm}^{-3}$, RRC of $10^{-10} \text{ cm}^3/\text{s}$, RS of $2 \Omega \text{ cm}^2$, and RSH of $500 \Omega \text{ cm}^2$, along with a buffer layer thickness of 0.01 μm for SnO₂ and a 5 eV metal work function

Fig. 12. The $J(V)$ characteristics of the primitive SnSe/SnO₂ (red line), optimized SnSe/SnO₂ without HTL (blue line), and optimized SnSe/SnO₂ with HTL (black line).

of the rear contact, resulted in a high conversion efficiency of 15.45%. Finally, to improve hole transport and minimize charge recombination at the rear contact surface, the inclusion of CuSCN as a hole transport layer was proposed and investigated. By incorporating CuSCN as an HTL into the solar cell based on SnSe with the optimized parameters, the anode/CuSCN/SnSe/SnO₂/*i*-ZnO/ZnO/cathode structure achieved a notable device performance, with an impressive conversion efficiency of 19.68%.

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