Indonesian Journal of Electrical Engineering and Computer Science
Vol. 24, No. 1, October 2021, pp. 70~80
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v24.i1.pp70-80

The absorber and buffer layer thicknesses for CdTe/CdS based thin film solar cell efficiency at various operational temperatures

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Article Info

Article history:

Received May 22, 2021
Revised Jul 28, 2021
Accepted Aug 4, 2021

Keywords:

CdTe/CdS
SCAPS-1D
Solar cell
Thin film solar cell

ABSTRACT

Cadmium telluride (CdTe)/cadmium sulfide (CdS) solar cell is a promising candidate for photovoltaic (PV) energy production, as fabrication costs are compared by silicon wafers. We include an analysis of CdTe/CdS solar cells while optimizing structural parameters. Solar cell capacitance simulator (SCAPS)-1D 3.3 software is used to analyze and develop energy-efficient. The impact of operating thermal efficiency on solar cells is highlighted in this article to explore the temperature dependence. PV parameters were calculated in the different absorber, buffer, and window layer thicknesses (CdTe, CdS, and SnO2). The effect of the thicknesses of the layers, and the fundamental characteristics of open-circuit voltage, fill factor, short circuit current, and solar energy conversion efficiency were studied. The results showed the thickness of the absorber and buffer layers could be optimized. The temperature had a major impact on the CdTe/CdS solar cells as well. The optimized solar cell has an efficiency performance of >14% when exposed to the AM1.5 G spectrum. CdTe 3000 nm, CdS 50 nm, SnO2 500 nm, and (at) T 300k were the I-V characteristics gave the best conversion open circuit voltage (Voc)=0.8317 volts, short circuit current density (Jsc)=23.15 mA/cm2, fill factor (FF)%=77.48, and efficiency (η)%=14.73. The results can be used to provide important guidance for future work on multi-junction solar cell design.

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1. INTRODUCTION

The conversion of solar energy by using photovoltaic (PV), is a direct transformation of energy radiation into electrical power, is one of the simple methods to reduce the existing natural resources exhausting such as nuclear fuel, gas, oil, and coal that produce environmental problems [1]-[9]. Low-cost high-performance applications made By reaching a target of less than one us dollar per peak watt, the cadmium telluride (CdTe) solar cell is dominating the next generation of solar cells., which is a benchmark for competitiveness with other electricity generation resources such as fossil fuels, nuclear, biomass, geothermal [1]-[11]. The solar cells, based on polycrystalline CdTe thin film, have shown high efficiency, and long-term performance under AM1.5 illumination [12]-[14]. CdTe/CdS solar cell is a promising candidate for practically the economical worthwhile large-scale global production [11], [15]. The technology has succeeded in developing key features of CdTe compounds, in particular defects that control the photovoltaic performance and are utilized for an absorbent layer of the incoming light [11], [15]. Cadmium sulfide (CdS), which is the main function of the buffer layer is to be an excellent heterojunction companion to the p-type absorber layer with minimal mismatching the lattice structure, to be transparent to incident light, and also the defects like interface states to be minimized [15], [16]. The ability of the window layers to transmit the majority of the light in the solar spectrum is dependent on their large band gaps. SnO2 is easy to implement and inexpensive, sufficiently conductive making it the general choice to be used as the n-type in the junction in the Solar cell, which at the same time needs to be to serve as front contact [17].

One of the most effective factors on the Solar cell's panels' efficiency and its lifetime, is the temperature of operation. For each increase in temperature of (1°C) the solar efficiency will be reduced by 0.2% to 0.5% [18], [19]. Standard test condition (STC) is used in designing and testing the solar cell under 25°C, but the operating conditions can be much higher up to +40°C, which reduces the η (efficiency) by 5.12% according to STC conditions [11]. Moreover, there is an acceleration in the age of the solar cell panel due to the thermally triggered degradation mechanism as a result of the increased temperature in the panels [20], [21]. To reduce photovoltaic cell temperature, huge efforts have been devoted to improving electrical conversion efficiency, altering surface emissivity, and reflecting unusable photons. Solar cells currently have an efficiency of approximately 8-29% in laboratory settings, that efficiency would help to reduce reliance on non-renewable resources [2], [15], [21].

In the current research, a numerical study is presented of the thin film CdTe/CdS based solar cells using solar cell capacitance simulator (SCAPS)-1D 3.3.08 (Ver. May 2020). The key parameters, including open-circuit voltage (Voc), fill factor (FF), short circuit current (Isc), and the efficiency (η) were calculated for solar cell standardized measurements spectrum the AM1.5 spectrum, 100 mW/cm2, 300K [11], [22]. We study the buffer layer thickness influence on the performance of the CdTe solar cells, the absorber layer thickness effect, and the temperature impact on the solar cell key parameters. The characteristic J-V was calculated for various conditions (thickness, temperatures).

2. RESEARCH METHOD

The proposed structure of the photovoltaic is hetero-junction CdTe/CdS as shown in Figure 1. An analysis is done with different values for each parameter to investigate the quality of the output performance in the term of solar cell efficiency. Computer-aided design is used with a wide number of entry parameters to represent the required variation in the CdTe/CdS photovoltaic. In this study, the program solar cell capacitance simulator (SCAPS-1D 3.3.08) is used for solar cell thin film simulation. SCAPS-1D is a one Dimensional mathematical modeling tool [22]-[24]. It is based on solving the semiconductor device modeling semiconductor equations poisson's and continuity equation. These semiconductor device equations are used to describe the whole device's simulation domain [23], [24]. The structure layers that are emphasized in the modeling are. first, the tin oxide (SnO2) is a window layer. (SnO2) belongs to the transparent conducting oxide (TCO) family. since polycrystalline SnO2 thin films are wide-bandgap semiconductors that are highly being used in thin film transistors as active channel material or TCO electrodes in the production of organic ight-emitting diodes (LEDs), solar cells, and flexible displays [25]. And molybdenum (Mo) as back contact layer is a very common contact for solar cell, cadmium telluride (p-CdTe) as an absorber layer. And cadmium sulphide (n-CdS) as a buffer layer. The used paramters of the baseline cell arein Table 1.

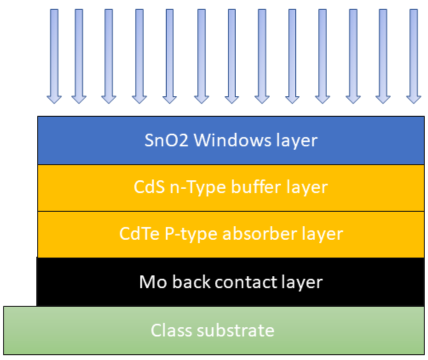

Figure 1. Solar cell structure

Table 1. SCAPS-1D used paramters for basline cell

Paramter	CdTe	CdS	SnO2
t (μm)	0.5	0.05	0.500
Eg (eV)	1.45	2.4	3.600
χ (eV)	3.9	4	4
dielectric permittivity (relative)	9.4	10	9
CB effective density of states (cm^{-3})	8×10^{17}	2.2×10^{18}	2.2×10^{18}
VB effective density of states (cm^{-3})	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
electrons thermal velocity (cm/s)	1×10^{7}	1×10^{7}	1×10^{7}
holes thermal velocity (cm/s)	1×10^{7}	1×10^{7}	1×10^{7}
μe (cm^2/Vs)	320	100	100
μp (cm^2/Vs)	40	25	25
donor density ND (cm^{-3})	0	1.1×10^{18}	1×10^{17}
acceptor density NA (cm^{-3})	2×10^{14}	0	0

The primary performance parameters for solar cells are short circuit current (Isc), open-circuit voltage (Voc), maximum power (Pmax), and fill factor (FF). These can be characterized by a current density-voltage (JV) measurement (Figure 2). The conversion efficiency (η) is determined by these primary parameters. For reliable solar cell I-V test properties, the measurements should be performed under (STC). So that the total irradiance on the solar cell is equal to 1000 W/m2 and the used spectrum is AM1.5. Another important parameter should be taken into concern because solar cell performance highly relies on the temperature, solar cell temperature is constant at 25°C [11], [22].

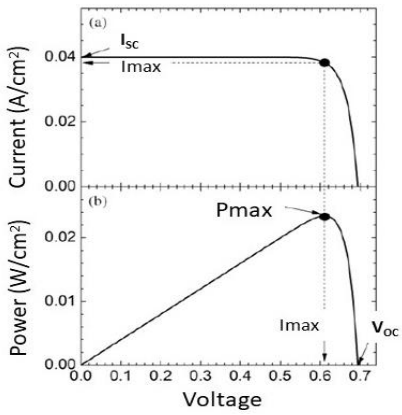

Figure 2. (a) Example of an I-V properties (b) Maximum power characteristic for a solar cell under illumination [26]

Overall current (I) is the diode dark (Id) current reduced by the amount of the light-induced current (IL) and expressed as (1);

$$I = I_o\left[\exp\left(\frac{qv}{KT}\right) - 1\right] - I_L \tag{1}$$

where the charge is q (electron and hole). k is a constant (Boltzmann's). The saturation current (Io), which is known as diffusion current, or leakage. Every solar cell design has a specific Ioas a part of design character tics. Io depending on contact materials, absorber, and geometry of the cell.

2.1. Isc

Short circuit current is the light-generated current or photon current, which flows when the load is zero in the external circuit. By shortening the positive and negative terminals, it can be achieved. A solar cell's short-circuit current is determined by the photon flux incident on it, which is controlled by the incident light spectrum. The peak current that a solar cell can generate is known as the short circuit current density. The optical properties of the solar cell, such as absorption and reflection within the absorber layer, have a significant impact on the maximum current that the solar cell can generate. Short circuit current density (Jsc) is determined by two forms of loss in the standard 100 mW/cm2 solar spectrum (AM1.5). Optical losses occur when photons either weren't absorbed or were absorbed without generating electron-hole pairs in the solar cell. Since photogenerated electron-hole pairs recombine before being collected, recombination losses do not all contribute to Jsc.

2.2. Voc

Open circuit voltage is calculated by setting I=0 in the overall current expression i.e. I=0 when V=Voc, No current flows through the external circuit at this point. The open-circuit voltage is the voltage which a solar cell can deliver in the circuit for maximum load, in another word;

$$\mathrm{Voc} = \frac{\mathrm{KT}}{\mathrm{q}} \ln\left(\frac{\mathrm{IL}}{\mathrm{Io}} + 1\right) \approx \frac{\mathrm{KT}}{\mathrm{q}} \ln\left(\frac{\mathrm{IL}}{\mathrm{Io}}\right) \quad (2)$$

In (2) shows that the open-circuit voltage depends on the solar cell's saturation current (IO), in another word, the photon current generated. IL practically has a small variation, so that the saturation current has an important role in improving the performance of the solar cell. Since the value of saturation current may change by order of magnitude depending on the interfaces between materials that forming the solar cell and the martial characteristics. Minimizing IO is essential to optimizing solar cell performance in general. The saturation current (IO) is dependent upon the solar cell recombination. Hence, Voc is an indicator of the amount of recombination in the instrument. At room temperature, the factor (KT/q) in (2) has a value of (0.026 V), and the natural logarithm of (10) is equal to (2.3). For an ideal solar cell, therefore, VOC increases by (60 mV) at room temperature if ISC increases by a single order of magnitude.

2.3. FF

A measure of the knee's sharpness in an I-V curve is the fill factor, also known as the curve factor Figure 2, shows how well a junction has been made in the cell. The fill factor is the ratio between the product of, open-circuit voltage and short circuit current, and the maximum generated power by a solar cell. Figure 2 shows the point on the solar cell's J-V characteristic at which the solar cell has the maximum output power (Pmax). It is very important to optimize the operation of the solar cells at the Pmax to ensure maximum power production. In practice, a series of resistance Rs and a shunt resistance Rp influence the FF. The presence of series resistance can lower the FF and tends to be higher when the open-circuit voltage is high. The maximum value of the fill factor is one that isn't possible. In Si, its maximum value is 0.88.

$$\mathrm{FF} = \frac{\mathrm{Pmax}}{\mathrm{Isc\ Voc}} = \frac{\mathrm{Imax\ \ Vmax}}{\mathrm{Isc\ \ Voc}} \quad (3)$$

2.4. Pmax and η

The maximum power produced by the device is realized when the current and voltage of the device reach their maximum levels on the characteristics. As illustrated in Figure 2, the maximum power is generated at a single operational point (Vmax, Imax). Vmax and Imax, on the other hand, are difficult to see on the IV graph. Instead, since they are cross-points with the x and y axes, Voc and Jsc stand out. The efficiency of a solar cell is defined as the ratio of input power in light to output power in electricity.

Thus: The maximum output power can be given in (4).

$$\mathrm{Pmax} = \mathrm{Imax\ Vmax} = \mathrm{Voc\ Isc\ FF} \quad (4)$$

The power conversion efficiency of the solar cell can be given as:

$$\eta\% = \mathrm{Eff}\% = \frac{\mathrm{Pout}}{\mathrm{Pin}} = \frac{\mathrm{Voc\ Isc\ FF}}{\mathrm{Pin}} \quad (5)$$

Pin is defined as the incident power.

3. RESULTS AND DISCUSSION

The proposed CdTe solar cell performance is shown in Figure 3, aimed at investigating the efficiency of the SnO_2/CdS/CdTe/Mo (0.5/0.05/2) µm baseline cell structure. J-V characteristics take in dark and light plots (Voc=0.8317 volt, Jsc=23.154656 mA/cm2, FF%=76.48 and η%=14.73). The ratio of the photon-generated electrons to the number of photons incident is known as the quantity efficiency (QE) of a solar cell [26]. As shown in Figure 4, the QE spectrum provides details on the optical and accumulated losses in solar cells. The QE is also affected by the change in absorber layer thickness. Over the entire spectral spectrum, it is less than 90% and even nil at below 200 nm and over 850 nm. The quantum efficiency with a peak value of 89.7% at λ=(650-800) nm and falls off in the range below (300-350).

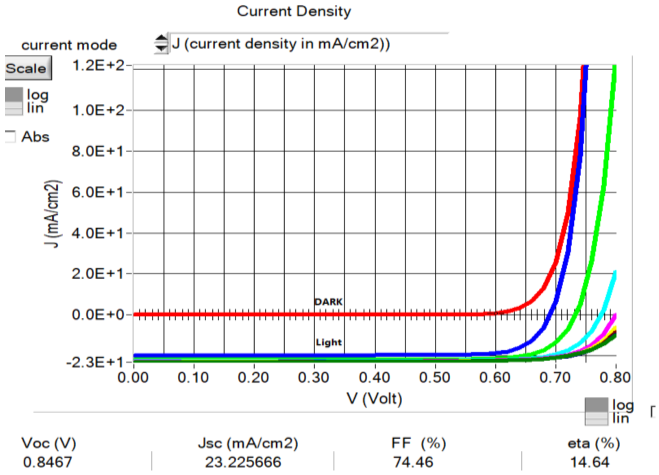

Figure 3. Dark/light J-V characteristics of CdTe solar cell

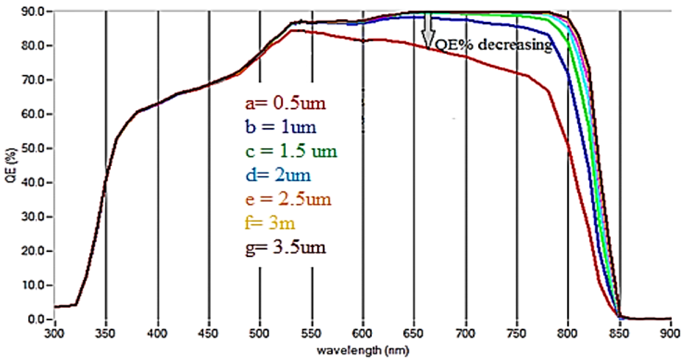

Figure 4. Quantum efficiency vs absorber layer thickness

3.1. Absorber layer thickness effect

The simulation is started by adjusting the thickness of the absorber layer from 500 to 4000 nm with the illumination conditions AM1.5 (100 mW/cm2) (see Table 2). We also observed in Table 2 the best parameters of the photovoltaic where the thickness of the absorber layer had been obtained for 3000 nm. The thickness of the absorber layer takes effect on the cell's output efficiency. Figures 5-8 reveal that as the thickness of CdTe increases, the values of open circuit voltage (Voc), short circuit current density (Jsc), fill factor (FF), and power conversion efficiency (η%) rise. This is due to the production of electron-hole pairs. The long-wavelength photons with the absorber layer will be deeper. The cell's best recorded power conversion efficiency value is 14.73% of the 3 µm absorber layer thickness. This is as shown in Table 2.

Table 2. Output performance of solar cells to absorber layer thicknesses

CdTe Thickness (µm)	Voc (volt)	Jsc (mA/cm2)	FF%	Eff%
0.5	0.6911	19.97724	81.53	11.26
1	0.7326	22.085416	81.08	13.12
1.5	0.7762	22.676362	79.74	14.04
2	0.7997	22.936554	79.12	14.51
2.5	0.8181	23.077322	77.82	14.69
3	0.8317	23.154656	76.48	14.73(max)
3.5	0.841	23.195419	75.63	14.7
4	0.8467	23.21675	74.46	14.64

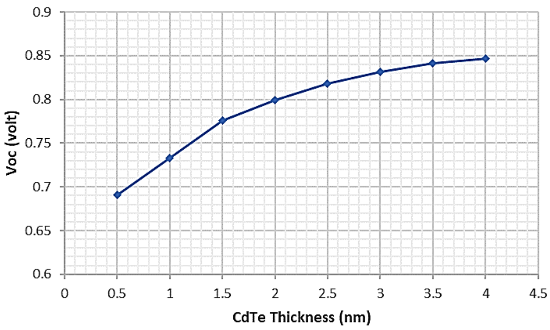

Figure 5. Voc relationship with CdTe layer thickness

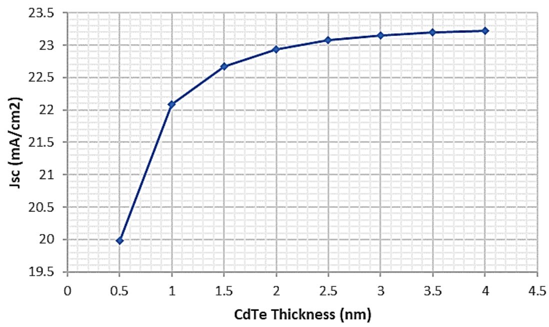

Figure 6. Jsc relationship with CdTe layer thickness

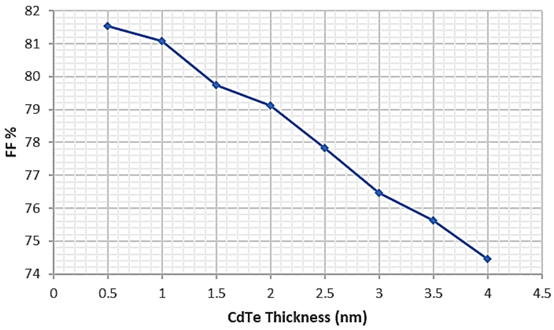

Figure 7. FF% relationship with CdTe layer thickness

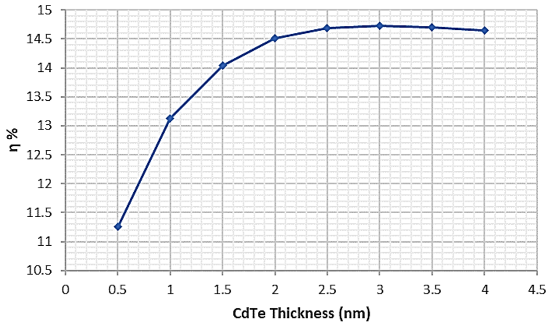

Figure 8. η% relationship with CdTe layer thickness

3.2. Buffer layer thickness effect

The variance in nanoscale of the CdS buffer layer thickness makes the system sensitive to a slight change in the thickness effect (Table 3) with a fixed CdTe thickness of (1µm), which tends to differ in the performance parameters. The results related to CdS layer thickness in Figures 9-13 are dark/light performance, Voc, Jsc, FF%, and η% will be decreased when the thickness of CdS increased. If more photons that hold greater energy than the energy bandgap of the CdS are absorbed by this layer, the number of photons that may enter the absorber layer will also decrease. The effect of the output parameter for the SnO2 window layer thickness of the CdTe cell was found to be similar to the CdS layer influence but varying in magnitude. There will be a drop in Voc, Jsc, and η% in proportional to an increase in window layer thickness. Practically the 40-50 nm range is the preferred and optimized buffer layer thickness in CdTe-based solar cells.

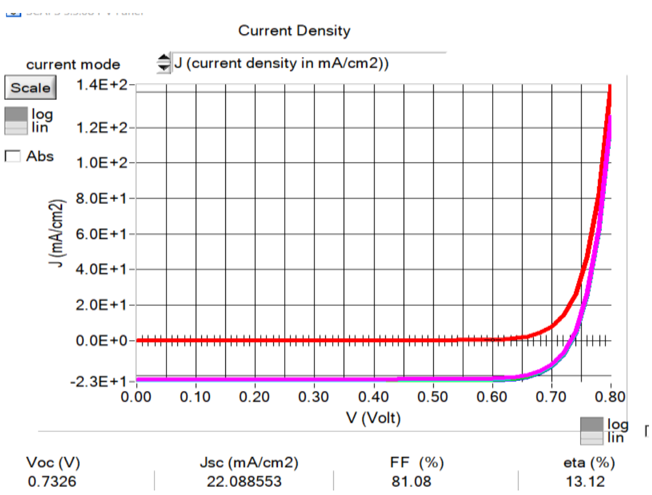

Figure 9. Dark/light J-V characteristics of CdTe solar cell

Table 3. Output performance of basline (CdTe 1µm) solar cells in relation to buffer layer thicknesses

CdS Thickness (nm)	Voc (volt)	Jsc (mA/cm2)	FF%	Eff%
20	0.7344	23.25891	81.15	13.86 (max)
30	0.7337	22.83026	81.12	13.59
40	0.7331	22.44095	81.1	13.34
50	0.7326	22.08542	81.08	13.12
60	0.7321	21.76154	81.06	12.91
70	0.7316	21.46576	81.05	12.73
80	0.7312	21.19533	81.03	12.56
90	0.7308	20.94776	81.01	12.4
100	0.7304	20.72087	81	12.26

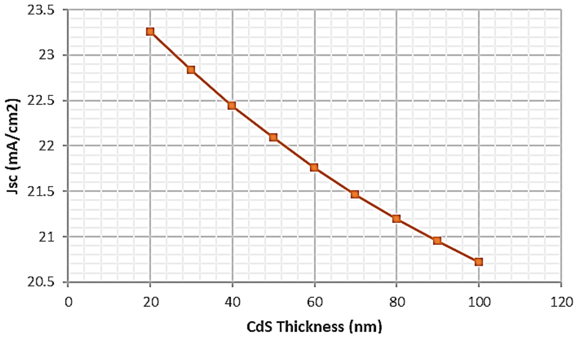

Figure 10. Jsc relationship with CdS layer thickness

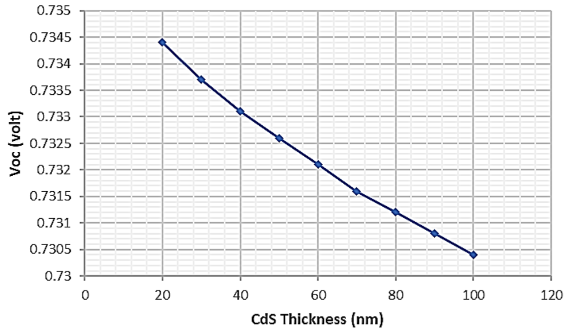

Figure 11. Voc relationship with CdS layer thickness

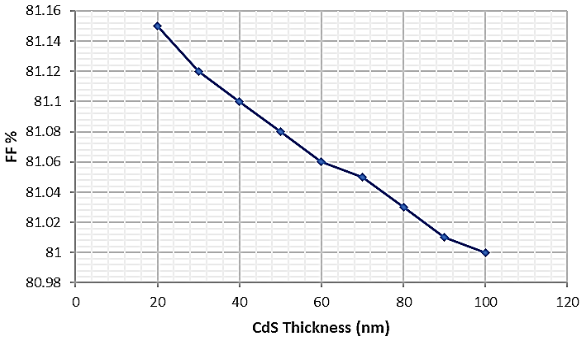

Figure 12. η% relationship with CdS layer thickness

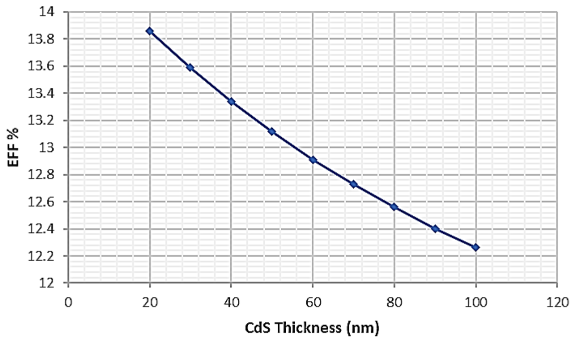

Figure 13. η% relationship with CdS layer thickness

3.3. The temperature of operation effect

Operating temperature is a very important parameter that affects solar cell performance. In this work the used operating temperature, for most of the simulations of solar cells and provided the best result is 300 K or 27°C (see Figure 14). Rising the operating temperature reduces system efficiency. The most affected parameter is the open-circuit voltage (Voc) which increases in temperature. This is due to the inverse dependence on temperature of the saturation current according to (1) and (2). The bandgap energy is unstable even at high temperatures, allowing more electrons and holes to recombine. Figures 15-18, respectively, demonstrates the effect of operating temperature on open circuit voltage, short circuit current density, fill factor, and power efficiency. It is obvious that the (FF%, Eff%, Jsc, and Voc) are dropping by rising T from the value of 290k- 380k

Open circuit voltage (Voc) is the most significant parameter of solar cell efficiency. It is the temperature function that is shown in (2). 290 K to 380 K for the temperature range. The Voc decreases with increasing temperature. The effect of variation in temperature upon the Voc is shown in Figure 11. The Voc has a higher value of 753 mV at 290 K° and decreased with temperature to meet its minimum value of 585 mV at 380 K, which decreases periodically with increased temperature.

Solar cell efficiency is the most important parameter that shows solar cell's performance on temperature and FF between 0.758 and 0.817. Figure 18 indicates the efficiency at the different temperatures. The maximum value of efficiency 13.53% at temperature 290K and 9.75% at temperature 380K obtained minimum.

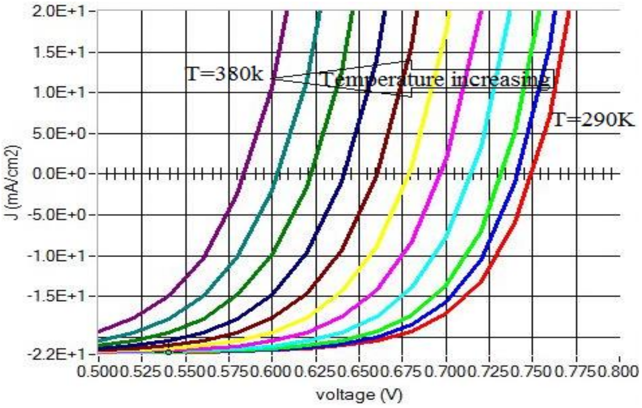

Figure 14. Illuminated I-V characteristics for different values of operating temperature

3.4. I-V characteristics vs Temperature

The operating temperature varying effect on the characteristics of the solar cell current-voltage characteristics also simulated where the temperature varies as (0, 27, 72, 87)°C. The set of four current-voltage characteristics curves, one for each temperature degree, is plotted from Figure 19 shown. The best result obtained optimum operating temperature for solar cell simulation is about 27°C. The output performance of (Eff%, Voc, FF%, and Jsc) was decreased when the operating temperature increases. Therefore, it was necessary to maintain the solar cell temperature to an appropriate rate for good operation and production.

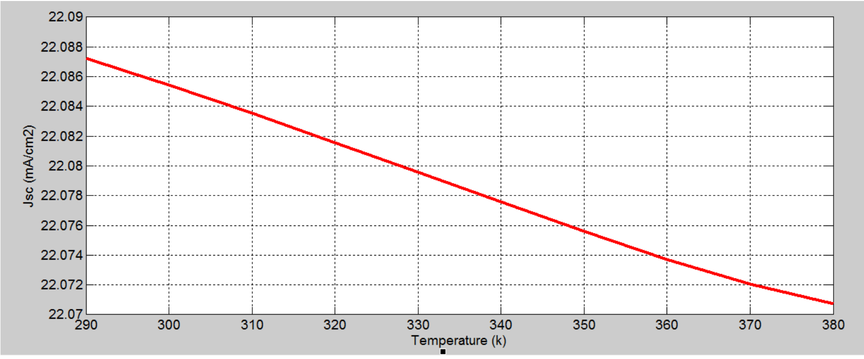

Figure 15. Jsc relationship to the temperature of operating

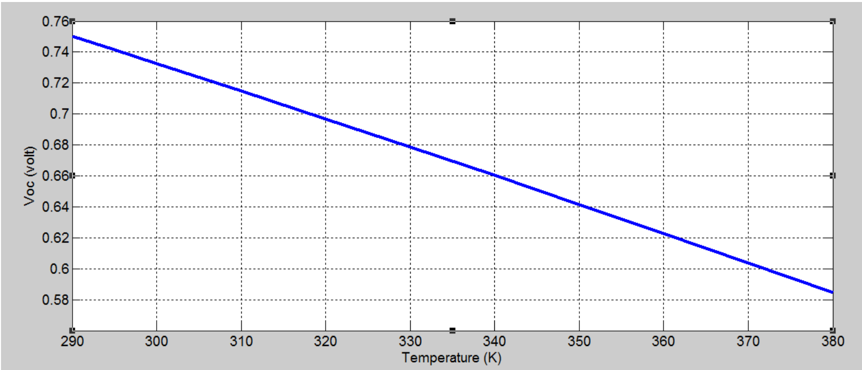

Figure 16. Voc relationship to the temperature of operating

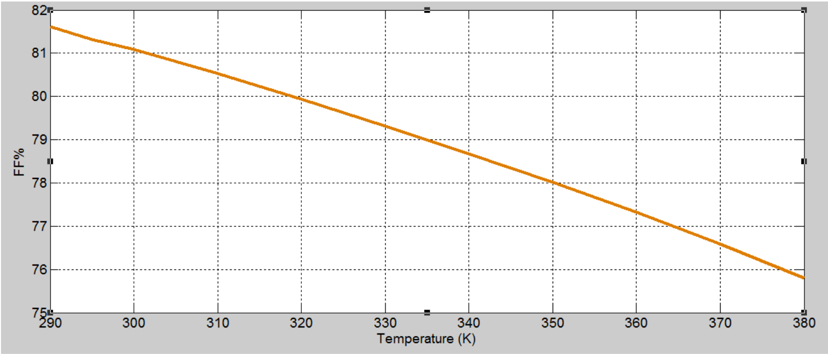

Figure 17. FF% relationship to the temperature of operating

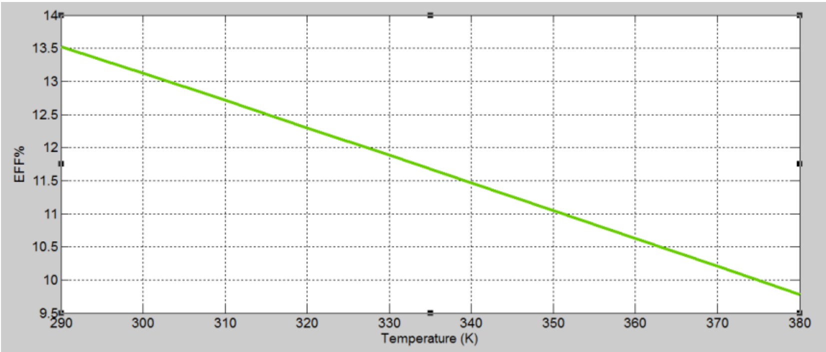

Figure 18. Power conversion efficiency Eff% relationship to the temperature of operating

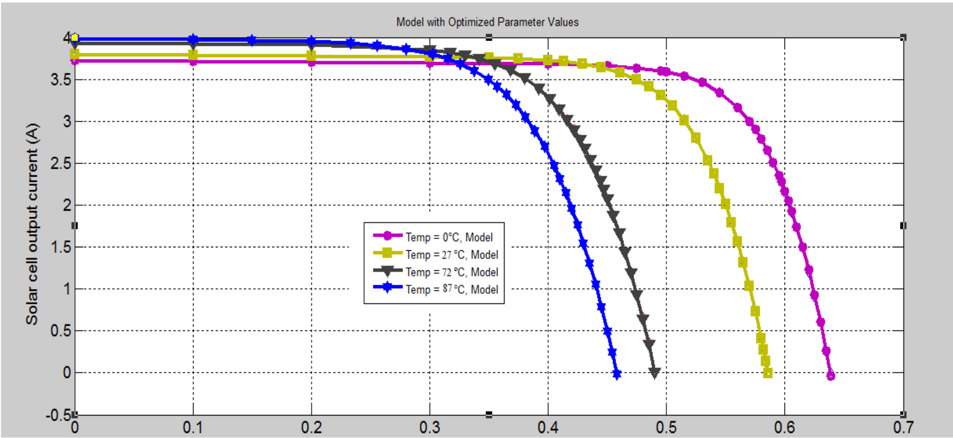

Figure 19. Current-voltage characteristics of varying operating temperatures

4. CONCLUSION

CdTe/CdS thin-film solar cells have shown promise in PV manufacturing due to their high conversion efficiency and low cost of production. Increased photocurrent and system performance are facilitated by improved layer coverage and Voc values, as well as optimization of the thickness of the window and absorber layers, resulting in improved stability. we have investigated the effect of temperature on the performance of thin-film CdTe solar cells. SCAPS-1D 3.2.00 is used to perform the simulation of solar cells. The variation of thickness for both the buffer and absorber layers is also demonstrated. The effects of all these variations are examined on the short circuit current Isc, open-circuit voltage Voc, fill factor FF, maximum power Pmax and efficiency η. The temperature is varied from 280-380K while solar cell CdTe thickness is varied from 500 to 4000 nm, CdS 20 nm to 100 nm. It is observed that the Voc, FF, Isc, and efficiency decrease with increasing temperature. As a result, we may say that CdTe/CdS PV technology still needs extensive research into several issues, including interface defects, more effective blocking of diffusion impurities, and CdTe doping, all of which will be essential components of additional research.

ACKNOWLEDGMENTS

Prof. Marc Burgelman of the University of Gent in Belgium generously provided the SCAPS program for our research. The authors are also thankful for the facilities provided by the University of Mosul and Northern Technical University, which contributed to enhancing the quality of this research.

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