Numerical modeling of multi-junction solar cell-based CIGS with two sub-cells in parallel using silvaco TCAD

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The multi-Junction solar cell technique was suggested for achieving high efficiency. This paper describes the simulation of a solar cell for double junction CGS/CIGS solar cell using Silvaco ATLAS software. The simulated device performance was demonstrated in the form of current-voltage (I-V) characteristics and quantum efficiency (QE). By simulation of the tow solar cell, we have obtained for solar the top cell maximum open-circuit voltage 1.15V, a short circuit current density of 18.74 mA, a fill factor (FF) of 87.79 % and an efficiency of 18.27% and for the bottom solar cell is maximum open-circuit voltage 0.57 V, a short circuit current density of 21.52 mA, a fill factor (FF) of 82.82% and an efficiency of 10.26%. For the Tandem whose sub-cells are tied in parallel, the maximum open-circuit voltage 1.16V, a short circuit current density of 29 mA, a fill factor (FF) of 83.06% and an efficiency of 28.11%.

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1. Introduction

The thin-film multi-junction have been evolved into the ripest form while are between the most promising structures for third-generation photovoltaic (PV) devices because they possess high efficiency and at low cost [1,2] For that reason, it has been used by utilizing different materials with different band-gaps in absorber materials to harvest the available solar spectrum with fewer losses from thermalization power. [3,4]

Multi-junction has achieved great success in the field of solar cells[2] due to the fact that the semiconductor which has higher bandgap energy can absorb the high power(short wavelength parts of solar spectrum energy). For low band gap semiconductors, it is the contrary. [5,6]

The most essential thin-film solar cells used in the thin-film solar cells is the copper-indium-gallium-diselenide (CIGS) because it is a high absorption coefficient and adjustability of the graded band-gap for the solar spectrum. [7], it has direct band-gap energy and thinner than silicon wafers [8]. Cu (In, Ga) $(Se, S)_2$ (CIGS) have been regarded as favourable candidate materials because it is wide band-gap varying from 1.05 eV to 1.68 eV [9,10].

The purpose of this paper is to offer a solution to increase the efficiency of the multi-junction solar cell-based on CIGS, while we focused on studying the monolithic tandem cell with the structure (ZnO/CdS/CGS/ZnO/CdS/CIGS/Mo) by linking between the two sub-cell parallel.

In this paper, we tried to increase the efficiency of the tandem CIGS solar cell by connecting the two sub-cells in parallel.

The multi-junction solar cell was presented; it is composed of Zinc oxide as a window layer, cadmium sulfide (CdS) as a buffer layer, copper gallium diselenide (CGS) as the absorber layer and Zinc oxide (ZnO), cadmium sulfide (CdS) as a second buffer layer and copper also indium gallium diselenide (CIGS)as the second absorber layer and molybdenum respectively. The

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structural parameters of the proposed solar cell were optimized and doping concentration, the thickness of layers, and CIGS band gap were obtained under current matching conditions. The efficiency of 28.11% and fill factor of % 83.06 was achieved.

In the following section, the theoretical and important parameters of the solar cell are shown. Then, the structure of the proposed solar cell is designed and the method of optimization and the results of numerical simulation are explained in section 3. In the last section, the conclusion is given.

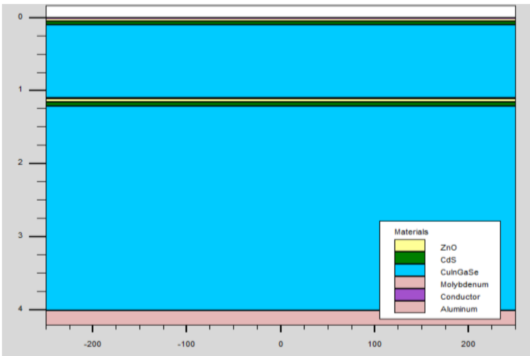

Fig. 1. The optimized solar cell structure.

2. Material and methods

In this paper, for simulating the solar cells we used the Atlas software of Silvaco, ATLAS provides general capabilities for physically-based two (2D) and three-dimensional (3D) simulation of semiconductor devices [11,12]. Silvaco software is a very powerful simulator that is used in electronics [8,12]. It demonstrates the electrical behavior of the device to obtain different electrical characteristics such as conversion efficiency (η), short circuit current (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and quantum efficiency (QE) [7].

In the software, Silvaco Atlas 2D, we have to input of the device all the information and specifications of all materials utilized in the solar cell parameters which are those of material parameters. The semiconductor properties of ZnO, CdS, CGS and CIGS layers used in the simulation are presented in Table 1.

For calculating the band-gap of the semi-conductor Cu ($In_{(1-x)}$ Ga_x) Se_2 an approximate expression was used:

$$Eg\ (x) = 1.011 + 0.664x - 0.249(1-x) \tag{1}$$

The Eg is ranging from 1.011 eV to 1.68 eV for x=0 (CIS) and x=1 (CGS), respectively.

The electron affinity of CIGS is expressed given below:

$$\chi(x) = -0.242x^2 - 0.454x + 4.68 \tag{2}$$

The relative permittivity:

$$\mathcal{E}(x) = 15.1 - 5x \tag{3}$$

In this work, the simulations were all performed AM1.5 solar spectrums with P = 1000W/cm² and at temperature T = 300 K using the one diode ideal model.

Table 1 shows the description for the parameters used in the simulation and the basic parameters that are used in the study.

Table 1. The Parameters for the simulations were given the tables.

Parameters	ZnO	CdS	CGS	ZnO	CdS	CIGS
Thickness (µm)	0.05	0.05	1	0.05	0.05	2.8
ε	9	10	10.1	9	10	13.55
Eg (eV)	3.3	2.48	1.675	3.3	2.48	1.045
χ(eV)	4.5	4.18	3.984	4.5	4.18	4.51
μ_n(cm2 /Vs)	100	100	100	100	100	100
μ_p(cm2 /Vs)	25	25	25	25	25	25
Nc (cm^{-3})	$2.2e^{18}$	$2.41e^{18}$	$2.2e^{18}$	$2.2e^{18}$	$2.41e^{18}$	$2.2e^{18}$
NV (cm^{-3})	$1.8e^{19}$	$2.57e^{19}$	$1.8e^{19}$	$1.8e^{19}$	$2.57e^{19}$	$1.8e^{19}$
Nd (cm^{-3})	$1e^{18}$	$5e^{17}$	/	$1e^{18}$	$1e^{17}$	/
Na (cm^{-3})	/	/	$8e^{16}$	/	/	$8e^{16}$

3. Simulation results and discussions

The simulation work has been performed aiming for high efficiency and more stable CIGS tandem solar cells. The simulation results can be seen in Fig. 2, 3 and 4. This figure presents the cell parameters such as V_{OC}, J_{SC}, FF and η from SILVACO simulation.

To match different solar cells; Often short circuit current density (J_{SC}) is used in place of short circuit current (I_{SC}), where $J_{SC} = I_{SC} / A$, A represents the cell surface area. By applying a voltage to the cell, the current decreases and the voltage develop as the charge builds up at the terminals. The resulting current can be thought of as the sum of the short circuit current I_{SC}, produced by the process of absorbing the photons. The current density is as follows [7]:

$$J = J_{SC} - J_0 \left(e^{\frac{qV}{TK_B}} - 1 \right) \tag{4}$$

where, J_0 is a constant, q is the electron charge and V is the applied voltage. The open circuit voltage V_{OC} can be calculated by setting J= 0:

$$V_{OC} = \frac{TK_B}{q} \operatorname{Ln}\left(\frac{J_{SC}}{J_0} + 1 \right) \tag{5}$$

The maximum output power density of a solar cell is achieved somewhere between V=0 and V=V_{OC} at a voltage V_m. The corresponding current density is called J_m, and thus the maximum power density is:

$$Pm = J_m * V_m \tag{6}$$

So the efficiency of solar cell is defined as, it is the ratio of maximum electrical power density produced on the incident light power density.

$$\eta = \frac{P_{max}}{P_{inc}} = \frac{I_{max} V_{max}}{P_{inc}} \tag{7}$$

We have first demonstrates the variation of the quantum efficiency (QE) versus wavelength for both the top and bottom cells of the tandem solar cell in Fig. 2. Which shows a maximum in the QE around 0.38 µm and 0.83 µm for the top and the bottom cell respectively.

The top sub-cell of the tandem absorbed the short wavelength region below 0.7 µm then the bottom sub-cell start to absorb the wavelength range between 0.78 and 1.1 µm.

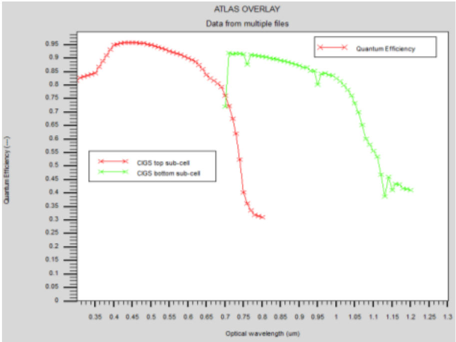

Fig. 2. QE of the CGS/CIGS tandem solar cell as function of wavelength.

Fig. 3 displayed the variation of the current versus the voltage of the top, bottom, and tandem solar cells and their photovoltaic parameters are indicated in Table 2. Which is the top and bottom sub cell together. To extract the characteristic IV of the top and the bottom cell of the tandem cell separately. We used two sets of anodes and cathodes. For the top, the cathode was in the Window layer ZnO and we put an anode in the absorber layer CGS .for the bottom, the cathode and the anode were placed at the front contact ZnO and the back contact Mo respectively.

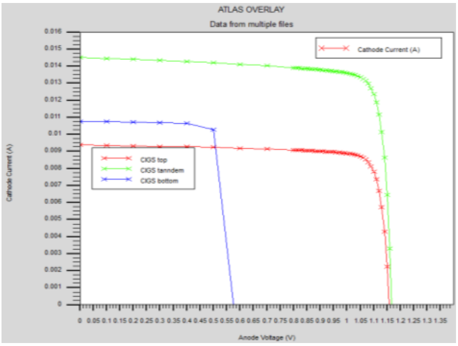

Fig. 3. J(V) characteristics for the CGS top cell, CIGS bottom cell and CGS/CIGS tandem cell.

As well as in Fig.4 shows the P (V) characteristics of the top, bottom, and tandem solar cells. For the CIGS/CIGS tandem cell, V_{oc}= 1.16V, which is equal to the V_{oc} of CGS top cell. It shows that J_{sc} from the CIGS tandem cell is about 29mA/cm², which can lead to a non-ideal current matching between top and bottom cells. This implies an optimized CIGS top and bottom cells are in parallel. In this study we are interested about the parallel-connected CGS and CIGS cells forming the tandem cell. The fill factor of the tandem cell is 83.66% and the conversation efficiency of the tandem cell to 28.11% which is higher than those of the single CIGS and CGS cells (18.27% and 10.26%). The table 2 Photovoltaic parameters of the top, bottom and tandem solar cells.

Table 2. Parameters PV of the optimized CIGS device.

	V_{oc} (V)	J_{SC}(mA/cm²)	FF (%)	η (%)
CGS top cell	1.15	18.74	87,79	18.27
CIGS bottom cell	0.57	21.52	82.82	10.26
CGS/CIGS tandem cell	1.16	29.00	83.06	28.11

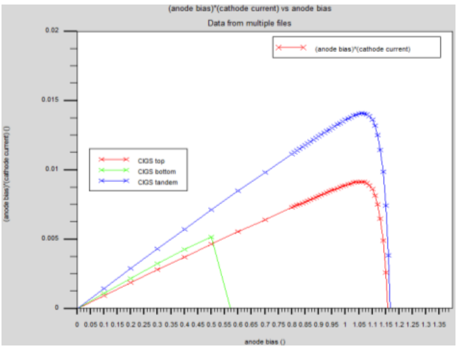

Fig. 4. P(V) characteristics for the CGS top cell, CIGS bottom cell and CGS/CIGS tandem cell.

4. Conclusion

Premised on the Silvaco-Atlas software, a double junction CGS/CIGS solar cell is simulated numerically, which consists of two sub-cells connected in parallel -based thin-film solar cell under AM1.5. I (V) and P (V) characteristics and external quantum efficiency have been shown. The V_{oc} of 1.16 V, equal J_{sc} of 29 mA/ cm^2, and the maximum efficiency of 28.11 % are achieved. Also, the good fill factor equal to 83.11% demonstrates the ideal I-V responses for the solar cell.

In this study, we had a numerical simulation of the CGS/CIGS tandem solar for contributing to improving manufacturing high-efficiency CGS/CIGS tandem solar cells.

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