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Improving the Efficiency of CdTe/CdS Thin Film Solar Cell Using Tunnel Junction

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Abstract: There is a long time that CdTe/CdS thin film solar cells are globally attractive due to high efficiency, low production cost, not being sensitive to solar radiation angle. In a CdTe/CdS solar cell, electrical loads produced at distances >1 μm from joint part of CdTe and CdS have a little role in electrical conductivity mechanism due to the extent of link discharge area. Thus, it is important to decrease thickness of CdTe in order to reduce raw material use and also remix losses. On the other hand, decrease in thickness of CdTe layer would possibly increase surface remix of carriers at rear link causing decline in cell parameters. Therefore, exact considerations must perform to determine optimum thickness of CdTe absorptive layer. In this study, putting a tunnel junction within substrate structure of CdTe/Ge solar cell causes quantum tunneling between layers leading to increase in efficiency of thin layer solar cell. Simulation condition is under AM1.5 optical radiation. The results of our research with proposed structure caused 2.5, 4, 7.65 and 3.35% of increase in efficiency, Voc, Jsc and fill factor, respectively.

Key words: Solar cell, thin layer, open circuit voltage, CdTe, CdS, tunnel junction

INTRODUCTION

Two main factors of each solar cell are increase of efficiency and decrease of production cost. In this regard, several materials and technologies are studied. The CdTe thin film solar cell is one of the photovoltaic devices appropriate in terms of efficiency and production cost. The CdTe material is a compound semi-conductor of III-V group; its important feature is direct band gap energy having a value close to optimum one due to solar spectrum to transform maximum photovoltaic energy. Direct band gap 1.5 ev and high absorption coefficient of CdTe (5×10^5 cm) means that a high quantum efficiency of cell is expected in a wide range of wavelengths from ultra-violent to CdTe band gap (825 nm). Photons with low wavelength and energy more than that of CdTe band gap would absorb to this material, thus, CdTe is a proper material for thin film solar cells. According to high absorption coefficient of CdTe for photons with an energy more than its Eg, just a little thickness (about 2-8 μm) of CdTe layer is enough to absorb 99% of AM1.5 solar spectrum photons; this amount is almost 100 times less than thickness of crystalline silicon solar cells. In the recent years, many studies have been conducted in order to decrease thickness of CdTe layer obtaining low cost cells. In this regard, it is important to absorb part of light photons outside space load area. Applying several materials from III-V group with different energy bands causes absorption of different spectrums and wavelengths in this device; this leads to 41.3% of increase in efficiency. Further, solar cells of III-V group can be optimized using concentrators. In this situation, density of produced current is reported at interval of 6.27-15.04 Acm^{-2} (X470-1150). As a result, one of the methods to improve light absorption is to increase electric field in bottom layer. Thus, goal of this research is to study maximum amount of tunneling process and values of restrictive changes as a function of density. Success in tunnel junction simulation creates solar cell with higher efficiency. In this study, features of CdTe solar cell are calculated using Sivalco software. Therefore, we study effects caused by change in thickness of CdTe layer on cell parameters and to present a proper method to overcome voltage decline in Cdte/CdS solar cell open circuit using tunnel junction and finally to optimize CdTe/CdS solar cell parameters.

MATERIALS AND METHODS

Numerical solution: A solar cell is a p-n bond in its simplest mood that its feature of voltage-current is transferred to 4th area. Short-circuit current cell is equal to optical carriers that are transferred to output terminals through separation field. But, this amount is always less than optical carriers due to remix available in device.

Disregarding bond structure, main equations of carriers transfer into semi-conductors are always poison equation and also equations of cell flow continuity. In this simulation, equations are solved independent of time thus, we have:

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$$\nabla(\varepsilon\nabla\psi) = -q(p - n + N_D - N_A) \quad (1)$$

$$\nabla Jn = -q(G - R) \quad (2)$$

$$\nabla Jp = -q(G - R) \quad (3)$$

Where:

- ε = The throughput
- ψ = The electrical potential
- q = The electrical load
- N_A = The density of recipient atoms
- G = The carriers production rate
- R = The remix rate of carriers
- n, p = The density of electrons
- j_n, j_p = The current density of electrons and of cells, respectively

In a CdTe/CdS hyperlink solar cell, CdS layer is not an active layer in terms of photoelectrical in fact, it is a clear layer to transfer maximum light into CdTe absorptive layer (Fauzi *et al*., 2010). Thus, main thickness of discharge area in CdTe layer is considered in the study of hyperlink energy band diagram. Photoelectric quantum efficiency of this cell is composed of two drifty and diffusion parts causing by production of electron-cell pairs in load area and neutral area of CdTe layer, respectively. Solving continuity equation at space load and neutral areas and considering drift and diffusion components, we can simplify quantum efficiency of a solar cell as below (Kosyachenko *et al*., 2009):

$$\eta = 1 - \frac{\exp(-\alpha W)}{1 + \alpha L_n} \quad (4)$$

Where:

- α = The light absorption coefficient in CdTe
- W = The width of space load area
- L_n = The length of electron penetration

Considering surface remix effect in rear link and remix effect in joint area of CdTe and Cds, drift and diffusion of components of quantum efficiency are as below, respectively:

$$\eta_{diff} = \frac{\alpha L_n}{\alpha^2 L_n^2 - 1} \times \exp(-\alpha W) \times \left\{ \alpha L_n - \frac{\frac{S_b L_n}{D_n}\left[\cosh\left(\frac{d-W}{L_n}\right) - \exp(-\alpha(d-W))\right]}{\frac{S_b L_n}{D_n}\sinh\left(\frac{d-W}{L_n}\right) + \cosh\left(\frac{d-W}{L_n}\right)} + \frac{\sinh\left(\frac{d-W}{L_n}\right) + \alpha L_n \exp(-\alpha(d-W))}{\frac{S_b L_n}{D_n}\sinh\left(\frac{d-W}{L_n}\right) + \cosh\left(\frac{d-W}{L_n}\right)} \right\} \quad (5)$$

$$\eta_{drift} = \frac{1 + \frac{S}{D_p}\left(\alpha + \frac{2}{W}\frac{\psi_0 - qV}{kT}\right)^{-1}}{1 + \frac{S}{D_p}\left(\frac{2}{W}\frac{\psi_0 - qV}{kT}\right)^{-1}} - \exp(-\alpha W) \quad (6)$$

Where:

- k = The Boltzmann constant
- ψ = The height of potential barrier
- V = The applied voltage
- S_b = The surface remix speed at rear joint
- S = The remix speed at CdTe and CdS joint area
- 'd' = The thickness of CdTe layer

Total quantum efficiency at CdTe layer is equal to sum of two drifty and diffusion components. A solar cell needs free load carriers to operate. First, electrons are induced by light radiation and correspond cells are made at capacity band that is called separation of excitons (cell- electron joints). However, induced electrons return to their basic mood through several methods. When an electron performs a transition from conduction band to capacity band, then a pair of cell-electron is removed. Remix might accompany emission of a photon; this type of combination is called non-radiative. Of course non-radiative remixes are also, possible (e.g., auger remix) (Eq. 8). In condition of thermal balance, remix of semi-conductor type 'n' is equal to production setting. When extra carriers are produced by light radiation, then, remix setting would increase since remix is appropriate with number of electrons in conduction band and also number of cells in capacity band. Pure remix setting (Eq. 9) condition of low injection) obtains from the relation below (Soga, 2006; Wurfel, 2005):

$$U = \beta np - \beta n_{n0}p_{n0} = \beta(n_{n0} + \Delta n)(p_{n0} + \Delta p) - \beta n_{n0}p_{p0} \cong \beta n_{n0}\Delta p = \frac{\Delta p}{1/\beta n_{n0}} = \frac{\Delta p}{\tau_p} \quad (7)$$

According to Eq. 7, pure remix setting is appropriate with density of additional minority carrier. Lifecycle of minority carriers similarly defined in semiconductor type 'p' (electron). Lifecycle of a minority carrier and pure remix setting for a semiconductor type 'n' is as below (Soga, 2006):

$$\tau_p = \frac{1}{v_{th}\sigma_p N_t},\ U = \frac{\Delta P}{\tau_P} \quad (8)$$

When a semi conductor type 'n' is uniformly exposed to light to produce extra carriers, then, cell density gradient creates a release flow equal to surface remix flow (Eq. 9):

$$qD_p \frac{dq_n}{dx}\Big|_{x=0} = qU_s = qS(P_s - P_{n0}) \tag{9}$$

We can use Eq. 10 to calculate short-circuit cell flow based on radiation of AM1.5 spectrum where $\eta\lambda_i$ is quantum efficiency at λ_i wavelength, $\Delta\lambda_i$ distance between adjacent wavelengths, h_{vi} energy of i_{th} photon, T_λ front joint optical transmission coefficient and $\varphi(\lambda)$ light power in terms of $mWcm^{-2}\ \mu m^{-1}$:

$$J_{sc} = q\sum_i \eta(\lambda_i)\frac{T(\lambda_i)\phi_i(\lambda_i)}{h\nu_i}\Delta\lambda_i \tag{10}$$

For voltage of open circuit, we have (Eq. 8 and 9):

$$V_{oc} = \frac{nKT}{q}\ln\left(\frac{I_{sc}}{I_0}+1\right) \tag{11}$$

When solar cell operates under the condition with maximum output power, then, optimum voltage and current are V_m and I_m, respectively. Also, I_{sc} and V_{oc} determine efficiency of a solar cell. Final efficiency of converting solar energy into electricity is defined as ratio of maximum output electrical power to incident light full power:

$$\eta = \frac{V_m I_m}{P_{in}} = \frac{j_{sc}\times V_{oc}\times FF}{P_{in}} \tag{12}$$

Where:

- J_{sc} = The photo current density measured at short-circuit
- V_{oc} = The open circuit voltage
- FF = The cell fill factor
- $P_{in\ severity}$ = The incident light

FF has values between 0 and 1 and is formulated as below:

$$FF = \frac{P_{max}}{J_{sc}V_{oc}} = \frac{V_m I_m}{J_{sc}V_{oc}} \tag{13}$$

Tunneling takes place when the majority of carriers from substance type n and type p have the degenerate bilinear contamination (high contamination with impurities) and so, the electrons are allowed to pass within the potential dam (to tunnel) and in normal condition such intrusion is not possible. Tunneling is based on quantum transfer probability per time unit and the exponential ratio of momentum average (k(0)) in the tunneling path in discharge area that will be addressed in the following equation. This momentum corresponds to the radiation carriers with intersected momentum with zero and energy of fermi level (Eq. 12):

$$T_t = \exp\left[-2\int_{-x1}^{x2}\left|\bar{k}(x)\right|dx\right] \tag{14}$$

Differentiating between tunnel junction and tunnel diode is that the former is on single-crystal network connecting to solar cells while the latter acts as a separate components and detached from the circuit. Also, the transit coefficient for the particle that tunnels through a potential dam can be obtained from following Eq. 15:

$$T = \frac{e^{-2\int_{x1}^{x2}dx\sqrt{\frac{2m}{\hbar^2}(V(x)-E)}}}{\left(1+\frac{1}{4}e^{-2\int_{x1}^{x2}dx\sqrt{\frac{2m}{\hbar^2}(V(x)-E)}}\right)^2} \tag{15}$$

Where:

- x1, x2= The two classical turning points for potential limit
- m = The mass and
- h = The Planck constant
- x = The displacement along particle motion
- V = The particle potential energy
- E = The particle energy that depends to particle movement along x direction
- M = The quantity explained with V(x)-E and has no accepted term in the physics

By examining above equations one can understand that the superficial recombination in the back connection significantly decreases the density of existing electrons in the CdTe layer and increases electrical field and it leads to absorption and consequently increase of open-circuit voltage and so, it affects the cell short-circuit current. As the CdTe layers thickness decreases, this effect is intensified. Thus, a great part of carriers are lost and the cell short-circuit current is sustained a great drop that by using the tunnel junction one can compensate, it to some extent and give rise to enhancement of efficiency even with respect to the cell primary state.

Structure and simulation of reference CdTe/CdS solar cell: Figure 1 shows the proposed structure for simulation of CdTe solar cell. This solar cell is subjected to radiation

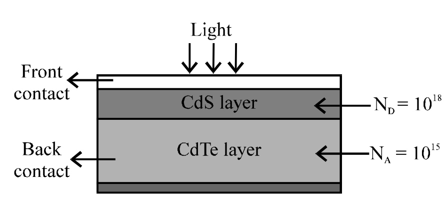

Fig. 1: The proposed structure of CdTe/CdS solar cell

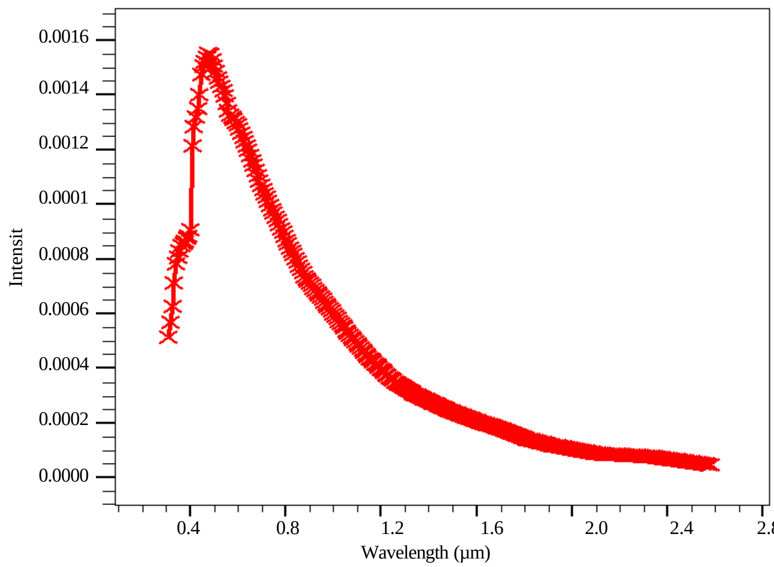

Fig. 2: The AM1.5 spectrum

Table 1: Physical parameters adopted in the simulation (Pulfrey *et al*., 2010; Valdivira *et al*., 2008)

Layer properties			
Parameters	ITO	CdS	CdTe
m_n^*/m_0	0.275	0.171	0.25
M_p^*/m_0	0.275	0.7	0.7
Dielectric constant (ε/ε0)	9	10	9.4
Electron affinity (eV)	4.5	4.3	4.28
Electron mobility µe (cm²/Vs)	100	100	320
Hole Mmobility µh (cm²/Vs)	25	25	40
Electron/Hole density n, p (cm^{-3})	n:10^{18}	n:10^{17}	p:10^{17}
Band gap energy Eg (eV)	3.6	2.42	1.5
Conduction band effective density of states NC (cm^{-3})	2.2×10^{18}	2.2×10^{18}	8×10^{17}
Valence band effective density of states NV (cm^{-3})	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
Capture cross section σe, σh (cm^2)	e:10^{-15} h:10^{-12}	e:10^{-17} h:10^{-12}	e:10^{-11}
Acceptor/Donor defect concentration NDG, NAG (cm^{-3})	A:10^{15}	A:10^{17}	D:10^{17}
Defect peak energy EA, ED (eV)	Midgap	Midgap	Midgap
WG (eV)	0.1	0.1	0.1

of composite spectrum of Am1.5 (Fig. 2). Thereby, the received light power is considered as 1000 W m^{-2}. The constituents of the junction are placed between a transparent layer of conductive oxide in forward connection and a metal layer in back connection. Considering the gap energy of CdTe big band, one of the existing challenges regarding the CdTe solar cell is selecting an appropriate metal for constituting one-ohm connection with low resistance. The objective of this simulation is examining the impact of variation of CdTe layer thickness on main parameters and its optimization using the tunnel junction layer between CdTe and Ge layer for increasing the efficiency.

Considering the CdS and CdTe and ITO polycrystal properties, the physical parameters of these three substances depends to growth conditions and adopted

Table 2: Comparing the reference value from a CdTe/CdS solar cell and the simulated value

Parameters	Reference cell	Simulated cell
V_{oc} (mV)	870.000	875.000
J_{sc} (mA/cm²)	22.680	22.400
Fill factor	0.750	0.807
Efficiency (%)	15.000	15.800

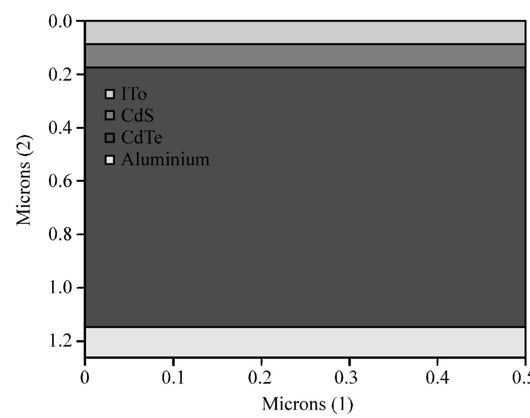

Fig. 3: Standard structure of CdTe/CdS solar cell that CdTe thickness is 1 µn

technics of variables, the amount of gap band adopted for Ge equals with 0.67 eV and the amount of its guidance band difference with CdTe is -0.88e17 (Valdivia *et al*., 2008). Table 1 represents the best physical parameters of adopted standard in stimulation within this study. And also in Table 2, we compare the value of reference from a CdTe/CdS solar cell and our simulated value (Kanevce and Gessert, 2011).

Within the first part of simulation, a standard cell of thin later is simulated according to (Fig. 3) that the CdS

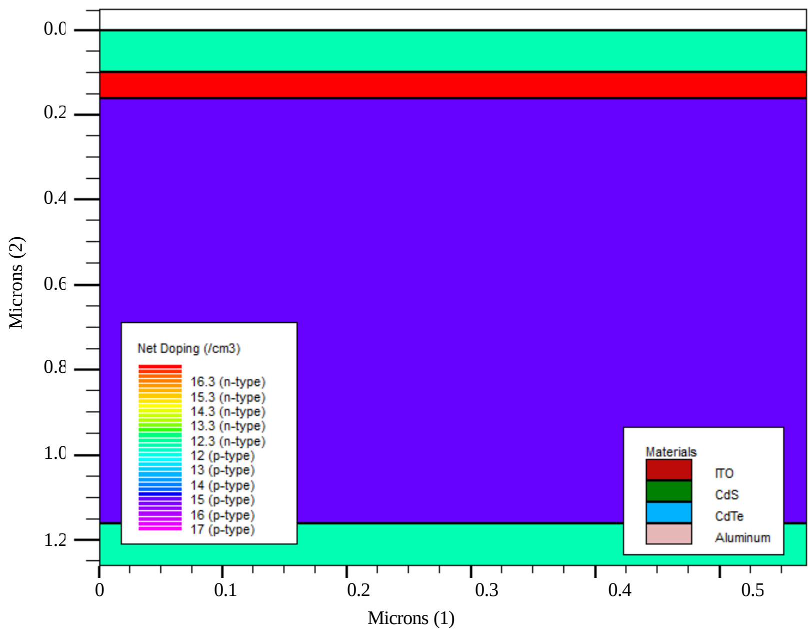

Fig. 4: The rate of giver and receivers atoms in CdTe/CdS solar cell

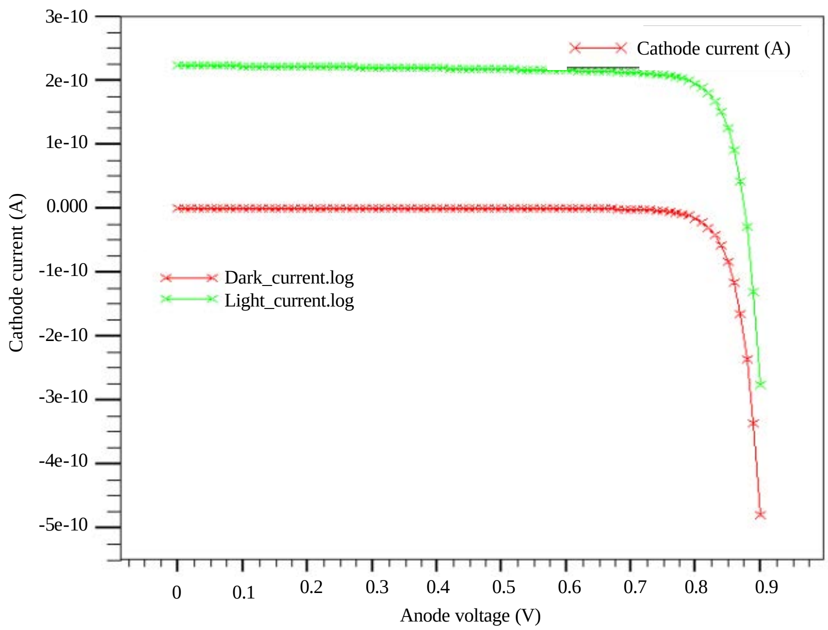

Fig. 5: The diagram of current at darkness and current in the light mode for simulated solar cell

layer thickness is 60 nm, the CdTe layer is 1 μn and the transparent layer on the ITO cell is 100 nm and one use aluminum as the end contact.

The density of giver atoms in CdS layer is 10^{17} cm^{-3}, the density of receiver atoms in the CdTe layer is 10^{15} cm^{-3} where the developed doping rate is shown in Fig. 4. Also, the lifetime of carriers and the rate of recombination in the back connection have been considered s10^{-8} and s10^{8} m, respectively (Emcore photovoltaics in 2006). Figure 5 deals with the I-V characteristic of CdTe/CdS solar cell in the darkness and under radiation of AM1.5 spectrum, considering the diagram of J_{sc}, V_{oc} and P_{max} values are 22.4 mA cm^{-2}, 0.875 v and 15.8 mW cm^{-2}, respectively.

RESULTS AND DISCUSSION

As it has been mentioned, >90% of photons are absorbed with an energy higher than CdTe band gap energy within the CdTe solar cell considering the high absorption coefficient of CdTe with a small thickness of this substance (near 1 μn). Thus, decrease of thickness of this layer is of high importance (Kosyachenko *et al*., 2009; Soga, 2006; Wurfel, 2005). The rate of generating carriers where the junction of CdTe and CdS takes place is of order of 10^{22} cm^{-3} sec. However, as the distance from the junction location increase, this amount decreases with a coefficient from 10^{-1} order. Thus, the effective thickness of CdTe layer is almost 1 μn and developed carriers contribute less in greater distances in generating current. Similarly, in greater distances due to lack of electrical field, the developed carriers in the semi conductor stack are recombined and are not able to produce the electrical current (Kosyachenko *et al*., 2009; Soga, 2006; Wurfel, 2005; Kanevce and Gessert, 2011). Thus, by adopting the tunnel junction, a strong electrical field emerges and it leads to increase of output current and voltage. The aim of this article is optimizing the cell and finding a solution for improving the efficiency and decrease of cell thickness that results in decrease of manufacturing cost and enhancing the efficiency within the CdTe/Ge connection that is a tunnel junction that leads to fostering the electrical field and increasing the outlet current. The difference between tunnel junction and the tunnel diode is that the former is on the single-crystal network that connects two solar cells while, the latter acts as a separated component and detached from a circuit.

The impact of quantum tunnel on performance of CdTe/CdS thin layer solar cell: Many studies have been conducted in order to improve the light absorption in the absorber layer by increasing the light path length. One the adopted method is tunnel junction that results in developing strong electrical field in that area. Though, the metal at the end of the cell is used both as reflector and electrode, however, this method of using metal has some downsides such as inherent absorption at its connection interface. As the electrical field increases, the tunnel junction leads to decrease of regional recombination (Pulfrey *et al*., 2010; Valdivia *et al*., 2008; Siedel *et al*., 2007).

The structure of CdTe/CdS solar cell is depicted in Fig. 6 by using tunnel junction layer that is designed by tunnel junction through CdTe and germanium. The Ge is a highly useful substance for adopting in tunneling in CdTe structure that as a result of 0.67 eV gap band and developing a junction for indirect tunneling is useful (Pulfrey *et al*., 2010; Seidel *et al*., 2008; Song *et al*., 2015).

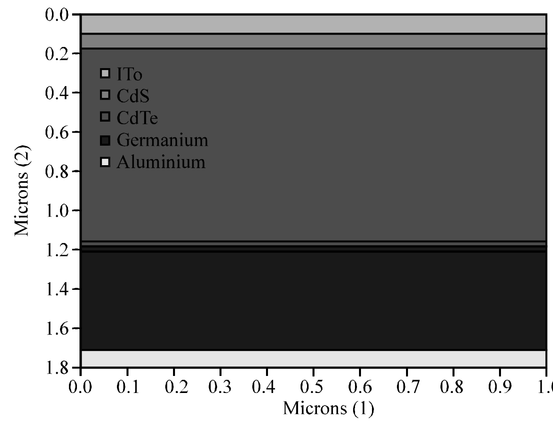

Fig. 6: Structure of CdTe/Cds solar cell using tunnel junction

The relationship between the electric field and the potential is as "V_A-V_B = ED". Therefore, there is no field in the points in which the potential is constant. In the other words, the field is zero in most of the areas. In the areas of link connections, because of the existence of a large slope in the potential, there is a strong field which its existence in the connection of the tunnel junction causes the generated minority carrier to be drawn by this strong field from the n-p link to other direction of the n-p link on one side and in a distance less than a penetration length from the transient area and as a result produces current. Also, the existence of a large field causes reflecting the minority carriers towards the n-p link and as a result, it causes more participation of minority carriers in order to produce a greater luminous current which also results in increasing the current in the link area. The generated electric field in the link causes increase in the current in the link. Figure 7 has proceeded to displaying, it (Pulfrey *et al*., 2010). Figure 8 represents the validity of the great electric field generated in a tunnel junction connection.

According to the statements mentioned above and the discussions explained in the field of the generated electric field and it was proceeded to in Fig. 9, among the influences of the generated electric field is band-to-band tunneling which it has resulted in increasing the current in the link area which in Fig. 9, it is proceeded to display the increase in current in the link area. Figure 9 is the validity for the performance of tunneling link in which the band-to-band tunneling is displayed.

Figure 10, the current is represented in both states of CdTe/CdS solar cell lighting without tunnel

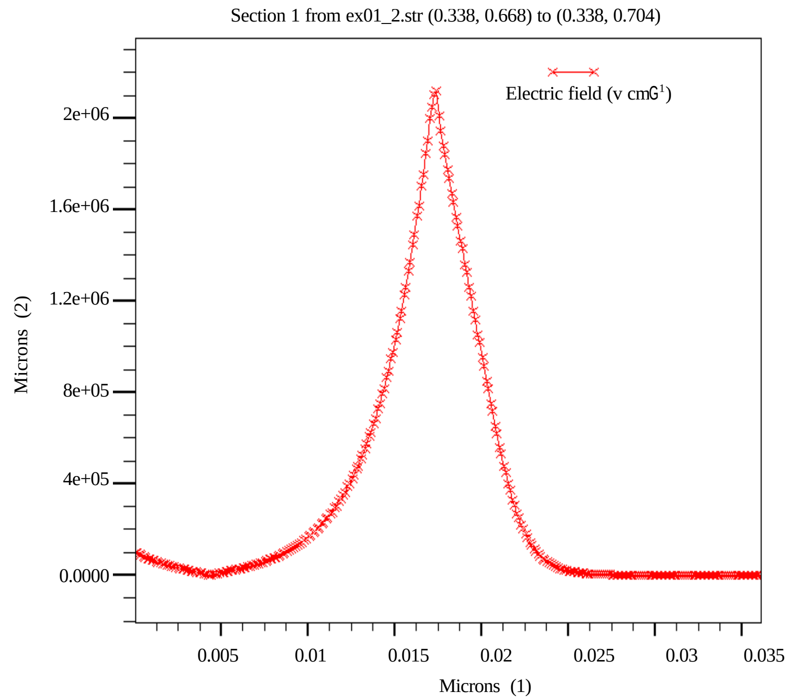

Fig. 7: Representation of great electric field generated in tunnel junction connection

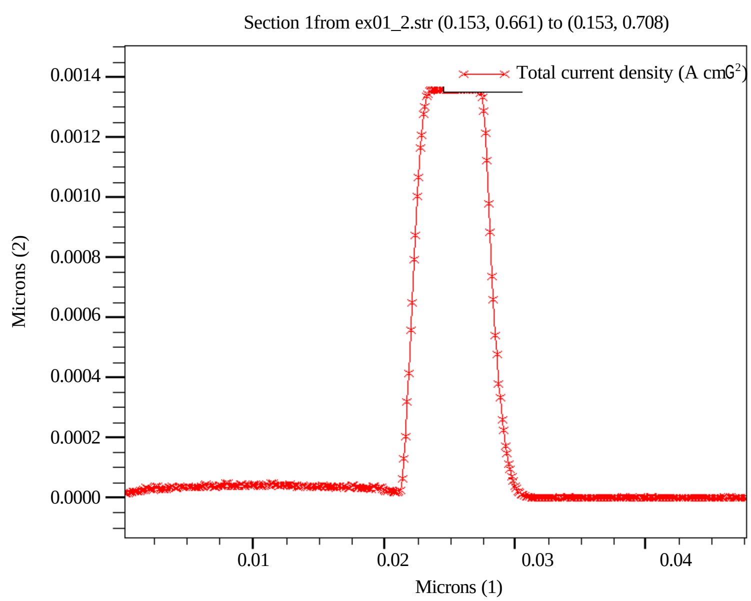

Fig. 8: Increase in the current in the tunnel junction due to the influence of the electric field of the link

Table 3: Values extracted from typical CdTe/CdS solar cell and CdTe/CdS solar cell simulations using tunnel junction

Parameters	CdTe cell	CdTe cell with tuunel junction
V_{oc} (mV)	875.000	910.000
J_{sc} (mA/cm^2)	22.400	24.100
Fill factor	0.807	0.834
Efficiency (%)	15.800	18.300
Pm (mW/cm^2)	15.800	18.300

junction and with tunnel junction which increase in overall efficiency, V_{oc} and J_{sc} may be observed visually.

The values extracted from the typical CdTe/CdS solar cell and CdTe/CdS solar cell simulations are obtained using the tunnel junction obtained in Table 3.

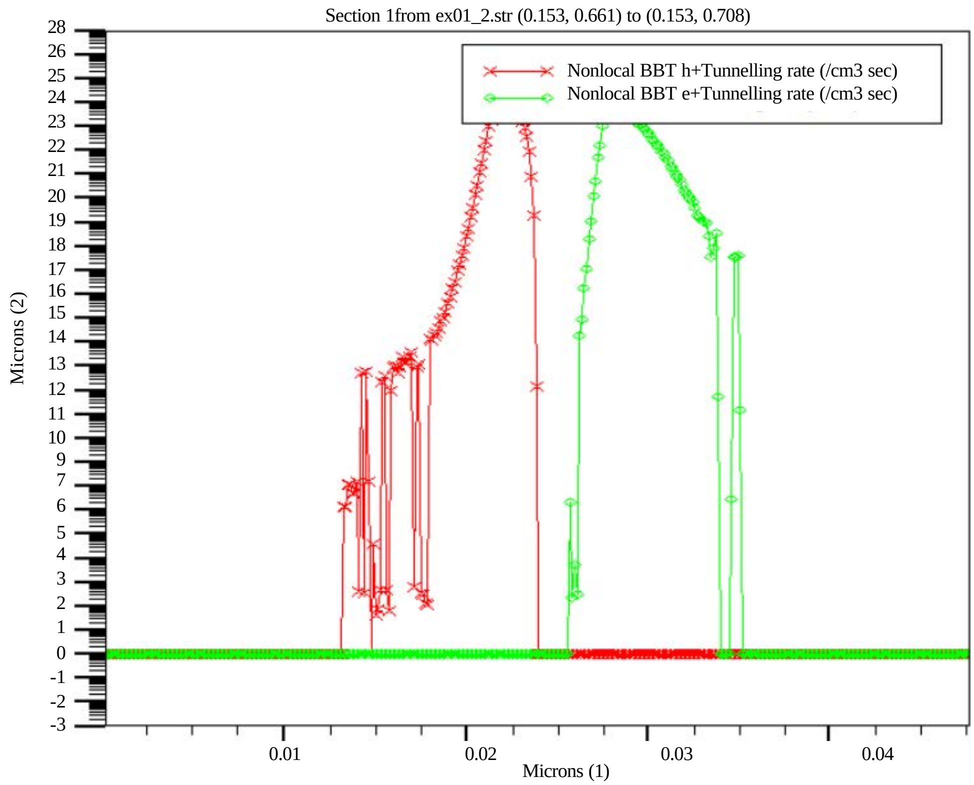

Fig. 9: Level of band tunneling in tunnel juction

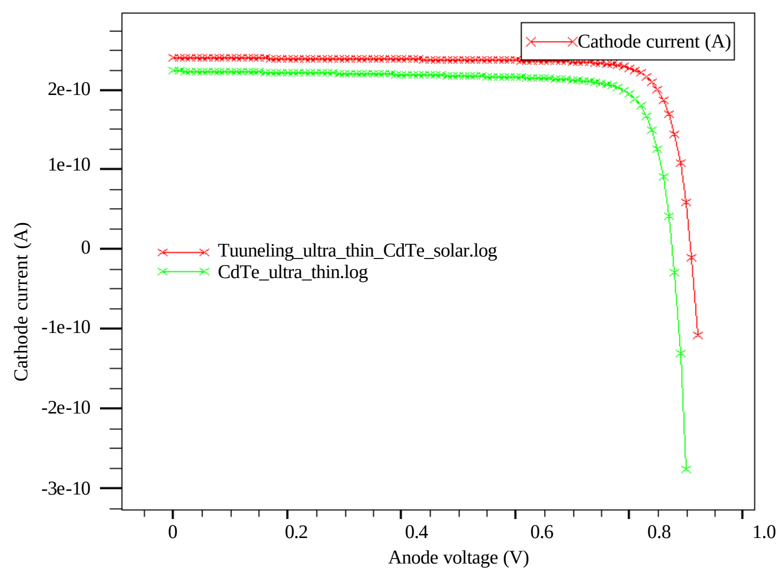

Fig. 10: Current in CdTe/CdS solar cell lighting without tunnel junction and with tunnel junction

The conditions of simulation is under the AM1.5 luminous wave radiation which the result of our research with our suggested structure have caused increase in the efficiency up to 2.5%, increase in V_{oc} up to 4%, increase in J_{sc} up to 7.6% and increase in fill factor up to 3.35%.

CONCLUSION

Results obtained from the influence of change in the CdTe layer thickness from 1-7 μm were investigated on cell parameters in which the level of V_{oc}

has been = 0.900 mV in 7 μm thickness and in a 1 μm thickness, it has been = 0.875 Mv (Kanevce and Gessert, 2011; Amin *et al*., 2007). As it is represented in Fig. 10, adding a tunnel junction causes improvement in cell parameters, especially in 1 μm thickness. The values of V_{oc} and J_{sc} of the piece have been promoted considerably and this problem is the most important factor in increasing the cell efficiency. According to the relationship between V_{oc} and material band split energy, the existence of tunnel junction in small thicknesses of CdTe layer causes generating more electric fields in the piece which have caused increase in the V_{oc} of the piece. Observing this effect even without considering its numerical value is of a particular importance. Among other important obtained results, the descending trend of changes in the V_{oc} of the piece with the increase of CdTe layer thickness can be mentioned. In another part of this research, the CdTe layer thickness is assumed = 1 μm in order to observe the effect of tunnel junction and the cell parameters are obtained considering different values of surface recombination velocity from 10^2-10^8 m sec^{-1} in the back surface and the structure of a CdS/CdTe solar cell was investigated through numerical solution methods. In order to reduce the losses due to recombination and yet, economizing in use of the material, many attempts are carried out to design a CdTe cell with a thin absorbent layer. We can cause increase in the electric field of an area through placing a tunnel junction in the cell, so that the parameters and also the cell efficiency would be improved in small thicknesses. In small thicknesses of CdTe layer, the existence of a tunnel junction causes increase in the V_{oc} of the piece and this matter is the most important factor to increase the cell efficiency due to adding tunnel junction which the result of our research with our suggested structure resulted in increasing the efficiency up to 2.5% (V_{oc} = 910 mV, J_{sc} = 24.1 mA, FF = 0.834, Eff = 18.3), increasing the J_{sc} up to 7.6% and increasing the fill factor up to 3.35%.

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