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Simulation of $CZTS(Se)_4$ Tandem Solar Cells By AFORS-HET Software

Buthina M. Jandary[1], Ayed N. Saleh[2]
[1,2] Physics Department, College of Education for pure science, University of Tikrit, Tikrit, Iraq.
[1]buthina088@gmail.com,[2]ayad.ns@tu.edu.iq

Abstract

In this work, solar cells were simulated single, mechanically and monolithically stacked based on the CZTS (Se) $_4$ absorption layer, both layers of tandem solar cell were simulated using by AFORS-HET software (one-dimensional). Electrical properties of the monolithical tandem cell, it's determined after the current matching to the top and bottom sub-cell. The short circuit current density Jsc is about 23.9 mA. cm^{-2} when the top cell thickness is 384 nm in conjunction with the 1000 nm bottom cell thickness. The maximum efficiency obtained is approximately 23.1% with an open circuit voltage Voc ~ 1146.9 mv. The efficiency of the mechanical tandem cell with series connection was 23.76 % at open circuit voltage Voc ~ 1166.9 mv and the efficiency about 26.62 % at open circuit voltage Voc ~ 475.2 mv for mechanical tandem cell with parallel connection when the both cells had the same thickness(1000nm).

Keywords: Tandem thin-film solar cell, $CZTS(Se)_4$, AFORS-HET simulation.

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محاكاة الخلية الشمسية المتعددة $CZTS(Se)_4$ بأستخدام برنامج AFORS-HET

بثينة محمود جنداري [1]، عايد نجم صالح [2]

[1،2] قسم الفيزياء، كلية التربية للعلوم الصرفة، جامعة تكريت، تكريت، العراق.

[1]buthina088@gmail.com, [2]ayad.ns@tu.edu.iq

ألملّخص

في هذا العمل، تم محاكاة الخلايا الشمسية المنفردة، والخلايا المتعددة المنضدة بالتعاقب والمنضدة ميكانيكيا على أساس طبقة الامتصاص $CZTS(Se)_4$، تم محاكاة كلتا طبقتي الخلية الشمسية المتعددة المنضدة بالتعاقب باستخدام الخواص الكهربائية للمواد أحادية الأبعاد بواسطة برنامج AFORS-HET. حيث يتم تحديد أدائها بعد مطابقة التيار للخلايا الفرعية العليا والسفلى. تبلغ كثافة تيار قصر الدائرة Jsc حوالي 23.9 ملّي أمبير. سم $^{2-}$ عندما يبلغ سمك الخلية العليا 384 نانومتر و سمك الخلية السفلية 1000 نانومتر. بلغت أقصى كفاءة تم الحصول عليها حوالي 23.1٪ مع فولطية الدائرة المفتوحة 1146.9 ~ Voc ملي فولت تقريبا. أما كفاءة الخلية المنضدة ميكانيكيا بلغت 23.76 ٪ و جهد الدائرة المفتوحة 1166.9 ~ V_{OC} ملّي فولت عندما تكون الخليتان العليا والسفلى متصلتين على التوالي بينما بلغت الكفاءة حوالي 26.62 ٪ عند جهد الدائرة المفتوحة 475.2 ~ V_{OC} ملّي فولت تقريبا للخليتين العليا والسفلى المتصلتين على التوازي عندما تكون كلتا الخليتين بنفس السمك (1000) نانو متر.

الكلمات الدالة: الخلايا الشمسية الرقيقة المتعددة، $CZTS\ (Se)_4$، برنامج المحاكاة AFORS-HET.

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1. Introduction:

Many specialists in recent years have been interested in tandem solar cells, because they have big efficiency and reduced production costs (very high efficiency can indirectly reduce the cost of solar). The high efficiency of these photovoltaic PV cells semiconductor materials that absorb diverse parts of the spectrum of solar order to attain the technological benefit required for these cells, it is necessary to develop inexpensive materials that can be stacked in a certain way [1,2]. The tandem cell contains several different models, including a homogeneous stacked cell with two terminal (2T) and a mechanically stacked cell with two or four terminal (2T, 4T) as shown in Fig 1. The 2T design involves connecting the cells (Top and Bottom sub cells) stacked in tandem electrically together through a tunnel junction or joint connection , resulting in a serial electrical connection, which means that only two external electrical contacts are required [3]. In mechanical design, cells are stacked (Top and Bottom) on separate substrates, working independently, where the two cells are connected separately to an outer circle in a seriese or parallel and must be the window layer semi-transparent to allow light to pass [4] .

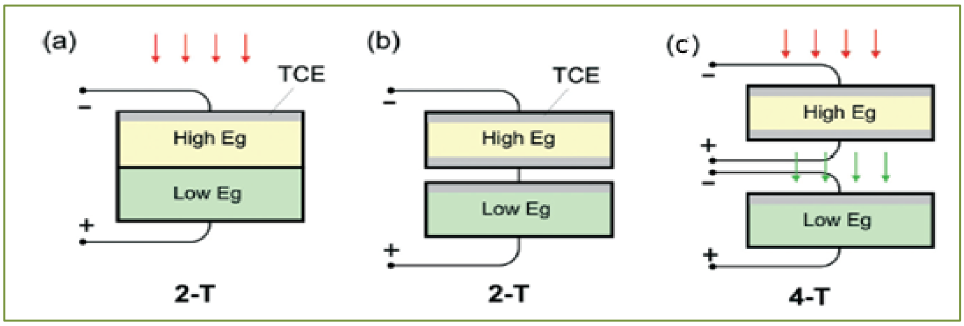

Fig. 1: a) Monolithically, **b)** and **c)** Mechanically (2T, 4T) stacked tandem solar cells [5].

2. Simulation Approach By AFORS-HET:

AFORS-HET (Automat FOR Simulation of Heterostructures) is a one dimensional numerical computer program for simulation multi-layer homo- or Heterojuction solar cells as well as some usual solar cell characterization methods. like current-voltage (I-V), internal quantum efficiency (IQE), capacitance voltage, spectral response, etc, The software solves Poisson's equation and the continuity equations, based on Maxwell Boltzmann statistics, in the whole structure and simulate electrical properties of solar cell, by using different numeral

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models. has been developed at HZB since the year 2000, and is free-on-demand. For more details, can be found in the developer's guide provided with the software [6].

3. Theoretical Analysis:

J-V properties in solar cells are the standard method for calculating cell output and evaluating its performance under illumination. Using the diode equation, which is given as follows: [7,8]

$$J(V) = J_{sc} - J_0\left(e^{\frac{qV}{nkT}} - 1\right) \quad (1)$$

J_{SC} is the short circuit current density due to the falling light, the current source in the circuit equivalent to a luminous solar cell, J_0 is the saturation current (or dark current) due to the recombination processes occurring inside the cell. *V* applied voltage, *q* charge, *k* Boltzmann's constant and *T* the temperature in Kelvins and n The ideal factor is between 1 and 2 according to the basic method of recombination. The most important factors to study photovoltaic cells are the voltage of the open circuit, V_{OC}, known as the voltage required to balance the intensity of the J_{SC} at the light and dark current intensity can be determined analytically by rearranging equation (1)

$$V_{OC} = \frac{nK_BT}{q}\left[ln\left(\frac{J_{SC}}{J_0} + 1\right) + 1\right] \quad (2)$$

For Tandem cell ,The currents of the Top cell (J_T) and the current density of the Bottom cell (J_B) are mathematically give to the following:

$$J_T = q\int_0^{\lambda T} I(\lambda)\left\{1\, e^{-\alpha_T(\lambda)t_T}\right\}\, d\lambda \quad (3)$$

$$J_B = q\int_0^{\lambda T} I(\lambda)e^{-\alpha_T(\lambda)t_T}\left[1 - e^{-\alpha_B(\lambda)t_B}\right\}\; d\lambda + q\int_{\lambda B}^{\lambda T} I(\lambda)\left\{1 - e^{-\alpha_B(\lambda)t_B}\right]\right\} d\lambda \quad (4)$$

Where I (λ) is the intensity, (t_T, t_B) the thickness of the Top and Bottom cells and ($\boldsymbol{\alpha}_T$, $\boldsymbol{\alpha}_B$) are the absorption coefficients of the Top and Bottom cells, The λ_T and λ_B values are given as λ_T=hc/Eg_T, λ_B=hc/Eg_B, where h Planck's constant, c are the velocity of light, Eg_T and Eg_B represent the band gap energies of the Top and Bottom subcell. If the two-link solar cells are connected to a series, the current of the photovoltaic current is limited to the smallest optical stream produced by the sub-cells. Therefore, the currents of the photoelectric current must

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have the same value and this is called the current matching condition [9]. The open circuit voltage of the Tandem cell (V_{OC}) is the sum of the open circuit voltage of the Top cell (V_{OCT})and the Bottom cell V_{OCB},expressed in [10]:

$$V_{OC} = V_{OCT} + V_{OCB} = \frac{K_B T}{q}\left[ln\left(\frac{J_{SCT}}{J_{0,T}} + 1\right) + \ln\left(\frac{J_{SCB}}{J_{0,B}} + 1\right)\right] \tag{5}$$

The saturation current density is given, taking into account the speed of surface recombination:

$$J_0 = qn_i^2 \frac{L_n}{\tau_n N_A}\left(\frac{\left(\frac{S_n\tau_n}{L_N}\right) cosh\left(\frac{x_j}{L_n}\right) + sinh\left(\frac{x_j}{L_n}\right)}{\left(\frac{S_n\tau_n}{L_N}\right) sinh\left(\frac{x_j}{L_n}\right) + cosh\left(\frac{x_j}{L_n}\right)}\right) + qn_i^2 \frac{L_p}{\tau_p N_D}\left(\frac{\left(\frac{S_P\tau_P}{L_P}\right) cosh\left(\frac{H}{L_P}\right) + sinh\left(\frac{H}{L_P}\right)}{\left(\frac{S_P\tau_P}{L_P}\right) sinh\left(\frac{H}{L_P}\right) + cosh\left(\frac{H}{L_P}\right)}\right) \tag{6}$$

Where L_n and L_p represent the length of the diffusion of the minority carriers, S_n S_p surface recombination, τ_{n}, τ_p life time of the minority carriers. N_A, N_D the concentration of acceptor and donor doping, xj and H are the neutral region thicknesses for p and n, respectively.

The Extemal Quantum efficiency (EQE) is closely related to the design of each cell as well as the band gap of the materials from which the solar cell is made, Jsc can be expressed using the flux intensity and the external quantum efficiency, which represents the probability of a photon with enough energy to induce electron-hole pairs that is collected at the contacts. This relationship is explained below [9]:

$$J_{SC} = q\int b_s(E) EQE(E)\, dE \tag{7}$$

Where bs (E) is the density of the flux of photons, per unit of time in the energy range from E to E + dE, and EQE (E) is the efficiency of the external quantum, wich measures the probability of producing a pair of electron-hole when the photons fall into the active region. According to the quantum efficiency definition, EQE can be calculated: the ratio of the number of carriers collected at the electrodes for one particular wave length with the total number of incident photon of that wavelengths. They represent all photons of light (total power), whether reflected, absorbed or transferred:

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$$\mathrm{EQE}(\lambda) = \frac{\left({J_{sc}}/{q}\right)}{{I}/{E_{ph}}} \tag{8}$$

Therefore the ratio gives the number of carriers at the electrodes per unit area, I - the intensity of light falling in Wm^{-2} and Eph is photon energy Equation (8) can be written as follows: [9]:

$$EQE = hc\frac{{J_{sc}}/{q}}{I.\lambda} \tag{9}$$

Where $E_{ph} = \frac{hc}{\lambda}$.

AFORS-HET used Shockley-Read-Hall model to describe the recombination currents in bulk levels and the absorption method is carried out according to Lambert Berr model [6,11]:

$$I = I_0\, e^{-\alpha x} \tag{10}$$

where I and I_0 are the current flux and initial flux at a penetration depth x. According of this theory, creates electron-hole in active layer of a solar cell, wich that should be separated before recombination. The absorption coefficent $\alpha(\lambda)$ is calculated from the spectral absorption of each semiconductor layer within the stack [12,13]:

$$\alpha(\lambda) = \frac{4\pi k(\lambda)}{\lambda} \tag{11}$$

Finally, the Fill factor (FF) and efficiency (η) of the solar cell is calculated by the following equations [7,8]:

$$FF = \frac{J_{mP} V_{mP}}{J_{sc} V_{oc}} \tag{12}$$

$$\eta = \frac{P_{max}}{P_{in}} = \mathrm{FF}\ \frac{\mathrm{J_{SC}} \times \mathrm{V_{OC}}}{Illumination\ power} \tag{13}$$

Where the η is described as the ratio between the maximum power generated by the cell and the power incident on it.

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4. Mechanically Stacked Tandem Solar Cells:

The first concept of Tandem solar cells was already mentioned in 1955 and the concept was first piloted in 1978 [14]. The mechanically stacked solar cells are designed easily by integrating the bandgap subunits into any contact arrangement, and neglecting the splicing factor. The manufacturing of the cells was mechanically limited and limited due to: a- the cost of merging cells on multiple substrates; b- The assembly of parts of the devices off-site, which increases the difficulty of processing and cost, and lead to loss of performance due to joint delivery. c-Excessive weight also limits the practicality of these devices for space applications because of fixturing hardware used to stack the sub cells together and use the multiple substrates [15]. The $CZTS(Se)_4$ Direct bandgap compound semiconductor materials provide significant advantages, due better optical property and high electron mobility .It's having high absorption co-efficient thus with a very thin thickness (1 to 2μm), these material group can absorb appreciable amount of solar light due to their high absorption co-efficient ($>10^{-4}cm^{-1}$). Theoretically, Band gap of CZTSSe alloy varies in between 1.5 and 1.0 eV depending upon S/Se ratios. Suitable and tunable optical properties make kesterite as ideal solar absorber layers [16,17].

The structure of the studied cell, shown in Fig 2, contains ZnO as a window layer n-type, is transparent and conductive and which is responsible transmit the light to the absorber layer and extract photogenerated electrons, CdS as n-type a wide band gap thin buffer layer, allows more light to reach the junction and increases the EQE at the short wavelength region [18,19], CZTS and CZTSe as a absorption layer of type p, where the conversion of photons into electron-hole pairs takes place, CZTS top cell and CZTSe the bottom cell.

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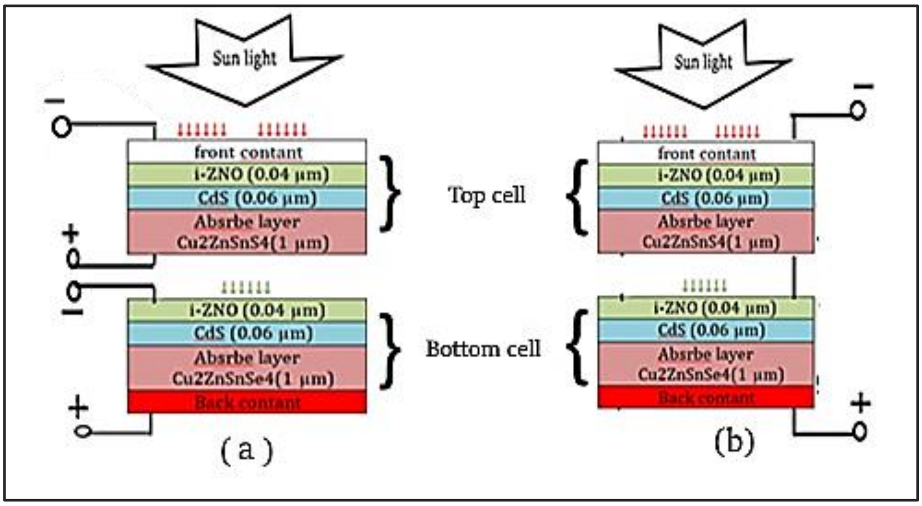

Fig. 2: The structure of Mechanical tandem cell.a) series and b) parallel configuration.

The properties of the materials are shown in Table 1 ,For CdS and ZnO, as specified in AFORS-HET program. As for the CZTS and CZTSe absorption classes taken from the indicated sources.

Table 1: Material parameters.

parameters	Symbol (unit)	i-ZnO	CdS	CZTS	CZTSe
Thickness	d (µm)	0.04	0.06	1	1
Dielectric permittivity	dk	9 [20,21]	10 [20,21]	7[21]	13.6 [22]
Electron Affinity	chi (eV)	4.4 [22,23]	4.2 [22]	4.3[24]	4.35[22]
Bandgap	E_g (eV)	3.37 [21]	2.42 [21]	1.5	1
Density of states in CB	Nc (cm^{-3})	2.2×10^{18}[22]	1.8×10^{19} [23]	2.2×10^{18} [23]	2.2×10^{18} [25]
Density of states in VB	Nv(cm^{-3})	1.8×10^{19}[25]	2.2×10^{18}[21]	1.8×10^{19} [23]	1.8×10^{19} [25]
Electron mobility	µn ($cm^2.Vs^{-1}$)	100[23]	100[23]	100 [21]	100[23]
Hole mobility	µp ($cm^2.Vs^{-1}$)	25 [23]	25 [23]	25 [21]	25 [23]
Acceptor concentration	N_a (cm^{-3})	0	0	8×10^{15}	2×10^{16}
Donor concentration	N_d (cm^{-3})	1×10^{19}	1×10^{17}	0	0
Thermal velocity of electron and hole	υ(cm/s)	1×10^7	1×10^7	1×10^7	1×10^7
Totale trap density	Nt ($cm-^3$)		1×10^{15}	1×10^{16}	1×10^{16}
Characterisitic Energy	Et (ev)		1.2	0.5	0.5
Type Charge			Single / A	Single / D	Single / D
n **k**		Fil AFORS-HET		2.85[14] 0.1 [14]	2.45[24] 0.6 [24]

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In this research, the mechanical tandem cell is used, because a device has two advantages; First, the J-V characteristics of the individual bottom- and top cell as well as the tandem cell can be measured. Second, since the subcells are electrically and optically separated, it is easy to connect the two cells electrically, seriese or in parallel using external wires.

5. Results and Discussion:

5.1 CZTS and CZTSe Single Solar Cells:

The CZTS and CZTSe solar cells are first simulated separately using the simulation parameters shown in Tables 1.we can see the simulation results of the J–V characteristics as shown in Fig. 3a. Thickness of the absorption layer (1µm) in the studied cells , the simulation results show that V_{OC} = 691.7 mv for CZTS is greater than V_{OC} = 475.2 mv for CZTSe, because the band gap of the CZTS layer is large compared to the CZTSe band gap. On the other hand, Jsc = 24.59 mA / cm^2 for CZTS is less than Jsc = 45.5 mA / cm^2 for CZTSe, where the difference in the value of Jsc is explained by the QE scheme for the CZTS layer which covers a large area (Due to the smaller gap in the CZTSe layer) as shown in Fig 3b. This means allowing low-energy photons to generate photo current, increasing the short-circuit current of the cell. Thus, efficiency CZTSe (Eff =16.91%) is higher than efficiency CZTS (Eff= 11.91%).

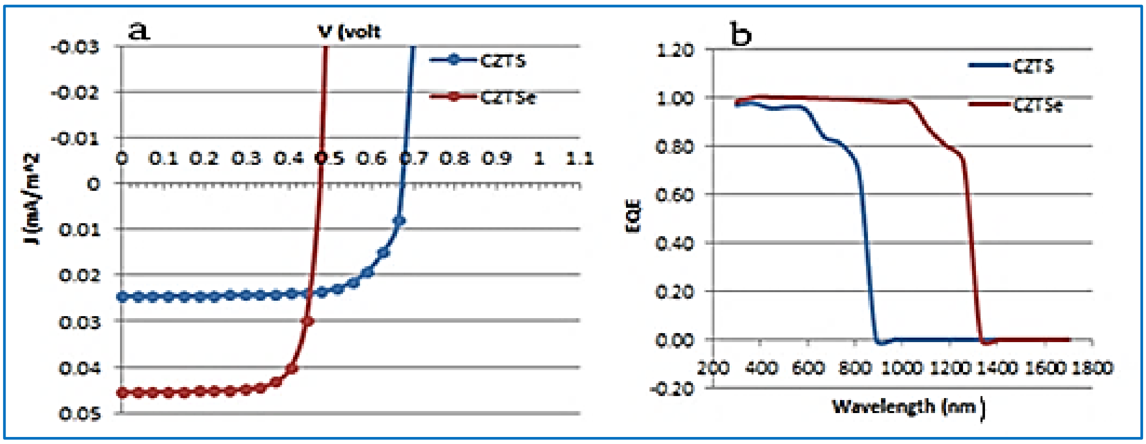

Fig. 3: The single CZTS and CZTSe solar cells:a) J–V characteristics b) EQE versus wavelength.

5-2 Parallel Connect:

When the two sub cells CZTS and CZTSe are electrically connected in parallel, the J-V characteristic are based on the following equations:

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$V_{Tandem}=V_{Top}=V_{Bottom}$ (14)

$J_{Tandem}=J_{Top}+J_{Bottom}$ (15)

The complete J-V property can be built into a parallel tandem as in the Fig .4a. refer to the equations (12,13), the fill factor (FF) and efficiency (η). For the parallel connection equat to FF = 79.92 % and η =26.62 % , respectively.

The voltage value of the tandem cell (Voc=475.2 mv) is equal to cell's voltage that gives less voltage, CZTSe the Bottom cell because it have the lowest energy gap. Therefore the Jsc of the tandem cell current will be equal 70.09 mA/cm^2.

5-3 Series Connect:

Now we can connected the sub cells CZTS and CZTSe are electrically in series. The total generated photocurrent will be constant throughout the device (conservation of charge) in steady state and the voltages generated by the sub cells will add up, where the J-V characteristic depend on the following equations:

$J_{Tandem}=J_{Top}=J_{Bottom}$ (16)

$V_{Tandem}=V_{Top}+V_{Bottom}$ (17)

In the tandem cell studied here: The Bottom cell generates a much larger optical current than the Top cell. This means that the amount of electrons that reach from the Bottom cell does not find enough holes to combine with it. The extra electrons to charge the electrodes (attached to the sub-cells) at the negative charge, reducing the voltage through the Bottom cell As a result, in steady-state the excess of electrons negatively charges the connected electrodes of the sub cells. This charging reduces the effective voltage across the bottom cell, and thus also the extracted current from the bottom cell. In addition to, the additional electrons provide a stronger voltage-drop across the top cell and therefore a higher current flows through the top cell, which achieves an important boundary condition - that the current in both sub-cells must remain equal, the total generated photocurrent (According to Kirchhoff's first law, the current flowing through the individual cells must be equal, and its value equals the value of the least current produced by the two connected cells in the series). Jsc = 24.5 mA/cm^2 is very close to the current of CZTS top cell wich have higer energy gap (High recombination) ,and

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constant throughout the device (conservation of charge in steady state). while, the voltages generated Voc =1166.9 mv , is limited by the sum of open circuit voltage of the individual sub cells, The J-V curve of the series tandem cell.as shown in Fig. 4b. ,we can calculated of the fill factor (FF) and efficiency η by equations(12,13): were FF=83.10% and η=23.76 %.

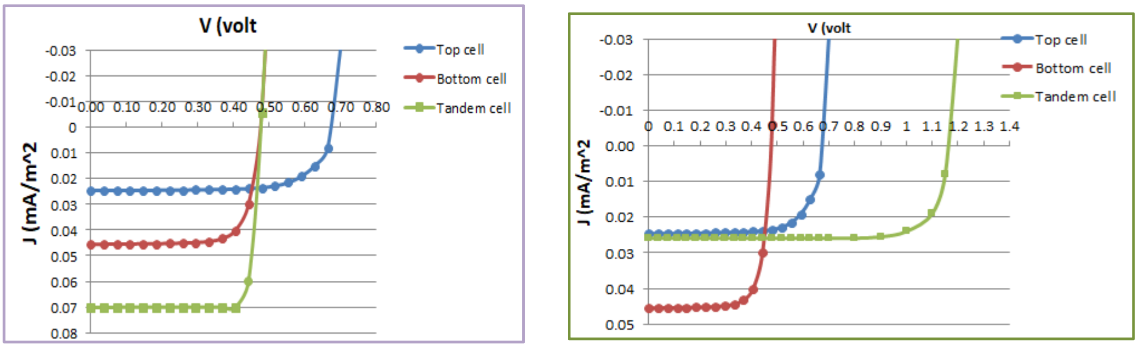

Fig. 4 a: The current-voltage characteristic of parallel tandem solar cell. **b:** The current-voltage characteristic of bottom and top cells of series tandem cell.

6. Monolithically Stacked Tandem Solar Cells:

The fundamental concept of a monolithical tandem solar cell, is stacking different light absorber layers, connected electrically and optically in series, each utilizing a part of the solar spectrum and allowing the passage through of the other part, which the highest-energy photons are captured by the material with the largest bandgap, this material will be transparent for low energy light which can be passed on to the second absorber layer with the lower bandgap [26,27]. Because photons must cross the cell to gain access the appropriate layer to be absorbed, transparent conductors must be used to collect the electrons that are created in each layer, but producing a tandem cell is not an easy task, Because of the challenges facing the manufacture of 2T active devices: which are the current match between the top and bottom cell, minimizing the loss of recombination between cell layer and greatly reducing physical thinness [28]. The monolithic tandem solar cells are designed using the structure shown in Fig.5. Top cell is made of larger band gap CZTS absorber layer (Eg = 1.5 eV) and the bottom cell is made of lower band gap CZTSe bottom cell (Eg = 1 eV). Assuming the solar cell combined CZTS (Se) is an ideal cell, where there is no electrical resistance and no optical loss. It is also assumed that optical loss and interference in each interface is negligible. The concept of a monolithic tandem cell depends on a set of solar cells with the same optical objective. Cells are sequentially connected and arranged according to the

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semiconductor band gap, where each cell absorbs the solar spectrum that complies with band gap energy [29].

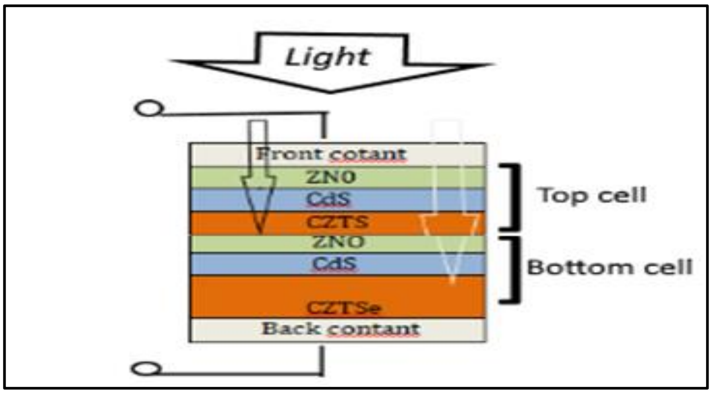

Fig. 5: The structure of monolithica tandem cell, with CZTS top cell and CZTSe bottom cell.

The thin-film $CZTS(Se)_4$ solar cells can be used for low-cost and large-scale photovoltaic applications because they have a scalable band gap in a range of 1.0 to 1.5 ev, allowing for effective absorption of fallen photons with a small thick of microns [30,31]. The efficiency of tandem solar cells is limited by the solar cell that produces the low current. A standard of equal current must be achieved, between cells that build side by side, all cells must have the same photocurrent (current matching), equivalent optical absorption may not mean an equal current produced by the subunits due to loss of recombination for electron hole pairs. Current matching is one of the most important factors that determine the important characteristics of a cell, such as efficiency. In order to obtain the best results, both cells are simulated independently, with the addition of an equivalent imaginary absorption layer, where layer CZTSe is taken as a layer (P+) with the same electron affinity and the thickness of the bottom cell to ensure optical and electrical contact. It also has a high density of defects, and the layer (CZTS) is taken as a layer (n+) with sufficient electron affinity to avoid any band discontinuity for electrically inactiveness of this layer.

The total density of the current (J_{SC}) of the tandem cell, is determined by the minimum current produced by the component solar cells (the sub-cell) and the total open circuit voltage (V_{OC}) equals to sum the open circuit voltage of the single solar cells.

The variation in the short circuit current densities for the ($J_{sc\ TOP}$) and (Jsc bottom) subcells, indicates that the current matching can be achieved by the intersection point of the top and bottom short circuit currents of the cell as shown in Fig. 6.

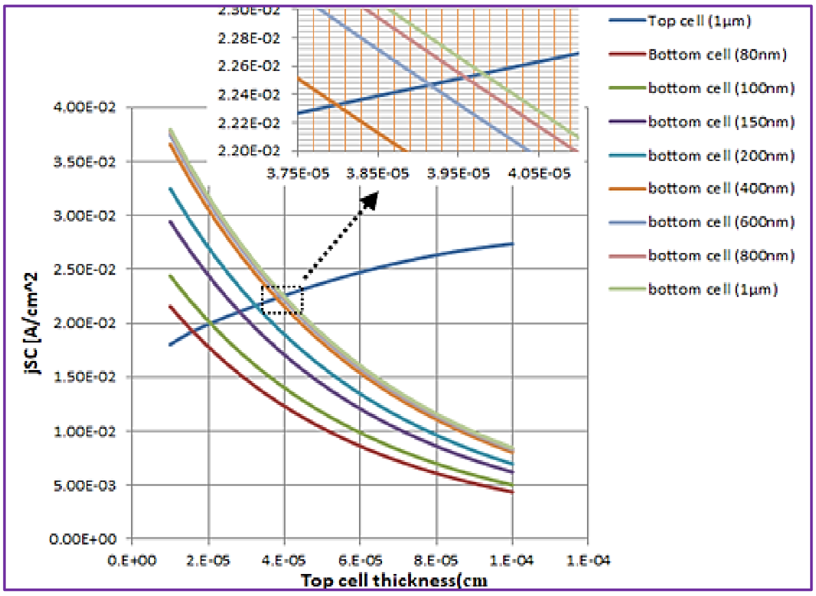

Fig. 6: Matching current density of CZTS top cell and CZTSe bottom cell.

The values of the top cell thickness and the thickness of the bottom cell at the corresponding short circuit current matching density values of the top cell and bottom cell shows in Fig.7a . We observe from Fig .7b,c. A growing density of (Jsc) and (V_{OC}) with increase bottom thickness, because of the good absorption of solar energy, which leads to the increase of the generated charge carriers.

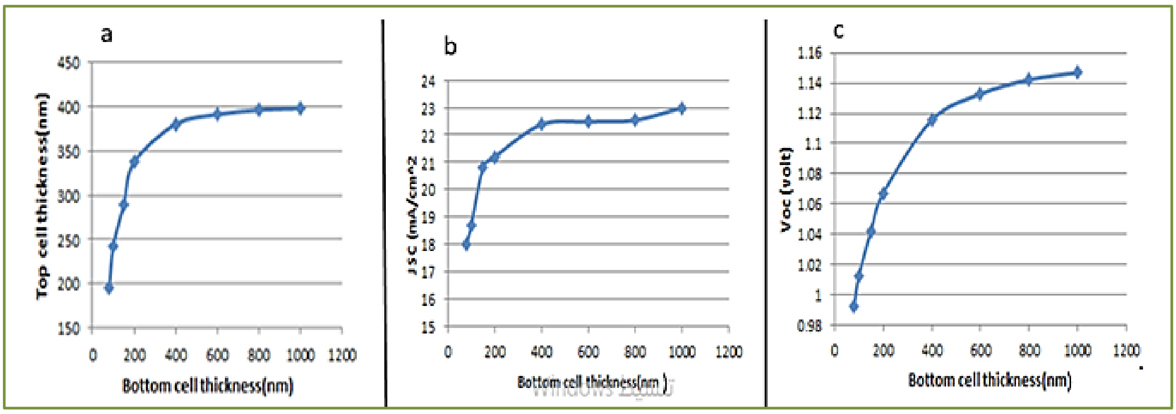

Fig. 7: a) Thickness of top CZTS and bottom CZTSe cell at current matching condition. **b)** current density (Jsc) and **c)** open circuit voltage (V_{OC}) of tandem cell , with CZTSe bottom cell at different thicknesses.

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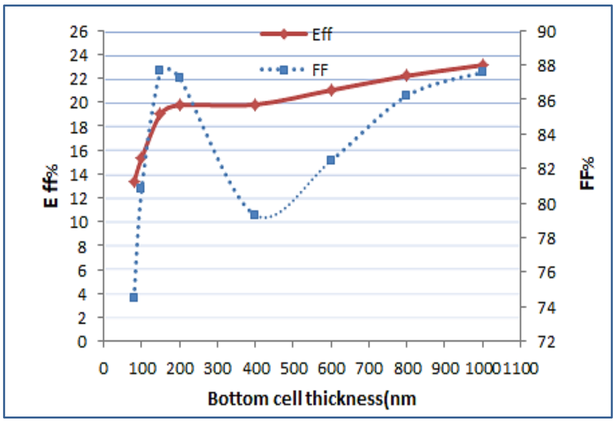
As shown in Fig. 8. We observ that tandem cell efficiency increases with bottom cell thickness, also can be observed the fill factor decreases and increases as a result of shift from the absorption of photons with short wavelengths to the absorption of photons with long wavelengths [32]



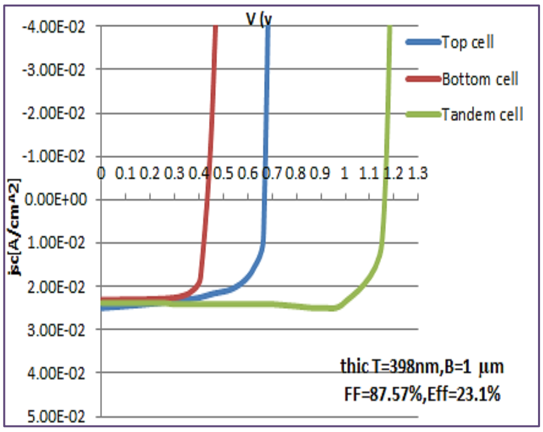


Fig. 8 : Tandem cell efficiency and the filler factor. **Fig. 9 :** Current-voltage characteristics.

The current match point of Fig. 6. can be selected to study the curve of the current-voltage (J -V), as shown in Fig. 9. We can find efficiency and fill factor according to equations (12,13), where FF=87.57 % and η=23.1 % , the value of efficiency and fill factor is close to the value of efficiency and the fill factor when connecting cells mechanically sequentially due the cells are the same without changes in the parameters, they behave the same behavior. The value of Jsc=23 mA.cm^{-2} and Voc =1146.9 mv. The Top and Bottom cell current is equal (current matching) ,when the thickness of the Top cell equals 398 nm and the thickness of the Bottom cell equals 1000 nm. On the other hand, the efficiency of the monolithically stacked tandem is less than the efficiency of the mechanically tandem but it sensitive to wider spectral range because the good absorption of solar energy in the short wavelength of the upper cell and in the long wavelength of the bottom cell led to the generation of an photo current over a broad spectrum. The Quantitative Efficiency Scheme (QE) indicates that the top cell absorbs a wave that reaches a length of more than 800nm, becomes a long wavelength invisible and is absorbed heavily in the bottom cell This indicates a large absorption process in the bottom cell thus improving the total quantm efficiency (QE) of the tandem cell, The external quantum efficiency (EQE) spectra gives an indication about the performance of a solar cell at a certain wavelength as shown in QE in Fig. 10. The main results obtained from simulating the cells studied for this study were included in Table 2.

Table 2: The main results obtained from simulating CZTS and CZTSe bsorber based cells and performance parameters for single and tandem cell.

Solar cell configuration with absorber thickness	Voc(mv)	Jsc (mA/cm^2)	FF %	E ff %
CZTS single cell (1µm)	691.7	24.59	70.02	11.91
CZTSe single cell (1µm)	475.2	45.5	75.53	16.33
(Mechanical) Series tandem cell(1µm)	1166.9	24.5	83.10	23.76
(Mechanical)Parallel tandem cell (1µm)	475.2	70.09	79.92	26.62
CZTS Top cell in tandem cell (monolithical) structure(384.5nm)	693	24.9	64.34	11.11
CZTSe Bottom cell in tandem cell(monolithical) structure(1µm)	453.9	22.55	73.97	7.571
(monolithical) tandem cell	1146.9	23	87.57	23.1

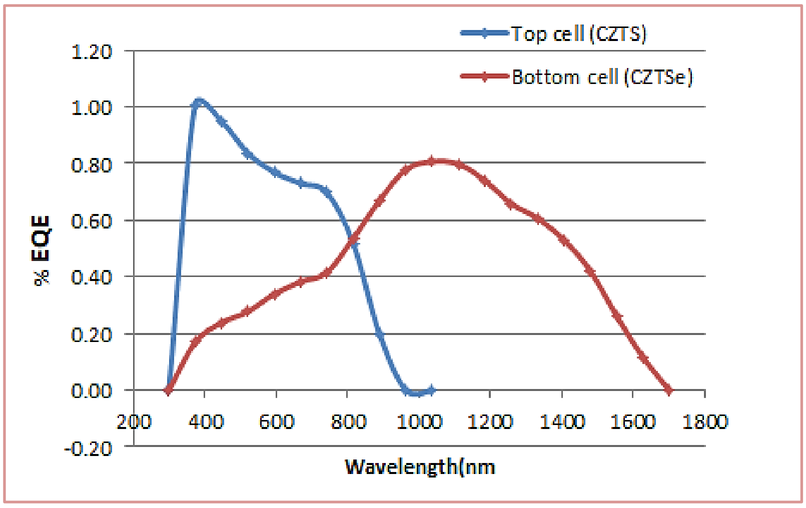


Fig. 10: quantum efficiency for CZTS top cell CZTSe bottom cell.

7. Conclusion:

The different designs of the tandem cell were simulated by using the AFORS-HET software. The suggested tandem cell structures (mechanically and monolithically stacked) showed the ability to achieve improved efficiency of the solar cells based on the absorption (CZTS(Se)$_4$) layer. Efficiency ~ 23.1% from monolithically stacked tandem cell and 23.76 %, 26.62% from Series and Parallel mechanically tandem stacked, respectively. We think the thiner thickness cells and the light weight for the monolithically stacked tandem cell, It makes a favorite for space applications, while the mechanical stack tandem cell is better for high concentration applications here on Earth. Because the four-terminal (4T) stacked cell can be configured to match the voltage or current (equal voltage or equal current) either by carriers or parallel by wire (wire can be connected). In addition, the voltage matching in the Parallel mechanically tandem cell is easier than matching current in the monolithical tandem cell .

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