

Numerical Analysis and Performance Enhancement of Nanostructured CdTe Solar Cells

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Abstract:

The research presented in this article is predicated on a thorough examination of methods to enhance the efficiency of thin film solar cells using CdTe compound material. The presented method employs the numerical modeling program SCAPS 1D. This program is based on the Poisson equation, which connects charge carriers to electrostatic potential, and the continuity equation, which describes how charge carriers move. We focused on studying the effect of illumination and the thickness of the CdTe absorbing layer on the performance and efficiency of the solar cell, including parameters related to the solar cell outputs such as short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), efficiency (η), and the quantum yield of the cell. The results of the numerical simulations using the program showed that the CdTe cell behaves like a p-n junction. The results indicated that the thickness of the absorbing layer has a significant impact on the parameters related to the solar cell outputs, with the best results recorded at a thickness of $4\mu\text{m}$ compared to other thicknesses, while the quantum yield of the solar cell at the same thickness was 89.85% at a wavelength of 660 nm.

1. Introduction

Multi-layer thin-film solar cells have a lot of potential to be more efficient and cost-effective than other types of solar cells. Where the latter has made great strides in the business world, notably in electronics and solar cells [1]. CdTe-based solar cells are the best choice for photovoltaic energy conversion among thin-film cells because they have a good chance of making solar cells that are cheap, efficient, dependable, and stable [2]. Different techniques may be used to simulate thin film solar cells; however, this work investigated the influence

of layer thickness on solar cell performance, aiming to enhance efficiency [3]. This research uses the Solar Cells Capacitance Simulator (SCAPS) to simulate metal oxide heterojunction solar cells.

2. Basic Equations Used for Simulating Solar Cells

The numerical simulation of solar cells relies on solving a set of mathematical equations related to the electrostatic potential and charge carrier density, which summarize the most important physical phenomena occurring within the solar cell. These

equations are defined by the Poisson equation, the continuity equation, and the transport equation. Poisson's Equation And it is the most important equation relied upon to describe electrostatic phenomena within the solar cell, and it is written mathematically in one dimension according to the following equation [4]:

(1)

$$\nabla\psi(x,t) = \frac{q}{\epsilon_0\epsilon_r}(p(x,t) - n(x,t) + N_{D^+} - N_{D^-} + \rho_l(x,t))$$

Where: the electrostatic field is represented by ψ the relative permittivity and in vacuum ; are represented by ϵ_0, ϵ_r , the elementary charge is represented by q , the electron and hole densities are represented by n, p , the donor and acceptor ion concentrations are represented by N_{D^+}, N_{D^-} , and the difference between the type charge n, p is represented by ρ_l .

The continuity equations express the state of both electrons and holes, whether they are being transported, accumulating, or can be generated or annihilated according to the following equations [5]:

• Electronic state

$$\frac{1}{q} \nabla j_n(x,t) = R_n(x,t) + \frac{\partial n(x,t)}{\partial t} - G_n(x,t)$$

(2)

• The state of the holes

$$\frac{1}{q} \nabla j_p(x,t) = R_p(x,t) + \frac{\partial p(x,t)}{\partial t} - G_p(x,t)$$

(3)

Where: the electron-hole recombination rate represents the generation.

3.Solar Cell Simulation Program SCAPS

Solving the fundamental equations governing the behavior of charge carriers allows us to understand the current-voltage characteristics of the solar cell, in addition to other physical media. The results obtained provide useful information about the performance of the solar cell. There are many difficulties in solving the basic equations analytically, so researchers resort to solving them using numerical methods, which require a large number of iterations. Researchers have developed

several programs to simulate solar cells that provide accurate results, the most important and widely used of which is the SCAPS program. The SCAPS program is the SCAPS-1D simulator developed by Marc Burgelman. It is a program designed to run on the Windows operating system, allowing for the modeling of the physical and electrical behavior of the solar cell. It also allows for saving time and costs before the manufacturing process, thereby being able to improve the performance of solar cells. This program is based on solving basic differential equations using the finite difference method.

4. Structure of the CdTe solar cell

The solar cell to be studied in this work consists of a cell containing three layers. The first layer is made of tin oxide, which represents the transparent layer. The second layer is made of cadmium sulfide, which represents the n-type layer. The last layer is made of CdTe, which represents the p-type layer, as shown in the figure.

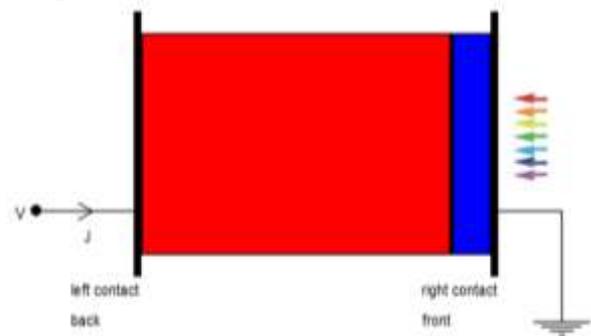


Figure 1: Structure of the CdTe solar cell

5.Determination of Constants and Initial Conditions for Simulating a CdTe Solar Cell

We have determined all the physical constants related to each layer that makes up the solar cell, and they are detailed in the following table:

In this work, we will study the effect of illumination on the current-voltage properties. We will also vary the thickness of the CdTe absorbing layer on the outputs of the cell, represented by the open-circuit voltage, short-circuit current, fill factor, efficiency, and quantum yield of the solar cell to be studied.

6. Results and discussion

6.1. Effect of illumination on the current-voltage characteristics of the CdTe solar cell

Figure 2 The curve of the variations in both the fill factor and the efficiency of the CdTe solar cell, with the layer thickness fixed at 4µm using the SCAPS program. The curve shows that the behavior of the

solar cell, whether in the dark or when exposed to light, exhibits the same behavior as the p-n junction, which proves that the semiconductor of type CdTe is suitable for use in solar cells. The curve shows that there is a shift between the curve of the cell in the dark and the illuminated state. This shift represents the photocurrent generated by exposing the cell to light [6].

6.2. Effect of CdTe layer thickness on current-voltage properties:

Figure 3 The current density-voltage curve for a CdTe solar cell after changing the layer thickness each time from 4µm to 6µm using the SCAPS program shows clear changes in current density when altering the thickness of the CdTe layer, with the maximum current density recorded at a thickness of 4µm as shown in Table 2. These changes in current density are primarily related to changes in the depletion region width, which clearly affect charge carriers.

6.3. Effect of the CdTe layer thickness on the open-circuit voltage and short-circuit current:

Figure 4 The curve of changes in both the short-circuit current and open-circuit voltage of a CdTe solar cell after changing the layer thickness each time from 4µm to 6µm using the SCAPS program. From the curve, we observe that changing the thickness of the CdTe layer has a significant impact on the values of the short-circuit current and open-circuit voltage. As the thickness of the layer increases, we observe a continuous increase in the values of the short-circuit current, reaching a maximum value of 24.21 mA/cm² as shown in Table (2). on the other hand, we observe an increasing decrease in the open-circuit voltage values with the increase in the thickness of the CdTe layer. These results can be explained by the fact that the increase in the thickness of the CdTe layer will enable the absorption of more photons, thereby generating more charge carriers [7].

6.4. Effect of the CdTe layer thickness on the fill factor and efficiency

The effect of the CdTe layer thickness on the fill factor and efficiency Figure 5 The curve of changes in both the fill factor and efficiency for a CdTe solar cell after varying the layer thickness each time from 4µm to 6µm using the SCAPS program. From the curve, we observe that the thickness of the CdTe layer has a clear effect on the changes in the values of both the fill factor and efficiency. The curve shows that with the increase in the thickness of the CdTe layer, the values of these two factors decrease, where we record the highest value for both the fill factor and efficiency at a thickness of 4µm, reaching 66.44% and 16.03% respectively, as shown in Table 2.

6.5. Quantum efficiency of the solar cell

The quantum efficiency QE(%) is considered one of the important factors in cells and is defined as the number of electron-hole pairs generated per photon. Or it is the ratio between the amount of electrons collected and the amount of photons incident on the cell at each wavelength (λ). Therefore, this important quantity allows us to know the capacity of the solar cell as well as the current loss that occurred within the cell itself. Figure 6 illustrates the curve of quantum yield changes as a function of the wavelength of photons incident on the cell, varying within the range (nm 300-900) for a CdTe solar cell, after changing the layer thickness each time from 4µm to 6µm. The results show that the CdTe layer absorbs the entire ultraviolet and visible spectrum well, while we observe stability in the quantum yield values at wavelengths between (nm 850-650). Knowing that the shape of the quantum yield curve is influenced by several factors, the most important of which are light losses within the cell and the presence of crystalline defects that affect the generation current. It is also noted that changing the thickness of the CdTe layer does not significantly alter the quantum yield values of the cell, as we recorded the highest yield value at a thickness of 4µm, reaching 89.85% at a wavelength of 660 nm [8].

Table 1. Physical constants used for simulating the CdTe solar cell

CdTe	CdS	SnO ₂	Thin layers parameters
4-6	0.025	0.5	e (µ.m)
1.5	2.4	3.6	Eg (eV)
3.9	4	4	X (eV)
9.4	10	9	ε/ ε₀
8.0 X 10 ⁺¹⁷	2.2 X 10 ⁺¹⁸	2.2 X 10 ⁺¹⁸	N_c (cm⁻³)
1.8 X 10 ⁺¹⁹	1.8 X 10 ⁺¹⁹	1.8 X 10 ⁺¹⁹	N_v (cm⁻³)
1.0 X 10 ⁺⁷	1.0 X 10 ⁺⁷	1.0 X 10 ⁺⁷	V_e (cm/s)

$1.0 \times 10^{+7}$	$1.0 \times 10^{+7}$	$1.0 \times 10^{+7}$	V_h (cm/s)
$3.2 \times 10^{+2}$	$1.0 \times 10^{+2}$	$1.0 \times 10^{+2}$	μ_e (cm ² /Vs)
$4.0 \times 10^{+1}$	$2.5 \times 10^{+1}$	$2.5 \times 10^{+1}$	μ_h (cm ² /Vs)
$2.0 \times 10^{+14}$	$0/1.0 \times 10^{+18}$	$0/1.0 \times 10^{+7}$	N_a/N_d (cm ⁻¹)

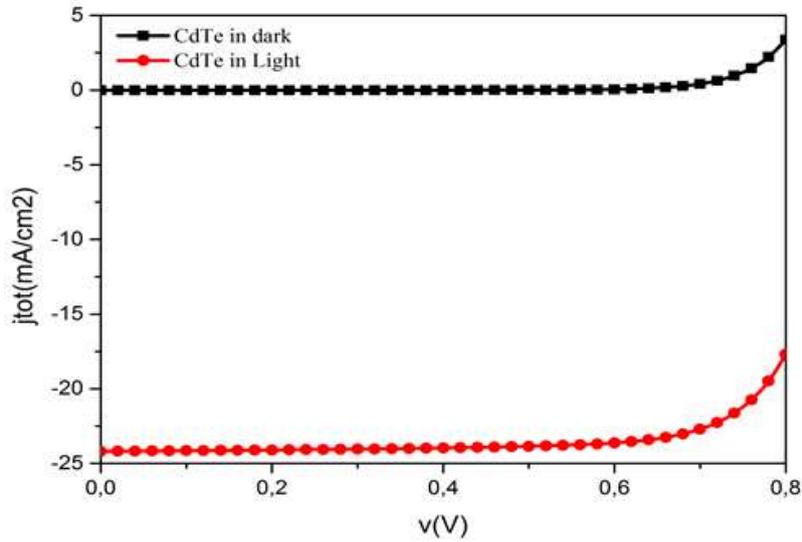


Figure 2: Curve of the change's current density as a function of voltage for a CdTe solar cell for different thickness values for thickness.

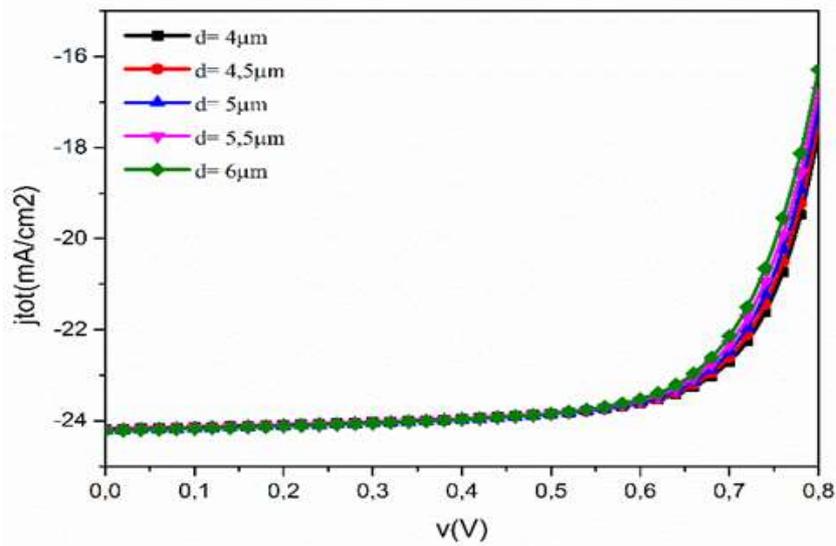


Figure 3: The curve of the change's current density as a function of voltage for a CdTe solar cell for different thickness values.

Table 2: Results of the CdTe solar cell simulation

CdTe layer thickness	Voc (v)	Isc (mA/cm ²)	FF(%)	η(%)
4.0μm	24,184	0,997	66,4466	16,0358
4.5μm	24,199	0,997	66,0173	15,928
5.0μm	24,208	0,992	65,7694	15,8009
5.5μm	24,214	0,985	65,6195	15,6602
6.0μm	24,217	0,977	65,5086	15,5101

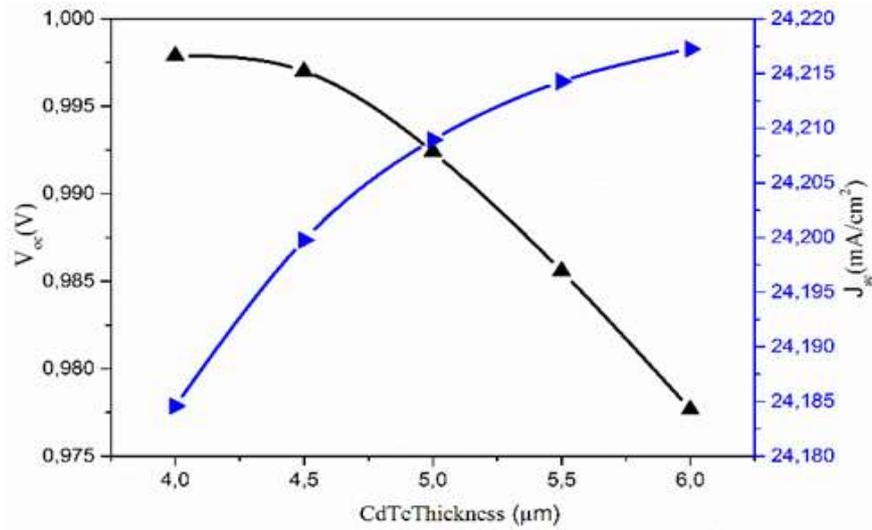


Figure 4: The curve of changes in both short-circuit current and open-circuit voltage for a CdTe solar cell for different thickness values.

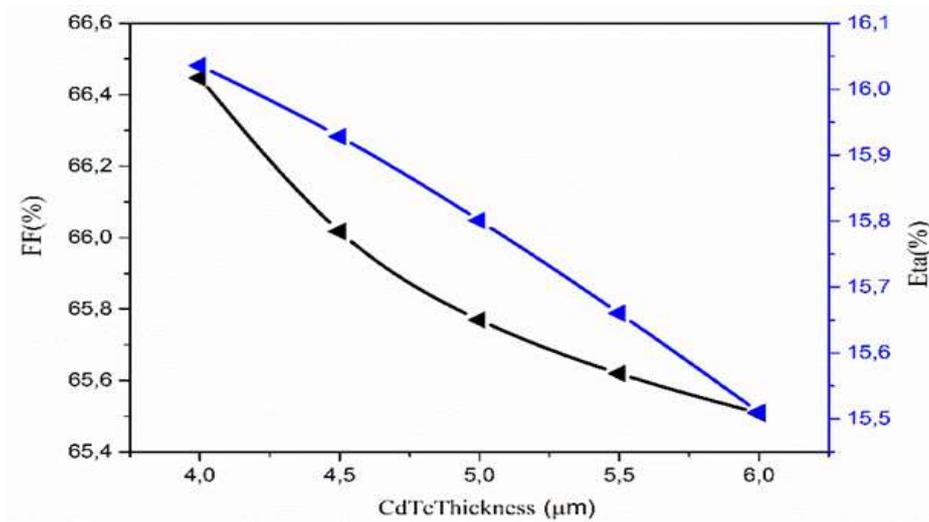


Figure 5: The curve of variations in both the fill factor and efficiency for a CdTe solar cell for different thickness values.

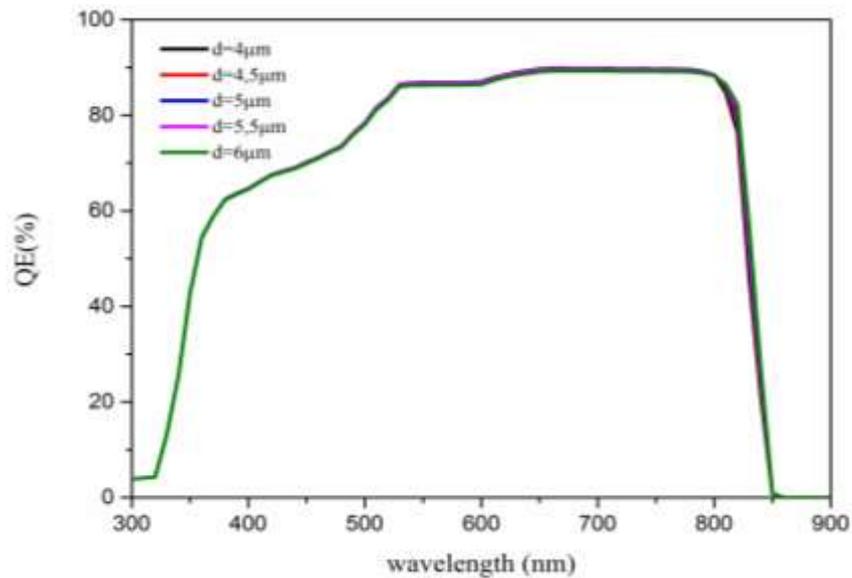


Figure 6: The curve of quantum yield changes as a function of wavelength for a CdTe solar cell for different thickness values

7. Conclusions

This work aims to improve the efficiency of multi-layer solar cells by conducting numerical simulations using the one-dimensional solar cell simulation program SCAPS-1D. This program is one of the most advanced simulation tools in the study of solar cells, as researchers increasingly use it to develop, predict, analyze, and interpret results before implementing them in reality due to the high manufacturing costs. In this work, we focused on studying the effect of illumination on this cell, and the results showed that the CdTe cell exhibited the same behavior as a p-n junction. We also studied the effect of the thickness of the CdTe layer on the cell's outputs, where the results indicated that the thickness of the absorbing layer has a clear impact on the performance of the solar cell. We recorded the best results at a thickness of 4 μ m compared to other thicknesses. The study of the solar cell's quantum yield when changing the thickness of the CdTe layer showed that the latter does not change much, as we recorded the maximum yield value at a thickness of 4 μ m, reaching 89.85% at a wavelength of 660nm. From the above, it is evident that CdTe solar cells have yielded good results in terms of efficiency and performance. There are still other mediums that can be studied in the future, such as changing the type of transparent layer and the n-type layer, in order to improve both the open-circuit voltage, short-circuit current, and the quantum efficiency of the cell.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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