https://doi.org/10.3311/PPch.38728

Periodica Polytechnica Chemical Engineering, 69(1), pp. 35–45, 2025

A Comprehensive Simulation Study of CdTe Energy Gap Effects on CdTe/CdS Solar Cell Characteristics: SCAPS-1D

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Received: 02 November 2024, Accepted: 06 February 2025, Published online: 19 February 2025

Abstract

The energy gap of the CdTe absorber layer in CdTe/CdS solar cells has a dominant effect on their performance. In this work, the effects of altering the energy band gap of CdTe (1.37 eV; 1.47 eV; 1.54 eV) on the features of the solar cell were analyzed using SCAPS-1D program. From our results, CdTe energy gap was found to be directly proportional to the open-circuit voltage (Voc), meaning that higher energy gaps gave higher Voc. But this was compensated by a fall in the short circuit current density (Jsc) due to light capture reduction effect which also contributes to the powering up of the cell. An appropriate energy bandgap of 1.47 eV for the CdTe layer has been calculated to secure high values of Voc and quite a high Jsc to increase overall conversion efficiency of the solar cell. Moreover, a noticeable trend appears in capacitance and conductance whereby smaller energy gaps yielded higher capacitance and conductance. The quantum efficiency was also changed; lower energy gaps had a better ability to absorb the photons and have higher efficiency to varying ranges of wavelengths. This study underscores the critical role of accurately tuning the CdTe energy gap during fabrication to optimize the efficiency of CdTe/CdS solar cells.

Keywords

CdS/CdTe solar cell, bandgap engineering, capacitance, conductance, J-V-curve, SCAPS-1D

1 Introduction

The search for an adequate supply of clean power worldwide has kept photovoltaic technologies at the frontline of innovation. Within the various classes of photovoltaic (PV) technologies [1–4], the CdTe thin-film solar cells have turned out to be quite promising [5–9]. Because of their high efficiency, low manufacturing cost, and the availability of the constituent material, cadmium telluride. Cadmium telluride based and cadmium sulfide based thin film solar cells have gained much attention because of their possibility for high efficiency and the prospect of low production cost. CdTe has an energy gap (band gap) of about 1.45 eV, which is very suitable for photovoltaic conversion and thus should be used in the manufacture of solar cells [1, 10–12]. This work will set the intention of formally systematically modeling the impact of modulating the energy gap of CdTe on the attributes of the CdTe/CdS solar cells.

The conversion efficiency of CdTe/CdS solar cells depends uniquely on the band gap of the materials, the cell's geometrical parameters, and technological factors.

Band gap and absorption coefficient: CdTe has a direct band gap of 1.45 eV, and CdS of 2.4 eV, implying that the material can effectively absorb sunlight, which is vital for strong photovoltaic performance [1, 10–12]. Important crucial essential characteristic of these materials that determine the effectiveness of solar cells is the absorption coefficient of these materials in the given range of the spectrum [13, 14]. Structural optimization: In the discussions of the present work, many papers have directed efforts on modifying the structural parameters of the CdTe/CdS solar cells for better performance. This entails varying the thickness of the absorbing and window layers, the buffer, and the back contact layers [15]. Optimization of these parameters is expected to enhance the open circuit voltage, the short circuit current density, the fill factor, and the overall conversion efficiency.

Alloying and band gap engineering: However, by incorporating selenium or zinc into the CdTe matrix, it is possible to tailor the band gap in order to increase cell

Cite this article as: Mekky, A-b. H. "A Comprehensive Simulation Study of CdTe Energy Gap Effects on CdTe/CdS Solar Cell Characteristics: SCAPS-1D", Periodica Polytechnica Chemical Engineering, 69(1), pp. 35–45, 2025. https://doi.org/10.3311/PPch.38728

efficiency [16–18]. For example, adding selenium into the material to create CdSeTe can help in lowering the band gap, improve current harvest and quantum yield at the longer part of the spectrum [19, 20]. In the same way, doping of the CdS window layer with ZnS to create $Cd_{1-x}Zn_xS$ will enhance the band gap and decrease the resistivity than that of the CdS enhancing the efficiency of the film [21].

Fabrication techniques and treatments: The fabrication atmosphere and the post-deposition treatments greatly influence the electrical profile and efficiency of the CdTe/CdS solar cells [22, 23]. For example, the surface of the CdS layer can be cooled and then reheated before the deposition of the next layer, CdTe to improve its crystallinity and increase the energy conversion efficiency [24]. Moreover, the type of materials used for the buffer layer and even the oxygen level during fabrication impacts the interface energy barriers and defects that seem to hold the key to high performance of the cells [25].

Nanostructures and morphology: Several factors related to radio morphology of CdTe such as nanorods, nanowalls and nanoclusters are also known to influence the efficiency of the solar cells. It means that various nanostructures may cause changes in the band gap energy and optical transmittance that can affect the solar cells' efficiency [26].

Nevertheless, the drive towards improved efficiency requires knowledge of, and precise regulation of, the key performance factors implicated on a solar cell. Among these critical parameters is the energy gap in the CdTe absorber layer which forms part of the CdTe/CdS solar cell construct. Namely, the energy gap is a parameter of semiconductors that reflects the capability to generate a free electron hole pair at the PV cell, when an electron is excited from the valence band to the conduction band by the energy of the photon with the minimum energy allowed by the semiconductor [27].

The thickness of the CdTe absorber layer plays significant role in determination of the efficiency of the solar cell because it defines photon absorption and charge carrier generation. A reduced bandgap enables the absorption of wider wavelength photons and therefore a possibility to increase the short circuit current densities (Jscs), the highest current density which can flow through the cell under ideal conditions. But if the energy gap is low, it also leads to low open-circuit voltage (Voc), the maximum voltage that can be output by solar cells, because of the higher recombination rate of charges [28]. Thus, the interrelationship between energy gap, current, and voltage indicates that there should be an efficient balance for enhancing the effectiveness of solar cells [29–31].

In this work, the reader will find a discussion regarding the correlation between the CdTe absorber layer energy gap and the capabilities of the CdTe/CdS solar cells utilizing the highly effective SCAPS-1D software [32]. This work systematically changes the value of the energy gap of CdTe while keeping all other parameters fixed so that overall effects on specific solar cell performance parameters are well understood. These parameters include the Voc, the Jsc, capacitance, conductance, and quantum efficiency (QE). Through this research, the authors will seek to buffer the linkage between the CdTe energy gap and the aforementioned three critical performance factors to establish how the properties of room materials influence device performance.

The energy level of CdTe has a significant impact on the behaviour of CdTe/CdS solar cells, together with J-V characteristics. This means that proper control of the band gap, along with alloying, structural modifications, and sensible fabrication technologies, could enhance efficiency and performance. These aspects will be elaborated further in this comprehensive simulation study to enable an understanding of the design and fabrication of CdTe/CdS solar cells.

2 Methods and calculations

Here, the SCAPS-1D simulation software, which has been broadly employed in studying the behavior of photovoltaic devices, was used to examine the effect of the energy gap of the CdTe absorber layer on the performance of the CdTe/CdS solar cell. The SCAPS-1D model comprises the active or absorber layer, which in the present case is CdTe, the buffer layer, which is CdS, and the front and back contact layers.

The simulation process involved the following steps:

1. Modeling the CdTe/CdS solar cell: The first step in our simulation process was to simulate the structure of the CdTe/CdS solar cell in SCAPS-1D and specify independent layers. The model assumed steady-state material parameters, which include the band gap, thickness, electron affinity, and dielectric permittivity of CdTe and CdS.
2. Varying the CdTe energy gap: We then changed the energy band gap of the CdTe absorber layer to model three variants of energy band gaps for the solar cell: 1.37 eV, 1.47 eV, and 1.54 eV, respectively. This enabled us to study the influence of the various energy gaps on the solar cell's overall performance.
3. Defining working point conditions: For the characterize solar cells at standard test conditions for the measurement of characterize solar cells at standard test conditions for the measurement of simulation's

working point conditions; we selected incident light intensity 100 mW/cm^2, temperature 300 K, and frequency 1 MHz. These parameters characterize solar cells as standard test conditions for measuring solar cell efficacy.

4. Running simulations: The energy gap scenarios were then applied to the model's working conditions in the SCAPS-1D simulations. The software also predicted other performance characteristics, namely J-V characteristics, capacitance conductance, and QE of the fabricated solar cell.
5. Analyzing results: The simulation results are examined in detail to investigate the relationship of the CdTe energy gap to various performance characteristics. As such, we look at the characteristics of the solar cell in various energy gap scenarios and make deductions relating to the most suitable energy gap for functional CdTe/CdS solar cell performance.

The use of SCAPS-1D simulation techniques made it possible to realize the sensibility of the CdTe energy gap to the performance of the solar cell without undertaking experimental procedure. This method helped in understanding the processes causing the given trends and in further definition of the configuration of the CdTe/CdS solar cells for enhanced efficiency. All steps of numerical simulations were performed by the factor of the typical AM1.5 G solar spectrum.

In this work, we have used a diagrammatic representation (Fig. 1) showing the various layers in the CdTe/CdS solar cell to provide a comprehensive description of the solar cell. This design illustrates how each part cooperates to give the cell in question efficient performance.

The absorber layer uses CdTe as a material and is critical to the composition of the solar cell. It captures sunlight. When photons strike it, they produce electron-hole pairs. Usually not more than 4 μm in thickness, this layer is designed to absorb maximum light and minimize recombination losses. The forbidden energy band of CdTe is adjustable between 1.37 eV, 1.47 eV, and 1.54 eV and plays a central role in achieving optimal spectrum absorption.

Following the absorber layer in the structure is the buffer layer which comprises of CdS. This layer behaves as a barrier and at the same time charges transport pathway also needed to minimize recombination at the CdTe junction. The optoelectric performance of the sample is governed by the CdS layer that is fabricated to be about 25 nm thick to allow for the transmission of light alongside efficient charge transport. Electron transport is encouraged by the band gap of around 2.4 eV of CdS and back recombination is controlled.

Front contact can be of transparent conducting oxides such as tin doped indium oxide (ITO). This contact enables light to get into the solar cell while at the same time giving a channel where the extracted electrons can go. High light transmittance and electrical conductivity are important in reducing the electrical resistive film thickness while at the same time increasing the amount of light that can be captured.

On the other hand, the back contact, which often comprises of silver or aluminium, gathers the electrons that move in the solar cell. It also acts as an electrode to close the electric circuit to let current flow to external load.

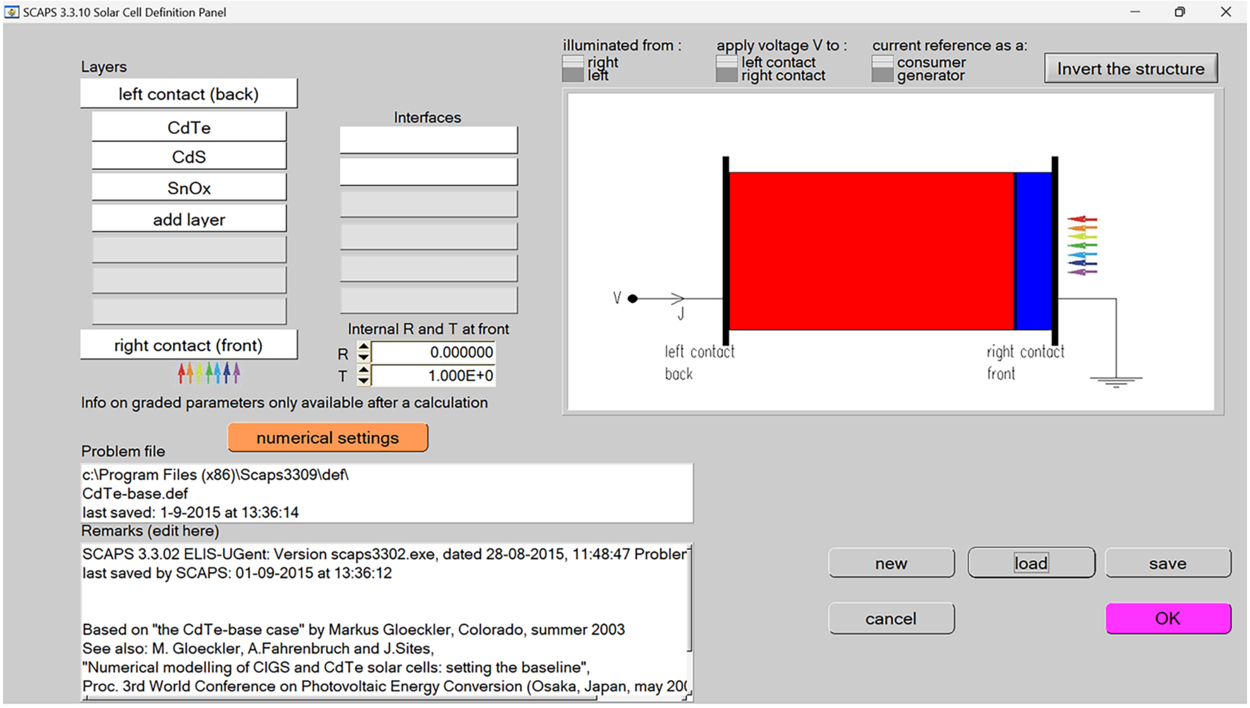
The criticality of the different layers is their interactions to facilitate efficiency within the cell. The electric field formed at the contact interface of the CdTe and CdS can help in the decoupling of the generated electron hole pairs wherein the electrons are repelled towards the CdS layer while the holes towards the CdTe. Nevertheless, recombination can occur at the interface or inside the volume of the absorber. To lessen these recombination losses, the thickness and band gap of each layer must be reduced; in effect, increasing efficiency.

It also presents numerical calculations of how various energy gaps in the absorber layer affect the Voc, Jsc, fill factors (FF) and overall conversion efficiencies (PCE). Fig. 1 shows the structure that is used for lattice simulations with the help of the SCAPS-1D tool, which means that the performance in terms of different configurations and materials, can be predicted by the researchers.

Thus, Fig. 1 is crucial for the understanding of the functioning of CdTe/CdS solar cells. This shows how the multilayer and material disposition of the article improve the performance of the product. The examination of this structure helps to develop tactics to increase efficiency, decrease costs, and sustain the applicability of CdTe/CdS solar cells in renewable energy technologies.

As we show in Table 1, working point settings, we attempt to simulate, and with specific layer stricture which are described specifically in Table 2.

Table 1 documents the working point settings for the SCAPS-1D of the proposed CdTe/CdS solar cell. This table contains necessary characteristics which allow defining conditions under which operation of the solar



R 0.000000
T 1.000E+0

Info on graded parameters only available after a calculation

Problem file
c:\Program Files (x86)\Scaps3309\def\
CdTe-base.def
last saved: 1-9-2015 at 13:36:14

Remarks (edit here)
SCAPS 3.3.02 ELIS-UGent: Version scaps3302.exe, dated 28-08-2015, 11:48:47 Probler
last saved by SCAPS: 01-09-2015 at 13:36:12

Based on "the CdTe-base case" by Markus Gloeckler, Colorado, summer 2003
See also: M. Gloeckler, A.Fahrenbruch and J.Sites,
"Numerical modelling of CIGS and CdTe solar cells: setting the baseline",
Proc. 3rd World Conference on Photovoltaic Energy Conversion (Osaka, Japan, may 20(

Fig. 1 Schematic of CdTe/CdS solar cell layers

Table 1 Working point settings

Conditions	Values
Power from spectrum (mW/cm^2)	100.0000
Incident power on solar cell structure (mW/cm^2)	100.0000
Temperature (K)	300.00
Workpoint bias voltage (volt)	0.0000
Frequency (Hz)	1.0000e + 06

cell is analyzed. Essential input parameters include the power density from the solar spectrum which is set at 100 mW/cm^2 as test conditions for solar cells. The intensity of the incident power on the solar cell structure is kept constant at 100 mW/cm^2 to afford consistent measurement of the efficiency of the cell. Since the temperature parameter is set at 300 K, a standard setting for these simulations, it becomes possible to judge the impact of heat on performance. Also, for the workpoint bias voltage it has been set to 0 V, so the evaluation is done under the open-circuit conditions. Since the static charge carrier density is to be determined, the frequency of 1 MHz is added to define dynamic characteristics of the charge carriers during the simulation.

Table 2 lists the productivity of the SCAPS-1D simulation's definite parameters for the particular CdTe/CdS photovoltaic cellunder study [33]. The following table is important in describing the properties required for each of the layers in solar cell structure as shown below.

Table 2 Specific layer considerations set in SCAPS setting [33]

Parameters	CdTe	CdS	SnOx
Band gap (eV)	1.37 1.47 1.54	2.4	3.6
Thickness (μ)	4	0.025	0.5
Electron affinity (eV)	3.9	4	4
Dielectric permittivity (relative)	9.4	10	9
CB effective density of state (1/cm^3)	8E + 17	2.2E + 18	2.2E + 18
CV effective density of state (1/cm^3)	1.8E + 19	1.8E + 19	1.8E + 19
Electron thermal velocity (cm/s)	1E + 7	1E + 7	1E + 7
Hole thermal velocity (cm/s)	1E + 7	1E + 7	1E + 7
Electron mobility (cm^2/Vs)	3.2E + 2	1E + 2	1E + 2
Hole mobility (cm^2/Vs)	4E + 1	2.5E + 1	2.5E + 1
ND Shallow uniform donor density (1/cm^3)	0	1.1E + 8	1E + 17
NA Shallow uniform acceptor density (1/cm^3)	2E + 14	0	0

The table includes three primary materials: CdTe, CdS, and SnOx. For the absorber layer (CdTe), the energy gaps are varied at three different values: The energy band gaps were calculated to be energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green). These variations are important since they impact the photovoltaic parameters of the solar cell including Voc and PCE.

Data on each layer for the thickness in micrometers, electron affinity in electron volts and dielectric permittivity in relative for each layer are given. The thickness range of the absorber layer for CdTe is 4 μm, and the thickness of the buffer layer, CdS, is 0.025 μm. SnOx is applied as a transparent conductive oxide (TCO) with a thickness of 0.5 μm.

Other important parameters are the effective state's density in the conduction band and in the valence band, electron and hole thermal velocities equal to 1.0 × 10^7 cm/s for all materials. Mobility values are also specified: CdTe is 3.2 × 10^2 m^2/Vs for electron mobility and 4 × 10 m^2/Vs for hole mobility while the non-lattice matched CdS is lower than CdTe.

Also, for determining the doping characteristics of each layer, the data concerning donor and acceptor densities are presented in the table. For CdTe, the acceptor density cm^{-3} while for CdS is 2 × 10^{14} cm^{-3} donor density is 1.1 × 10^{18}.

Overall, the data in Table 2 is important for dissecting the characteristics of various layers within a CdTe/CdS solar cell including the basic information that determines its performance as a solar cell.

3 Results and discussion

Consequently, the energy gap of the absorber layer in CdTe/CdS solar cells has a direct impact on the given device's performance characteristics. Optimally tuning the energy gap enhances light trapping and charge generation efficiency. In this research, the effect of the energy gap of the CdTe absorber layer on the CdTe/CdS solar cell is analyzed with SCAPS-1D simulation program. To assess the analytical results, we studied the effect of changing the energy gap of CdTe (1.37, 1.47, and 1.54 eV) on the main performance characteristics of the solar cell: the J-V-curve, the capacitance-frequency and capacitance-voltage characteristics, the conductance-frequency and conductance-voltage characteristics, as well as QE.

On this basis, we found that the energy gap cell fabrication technique of CdTe/CdS to impact the solar cell's performance indicators. The outcomes of this section enable an overall appreciation of the electrical and optical CdTe/CdS solar cell performance under varying CdTe layer energy gaps. This knowledge is essential for enhancing the solar cell fabrication technique of CdTe/CdS to achieve high efficiency.

Table 3 CdTe/CdS solar cell parameters realized from considered J-V-curve with various energy gap for CdTe layer

Energy gap (eV)	VOC (V)	JSC (mA/cm^2),	FF (%)	PCE (%)
1.37	0.7526	24.18	75.34	13.71
1.47	0.9013	24.18	71.68	15.62
1.54	1.1611	24.19	58.64	16.47

Table 3 shows the critical performance parameters of the CdTe/CdS solar cells for the variation energy band gap for the CdTe layer is observed as 1.37 eV, 1.47 eV and 1.54 eV. The performance parameters that can be regarded as for a comparison of the tandem solar cells are Voc, Jsc, FF, and PCE. Studying these outcomes helps to understand the impact of energy gap fluctuations on the performance of solar cells and highlights the need to achieve higher energy efficiency.

Another noticeable feature in Table 3 is an increase in the Voc with the increase in the energy gap. For example, Voc increases from 0.7526 V at energy gap of 1.37 eV to 1.1611 V at the energy gap of 1.54 eV. This can be due to the laws of physics governing solar cells. When the energy gap increases, the built-in potential is enhanced at the *p-n* junction, and a broader voltage output is when the cell is in an open-circuit condition. This enhancement in Voc is particularly advantageous because it suggests more excellent capability for energy harvesting from the solar cell. This increasing voltage means the cell can convert the higher portion of the absorbed photonic energy into synthetic electrical energy.

An important basic parameter in a photovoltaic solar system is the Jsc.

However, no strong correlation can be drawn between Voc and Jsc where the latter is held relatively constant with a value of around 24 mA/cm^2 for all the energy gaps studied. This indicates that solar radiation absorption remains consistent across the studied energy gaps by the energy so long as it falls within this range. The steady Jsc demonstrates that there is little degradation of solar cells ability to produce current from the incident light, which has favorable light trapping as well as efficient charge carrier generation. Nonetheless, it also reveals that maintaining a stable Jsc is beneficial as overall conversion efficiency of the humans the solar cell is defined by Voc as well as fill factor.

The FF offers a somewhat different picture. However, upon reducing the energy gap range from 1.37 to 1.54 eV, the FF decreases to 58.64%. This yields doubt as to whether the device can sustain a high operation performance level. Where the maximum current of solar cell (IM)-value is larger, a lower FF is generally an indication of higher losses in the solar cell area, and can be caused by for instance an increasing series resistance or a decreasing charge carrier collection efficiency. By reducing FF at the higher energy gap, we find that though the voltage increases, the ability to utilize the voltage decreases. This behavior demonstrates that optimizing the solar cell is a difficult design problem because improving one characteristic often means degrading the other.

PCE is defined as the ratio of an operating system's output power to its input power.

The effects on R, Voc, and Jsc are all positive where PCE presents an increasing trend, rising from 13.71% at 1.37 eV to 16.47% at 1.54 eV. Such a positive relationship between the energy gap and efficiency gives considerable account of Voc in defining PCE. This, combined with the observed increase of Voc with the rise of the energy gap, improves the overall efficiency despite the decrease of FF. This trend suggests that although the problems related to the less than optimum FF may limit device efficiency due to increased energy gaps, the improved voltage production can result into better energy collection.

This is summarized in Table 3 where one can also observe the complex interrelation between various performance parameters in CdTe/CdS solar cells. A dramatic rise in Voc with larger energy gaps underlines the prospects of enhanced energy harvest, as well as the factised Jsc evidences steadfast potential for light absorption. Nevertheless, the decreasing FF with increasing energy gap represents some major difficulties that must be successfully solved to advance the conversion efficiency of the solar cells. In general, it is wel understood that one has to work further to enhance the solar cell engineering and try to achieve the balance of energy gap, voltage output and FF to enhance the PCE at its fuller possible extent. This broader understanding of the performance values is vital for developing the area of photovoltaic science and optimising the prospects of solar power as a renewable source of energy.

Fig. 2 shows the J-V-curves of the CdTe/CdS solar cell when the energy gap of the CdTe layer is changed. The figure concerns the effect that the energy gap of the CdTe absorber can have on the solar cell. For the first CdTe layer with an energy gap of 1.37 eV we have the JV curve represented by the red color, for the second CdTe layer with an energy gap of 1.47 eV, the J-V curve is represented in blue color and for the third CdTe layer with an energy gap of 1.54 eV, the J-V curve is represented in green color.

However, as the energy gap of the CdTe layer increases the Voc increases and the short circuit current Jsc reduces. This is so since the energy range involved define how much of the light is absorbed by the CdTe layer. Greater separation of energy implies that more photons are being absorbed thus causing higher Voc. But a large energy gap decreases the number of charge carriers, produced by the absorbed photons, which decreases Jsc.

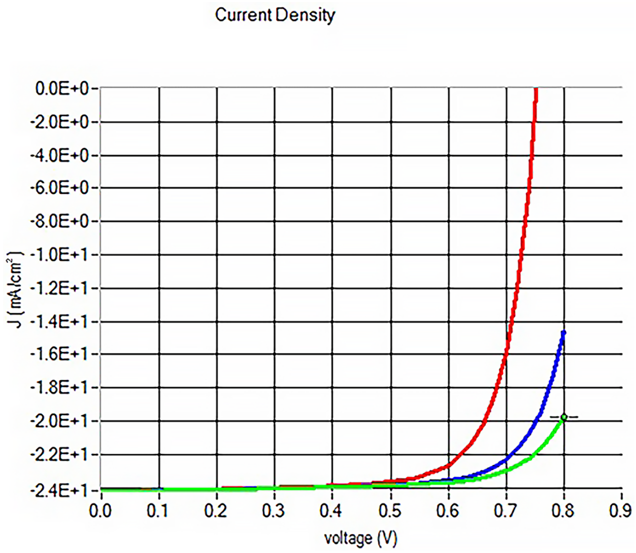


Fig. 2 CdTe/CdS solar cell JV- features with various energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green) for CdTe layer

The performance of solar cell in general depends with the Voc, Jsc, and FF where these parameters are calculated as a product. The FF gives an indication of how effective is a solar cell in converting the light energy into electrical energy. The figure indicates that the FF also decreases with increase in the energy gap of the CdTe layer. This is so because as the energy gap increases the resistance in the solar cell decreases the value of FF.

The figure shows that the CdTe/CdS with a band gap of 1.47 eV shows the highest performance overall. This is due to a right proportion of Voc and Jsc established by the council of Minerva. While the solar cell with a 1.54 eV energy gap achieves the highest Voc (1.1611 V), it exhibits the lowest Jsc and FF due to reduced charge carrier generation and increased resistive losses. The solar cell with energy gap of 1.37 eV has the lowest Voc, while the one with the Jsc has the highest Jsc.

The work also uncovers the research findings about the dependence of the efficiency of the CdTe/CdS solar cell on the energy gap of the CdTe absorber layer. For the CdTe layer, the best energy gap is equal to 1.47 eV. This energy gap result in an average value of Voc and Jsc to yield the best performance of the solar cell.

The Mott-Schottky plot of the CdTe/CdS solar cell with different energy gaps of the CdTe layer is presented in Fig. 3. The Mott-Schottky plot is an electrochemical method for characterization of semiconductor electrolyte

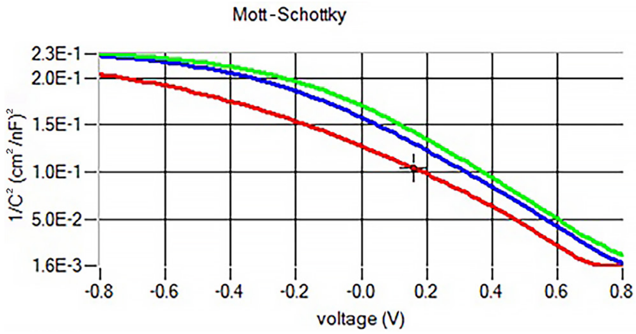


Fig. 3 Mott-Schottky plot of CdTe/CdS solar cell with various energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green) for CdTe layer

junctions with objective to find out the flat band potential, doping density, and density of state at the junction interface.

In this figure, the x-axis is directly related to the applied voltage, and the y-axis is the inverse square of capacitance ($1/C^2$). The trends predict that the amount of capacitance in the solar cell is inversely proportional to the amount of voltage applied to the solar cell. This is because the width of the depletion layer formed at the junction of the semiconductor increases with the increase of voltage across the device, resulting in a decrease in capacitance.

The plot also demonstrated that the capacitance of the solar cell depends on the energy gap of the CdTe layer. The value of capacitance decreases with an increase in the energy gap of the solar cell and vice versa; the least value of energy gap available is 1.37 eV, and the highest value of capacitance available is 0.065 F. This is so because the depletion width of the semiconductor is larger in the case of the solar cell with highest energy gap.

The Mott-Schottky plot is a very effective diagnostic technique used to analyze the properties of semiconductor based devices. This measurement can be used to quantify the dopant concentration and the flat band potentials of the device as well as the density of interface states. These parameters are used for qualifying the characteristics of the device and used in optimizing the structure.

In the context of this study, the Mott-Schottky plot confirms the trend observed in the J-V curves: The CdTe/CdS solar cell with an energy gap of 1.47 eV is shown to present the most favorable capacitance characteristics. The developed storyline shows that the capacitance values of the solar cells increase with a decrease in the energy band gap, which may suggest a larger depletion region and a lower electric field in the absorber layer. This aspect may affect the charge carrier collection efficiency and in extension the efficiency of the solar cell.

The capacitance-frequency characteristics of the CdTe/CdS solar cell with different energy values of the CdTe layer are shown in Fig. 4. The above plot explains how the capacity of the solar cell depends on the frequency of the voltage used. The frequency axis x was plotted to range from 10^2 Hz to 10^6 Hz, the y-axis was plotted to denote capacitance in nF/cm^2.

The plot displays three distinct curves, each representing a different energy gap for the CdTe layer: The disparities were energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green). It is evident from the curves that capacitance of the stacked solar cell goes on decreasing as the frequency increases. This behaviour is akin to semiconductor devices and is mostly due to the behaviour of the depletion area present in the semiconductor in response to variations in the oscillation frequency of the voltage signal being imposed on it.

From curves it can be seen that the solar cell with the lowest energy gap of 1.37 eV provides the highest capacitance throughout the range of frequencies. On the other hand, the solar cell that possesses the largest energy band gap of 1.54 eV has the least capacitance. This observation means that the capacitance of the solar cell is dependent of the inverse on the energy gap of the CdTe layer.

This trend can be understood from a reduction of the energy gap effect on the depletion width. A larger energy gap normally results to a wider depletion region in the semiconductor. More extension of depletion region leads to low capacitance value because the strength of the electric field in the depletion region is low and the device can store little charge.

Fig. 4 also presents the role of the energy gap of the CdTe layer in controlling the capacitance behaviors of the solar cell. Accordingly, the present data indicates that a lower energy gap in a material leads to higher capacitance, which may allow for more efficient charges storage and collection.

The conductance-frequency characteristics of the CdTe/CdS solar cell with different energy gaps of the CdTe layer are shown in Fig. 5. The given plot shows the correlation

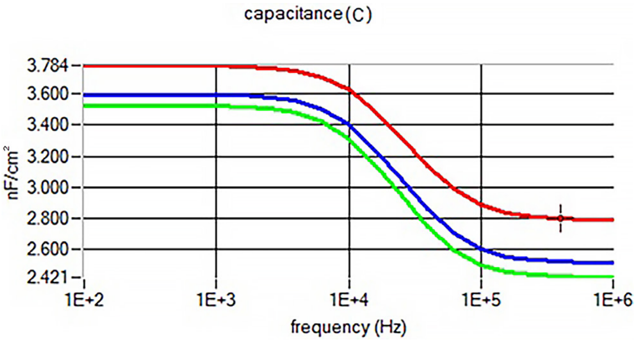


Fig. 4 Capacitance-frequency curve of CdTe/CdS solar cell with various energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green) for CdTe layer

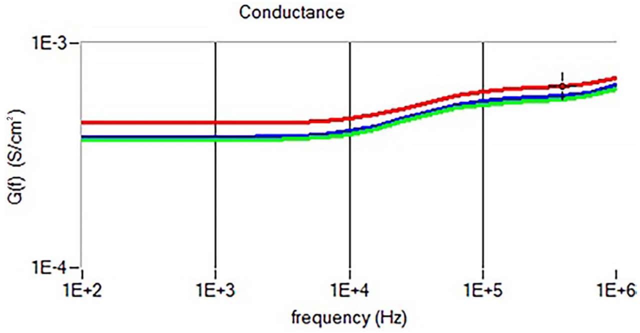


Fig. 5 Conductance-frequency curve of CdTe/CdS solar cell with various energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green) for CdTe layer

of the conductance of the solar cell and frequency of the applied voltage. The x-coordinate of the diagram is the frequency in cycles per second in the range 10^2 Hz to 10^6 Hz; the y coordinate is the conductance in Siemens per square centimeter S/cm^2.

The plot displays three distinct curves, each representing a different energy gap for the CdTe layer: 1.37 eV (red), 1.47 eV (blue), and first and 1.54 eV (green). The curves demonstrate that the conductivity of the solar cell in general increases with the increase in the frequency. This behavior is typical for the semiconductor devices and connected with possibility of the charge carriers to react on the changing of the electric field which is induced by the voltage.

Evaluating graphs, it is illustrated that the curve refers to the solar cell with the minimum energy gap of 1.37 eV has the maximum conductance at all the frequencies presented. At the same time, the material with the largest value of the energy gap is related to the minimal conductance being 0.54 eV. This observation indicates that there is a direct relationship between the conductance of the solar cell and the energy gap of the CdTe layer.

Explaining this trend it is necessary to focus on the influence of the energy gap on the mobility of the charge carriers. A smaller energy gap tends to give higher mobility of charge carriers because a smaller band gap allows charge carriers to move more easily in the semiconductor. Higher mobility of charge carries means that it has high conductivity thus high conductance.

Fig. 5 also indicates that the energy gap of the CdTe layer plays a paramount role in the conductance behavior of the developed solar cell. They further support the notion that conductance values are higher for a lower energy gap system hence better charge transport and efficiency of solar cells.

In Fig. 6, there shows the capacitance-voltage curve of the CdTe/CdS solar cell with different energy gaps of the CdTe layer. This plot shows the capacitance behaviour of the solar cell as a function of the amount of applied voltage. The x-axis indicates the voltage where voltage range is –0.8 V–0.8 V, and the y-axis indicate the capacitance in nanofarads per square centimeter (nF/cm^2).

The plot displays three distinct curves, each representing a different energy gap for the CdTe layer: 1. For red it's 37 eV, for blue – 1.47 eV and for green 1.54 eV. The curves were marked by behaviors that are most typical for the capacitive response of semiconductor structures, in particular, the squared capacitance decreases with increasing of the applied voltage value. This is due to an increase of the depletion layer width in the semiconductor at higher voltages meaning that the material has poor charge storage capacity.

In examining the curves, it is found that the solar cell with the lowest energy band gap of 1.37 eV affords the highest capacitance at all voltage ranges. Instead, the solar cell with maximum energy band gap of 1.54 eV possesses the least capacitance value. This observation led the researchers to conjecture that the capacitance of the solar cell is an anti-function of the energy gap of the CdTe layer.

The following trend can be explained when the influence of energy gap on the depletion width is known. A larger energy gap normally results in a wider depletion region in the semiconductor. A larger depletion region leads to a lower capacitance because the electric field across the depletion region is smaller, thus, the ability of the device in storing charge is minimized.

Fig. 6 also displays that the energy gap of the CdTe layer plays an important role in controlling the capacitance behavior of the solar cell. From the characteristics obtained in this study, it can be deduced that a smaller

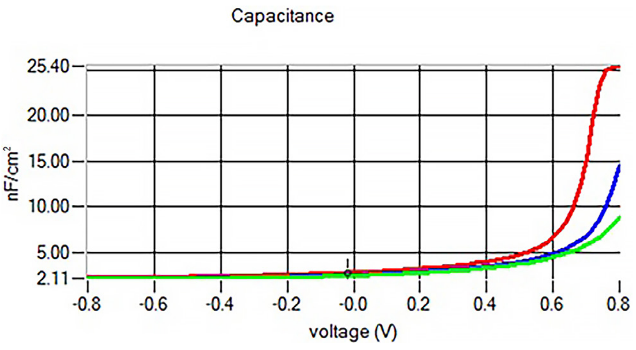


Fig. 6 Capacitance-voltage curve of CdTe/CdS solar cell with various energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green) for CdTe layer

energy gap means higher capacity values, which may improve the storage and collection process of charges.

Fig. 7 shows the conductance-voltage characteristics of the CdTe/CdS solar cell with diverse energy bandgap values of the CdTe layer. The following plot shows how the conductance of the solar cell varies with the voltage across the solar cell. On the x-axis, the range of voltage is –0.8 V – 0.8 V and on y-axis, the conductance in Siemens per square centimeter (S/cm^2).

The plot displays three distinct curves, each representing a different energy gap for the CdTe layer. The threshold energies of the LEDs are respectively 37 eV (red), 1.47 eV (blue), and 1.54 eV (green). The curves show the typical qualitative dependence of conductance on voltage observed in semiconductors, according to which conductance rises with the elevation of voltage. This is a result of reducing the depletion region width of a semiconductor as the voltage increases, making it able to conduct current to a higher level.

The curves show that although the optimized solar cell had the lowest energy gap of 1.37 eV, it had the highest conductance over the entire range of voltage. On the other hand, the solar cell with the largest energy band gap of 1.54 eV demonstrated the lowest conductance. From this observation, it could be deduced that the solar cell's conductance is a function of the energy gap of the CdTe layer.

The fact that a similar trend has been observed can be explained by occupying the energy gap and its influence on the mobility of the charge carriers. Since a lower energy gap means a smaller band gap, the charge carriers can move much more freely within the semiconductor, and hence, carriers' mobility is also higher. Since charge carrier mobility is an inverse function of the resistivity, higher charge carrier mobility means higher conductance.

Thus, Fig. 7 shows how the energy gap of the CdTe layer affects the conductance properties of the solar cell. In particular, higher conductance values can be estimated for materials with an energy gap less than 2 eV, providing better charge transport and efficiency in developing solar cells.

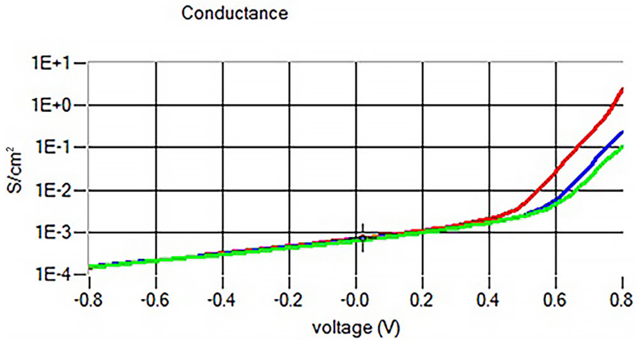


Fig. 7 The conductance-voltage curve of CdTe/CdS solar cell with various energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green) for CdTe layer

In the energy bandgap range of the CdTe layer of the solar cell, Fig. 8 displays the QE profile of the CdTe/CdS solar cell. The graph showcased in the plot deals with the accent in which the QE of the solar cell is connected to the wavelength of the light incidence. The lateral axis is the wavelength (nm) that slopes from 300 to 900, and the vertical axis is the QE in %.

The plot displays three distinct curves, each representing a different energy gap for the CdTe layer. For the red color, the energy level is equal to 37 eV, for the blue, it is 1.47 eV, and for the green color, 1.54 eV. The curves also display the electric QE characteristic of a standard solar cell, where the QE rises with the wavelength up to a certain value, after which it declines.

Comparing the curves, it can be stated that the solar cell with the lowest energy gap of 1.37 eV has a higher QE by the range of wavelengths compared to other two. This is so because a smaller energy gap means a smaller band gap hence it is capable of capturing light of lower wavelength thus high QE.

Further increasing energy gap causes a shift of QE peak towards region of short wavelengths and generally low QE of the diode. This is because, to absorb the longer wavelengths photons their energy gap has to be wide and thus limiting the same.

It is also revealed from the plot that the solar cell with an energy gap of 1.54 eV possesses a broader distribution of QE, meaning that it has the ability to absorb photons of lesser number of wavelengths. This may be because of the increase in band gap, which in essence tends to reduce photon's ability to be absorbed by the PV material with a consequent reduced QE.

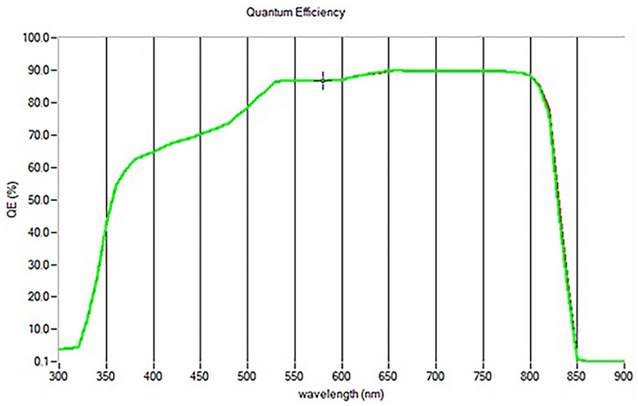


Fig. 8 QE for CdTe/CdS solar cell with various energy gap of 37 eV (red), 1.47 eV (blue), and 1.54 eV (green) for CdTe layer

Fig. 8 also shows that the QE of the solar cell under consideration depends on the energy gap value of the CdTe layer. The data also implies that the lower energy gap would mean higher QE at most wavelengths, thus a higher efficiency and effectiveness of energy conversion for the solar cell.

4 Conclusions

In this work, CdTe/CdS solar cells were examined, with the SCAPS-1D simulation tool utilized to explore details regarding the energy gap in the CdTe absorber layer. Thus, the obtained results have indicated that assessing the energy gap of the CdTe layer is critically important for determining the solar cell's electrical and optical properties.

Our simulations revealed a clear trend: the larger energy gap in a CdTe layer means a higher Voc. This is because a large restricted band width enables the material to absorb high energy photons leading to higher voltage output. While higher energy gaps improve Voc, they simultaneously reduce Jsc, presenting a trade-off that must be addressed for optimized performance. A wider band gap also means that the material can absorb fewer low-energy photons and, therefore, produces a lesser short circuit current Jsc. The best overall performance is expected to be realized with the CdTe layer's energy gap of 1.47 eV. This energy gap thus tries to capture the advantageous of a high Voc and a relatively high Jsc, to make the solar cell more efficient.

Moreover, the present study proposed that the energy gap determines the capacitance and conductance properties of the solar cell. Below the bar end, a lower energy gap is observed due to its smaller band gap, which boosts capacitance and conductance values. This can be attributed to the improvement of carrier mobility within the semiconductor, leading to better charge storage and transport.

Another vital photovoltaic characteristic affected by the energy gap of the CdTe layer was the solar cell's QE, the tiny count per photon. Reduced energy gap meant higher QE at longer wavelengths, further implying better light capture and energy conversion.

These results are especially important for stressing how controlling the energy gap of the CdTe layer during fabrication is essential for achieving enhanced performance of the CdTe/CdS solar cell. Future work on this parameter addresses the potential for new positive increases in the creation of CdTe/CdS solar cells.

Acknowledgment

The authors wish to thank Dr. M. Burgelman's group of Electronics and Information Systems (ELIS), University of Gent, for the SCAPS-1D program tool.

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