

Article

Towards Sustainable Perovskite Solar Cells: Lead-Free High Efficiency Designs with Tin and Germanium

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Abstract: This study focuses on the development of efficient and environmentally friendly Lead-free Perovskite solar cells (PSCs) using Tin and Germanium as absorber materials. The study was performed using SCAPS-1D simulations (version 3.11) to explore the performance of PSCs. The investigation took into consideration optimizing the electron transport layer's (ETL) material and thickness, and TiO_2 , ZnO , and WO_3 were investigated for this purpose. The current results show that Sn-based PSCs achieved a maximum power conversion efficiency of 23.19% with TiO_2 as the ETL, while Ge-based PSCs reached a power conversion efficiency of 14.83%. Additionally, the ETL doping concentration optimization revealed that the doping concentration had little impact on the device performance. These results emphasize the potential of Sn- and Ge-based PSCs as sustainable alternatives to Lead-based technologies, offering a pathway toward safer and more efficient solar energy solutions.

Keywords: lead-free perovskite solar cells; tin-based perovskites; germanium-based perovskites; SCAPS-1D simulation; sustainable photovoltaics



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1. Introduction

In recent years, the demand for finding new renewable energy resources has increased, in order to secure sustainable energy for the future [1,2]. Solar energy is considered one of the main renewable energy resources, especially the use of solar cells. Different types of solar cells are available commercially, like mono crystalline Silicon (Si) solar cells [3,4], while other types are still under development due to their promising future, such as Perovskite solar cells [5,6]. Perovskite solar cells have gained researchers' attention worldwide, as this type of solar cell may replace Si-based solar cells, given that they promise to offer higher efficiencies with lower production costs [7,8]. Yet these solar cells did not achieve what it takes to replace Si solar cells, due to a few reasons such as their short lifetime and associated toxicity [9,10].

Different designs and structures were developed for Perovskite solar cells, such as Tandem Perovskite-Si solar cells [11], 2D/3D heterostructure Perovskite solar cells [12], Tin-based Perovskite solar cells [13], and quantum dot Perovskite solar cells [14]. Some of these types that could reach high efficiencies are based on a Perovskite composite that has Lead (Pb), using $\text{CH}_3\text{NH}_3\text{PbI}_3$ as the absorber layer [15]. Due to the use of Pb, this type of solar cell is not preferred, due to its high toxicity [16]. Other structures are based on Tin (Sn), such as $\text{CH}_3\text{NH}_3\text{SnI}_3$ Perovskites and Germanium based (Ge) Perovskites. $\text{CH}_3\text{NH}_3\text{GeI}_3$ Perovskites are being investigated, as they do not suffer from high toxicity like Pb-based Perovskites, hence allowing for the investigation of new Perovskite structures that could reach high efficiencies [17,18].

Germanium-based Perovskite solar cells are one of the main alternatives to Pb-based solar cells, due to their safer behavior. In their work, Meng et al. investigated Ge-based Perovskite solar cells with $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{S}$ as the electron transport layer (ETL), and MASnBr_3 as the hole transport layer (HTL). In their work, they optimized different parameters such as the layer's thicknesses, bandgap, electron affinities, and other parameters. They were able to reach 13.18% power conversion efficiency (PCE) in their simulated model by using SCAPS-1D simulations [19]. In another study performed by Lakhdar et al., Ge-based Perovskite solar cells were studied, along with changing the ETL materials to enhance the cells' PCE. In this work, C_{60} was added as an ETL to enhance the PCE. By using C_{60} , the suggested structure was able to achieve 13.5% PCE [20]. Moreover, Pindolia et al. studied RbGeI_3 as a Perovskite active light absorption layer. This study investigated different parameters, such as changing the ETLs and HTLs, material thicknesses, doping concentrations, and others to find the best PCE. Through these results, a 10.11% PCE with Fill Factor (FF) ~63.6% was achieved [21].

In their efforts to analyze a high-efficiency Lead-free Perovskite solar cell, Salih et al. studied a structure based on utilizing $\text{CH}_3\text{NH}_3\text{SnI}_3$ structures [22]. In this work, the team investigated the absorber layer thickness effect on the power conversion efficiency, along with the effect of changing different HTLs. This study showed that using Cu_2O is the best choice as an HTL, while reaching an efficiency of 24.54% by using SCAPS-1D simulations. In another experimental work carried out by Shao et al., a 9% Sn-based Perovskite solar cell was achieved by depositing near-single crystalline Formamidinium Tin Iodide to reduce Sn vacancies and oxide sites in the deposited films [23]. In another investigation carried out by Wang et al., Phenylhydrazine Hydrochloride was added to FASnI_3 Perovskite films to reduce the existing Sn^{4+} formation and prevent the further degradation of FASnI_3 , which allowed for the development of an 11.4% Tin-based Perovskite Solar cell [24].

Tin-based Perovskite absorbers ($\text{CH}_3\text{NH}_3\text{SnI}_3$) exhibit a smaller bandgap of 1.3 eV, enabling better absorption of the solar spectrum, particularly in the infrared region. This characteristic contributes to the higher short-circuit current density observed in Sn-based PSCs. However, the oxidation of Sn^{2+} to Sn^{4+} presents significant challenges, as it introduces deep trap states that promote recombination losses and affect long-term device stability. Recent advancements, such as incorporating passivation agents or modifying fabrication techniques, have shown promise in overcoming these issues and improving device performance [25].

On the other hand, Germanium-based Perovskite absorbers ($\text{CH}_3\text{NH}_3\text{GeI}_3$) feature a wider bandgap of 1.9 eV. While this limits their ability to absorb lower-energy photons, it results in higher open-circuit voltages and potentially better stability due to lower defect densities and improved charge carrier mobility. These properties make Ge-based absorbers a preferred choice for achieving more stable and safer PSCs. However, their lower quantum efficiency, especially in the IR region, underscores the need for further material optimization [22].

In comparison to traditional Pb-based Perovskites, Sn- and Ge-based materials offer an environmentally friendly alternative. While Pb-based absorbers achieve higher efficiencies, the toxicity and environmental impact of Lead leads to exploring Lead-free options [26].

In simulations, Perovskite solar cells often exhibit higher efficiencies than their experimental counterparts, due to the absence of parasitic electrical losses. This difference is noted because SCAPS-1D assumes ideal conditions, including perfect interfaces, negligible series resistance, and optimal charge transport. Therefore, differences between simulated and experimental results can be related to real world factors such as interface recombination, contact resistance, and variations in material quality [27].

In the current work, we report on the development of high-efficiency Lead-free Perovskite solar cells based on Tin and Germanium using SCAPS-1D simulations. The results were found by optimizing the electron transport material, thicknesses, and ETL doping concentrations. This was performed for two different structures including Tin- and Ge-based Perovskite structures. It was found that PSCs with TiO_2 as the ETL can achieve 23.19% power conversion efficiency when compared to their Germanium counterparts. The results also achieve high-efficiency PSCs that are sustainable and less toxic than Lead-based cells.

2. Materials and Methods

In the scope of the current results, SCAPS 3.8 1D was utilized as a specialized 1D simulator of solar cells. This software was developed by the electronics and information systems department at the University of Ghent in Belgium [28]. The software is valued for its ability to model a broad range of semiconductor materials, its user-friendly interface, and its capacity to simulate various device configurations (e.g., Perovskite solar cells). Additionally, SCAPS-1D supports different material layers (up to seven different levels), facilitates interface modeling, and can accurately simulate electrical properties. SCAPS-1D is considered one of the most specialized solar cell simulation tools, as it offers the option to simulate solar cells with multi-layers. SCAPS-1D solves Poisson's equation, Equation (1), the continuity equation for electrons and holes, and Equations (2) and (3), which are shown below:

$$\frac{d}{dx} \left(-\epsilon(x) \frac{d\psi}{dx} \right) = q[p(x) - n(x) + N_D^+(x) - N_A^-(x) + p_t(x) - n_t(x)] \quad (1)$$

$$\frac{dp_n}{dt} = G_p - \frac{p_n - p_{n0}}{\tau_p} + p_n \mu_p \frac{d\xi}{dx} + \mu_p \xi \frac{dp_n}{dx} + D_p \frac{d^2 p_n}{dx^2} \quad (2)$$

$$\frac{dn_p}{dt} = G_n - \frac{n_p - n_{p0}}{\tau_n} + n_p \mu_n \frac{d\xi}{dx} + \mu_n \xi \frac{dn_p}{dx} + D_n \frac{d^2 n_p}{dx^2} \quad (3)$$

The simulations were carried out under standard conditions, which includes a temperature of 300 K, air mass (AM) of 1.5 G, and irradiation intensity of 1000 W/m^2 . The flow chart shown in Figure 1 below presents the operation on the SCAPS-1D software (version 3.11). Mainly, SCAPS-1D takes the parameters of each layer, then performs its simulations by using both Poisson's and the continuity equations presented previously. The light entrance can be defined from the forward direction or backward direction based on the need of the simulated structure.

In this work, the solar cell structure, as shown in Figure 2 below, is composed of ETL/Perovskite absorber layer/HTL. In both structures, the light is defined as entering the ETL layer through the FTO from the front contact.

This setup follows a forward (p-i-n) solar cell junction. In the scope of the current work, the Perovskite thickness and parameters were published elsewhere [17,18,22,29]. In addition to this, the HTL is fixed to be CuO_2 , which can be considered an optimized choice for both Ge- and Sn-based Perovskite solar cells, as published elsewhere [29]. For the current results, three different materials were chosen to be optimized to compare their performances, and these materials were Titanium Dioxide (TiO_2), Zinc Oxide (ZnO), and Tungsten Oxide (WO_3). In order to simulate the suggested structures, the electrical and optical properties and defect density inside the layers and at the interface of the used materials were set in SCAPS-1D, and are shown in Tables 1 and 2 below [17,18,30].

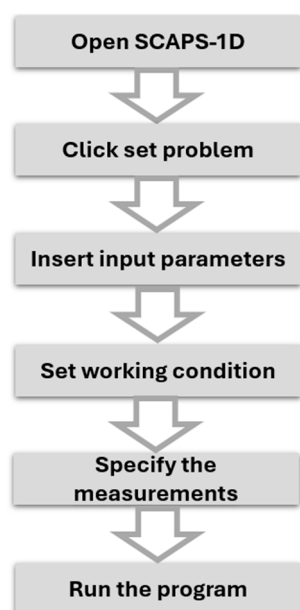


Figure 1. Flow chart showing how SCAPS-1D works to produce its simulations.

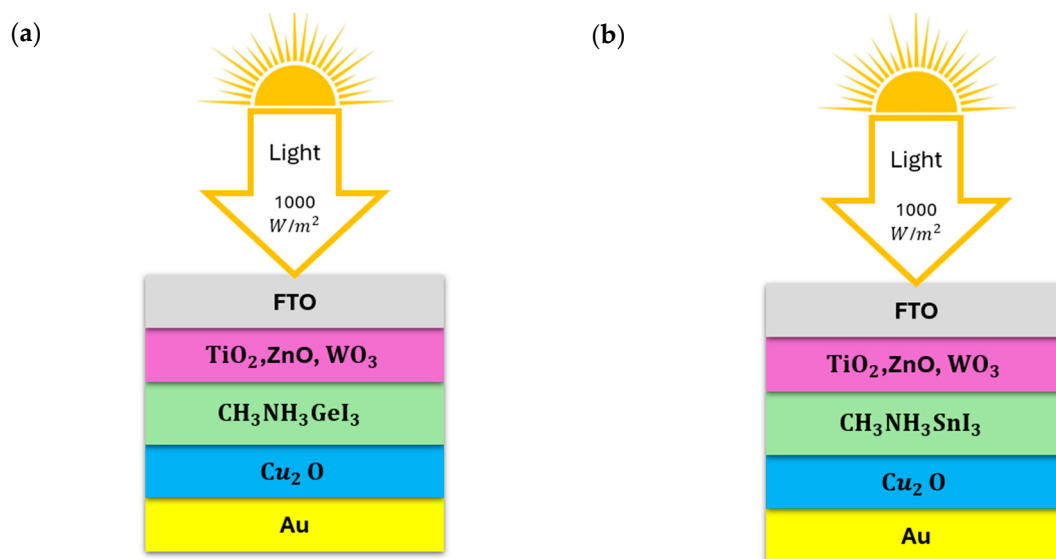


Figure 2. Schematic illustration of the simulated Perovskite solar cells: (a) Germanium-based Perovskite solar cell and (b) Tin-based Perovskite solar cell.

Table 1. The electrical and optical properties and defect density values inside the layers of the selected materials to build both Perovskite solar cells' structures.

Parameters	FTO	Cu_2O	$\text{CH}_3\text{NH}_3\text{SnI}_3$	$\text{CH}_3\text{NH}_3\text{GeI}_3$	TiO_2	ZnO	WO_3
Thickness (nm)	0.3	100	500	50	100	50	50
Bandgap energy E_g (eV)	3.5	2.170	1.3	1.9	3.25	3.3	2.7
Electron affinity χ (eV)	4	3.100	4.170	3.980	4	4	3.7
Relative permittivity ϵ_r	9	7	6.5	10	10	9	22
Effective conduction band density CB ($1/\text{cm}^3$)	2.2×10^{18}	2.2×10^{19}	2.2×10^{19}	2.2×10^{16}	2.2×10^{18}	2×10^{18}	1×10^{18}

Table 1. *Cont.*

Parameters	FTO	Cu ₂ O	CH ₃ NH ₃ SnI ₃	CH ₃ NH ₃ GeI ₃	TiO ₂	ZnO	WO ₃
Effective valence band density VB (1/cm ³)	2.2×10^{19}	2.2×10^{19}	2.2×10^{19}	2.2×10^{15}	1.1×10^{19}	1.8×10^{19}	1.1×10^{19}
Electron thermal velocity (cm/s)	1×10^7	1×10^7	1×10^7	1×10^7	1×10^7	1×10^7	1×10^7
Hole thermal velocity (cm/s)	1×10^7	1×10^7	1×10^7	1×10^7	1×10^7	1×10^7	1×10^7
Electron mobility μ_n (cm ² /Vs)	20	80	1.600	1.620×10^3	100	100	10
Hole mobility μ_p (cm ² /Vs)	10	80	1.600	1.100×10^3	25	25	1
Shallow uniform donor density N _D (1/cm ³)	10^{19}	0	0	0	10^{19}	10^{18}	1×10^{17}
Shallow uniform acceptor density N _A (1/cm ³)	0	10^{18}	3.2×10^{15}	9×10	0	0	1×10^{15}
Defect type	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
Capture cross-section hole (cm ²)	2×10^{-15}	1×10^{-15}	2×10^{-15}	2×10^{-15}	1×10^{-14}	1×10^{-15}	1×10^{-15}
Capture cross-section electrons (cm ²)	2×10^{-15}	1×10^{-15}	2×10^{-15}	2×10^{-15}	1×10^{-14}	1×10^{-15}	1×10^{-15}
Energetic distribution	Single	Single	Single	Single	Single	Single	Single
Reference for defect energy level E _t	Above Ev	Above Ev	Above Ev	Above Ev	Above Ev	Above Ev	Above Ev
Energy level with respect to Reference (eV)	0.600	0.650	0.650	0.650	0.600	0.600	0.600
Defect density N _t (1/cm ³) uniform	1×10^{16}	1×10^{16}	1×10^{13}	1×10^{13}	1×10^{16}	1×10^{15}	1×10^{15}

Table 2. Defect density values interface of the device.

Parameters	HTL/Perovskite	ETL/Perovskite
Defect type	Neutral	Neutral
Capture cross-section hole (cm ²)	1×10^{-14}	2×10^{-15}
Capture cross-section electrons (cm ²)	1×10^{-15}	2×10^{-15}
Energetic distribution	Single	Single
Reference for defect energy level E _t	Above Ev	Above Ev
Energy level with respect to Reference (eV)	0.650	0.650
Defect density N _t (1/cm ³) uniform	1×10^{13}	1×10^{13}

3. Results and Discussion

After setting the thickness and parameters of both the Perovskite and HTLs, the ETL layer was varied in thickness between 20 and 200 nm in the CH₃NH₃GeI₃ structure. The

variation in the thickness was to evaluate the photovoltaic performance while changing the ETLs' thicknesses. Figure 3 presents the results as a function of ETL thickness. For this purpose, the power conversion efficiency (PCE), open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), and Fill Factor (FF) were all obtained. The results for the V_{oc} and PCE for this structure show that the PCE values decrease with increasing thickness, while V_{oc} is almost constant for the structures with TiO_2 and ZnO , but decreases for the structure with WO_3 . It can also be seen from these results that setting the ETL as ZnO has the best performance in terms of the PCE. However, they show a slightly decreased performance as the thickness grows. It can be noted that the PCE ranges between (13.44 and 14.83) % when comparing WO_3 to ZnO , while the V_{oc} ranges between (1.057 and 1.060) V, the open-circuit voltage does not change significantly. This could be related to the increase seen in the short-circuit current, which increased from ~ 14.4 mA/cm² for WO_3 to ~ 15.7 mA/cm² for ZnO . On the other hand, the FF has slight changes between the three different ETL materials, with a value ~ 88.55 for ZnO .

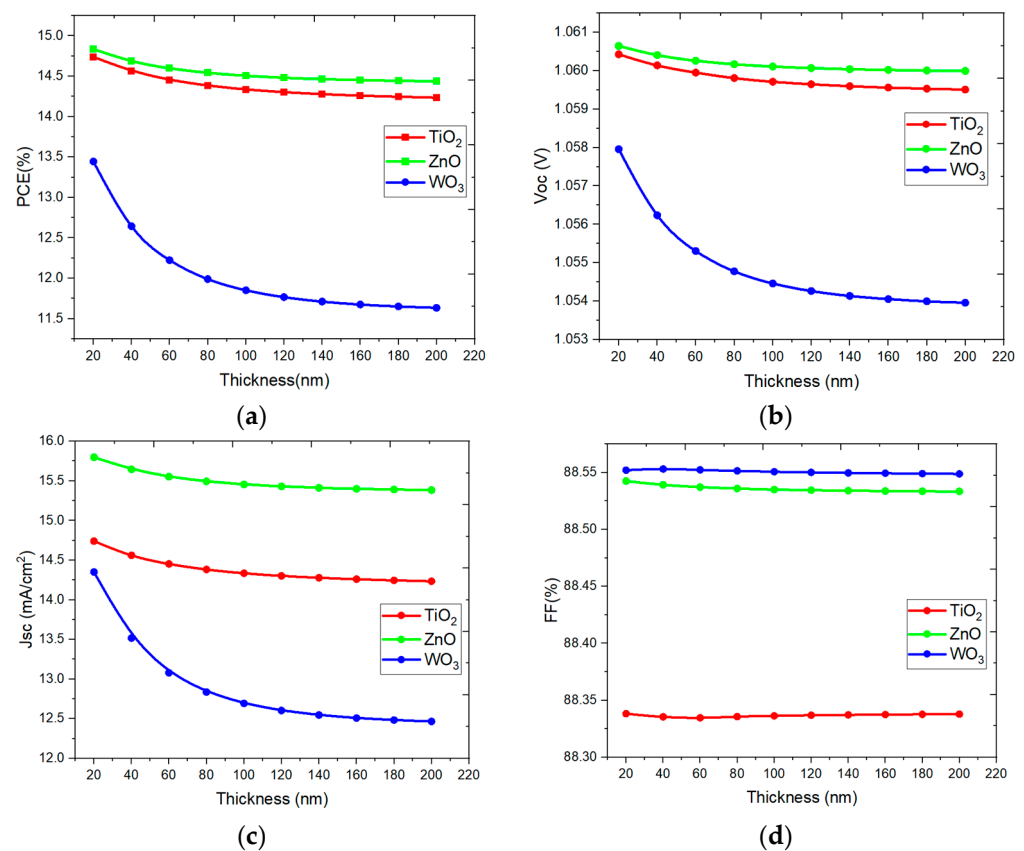


Figure 3. Variations in (a) PCE, (b) V_{oc} , (c) J_{sc} , and (d) FF as a function of the ETL thickness for the three ETL materials TiO_2 , ZnO , and WO_3 for the Ge-based Perovskite structure.

Increasing the different ETLs' thickness causes electrons to travel a greater distance to reach the top electrode, increasing the likelihood of electrons' recombination with minority carriers (holes). This, in turn, causes a loss in the V_{oc} . In addition, the structure with a WO_3 ETL has a substantial decrease in PCE, J_{sc} , and V_{oc} when compared to the structures with TiO_2 and ZnO , most likely owing to the lower light transmission through the WO_3 layer. This decrease in light transmittance is confirmed by Figure 4a,b, which shows the quantum efficiency of the cells with the optimized ETL for each Perovskite structure. From these graphs, it can be concluded that the Tin-based structure performs better than the Germanium-based structure over a wide range spectrum, which will also be shown in a later result. This can be attributed to the small bandgap on Sn (1.3 eV) compared to Ge

(1.9 eV), which allows Sn structures to absorb less energy photons and convert them to electrons. It can also be concluded that the Sn-based structures combined with TiO_2 ETL enhance the photon transmission and charge extraction. Furthermore, the WO_3 structure has the lowest ability for light conversion to electrons, especially at the lower wavelengths. Additionally, the quantum efficiency results agree with the trend seen in the short-circuit results, which show a good balance between the optical and electronic properties.

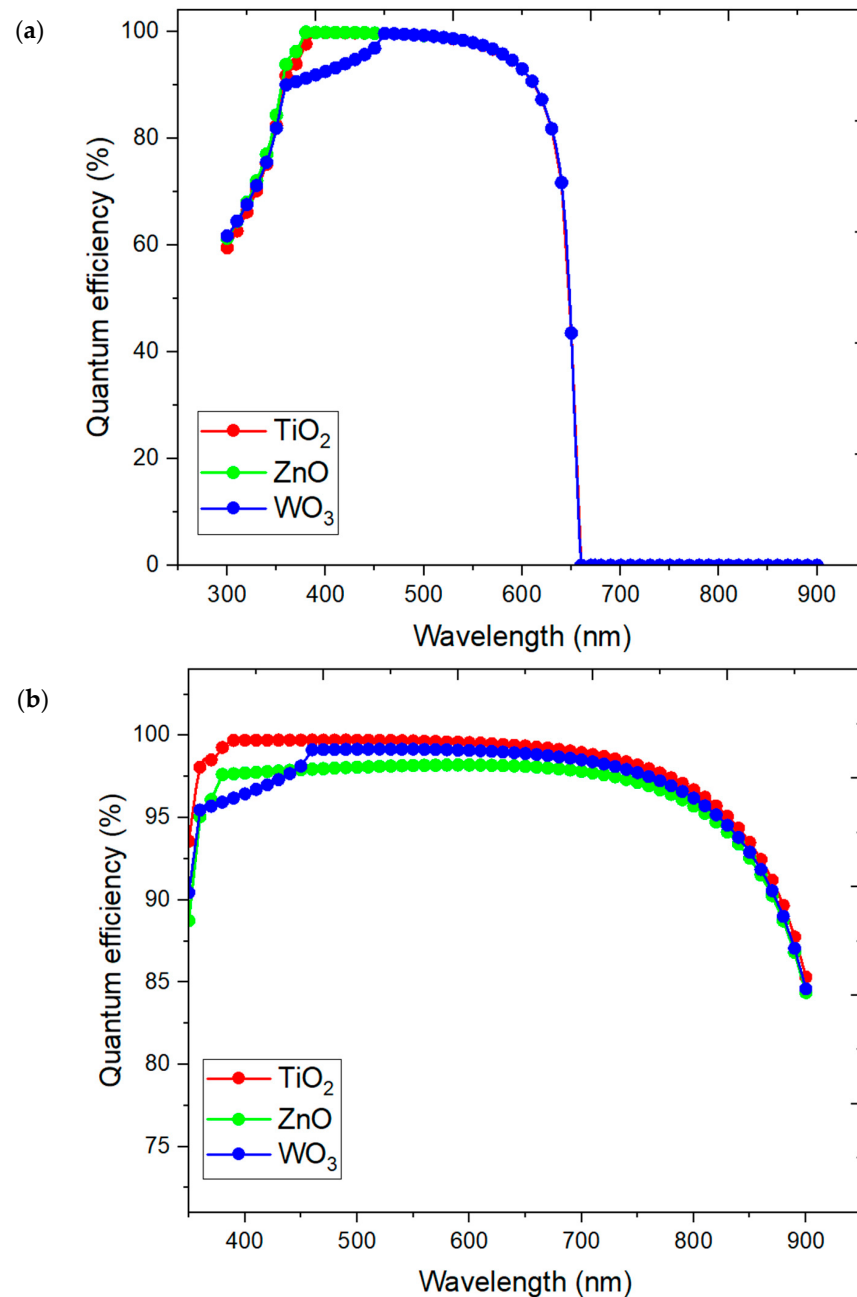


Figure 4. Effect of the ETL thickness on the quantum efficiency of the PSC with (a) Sn as the absorber layer and (b) Ge as the absorber layer.

The ETL layer thickness was also varied between 20 and 200 nm in the $\text{CH}_3\text{NH}_3\text{SnI}_3$ structure. The results are shown in Figure 5 below. The variation in the thickness was used to evaluate the photovoltaic performance while changing the ETLs' thicknesses. For this purpose, all parameters such as the PCE, V_{oc} , J_{sc} , and FF were also obtained. The results for the PCE, V_{oc} , and the Tin-based structures show higher values than those for the Ge-based structures. For the Tin-based structure with ETL set to TiO_2 , the PCE reaches ~23.19%.

However, the V_{oc} shows a value of ~ 0.80 V, which is lower than that of the Ge-based structure that reached ~ 1.06 V. This decrease is attributed to the lower bandgap (1.3 eV) of the Tin-based structure compared to the Germanium-based structure with a bandgap of ~ 1.9 eV). Additionally, the Germanium structure typically has better stability, lower defect densities, and a higher charge carrier mobility, resulting in more efficient charge extraction and reduced recombination losses. Moreover, the oxidation of Tin (from Sn^{2+} to Sn^{4+}) creates deep trap states that enhance the charge carrier recombination, along with higher defect densities and a lower carrier mobility, all of which contribute to a lower V_{oc} and FF. Despite the decreased open-circuit voltage, the short current can show much higher values than those found for the Ge structure. The short-circuit current can reach values of around 34 mA/cm^2 . This is primarily due to the smaller bandgap of the Tin-based material, which allows it to absorb a wider range of sunlight spectra, including lower-energy (longer-wavelength) photons that contribute to a higher photocurrent. While the lower V_{oc} is caused by increased recombination losses and defects, the enhanced absorption, especially in the infrared region, compensates for this, and results in a higher short-circuit current.

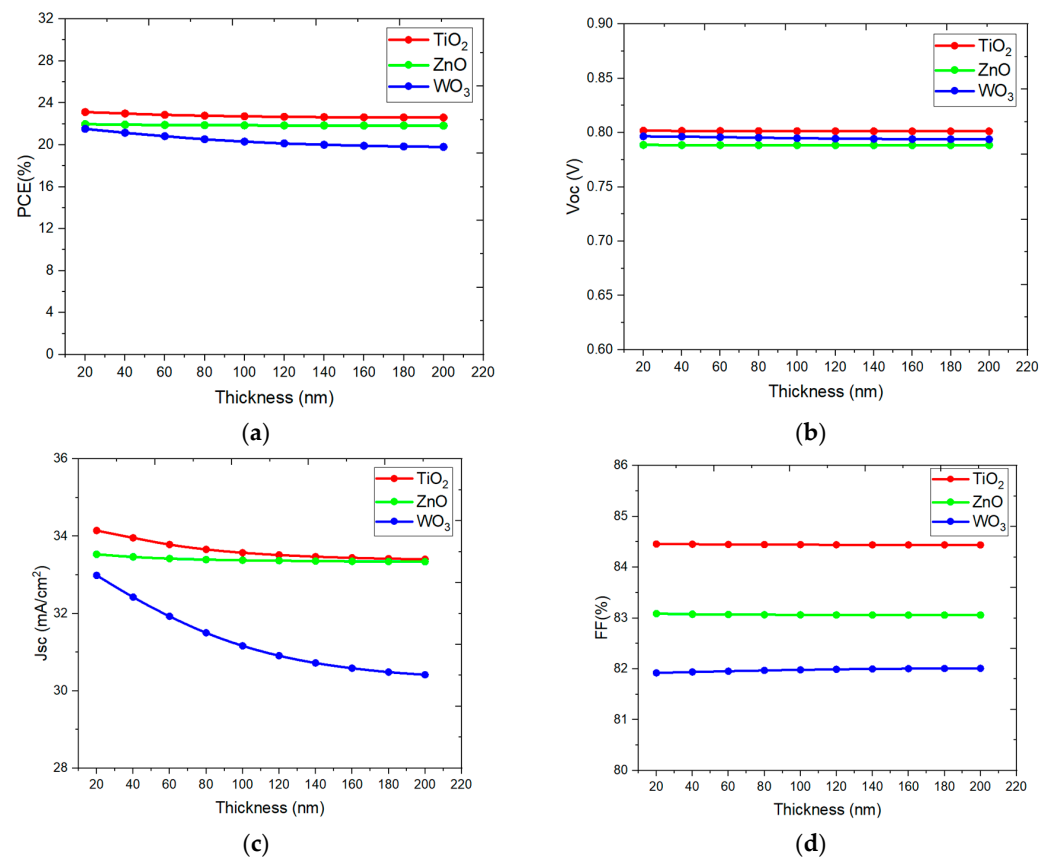


Figure 5. Variations in (a) PCE, (b) V_{oc} , (c) J_{sc} , and (d) FF as a function of the ETL thickness for the three ETL materials TiO_2 , ZnO , and WO_3 for the Sn-based Perovskite structure.

In order to investigate the effect of changing the donor's doping concentration on the J-V results, the doping concentration of the donors (N_d) was varied between $(10^{16}–10^{20}) \text{ cm}^{-3}$. The results are shown in Figure 6, with respect to the three ETLs used in this study. By looking at Figure 6a–c, it can be noted that the open-circuit voltage is ~ 0.8 V, despite the change in the doping concentration or changing the ETLs' material. This result is expected, as the open-circuit voltage is mainly controlled by the Perovskite's layer type, and not by its thickness. On the other hand, by looking at the values of the short-circuit current density in Figure 6a, it can be seen that when the ETL is WO_3 , the J_{sc} values vary between 33.8 mA/cm^2 when the doping concentration is $\sim (10^{16}–10^{17}) \text{ cm}^{-3}$ and 34.3 mA/cm^2

when the doping concentration is $\sim(10^{19}\text{--}10^{20})\text{ cm}^{-3}$. Additionally, by looking at Figure 6b when the ETL is set to ZnO, it is also observed that the J_{sc} values range between $(33.5\text{ and }34.3)\text{ mA/cm}^2$ when the doping concentration varies between $(10^{16}\text{ and }10^{20})\text{ cm}^{-3}$. Moreover, in Figure 6c, where the ETL is set to TiO_2 , it can be seen that the J_{sc} has very close values from the results obtained in Figure 6a, where J_{sc} changes between $(33.8\text{ and }34.3)\text{ mA/cm}^2$ when the doping concentration changes between $(10^{16}\text{ and }10^{20})\text{ cm}^{-3}$. Additionally, the short-circuit current changes with small values by increasing the donor's doping concentration. Hence, the lower concentration can be used for the Perovskite layer, while maintaining high PCE without the need to increase the doping concentration, which is more desirable in the industry to minimize production costs.

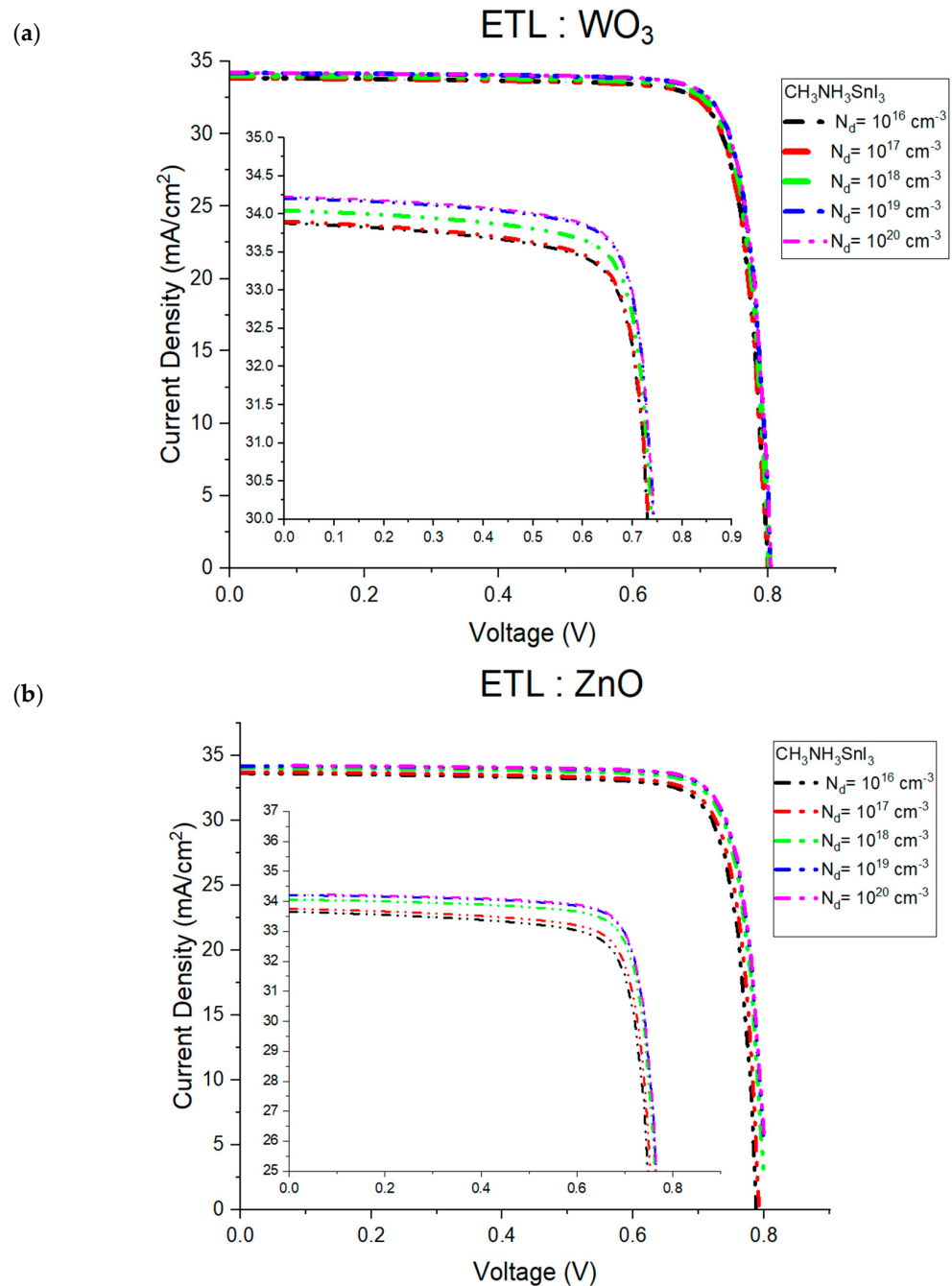


Figure 6. Cont.

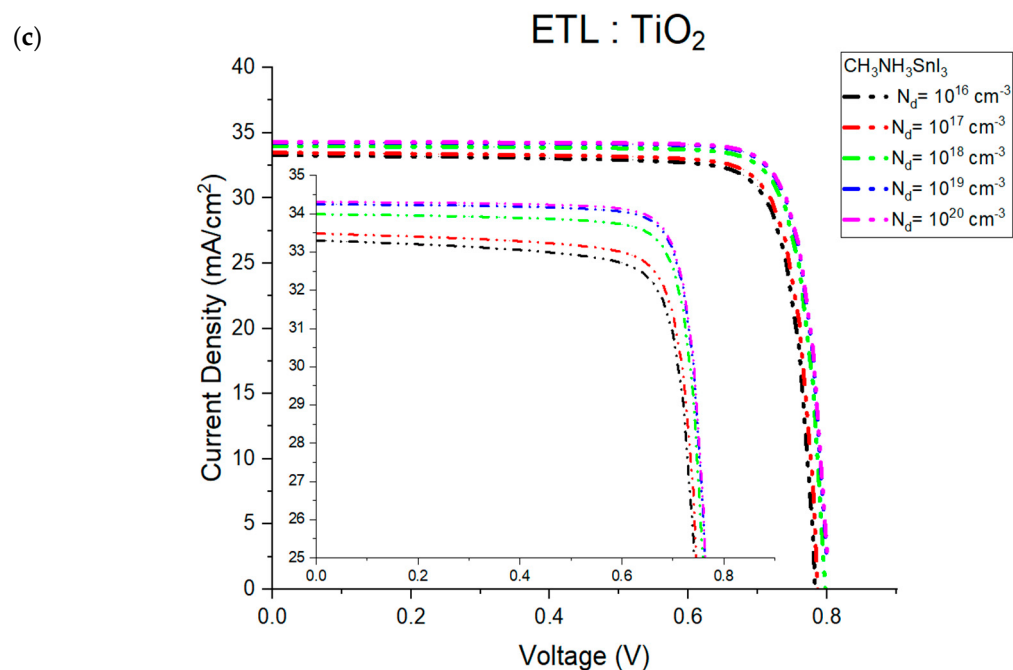


Figure 6. The current density versus open-circuit voltage graphs for Tin-based structures while changing the donor's doping concentration (N_d): (a) with WO_3 as the ETL, (b) with ZnO as the ETL, and (c) with TiO_2 as the ETL.

The current density versus open-circuit voltage results that were obtained for the Ge-based structure are shown in Figure 7. This graph also shows the effect of varying the donor's doping concentration of the Perovskite layer between (10^{16} and 10^{20}) cm^{-3} . Figure 7a–c shows that the open-circuit voltage is 1.02 V. This deviation in the open-circuit voltage when using the Ge-based structure compared to the Tin-based structure is due to the difference in the bandgap between both structures. It can be noted that the short-circuit current density for all three investigated structures is around 16 mA/cm^2 . Furthermore, changing the doping concentration from 10^{16} cm^{-3} to 10^{20} cm^{-3} does not have direct effect on the short current density. These results are in agreement with the results shown in Figure 6, which means that the doping concentration will not make any difference if increased. Hence, a lower doping concentration can be implemented, which is more suitable for industrial needs.

It can be noted from Figures 6 and 7 that the Tin-based Perovskite structures with the different types of ETLs approach higher short-circuit current densities while maintaining a lower open-circuit voltage. Despite the lower open-circuit voltage, the power conversion efficiency is higher in the Tin-based structure than in the Germanium-based structure. Moreover, when comparing the results according to the used ETL, it can be found that TiO_2 achieved the best PCE compared to the other two ETL materials. This can be attributed to its superior electron mobility and excellent charge-extraction capabilities, which minimize recombination losses. Additionally, TiO_2 is highly stable, ensuring consistent performance over time, and its ability to form a high-quality, conformal layer enhances the overall efficiency of the device. In contrast, ZnO and WO_3 may exhibit lower electron mobility and higher defect densities, which can hinder charge transport and reduce the PCE.

On the other hand, Figure 6 also shows the donor's doping concentration variation between 10^{16} cm^{-3} and 10^{20} cm^{-3} . It can be noted that changing the doping concentration does not significantly influence the values of the short-circuit current density nor the open-circuit voltages, because doping concentrations tend to reach a saturation point beyond a certain level. Once the doping concentration exceeds a specific threshold, further increases

may have little impact on the material's electronic properties, such as carrier mobility or energy levels. This helps explain why varying the doping concentration between 10^{16} cm^{-3} and 10^{20} cm^{-3} does not significantly affect the short-circuit current nor the open-circuit voltage. A summary of the main obtained results from the study is shown in Table 3 below.

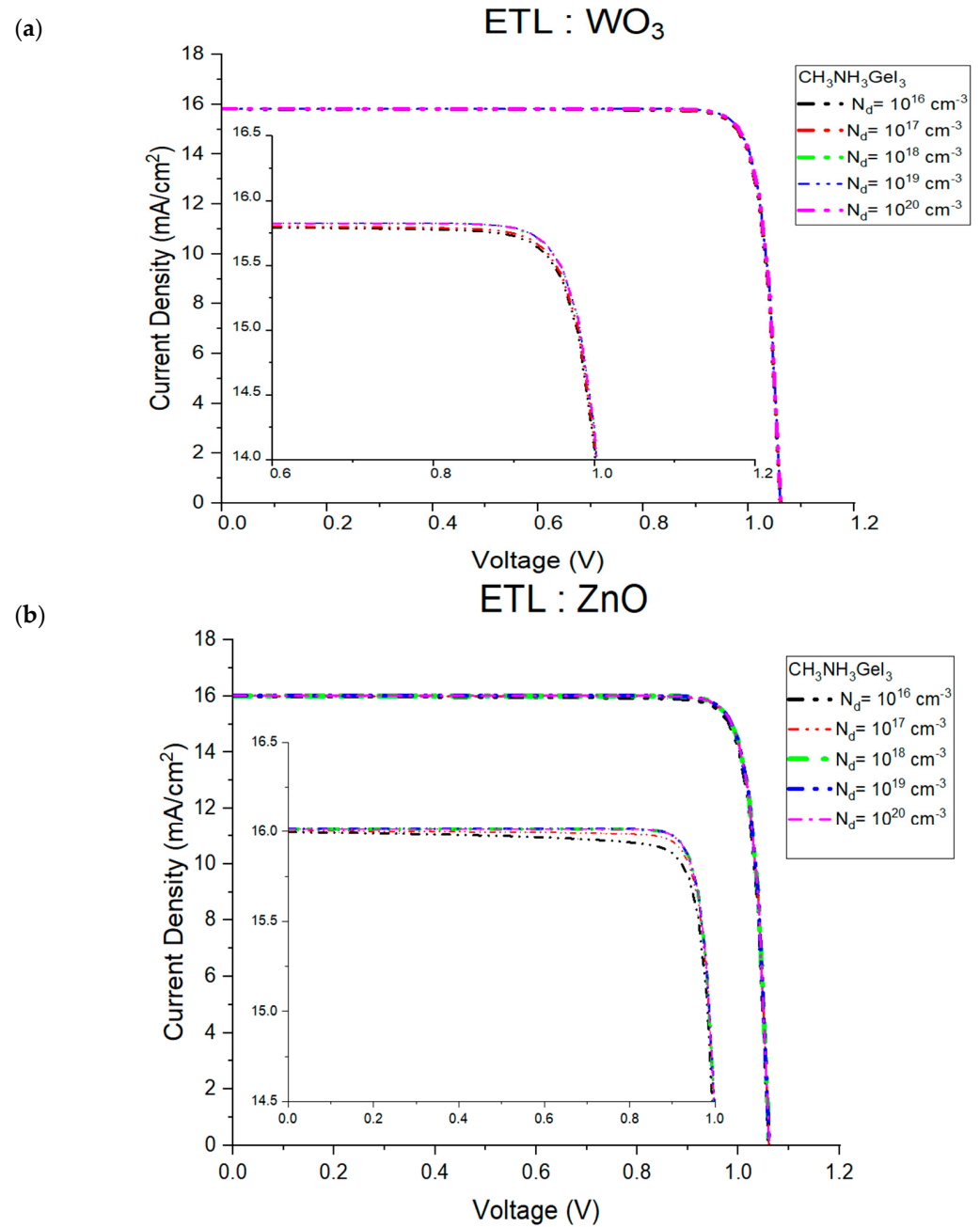


Figure 7. Cont.

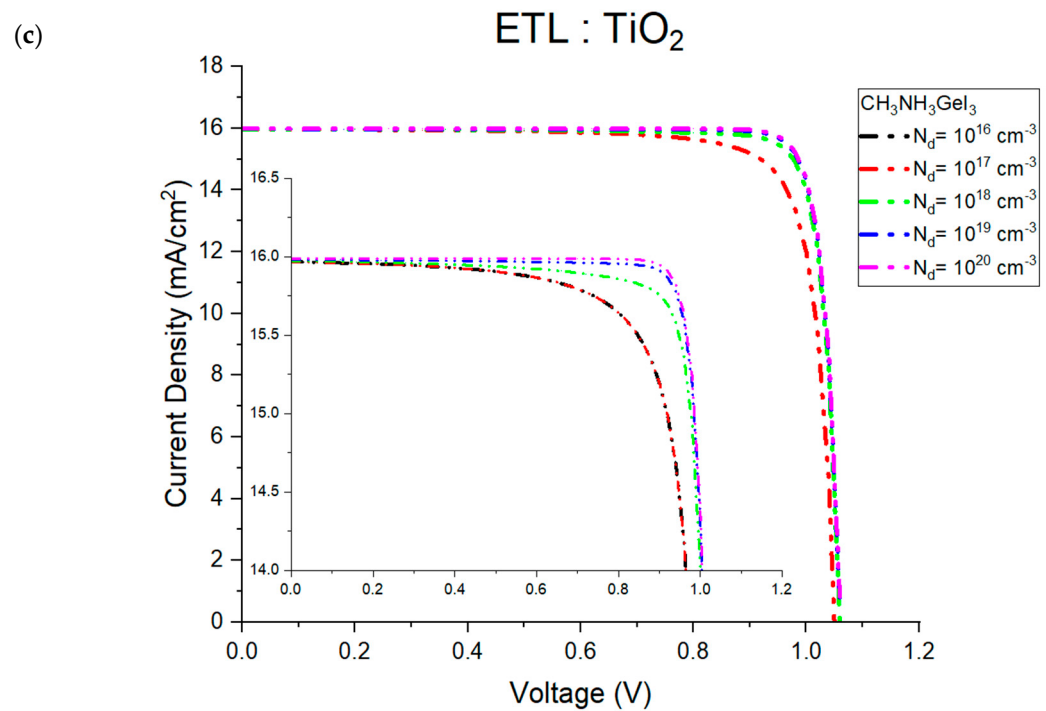


Figure 7. The current density versus open-circuit voltage graphs for the Ge-based structures while changing the donor's doping concentration (N_d): (a) with WO_3 as the ETL, (b) with ZnO as the ETL, and (c) with TiO_2 as the ETL.

Table 3. Comparison of the main characteristics and results for $\text{CH}_3\text{NH}_3\text{SnI}_3$ and $\text{CH}_3\text{NH}_3\text{GeI}_3$ solar cells.

Parameters	$\text{CH}_3\text{NH}_3\text{SnI}_3$ (Tin-Based)	$\text{CH}_3\text{NH}_3\text{GeI}_3$ (Germanium-Based)
Power Conversion Efficiency (PCE)	23.19%	14.83%
Open-circuit Voltage (V_{oc})	~ 0.80 V	~ 1.06 V
Short-circuit Current Density (J_{sc})	~ 34 mA/cm ²	~ 15.7 mA/cm ²
Fill Factor (FF)	$\sim 83\%$	$\sim 88\%$
Bandgap	1.3 eV	1.9 eV
ETL Material (Optimized)	TiO_2	ZnO
ETL Thickness (Optimized)	< 50 nm	< 30 nm
Impact of ETL Material	$\text{TiO}_2 > \text{ZnO} > \text{WO}_3$	$\text{ZnO} > \text{TiO}_2 > \text{WO}_3$
ETL Doping Concentration Effect	Minimal effect on PCE	Minimal effect on PCE

4. Conclusions

This work demonstrates the promise of Tin- and Germanium-based Perovskite solar cells as practical Lead-free alternatives, addressing both efficiency and sustainability challenges. The simulations revealed that TiO_2 is the most effective ETL material, enabling better device performance compared to its ZnO and WO_3 counterparts. Sn-based PSCs achieved a higher efficiency of 23.19%, while Ge-based PSCs reached 14.83%. Interestingly, the doping concentration of the absorber layer showed minimal effect on the overall performance, which is better for cost-effective manufacturing. These findings highlight the potential of Sn and Ge Perovskites to contribute to the future of renewable energy by combining high efficiency with reduced environmental impact. Moving forward, experimental work will be essential to validate these results and further improve the stability and scalability of these devices.

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