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Analysis of CdS/CdTe Thin Film Solar Cells as a Function of CdS Doping Concentration: A Numerical Simulation Perspective

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ABSTRACT

Cadmium Telluride (CdTe) photovoltaics, incorporating a thin film of Cadmium Sulfide (CdS), present a cost-effective yet less efficient solar cell technology. Improving CdS/CdTe solar cell efficiency involves optimizing parameters like doping concentration and CdS layer thickness. However, limited research on cell defects necessitates a comprehensive analysis, including the often-overlooked impact of temperature. This study aims to analyze defect-free and defective CdS/CdTe solar cells, exploring the effects of doping concentration and other parameters. Using the SCAPS-1D simulator, design parameter variations will be investigated, and key metrics—open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF), and efficiency (η)—will be extracted. Simulation results indicate minimal efficiency impact from increased doping concentration in the n-type CdS layer for defect-free devices. The optimal doping concentration for CdS is 5×10^{18} cm^{-3}, with an optimum electron affinity of 4.0 eV. CdS thickness shows no significant efficiency impact, with the chosen optimum at 10 nm. In the defect-free CdS/CdTe solar cell, key metrics were Voc: 1.06 V, Jsc: 24.60 mA cm^{-2}, FF: 87.89%, and η: 23.01%. Analysis of defects revealed single acceptor defects significantly impacting solar cell performance in both interfacial and bulk defects. Defect structure simulations demonstrated that increasing doping concentration, decreasing electron affinity, and thickness enhance efficiency. New optimum values for these parameters—1×10^{18} cm^{-3}, 4.0 eV, and 10 nm—yielded Voc: 1.03 V, Jsc: 23.88 mA cm^{-2}, FF: 87.15%, and η: 21.40%. Additionally, a temperature decrease was associated with increased efficiency.

Keywords: CdS/CdTe solar cell; doping concentration; thickness; defect; temperature

INTRODUCTION

Solar energy generated by the sun's radiation is a renewable and eco-friendly source. It can be used for electricity production or heating water without causing harm to ecosystems. The demand for solar energy has increased over time as people aim to reduce dependence on fossil fuels and carbon emissions. Solar cells, which use semiconducting silicon materials, absorb photons from sunlight to produce current for daily activities. Installing solar panels on roofs not only provides electricity but also benefits remote areas lacking the necessary amenities. (Sze et al. 2007; Abdelkadir et al. 2023)

The assessment of solar cells involves four key metrics: open circuit voltage (Voc), short circuit current density (Jsc), fill factor (FF) and solar cell conversion efficiency (η). Voltage measured across a cell without allowing any flow is denoted by Voc; it shows the highest possible electrical potential. Jsc, on the other hand, measures how much amperage can be generated from light when there's no resistance in the material present within that particular PV panel. When assessing FF values for cells we look at power output over total photogenerated current – which gives us an idea about internal recombination losses inside said panels as well. Finally, η captures just what proportion of all incoming sunlight is converted into usable electricity. (Ahmmed et al. 2020; Benzetta et al. 2020; Devi et al. 2016; Hossain et al. 2022; Ngoy et al. 2021)

To improve the efficiency of the solar cells, the electrical properties of the n-type layer (buffer layer) can be varied such as doping concentration and thickness. Studies have shown that as the concentration of donor doping in the buffer layer increases, the efficiency of the solar cell improves. However, when the concentration reaches 1×10^{18} cm^{-3}, the efficiency decreases. The optimal concentration for buffer donor doping is 1 x 10^{18} cm^{-3}, at which the efficiency reaches 14.01% (Baig et al. 2018, Jhuma et al. 2020, Osman et al. 2021, Putra et al. 2021, Smith et al 2021). In a study using SCAPS-1D, the thickness of the buffer layer was varied from 0.1 to 1 µm, while keeping other parameters constant. According to their result, a thinner buffer layer leads to a more efficient solar cell design, as more photons can reach the absorber layer and contribute to an increase in power conversion efficiency (PCE). The optimal thickness for the buffer layer was determined to be 0.1 µm (Baig et al. 2018; Belarbi et al. 2020; Khattak et al. 2018; Nykyruya et al. 2019; Shukla et al. 2019; Tinedert et al. 2020).

Bulk defects in CdS refer to structural irregularities within the material, such as vacancies, interstitials, dislocations, impurities, and substitutional defects. These defects can affect the electrical, optical, and mechanical properties of CdS, impacting the performance of semiconductor devices. In the case of a heterojunction between CdS and CdTe, interfacial defects can occur due to mismatches in lattice structure, atomic arrangements, or the presence of impurities. These defects are known as interfacial defects, occurring at the interface between the two semiconductor materials. The study investigates the impact of different defect concentrations (ranging from 1×10^{14} to 1×10^{20} cm^{-3}) on the photovoltaic performance of CdS/CdTe solar cells. The research finds that the photovoltaic performance of the solar cells is not significantly impacted by defect concentrations below 10^{14} cm^{-3}. However, as the defect concentration increases beyond this threshold level, the efficiency of the solar cells decreases, dropping to nearly zero at concentrations of 10^{20} cm^{-3}. Different types of defects (neutral, single donor, and single acceptor) also impact the photovoltaic performance differently. Both the concentration and charge type of defects in the absorber layer (CdTe) affect the photovoltaic performance parameters of CdS/CdTe solar cells. (Mathur et al. 2020; Pal et al. 2021)

In a recent study, the impact of interfacial defect density in the CdS/Perovskite layer on the performance of the solar cell was investigated. The researchers found that there is a defect energy level located at 0.6 eV below the conduction band edge of the CdS layer. This discovery aligns with previous findings but with an intriguing difference. The device's sensitivity to defect density has increased compared to earlier studies. The threshold for defect density, previously at 10^{14} cm^{-3}, has now been reduced to 10^{11} cm^{-3}. The study revealed that the highest Voc (open-circuit voltage) of 1.20 V was achieved within a narrow range of absorber thickness, specifically less than 500 nm, and at defect densities below 10^{11} cm^{-3} at the CdS/Perovskite interface. Outside of this range, the Voc decreases, and at defect densities exceeding 10^{15} cm^{-3}, it reaches its lowest value of 0.95 V. The short-circuit current density (Jsc) was found to be primarily independent of defect density. As the absorber thickness increased from 300 to 1000 nm, the Jsc increased slightly from 22 to 27 mA cm^{-2}. The fill factor (FF) was not significantly affected by the absorber layer thickness but showed a substantial decrease of approximately 50% when the defect density exceeded 10^{13} cm^{-3}. Finally, the study observed that a maximum efficiency of 28% was achieved with absorber thicknesses greater than 700 nm and defect densities below 10^{11} cm^{-3} (Chowdhury et al. 2019).

Maintaining optimal working temperatures is crucial for solar cell performance. Elevated temperatures negatively impact the characteristics of photovoltaic materials and devices. In CdTe solar cells (2000 nm thickness), temperature variation significantly affects performance. Open-circuit voltage peaks at 2.45 V (200 K) and drops to 0.64 V (400 K). Short-circuit current density decreases from 27.90 to 27.15 mA cm^{-2} (200 K to 400 K). Filling factor peaks at 330 K and drops at 400 K. Efficiency ranges from 32.29% (200 K) to 15.53% (400 K) (Khaledi et al., 2022).

This study aims to address the efficiency challenges faced by CdS/CdTe solar cells. The efficiency of CdS/CdTe solar cells can be improved by optimizing key parameters in the CdTe and CdS layers. This includes carefully considering doping concentration in the CdS layer, where excess buffer layer thickness may reduce photon access to the absorption layer, adversely affecting efficiency. Additionally, the thickness of the CdS layer is a critical factor, as an excessive thickness can result in absorption losses in CdTe. A notable gap in knowledge exists regarding the impact of interfacial and bulk defects on performance optimization. Consequently, this study seeks to comprehensively investigate and analyze these defects, focusing on parameters such as doping concentration, thickness, electron affinity, and temperature. Utilizing the SCAPS-1D simulator, the goal is to determine optimal values for these parameters, ultimately maximizing the efficiency of CdS/CdTe solar cells.

METHODOLOGY

MODELLING

SCAPS-1D stands out as a widely utilized software designed for the comprehensive simulation of solar cell performance. Its reliability has been established through meticulous comparisons with actual solar cell outcomes. The software exhibits a versatile capacity to simulate an array of materials and intricate defect profiles, encompassing various defect types (acceptor, neutral, and donor) along with diverse energy distributions (single, uniform, Gauβ, CB tail, and VB tail). This multifaceted functionality positions SCAPS-1D as a preferred choice for researchers delving into the intricacies of solar cell performance. Notably, SCAPS-1D enables users to extract crucial electronic parameters such as Voc, Jsc, FF, and η. Consequently, in the context of this study, SCAPS-1D has been specifically selected as the simulation tool due to its comprehensive capabilities and reliability.

In Figure 1, we present a comprehensive depiction of the methodology employed for the analysis of CdS/CdTe solar cell performance within the scope of this study. The investigation unfolds four distinct phases, each contributing to a nuanced understanding of the solar cell's behaviour. The initial phase focuses on a meticulous examination of the CdS/CdTe solar cells, wherein the doping concentration and electronic properties of the CdS layer are systematically adjusted. The outcomes of this phase are meticulously plotted on a performance graph, providing a visual representation of the intricate interplay between these influential parameters and the resultant solar cell performance. The process is repeated as another parameter needs to be varied. In the second phase, bulk and interfacial defects are added to the model to investigate their impact on the performance of the solar cells. In the third phase, the solar cell performance is studied by comparing the results of models with and without defects using various electrical properties. In the last phase, the external factor like the effect of temperature on solar cell performance is studied. The performance data is plotted on a graph for analysis in all phases, and the process is repeated for additional external factors as needed.

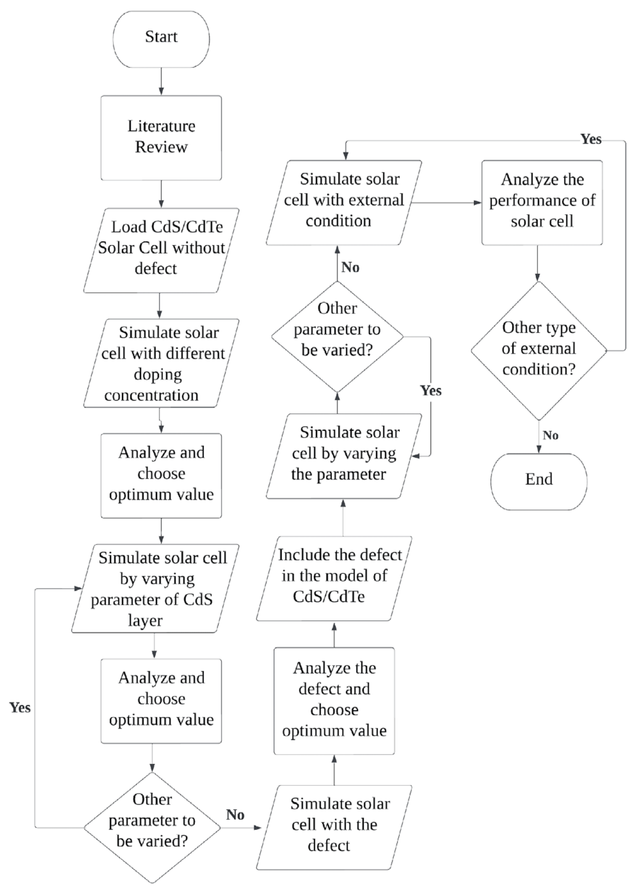


FIGURE 1. Flowchart of the study

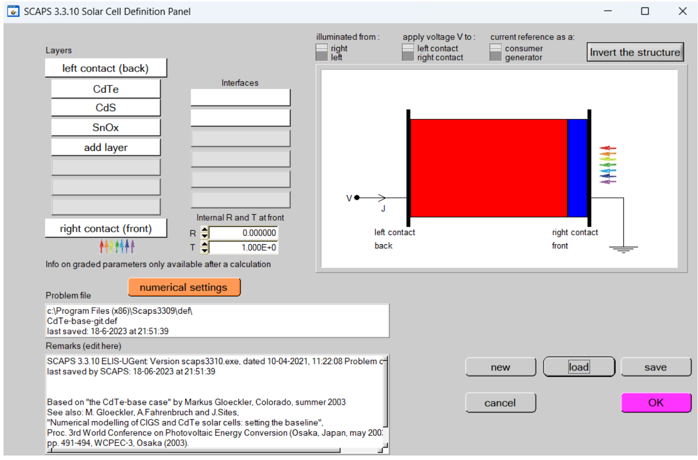


FIGURE 2. The layers in CdS/CdTe solar cell

In this study, the model of the CdS/CdTe solar cell used that is provided by SCAPS-1D. There are three layers in the CdS/CdTe solar cell, as shown in Figure 2. The variation in the value of electrical parameters and the default value of the parameter is shown in Table 1.

DEFECT PROFILES

The defect in the solar cell occurred in the layer of the solar cell. For bulk defects, the CdS layer, which is an n-type layer, is involved. By introducing the concentration of defect and capture cross section holes and electrons as 1.0×10^{19} cm^{-3}, 1.0×10^{-12} cm^2 and 1.0×10^{-17} cm^2, respectively, the analysis is done by observing the changes of energy with respect to a reference, Et from 0.2 eV to 2.2 eV in different energy distribution which is single, uniform and Gauβ. Then, the impact of changing both of the capture cross section of charge carriers on the performance of the solar cell is investigated. The bulk defect profile is shown in Figure 3.

CdS and CdTe layers are used to carry out the interfacial defect analysis. The simulation is done by changing the Et from 0.2 eV to 1.4 eV in different energy distributions. All types of defects, such as neutral, donor and acceptor, are investigated.

Lastly, some defects are included in the CdS/CdTe solar cell. The electrical parameter needs to be adjusted to compare the result with the previous model without defects.

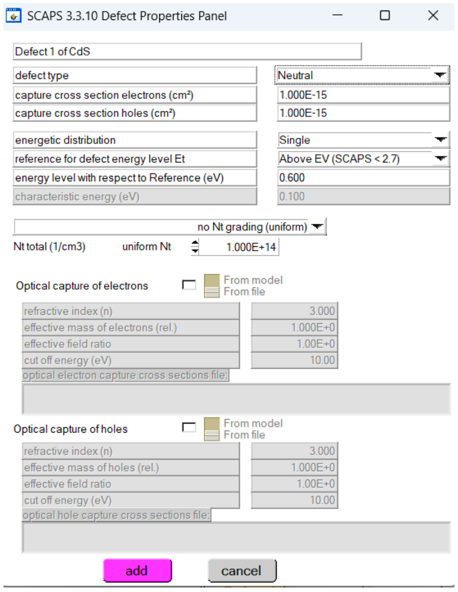


FIGURE 3. Bulk defect profile

EXTERNAL FACTOR OF SOLAR CELL

The simulation is done by adjusting the temperature in the CdS/CdTe solar cell model with defects. The temperature is varied in the “Working Point”. The variation of the temperature is from 270 K to 350 K. The “Working Points” panel is shown in Figure 4.

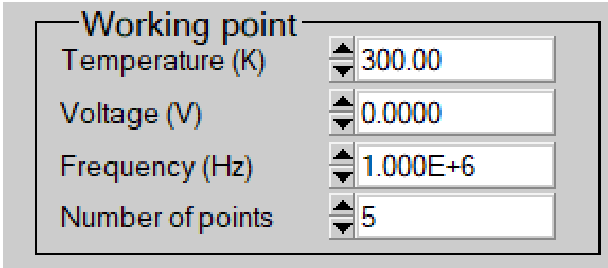


FIGURE 4. Panel of “Working Point”

TABLE 1. Electrical parameter of CdS/CdTe solar cell

Parameter	CdTe	CdS	SnOx
Thickness (nm)	4000	Varied	500
Bandgap (eV)	1.50	2.40	3.60
Electron affinity (eV)	3.90	Varied	4.00
Dielectric permittivity (relative)	9.40	10.00	9.00
CB effective density of states (cm^{-3})	8.0×10^{17}	2.2×10^{18}	2.2×10^{18}
VB effective density of states (cm^{-3})	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
Electron thermal velocity ($cm\ s^{-1}$)	1.0×10^{7}	1.0×10^{7}	1.0×10^{7}
Hole thermal velocity ($cm\ s^{-1}$)	1.0×10^{7}	1.0×10^{7}	1.0×10^{7}
Electron mobility ($cm^2\ V^{-1}\ s^{-1}$)	3.2×10^{2}	1.0×10^{2}	1.0×10^{2}
Hole mobility ($cm^2\ V^{-1}\ s^{-1}$)	4.0×10^{1}	2.5×10^{1}	2.5×10^{1}
Shallow uniform donor density ND (cm^{-3})	0.0×10^{0}	Varied	1.0×10^{17}
Shallow uniform acceptor density NA (cm^{-3})	1.0×10^{17}	0.0×10^{0}	0.0×10^{0}

RESULTS AND DISCUSSION

ELECTRICAL PARAMETER OF SOLAR CELL

The basic structure of CdS/CdTe is produced using the existing CdS/CdTe cells in the SCAPS-1D. The cell layer thickness and electron affinity for the n-type layers used are 10.0 nm and 4.0 eV. The doping concentration used is 1×10^{18} cm^{-3}.

The study found that increasing the density of n-type doping in the CdS layer of CdS/CdTe solar cells had a negligible effect on the open circuit voltage (Voc), showing almost a straight line. While the short circuit current density (Jsc) increased slightly at lower doping levels, a slight Jsc variation with a non-linear trend occurred. The fill factor (FF) increased as the doping concentration improved due to its relationship with Voc and Jsc mentioned in equation (1), with FF having an increasing trend in an almost straight line.

$$FF = \frac{P_{mp}}{V_{oc} \times J_{sc}} \tag{1}$$

The solar cell efficiency (η) is influenced by Voc, Jsc, and FF which is proved by equation (2), with efficiency increasing as doping concentration rises up to an optimal value of 5×10^{18} cm^{-3}, corresponding to an efficiency of 23.01%. The optimal values at this concentration are observed with Voc of 1.06366 V, Jsc of 24.61446 mA cm^{-2}, and FF of 87.89%. The effect of doping concentration on solar cell performance is shown in Figure 5.

$$\eta = \frac{V_{oc} \times J_{sc} \times FF}{P_{in}} \tag{2}$$

Increasing the electron affinity of the CdS layer in a CdS/CdTe solar cell slightly increases the open circuit voltage (Voc) but this is considered negligible. The short circuit current density (Jsc) slightly increases from 4.00

eV to 4.20 eV, then decreases from 4.20 eV to 4.50 eV. The fill factor (FF) shows a decreasing trend from 4.3 eV to 4.5 eV, indicating an increase in losses within the cell, possibly from recombination losses. Since Voc and Jsc have small variations, FF plays a more important role in determining the cell's efficiency. The optimum electron affinity value is between 4.0 eV and 4.1 eV, with 23.01% efficiency achieved at 4.0 eV. At this value, Voc is 1.06366 V, Jsc is 24.61446 mA cm^{-2}, and FF is 87.89%. The effect of electron affinity on the performance of solar cells is shown in Figure 6.

There are no changes in Voc, Jsc, FF and η in the variation of thickness of the CdS layer from 10 nm to 50 nm. There are a few reasons why the electrical parameters are unchanged. First, it is set as the perfect CdS/CdTe model solar cell; thus, there is no interfacial and bulk defect in the Et of CdS and CdTe. Therefore, as the photons excite the electrons to pass from CdS to CdTe, a constant number of electrons will penetrate through it. Consequently, the thickness of the CdS layer does not affect the electron transport to the absorber layer in the perfect CdS/CdTe solar cell. The optimum value is chosen as 10.0 nm since it is the default value of the CdS layer. The result of the effect of varying thickness of CdS on the performance of CdS/CdTe solar is shown in Table 2.

TABLE 2. Effect of variation in thickness of CdS on the performance of solar cell

Thickness (nm)	Voc (V)	Jsc (mA cm^{-2})	FF (%)	η (%)
10 - 50	1.07	24.61	87.89	23.01

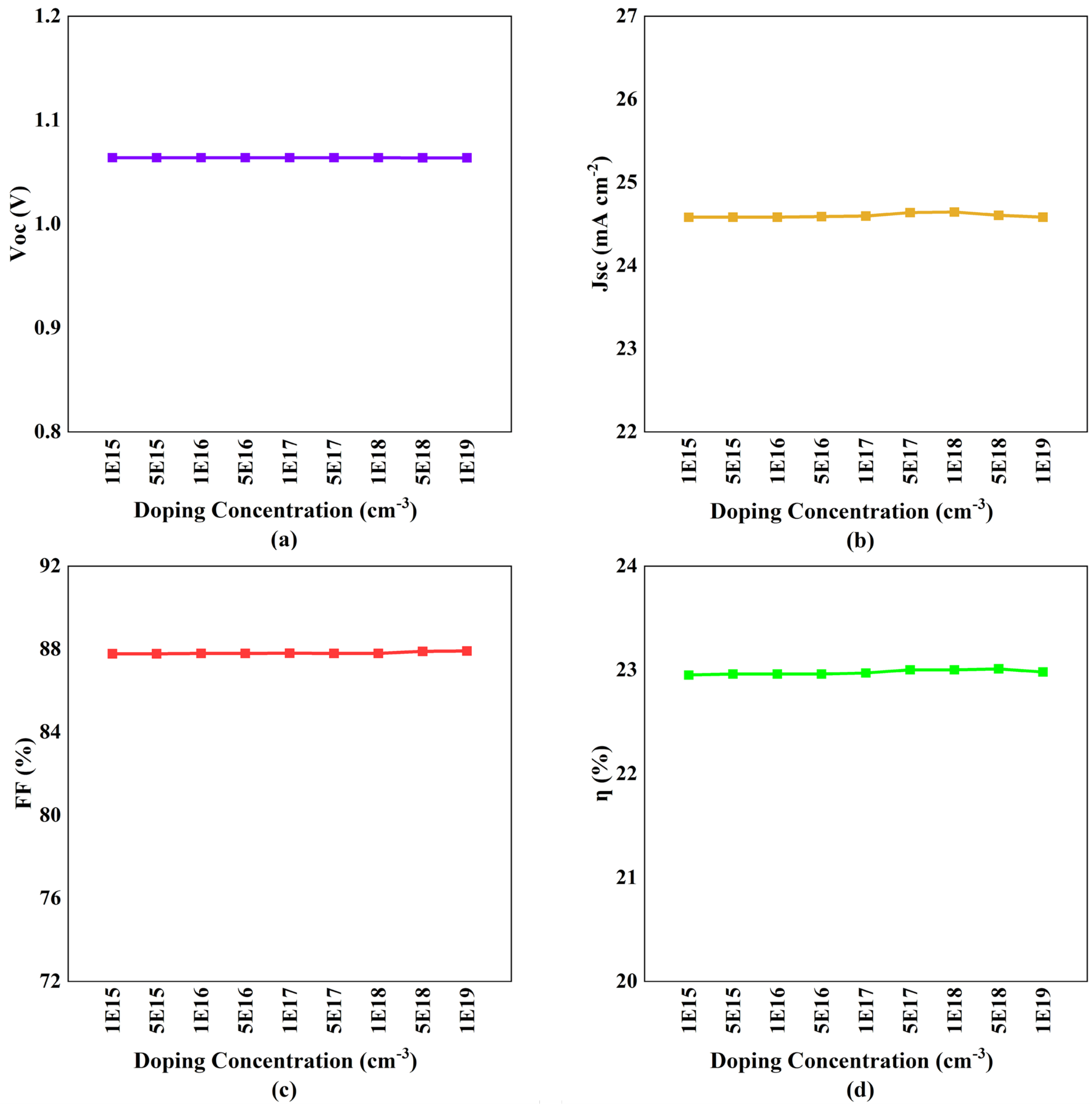


FIGURE 5. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against doping concentration of CdS layer

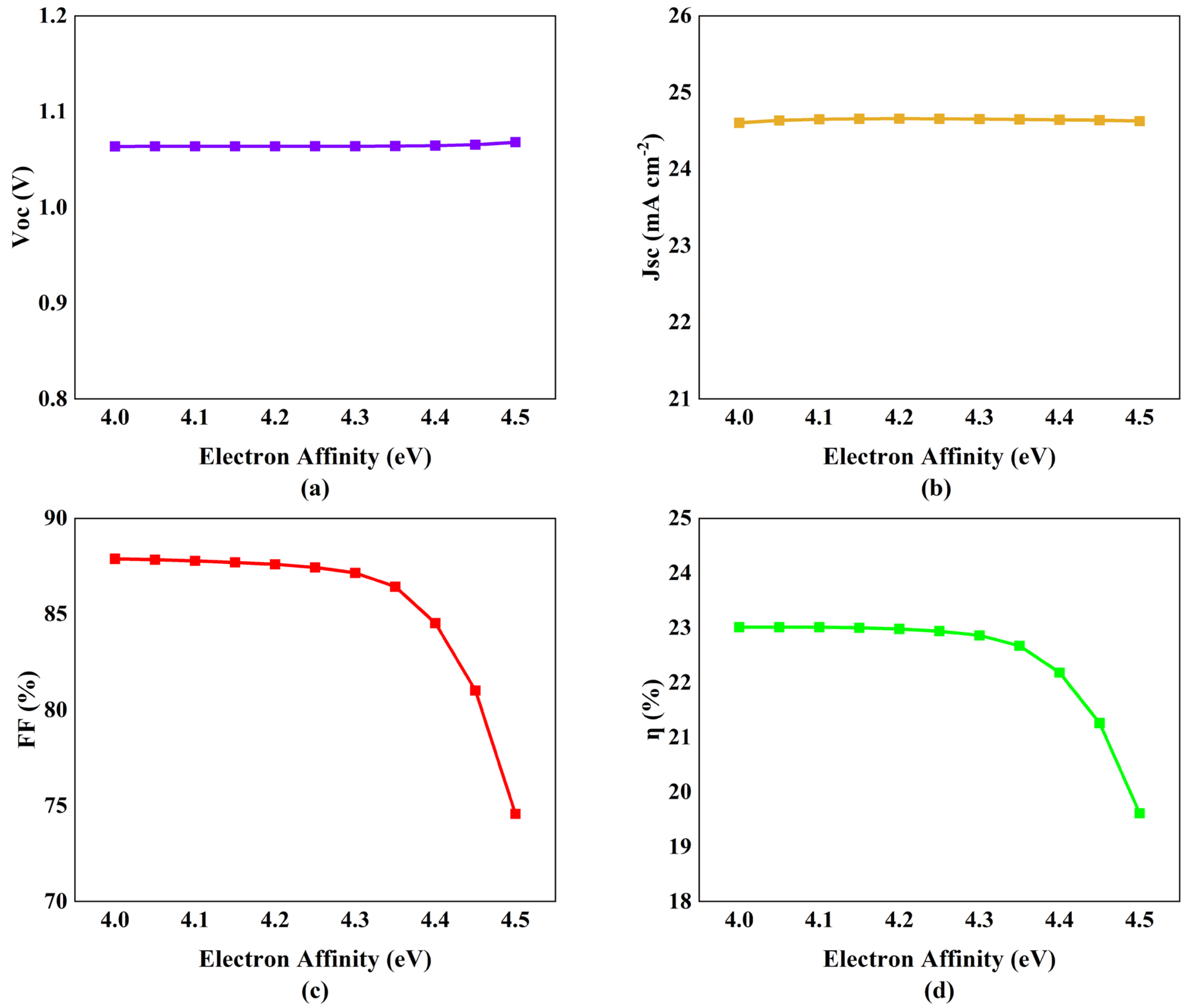


FIGURE 6. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against electron affinity of CdS layer

DEFECT PROFILES

Figure 7 shows the effect of different energy distributions on the performance of a solar cell. For single, uniform, and Gaussian acceptor bulk defects, increasing Et causes a decrease in Voc up to 0.8 eV and a slight increase after that. All three distributions show a peak Jsc at 0.6 eV. In Figure 7 (c), all three distributions show the same trend of a dramatic decrease in FF from 0.2 eV to 0.4 eV, followed by a significant increase up to 0.6 eV and a slight increase thereafter. The optimal value for energy distribution in all cases is 0.6 eV, which leads to the highest efficiency of 21.98%.

For donor and neutral bulk defects, all values (Voc, Jsc, FF and η) remain constant, although the Et increases from 0.2 eV to 2.2 eV. This result indicates that the donor and neutral defects do not play an essential role in affecting the performance of the CdS/CdTe solar cell. By comparing the efficiency from the perfect model of the CdS/CdTe solar cell in the "Electrical Parameter of Solar Cell" section, the overall efficiency is decreased to only 0.86%. The performance of neutral and donor defects is recorded in Table 3.

In Figure 8, this study is about the impact of different capture cross section electrons and holes values on solar cell performance. Increasing both the capture cross section electrons and holes leads to an increase in the Voc value. Fixing the capture cross section electrons and holes as 1×10^{-17} cm^2 and 1×10^{-15} cm^2 respectively, results in the highest Jsc value of 24.00114 mA cm^{-2} compared to other values of capture cross section charge carries. As the capture cross section electrons decrease and the capture cross section holes increase, the FF value will increase. Consequently, the efficiency increased. Optimal values for capture cross section electrons and holes are 1×10^{-17} cm^2 and 1×10^{-13} cm^2 respectively, which result in a Voc value of 1.063 V, Jsc value of 24.0127 mA cm^{-2}, and FF value of 85.74%.

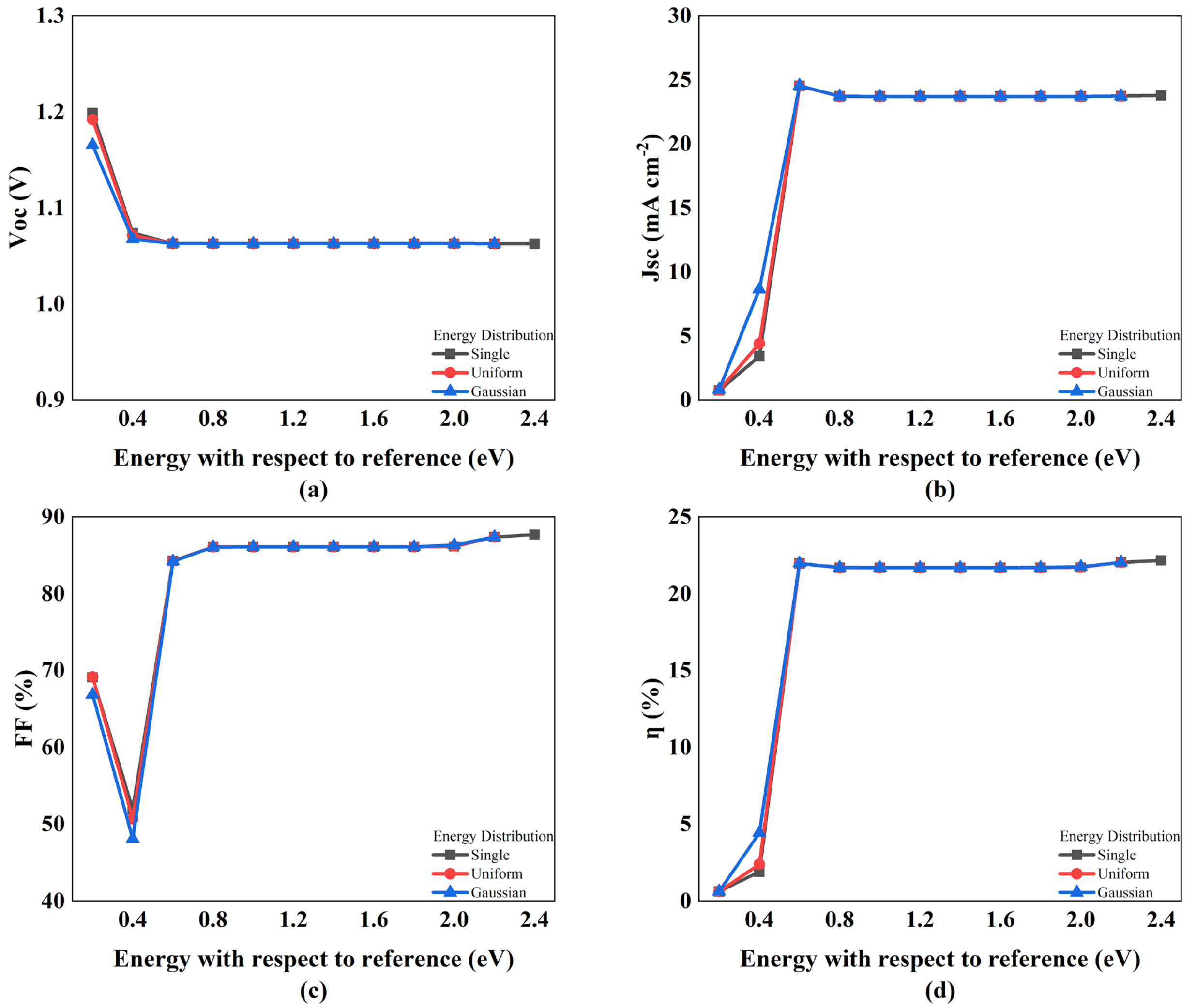


FIGURE 7. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against Et of acceptor bulk defect in CdS layer in different energy distribution

TABLE 3. Effect of variation in Et in single, uniform and Gaussian for neutral and donor defect

Defect Type	Energy Distribution	Et (eV)	Voc (V)	Jsc (mA cm^{-2})	FF (%)	η (%)
Neutral	Single	0.2 – 2.2	1.06	23.73	87.83	22.15
	Uniform		1.06	23.73	87.83	22.15
	Gaussian		1.06	23.73	87.83	22.15
Donor	Single	0.2 – 2.2	1.06	23.73	87.83	22.15
	Uniform		1.06	23.73	87.83	22.15
	Gaussian		1.06	23.73	87.83	22.15

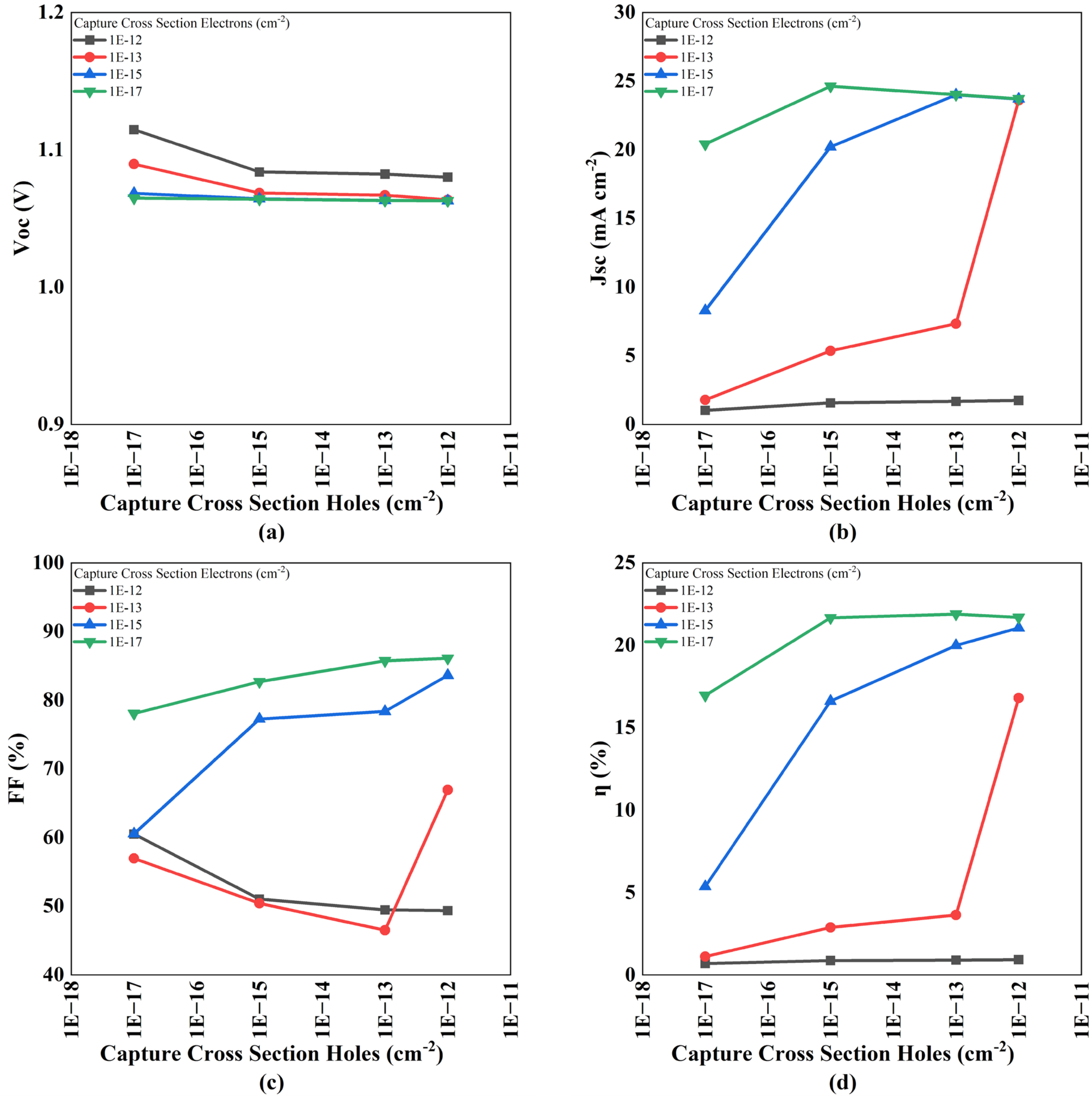


FIGURE 8. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against capture cross section holes and electrons

For single acceptor interfacial defect, Voc decreases from 0.9732 V to 0.8163 V as the Et increases. Similar trends are observed for uniform and Gaussian acceptor bulk defects. All three energy distributions show an increasing trend for Et in the acceptor bulk defect, with Gaussian having the lowest peak Jsc value of 23.388764 mA cm^{-2} and single acceptor defect having the highest value of 24.135739 mA cm^{-2}. The peak values of FF for all three energy distributions occur at 1.4 eV. The highest value of η is observed at 1.4 eV for single and uniform defects, while the highest value for Gaussian occurs at 0.2 eV. The optimum values for Voc, Jsc, and FF are 1.0295 V, 24.592233 mA cm^{-2}, and 87.64%, respectively, for single acceptor bulk defect at 0.6 eV of Et. For uniform bulk defect, the values are 1.0185 V, 24.590617 mA cm^{-2}, and 87.42% respectively. Lastly, for Gaussian bulk defect, the values are 1.0258 V, 23.388764 mA cm^{-2}, and 86.85%. The effect of various Et of acceptor interfacial defect in different energy distributions on the performance of the solar cell is shown in Figure 9.

The analysis of neutral interfacial defect is shown in Figure 10. As the activation energy increases, Voc remains constant from 0.2 eV to 1.2 eV and then slightly increases at 1.4 eV. Straight lines are shown in Jsc and FF graphs, indicating that they do not significantly impact the performance of the solar cell. The trend of η (efficiency) follows the same pattern as the Voc graph. The value of η is 22.24% from 0.2 eV to 1.2 eV and increases to 22.49%

at 1.4 eV. From Figure 11 (a), for all of the neutral interfacial defects, as the energy with respect to Et increases, the Voc are constant from 0.2 eV to 1.2 eV and increases slightly to 1.4 eV. In Figure 11 (b) and (c), the graph for all energy distribution shows a pure straight-line graph, which means that Jsc and FF do not play a role in the performance of the solar cell. The η graph in Figure 11 (d) shows the same trend as the graph in Figure 11 (a), which is the Voc graph. The value of η is 22.24% from 0.2 eV to 1.2 eV and increased to 22.49% at 1.4 eV.

The changes in the solar cell's behaviour, influenced by different defects and activation energies, happen because these defects affect how the solar cell handles electricity. For a single acceptor interfacial defect, the solar cell's ability to produce electrical voltage drops when the activation energy increases. Different defects also impact how efficiently the solar cell turns light into electricity, as shown by changes in current density and fill factor. The peaks in performance at specific activation energies highlight that the type and distribution of defects matter. For neutral interfacial defects, there's less impact on the cell's performance, with the voltage staying primarily constant. Overall, these variations show how different defects and their energy levels affect how well the solar cell works.

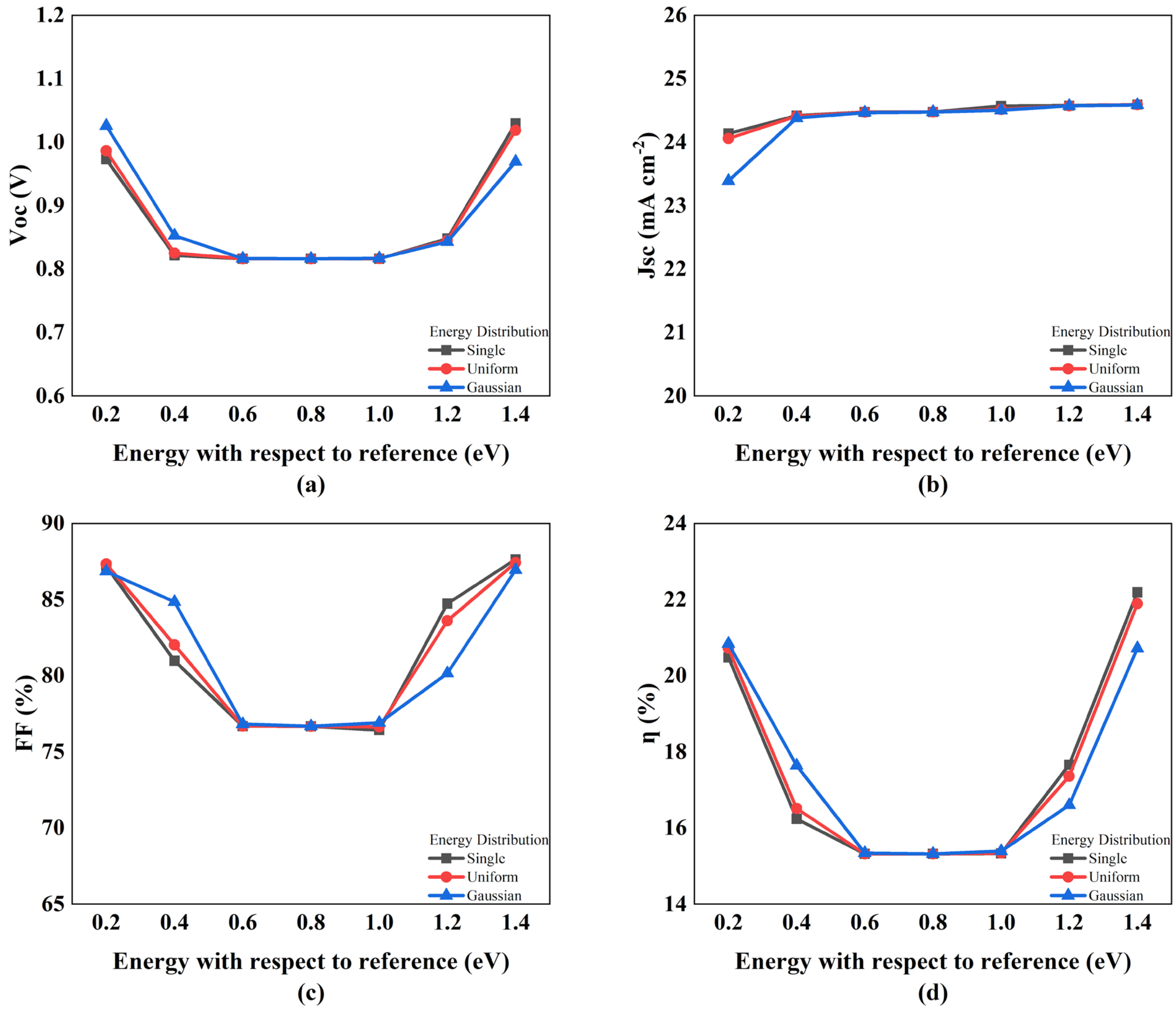


FIGURE 9. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against Et of acceptor interfacial defect in different energy distribution

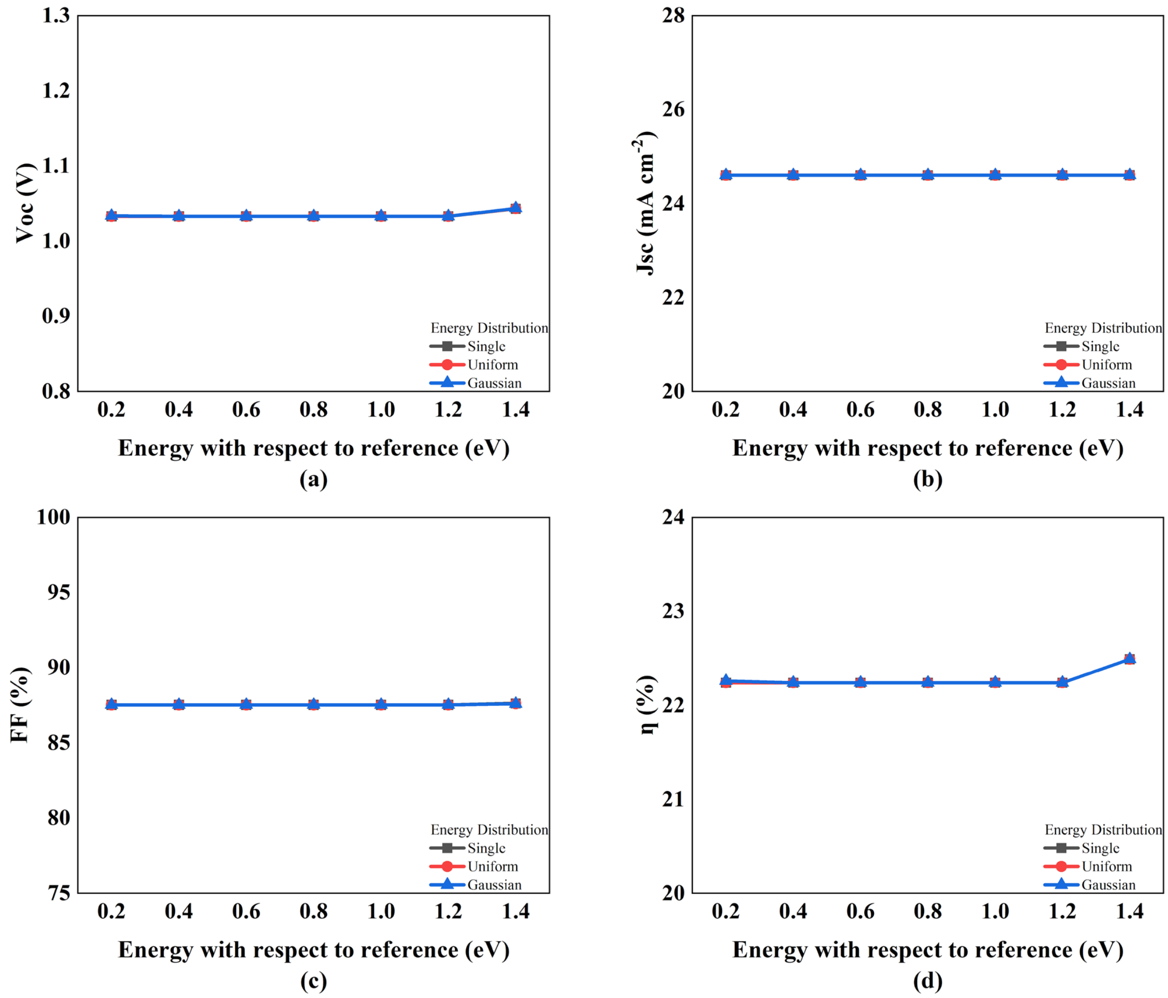


FIGURE 10. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against Et of neutral interfacial defect in different energy distribution

After analyzing all the defects above, some are considered for the following simulation. To build a defect model of CdS/CdTe solar cell, the single acceptor bulk and interfacial defects are included. For bulk defect, the defect concentration is set as 1.0×10^{19} cm^{-3} and the capture cross section electrons and capture cross section holes are set as 1.0×10^{-17} cm^2 and 1.0×10^{-12} cm^2 respectively. For the interfacial defect, the defect concentration is set as 1.0×10^{14} cm^{-3} and both the capture cross section electrons and capture cross section holes are set as 1.0×10^{-17} cm^2.

Figure 12 shows the effect of doping concentration on the performance of the solar cell with bulk and interfacial defects. Increasing the doping concentration of the n-type layer has a significant impact on the performance of a solar cell. The Voc remains steady from 1×10^{15} cm^{-3} to 1×10^{18} cm^{-3}, but decreases after 5×10^{18} cm^{-3}, with a decrease of approximately 0.02 V from 1×10^{18} cm^{-3} to 1×10^{19} cm^{-3}. The Jsc decreases as the doping concentration of the n-type layer increases from 5×10^{17} cm^{-3} to 1×10^{19} cm^{-3}. The decrease in Jsc is approximately 0.47 mA cm^{-2} between each point, resulting in a straight-line trend from 5×10^{17} cm^{-3} onwards. The value of FF is influenced by Voc and Jsc, both of which decrease from 5×10^{17} cm^{-3} to 1×10^{19} cm^{-3}. However, the decrease in Voc and Jsc leads to an increase in FF. Increasing the doping concentration increases the value of FF, offsetting the decrease in Voc and Jsc. The overall result is an increase in η. Therefore, the optimal doping concentration is found to be 1×10^{19} cm^{-3}, resulting in the highest efficiency of 21.40%.

Figure 13 shows the impact of increasing the electron affinity of the n-type layer (CdS layer) on the performance of a defective CdS/CdTe solar cell. Voc increases with an increase in electron affinity but only decreases between 0.0001 and 0.0100 V. The decreasing trend from 4.4 eV to 4.5 eV is significant while Jsc slightly decreases between 4.40 eV and 4.50 eV, with a decrease of about 0.032 mA cm^{-2}. FF decreases significantly from 4.40 eV to 4.50 eV, with a difference of 37.33%, affecting the η of the solar cell. The decreasing trend of Voc, Jsc and FF across the electron affinity results in a decrease in η. The optimum value for electron affinity is found to be 4.0 eV, resulting in the highest η of 21.40%.

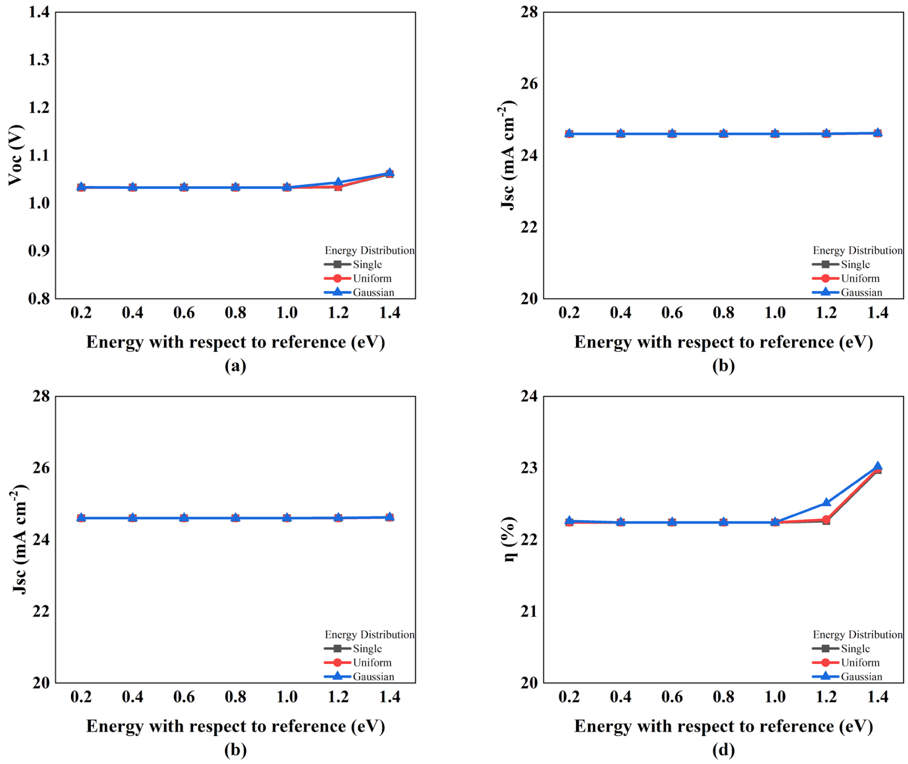


FIGURE 11. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against Et of donor interfacial defect in different energy distribution

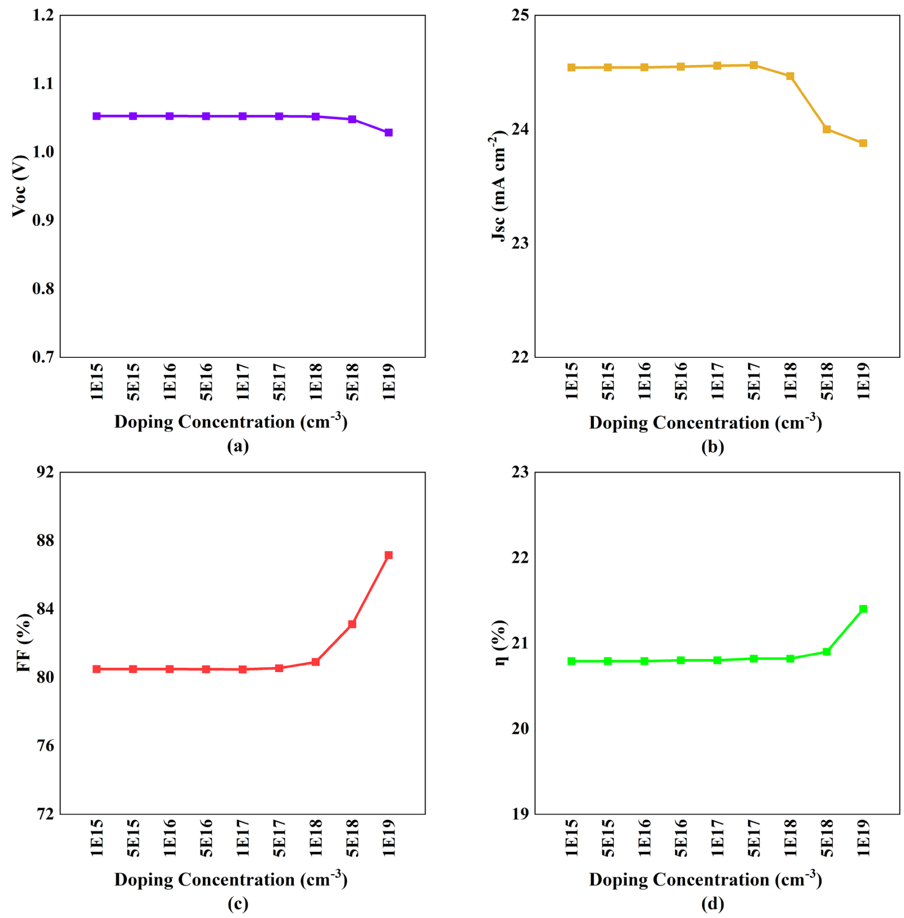


FIGURE 12. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against doping concentration of CdS layer

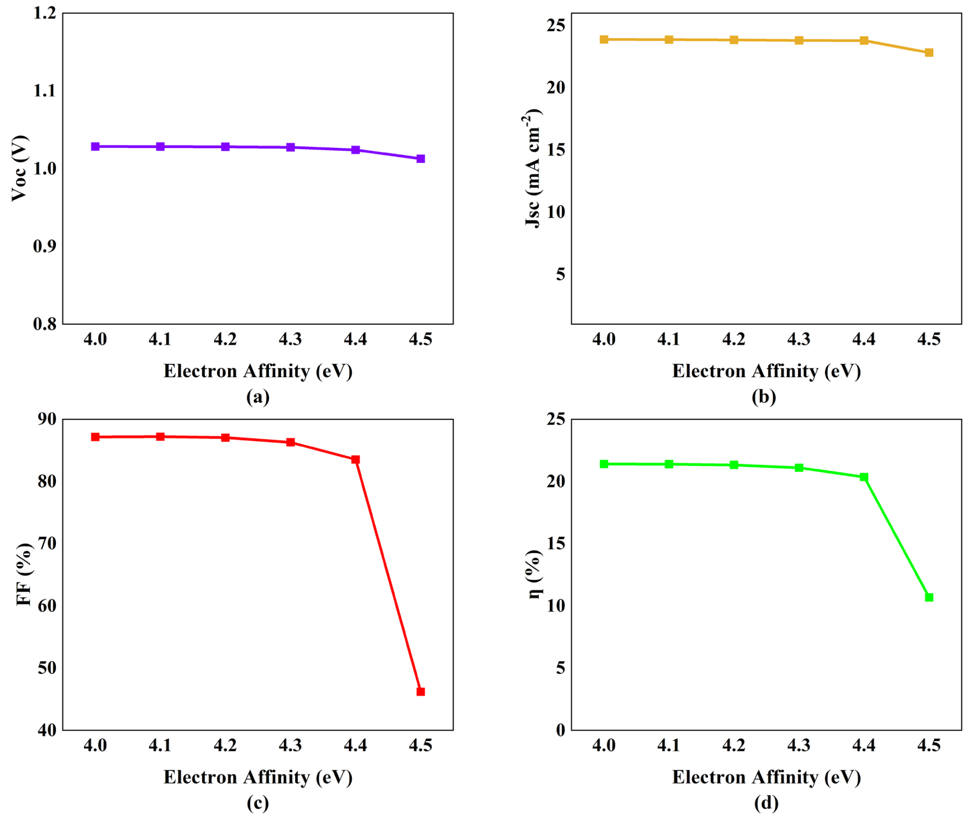
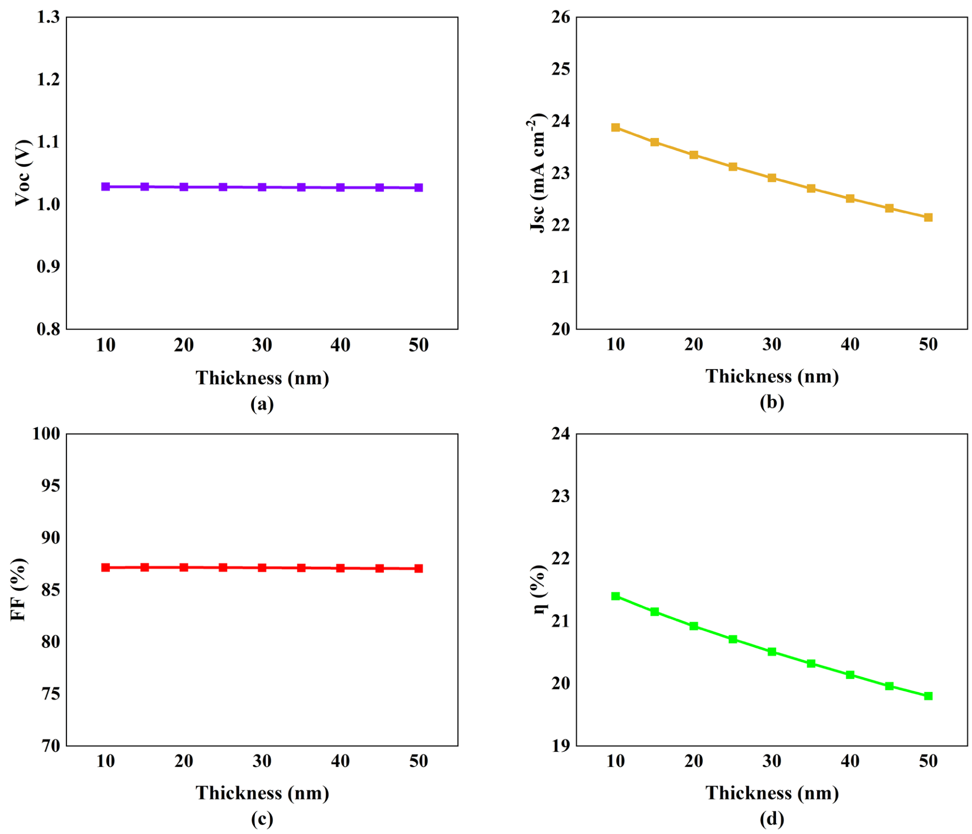


FIGURE 13. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against electron affinity of CdS layer



GURE 14. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against thickness of CdS layer

Figure 14 shows the impact of increasing the thickness of the n-type layer (CdS layer) on the performance of a defective CdS/CdTe solar cell. The thickness of the CdS layer has a minimal effect on the Voc of the CdS/CdTe solar cell, so Voc is not important for η. Meanwhile, Jsc significantly decreases as the thickness of CdS increases, making it essential for η. FF decreases slightly but can be considered negligible, so it does not play a role in η. Based on the equation (2), Jsc is the main factor influencing efficiency. The graph Figure 14 (d) confirms the decreasing trend in efficiency with increasing CdS thickness which fulfill the equation (2). The optimum thickness is 10 nm, giving an efficiency of 21.40%. At 10 nm, Voc is 1.0284 V, Jsc is 23.87814 mA cm-2, and FF is 87.15%.

EXTERNAL FACTOR OF SOLAR CELL

Figure 15 shows the impact of increasing the temperature on the performance of a defective CdS/CdTe solar cell. From the Figure 15, the Voc of the CdS/CdTe solar cell decreases significantly as the temperature increases, indicating its important role in efficiency while Jsc remains relatively constant with temperature. As the temperature goes up, the efficiency of a defective CdS/CdTe solar cell goes down due to open-circuit voltage (Voc) and fill factor (FF) decreasing as the temperature rises. These reductions in Voc and FF make the overall efficiency of the solar cell drop. Even though the short-circuit current density (Jsc) stays somewhat steady with temperature, it doesn't significantly impact efficiency. So, in simple terms, the solar cell doesn't work with higher temperatures, and its efficiency decreases.

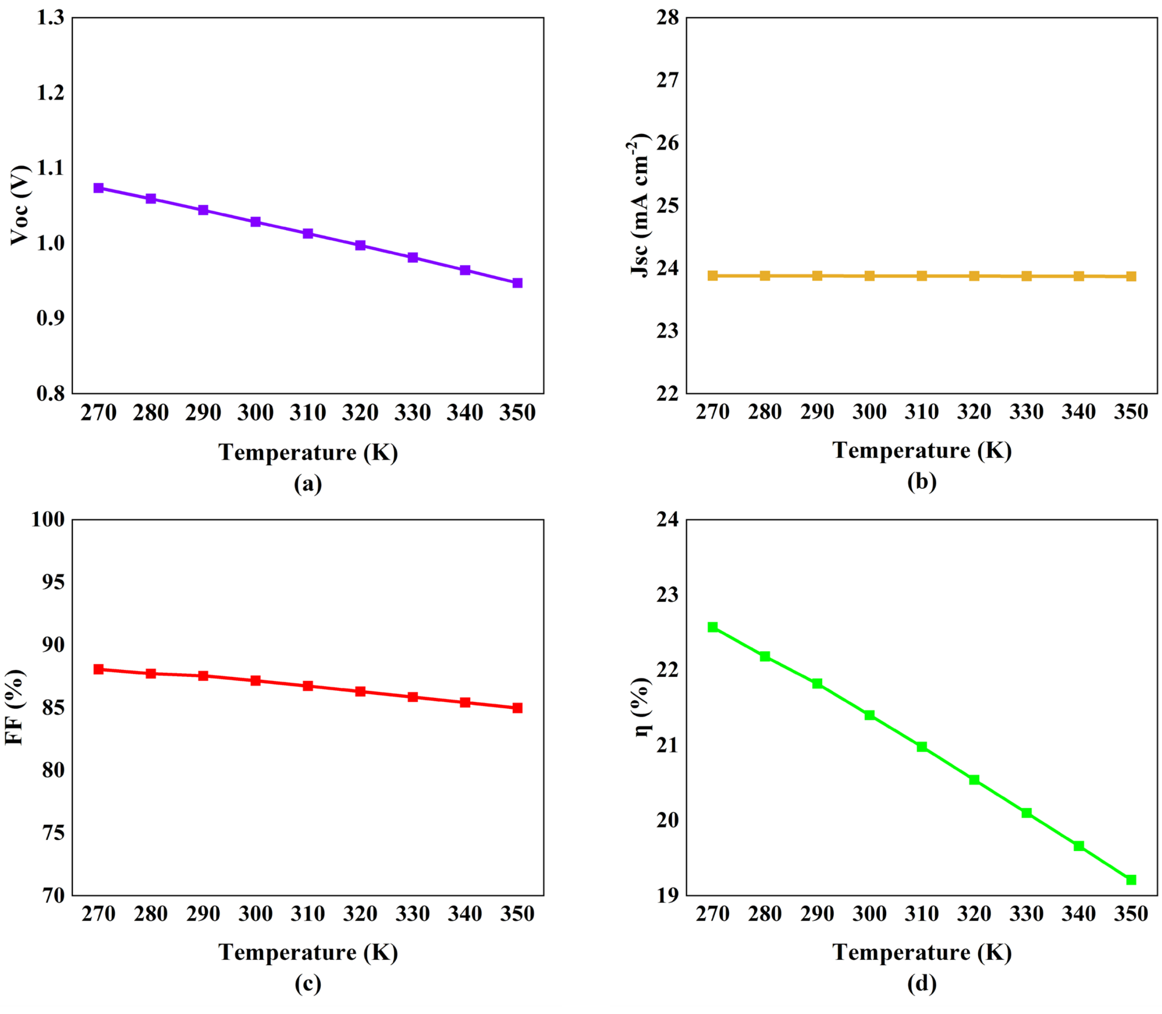


FIGURE 15. Graph of (a) Voc, (b) Jsc, (c) FF, (d) η against temperature

ERROR ANALYSIS

By conducting error analysis, a model of a CdS/CdTe solar cell comprising n-SnO2, n-ZTO, n-CdS:O, p-$CdTe_{1-x}S_x$ (x = 0.12), p-CdTe, and ZnTe layers, is systematically compared to evaluate its performance and identify opportunities for improvement in efficiency (Ngoupo et al. 2019). In this study, a SCAPS-1D model is used to conduct all the results above. In order to maintain the accuracy of the error analysis, the parameters of the CdS/CdTe are set as the same values. Both models consist of interfacial defects.

TABLE 4. Effect of variation in Et in single, uniform and Gaussian for neutral and donor defect

Electrical Parameter	Ngoupo Model	SCAPS-1D Model
Voc (V)	1.0055	1.0277
Jsc (mA cm^{-2})	25.860	23.123
FF (%)	78.31	87.15
η (%)	20.36	20.71

Table 4 compares the Ngoupo model and the SCAPS-1D model with almost the same result. By comparing the Ngoupo model and SCAPS-1D models for a CdS/CdTe solar cell, the analysis reveals a 2.19% increase in open-circuit voltage (Voc) in favour of the SCAPS-1D model. Conversely, the Ngoupo model exhibits a 7.47% higher short-circuit current density (Jsc). Additionally, the SCAPS-1D model demonstrates an 11.18% improvement in fill factor (FF) compared to the Ngoupo model. Regarding efficiency (η), the SCAPS-1D model shows a 1.22% increase over the Ngoupo model. These comparisons highlight the performance differences between the two models in various electrical parameters of the CdS/CdTe solar cell.

The Ngoupo solar cell model might have lower efficiency than a SCAPS-1D model of a CdS/CdTe solar cell because it has more layers. These extra layers could create defects and losses in how electrical charges move, making the solar cell less effective.

CONCLUSION

The simulation compared the performance of CdS/CdTe solar cells with and without defects. In the perfect solar cell, changing the doping concentration in the CdS layer had a minimal effect. However, increasing the electron affinity of the CdS layer led to a drop in efficiency. Changing the thickness of the CdS layer did not impact the key performance indicators. The optimal values of doping concentration, electron affinity, and thickness for the defect-free solar cell were found to be 5×10^{18} cm^{-3}, 4.0 eV, and 10 nm, respectively, resulting in an efficiency of 23.01%.

In the analysis of bulk defect, the capture section of holes increased while the capture section of electrons decreased, maximizing efficiency. Acceptor defects in both bulk and interfacial regions had a significant impact on the solar cells, regardless of energy distribution. Donor and neutral defects had a minor impact on the efficiency of the CdS/CdTe solar cell.

Single acceptor bulk and interfacial defects were introduced, creating imperfections in the CdS/CdTe layer and building a defect model for the solar cell. Increasing the doping concentration led to a noticeable increase in efficiency, with the optimal doping concentration changing to 1×10^{19} cm^{-3}. The efficiency decreased with an increase in electron affinity, similar to the trend observed in the perfect solar cell. The optimal electron affinity remained at 4.0 eV. When varying the thickness, the efficiency decreased with an increase in thickness, which was more logical compared to the result in the perfect solar cell. The optimal thickness was found to be 10 nm, resulting in an efficiency of 21.40%. The simulation confirmed the temperature effect observed in previous studies, where an increase in temperature led to a decrease in efficiency.

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DECLARATION OF COMPETING INTEREST

None

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