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Simulation Studies on Thin-Film Solar Cells Based on Ultrathin Sn-Ge-Se-Pb (TGSL) Absorber

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Abstract: In this study the novel absorber Sn-Ge-Se-Pb (TGSL) based thin-film solar cells with CdS as a buffer layer, indium tin oxide (ITO) as charge-collecting contacts, and Mo as the back contact is proposed, and its photovoltaic performance is evaluated theoretically. The considered study is carried out on the basis of the variation of Pb-ratio. Moreover, the effect of optical losses resulting from the reflection losses at interfaces air/ITO, ITO/CdS, CdS/ TGSL, and absorption losses in ITO and CdS have been taken into calculation. Further, the influence of reflectivity of back contact (Mo) and the optimum energy gap and thickness of TGSL have been studied in correlation with the solar cell performance of the considered absorbent. The short-circuit current density is greatly affected by the optical loss than by the loss due to recombination. Based on the TGSL absorber, solar cells with an efficiency of more than 16% can be obtained using certain conditions of the used materials.

Keywords: Sn-Ge-Se-Pb; thin film; solar cells; recombination losses; optical losses; efficiency of solar cell.

1. Introduction

Long-term sustainability and cost are the most important factors on which solar cell manufacturing technology depends. Thus, the selection of promising absorber materials with a small thickness, appropriate energy gap and a high absorption coefficient is one of the goals that most researchers are looking for in this field.

Many materials were used as an absorber layer such as, copper-zinctellurium selenide (CZTS), copper-indium-gallium-diselenide (CIGS), cadmium-telluride (CdTe), lead sulfide PbS, and antimony selenide (Sb_2Se_3) because of their, high efficiency, excellent performance, and low cost [1–4]

Improving the performance of solar cells requires a careful study of the physical properties of all materials and layers used in these cells. Although practical studies are real and more realistic than theoretical studies in this field, they do not give all the details and information needed to improve the performance of these cells, and for this reason, it may be more appropriate to use mathematical models. It was reported that theoretical studies have great importance for understanding and designing thin-film solar cells based on CdTe [5-8], CITS [9, 10], and CIGS [11-14]. Recently, it is reported that new semiconductor materials like CZTS, Sb_2Se_3, Sb_2S_3, and GeSe can be used as replacements for thin film solar cells [15, 16].

In the present work, the p-type Sn-Ge-Se-Pb (TGSL) is studied theoretically for the first time as an absorber of solar cells with structure ITO/CdS/(TGSL)/Mo/glass. The reflection losses in interfaces air/ITO, ITO/CdS, CdS/(TGSL), and absorption losses in ITO and CdS have been investigated. Besides, the recombination losses at front and back surface of the absorber layer are considered in calculations. Finally, the influence of reflection of back contact (Mo) on the performance of solar cell parameters have been studied.

2. Model methodology

2.1 Structure of solar cell

In this work, the decrease in the efficiency of solar cells was attributed to two types of losses. Firstly, the optical loss and results from two basic processes, which are the reflection of the incident light at the different interfaces (air/ITO, ITO/CdS, CdS/

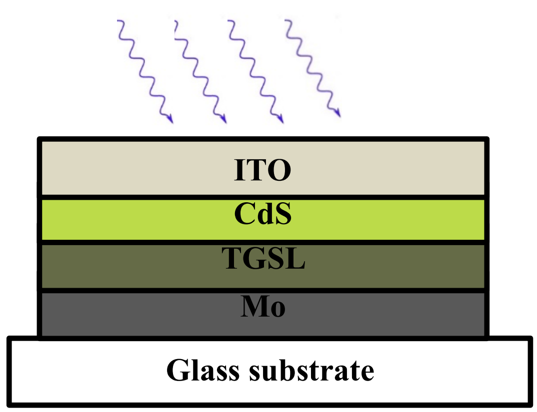

Fig. 1: Schematic representation of substrate solar cell based on TSGL as absorber layer.

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TGSL) and the absorption of a portion from the incident light in the upper layers (indium tin oxide ITO, cadmium sulfide CdS). The quantitative estimation of optical losses depends on a set of optical properties of the used materials, such as the index of refraction, extinction coefficient, and the optical energy gap of the used substance. Secondly, the loss is a result of the recombination of the generated carriers. In this aspect, the continuity equation takes into consideration the drift and diffusion components of the photocurrent to determine the recombination losses. The quantitative limitation of the recombination losses depends on the physical properties of both the absorbent layer and contact junction. The absorbent properties like absorption coefficient, thickness, carrier, energy gap, mobility, lifetime, and junction properties (barrier height and free space width). In addition, the effect of reflectivity from back contact and the optimum thickness and energy gap of TGSL will be taken into account to enhance the performance of thin-film solar cells. The performance of this device will be assessed under AM1.5 standard conditions.

2.2 Reflection and absorption losses

The reflection and absorption losses (Optical loss) can be evaluated quantitatively by computing the short-circuit current density (JSC) according to this formula [5]:

$$J_{SC} = q\sum_i T(\lambda)\frac{\Phi_i(\lambda_i)}{h\nu_i}\eta_{int}(\lambda_i)\Delta\lambda_i \tag{1}$$

Φi is the power density solar- radiation, Δλ is the interval between adjacent wavelengths, hv is the photon energy, T(λ) is transmitted light reaching the absorber layer (TGSL) and $\eta_{int}(\lambda)$ is the internal quantum efficiency. The maximum value T(λ) is unity and the variation from this value is due to the optical losses. In this case, we assume that $\eta_{int}(\lambda)=1$ (i.e., neglecting the recombination losses). The reflection from the interfaces air/ ITO, ITO/CdS, CdS/ TGSL, and absorption in ITO and CdS layers result in the optical loss.

The transmission as a function of the reflection at the existing interfaces is given by:

$$T(\lambda) = (1-R_{12})(1-R_{23})(1-R_{34}) \tag{2}$$

where R_{12}, R_{23} and R_{34} are the reflectivity's at interfaces between air/ITO, ITO/CdS and CdS/ TGSL, respectively.

The reflection can be calculated using the refractive indices (n) and extinction coefficients (k) of the considered materials as follows:

$$R_{ij}(\lambda) = \frac{\left|n_i^*-n_j^*\right|^2}{\left|n_i^*+n_j^*\right|^2} = \frac{(n_i-n_j)^2+(k_i-k_j)^2}{(n_i+n_j)^2+(k_i+k_j)^2} \tag{3}$$

Since, n^* represents the complex index of refraction and is given by $n^* = n - ik$, the values of the refractive index n and extinction coefficient k of both ITO and CdS, are taken from the literature data [6, 7].

If a part of the incident light is absorbed in ITO and/or CdS, Eq.2 will take the form:

$$T(\lambda) = (1-R_{12})(1-R_{23})(1-R_{34})e^{-\alpha_1 d_1}e^{-\alpha_2 d_2} \tag{4}$$

α_1 and α_2 the absorption coefficients of ITO and CdS, d_1 and d_2 their thickness, respectively.

The optical losses can be evaluated quantitatively by calculating the short-circuit current density J_{SC} from Eq. 1 and using the following Equation:

$$Losses\ (\%) = \left(1-\frac{J_{SC}}{J_{sc}^{max}}\right)\times 100 \tag{5}$$

the maximum value of short-circuit current density J_{sc}^{max} can be obtained at $T(\lambda)=1$ and $\eta_{int}(\lambda)=1$. keep in mind that in Eq. 1 should be applied over the spectral range from λ=300 nm to $\lambda = \lambda_g = hc/E_g$, where E_g is the optical energy gap of the absorber layer, it mainly depends on the Pb-ratio.

2.3 Recombination losses

The internal quantum yield (η_{int}) considered as an important parameter that affects J_{SC}. It is explained as the ratio between the photogenerated electron–hole pairs and the total amount of the absorbed photons by the absorber layer. The optimal value of η_{int} is 1, The variation from this unity is due to the recombination losses and not using appropriate parameters for the absorbent material (thickness, absorption coefficient, charge lifetime, mobility, energy gap, etc.) and contact junction (barrier height, width of space charge region, etc.). Lavagna et al solved the continuity equation and obtained an expression of the quantum efficiency [18]. This expression was simplified by Kosyachenko et al and achieved the following expression of the internal quantum efficiency [19].

$$\eta_{int} = \frac{1+(S_f/D_p)[\alpha+(2/W)(\varphi_o-qV)/kT]^{-1}}{1+(S_f/D_p)[(2/W)(\varphi_o-qV)/kT]^{-1}} - \frac{\exp(-\alpha W)}{1+\alpha L_n} \tag{6}$$

Symbols	Characteristic
S_f	recombination velocity at the front surface of the absorber
D_p	diffusion coefficient of the holes
μ_p	hole mobility = qD_p/kT
W	width of space-charge region
α	absorption coefficient of the absorber
V	voltage
φ_o	barrier height
L_n	diffusion length of minority carriers = $(\tau_n D_n)^{1/2}$
τ_n	lifetime of electron
D_n	diffusion coefficient of the electrons = μ_n KT/q

The maximum short-circuit current density $J_{SC(\max)}$ is obtained at $S_f = 0$ and $S_b = 0$. It should be noted that Eq.6 does not take into consideration the recombination at the back surface of the absorber layer.

Eq.6 to can be used to find the expression for the drift component of the photoelectric quantum yield. The photoelectric quantum that takes place in the space-charge region is equal to the absorptivity of this layer, that is, $1 - \exp(-\alpha W)$. Thus, subtracting the term $1 - \exp(-\alpha W)$ from the right side of Eq.6 results in the expression for the diffusion component of the photoelectric quantum yield:

$$\eta_{diff} = \exp(-\alpha W)\frac{\alpha L_n}{1+\alpha L_n} \quad (7)$$

The above equation ignores the recombination at the back surface of the absorber layer. From eq. 6 and 7, the drift component of the photoelectric quantum yield taking into account surface recombination at the front and back interface found to be as follows:

$$\eta_{drift} = \frac{1+(S_f/D_p)[\alpha+(2/W)(\varphi_o-qV)/kT]^{-1}}{1+(S_f/D_p)[(2/W)(\varphi_o-qV)/kT]^{-1}} - \exp(-\alpha W) \quad (8)$$

Also, the diffusion component of the internal quantum efficiency (η_{dif}) can be obtained from solution of continuity which is simplified with sufficient accuracy and expressed as follows [13],

$$\eta_{dif} = \frac{\alpha L_n}{\alpha^2 L_n^2 - 1}\exp(-\alpha W) \times \left\{\alpha L_n - \frac{\left(\frac{S_b L_n}{D_n}\right)[\cosh((d-W)/L_n) - \exp(-\alpha(d-W))] + \sinh((d-W)/L_n) + \alpha L_n \exp(-\alpha(d-W))}{\left(\frac{S_b L_n}{D_n}\right)\sinh[(d-W)/L_n] + \cosh[(d-W)/L_n]}\right\} \quad (9)$$

S_b and d represent the velocity of the recombination at back surface of the absorber layer, and its thickness respectively. The summation of Eq.8 and Eq.9 results in the total internal efficiency with recombination losses at front and the back surface of the absorber layer

$$\eta_{int} = \eta_{drift} + \eta_{dif} \quad (10)$$

In order to compute the recombination loss, the following form ia applied:

$$J_{SC} = q\sum_i \frac{\Phi_i(\lambda_i)}{h\nu_i}\eta_{int}(\lambda_i)\Delta\lambda_i \quad (11)$$

2.4 Reflection from back contact

When the absorbent material thickness is very small, then this thickness is not enough to absorb all the photons that reach it. Therefore, there is a part of these photons will reach the back contact and may be reflected from it and re-absorbed again. Accordingly, the reflection from back contact can partially compensate for this absorption loss, since the back contact is a metal electrode and its reflectivity can be reaching 100 %. Therefore, the effect of the reflection from the metallic back contact may enhance the absorption in the absorber layer and consequently increase the photogenerated carriers. To compute theoretically the effect of reflectivity from the back contact on internal efficiency, the following formula [20] can be used;

$$\eta_{int}(R) = \eta_{int}(1 + Re^{-\alpha d}) \quad (12)$$

R, α, and d are the reflectivity from the back contact, the absorption coefficient of the absorber layer, and d its thickness respectively. In present study, it is assumed that R=100%.

2.5 Solar cell parameters

The above estimated values of J_{SC} will be used to determine the cell parameters using the the equation of p-n junction current

$$J = J_S\left[exp\left(\frac{eV}{AkT}\right) - 1\right] - J_L \quad (13)$$

where J_L, Js, e, A, k, and T are the photocurrent density, the reverse saturation current, e is the charge of an electron, the diode quality factor, the Boltzmann constant, and the temperature in Kelvin. Respectively. Besides, the minus sign in the above equation means that photocurrent JL is in the opposite direction. This is the reason why the current is negative at the first part of the light J-V curve. On the other hand, this means also that the solar cell generates energy not consumes energy.

Two limiting cases are taken into consideration, (a) the short-circuit condition density that occurs when R = 0, so, V = 0. The current in this case is referred to as the short-circuit current density, or

$$J = J_{SC} = J_L \quad (14)$$

(b) the open-circuit condition and occurs when R→∞and the net current density are zero, therefore, the voltage produced is the open-circuit voltage. The photocurrent, herein, is balanced by the forward-biased direction current, so, we have:

$$J = 0 = J_S\left[exp\left(\frac{eV_{OC}}{AkT}\right) - 1\right] - J_L \quad (15)$$

The open-circuit voltage V_{OC} can be expressed as:

$$V_{OC} = V_t ln\left(1 + \frac{J_L}{J_S}\right) \quad (16)$$

Where $V_t = A\,k\,T / e$ is the thermal voltage.

The power delivered to the load is

$$P = JV = J_S\left[exp\left(\frac{eV}{AkT}\right) - 1\right]V - J_L V \quad (17)$$

We may find the current and voltage which will deliver the maximum power to the load by setting the derivative equal to zero, or $dP/dV=0$. Using Eq.17, we find:

$$\frac{dP}{dV} = 0 = J_S\left[exp\left(\frac{eV_m}{AkT}\right) - 1\right] + J_S V_m\left(\frac{e}{AkT}\right)exp\left(\frac{eV_m}{AkT}\right) - J_L \quad (18)$$

Vm represents the voltage that produces the maximum power. Eq.18 can be rewritten in the form:

$$\left(1 + \frac{V_m}{V_t}\right)exp\left(\frac{eV_m}{AkT}\right) = 1 + \frac{J_L}{J_S} \quad (19)$$

The efficiency of a solar cell is defined as the ratio of output electrical power P_m to incident optical power P_{in} as follows;

$$\eta = \frac{P_m}{p_{in}} \times 100\% = \frac{FF \times J_{SC} \times V_{0C}}{P_{in}} \quad (20)$$

where *FF* is the fill factor which measures the realizable power from a solar cell, and Pin represents the density of the total Global spectrum AM 1.5. The fill factor can be formulated as:

$$FF = \frac{J_m \times V_m}{J_{SC} \times V_{0C}} \quad (21)$$

The values of *n* and *k* for TGSL are taken from Ref. [21]and the other parameters used in this study are recorded in Table 1.

Table 1: Thickness of ITO (dITO), Thickness of CdS (dCdS), barrier height (φ_o- qv), the velocity of recombination at the back surface of TGSL(S_b), recombination velocity at the front surface of TGSL (S_f), electron mobility (μ_n), hole mobility (μ_p), electron lifetime (τn), temperature (T), width of the space-charge region (W) and thickness of TGSL (d_{TGSL}).

Parameter	Value
d_{ITO}	100 (nm)
d_{CdS}	100 (nm)
φ_o- qv	1 (eV)
S_f	10^7 (cm/s)
S_b	10^7 (cm/s)
μ_n	10^3 cm²/(Vs)
μ_p	10^2 cm²/(Vs)
τ_n	1 (μs)
T	300 (K)
W	100 nm

3. Results and discussion

3.1 Effect of optical losses

Figure 2 represents the calculated transmission considering the reflection at interfaces air/ITO, ITO/CdS, CdS/ TGSL as well as the absorption within the window layer (ITO) and buffer layer (CdS). It is obvious from Fig.2-A that the transmission is high and the average value is greater than 84% for most Pb-ratios. This indicates that a small part of the incident light can be missed due to reflection at different interfaces.

The calculated value of T due to the effect of both reflection at all interfaces and absorption in ITO and CdS layers is shown in Fig.2-B. It observed that there is a significant reduction in T particularly in the low wavelength range as a result of the absorption procedure which occurs in ITO and CdS. Besides, we can see that the values of T increase with increasing x-ratio as shown in the inset figure.

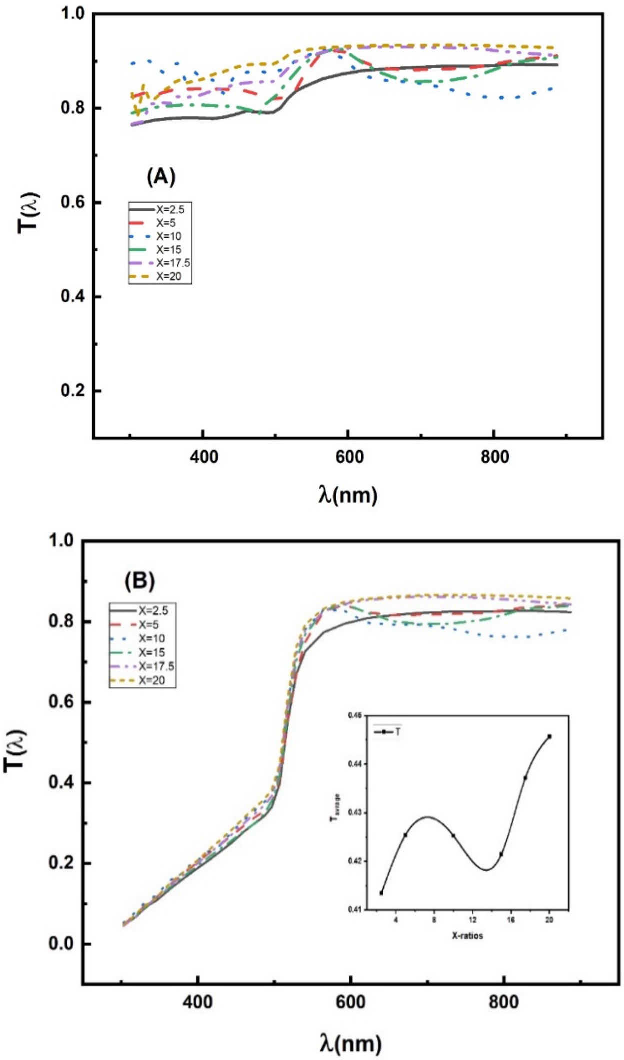


Fig. 2: (A) The calculated transmittance T due to reflection at interfaces and (B)when the absorption in ITO and CdS are considered. The inset figure is the average transmittance as a function of Pb-ratio (x-ratio).

Figure 3 illustrates the dependence of JSC on x-ratio and the corresponding losses due to reflection (Fig.3-A) and reflection & absorption (optical losses) (Fig. 3-B). It can be seen that with increasing x-ratio, JSC increases and records its maximum value around 20 mA/cm2. In order to calculate the optical losses, the calculated maximum short-circuits current density $J_{JSC(max)}$ has a value of 22.19 mA/cm2. Using Eq.5 and the JSC data (from Fig.3-A), it can be observed that at high Pb-ratios around 91.5% of the incident light is converted to photocurrent, leaving 8.5 losses due to reflection at interfaces. When the absorption in ITO and CdS (absorption losses) are taken into consideration, the above value of JSC (at x=20) decreases approaching the value of 15 mA/cm2, consequently, the optical losses are about 33%. This indicates that the main optical loss is due to the absorption in the top layers (ITO and CdS).

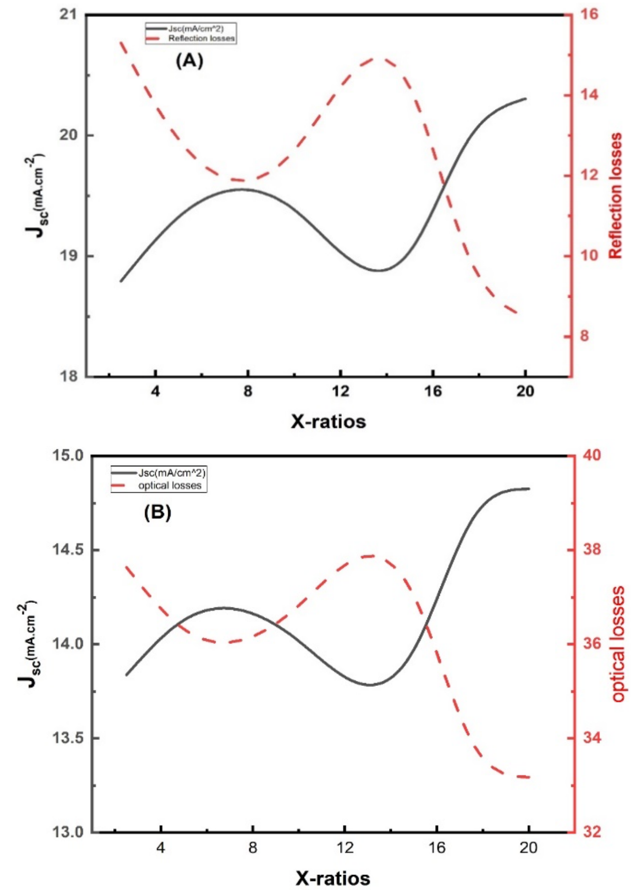


Fig. 3: Variations of J_{SC} with Pb-ratio (x-ratio). (A) and (B) represents the cases (reflection losses), and (reflection and absorption losses) respectively.

At this point, it is clear that the values and behaviour of J_{SC} and then the optical losses mainly depend on the values of the optical parameters (*n, k, α*) of the used materials. Where the behaviour of J_{SC} is similar to that of the behaviour of average transmittance as shown in the inset of Fig.2-B.

The cell parameters (V_{oc}, *FF*, *η*) can be determined from power-voltage curves as shown in Fig.4, current-voltage curves as shown in Fig. 5 and using Eqs.20 and 21.

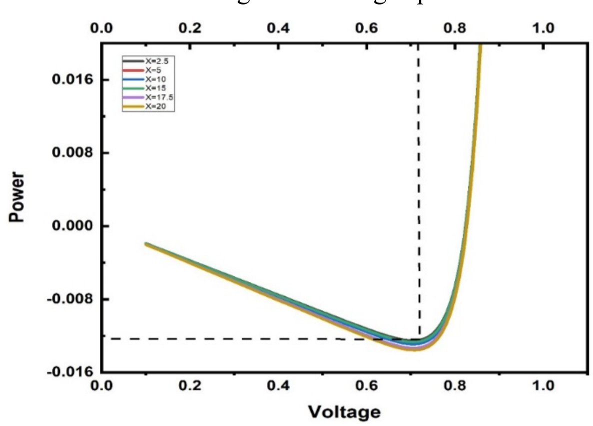


Fig. 4: The power-volatge curves of TGSL solar cell as a function of Pb-ratio.

As can be seen from Fig.5, with varying the x-ratio the shift of the *J-V* curves can be observed. Using the results of Fig.5, the solar cell efficiency of TGSL is calculated using Eq.20, wherein the fill factor value can be calculated using Eq.21. The resulting data of V_m, J_m, V_{OC}, and *FF* for different x-ratios are recorded in table 2.

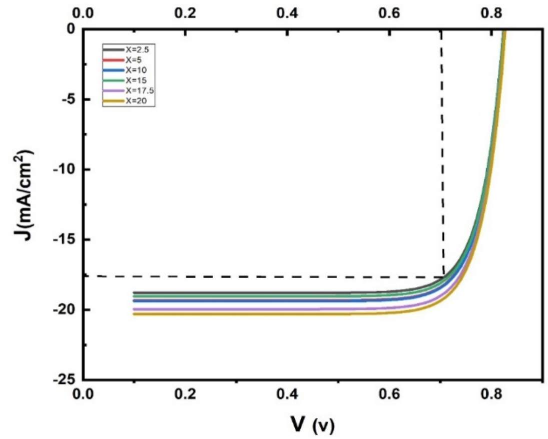


Fig. 5: Variations of current with voltage for solar cell-based TGSL at different ratios of Pb- under the effect of optical losses.

Table 2: Values of *the parameters;* V_m, V_{oc}, J_m, and *FF* of TGSL solar cells derived from Fig.5.

x	V_m (V)	V_{oc} (V)	J_m(mA/cm^2)	*FF*
2.5	0.723	0.824	17.197	0.803
5	0.728	0.825	17.466	0.797
10	0.723	0.826	17.806	0.804
15	0.716	0.827	17.473	0.795
17.5	0.729	0.828	18.251	0.805
20	0.721	0.827	18.994	0.815

From this table, it can be seen that the variation of *VOC* and FF on the x-ratio is so small and the values of *JSC* play an important in the values of cell efficiency. Maximum efficiency of around 14 % has been recorded for large values of x-ratio as shown in Fig.6.

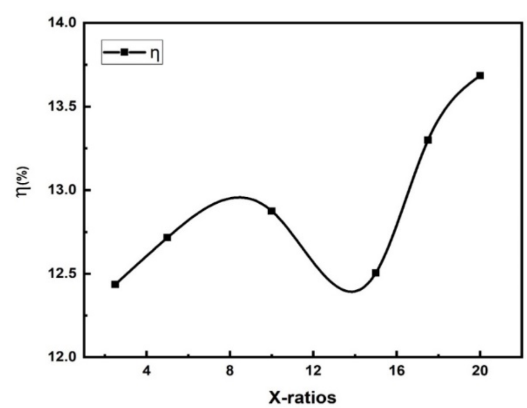


Fig. 6: The effect of Pb-ration on the efficiency of the considered solar cell under the influence of optical losses.

3.2 Effect of recombination losses

The impact of recombination losses on internal efficiency and photocurrent can be calculated using Eqs.6-11. The spectra of internal quantum efficiency at different ratios of Pb are shown in Fig.7 presenting the influence of recombination losses on the shape and values of quantum efficiency, where the recombination velocity has a value of 10^7cm/s. Comparing this result (Fig.7-a) with the result obtained in the absence of recombination losses (S=0) (Fig.7-b), it can be seen that there is no difference in the behavior of internal quantum efficiency, while its value decreases when the recombination losses are taken into calculations. In addition, even when ignoring the recombination losses, the quantum efficiency value will be less than unity. This cannot be attributed to the recombination losses but can be explained in terms of not using the optimal value for each of the absorber thicknesses and the wideness of the space-charge zone. As the thickness of 300 nm is not enough to absorb all the incident light wavelength and then small diffusion internal quantum efficieny (difussion photocurrent) can be obtained.

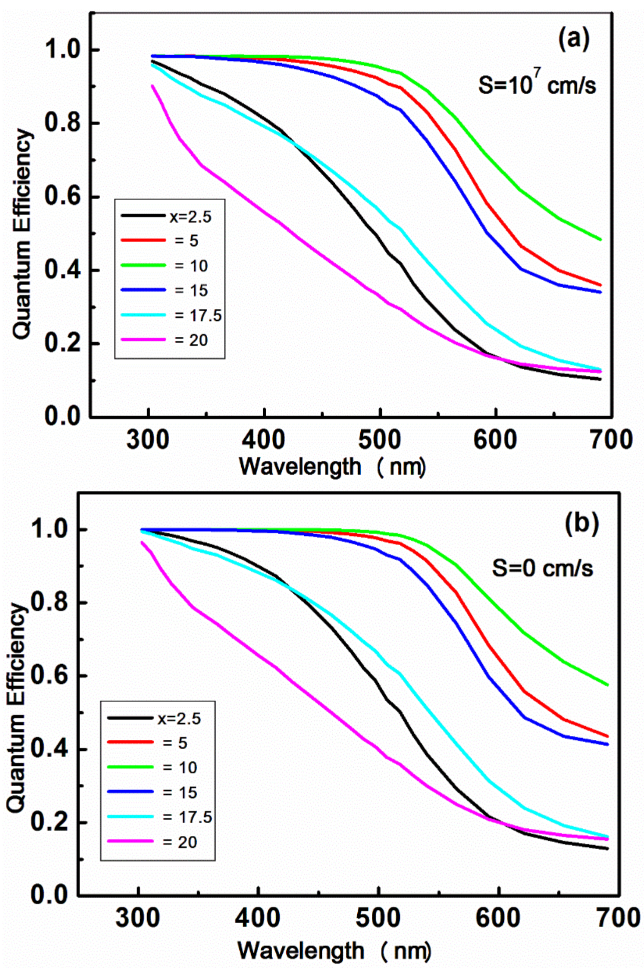


Fig. 7: Variations of internal quantum efficiency of TGSL solar cell of different Pb-ration (a) under the influence of recombination losses and (b) without recombination losses.

Moreover, the width of the space-charge region is narrow (100 nm) and creates a large value of drift photocurrent (drift internal quantum efficiency).

The effect of recombination losses on JSC of TGSL solar cells on Pb-ratio is displayed in Fig.8 where the maximum value of recombination losses is around 17 % and these losses are so small compared with the optical losses. The maximum calculated photocurrent in the presence of recombination losses is around 14 mA/cm2 and this value is smaller than this recorded in the case of optical loss (see Fig.3). This can be explained in terms of Eqs. 6-11, where JSC depends mainly on the thickness of the absorber (dTGSL) and the width of the space-charge region (W). Consequently, it is expected that the values of JSC are small because of the small values of dTGSL and W as well as the behavior of JSC is similar to the variation of absorption coefficient with Pb- ratio as shown in the inset of Fig.8.

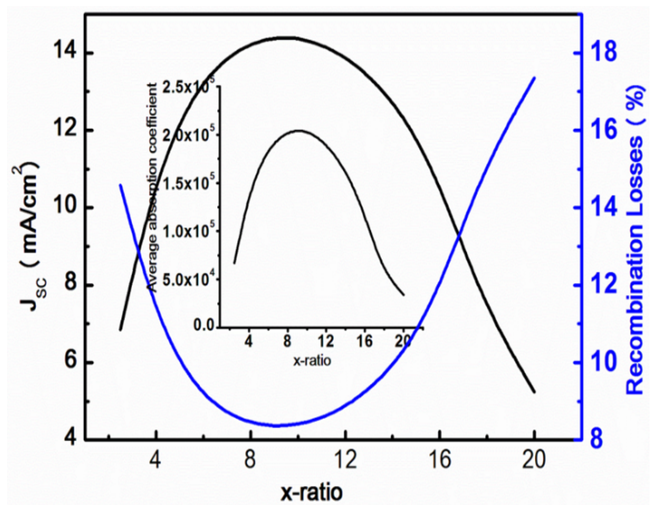


Fig. 8: The calculated J_{SC} as a function of Pb-ratio and the corresponding recombination losses, inset is the average absorption coefficient as a function of Pb-ratio.

Figure 9 shows the J-V curves of the TGSL solar cell as a function of Pb-ratio under the influence of recombination losses. From this figure, the cell parameters have been calculated and listed in Table 3. From this table, it can be seen that at x=10 the cell efficiency records its maximum value of 9.8 % where the corresponding recombination losses are around 8.5 %. It can be observed that the values of efficiency depend mainly on the absorption coefficient of the absorbent.

As mentioned in section 2.5, when the thickness of the absorbent is small, then the reflectivity from back contact must be taken into account. Under this consideration, η_{int} can be calculated by applying Eq.12. Spectral internal quantum efficiency, and the J-V curves of TGSL solar cell as a function of Pb-ratio under the influence of recombination losses and the reflectivity from the back contact are shown in Fig.10 and Fig. 11, respectively.

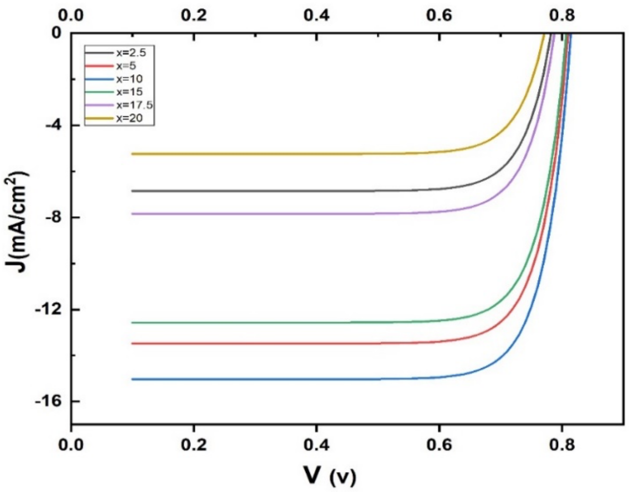
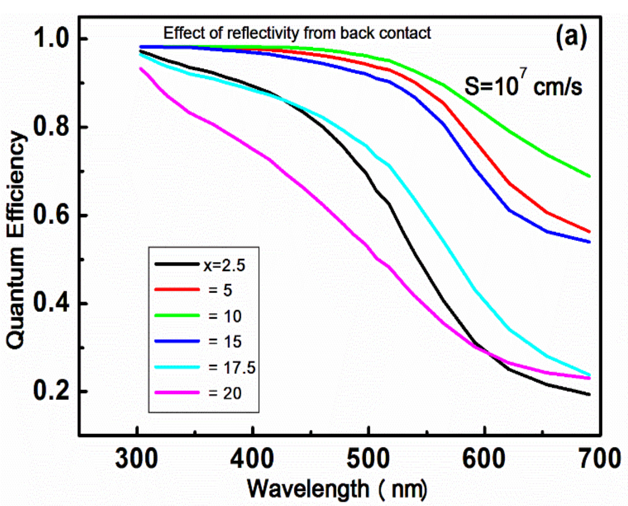


Fig. 9: The current-voltage curves of TGSL solar cell as a function of Pb-ratio under the effect of recombination losses.

Table 3: The parameter values of TGSL solar cells "Voc, FF, and η" extracted from Fig.9, Fig.11, and Fig. 12.

X	Recombination losses			Recombination losses and reflectivity from back cnotact			Optical and Recombination losses and reflectivity from back cnotact		
	V_{oc}	FF	η	V_{oc}	FF	η	V_{oc}	FF	η
2.5	0.782	0.796	4.26	0.795	0.805	6.09	0.787	0.806	4.94
5	0.810	0.787	8.60	0.817	0.796	10.15	0.814	0.784	8.61
10	0.816	0.798	9.79	0.819	0.791	10.89	0.816	0.806	9.71
15	0.808	0.803	8.16	0.814	0.812	9.89	0.808	0.802	8.27
17.5	0.787	0.801	4.94	0.800	0.811	6.99	0.797	0.795	6.00
20	0.769	0.796	3.21	0.789	0.806	5.23	0.786	0.804	4.69

As noted in Fig.10, Fig.11and table 3, the reflection from back contact improves the internal quantum efficiency and hence enhances the JSC and the cell efficiency. Accordingly, at x=10, JSC=16.8 mA/cm2, and η=10.9 % indicate that the reflectivity from back contact can improve cell efficiency by a ratio of 11%.



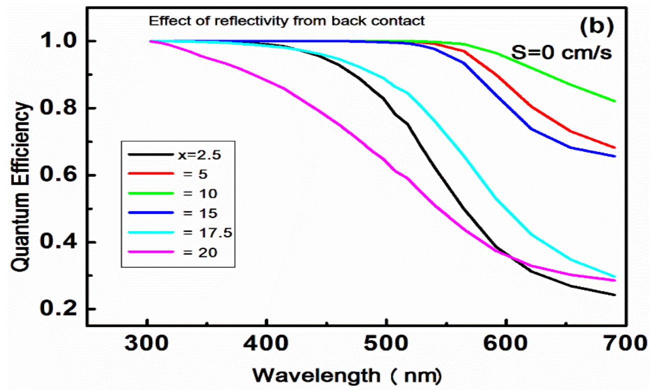


Fig. 10: The influence of reflection from back contact on the internal efficiency of TGSL solar cell as a function of Pb-ratio (a) under the effect of recombination losses and (b) without recombination losses.

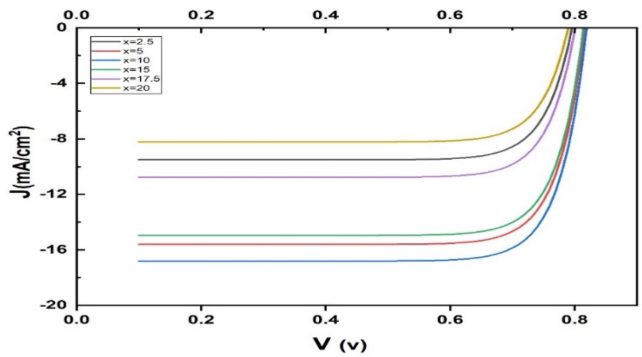


Fig. 11: The current-voltage curves of TGSL solar cell as a function of Pb-ratio under the effect of recombination losses and the effect of reflectivity from back contact.

3.3 Parameters affecting the efficiency of TGSL solar cells

In order to obtain real values for the efficiency of TGSL solar cells, both the optical and recombination in addition to the reflectivity from the back electrode losses are evaluated in Fig.12 and listed in Table 3

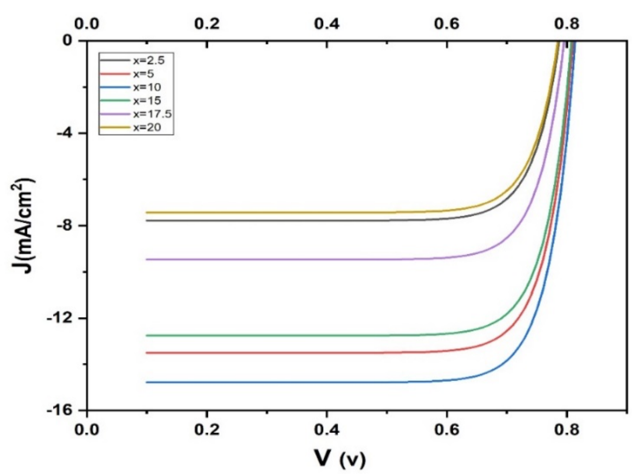


Fig. 12: The current-voltage curves of TGSL solar cell of different ratios of Pb under the effect of optical loss, recombination loss, and the reflection from back contact.

3.4 Improvement of the performance of TGSL solar cell

The first of these methods is decreasing the energy gap of the absorber layer to give a chance for more photons to be absorbed and thus, more photogenerated current can be accomplished. Non-absorption loss can be added to the reflection and absorption losses [22, 23]. Accordingly, the photons of energy lower than the band gap energy are lost due to the non-absorption by the absorbing material. Thus, it will be assumed that the energy gap of the absorbent TGSL is decreased from 1.76 eV to 1.42 eV. The results which describe this case are shown in Fig.13 (black curve). It can be seen that at x=10, JSC reaches its maximum value of around 17.7 mA/cm2. This indicates that when the energy gap decreased to 1.42 eV the JSC increases by a ratio of more than 40%.

The second method to improve cell efficiency is increasing the thickness of the absorber layer. To keep the cost as low as possible, it was assumed that the thickness of the absorbent layer is 1 µm and the width of the space-charge region is 300 nm. It can be seen in Fig. 13 that the increase of the thickness of the absorbent from 300 nm to 1 µm and the width of the space-charge region from 100 nm to 300 nm, leads to an increase in the short-circuit current density JSC from 21.1 mA/cm2 to 24.35 mA/cm2. It can be concluded that the thickness of the absorbent plays a significant role in increasing the photocurrent.

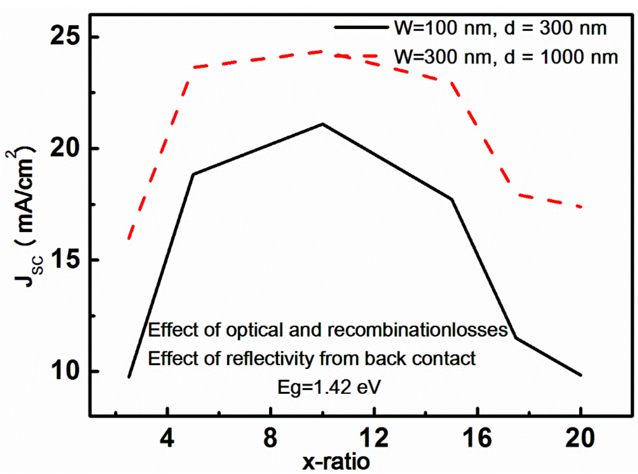


Fig. 13: JSC as a function of Pb-ratio of TGSL solar cell under the effect of optical and recombination losses and the effect of reflectivity from back contact, where Eg=1.42 eV from both curves. Black curve; d= 300 m and W= 100 nm and red curve; d= 1µm and W= 300 nm.

The J-V curves of the above two cases are shown in Fig.14. And the corresponding cell parameters are shown in Fig.15. From Fig.15, it can be seen the maximum efficiency of 14.23% is obtained for x=10 at d= 300 nm, and W= 100 nm and this efficiency increases up to 16.25% at d= 1µm a W= 300 nm. This improvement in the efficiency with a ratio of 14% is owed to the increase of VOC and JSC resulting from increases in both the absorbent thickness and the broadness of the space-charge region. These results accomplished on the base of optical and recombination losses, reflectivity from back contact, and the absorbent energy gap of E_g=1.42 eV.

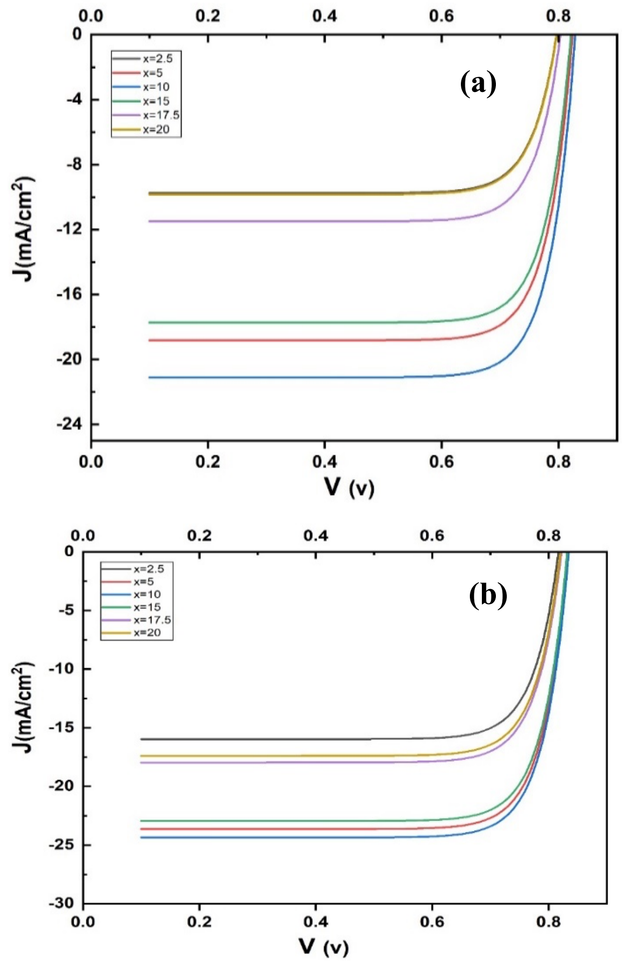
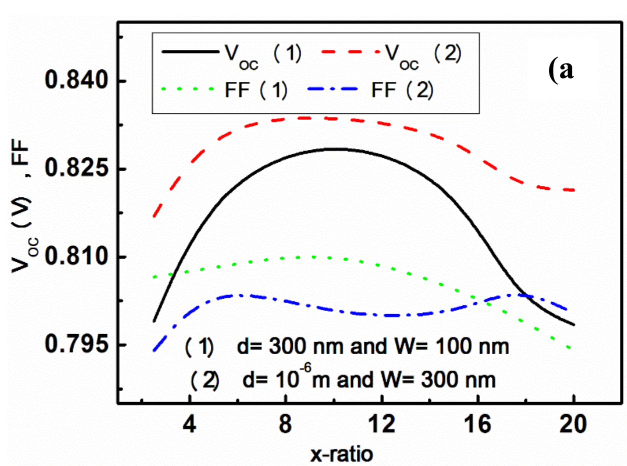


Figure 14: The current-voltage curves of TGSL solar cell of different ratios of Pb under the effect of optical loss, recombination loss, and the reflection from back contact, where E_g=1.42 eV for both curves. a) d= 300 nm and W= 100 nm, b) the d= 1µm and W= 300 nm.



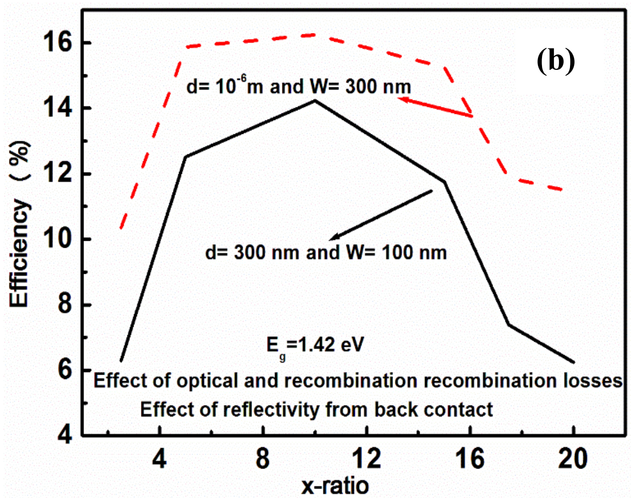


Fig. 15: a) Variations of VOC, FF, and b) the efficiency of TGSL solar cell with of Pb ratio under the effect of optical and recombination losses and the effect of reflectivity from back contact, where Eg=1.42 eV.

4. Conclusions

In this work, we addressed theoretically Sn-Ge-Se-Pb (TGSL) as a new absorbent with ultrathin thickness solar cell of the structure ITO/CdS/TGSL/Mo/glass substrate. Optical loss due to reflection at interfaces air/ITO, ITO/CdS, CdS/TGSL, and absorption in upper layers (ITO, CdS) was tested. Our results indicate that the maximum efficiency of around 14 % for large values of Pb-ratio and the absorption losses represented the essential part of the optical losses. The loss of recombination at the front-back surfaces of the absorber layer was taken into consideration. It was noted that the recombination losses have less effect than the optical losses. When the reflectivity from back contact was taken into consideration, the cell efficiency improved by a ratio of 11%. Our results demonstrate that decreasing the energy gap of the absorbent from 1.77 eV to 1.42 eV, increasing its thickness from 300 nm to 1 μm, and increasing the width of the space-charge region resulted in increasing the cell efficiency from 9.71% to 16.25%. The current work clearly demonstrates the possibility of using TGSL as absorbent substant in thin film solar cells and obtaining promising results when using certain conditions and parameters of the used materials in these cells.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: M. M. Abd El-Raheem; data collection: N. A. Hamed; analysis and interpretation of results M. M. Abd El-Raheem and H.A. Mohamed; draft manuscript preparation; M. M. Abd El-Raheem and M. M. Wakkad. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The data sets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Competing interests, the authors declare no conflict of interest.

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