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Numerical Analysis of $\text{SnO}_2/\text{Zn}_2\text{SnO}_4/\text{n-CdS}/\text{p-CdTe}$ Solar Cell Using the SCAPS-1D Simulation Software

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Abstract

This research includes the use of CdTe in the design of a solar cell. The SCAPS-1D computer program was used to simulate thin cell capacity of CdTe/CdS by numerical analysis with the addition of a buffer layer (Zn_2SnO_4) to enhance cell efficiency. The thickness of the window layer (n-CdS) was reduced to 25nm with the inclusion of an insulating layer of 50 nm thickness to prevent leakage towards the forward bias with respect to the lower charge carriers. As for the absorber layer thickness (p-CdTe), it varied between 0.5 μm and 6 μm . The preferable thickness in the absorbent layer was 1.5 μm . Different operating temperatures (298K-388K) were used, while the highest conversion efficiency ($\eta=18.43\%$) was obtained with the rest of the solar cell parameters ($V_{oc}=0.967$ V, $J_{sc}=26.66$ mA/cm², FF=71.40%).

Keywords: Thin Film Solar-Cells, solar cell (CdTe/CdS), program computer SCAPS-1D.

تحليل عددي للخلية الشمسية $\text{SnO}_2/\text{Zn}_2\text{SnO}_4/\text{n-CdS}/\text{p-CdTe}$

باستخدام برنامج المحاكاة SCAPS-1D

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الخلاصة

تضمن البحث استخدام الكاديوم تيلورايد CdTe في تصميم الخلية الشمسية، إذ تم استخدام البرنامج الحاسوبي SCAPS-1D لمحاكاة سعة الخلية الشمسية الرقيقة لـ CdTe/CdS عن طريق التحليل العددي بإضافة طبقة عازلة Buffer Layer (Zn_2SnO_4) وذلك لتحسين كفاءة الخلية، وتقليل سُمك الطبقة النافذة (n-windows Layer CdS) إلى (25nm) مع إدراج الطبقة العازلة Zn_2SnO_4 وبسُمك (50nm) لمنع التسرب بإتجاه الأمام بالنسبة لحاملات الشحنة الأقلية، أما سُمك طبقة الإمتصاص (p-absorber Layer CdTe) فقد تفاوتت السُمك ما بين (0.5 μm -6 μm)، وكان أفضل سُمك في الطبقة الماصة (1.5 μm). مع اختلاف درجات حرارة التشغيل التي تراوح مداها ما بين (298K-388K)، وكانت أعلى كفاءة تحويل تم

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الحصول عليها ($\eta=18.43\%$) مع بقية معاملات الخلية الشمسية ($J_{sc}=26.66$, $V_{oc}=0.967$ V) $(FF=71.40\%$, mA/cm^2).

Introduction

Thin-film solar cells are polycrystalline materials, which are very promising for the achievement of better efficiency and cost ratios than other thin-film cells [1]. This material provides low-cost and stable-working solar cells [2]. Cadmium telluride (CdTe) is produced from polycrystalline materials that can be deposited on the glass and are somewhat cheaper and easier to use. Deposition is achieved using a variety of different low-cost technologies, such as closed space sublimation (CSS), chemical vapor deposition (CVD), and chemical bath deposition (CBD) [3,2].

The CdTe cell contains a high absorption coefficient of no more than $5 \times 10^5 \text{ cm}^{-1}$, which implies that 99% of the photons fallen with energy greater than the energy gap can be absorbed inside the very thin absorption layer of the CdTe cell, i.e. within the first micron of the layer absorption [4]. Thus, most of the spectra in the electromagnetic spectrum of more than 850 nm can be absorbed, as CdTe cell has a direct light energy gap (direct band gap) of about 1.45 V and is very close to the ideal gap package for the solar cells. CdTe is a compound of semiconductors within the periodic table of II-VI, meaning that it is located within the third to fifth groups.

It is important that the binding energy is relatively high in the CdTe cell, which makes the material chemically and thermally stable and less susceptible to breakdown in efficiency, which makes it suitable for space research applications [4]. The solar cells demonstrated stable performance and high efficiency under the usual solar radiation (AM1.5) at the surface of earth [5].

The SCAPS-1D simulation program was developed for one-dimensional solar cell structures designed in the Department of Electronics and Information Systems of Gent University in Belgium. In this paper, it was used to simulate the solar cell approved. The starting point was based on the design of the conventional solar cell CdTe/CdS/SnO₂, where the absorption layer (p-CdTe absorber layer) thickness was 5 μm , window layer (n-CdS windows layer) thickness was 0.5 μm , and the TCO layer (SnO₂ type) thickness was 0.5 μm . This cell was the starting point for obtaining a thinner solar cell by inserting a buffer layer between the TCO Layer (SnO₂) and the n-CdS Layer. This layer works to obtain a thinner CdS layer because it acts in consuming a part of CdS. This layer prevents the process of Front bias or Front leakage for minority carriers (holes). This leakage is undesirable and a buffer layer (Zn₂SnO₄) is insulating and active chemically [6].

CdTe was deposited at a temperature higher than 425 °C. As a result of the diffusion that occurs between the two layers, CdTe and CdS, a region called CdSTe-alloy region, also known as the homojunction, is formed [6]. The precipitated layer (Zn₂SnO₄) on the windows layer (n-CdS) produces CdZnS, a material that has a greater energy gap and in turn greatly affects the amount of light entering the absorption layer (CdTe) in the photoelectric cell (PV). After sedimentation process, the appearance bends of the energy levels with respect to the deposited layers appear. The reason for this is the difference in the energy gap among the layers [3].

Several researchers used the traditional model CdTe/p-CdS/n-SnO₂ as a starting point for obtaining high efficiency and less material consumption with different treatment methods for obtaining a thinner solar cell. Dey and his group [7] reduced the thickness of the Absorption Layer (CdTe) to 1 μm in the presence of Buffer Layer (Zn₂SnO₄) with a thickness of 100nm and a Windows Layer (CdS) with a thickness of 100 nm. Their results showed values of $V_{oc}=1.02$ V, $J_{sc}=21.47$ mA/cm^2 , $FF=85\%$ and $\eta=18.68\%$. They also used other treatment methods to increase the efficiency. The researchers entered Back Surface Filed (BSF) of the solar cell to reduce the voltage barrier between the metal and the semiconductor and to reduce the recombination at the back surface. The results, using AMPS-1D program, were $V_{oc}=1.06$ V, $J_{sc}=24.27$ mA/cm^2 , $FF=87.6\%$ and $\eta = 22.61\%$.

The work of Khan and his group [8] was based on numerical analysis using the simulation AMPS-1D program in order to analyze the electrical and optical properties of the solar cells. The study took advantage of the traditional solar cell by making some adjustments to it, reducing the thickness of the Windows Layer (CdS) to 50nm and introducing ZnO as a Buffer Layer to improve the performance of the solar cell and prevent the leakage of minority carriers towards the forward direction. The thickness of the Absorbent Layer (CdTe) was 1 μm -5 μm while they results were $V_{oc}=1.08$ V, $J_{sc}=24.93$ mA/cm^2 , $FF=0.83\%$, and $\eta = 20.27\%$. This design was good at high temperatures.

Also, Hussein and his group [2] relied on the traditional three cell layers approach and modified it to explore the possibility of an effective and thinner cell. The treatment method that was used by the researchers replaced the CdS Layer with a Zn_xCd_{1-x}S Layer, while the concentration of impurities in the absorption layer was adopted in a shallow uniform acceptor density (N_A) of 5 × 10¹⁵ cm⁻¹ with a Back Surface Field (BSF). The cell transformation efficiency after the adjustment had the values of Voc=0.89 V, Jsc=30.41 mA/cm², FF=0.75%, and η=18.39%.

In another study, the traditional cell was also adopted and modified by adding the Buffer Layer (Zn₂SnO₄) as an insulating layer, called the High-Resistance Transparent Layer. This layer works to prevent the leakage of minority carriers (holes) in the forward direction, which is often an unwanted leakage [9]. The thickness of this layer was also small to ensure that light (photons) from the TCO Layer reaches the insulating layer and then the effective layer up to the absorption layer. This layer is considered a temporary storage for charges, where it reduces the process of recombination at the interface of TCO/CdS, which improves the performance of the solar cell [6]. The results were obtained so that the best thickness for the Absorbent Layer was 1.5μm, while the best thickness values for the Windows, Insulation, and TCO Layers were 25nm, 50nm, and 100nm, respectively. When these thicknesses were adopted for the Deposited Layers, the following results were obtained: Voc=0.967 V, Jsc=26.63 mA/cm², FF=71.41% and η=18.41%. The influence of the operating temperatures on the solar cell performance was investigated in a range of 25°C to 115°C.

Materials and Methods

The numerical models have become an important tool in designing any type of effective solar cells, as they worked to provide hypotheses for practical solutions and numerical modeling which can be used to theoretically obtain the physical practical details of solar cells [10, 11]. The SCAPS-1D simulation program was used to simulate the solar cell capacity of a type in which the Absorber Layer is p-CdTe and the Windows Layer is n-CdS, where possibilities of using thin layers were explored [12]. The SCAPS-1D simulation software solves basic semiconductor equations in one-dimension, such as Continuity equation, Poisson's equation, and Carrier density (electrons and holes). These equations include the Drift equation caused by the electric field and the Diffusion equation in which the difference in the concentration of charge carriers and recombination is calculated. These equations are as follows [13]:

$$J_n = q\mu_n nE + qDn \frac{dn}{dx} = q\mu_n \left(nE + \frac{KT}{q} \frac{dn}{dx} \right) = nn \frac{dEFn}{dx} \dots\dots\dots (1)$$

$$J_p = q\mu_p pE + qDp \frac{dp}{dx} = q\mu_p \left(pE + \frac{KT}{q} \frac{dp}{dx} \right) = \mu p P \frac{dEFp}{dx} \dots\dots\dots (2)$$

where E – represents the electric field (V/cm).

μ_n and μ_p the capacity values of electrons and holes (cm²/V-s), respectively.

J_n and J_p are the electron's and hole's current density values (mA/cm²), respectively.

D_n and D_p are the diffusion coefficients for electrons and holes (cm²/s), respectively.

The Continuity Equation can be written with electrons, as follows [5]:

$$\frac{\partial n(x)}{\partial t} = G_n(x) - R_n(x) \dots\dots\dots (3)$$

where G_n(x) is the generation process of electrons,

R_n(x) is the process of re-installation rate.

The Continuity Equation can be written with electrons, as follows [5]:

$$\frac{\partial p(x)}{\partial t} = G_p(x) - R_p(x) \dots\dots\dots (4)$$

where G_p(x) is the generation process of holes.

R_p(x) is the mean recombination of holes.

The Poisson's equation links the equation of charge density and the voltage of electrons (electrostatic voltage Φ), which is a starting point in obtaining the specific solution for the variations in static electricity in semiconductors [12]. It is written as follows:

$$\frac{d \ln(E(x))}{dx} \cdot \frac{d\Phi(x)}{dx} + \frac{d^2\Phi}{dx^2} = \frac{\rho(x)}{\epsilon_0(X)} \dots\dots\dots (5)$$

In case of constant (ε₀), Poisson's equation is expressed as follows:

$$\frac{d^2\Phi}{dx^2} = -\frac{\rho(x)}{\epsilon_0} \dots \dots \dots (6)$$

where ϵ_0 is the electron permittivity (F/cm).

$\rho(x)$ is the charge density (C/cm³).

The current passing through the solar cell can be calculated from the following equation:

$$I = I_0 \left(\exp \frac{qV}{kT} - 1 \right) \dots \dots \dots (7)$$

where I is the load circuit current, I_0 represents the saturation reverse current, T represents the temperature, and k is the Boltzmann constant. The open circuit voltage (V_{oc}) can be calculated from the following relationship:

$$V_{oc} = \frac{kT}{q} \ln \frac{I_{sc}}{I_0} + 1 \dots \dots \dots (8)$$

Fill Factor (FF) can be defined as the curve squared ($I - V$) whose magnitude is mainly related to the solar cell resistance loss [3], and it can be calculated from the following relationship:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \dots \dots \dots (9)$$

The cell also computes the solar efficiency from the equation:

$$\eta = \frac{OutPut\ Power(P_{out})}{InPut\ Power(P_{in})} \times 100\% \dots \dots \dots (10)$$

The efficiency formula can be written in another way:

$$\eta = \frac{FF \times I_{sc} \times V_{oc}}{P_{in}} \times 100\% \dots \dots \dots (11)$$

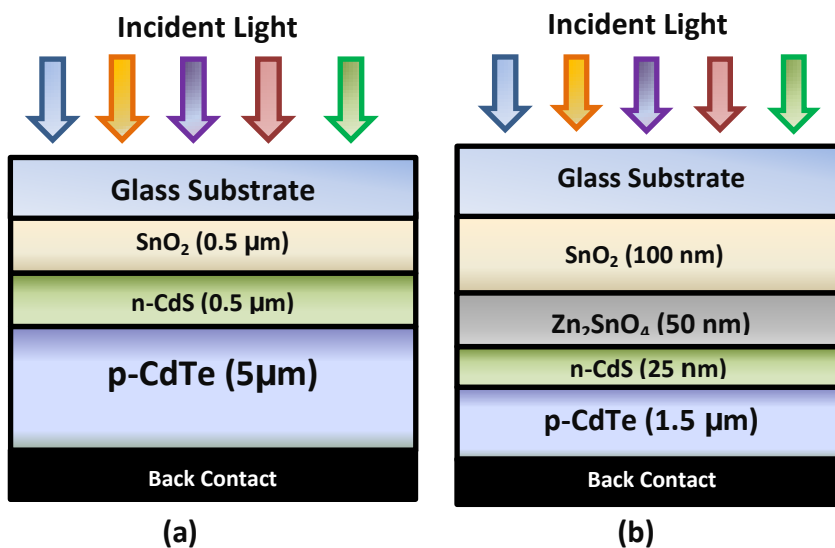


Figure 1 -Schematic structure for (a) The conventional cell Glass Substrate/SnO₂/CdS/CdTe (b) modified cell structure Glass Substrate/SnO₂/Zn₂ SnO₄/n-CdS/p-CdTe.

Figure-1 shows the schematic structure of the conventional Glass Substrate/SnO₂/CdS/CdTe cell and the modified cell structure of the Glass Substrate/SnO₂/Zn₂SnO₄/n-CdS/ p-CdTe.

By the design from Figure-1-b, the modified cell structure contains an additional layer which is the Buffer Layer (Zn₂SnO₄), located between the Transparent Conductive Oxide (TCO) and the Windows Layer, in order to achieve a thinner Windows Layer (Ultra-thin n-CdS). This layer acts to prevent unwanted forward directional leakage for minority carriers in the p-CdTe Layer [10,11,13].

As a result, we gain an increase in cell efficiency (η), by changing the thickness of layers in the traditional cell structure and adding the Insulating Layer to obtain the best thickness in terms of performance and efficiency [14]. The Buffer Layer (Zn_2SnO_4) was chosen as an Insulating Layer with an energy gap of 3.35 V and thickness of 50 nm. In this study, the thickness of the SnO_2 layer was reduced from 0.5 μm to 100 nm, whereas the thickness of the Windows Layer (n-CdS) was reduced from 0.5 μm to 25nm in the solar cell n-CdS/p-CdTe. The shallow uniform donor impurity concentration (N_D) was $1 \times 10^{15} \text{ cm}^{-3}$ in the Absorber Layer (p-CdTe). As a result of this modification, the absorption layer thickness was reduced to the maximum realization that the n-CdS/p-CdTe Layer is too thin [10]. Layer parameters were chosen based on the static data for these materials in addition to experimental data, which includes somewhat reasonable estimates. Table 1 shows the most important parameters used for this cell.

Table 1- Special material parameters for CdS/CdTe solar cell simulation.

Parameters	n- SnO_2 (μm)	n- Zn_2SnO_4 (μm)	n-CdS (μm)	p-CdTe (μm)
Thickness (μm)	0.1	0.01-0.3	0.001-0.2	0.5-6
Band gap (eV)	3.6	3.35	2.42	1.45
Electron affinity (eV)	4	4.5	4.5	4.28
Dielectric permittivity (relative)	9	9	9	9.4
CB effective density of states ($1/cm^3$)	2.200+18	2.200E+18	2.200E+18	7.500E+17
VB effective density of states ($1/cm^3$)	1.800E+19	1.800E+19	1.800E+19	1.800E+19
Electron thermal velocity (cm/s)	1.000E+7	1.000E+7	1.000E+7	1.000E+7
Hole thermal velocity (cm/s)	1.000E+7	1.000E+7	1.000E+7	1.000E+7
Electron Mobility (cm^2/Vs)	100	32	350	500
Hole Mobility (cm^2/Vs)	25	3	50	60
Shallow uniform donor density, N_D ($1/cm^3$)	1.000E+19	1.000E+19	1.000E+19	0
Shallow uniform acceptor density N_A ($1/cm^3$)	0	0	0	1.00E+15

Results and discussion

In the traditional case, we had three layers, namely TCO layer (SnO_2), the Windows Layer (CdS), and the Absorber Layer (CdTe). The following results were obtained: $V_{oc}=0.9180 \text{ V}$, $J_{sc}=21.628 \text{ mA/cm}^2$, $FF=73.56\%$ and $\eta=14.62\%$. As for the cell that was approved in this study, we have four layers, as shown in Figure-1. The Buffer Layer (Zn_2SnO_4) was added and it is often called the High-Resistance Transparent layer (HRT). The Buffer Layer helps using a Windows Layer that is thinner than the (CdS) Layer, that is, it is possible to expand the insulation layer at the expense of the (CdS) Layer to balance the charge that needs to be preserved so that the (P-CdTe) Layer is wide enough and (n-CdS) is a thinner layer. This is important when light reaches the Absorbent layer. The Insulating Layer reduces the process of surface recombination at the interface of layers TCO/CdS. Thus, we studied the effects of the thickness of each layer on the performance of the solar cell and on the performance of the curve (I-V). We also tested the quantitative efficiency (QE) after the application of the Insulation Layer.

A- Effects of the Absorption Layer thickness (CdTe) on the electrical and optical properties of the solar cell

The tellurium cadmium substance has a high absorbency of up to $5-10^5 \text{ cm}^{-1}$. This substance has a high ability to generate electron-hole pairs. Thus, increasing the thickness of this Absorber Layer has a positive effect on the efficiency of the solar cell. We found that increasing the thickness of the Absorbent Layer (CdTe) leads to an increase in the curve of I-V, which provides a complete visualization of the short circuit current (J_{sc}), the open circuit voltage (V_{oc}), and the fill factor (FF%). From these parameters, one can find the efficiency of the solar cell ($\eta\%$).

Figure-2 shows the output parameters for the solar cell depending on the thickness of the Absorption Layer (CdTe). It is clear from the figure that the output parameters with respect to the solar cell remain constant when a thickness of $2\mu\text{m}$ is exceeded. When the thickness of the Absorption Layer was increased, the Energy Absorption and the rate of generation of an pair (electron-hole) were increased. As a result, V_{oc} and J_{sc} were increased, with the FF% factor being established after reaching a thickness value of $1.5\mu\text{m}$. Thus, the thickness of the Absorbent Layer (CdTe) can affect solar cell parameters in different ways, based on the decrease in thickness [15].

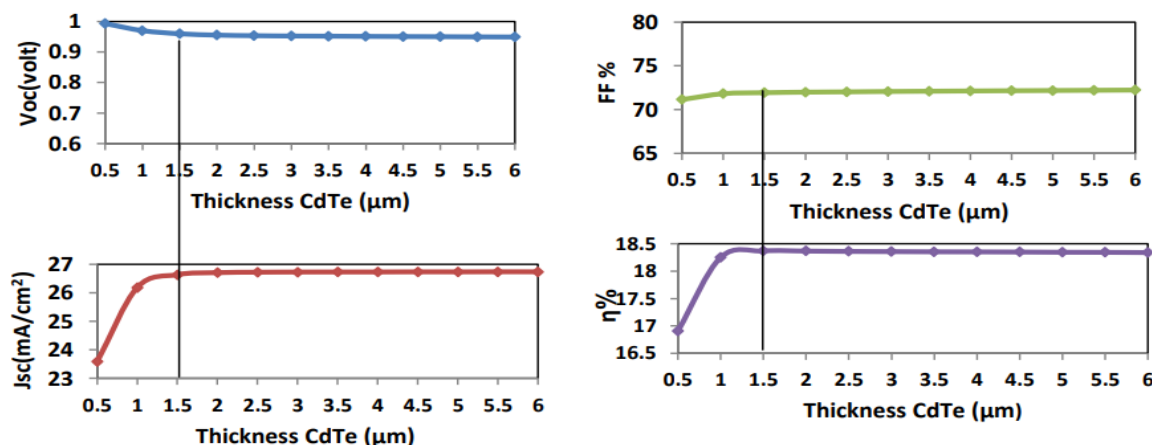


Figure -2 Effects of CdTe thickness on the electrical properties of the solar cell.

The decrease in J_{sc} when the absorption layer thickness is lower than $1.5 \mu\text{m}$ is due to incomplete absorption of the fallen photons and increased recombination at the back contact, which is close to the depletion area when the thickness value is low. Then, the diffusion length (L_{diff}) decreases and the minority carrier lifetime also decrease. Figure-2 shows that the best thickness for the Absorbent Layer (CdTe) is $1.5\mu\text{m}$.

Figure-3 shows the properties of the curve (I-V) through which the Maximum Power Point (Mpp) was reached here. Therefore, the FF% factor could be calculated to have a value of $FF\%=1$, which often appears as a square in the ideal case. The value of the full factor is lower than this value due to the Shunt Resistance (R_{sh}) and Series Resistance (R_s).

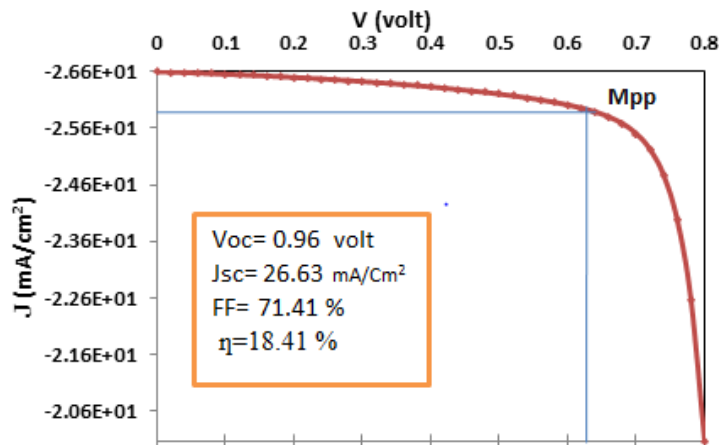


Figure 3- Curve properties (I-V) and determination of the maximum power point.

Figure-4 shows the effects of the Absorbent Layer thickness (CdTe) on the I-V curve. We found that any increase in the thickness of the Absorber Layer will increase the I-V curve, as a result of the increase in the energy absorption and thus the rate of the pair generation (electron– hole) to a certain extent. The value is then fixed regardless of the change in thickness since most of the photons have been absorbed, which explains why the colors are identical in Figure-4.

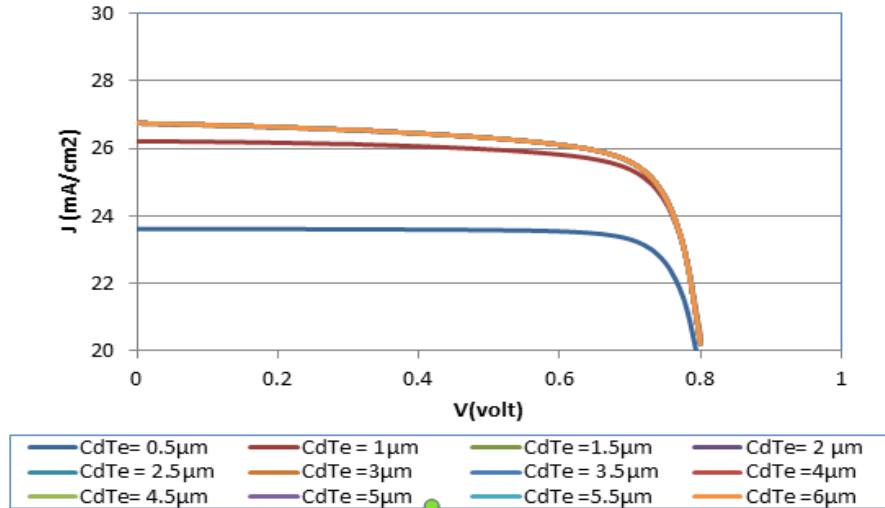


Figure 4- Effects of CdTe thickness on the properties curve (I-V).

As for the Quantum Efficiency (QE), which is one of the important visual factors in solar cell applications, it can be defined as the number of pairs (electron-hole) generated by each absorbed photon. Quantitative efficiency is used to know the spread length, the permanence of minority carriers, and the speed of surface recombination for the front and back surfaces [16].

Figure-5 shows the effects of the QE on the thickness of the Absorption Layer (CdTe). The Quantitative Efficiency (QE) is a function of Depletion Width (W), diffusion length of minority charge carrier, absorption coefficient, and wavelength respectively [17]. It is noted through the graph that the Quantitative Efficiency was increased with increasing thickness of the Absorption Layer, which means the falling photons of different wavelengths absorbed at different depths of the cell. In short wavelengths, it is noted that recombination is high, so the Quantum Efficiency (QE) will be very small, then it is increased with increasing thickness due to increasing the generation of the pair (electron-hole) to a certain extent. Then it reaches a fixed value, which explains why the colors match in Figure-5, that is, light absorption is good within the wavelengths between 550nm-800nm.

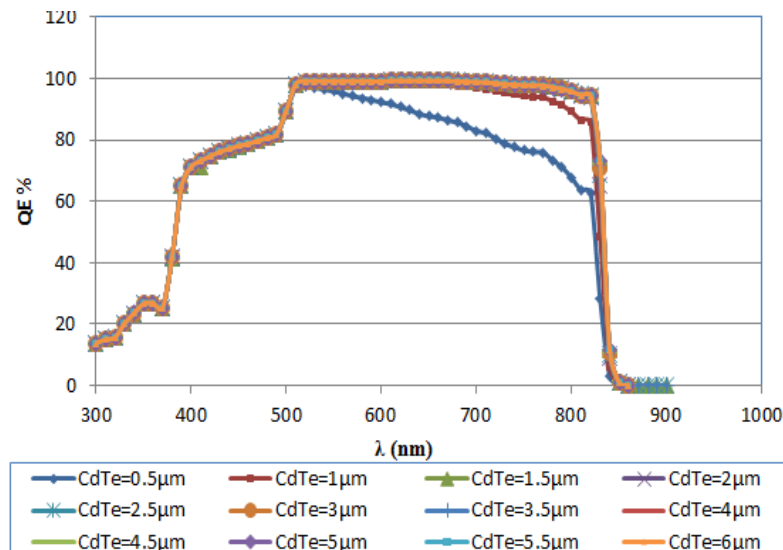


Figure 5 - The effects of CdTe thickness on Quantitative Efficiency. (QE)%

B- Effects of thickness Windows Layer (n-CdS) on electrical and optical properties of solar cell

Through the designing of the solar cell, the thickness of the Window Layer (n-CdS) was tested in a range between 1 and 200nm in order to reach the optimum thickness. The thickness was chosen to be 25nm, which is identical to what was approved by Kobo and his group [18]. This thickness is considered the best for the Windows Layer, which is always preferred to be thinner than the Absorbent Layer, so that the falling light (photons) can reach the Depletion Layer and the Substrate/(p-CdTe) Layer. The (n-CdS) layer is highly deformed in order to reduce contact resistance for the front contact.

Figure-6 shows the effects of thickness (n-CdS) on the electrical properties of the solar cell. Increasing the thickness of this layer has negative effects on the cell parameters, since the short circuit current (J_{cs}) as well as the open circuit voltage (V_{oc}) are relatively low. The cell efficiency ($\eta\%$) gradually decreases with increasing layer thickness. Also, the fill factor ($FF\%$) increases slightly with increasing thickness due to the decrease in Series Resistance (R_s) as a result of high doping [11].

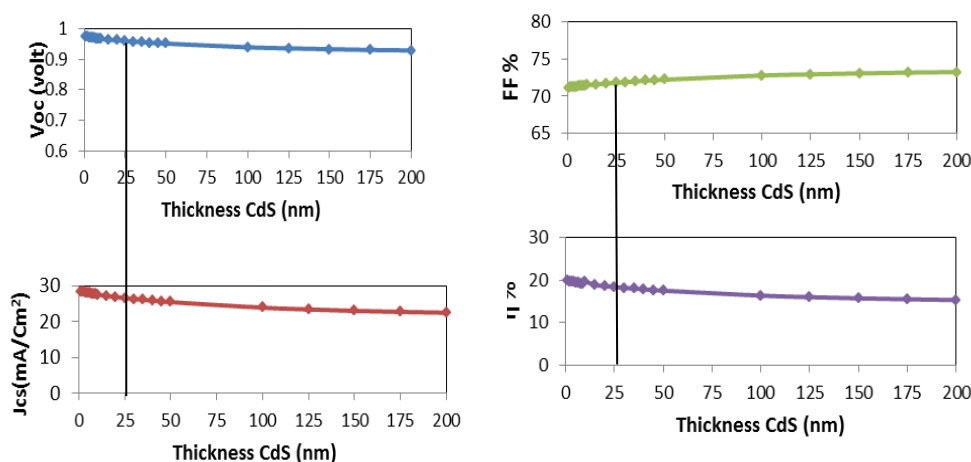


Figure 6- The effects of thickness on the solar cell electrical properties

As for the Quantum Efficiency (QE) and its impact on the thickness of n-CdS, the increase in thickness of this layer affects the Quantum Efficiency of the solar cell, as a result of some photons causing the vibration of the atoms around their equilibrium positions. This phenomenon does not contribute to the light current, and thus causes losses in the structure of the solar cell. This leads to a decrease in the number of photons that reach the Absorption Layer, and thus a decrease in the Quantum Efficiency (QE) of the solar cell [19]. The best thickness of the window layer was 25nm when the Quantum Efficiency (QE) was high. Figure-7 shows that the Quantum Efficiency (QE) was increased above the wavelength of 520nm.

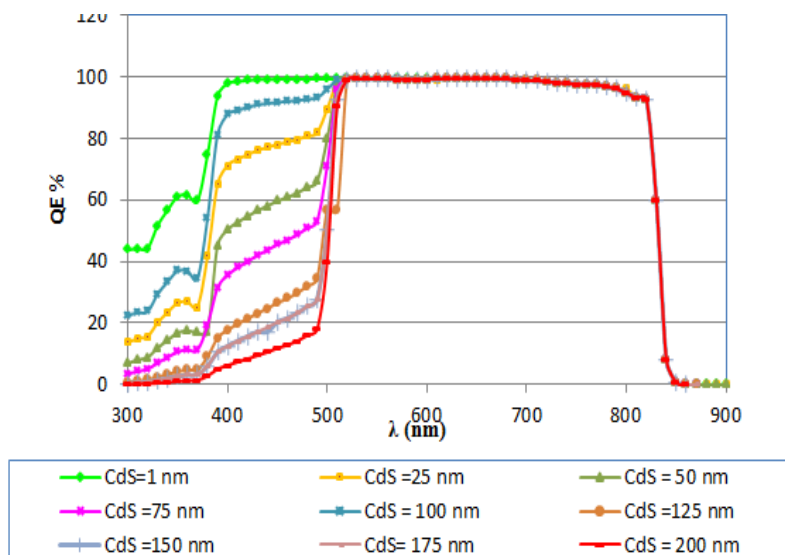


Figure 7 - Effects of Thickness (n-CdS) on Quantitative Efficiency (QE)

C- The effects of temperature on the properties of solar cell

The effects of varying temperatures on the electrical properties of the solar cell was studied, which was represented by the I-V curve, the short circuit current (J_{sc}), the open circuit voltage (V_{oc}), the fill factor (FF%), and the solar cell efficiency ($\eta\%$). We also investigated the optical properties of the solar cell as represented by the Quantum Efficiency (QE). Thickness values for these solar cell layers were approved, as shown in Figure-1. These values were 1.5 μm for the absorber layer, 25nm for the windows layer, 50nm for the buffer layer, and 100nm for the TCO Layer.

The thermal effects on the cell properties were studied within a thermal range of 298K to 388K. Figure-8 shows the effects of different temperatures on the properties of the I-V curves. A clear decrease in the values of open circuit voltage (V_{oc}) is observed with increasing temperatures, due to the fact that high temperatures will be decreased in forbidden energy gap and increased as a result of the saturation current [20]. This is because the density of the charge carriers is exponentially associated with the temperature, which will enable the electrons in the valence band to acquire sufficient energy and move to the conduction band. Such an effect would leave a hole at which the barrier voltage decreases and the width of the depletion area decreases. Also, the saturation current caused by the minority carriers increases, which leads to a decrease in the amount of V_{oc} . As for the I-V curves, it is observed that they shift to the left as the temperature is increased.

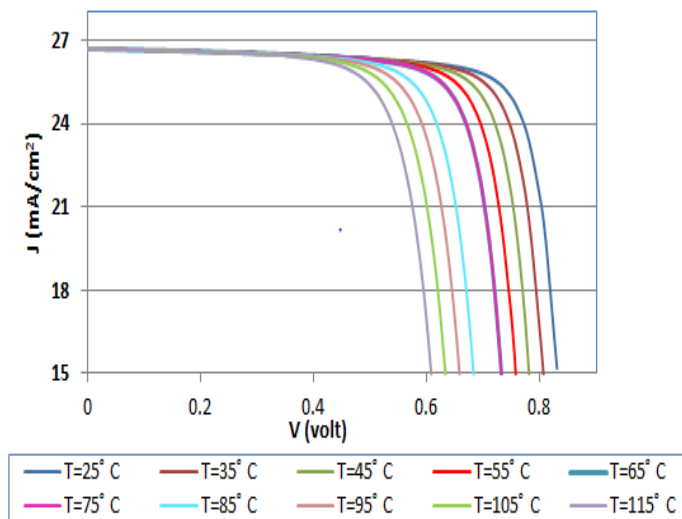


Figure -8 The effects of different temperatures on the properties of a curve (I-V)

Figure-9 also shows the effects of temperature on the output parameters of the solar cell. Among them, we found that the open circuit voltage (V_{oc}) decreases with increasing temperature. As for the short circuit current (J_{sc}), it does not depend to a large degree on the temperature, as the current increases with a slight degree when the temperature increases. The reason for this is the increasing absorption of the incident light due to the shortfall in the forbidden energy gap resulting from the increase in temperatures [20].

The solar cell is considered to be a good cell as the Fill Factor FF% approaches one, i.e. whenever the curve (I-V) approaches the square shape, as shown in fig. 3. It is noticed through the figure that the Fill Factor is affected by rising the temperature, which appears to be decreasing in values, due to increase the presence of saturation current at the expense of the carrier density and the apparent decrease in the values of open circuit voltage (V_{oc}). This leads to an increase in the recombination process at the interface [5].

As for the efficiency of the solar cell ($\eta\%$), it is negatively affected by increasing the temperature. In the case of higher temperature, the lower efficiency is due to the increase in the reverse saturation current, which leads to decreasing the open circuit voltage (V_{oc}) and, thus, the efficiency of the cell decreases. These measurements were obtained under an AM1.5 G solar radiation and at temperatures ranging between 298K and 388K [21].

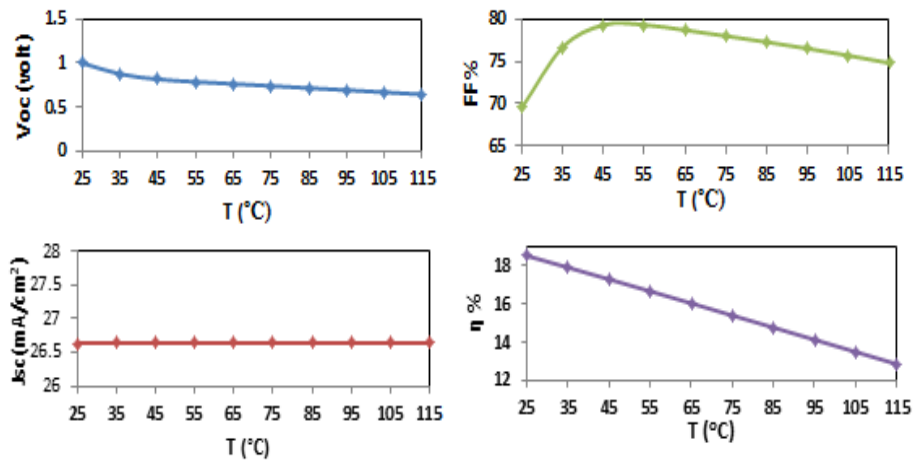


Figure -9 The effects of different temperatures on the solar cell electrical properties

The effect of temperature on the Quantum Efficiency (QE) was very slight, as shown in Figure-10. This is because the short circuit current (J_{sc}) is affected slightly with increasing temperature. While the open circuit voltage (V_{oc}) decreases with increasing temperatures, due to the increase in saturation current resulting from the decrease in the forbidden energy gap, because the density of the charge carriers will be exponentially proportional to the rise in temperatures. Thus, the effect of temperature on Quantum Efficiency (QE) will be very weak. The relationship describing the correlation of the light current I_L , the Quantum Efficiency β_λ of the incident photons, and wavelength λ [22] can be written as follows:

$$I_L = q\beta_\lambda N_\lambda = \frac{q\beta_\lambda}{hc} F_\lambda \dots \dots \dots (12)$$

$$N_\lambda = n\lambda/\beta_\lambda$$

where $n\lambda$ is the average generation of pairs (electron-hole) per unit area.

N_λ is the number of incident photons per unit area and per unit wavelength.

$F_\lambda \cdot \lambda$ is the solar flux with wavelength.

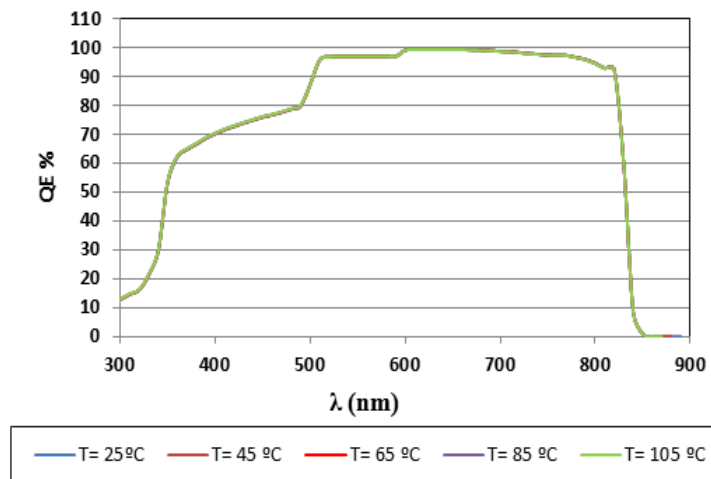


Figure 10- The effects of different temperatures on Quantum Energy (QE)

Conclusions

The highest modification result was obtained from the conventional SnO₂/n-CdS/p-CdTe cell by adding the Buffer Layer (Zn₂SnO₄) to the cell so that a thinner solar cell was obtained as a result of changing the thickness of the layers. Hence, the best thickness of the Absorber Layer was 1.5 μm, while that of the Windows Layer was 25 nm, of the Buffer layer was 50 nm, and of the TCO layer (SnO₂) was 100 nm. As a result, we obtained the following values: Voc=0.978 V, Jsc=26.635 mA/cm², FF=71.41%, and η= 18.41%, at a temperature of 300 K.

By adopting the thickness of the layers above, we can reduce the amount of the materials used and thus the time and cost, in addition to improving the properties of the solar cell by reducing the recombination processes that occur in the solar cell. This cell proved acceptable stability at high temperatures.

References

1. Matin, M. A., Tomal, M.U., Robin, A.M. and Amin, N. **2013**. "Numerical Analysis of Novel Back Surface Field for High Efficiency Ultrathin CdTe Solar Cells", *International Journal of Photo energy*, **2013**, Article ID 652695, 8 pages.
2. Hossain, Sharafat, Nowshad Amin, M. A. Martin, M. Mannir Aliyu, Takhir Razykov, and Kamaruzzaman Sopian., **2011**. "A Numerical Study on The Prospects of High Efficiency Ultra Thin Zn_xCd_{1-x}S/CdTe Solar Cell", *Chalcogenide letters*, **8**(3): 263-272.
3. Chetan Singh Solanki, **2013**. "Solar Photovoltaic Fundamentals, Technologies and Applications", Second Edition, PHI Learning Private Limited, Delhi-110092.
4. Noshad A., Matin, M.A., Aliyu, M.M., Alghoul, M.A., Karim, M.R. and Sopian, K. **2010**. "Prospects of Back Surface Field Effect in Ultra-Thin High-Efficiency CdS/CdTe Solar Cells from Numerical Modeling", Hindawi Publishing Corporation, Volume 2010, Article ID 578580, 8 papers.
5. Mouhammed, Adnan Alwan, and Ayed N. Saleh., **2019**. "Simulation Effect of Ga₂O₃ Layer Thickness on CdTe Solar Cell by SCAPS-1D." *Tikrit Journal of Pure Science*, **24**(6): 110-116.
6. Mary D Archer, Martin A Green, **2014**. "Clean Electricity From Photovoltaic", *Series on Photo conversion of Solar Energy*, **4**.
7. Dey, Mrinmoy, Maitry Dey, M. A. Matin, and Nowshad Amin. **2015**. "Design of High Performance and Ultra-Thin CdTe Solar Cells with SnTe BSF from Numerical Analysis." In 2015 18th International Conference on Computer and Information Technology (ICCIT), pp. 573-576. IEEE.
8. Khan, N. A., K. S. Rahman, F. Haque, N. Dhar, M. A. Islam, Md Akhtaruzzaman, Kamaruzzaman Sopian, and Nowshad Amin., **2014**. "Design optimization of CdTe Thin Film Solar Cells from Numerical Analysis.", In 8th International Conference on Electrical and Computer Engineering, pp. 508-511. IEEE.
9. Wu, Xuanzhi., **2004**. "High-efficiency polycrystalline CdTe thin-film solar cells.", *Solar energy*, **77**(6): 803-814.
10. Matin, M. A., Nowshad Amin, Azami Zaharim, and Kamaruzzaman Sopian., **2010**. "A study towards the possibility of ultra thin Cds/CdTe high efficiency solar cells from numerical analysis." *WSEAS Transactions on Environment and Development*, **6**(8): 571-580.
11. Fouad M. Abdulla. **2019**. "Calculating the variations of sunrise, sunset and day length times for Baghdad city. With comparison to different regions of the world in year 2019" , *Iraqi Journal of Science*, **60**(12).
12. Pourdadaash, Mohammad Hossein, Veeraiyah Thangasamy, Jacqueline Lukose, Mohammadreza Aghaei, and Ajmal Hussain Shah., **2014**, "Numerical Analysis on Prospects of High Efficiency CdS/CdTe Thin Film Solar Cell." In IEEE Symposium on Industrial Electronics & Applications (ISIEA), pp. 86-91. IEEE.
13. Ganvir, Rasika., **2016**. "Modelling of the Nanowire CdS-CdTe Device Design for Enhanced Quantum Efficiency in Window-Absorber Type Solar Cells."
14. Anfal J. Katafa, Mazin K. Hamid, **2020**. "Influence of ZnO Nanoparticles on Candida albicans of Human Male Pleural Fluid", *Iraqi Journal of Science*, **61**(3).

15. Ngoupo, A. Teyou, S. Ouédraogo, and J. M. Ndjaka., **2019**. "Numerical analysis of interface properties effects in CdTe/CdS: O thin film solar cell by SCAPS-1D." *Indian Journal of Physics*, **93**(7): 869-881..
16. Scheer, Roland, and Hans-Werner. **2011**. "*Schock. Chalcogenide Photovoltaics: Physics, Technologies, and Thin Film Devices*", John Wiley & Sons, (BOOK)
17. Tress, Wolfgang, Karl Leo, and Moritz Riede. **2012**. "Optimum mobility, contact properties, and open-circuit voltage of organic solar cells: A drift-diffusion simulation study." *Physical Review B*, **85**(15): 155201.
18. Teyou Ngoupo, S. Ouédraogo, F. Zougmore, J. M. B. Ndjaka. **2015**. "New architecture towards ultrathin CdTe solar cells for high conversion efficiency.", *International Journal of Photo energy*. Volume 2015 Article ID 961812, 9 pages.
19. Subhi Al-Rawi, d. Shaker Jaber Shaker, d. Youssef Mawloud Hassan. **1990**. "Solid State Physics", University of Mosul.
20. Crane Martin, **1989**. "Solar Cells", translated by Dr. Youssef Mawloud Hassan, University of Mosul.
21. Abdel-baset, H. Mekky., **2019**. "Simulation and modeling of the influence of temperature on CdS/CdTe thin film solar cell." (2019), *The European Physical Journal Applied Physics*, **87**(3): 30101.
22. Faisal Al-Bassam, Falah Hassoun Oraibi. **2010**. "The effect of some factors on the maximum practical and theoretical values of the efficiency of the silicon solar cell," *Karbala University's scientific journal*, **VIII**(Second)/ Scientific.