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Simulation of Performance of Cadmium Telluride Solar Cell Using AMPS-1D Program

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Abstract: In this research, we have used the AMPS-1D program to study the enhancement of the Cadmium telluride cell efficiency by studying the relationship between efficiency and some variables, such as the thickness and doping density of the cell layers, type of the back contact metal, and changes in solar radiation and temperature. Simulation results showed that the efficiency increased largely with the increase in the thickness of the absorbent layer CdTe, until the value of (1500 nm), by reducing the thickness of the layer of CdS (n-type), and it does not depend on the thickness of the front contact layer (SnO₂). The efficiency depends largely on the doping concentration of the absorbent layer (N_A). When the efficiency increases with vaccination rate up to the value 10^{16} cm^{-3}, then it does not increase significantly, while a higher efficiency is reached when the vaccination of CdS layer is at the value 10^{17} cm^{-3}. The cell has a high stability at high temperatures with a decreasing rate of 0.08%/°C. The efficiency depends on the type of metal used as a back contact material in the cell under study, and showed that the Aluminum (Al) gives higher efficiency than other metals. As a result installation of Cadmium telluride cell by adoption of the values obtained increases the efficiency of the cell from 13.8% to 19.5%.

Keywords: Thin Film Solar Cell, Cadmium Telluride Cell Efficiency, Simulation, AMPS 1D

1. Introduction

The CdTe thin film solar cell basically consists of two semiconducting layers. A CdS layer serves as the n-type window material with energy bandgap, Eg = 2.42 eV and a CdTe layer (absorber) deposited on top with Eg = 1.45 eV. Research in CdTe dates back to the 1950s. A CdS/CdTe thin film solar cell was first fabricated using an evaporation technique in 1969 by Adrirovich et al. [1] with a conversion efficiency of 1%. In the late of 1980s [2], Tyan and Perez produced a solar cell with an efficiency of 10% based on a CdS/CdTe thin film. Afterwards an efficiency of 15.8% has been reached by Ferekides et al. [3]. At present, the CdTe solar cell makes more attraction to the researchers and commercials for its higher efficiency, low cost, highly stable and large scale fabrication opportunity. CdTe has larger

absorption coefficient ($> 5 \times 10^5$ cm^{-1}) due to its ideal and direct band gap energy 1.45 eV; which corresponds well to sunlight spectra and $\sim$ 99% of photons with energy greater than the band gap (E_g) can be absorbed within 1 μm of CdTe film [4, 5, 6]. Small-area CdTe cells already achieved efficiency of 16.5% in laboratory and 11% in the commercial modules. However, there are scopes to improve the CdS/CdTe solar cell performance further more by modified design and simple deposition technique to improve any one of cell output parameters [7]. The strategies for improving cell performance have been explored, utilizing AMPS-1D (Analysis of Microelectronic and Photonic Structures) simulator have also been discussed [8, 9].

The AMPS-1D program has been developed for pragmatically simulate the electrical characteristics of thin film hetero-junction solar cells. It has been proven to be a

very powerful tool in understanding device operation and physics for single crystal, poly-crystal and amorphous structure. To date, more than 200 groups worldwide have been using AMPS-1D for solar cell design [8].

The objective of this research is to use AMPS-1D program (analysis of microelectronic and photonic structure in one dimension) to obtain the optimum structure of the cadmium telluride solar cell (CdS/CdTe).

2. Modeling and Simulation

The major objectives of numerical modeling and simulation in solar cell research are testing the validity of proposed structures and geometry on cell performance and fitting of modeling output to experimental results. Fig. 1a and 1b illustrates the CdTe baseline case structure and the modified (Glass/SnO_2/CdS/CdTe/Al) structure of CdTe cell for higher conversion efficiency (η). The baseline case cell in this work contains of three principle layers: n-type SnO_2 as a TCO material (high transparence, high conductivity), n-type CdS as a window layer and p-type CdTe as an absorber layer. Considering the low cost feature Ag is used as a back contact material with back contact barrier height (Φ_{bL}) of 1.25 eV. Figures 1a, 1b illustrate the baseline case of CdS/CdTe cell and the modified structure for higher conversion efficiency (η).
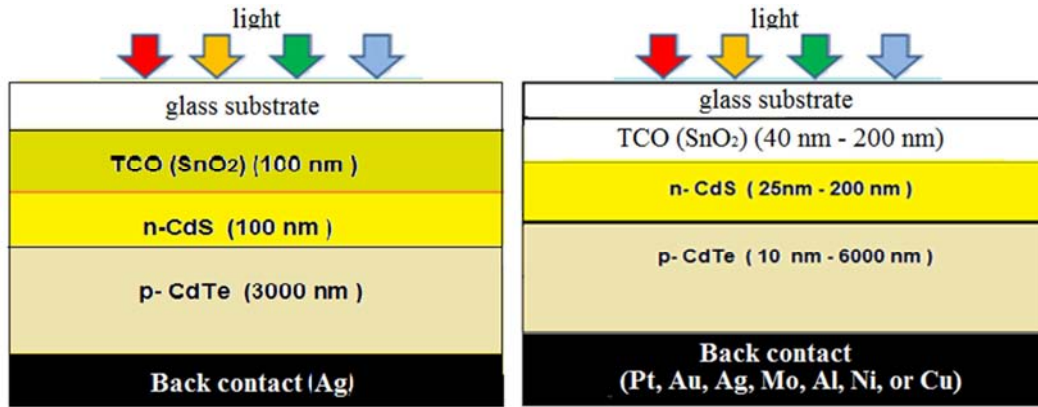

Figure 1. Structures of the CdS /CdTe solar cell: (a) conventional baseline case structure and (b) modified structure for higher performance.

In this analysis, we have varied the CdTe layer thickness from 10 nm up to 6000 nm, CdS window layer thickness from 25 nm to 600 nm and SnO_2 layer thickness from 10 nm to 200 nm and with different back contact materials; such as (Pt, Au, Ag, Mo, AL, Ni and Cu) and by keeping all other parameters at fixed value as shown in table 1 aiming to efficient and thinner CdS/CdTe solar cell.

Table 1. Material parameters used for cell simulation.

	n-SnO_2	**n-CdS**	**p-CdTe**
W (μm)	0.01-0.50	0.025-0.6	0.010 - 6
$\varepsilon/\varepsilon_o$	9	10	9.4
μ_e (cm^2/v_s)	100	350	500
μ_h (cm^2/v_s)	25	50	60
E_g (eV)	3.6	2.42	1.45
N_C (cm^3)	2.2×10^{18}	2.2×10^{18}	7.5×10^{17}
N_V (cm^3)	1.8×10^{19}	1.8×10^{19}	1.8×10^{18}
χ (ev)	4.5	4.5	4.28
N_A (cm^{-3})	--------	--------	5×10^{16}
N_D (cm^{-3})	10^{17}	10^{18}	--------

3. Results and Discussion

3.1. Effects of Layer Thickness

The effects of Cds, CdTe and SnO_2 thickness on the conversion efficiency of the solar cell were studied. The conventional CdTe baseline structure (glass/SnO_2/CdS/CdTe/Ag) was the starting point of this analysis. The conversion efficiency of 13.78% (*Open circuit voltage (Voc)* = 0.83 V, *Short circuit current density (Jsc)* = 25.035 mA/cm², *Fill factor (FF)* = 0.66) was found from the baseline case structure (figure 1a); where CdTe thickness was 5000 nm, SnO_2 was 500 nm, CdS was 100 nm, and Ag was taken as the final back contact metal with a barrier height of 1.25 eV, when the temperature is fixed at a value of 300 K and with the CdTe doping concentration (10^{15}) cm^{-3}, CdS doping concentration (10^{18}) cm^{-3}, the other conditions and parameters that applied in the simulation were given in table 1.

The CdS thickness has been varied from 25 nm to 600 nm to explore thinner window layer and the results obtained from AMPS-1D simulation are shown in figure 2.
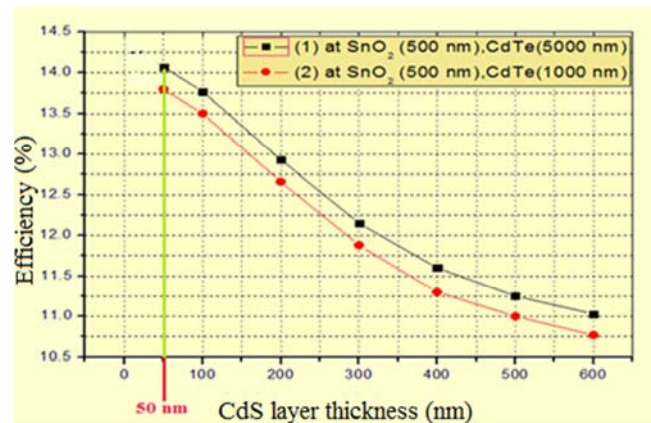

Figure 2. Relation between CdS layer thickness and the conversion efficiency of the baseline case cell at different thicknesses of CdTe layer.

Figure 2 shows that efficiency improved greatly with reduced CdS layer, the cell conversion efficiency increases when the CdS layer thickness is reduced. But from the other published works [10, 11, 12] to date; it is impractical to fabricate cells with CdS film thickness below 50 nm. It is found that when the operating wavelength is below 510 nm the quantum efficiency (QE) was significantly affected with increasing CdS layer thickness. This affected mainly on *Jsc* and finally the conversion efficiency of the cell. Considering the fabrication constraint, the CdS film thickness of 50 nm was selected with conversion efficiency of 14.08% (*Voc*= 0.83 V, *Jsc* = 25.46 mA/cm^2, FF= 0.664) (figure 2). This result is in a good agreement with other published works [10, 11].

To explore the thickness of CdTe absorber layer required to achieve maximum conversion efficiency; the CdTe absorber thickness was varied from 10 nm to 6000 nm to explore thinner CdTe absorber layer using AMPS-1D simulator, the simulated results are shown in figure 3. It is clear from figure 3 that the solar cell output efficiency is maximum for CdTe thickness greater than 2000 nm, and the efficiency decreases sharply below the CdTe thickness of 1500 nm; this indicates that 1.5 μm thickness of CdTe layer is sufficient to get a high efficiency. This value close to the theoretical minimum thickness (2 μm) required for CdTe layer to absorb 99% of the incident photons with energy greater than Eg [11]. The 1.5 μm thick CdTe cell shows efficiency of 14.5%, (at conditions in figure 3). These results are in a good agreements with related published results [10, 11, 12, 13].
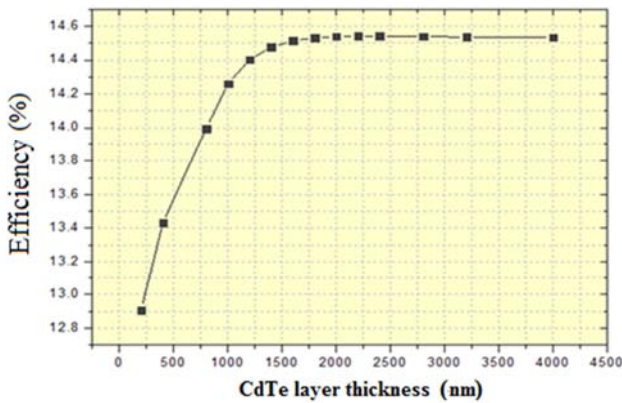
Figure 3. *Effect of CdTe film thickness on the cell conversion efficiency at 300 K, CdS with 100 nm thickness.*

The effect of the TCO layer (SnO$_2$) thickness on the cell conversion efficiency has been studied using AMPS-1D program. The TCO layer thickness was varied from 40 nm to 200 nm at 300 K, with 100 nm thickness for CdS layer, 1000 nm thickness for CdTe layer, while all parameters were fixed as shown in table 1.

Figure 4 shows the results obtained from AMPS simulation which indicate that the conversion efficiency is unaffected by TCO (SnO$_2$) layer thickness (remains constant at the value 14.12%), so the reduced value 100 nm for TCO layer thickness will be suitable.
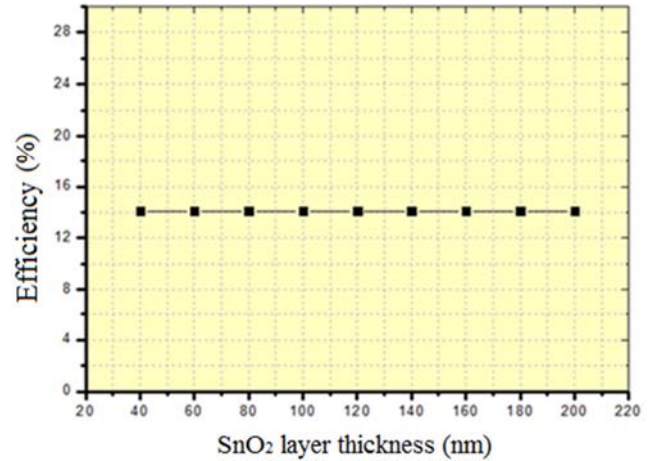
Figure 4. *Effect of the TCO layer (SnO$_2$) thickness on the cell conversion efficiency.*

3.2. Effects of Doping Concentration

In the baseline case cell CdTe layer doping concentration was (10^{15} cm^{-3}) with a conversion efficiency 14.12% (*Voc* = 0.85 V, *Jsc* = 25.27 mA/cm^2, FF = 0.66); (donor doping density (N$_D$) of CdS layer was fixed at the value (10^{18} cm^{-3})). It has been found that the conversion efficiency increases up to 16.2% (*Voc* = 0.97 V, *Jsc* = 24.89 mA/cm^2, FF = 0.66) with the CdTe doping density (10^{16} cm^{-3}), (at the thickness values 100 nm, 50 nm, 1000 nm of SnO$_2$, CdS, CdTe layers respectively). Figure 5 shows the effect of acceptor doping density (N$_A$) on the cell efficiency; where the efficiency was calculated at different values of N$_A$ and found that the conversion efficiency increases with the increase of acceptor doping density (N$_A$). Figure 5 shows that efficiency increases sharply with the increase of N$_A$ up to 3×10^{15} cm^{-3}, so the concentrations of 3×10^{15} cm^{-3} - 10^{16} cm^{-3} will be sufficient to enhance the cell conversion efficiency.
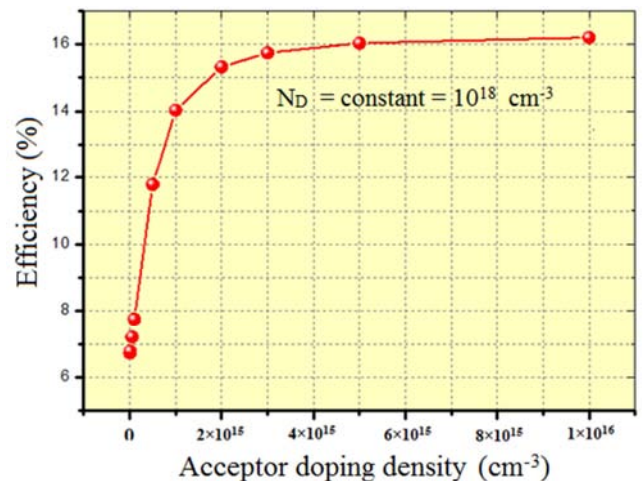
Figure 5. *Effect of acceptor doping density (N$_A$)(of CdTe layer) on the efficiency of the baseline case cell (glass/SnO$_2$/CdS/CdTe/Ag), at N$_D$= 10^{18} cm^{-3}.*
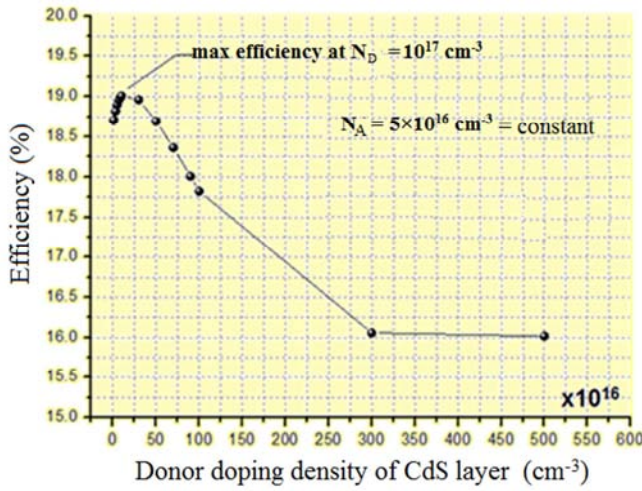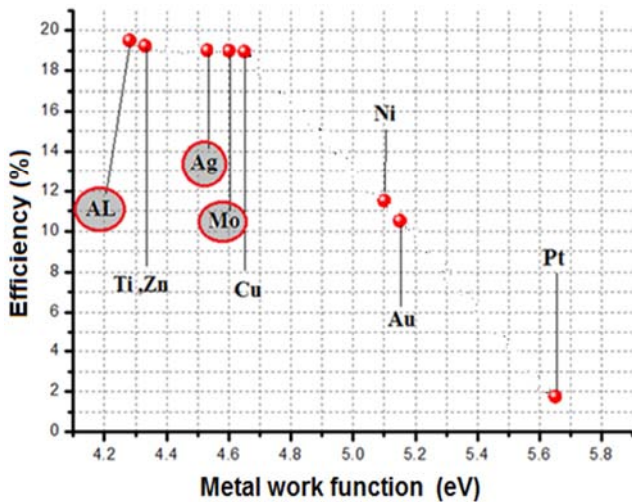
Figure 6. *Effect of donor doping density (N_D) (of CdS layer) on the conversion efficiency of the baseline case cell (glass/SnO_2/CdS/CdTe/Ag), at N_A=5×10^16 cm^-3.*
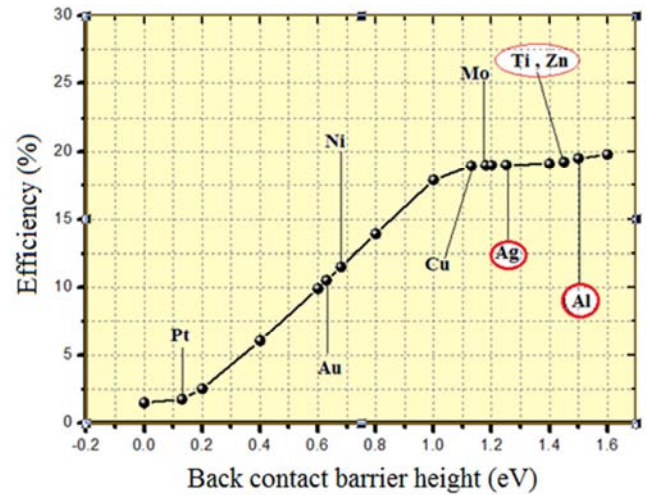
To investigate the effect of donor doping density (N_D) on the cell conversion efficiency, the acceptor doping density (N_A) (of CdTe layer) will be fixed at the value (5×10^{16} cm^{-3}) and the efficiency will be calculated as (N_D) is changed from 10^{16} cm^{-3} to 5×10^{18} cm^{-3}, the highest efficiency 19.01% has been obtained using AMPS-1D program at the value of donor

doping density (N_D) equal to 10^{17} cm^{-3}. The simulated results are shown in figure 6 and it has been obtained with 50 nm thickness for CdS layer, 1000 nm thickness for CdTe layer, while the other parameters were fixed as shown in table 1.

3.3. Effect of the Back Contact Barrier height (Φ_{bL})

In the baseline case cell (glass/SnO_2/CdS/CdTe/Ag) considering the simplicity and low cost feature silver was used as a back contact material with back contact barrier height (Φ_{bL}) of 1.25 eV. To investigate the effect of the back contact barrier heights on the cell conversion efficiency back contact materials (Ag, Ni, Cu, Pt, Al, Ti, Zn, Mo, Au) have been inserted in the modified cell; for the (p-type - metal) contact the back contact barrier height is calculated from the relation 1 [14]:

$$BHIBL(\Phi_{bL}) = CHI + EG - WF \qquad (1)$$

Where:

CHI the electron affinity (χ), EG the mobility band gap of the p-type material CdTe, WF (Φ_m) the metal work function. Table 2 shows the calculated barrier heights for some proposed metals as a back contact and the calculated efficiencies for the corresponding proposed structures of the modified cell.

Table 2. *The calculated barrier heights (from equ. 1) and calculated efficiencies using AMPS-1D simnulation program for some proposed structures including different back contact materials.*

The proposed structures	Work function range (metal)	Selected values	Barrier height BHIBL (eV) = CHI+EG -WF (ev) (Back contact)	Efficiency %
Glass/SnO_2 /CdS/CdTe /Pt	5.12-5.93	5.65	0.13	1.768
Glass/SnO_2 /CdS/CdTe /Au	5.1-5.47	5.15	0.63	10.524
Glass/SnO_2 /CdS/CdTe /Ni	5.04-5.35	5.1	0.68	11.517
Glass/SnO_2 /CdS/CdTe /Cu	4.53-5.1	4.65	1.13	18.95
Glass/SnO_2 /CdS/CdTe /Mo	4.36-4.95	4.6	1.18	18.983
Glass/SnO_2 /CdS/CdTe /Ag	4.52-4.74	4.53	1.25	19.01
Glass/SnO_2 /CdS/CdTe /Ti	4.33	4.33	1.45	19.23
Glass/SnO_2 /CdS/CdTe /Zn	3.63-4.9	4.33	1.45	19.23
Glass/SnO_2 /CdS/CdTe /Al	4.06-4.28	4.28	1.5	19.5 (max)

(a)

(b)

Figure 7. *(a) efficiency with metal work functions, (b) efficiency with back*

contact barrier heights.

Figures 7 (a), (b) and table 2 showed that the metals Al, Zn, Ti, Ag, are suitable and make good back contacts to get high efficiencies 19.5%, 19.23%, 19.23%, 19.01% respectively.

3.4. Effect of Solar Irradiance and Operating Temperature

Solar cells experience daily variations in light intensity, with the incident power from the sun varying from '0' to '1' kW/m^2, so it is important to investigate the effect of irradiance on solar cell performance with the variation of light intensity [12]. Figure 8 shows how the *I-V* curves for *(glass/SnO₂/CdS/CdTe/Ag)* cell vary with changes in irradiance; the curves move in the vertical direction much more than they move horizontally. When irradiance drops by half, the electricity generated and subsequently solar cell efficiency also reduces by half. The voltage slightly affected by changing irradiance. This result is in a good agreement with the other published works like [12, 15].
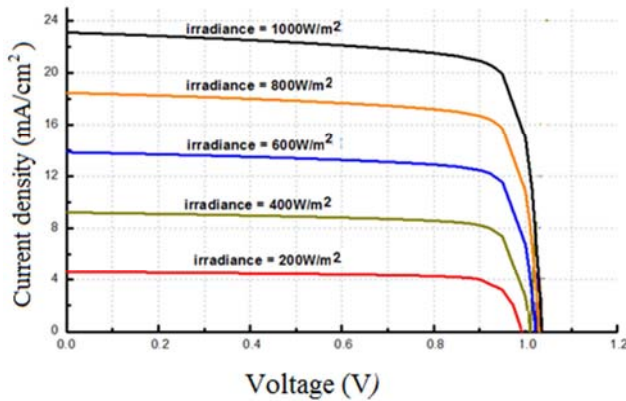

Figure 8. *I-V characteristics curves of (glass/SnO₂/CdS/CdTe/Ag) cell at different irradiance using AMPS-1D simulation program.*
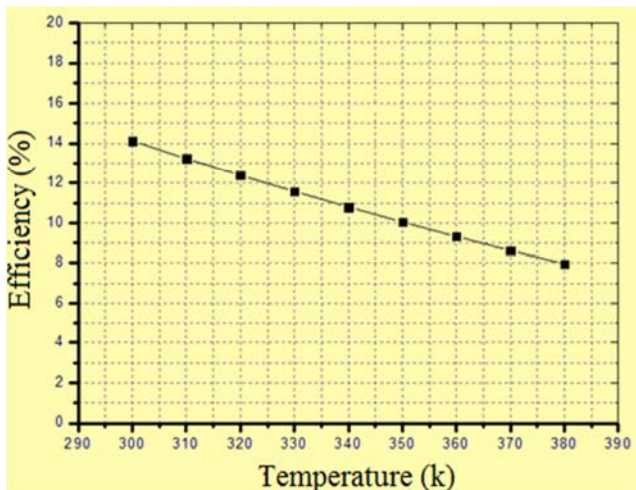

Figure 9. *Effect of operating temperature on the cell conversion efficiency.*

The relation between the conversion efficiency and operating temperature for the (glass/SnO₂/CdS/CdTe/Ag) cell has been studied using AMPS-1D program; the efficiency was calculated as the temperature is changed from 300 K (η = 14.12%) to 380

K (η = 7.96%), with 3000 nm CdTe thickness, 100 nm CdS thickness, and 100 nm SnO₂ thickness. The results are shown in figures 9, 10; it is evident from figure 9 that the conversion efficiency nearly linearly decreases with a rate of -0.08%/°C, which also indicates the degree of stability of the cell at higher operating temperature. Comparing with the results in the reference [16] for most crystalline and amorphous cells, this cell is more stable. Figure 10 indicates the same results represented by the light I-V characteristics curves.
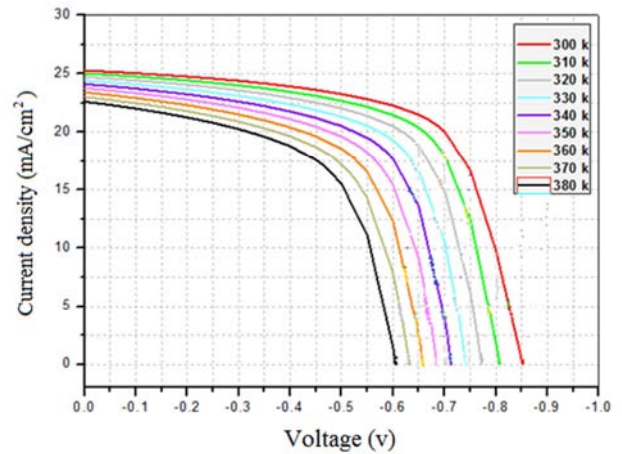

Figure 10. *Light I-V characteristics curves for the baseline case cell (glass /SnO₂/CdS/CdTe/Ag) at different operating temperatures.*
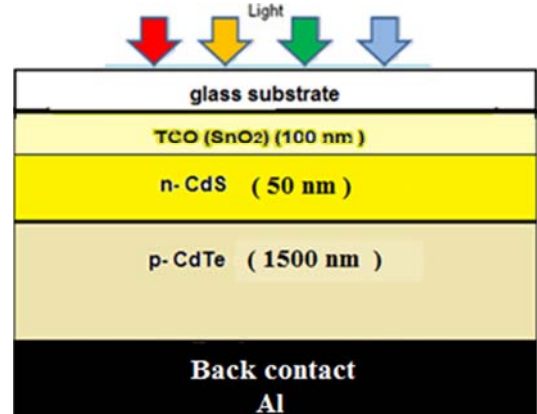

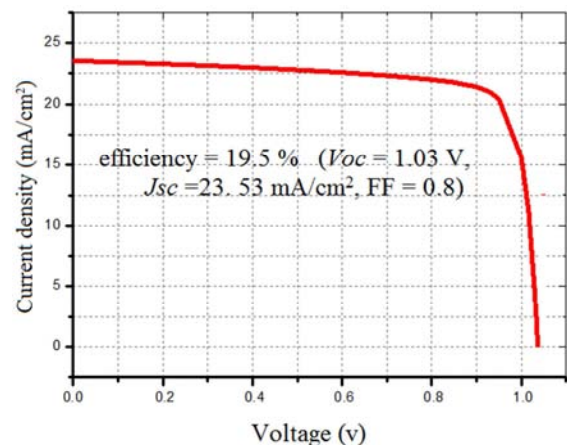**Figure 11.** *Modified structure for higher performance.*

Figure 12. Light I-V Characteristics for the modified structure (SnO_2/CdS/CdTe/Al) for higher conversion efficiency, where the best parameters values are applied using AMPS-1D program.

Finally we can consider the last results and insert the optimization parameters in the structure (glass /SnO_2/CdS/CdTe/Al) which correspond to the best conversion efficiency as was found from the previous results.

In this modified cell the parameters will be fixed as shown in figure 11, with the concentrations 5×10^{16} cm^{-3} (the today's achievable [11]), 10^{17} cm^{-3} of N_A, N_D respectively, Al metal will be used as a back contact material with back contact barrier height (Φ_{bL}) of 1.5 eV; according to this optimization values the high efficiency 19.5% (*Voc* = 1.03 V, *Jsc* = 23.53 mA/cm^2 and FF = 0.8) has been obtained.

4. Conclusions

In this research we have had a simulation study by AMPS-1D program on the conversion efficiency of Cadmium Telluride solar cell (SnO_2/CdS/CdTe). A high efficiency 19.5% (*Voc* = 1.03 V, *Jsc* = 23. 53 mA/cm^2, FF = 0.8) for ultrathin CdS/CdTe solar cell has been obtained with 1.5 μm of CdTe, 50 nm of CdS, 100 nm of SnO_2, and with the doping concentration of CdTe layer (5×10^{16}) cm^{-3}, doping concentration of CdS layer (10^{17}) cm^{-3}, and (Al) as the back contact metal with a barrier height of 1.5 eV, when the temperature is fixed at a value of 300 K.

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