



**46 % (46 %) [48 % (49 %)]-Maximal Efficiencies  $\eta_{I_{\max.}(II_{\max.})}$  investigated in Two New Single  $n^+(p^+) - p(n)$   $X(x)$ -Alloy Junction Solar Cells at 300 K, [ $X(x) \equiv \text{CdS}_{1-x}\text{Se}_x$ ,  $\text{CdS}_{1-x}\text{Te}_x$ ],  $0 \leq x \leq 1$ , According to Highest Hot Reservoir Temperatures,  $T_H$ , obtained from Carnot-Efficiency Theorem, being proved by Entropy Law**

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## Abstract:

In two new single  $n^+(p^+) - p(n)$   $X(x)$ -alloy junction solar cells at 300 K, [ $X(x) \equiv \text{CdS}_{1-x}\text{Se}_x$ ,  $\text{CdS}_{1-x}\text{Te}_x$ ],  $0 \leq x \leq 1$ , by basing on the same physical model-and-treatment method, as used in our recent works [1, 2], we obtain the highest (or maximal) efficiencies,  $\eta_{I_{\max.}(II_{\max.})}$ , given in the following.

At  $x=0$ ,  $\eta_{I_{\max.}(II_{\max.})}=42.24$  % (42.60 %) are investigated for  $\text{CdS}_{1-x}\text{Se}_x$  alloy-junctions, as given in Tables 2.2 (3.2), and  $\eta_{I_{\max.}(II_{\max.})}=41.92$  % (42.60 %), for  $\text{CdS}_{1-x}\text{Te}_x$  alloy-junctions, as given in Tables 4.2 (5.2), which can be compared with the corresponding ones given in the  $n^+(p^+) - p(n)$  crystalline CdS-junction solar cells [1], as:  $\eta_{I_{\max.}(II_{\max.})} = 43.22$  % (43.40 %), respectively.

Then, in particular, at  $x=1$ ,  $\eta_{I_{\max.}(II_{\max.})}=46.07$  % (46.59 %) and  $T_H=556.3$  K (561.7 K) are obtained for  $\text{CdS}_{1-x}\text{Se}_x$  alloy-junctions, and  $\eta_{I_{\max.}(II_{\max.})}=48.51$  % (48.88 %) and  $T_H=582.6$  K (586.8 K), for  $\text{CdS}_{1-x}\text{Te}_x$  alloy-junctions, as given in Tables 4.2 (5.2), respectively, which could be found to be the new and original results.

Finally, we can conclude that: (i)  $\eta_{I_{\max.}(II_{\max.})}$  and  $T_H$  increase with increasing  $x$ , and (ii), for obtaining the highest efficiencies, the  $(\text{CdS}_{1-x}\text{Se}_x, \text{CdS}_{1-x}\text{Te}_x)$ -alloy junctions could be chosen rather than the crystalline CdS-junctions [1].

**Keywords:** single ( $\text{CdS}_{1-x}\text{Se}_x$ ,  $\text{CdS}_{1-x}\text{Te}_x$ )-alloy junction solar cells; single crystalline CdS-junction solar cells; photovoltaic conversion factor; photovoltaic conversion efficiency

## 1. Introduction

In two new single  $n^+(p^+) - p(n)$   $X(x)$  -alloy junction solar cells at 300 K, [ $X(x) \equiv \text{CdS}_{1-x}\text{Se}_x$ ,  $\text{CdS}_{1-x}\text{Te}_x$ ],  $0 \leq x \leq 1$ , by basing on the same physical model-and-treatment method, as used in our recent works [1, 2], and also other works [3-6], some important results, obtained in the present work, are reported in the following.

(i)-As noted in Tables 2.1, 3.1, 4.1 and 5.1, the dark carrier-minority saturation current density  $J_{ol(ol)}$  decrease slightly with increasing  $r_{d(a)}$ -radius for given  $x$ , but it increases strongly with increasing  $x$  for given  $r_{d(a)}$ -radius. Then, as remarked in Tables 2.2, 3.2, 4.2 and 5.2, at a same  $V_{oc}$ , the photovoltaic conversion factor,  $n_{I(II)}(V_{oc})$ , also decrease slightly with increasing  $r_{d(a)}$ -radius for given  $x$ , but it also increases strongly with increasing  $x$  for given  $r_{d(a)}$ -radius. In other words, as discussed in Eq. (45), at a same  $V_{oc}$ , both  $J_{ol(ol)}$  and  $n_{I(II)}$  have the same variations for the same physical conditions. It should be noted here that, in Ref. [3], the “quality factor  $n$ ” was assumed to be equal to 1, meaning that the maximal efficiency value  $\eta_{max}$  could not be obtained.

(ii)-With such variations of  $n_{I(II)}(V_{oc})$ , as observed in Tables 2.2, 3.2, 4.2 and 5.2, the maximal values of  $\eta_{I(II)}$ ,  $\eta_{I(II)max}$ , and the corresponding ones of the H-reservoir temperature,  $T_H$ , are obtained at the corresponding  $V_{oc} = V_{oc;max}$ -values, marked in bold, increase with increasing  $x$  for given  $r_{d(a)}$ -radius.

(iii)-At  $x=0$ ,  $\eta_{I(II)max} = 42.24\%$  ( $42.60\%$ ) are investigated for  $\text{CdS}_{1-x}\text{Se}_x$  alloy-junctions, as given in Tables 2.2 (3.2), and  $\eta_{I(II)max} = 41.92\%$  ( $42.60\%$ ), for  $\text{CdS}_{1-x}\text{Te}_x$  alloy-junctions, as given in Tables 4.2 (5.2), which can be compared with the corresponding ones given in the  $n^+(p^+) - p(n)$  crystalline CdS-junction solar cells [1], as:  $\eta_{I(II)max} = 43.22\%$  ( $43.40\%$ ), respectively.

(iv)-Finally, at  $x=1$ ,  $\eta_{I(II)max} = 46.07\%$  (**46.59%**) and  $T_H = 556.3\text{ K}$  (**561.7 K**) are obtained for  $\text{CdS}_{1-x}\text{Se}_x$  alloy-junctions, and  $\eta_{I(II)max} = 48.51\%$  (**48.88%**) and  $T_H = 582.6\text{ K}$  (**586.8 K**), for  $\text{CdS}_{1-x}\text{Te}_x$  alloy-junctions, as given in Tables 4.2 (5.2), respectively, suggesting that in order to obtain the highest efficiencies, the ( $\text{CdS}_{1-x}\text{Se}_x$ ,  $\text{CdS}_{1-x}\text{Te}_x$ )-alloy junctions could be chosen rather than the crystalline CdS-junctions [1].

In Section 2, the energy-band-structure parameters and the dark minority-carrier saturation current density, due to the effects of  $x$ - Se concentration, impurity size, and heavy doping, are presented. In Section 3, the photovoltaic effect is investigated. Finally, some numerical results and concluding remarks are given and discussed in Section 4.

## 2. Energy-band-structure parameters and dark minority-carrier saturation current density, due to the effects of x- Se concentration, impurity size, and heavy doping

First of all, in two single  $n^+(p^+) - p(n)$   $X(x)$ - alloy junction solar cells,  $X(\equiv \text{CdS}_{1-x}\text{Se}_x, \text{CdS}_{1-x}\text{Te}_x)$ , we present the effects of x-concentration, donor (acceptor)  $[d(a)]$ -size, temperature  $T$  and heavy doping, affecting the energy-band-structure parameters [1, 2], in order to investigate the total minority-carrier saturation current densities, as follows.

### A. Effects of x-Se (Te) concentration

In the  $n^+(p^+) - p(n)$  single  $n^+(p^+) - p(n)$   $X(x)$  - alloy junction at  $T=0$  K, the energy-band-structure parameters are expressed as functions of  $x$ , are given in the following.

(i)-The unperturbed relative effective electron (hole) mass in conduction (valence) bands are given by [1, 2]:

$$m_c(x)/m_o = 0.11 (0.095) \times x + 0.197 \times (1 - x), \text{ and}$$

$$m_v(x)/m_o = 0.45 (0.82) \times x + 0.801 \times (1 - x), \quad (1)$$

so that when  $x=0$  one obtains:  $m_c(x)/m_o = m_{c(\text{CdS})}/m_o = 0.197$ ,  $m_v(x)/m_o = m_{v(\text{CdS})}/m_o = 0.801$ , and as  $x=1$ , one has:  $m_c(x)/m_o = m_{c(\text{CdSe})}/m_o = 0.11$ ,  $m_c(x)/m_o = m_{c(\text{CdTe})}/m_o = 0.095$ ,  $m_v(x)/m_o = m_{v(\text{CdSe})}/m_o = 0.45$ , and finally,  $m_v(x)/m_o = m_{v(\text{CdTe})}/m_o = 0.82$ .

(ii)-The unperturbed relative dielectric constant of the intrinsic of the single crystalline  $X$ - alloy is found to be defined by [1, 2]:

$$\epsilon_o(x) = 10.2 (10.31) \times x + 9 \times (1 - x), \quad (2)$$

which gives: as  $x=0$ ,  $\epsilon_o(x) = \epsilon_{\text{CdS}} = 9$ , and as  $x=1$ ,  $\epsilon_o(x) = \epsilon_{\text{CdSe}} = 10.2$  and  $\epsilon_o(x) = \epsilon_{\text{CdTe}} = 10.31$ .

(iii)-Finally, the unperturbed band gap is found to be given by [1, 2]:

$$E_{go}(x) \text{ in eV} = 1.84 (1.62) \times x + 2.58 \times (1 - x), \quad (3)$$

giving rise to:  $E_{go}(x) = E_{g\text{CdS}}(x) = 2.58$  eV as  $x=0$ , and as  $x=1$ , on gets:  $E_{go}(x) = E_{g\text{CdSe}}(x) = 1.84$  eV and  $E_{go}(x) = E_{g\text{CdTe}}(x) = 1.62$  eV.

Therefore, we can define the effective donor (acceptor)-ionization energy at  $r_{d(a)} = r_{do(ao)}$  in absolute values as [1, 2]:

$$E_{do(ao)}(x) = \frac{13600 \times [m_{c(v)}(x)/m_o]}{[\epsilon_o(x)]^2} \text{ meV}, \quad (4)$$

and then, the isothermal bulk modulus, by:

$$B_{do(ao)}(x) \equiv \frac{E_{do(ao)}(x)}{(4\pi/3) \times (r_{do(ao)})^3}. \quad (5)$$

### B. Effects of Impurity-size, with a given x

Here, the effects of  $r_{d(a)}$  and x-Se concentration affect the changes in all the energy-band-structure parameters, expressed in terms of the effective relative dielectric constant  $\epsilon(r_{d(a)}, x)$ , in the following.

At  $r_{d(a)} = r_{do(ao)} = r_{S(Cd)} = 0.104 \text{ nm}$  (0.148 nm), respectively, the needed boundary conditions are found to be, for the impurity-atom volume  $V = (4\pi/3) \times (r_{d(a)})^3$ ,  $V_{do(ao)} = (4\pi/3) \times (r_{do(ao)})^3$ , for the pressure  $p$ ,  $p_o = 0$ , and for the deformation potential energy (or the strain energy)  $\sigma$ ,  $\sigma_o = 0$ . Further, the two important equations [1, 2, 4], needed to determine the  $\sigma$ -variation  $\Delta\sigma \equiv \sigma - \sigma_o = \sigma$ , are defined by:

$\frac{dp}{dV} = -\frac{B}{V}$  and  $p = -\frac{d\sigma}{dV}$ , giving:  $\frac{d}{dV}(\frac{d\sigma}{dV}) = \frac{B}{V}$ . Then, by an integration, one gets:

$$[\Delta\sigma(r_{d(a)}, x)]_{d(a)} = B_{do(ao)}(x) \times (V - V_{do(ao)}) \times \ln\left(\frac{V}{V_{do(ao)}}\right) = E_{do(ao)}(x) \times \left[\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 - 1\right] \times \ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right). \quad (6)$$

Furthermore, we also shown [1, 2, 3] that, as  $r_{d(a)} > r_{do(ao)}$  ( $r_{d(a)} < r_{do(ao)}$ ), the compression (dilatation) corresponding the repulsive (attractive) force increases (decreases) the energy gap  $E_{gn(gp)}(r_{d(a)}, x)$ , and the effective donor (acceptor)-ionization energy  $E_{d(a)}(r_{d(a)}, x)$  in absolute values, obtained in the effective Bohr model, which is represented by:  $\pm [\Delta\sigma(r_{d(a)}, x)]_{n(p)}$ , respectively,

$$E_{gn(gp)}(r_{d(a)}, x) - E_{go}(x) = E_{d(a)}(r_{d(a)}, x) - E_{do(ao)}(x) = E_{do(ao)}(x) \times \left[\left(\frac{\varepsilon_o(x)}{\varepsilon(r_{d(a)})}\right)^2 - 1\right] = + [\Delta\sigma(r_{d(a)}, x)]_{n(p)},$$

for  $r_{d(a)} \geq r_{do(ao)}$ , and for  $r_{d(a)} \leq r_{do(ao)}$ ,

$$E_{gn(gp)}(r_{d(a)}, x) - E_{go}(x) = E_{d(a)}(r_{d(a)}, x) - E_{do(ao)}(x) = E_{do(ao)}(x) \times \left[\left(\frac{\varepsilon_o(x)}{\varepsilon(r_{d(a)})}\right)^2 - 1\right] = - [\Delta\sigma(r_{d(a)}, x)]_{n(p)}. \quad (7)$$

Therefore, from Equations 6 and 7, one obtains the expressions for relative dielectric constant  $\varepsilon(r_{d(a)}, x)$  and energy band gap  $E_{gn(gp)}(r_{d(a)}, x)$ , as:

$$(i)\text{-for } r_{d(a)} \geq r_{do(ao)}, \text{ since } \varepsilon(r_{d(a)}, x) = \frac{\varepsilon_o(x)}{\sqrt{1 + \left[\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 - 1\right] \times \ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3}} \leq \varepsilon_o(x),$$

$$E_{gn(gp)}(r_{d(a)}, x) - E_{go}(x) = E_{d(a)}(r_{d(a)}, x) - E_{do(ao)}(x) = E_{do(ao)}(x) \times \left[\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 - 1\right] \times \ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 \geq 0, \quad (8a)$$

according to the increase in both  $E_{gn(gp)}(r_{d(a)}, x)$  and  $E_{d(a)}(r_{d(a)}, x)$ , for a given  $x$ , and

$$(ii)\text{-for } r_{d(a)} \leq r_{do(ao)}, \text{ since } \varepsilon(r_{d(a)}, x) = \frac{\varepsilon_o(x)}{\sqrt{1 - \left[\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 - 1\right] \times \ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3}} \geq \varepsilon_o(x), \text{ with a condition, given by:}$$

$$\left[\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 - 1\right] \times \ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 < 1,$$

$$E_{gn(gp)}(r_{d(a)}, x) - E_{go}(x) = E_{d(a)}(r_{d(a)}, x) - E_{do(ao)}(x) = -E_{do(ao)}(x) \times \left[\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 - 1\right] \times \ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 \leq 0, \quad (8.b)$$

corresponding to the decrease in both  $E_{gn(gp)}(r_{d(a)}, x)$  and  $E_{d(a)}(r_{d(a)}, x)$ , for a given  $x$ .

### C. Effect of T, with given $x$ and $r_{d(a)}$

Here, as given in our previous works [1, 2], the intrinsic band gap  $E_{gin(gip)}(r_{d(a)}, x, T)$  is given by:

$$E_{gin(gip)}(r_{d(a)}, x, T) \text{ in eV} = E_{gn(gp)}(r_{d(a)}, x) - \frac{10^{-4} \times T^2}{T + 94 \text{ K}} \times \{4.3779x + 7.0043 \times (1 - x)\}, \quad (9)$$

which decreases, for given  $x$  and  $r_{d(a)}$ , with an increasing  $T$ .

Furthermore, in the  $n(p)$ -type  $X(x)$ -alloy, one can define the intrinsic carrier concentration  $n_{in(ip)}$  by:

$$n_{in(p)}^2(T, r_{d(a)}, x) \equiv N_c(T, x) \times N_v(T, x) \times \exp\left(\frac{-E_{gin(p)}(T, r_{d(a)}, x)}{k_B T}\right), \quad (10)$$

where  $N_{c(v)}(T, x)$  is the conduction (valence)-band density of states, being defined as:

$$N_{c(v)}(T, x) = 2 \times \left(\frac{m_{c(v)}(x) \times k_B T}{2\pi\hbar^2}\right)^{\frac{3}{2}} (\text{cm}^{-3}). \quad (11)$$

So, the numerical results of  $E_{d(a)}(r_{d(a)}, x)$ ,  $B_{do(ao)}(x)$ ,  $\varepsilon(r_{d(a)}, x)$  and  $E_{gin(gip)}(r_{d(a)}, x, T)$ , calculated using Equations 4, 5, 8a (8b) and 9, are reported in following Tables 1.1 and 1.2.

**Table 1.1** From Equations (5, 8a, 8b, 9) and in the n(p)-type  $CdS_{1-x}Se_x$ -alloy, the numerical results of the energy-band-structure parameters, reported below, suggest that, with increasing  $x$  and  $r_{d(a)}$ , both  $B_{do(ao)}(x)$  and  $\varepsilon(r_{d(a)}, x)$  decrease, while the other ones increase.

Donor		S	Se	Te	Sn
$r_d$ (nm)	$\nearrow$	<b><math>r_{do}=0.104</math></b>	0.114	0.132	0.140
$x$	$\nearrow$	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1
$B_{do}(x)$ in $10^8$ (N/m <sup>2</sup> ) $\searrow$		11.2, 7.70, 6.21, 4.89			
$\varepsilon(r_d, x)$ $\searrow$		<b>9.00</b> , 9.60, 9.90, <b>10.2</b>	8.63, 9.21, 9.49, 9.78	6.81, 7.26, 7.49, 7.72	5.95, 6.35, 6.55, 6.75
$E_d(r_d, x)$ meV $\nearrow$		33.1, 22.6, 18.3, 14.4	36.0, 24.6, 19.9, 15.6	57.8, 39.6, 31.9, 25.1	75.5, 51.7, 41.7, 32.8
$E_{gn}(r_d, x)$ eV $\nearrow$		<b>2.58</b> , 2.21, 2.02, <b>1.84</b>	2.58, 2.21, 2.03, 1.84	2.60, 2.23, 2.04, 1.85	2.62, 2.24, 2.05, 1.86
$E_{gin}(T = 300K, r_d, x)$ eV $\nearrow$		<b>2.42</b> , 2.08, 1.91, <b>1.74</b>	2.42, 2.08, 1.91, 1.74	2.44, 2.10, 1.92, 1.75	2.46, 2.11, 1.93, 1.76

  

Acceptor		Ga	Mg	In	Cd
$r_a$ (nm)	$\nearrow$	0.126	0.140	0.144	<b><math>r_{ao}=0.148</math></b>
$x$	$\nearrow$	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1
$B_{ao}(x)$ in $10^8$ (N/m <sup>2</sup> ) $\searrow$					15.9, 10.9, 8.80, 6.94
$\varepsilon(r_a, x)$ $\searrow$		9.97, 10.6, 11.0, 11.3	9.12, 9.72, 10.0, 10.3	9.03, 9.63, 9.93, 10.2	<b>9.00</b> , 9.60, 9.90, <b>10.2</b>
$E_a(r_a, x)$ meV $\nearrow$		110, 75.2, 60.8, 47.9	131, 89.9, 72.7, 57.3	134, 91.7, 74.1, 58.4	134, 92.3, 74.6, 58.8
$E_{gp}(r_a, x)$ eV $\nearrow$		2.55, 2.19, 2.01, 1.83	2.58, 2.21, 2.02, 1.84	2.58, 2.21, 2.02, 1.84	<b>2.58</b> , 2.21, 2.03, <b>1.84</b>
$E_{gip}(T = 300K, r_a, x)$ eV $\nearrow$		2.39, 2.06, 1.90, 1.73	2.42, 2.08, 1.91, 1.74	2.42, 2.08, 1.91, 1.74	<b>2.42</b> , 2.08, 1.91, <b>1.74</b>

**Table 1.2** From Equations (5, 8a, 8b, 9) and in the n(p)-type  $CdS_{1-x}Te_x$ -alloy, the numerical results of the energy-band-structure parameters, reported below, suggest that, with increasing  $x$  and  $r_{d(a)}$ , both  $B_{do(ao)}(x)$  and  $\varepsilon(r_{d(a)}, x)$  decrease, while the other ones increase.

Donor		S	Se	Te	Sn
$r_d$ (nm)	$\nearrow$	<b><math>r_{do}=0.104</math></b>	0.114	0.132	0.140
$x$	$\nearrow$	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1	0, 0.5, 0.75, 1
$\varepsilon(r_d, x)$ $\searrow$		<b>9.00</b> , 9.65, 9.98, <b>10.3</b>	8.63, 9.26, 9.57, 9.89	6.81, 7.30, 7.55, 7.80	5.95, 6.39, 6.60, 6.82
$B_{do}(r_{d0}, x)$ in $10^8$ (N/m <sup>2</sup> ) $\searrow$		11.2, 7.24, 5.59, 4.13			
$E_d(r_d, x)$ meV $\nearrow$		33.1, 21.3, 16.4, 12.2	36.0, 23.2, 17.9, 13.2	57.8, 37.2, 28.7, 21.2	75.5, 48.6, 37.6, 27.8
$E_{gn}(r_d, x)$ eV $\nearrow$		<b>2.58</b> , 2.10, 1.86, <b>1.62</b>	2.58, 2.10, 1.86, 1.62	2.60, 2.11, 1.87, 1.63	2.62, 2.13, 1.88, 1.63
$E_{gin}(T = 300K, r_d, x)$ eV $\nearrow$		<b>2.42</b> , 1.97, 1.74, <b>1.52</b>	2.42, 1.97, 1.75, 1.52	2.44, 1.98, 1.76, 1.53	2.46, 2.00, 1.77, 1.53

Acceptor		Ga	Mg	In	Cd
$r_a$ (nm)	$\nearrow$	0.126	0.140	0.144	$r_{ao}=0.148$
x	$\nearrow$	0 , 0.5, 0.75, 1	0 , 0.5, 0.75, 1	0 , 0.5, 0.75, 1	0 , 0.5, 0.75, 1
$\varepsilon(r_a, x)$	$\searrow$	9.96, 10.7, 11.0, 11.4	9.11, 9.78, 10.1, 10.4	9.03, 9.68, 10.0, 10.3	<b>9.00</b> , 9.65, 9.98, <b>10.3</b>
$B_{ao}(r_{ao}, x)$ in $10^8$ (N/m <sup>2</sup> )	$\searrow$				15.9, 13.9, 13.1, 12.4
$E_a(r_a, x)$ meV	$\nearrow$	110, 96.4, 90.7, 85.5	131, 115, 108, 102	134, 117, 110, 104	134, 118, 111, 105
$E_{gp}(r_a, x)$ eV	$\nearrow$	2.55, 2.08, 1.84, 1.60	2.58, 2.10, 1.86, 1.62	2.58, 2.10, 1.86, 1.62	<b>2.58</b> , 2.10, 1.86, <b>1.62</b>
$E_{gip}(T = 300K, r_a, x)$ eV	$\nearrow$	2.39, 1.95, 1.72, 1.50	2.41, 1.97, 1.74, 1.52	2.42, 1.97, 1.74, 1.52	<b>2.42</b> , 1.97, 1.75, <b>1.52</b>

### D. Heavy Doping Effect, with given T, x and $r_{d(a)}$

Here, as given in our previous works [3], the Fermi energy  $E_{Fn}(-E_{Fp})$ , band gap narrowing (BGN), and apparent band gap narrowing (ABGN), are reported in the following.

First, the Fermi energy  $E_{Fn}(-E_{Fp})$ , obtained for any T and any d(a)-density,  $N_{d(a)}$ , being investigated in our previous paper [3], with a precision of the order of  $2.11 \times 10^{-4}$ , is found to be given by:

$$\frac{E_{Fn}(u)}{k_B T} \left( \frac{-E_{Fp}(u)}{k_B T} \right) = \frac{G(u) + Au^B F(u)}{1 + Au^B}, A = 0.0005372 \text{ and } B = 4.82842262, \quad (12)$$

where u is the reduced electron density,  $u(N_{d(a)}, T, x) \equiv \frac{N_{d(a)}}{N_{c(v)}(T, x)}$ ,  $F(u) = au^{\frac{2}{3}} \left( 1 + bu^{-\frac{4}{3}} + cu^{-\frac{8}{3}} \right)^{\frac{2}{3}}$ ,  $a = [(3\sqrt{\pi}/4) \times u]^{2/3}$ ,  $b = \frac{1}{8} \left( \frac{\pi}{a} \right)^2$ ,  $c = \frac{62.3739855}{1920} \left( \frac{\pi}{a} \right)^4$ , and  $G(u) \simeq \ln(u) + 2^{\frac{3}{2}} \times u \times e^{-du}$ ;  $d = 2^{3/2} \left[ \frac{1}{\sqrt{27}} - \frac{3}{16} \right] > 0$ .

Here, one notes that: (i) as  $u \gg 1$ , according to the HD [d(a)-X(x)- alloy] ER-case, or to the degenerate case, Eq. (12) is reduced to the function F(u), and (ii)  $\frac{E_{Fn}(u \ll 1)}{k_B T} \left( \frac{-E_{Fp}(u \ll 1)}{k_B T} \right) \ll -1$ , to the LD [a(d)-CdS<sub>1-x</sub>Se<sub>x</sub>- alloy] BR-case, or to the non-degenerate case, Eq. (12) is reduced to the function G(u).

Secondly, if denoting the effective Wigner-Seitz radius  $r_{sn(sp)}$ , characteristic of the interactions, by:

$$r_{sn(sp)}(N_{d(a)}, r_{d(a)}, x) = 1.1723 \times 10^8 \times \left( \frac{g_{c(v)}}{N_{d(a)}} \right)^{1/3} \times \frac{m_{c(v)}(x)}{\varepsilon(r_{d(a)}, x)}, g_{c(v)} = 1(1), \quad (13)$$

the correlation energy of an effective electron gas,  $E_{cn(cp)}(N_{d(a)}, r_{d(a)}, x)$ , is given as [4]:

$$E_{cn(cp)}(N_{d(a)}, r_{d(a)}, x) = \frac{-0.87553}{0.0908 + r_{sn(sp)}} + \frac{\frac{0.87553}{0.0908 + r_{sn(sp)}} + \left( \frac{2[1 - \ln(2)]}{\pi^2} \right) \times \ln(r_{sn(sp)}) - 0.093288}{1 + 0.03847728 \times r_{sn(sp)}^{1.67378876}}.$$

Now, taking into account various spin-polarized chemical potential-energy contributions such as [4]: exchange energy of an effective electron (hole) gas, majority-carrier correlation energy of an effective electron (hole) gas, minority hole (electron) correlation energy, majority electron (hole)-ionized d(a) interaction screened Coulomb potential energy, and finally minority hole (electron)-ionized d(a) interaction screened Coulomb potential energy, the band gap narrowing (BGN) are given as follows.

Then, in the n-type HD X(x)- alloy, the BGN is found to be given by:

$$\Delta E_{gn}(N_d, r_d, x) \simeq a_1 \times \frac{\varepsilon_0(x)}{\varepsilon(r_d, x)} \times N_r^{1/3} + a_2 \times \frac{\varepsilon_0(x)}{\varepsilon(r_d, x)} \times N_r^{\frac{1}{3}} \times (2.503 \times [-E_{cn}(r_{sn}) \times r_{sn}]) + a_3 \times \left[ \frac{\varepsilon_0(x)}{\varepsilon(r_d, x)} \right]^{5/4} \times \sqrt{\frac{m_v}{m_c}} \times N_r^{1/4} + a_4 \times \sqrt{\frac{\varepsilon_0(x)}{\varepsilon(r_d, x)}} \times N_r^{1/2} \times 2 + a_5 \times \left[ \frac{\varepsilon_0(x)}{\varepsilon(r_d, x)} \right]^{\frac{3}{2}} \times N_r^{\frac{1}{6}}, \quad N_r \equiv \left( \frac{N_d}{9.999 \times 10^{17} \text{ cm}^{-3}} \right), \quad (14n)$$

where  $a_1 = 3.8 \times 10^{-3}(\text{eV})$ ,  $a_2 = 6.5 \times 10^{-4}(\text{eV})$ ,  $a_3 = 2.8 \times 10^{-3}(\text{eV})$ ,  $a_4 = 5.597 \times 10^{-3}(\text{eV})$  and  $a_5 = 8.1 \times 10^{-4}(\text{eV})$ , and in the p-type HD  $X(x)$ - alloy, as:

$$\Delta E_{gp}(N_a, r_a, x) \simeq a_1 \times \frac{\varepsilon_0(x)}{\varepsilon(r_a, x)} \times N_r^{1/3} + a_2 \times \frac{\varepsilon_0(x)}{\varepsilon(r_a, x)} \times N_r^{\frac{1}{3}} \times (2.503 \times [-E_{cp}(r_{sp}) \times r_{sp}]) + a_3 \times \left[ \frac{\varepsilon_0(x)}{\varepsilon(r_a, x)} \right]^{5/4} \times \sqrt{\frac{m_c}{m_v}} \times N_r^{1/4} + 2a_4 \times \sqrt{\frac{\varepsilon_0(x)}{\varepsilon(r_a, x)}} \times N_r^{1/2} + a_5 \times \left[ \frac{\varepsilon_0(x)}{\varepsilon(r_a, x)} \right]^{\frac{3}{2}} \times N_r^{\frac{1}{6}}, \quad N_r \equiv \left( \frac{N_a}{9.999 \times 10^{17} \text{ cm}^{-3}} \right), \quad (14p)$$

where  $a_1 = 3.15 \times 10^{-3}(\text{eV})$ ,  $a_2 = 5.41 \times 10^{-4}(\text{eV})$ ,  $a_3 = 2.32 \times 10^{-3}(\text{eV})$ ,  $a_4 = 4.12 \times 10^{-3}(\text{eV})$  and  $a_5 = 9.80 \times 10^{-5}(\text{eV})$ .

Therefore, in the HD[d(a)-  $X(x)$  - alloy] ER, we can define the effective extrinsic carrier concentration,  $n_{\text{en(ep)}}^*$ , by :

$$n_{\text{en(ep)}}^* (N_{d(a)}, T, r_{d(a)}, x) \equiv \sqrt{N_{d(a)} \times p_o(n_o)} = n_{\text{in(ip)}}(T, r_{d(a)}, x) \times \exp \left[ \frac{\Delta E_{agn(aggp)}}{2k_B T} \right], \quad (15)$$

where the apparent band gap narrowing (ABGN),  $\Delta E_{agn(aggp)}$ , is defined by:

$$\Delta E_{agn}(N_d, T, r_d, x) \equiv \Delta E_{gn}(N_d, r_d, x) + k_B T \times \ln \left( \frac{N_d}{N_c(T, x)} \right) - E_{Fn}(N_d, T, x), \quad (16n)$$

$$\Delta E_{aggp}(N_a, T, r_a, x) \equiv \Delta E_{gp}(N_a, r_a, x) + k_B T \times \ln \left( \frac{N_a}{N_v(T, x)} \right) + E_{Fp}(N_a, T, x). \quad (16p)$$

## E. Total minority-carrier saturation current density

In the two  $n^+(p^+) - p(n)$   $X(x)$ - alloy -junction solar cells, denoted respectively by I(II), the total carrier-minority saturation current density is defined by:

$$J_{oI(oII)} \equiv J_{Eno(Epo)} + J_{Bpo(Bno)} \quad (17)$$

where  $J_{Bpo(Bno)}$  is the minority-electron (hole) saturation current density injected into the LD[a(d)-  $X(x)$ - alloy] BR, and  $J_{Eno(Epo)}$  is the minority-hole (electron) saturation-current density injected into the HD[d(a)-  $X(x)$ - alloy] ER.

### $J_{Bpo(Bno)}$ in the LD[a(d)- $X(x)$ - alloy]BR

Here,  $J_{Bpo(Bno)}$  is determined by [1, 2]:

$$J_{Bpo(Bno)}(N_{a(d)}, T, r_{a(d)}, x) = \frac{e \times n_{ip(in)}^2(T, r_{a(d)}, x) \times \sqrt{\frac{D_{e(h)}(N_{a(d)}, T, r_{a(d)}, x)}{\tau_{eB(hB)}(N_{a(d)})}}}{N_{a(d)}}, \quad (18)$$

where  $n_{ip(in)}^2(T, r_{d(a)}, x)$  is determined Eq. (10),  $D_{e(h)}(N_{a(d)}, T, r_{a(d)}, x)$  is the minority electron (minority hole) diffusion coefficient:

$$D_e(N_a, T, r_a, x) = \frac{k_B T}{e} \times \left[ 850 + \frac{5750}{1 + \left( \frac{N_a}{8 \times 10^{17} \text{ cm}^{-3}} \right)^{1.8}} \right] \times \left( \frac{\varepsilon(r_a, x)}{\varepsilon_0(x)} \right)^2 (\text{cm}^2 \text{s}^{-1}), \quad (19a)$$

$$D_h(N_d, T, r_d, x) = \frac{k_B T}{e} \times \left[ 85 + \frac{1165}{1 + \left( \frac{N_d}{4 \times 10^{17} \text{ cm}^{-3}} \right)^{0.44}} \right] \times \left( \frac{\varepsilon(r_d, x)}{\varepsilon_0(x)} \right)^2 (\text{cm}^2 \text{s}^{-1}), \quad (19b)$$

and  $\tau_{eB(hB)}(N_{a(d)})$  is the minority electron (minority hole) lifetime in the BR:

$$\tau_{eB}(N_a)^{-1} = \frac{1}{10^{-7}} + 3 \times 10^{-13} \times N_a + 1.83 \times 10^{-31} \times N_a^2, \quad (20a)$$

$$\tau_{hB}(N_d)^{-1} = \frac{1}{10^{-7}} + 11.76 \times 10^{-13} \times N_d + 2.78 \times 10^{-31} \times N_d^2. \quad (20b)$$

### **$J_{Eno(Epo)}$ in the HD[d(a)- X(x)- alloy]ER**

In the non-uniformly and heavily doped emitter region of d(a)- X(x) devices, the effective Gaussian d(a)- density profile or the d(a) (majority-e(h)) density, is defined in such the HD[d(a)- X(x) alloy] ER-width W, as [1, 2]:

$$\rho_{d(a)}(y, N_{d(a)}, W) = N_{d(a)} \times \exp \left\{ - \left( \frac{y}{W} \right)^2 \times \ln \left[ \frac{N_{d(a)}}{N_{do(ao)}(W)} \right] \right\} \equiv N_{d(a)} \times \left[ \frac{N_{d(a)}}{N_{do(ao)}(W)} \right]^{-\left( \frac{y}{W} \right)^2}, \quad 0 \leq y \leq W, \quad (21)$$

$$N_{do(ao)}(W) \equiv 7.9 \times 10^{17} (2 \times 10^5) \times \exp \left\{ - \left( \frac{W}{184.2 (1) \times 10^{-7} \text{ cm}} \right)^{1.066 (0.5)} \right\} (\text{cm}^{-3}),$$

where  $\rho_{d(a)}(y = 0) = N_{d(a)}$  is the surface d(a)-density, and at the emitter-base junction,  $\rho_{d(a)}(y = W) = N_{do(ao)}(W)$ , which decreases with increasing W. Further, the “effective doping density” is defined by:

$$N_{d(a)}^*(y, N_{d(a)}, T, r_{d(a)}, x) \equiv \rho_{d(a)}(y) / \exp \left[ \frac{\Delta E_{agn(agg)}(\rho_{d(a)}, T, r_{d(a)}, x)}{k_B T} \right],$$

$$N_{d(a)}^*(y = 0, N_{d(a)}, T, r_{d(a)}, x) \equiv \frac{N_{d(a)}}{\exp \left[ \frac{\Delta E_{agn(agg)}(N_{d(a)}, T, r_{d(a)}, x)}{k_B T} \right]}, \text{ and}$$

$$N_{d(a)}^*(y = W, T, r_{d(a)}, x) \equiv \frac{N_{do(ao)}(W)}{\exp \left[ \frac{\Delta E_{agn(agg)}(N_{do(ao)}(W), T, r_{d(a)}, x)}{k_B T} \right]}, \quad (22)$$

where the apparent band gap narrowing  $\Delta E_{agn(agg)}$  is determined in Eq. (16), replacing  $N_{d(a)}$  by  $\rho_{d(a)}(y, N_{d(a)}, W)$ .

Now, we can define the minority hole (minority electron) transport parameter  $F_{h(e)}$  as:

$$F_{h(e)}(y, N_{d(a)}, T, r_{d(a)}, x) \equiv \frac{n_{in(ip)}^2(T, r_{d(a)})}{p_o(n_o) \times D_{h(e)}} = \frac{N_{d(a)}^*}{D_{h(e)}} \equiv \frac{N_{d(a)}}{D_{h(e)}} \times \left( \frac{n_{in(ip)}}{n_{in(ip)}^*} \right)^2 \equiv \frac{N_{d(a)}}{D_{h(e)} \times \exp \left[ \frac{\Delta E_{agn(agg)}}{k_B T} \right]} (\text{cm}^{-5} \times \text{s}), \quad (23)$$

the minority hole (electron) diffusion length,  $L_{h(e)}(y, N_{d(a)}, T, r_{d(a)}, x)$  by:

$$L_{h(e)}^{-2}(y, N_{d(a)}, T, r_{d(a)}, x) = [\tau_{hE(eE)} \times D_{h(e)}]^{-1} = (C \times F_{h(e)})^2 = \left( C \times \frac{N_{d(a)}^*}{D_{h(e)}} \right)^2 = \left( C \times \frac{n_{in(ip)}^2(T, r_{d(a)})}{p_o(n_o) \times D_{h(e)}} \right)^2,$$

where the constant C was chosen to be equal to:  $2.0893 \times 10^{-30} (\text{cm}^4/\text{s})$ , and the minority hole (minority electron) lifetime  $\tau_{hE(eE)}$  as:

$$\tau_{hE(eE)} \equiv \frac{1}{D_{h(e)} \times L_{h(e)}^{-2}} = \frac{1}{D_{h(e)} \times (C \times F_{h(e)})^2}. \quad (24)$$

Then, under low-level injection, in the absence of external generation, and for the steady-state case, we can define the minority-h(e) density by:



$$p_o(y)[n_o(y)] \equiv \frac{n_{in(ip)}^2}{N_{d(a)}^*(y=W, T, r_{d(a)}, x)}, \quad (25)$$

and a normalized excess minority-h(e) density  $u(x)$  or a relative deviation between  $p(y)[n(y)]$  and  $p_o(y)[n_o(y)]$ .

$$u(y) \equiv \frac{p(y)[n(y)] - p_o(y)[n_o(y)]}{p_o(y)[n_o(y)]}, \quad (26)$$

which must verify the two following boundary conditions as:

$$u(y=0) \equiv \frac{-J_h(y=0)[J_e(y=0)]}{eS \times p_o(y=0)[n_o(y=0)]},$$

$$u(y=W) = \exp\left(\frac{V}{n_{l(l)}(V) \times V_T}\right) - 1.$$

Here,  $n_{l(l)}(V)$  is a photovoltaic conversion factor determined latter,  $S$  ( $\frac{cm}{s}$ ) is the surface recombination velocity at the emitter contact,  $V$  is the applied voltage,  $V_T \equiv (k_B T / e)$  is the thermal voltage, and the minority-hole (electron) current density  $J_{h(e)}(y, r_{d(a)}, x)$ .

Further, from the Fick's law for minority hole (electron)-diffusion equations, one has [1, 2]:

$$J_{h(e)}(y, r_{d(a)}, x) = \frac{-e(+e) \times n_{in(ip)}^2}{F_{h(e)}(y)} \times \frac{du(y)}{dy} = \frac{-e(+e) n_{in(ip)}^2 D_{h(e)}(N_{d(a)}, r_{d(a)}, x)}{N_{d(a)}^*(y, r_{d(a)}, x)} \times \frac{du(y)}{dy}, \quad (27)$$

where  $N_{d(a)}^*(y, r_{d(a)}, x)$  is given in Eq. (22),  $D_{h(e)}$  and  $F_{h(e)}$  are determined respectively in Equations (19) and (23), and from the minority-hole (electron) continuity equation as:

$$\frac{dJ_{h(e)}(y, r_{d(a)}, x)}{dy} = -e(+e) \times n_{in(p)}^2 \times \frac{u(y)}{F_{h(e)}(y) \times L_{h(e)}^2(y)} = -e(+e) \times n_{in(p)}^2 \times \frac{u(y)}{N_{d(a)}^*(y, r_{d(a)}, x) \times \tau_{hE}(eE)}, \quad (28)$$

Therefore, the following second-order differential equation is obtained:

$$\frac{d^2 u(y)}{dy^2} - \frac{dF_{h(e)}(y)}{dy} \times \frac{du(y)}{dy} - \frac{u(y)}{L_{h(e)}^2(y)} = 0, \quad (29)$$

Then, taking into account the two above boundary conditions given in Eq. (22), one thus gets the general solution of this Eq. (29), as:

$$u(y) = \frac{\sinh(P(y)) + I(W, S) \times \cosh(P(y))}{\sinh(P(W)) + I(W, S) \times \cosh(P(W))} \times \left( \exp\left(\frac{V}{n_{l(l)}(V) \times V_T}\right) - 1 \right), \quad (30)$$

where the factor  $I(W, S)$  is determined by:  $D_{h(e)}(N_d, T, r_{d(a)}, x)$

$$I(T, r_{d(a)}, x, W, S) = \frac{D_{h(e)}(y=W, N_{do(ao)}(W), T, r_{d(a)}, x)}{S \times L_{h(e)}(y=W, N_{do(ao)}(W), T, r_{d(a)}, x)}. \quad (31)$$

Further, since  $\frac{dP(y)}{dy} \equiv C \times F_{h(e)}(y) = \frac{1}{L_{h(e)}(x)}$ ,  $C = 2.0893 \times 10^{-30}$  ( $cm^4/s$ ), for the X(x)-alloy, being an empirical parameter, chosen for each crystalline semiconductor,  $P(y)$  is thus found to be defined by:

$$P(y) \equiv \int_0^y \frac{dy}{L_{h(e)}(y)} \quad , \quad 0 \leq y \leq W \quad , \quad P(y=W) \equiv \left( \frac{1}{W} \times \int_0^W \frac{dy}{L_{h(e)}(y)} \right) \times W \equiv \frac{W}{L_{h(e)}^*(y)} = \frac{L_{h(e)}(y)}{L_{h(e)}^*(y)} \times \frac{W}{L_{h(e)}(y)}, \quad (32)$$

where  $L_{h(e)}^*(y)$  is the effective minority hole (minority electron) diffusion length. Further, the minority-hole (electron) current density injected into the HD[d(a)- X(x) alloy] ER is found to be given by:

$$J_{h(e)}(y, W, N_{d(a)}, T, r_{d(a)}, x, S, V) = -J_{Eno}(y, W, N_d, T, r_d, x, S) [J_{Epo}(y, W, N_a, T, r_a, x, S)] \times \left( \exp\left(\frac{V}{n_{i(II)}(V) \times V_T}\right) - 1 \right), \quad (33)$$

where  $J_{Eno(Epo)}$  is the saturation minority hole (minority electron) current density,

$$J_{Eno(Epo)}(y, W, N_{d(a)}, T, r_{d(a)}, x, S) = \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(y, N_{d(a)}, T, r_{d(a)}, x) \times L_{h(e)}} \times \frac{\cosh(P(x)) + I(W, S) \times \sinh(P(x))}{\sinh(P(W)) + I(W, S) \times \cosh(P(W))}. \quad (34)$$

In the following, we will denote  $P(W)$  and  $I(W, S)$  by  $P$  and  $I$ , for a simplicity. So, Eq. (30) gives:

$$J_{Eno(Epo)}(y = 0, W, N_{d(a)}, T, r_{d(a)}, x, S) = \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(y, N_{d(a)}, T, r_{d(a)}, x) \times L_{h(e)}} \times \frac{1}{\sinh(P) + I \times \cosh(P)}, \quad (35)$$

$$J_{Eno(Epo)}(y = W, W, N_{d(a)}, T, r_{d(a)}, x, S) = \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(y=W, N_{d(a)}, T, r_{d(a)}, x) \times L_{h(e)}} \times \frac{\cosh(P) + I \times \sinh(P)}{\sinh(P) + I \times \cosh(P)}, \quad (36)$$

and then,

$$\frac{J_{h(e)}(y=0, W, N_{d(a)}, T, r_{d(a)}, x, S, V)}{J_{h(e)}(y=W, W, N_{d(a)}, T, r_{d(a)}, x, S, V)} \equiv \frac{J_{Eno(Epo)}(y=0, W, N_{d(a)}, T, r_{d(a)}, x, S)}{J_{Eno(Epo)}(y=W, W, N_{d(a)}, T, r_{d(a)}, x, S)} = \frac{1}{\cosh(P) + I \times \sinh(P)}. \quad (37)$$

Now, if defining the effective excess minority-hole (electron) charge storage in the emitter region by:

$$Q_{h(e)}^*(y = W, N_{d(a)}, T, r_{d(a)}, x) \equiv \int_0^W +e(-e) \times u(y) \times p_o(y) [n_o(y)] \times \frac{\tau_{hE(eE)}(N_{d(a)}, T, r_{d(a)}, x)}{\tau_{hE(eE)}(\rho_{d(a)}(x), T, r_{d(a)}, x)} dy, \text{ and the}$$

effective minority hole (minority electron) transit time  $[htt(ett)]$  by:  $\tau_{htt(ett)}^*(y = W, W, N_{d(a)}, r_{d(a)}, x, S) \equiv$

$Q_{h(e)}^*(y = W, N_{d(a)}, T, r_{d(a)}, x) / J_{Eno(Epo)}(y = W, W, N_{d(a)}, T, r_{d(a)}, x, S)$ , and from Equations (24, 31), one obtains:

$$\frac{\tau_{htt(ett)}^*(y=W, W, N_{d(a)}, T, r_{d(a)}, x, S)}{\tau_{hE(eE)}} \equiv 1 - \frac{J_{Eno(Epo)}(y=0, W, N_{d(a)}, T, r_{d(a)}, x, S)}{J_{Eno(Epo)}(y=W, W, N_{d(a)}, T, r_{d(a)}, x, S)} = 1 - \frac{1}{\cosh(P) + I \times \sinh(P)}. \quad (38)$$

Now, some important results can be obtained and discussed below.

As  $P \ll 1$  (or  $W \ll L_{h(e)}$ ) and  $S \rightarrow \infty$ ,  $I \equiv I(W, S) = \frac{D_{h(e)}(N_{do(ao)}(W), T, r_{d(a)}, x)}{S \times L_{h(e)}(N_{do(ao)}(W), T, r_{d(a)}, x)} \rightarrow 0$ , from Eq. (38), one has:

$$\frac{\tau_{htt(ett)}^*(y=W, W, N_{d(a)}, T, r_{d(a)}, x, S)}{\tau_{hE(eE)}} \rightarrow 0, \text{ suggesting a completely transparent emitter region (CTER)-case, where,}$$

from Eq. (36), one obtains:

$$J_{Eno(Epo)}(y = W, N_{d(a)}, T, r_{d(a)}, x, S \rightarrow \infty) \rightarrow \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(y=W, N_{d(a)}, T, r_{d(a)}, x) \times L_{h(e)}} \times \frac{1}{P(W)}. \quad (39)$$

Further, as  $P \gg 1$  (or  $W \gg L_{h(e)}$ ) and  $S \rightarrow 0$ ,  $I \equiv I(y = W, r_{d(a)}, x, S) = \frac{D_{h(e)}(N_{do(ao)}(W), T, r_{d(a)}, x)}{S \times L_{h(e)}(N_{do(ao)}(W), T, r_{d(a)}, x)} \rightarrow \infty$ , and

from Eq. (38) one has:  $\frac{\tau_{htt(ett)}^*(y=W, W, N_{d(a)}, T, r_{d(a)}, x, S)}{\tau_{hE(eE)}} \rightarrow 1$ , suggesting a completely opaque emitter region

(COER)-case, where, from Eq. (36), one gets:

$$J_{Eno(Epo)}(y = W, N_{d(a)}, T, r_{d(a)}, x, S \rightarrow 0) \rightarrow \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(y=W, N_{d(a)}, T, r_{d(a)}, x) \times L_{h(e)}} \times \tanh(P). \quad (40)$$

In summary, in the two  $n^+(p^+) - p(n)$  X(x)-alloy junction solar cells, the dark carrier-minority saturation current density  $J_{ol(oII)}$ , defined in Eq. (17), is now rewritten as:

$$J_{ol(oII)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, r_{a(d)}, x) \equiv J_{Eno(Epo)}(W, N_{d(a)}, T, r_{d(a)}, x, S) + J_{Bpo(Bno)}(N_{a(d)}, T, r_{a(d)}, x), \quad (41)$$

where  $J_{Eno(Epo)}$  and  $J_{Bpo(Bno)}$  are determined respectively in Equations (36, 18).

### 3. Photovoltaic conversion effect at 300K

Here, in the  $n^+(p^+) - p(n)$   $X(x)$  -alloy junction solar cells at  $T=300$  K, denoted respectively by  $I(II)$ , and for physical conditions, respectively, as:

$$W = 0.1 \mu\text{m}, N_{d \equiv S(a \equiv Cd)} = 10^{20} \text{ cm}^{-3}, r_{d(a)}, x, S = 100 \left( \frac{\text{cm}}{\text{s}} \right); N_{a \equiv Cd(d \equiv S)} = 10^{17} \text{ cm}^{-3}, r_{a(d)}, x, \quad (42)$$

we propose, at given open circuit voltages:  $V_{ocI(ocI2)}$  and  $V_{ocII1(ocII2)}$ , the corresponding data of the short circuit current density  $J_{scI(II)}$ , in order to formulate our following treatment method of two fix points, as:

$$\text{at } V_{ocI(ocI2)} = V_{ocII1(ocII2)} = 2.041 (2.076) \text{ V},$$

$$J_{scI(scI2)} = J_{scII1(scII2)} = 0.00749 (0.00939) \text{ (A/cm}^2\text{)}, \quad (43)$$

noting that these numerical results are given in Ref. [6], in which the authors assumed that the “quality factor  $n$ ” is equal to 1.

Now, we define the net current density  $J$  at  $T=300$  K, obtained for the infinite shunt resistance, and expressed as a function of the applied voltage  $V$ , flowing through the  $n^+(p^+) - p(n)$   $X(x)$ -alloy junction of solar cells, as:

$$J(V) \equiv J_{ph.}(V) - J_{ol(olI)} \times (e^{X_{I(II)}(V)} - 1), \quad X_{I(II)}(V) \equiv \frac{V}{n_{I(II)}(V) \times V_T}, \quad V_T \equiv \frac{k_B T}{e} = 0.02585 \text{ V}, \quad (44)$$

where the function  $n_{I(II)}(V)$  is the photovoltaic conversion factor (PVCF), noting that as  $V = V_{oc}$ , being the open circuit voltage,  $J(V = V_{oc}) = 0$ , the photocurrent density is defined by:  $J_{ph.}(V = V_{oc}) \equiv J_{scI(scII)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x, V_{oc})$ , for  $V_{oc} \geq V_{ocI(ocII1)}$ .

Therefore, the photovoltaic conversion effect occurs, according to:

$$J_{scI(scII)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x, V_{oc}) \equiv J_{ol(olI)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x) \times (e^{X_{I(II)}(V_{oc})} - 1), \quad (45)$$

where  $n_{I(II)}(V_{oc}) \equiv n_{I(II)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, r_{a(d)}, x, V_{oc})$ , and  $X_{I(II)}(V_{oc}) \equiv \frac{V_{oc}}{n_{I(II)}(V_{oc}) \times V_T}$ .

Here, one remarks that (i) for a given  $V_{oc}$ , both  $n_{I(II)}$  and  $J_{ol(olI)}$  have the same variations, obtained in the same physical conditions, as observed in the following calculation, (ii) the function  $(e^{X_{I(II)}(V_{oc})} - 1)$  or the PVCF,  $n_{I(II)}$ , representing the photovoltaic conversion effect, converts the light, represented by  $J_{scI(scII)}$ , into the electricity, by  $J_{ol(olI)}$ , and finally, for given  $(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x, V_{oc})$ -values,  $n_{I(II)}(V_{oc})$  is determined.

Now, for  $V_{oc} \geq V_{ocI(ocII1)}$ , one can propose the general expressions for the PVCF, in order to get exactly the values of  $n_{I1(II1)}(V_{ocI(ocII1)})$  and  $n_{I2(II2)}(V_{ocI2(ocII2)})$ , as functions of  $V_{oc}$ , by:

$$n_{I(II)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x, V_{oc}) = n_{I1(II1)}(V_{ocI(ocII1)}) + n_{I2(II2)}(V_{ocI2(ocII2)}) \times \left( \frac{V_{oc}}{V_{ocI(ocII1)}} - 1 \right)^{\alpha(\beta)}, \quad (46)$$

where, for example, the values of  $\alpha(\beta)$ , obtained for  $x = (0, 0.5, 0.75, \text{ and } 1)$ , will be reported in Tables 2.2 and 3.2, for  $\text{CdS}_{1-x}\text{Se}_x$  alloy junctions, and in Tables 4.2 and 5.2, for  $\text{CdS}_{1-x}\text{Te}_x$  alloy junctions, respectively. One also notes that those  $\alpha(\beta)$ -values depend on  $(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x)$ -ones.

So, one can determine the general expressions for the fill factors, as:

$$F_{I(II)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x, V_{oc}) = \frac{X_{I(II)}(V_{oc}) - \ln[X_{I(II)}(V_{oc}) + b]}{X_{I(II)}(V_{oc}) + a}, \quad a=1 \text{ and } b=0.72. \quad (47)$$

Finally, the efficiency  $\eta_{I(II)}$  can be defined in the  $n^+(p^+) - p(n)$   $X(x)$  alloy-junction solar cells, by:

$$\eta_{I(II)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x, V_{oc}) \equiv \frac{J_{scI(scII)} \times V_{oc} \times F_{I(II)}}{P_{in.}}, \quad (48)$$

being assumed to be obtained at 1 sun illumination or at AM1.5G spectrum ( $P_{in.} = 0.100 \frac{W}{cm^2}$ ).

It should be noted that the maximal values of  $\eta_{I(II)}$ ,  $\eta_{I(II)max.}$ , are obtained at the corresponding ones of  $V_{oc} = V_{oc;max.}$ , at which  $\frac{\partial \eta_{I(II)}(W, N_{d(a)}, T, r_{d(a)}, S, N_{a(d)}, T, r_{a(d)}, V_{oc})}{\partial V_{oc}} = 0$ , as those given in next Tables 2.2, 3.2, 4.2 and 5.2, being marked in bold. Further, from the well-known Carnot's theorem, being obtained by the second principle in thermodynamics, or by the entropy law, the maximum efficiency of a heat engine operating between hot (H) and cold (C) reservoirs is the ratio of the temperature difference between the reservoirs,  $T_H - T_C$ , to the H-reservoir temperature,  $T_H$ , expressed as:

$$\eta_{I(II)max.}(W, N_{d(a)}, T, r_{d(a)}, S, N_{a(d)}, T, r_{a(d)}, V_{oc;max.}) = 1 - \frac{T_C=300 \text{ K}}{T_H(W, N_{d(a)}, T, r_{d(a)}, S, N_{a(d)}, T, r_{a(d)}, V_{oc;max.})}. \quad (49)$$

## 4. Numerical Results and Concluding Remarks

We will respectively consider the two following cases of  $n^+(p^+) - p(n)$  -junctions such as:

*HD (Se ; Te; Sn) X(x) alloy ER – LD (Mg ; In ; Cd) X(x) – alloy BR* –case, according to: 3 ( $n^+p$ ) – junctions denoted by: ( $Se^+Mg, Te^+In, Sn^+Cd$ ), and

*HD (Mg ; In ; Cd) X(x) alloy ER – LD (Se ; Te; Sn) X(x) – alloy BR* –case, according to: 3 ( $p^+n$ ) – junctions denoted by: ( $Mg^+Se, In^+Te, Cd^+Sn$ ).

Now, by using the physical conditions, given in Eq. (42), we can determine various following photovoltaic conversion coefficients.

### (4. 1) X(x) $\equiv$ $CdS_{1-x}Se_x$ – Alloy

**Firs case: HD [ Se ; Te; Sn]  $CdS_{1-x}Se_x$  Alloy ER – LD [ Mg ; In ; Cd ]  $CdS_{1-x}Se_x$  Alloy BR**

Here, there are the 3 ( $n^+p$ ) –  $CdS_{1-x}Se_x$  junctions, being denoted by: ( $Se^+Mg, Te^+In, Sn^+Cd$ ).

Then, the numerical results of  $\frac{\tau_{htt}^*}{\tau_{hE}}$ ,  $J_{Bpo}$ ,  $J_{Eno}$  and  $J_{ol}$ , are calculated using Equations (38), (18), (36) and (41), respectively, and obtained, as those given in Table 2.1. Further, those of  $n_l$ ,  $J_{scl}$ ,  $F_l$ ,  $\eta_l$ , and  $T_H$ , are computed, using Equations (46, 45, 47, 48, 49), respectively, and reported in the following Table 2.2.

**Table 2.1** In the HD [(Se; Te; Sn)-  $CdS_{1-x}Se_x$ -alloy] ER-LD[( Mg; In; Cd )- $CdS_{1-x}Se_x$ -alloy] BR, for physical conditions given in Eq. (42) and for a given x, our numerical results of  $\frac{\tau_{htt}^*}{\tau_{hE}}$ ,  $J_{Bpo}$ ,  $J_{Eno}$  and  $J_{ol}$ , are computed, using Equations (38), (18), (36) and (41), respectively, noting that  $J_{ol}$  decreases slightly with increasing  $r_{d(a)}$ -radius for given x, but it increases strongly with increasing x for given  $r_{d(a)}$ -radius, being new results.

$n^+p$	$Se^+Mg$	$Te^+In$	$Sn^+Cd$
Here, $x=0$ , and for the ( $Se^+Mg, Te^+In, Sn^+Cd$ ) -junctions and from Eq. (34), one obtains: $\frac{\tau_{htt}^*}{\tau_{hE}} = (0, 0, 0)$ suggesting a completely transparent condition.			

$J_{Bpo}$ in $10^{-35}$ ( $A/cm^2$ ) $\searrow$	2.9988	2.9698	2.9602
$J_{Eno}$ in $10^{-38}$ ( $A/cm^2$ ) $\searrow$	1.0295	0.8985	0.7564
$J_{ol}$ in $10^{-35}$ ( $A/cm^2$ ) $\searrow$	2.9988	2.9707	2.9609

Here,  $x=0.5$ , and for the  $(Se^+Mg, Te^+In, Sn^+Cd)$  -junctions and from Eq. (34), one obtains:  $\frac{\tau_{ht}^*}{\tau_{hE}} = (0, 0, 0)$  suggesting a completely transparent condition.

$J_{Bpo}$ in $10^{-30}$ ( $A/cm^2$ ) $\searrow$	9.0481	8.9606	8.9315
$J_{Eno}$ in $10^{-35}$ ( $A/cm^2$ ) $\searrow$	6.8789	6.8402	6.7211
$J_{ol}$ in $10^{-30}$ ( $A/cm^2$ ) $\searrow$	9.0481	8.9607	8.9316

Here,  $x=0.75$ , and for the  $(Se^+Mg, Te^+In, Sn^+Cd)$  -junctions and from Eq. (34), one obtains:  $\frac{\tau_{ht}^*}{\tau_{hE}} = (0, 0, 0)$  suggesting a completely transparent condition.

$J_{Bpo}$ in $10^{-27}$ ( $A/cm^2$ ) $\searrow$	4.4951	4.4517	4.4372
$J_{Eno}$ in $10^{-33}$ ( $A/cm^2$ ) $\nearrow$	1.6729	1.7374	1.7954
$J_{ol}$ in $10^{-27}$ ( $A/cm^2$ ) $\searrow$	4.4951	4.4517	4.4372

Here,  $x=1$ , and for the  $(Se^+Mg, Te^+In, Sn^+Cd)$  -junctions and from Eq. (34), one obtains:  $\frac{\tau_{ht}^*}{\tau_{hE}} = (0, 0, 0)$  suggesting a completely transparent condition.

$J_{Bpo}$ in $10^{-24}$ ( $A/cm^2$ ) $\searrow$	2.0381	2.0184	2.0119
$J_{Eno}$ in $10^{-32}$ ( $A/cm^2$ ) $\nearrow$	1.0818	1.1671	1.2606
$J_{ol}$ in $10^{-24}$ ( $A/cm^2$ ) $\searrow$	2.0381	2.0184	2.0119

**Table 2.2** In the HD [(Se; Te; Sn)-  $CdS_{1-x}Se_x$ -alloy] ER-LD[( $Mg$ ;  $In$ ;  $Cd$ )- $CdS_{1-x}Se_x$ -alloy] BR, for physical conditions given in Eq. (42) and for a given  $x$ , our numerical results of  $n_I$ ,  $J_{scl}$ ,  $F_I$ ,  $\eta_I$ , and  $T_H$ , are computed, using Equations (46, 45, 47, 48, 49), respectively, noting that both  $\eta_{I_{max}}$  and  $T_H$ , marked in bold, increase with increasing  $x$  for given  $r_{d(a)}$ , being new results.

$V_{oc}(V)$	$n_I$	$J_{scl}(\frac{mA}{cm^2})$	$F_I(\%)$	$\eta_I(\%)$
Here, $x=0$ . For the $(Se^+Mg, Te^+In, Sn^+Cd)$ -junctions, the value of $\alpha$ given in Eq. (46) is: $\alpha = 1.052$ .				
$n^+p$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$
<b>2.041</b>	1.058; 1.058; 1.058	7.490; 7.490; 7.490	92.96; 92.96; 92.96	14.21; 14.21; 14.21
<b>2.076</b>	1.073; 1.073; 1.073	9.390; 9.390; 9.390	92.98; 92.98; 92.98	18.12; 18.12; 18.12
2.64	1.354; 1.354; 1.353	17.19; 17.19; 17.19	93.02; 93.02; 93.02	42.22; 42.23; 42.23
<b>2.65</b>	1.359; 1.359; 1.359	17.13; 17.13; 17.13	93.02; 93.02; 93.02	<b>42.23; 42.24; 42.24</b>
<b><math>V_{oc;max.} = 2.65 V</math></b>				<b><math>T_H(K) = 519.3; 519.4; 519.4</math></b>
2.66	1.364; 1.364; 1.364	17.07; 17.07; 17.07	93.02; 93.02; 93.02	42.23; 42.24; 42.24

3	1.543; 1.543; 1.543	13.65; 13.65; 13.66	93.00; 92.01; 93.01	38.10; 38.10; 38.10
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Here,  $x=0.5$ . For the  $(Se^+Mg, Te^+In, Sn^+Cd)$ -junctions, the value of  $\alpha$  given in Eq. (46) is:  $\alpha = 1.0635$ .

$n^+p$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$
<b>2.041</b>	1.274; 1.273; 1.273	7.490; 7.490; 7.490	91.84; 91.84; 91.84	14.04; 14.04; 14.04
<b>2.076</b>	1.291; 1.291; 1.290	9.406; 9.406; 9.406	91.86; 91.87; 91.87	17.94; 17.94; 17.94
2.68	1.649; 1.649; 1.649	18.02; 18.03; 18.03	91.93; 91.93; 91.93	44.41; 44.41; 44.42
<b>2.69</b>	1.655; 1.655; 1.655	17.96; 17.96; 17.96	91.93; 91.93; 91.93	<b>44.41; 44.41; 44.42</b>
<b><math>V_{oc,max.} = 2.69 V</math></b>			<b><math>T_H(K) = 539.7; 539.7; 339.8</math></b>	
2.70	1.662; 1.661; 1.661	17.89; 17.89; 17.89	91.93; 91.93; 91.93	44.40; 44.40; 44.41
3	1.852; 1.851; 1.851	14.80; 14.80; 14.80	91.91; 91.91; 91.91	40.81; 40.82; 40.82

Here,  $x=0.75$ . For the  $(Se^+Mg, Te^+In, Sn^+Cd)$ -junctions, the value of  $\alpha$  given in Eq. (46) is:  $\alpha = 1.071$ .

$n^+p$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$
<b>2.041</b>	1.415; 1.415; 1.415	7.490; 7.490; 7.490	91.13; 91.13; 91.13	13.93; 13.93; 13.93
<b>2.076</b>	1.434; 1.434; 1.433	9.403; 9.404; 9.404	91.16; 91.16; 91.16	17.79; 17.78; 17.80
2.69	1.836; 1.835; 1.835	18.49; 18.50; 18.50	91.24; 91.24; 91.24	45.39; 45.40; 45.40
<b>2.70</b>	1.843; 1.842; 1.842	18.43; 18.43; 18.43	91.24; 91.24; 91.24	<b>45.40; 45.41; 45.41</b>
<b><math>V_{oc,max.} = 2.70 V</math></b>			<b><math>T_H(K) = 549.4; 549.5; 549.5</math></b>	
2.71	1.850; 1.849; 1.849	18.36; 18.36; 18.36	91.24; 91.24; 91.24	45.40; 45.40; 45.41
3	2.054; 2.054; 2.053	15.38; 15.38; 15.38	91.22; 91.22; 91.22	42.09; 42.10; 42.10

Here,  $x=1$ . For the  $(Se^+Mg, Te^+In, Sn^+Cd)$ -junctions, the value of  $\alpha$  given in Eq. (46) is:  $\alpha = 1.0798$ .

$n^+p$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$	$Se^+Mg; Te^+In; Sn^+Cd$
<b>2.041</b>	1.590; 1.590; 1.590	7.490; 7.490; 7.490	90.29; 90.29; 90.29	13.80; 13.80; 13.80
<b>2.076</b>	1.610; 1.609; 1.609	9.384; 9.384; 9.384	90.32; 90.32; 90.32	17.59; 17.60; 17.60
2.71	2.072; 2.072; 2.071	18.80; 18.80; 18.80	90.43; 90.43; 90.43	46.06; 46.07; 46.07
<b>2.72</b>	2.080; 2.079; 2.079	18.73; 18.73; 18.73	90.43; 90.43; 90.43	<b>46.06; 46.07; 46.07</b>
<b><math>V_{oc,max.} = 2.72 V</math></b>			<b><math>T_H(K) = 556.2; 556.3; 556.3</math></b>	
2.73	2.088; 2.087; 2.087	18.66; 18.66; 18.66	90.42; 90.43; 90.43	46.06; 46.06; 46.07
3	2.302; 2.301; 2.301	15.89; 15.89; 15.89	90.40; 90.40; 90.40	43.10; 43.11; 43.11

### **Second case: $HD [Mg; In; Cd] CdS_{1-x}Se_x$ Alloy $ER - LD [Se; Te; Sn] CdS_{1-x}Se_x$ Alloy $BR$**

Here, there are 3  $(p^+n) - CdS_{1-x}Se_x$  junctions, being denoted by:  $(Mg^+Se, In^+Te, Cd^+Sn)$ .

Then, the numerical results of  $\frac{\tau_{ett}^*}{\tau_{eE}}$ ,  $J_{Bno}$ ,  $J_{Epo}$  and  $J_{oII}$ , are calculated using Equations (38), (18), (36) and (41), respectively, and obtained, as those given in Table 3.1. Further, those of  $n_{II}$ ,  $J_{scII}$ ,  $F_{II}$ ,  $\eta_{II}$ , and  $T_H$ , are computed, using Equations (46, 45, 47, 48, 49), respectively, and reported in the following Table 3.2.

**Table 3.1** In the HD [(Mg; In; Cd)- CdS<sub>1-x</sub>Se<sub>x</sub>-alloy] ER-LD[(Se; Te; Sn)- CdS<sub>1-x</sub>Se<sub>x</sub>-alloy] BR, for physical conditions given in Eq. (42) and for a given x, our numerical results of  $\frac{\tau_{ett}^*}{\tau_{eE}}$ ,  $J_{Bno}$ ,  $J_{Epo}$ , and  $J_{oII}$  are computed, using Equations (38), (18), (36) and (41), respectively, noting that  $J_{oII}$  decreases slightly with increasing  $r_{a(d)}$ -radius for given x, but it increases strongly with increasing x for given  $r_{a(d)}$ -radius, being new results.

$p^+n$	$Mg^+Se$	$In^+Te$	$Cd^+Sn$
Here, $x=0$ , and for the $(Mg^+Se, In^+Te, Cd^+Sn)$ -junctions and from Eq. (34), one obtains: $\frac{\tau_{ett}^*}{\tau_{eE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bno}$ in $10^{-35} (A/cm^2) \searrow$	1.7992	0.6102	0.2687
$J_{Epo}$ in $10^{-34} (A/cm^2) \searrow$	1.5401	1.3943	1.3480
$J_{oII}$ in $10^{-34} (A/cm^2) \searrow$	1.7200	1.4553	1.3749
Here, $x=0.5$ , and for the $(Mg^+Se, In^+Te, Cd^+Sn)$ -junctions and from Eq. (34), one obtains: $\frac{\tau_{ett}^*}{\tau_{eE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bno}$ in $10^{-30} (A/cm^2) \searrow$	4.5499	2.0135	1.1008
$J_{Epo}$ in $10^{-29} (A/cm^2) \searrow$	1.8969	1.7732	1.7332
$J_{oII}$ in $10^{-29} (A/cm^2) \searrow$	2.3519	1.9746	1.8432
Here, $x=0.75$ , and for the $(Mg^+Se, In^+Te, Cd^+Sn)$ -junctions and from Eq. (34), one obtains: $\frac{\tau_{ett}^*}{\tau_{eE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bno}$ in $10^{-27} (A/cm^2) \searrow$	2.0992	1.0386	0.6217
$J_{Epo}$ in $10^{-27} (A/cm^2) \searrow$	5.3289	5.0488	4.9572
$J_{oII}$ in $10^{-27} (A/cm^2) \searrow$	7.4281	6.0873	5.5789
Here, $x=1$ , and for the $(Mg^+Se, In^+Te, Cd^+Sn)$ -junctions and from Eq. (34), one obtains: $\frac{\tau_{ett}^*}{\tau_{eE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bno}$ in $10^{-25} (A/cm^2) \searrow$	8.9090	4.8693	3.1605
$J_{Epo}$ in $10^{-24} (A/cm^2) \searrow$	1.1251	1.0790	1.0638
$J_{oII}$ in $10^{-24} (A/cm^2) \searrow$	2.0160	1.5659	1.3798

**Table 3.2** In the HD [(*Mg*; *In*; *Cd*)- *CdS*<sub>1-*x*</sub>*Se*<sub>*x*</sub>-alloy] ER-LD[(*Se*; *Te*; *Sn*)-*CdS*<sub>1-*x*</sub>*Se*<sub>*x*</sub>-alloy] BR, for physical conditions given in Eq. (42) and for a given *x*, our numerical results of *n*<sub>II</sub>, *J*<sub>scII</sub>, *F*<sub>II</sub>, *η*<sub>II</sub>, and *T*<sub>H</sub>, are computed, using Equations (46, 45, 47, 48, 49), respectively, noting that both *η*<sub>II<sub>max</sub></sub> and *T*<sub>H</sub>, marked in bold, increase with increasing *x* for given *r*<sub>a(*d*)</sub>, being new results.

<i>V</i> <sub>oc</sub> (V)	<i>n</i> <sub>II</sub>	<i>J</i> <sub>scII</sub> ( $\frac{mA}{cm^2}$ )	<i>F</i> <sub>II</sub> (%)	<i>η</i> <sub>II</sub> (%)
Here, <b>x=0</b> . For the ( <i>Mg</i> <sup>+</sup> <i>Se</i> , <i>In</i> <sup>+</sup> <i>Te</i> , <i>Cd</i> <sup>+</sup> <i>Sn</i> )-junctions, the value of <i>α</i> given in Eq. (46) is: <i>β</i> = 1.0533.				
<i>p</i> <sup>+</sup> <i>n</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>
<b>2.041</b>	1.084; 1.081; 1.080	7.490; 7.490; 7.490	92.82; 92.84; 92.84	14.19; 14.19; 14.19
<b>2.076</b>	1.099; 1.096; 1.095	9.391; 9.395; 9.397	92.84; 92.85; 92.86	18.10; 18.11; 18.12
2.65	1.391; 1.388; 1.387	17.26; 17.29; 17.30	92.89; 92.90; 92.91	42.49; 42.57; 42.60
<b>2.66</b>	1.396; 1.393; 1.392	17.20; 17.23; 17.24	92.89; 92.90; 92.91	<b>42.49; 42.57; 42.60</b>
<b><i>V</i><sub>oc;max.</sub> = 2.66 V</b>		<b><i>T</i><sub>H</sub>(K) =521.6; 522.4; 522.6</b>		
2.67	1.402; 1.398; 1.397	17.13; 17.16; 17.17	92.89; 92.90; 92.91	42.48; 42.56; 42.59
3	1.579; 1.576; 1.575	13.79; 13.81; 13.82	92.87; 92.89; 92.89	38.44; 38.49; 38.51
Here, <b>x=0.5</b> . For the ( <i>Mg</i> <sup>+</sup> <i>Se</i> , <i>In</i> <sup>+</sup> <i>Te</i> , <i>Cd</i> <sup>+</sup> <i>Sn</i> )-junctions, the value of <i>α</i> given in Eq. (46) is: <i>β</i> = 1.064.				
<i>p</i> <sup>+</sup> <i>n</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>
<b>2.041</b>	1.293; 1.290; 1.288	7.490; 7.490; 7.490	91.74; 91.76; 91.77	14.02; 14.03; 14.03
<b>2.076</b>	1.311; 1.307; 1.306	9.389; 9.395; 9.397	91.76; 91.78; 91.79	17.88; 17.90; 17.91
2.68	1.675; 1.670; 1.668	17.94; 17.98; 18.00	91.83; 91.85; 91.86	44.16; 44.27; 44.32
<b>2.69</b>	1.681; 1.676; 1.674	17.88; 17.92; 17.93	91.83; 91.85; 91.86	<b>44.16; 44.27; 44.32</b>
<b><i>V</i><sub>oc;max.</sub> = 2.69 V</b>		<b><i>T</i><sub>H</sub>(K) =537.2; 538.3; 338.8</b>		
2.70	1.687; 1.682; 1.681	17.81; 17.85; 17.87	91.83; 91.85; 91.86	44.15; 44.27; 44.31
3	1.880; 1.875; 1.873	14.77; 14.80; 14.81	91.81; 91.83; 91.84	40.68; 40.76; 40.79
Here, <b>x=0.75</b> . For the ( <i>Mg</i> <sup>+</sup> <i>Se</i> , <i>In</i> <sup>+</sup> <i>Te</i> , <i>Cd</i> <sup>+</sup> <i>Sn</i> )-junctions, the value of <i>α</i> given in Eq. (46) is: <i>β</i> = 1.0712.				
<i>p</i> <sup>+</sup> <i>n</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>
<b>2.041</b>	1.428; 1.423; 1.421	7.490; 7.490; 7.490	91.07; 91.09; 91.10	13.92; 13.92; 13.93
<b>2.076</b>	1.447; 1.442; 1.439	9.390; 9.397; 9.401	91.10; 91.12; 91.13	17.76; 17.78; 17.78
2.69	1.852; 1.846; 1.843	18.41; 18.46; 18.49	91.18; 91.21; 91.22	45.15; 45.30; 45.37
<b>2.70</b>	1.859; 1.853; 1.850	18.34; 18.40; 18.42	91.18; 91.21; 91.22	<b>45.16; 45.31; 45.37</b>
<b><i>V</i><sub>oc;max.</sub> = 2.70 V</b>		<b><i>T</i><sub>H</sub>(K) =547.0; 548.5; 549.1</b>		
2.71	1.866; 1.860; 1.857	18.27; 18.33; 18.35	91.18; 91.21; 91.22	45.15; 45.30; 45.37
3	2.072; 2.065; 2.062	15.33; 15.37; 15.38	91.16; 91.18; 91.19	41.93; 42.04; 42.09
Here, <b>x=1</b> . For the ( <i>Mg</i> <sup>+</sup> <i>Se</i> , <i>In</i> <sup>+</sup> <i>Te</i> , <i>Cd</i> <sup>+</sup> <i>Sn</i> )-junctions, the value of <i>α</i> given in Eq. (46) is: <i>β</i> = 1.0801.				
<i>p</i> <sup>+</sup> <i>n</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>	<i>Mg</i> <sup>+</sup> <i>Se</i> ; <i>In</i> <sup>+</sup> <i>Te</i> ; <i>Cd</i> <sup>+</sup> <i>Sn</i>
<b>2.041</b>	<b>1.589; 1.581; 1.577</b>	<b>7.490; 7.490; 7.490</b>	<b>90.29; 90.33; 90.35</b>	<b>13.80; 13.81; 13.81</b>



<b>2.076</b>	1.609; 1.601; 1.597	9.391; 9.402; 9.407	90.32; 90.36; 90.38	17.61; 17.64; 17.65
2.71	2.072; 2.061; 2.056	18.87; 18.96; 19.00	90.43; 90.47; 90.48	46.25; 46.48; 46.59
<b>2.72</b>	2.080; 2.069; 2.064	18.80; 18.89; 18.93	90.43; 90.47; 90.48	<b>46.26; 46.48; 46.59</b>
<b><math>V_{oc,max.} = 2.72 \text{ V}</math></b>			<b><math>T_H(K) = 558.1; 560.5; 561.7</math></b>	
2.73	2.087; 2.077; 2.072	18.73; 18.82; 18.86	90.43; 90.47; 90.48	46.25; 46.47; 46.58
3	2.301; 2.290; 2.284	15.95; 16.01; 16.03	90.40; 90.44; 90.46	43.26; 43.43; 43.52

#### (4.2) $X(x) \equiv CdS_{1-x}Te_x - \text{Alloy}$

**Firs case: HD [ Se ; Te; Sn]  $CdS_{1-x}Te_x$  Alloy ER – LD [ Mg ; In ; Cd ]  $CdS_{1-x}Te_x$  Alloy BR**

Here, there are the 3  $(n^+p) - CdS_{1-x}Te_x$  junctions, being denoted by:  $(Se^+Mg, Te^+In, Sn^+Cd)$ .

Then, from above physical conditions, given in Eq. (42), the numerical results of  $\frac{\tau_{htt}^*}{\tau_{hE}}$ ,  $J_{Bpo}$ ,  $J_{Eno}$  and  $J_{ol}$ , are calculated using Equations (38), (18), (36) and (41), respectively, and obtained, as those given in Table 4.1. Further, those of  $n_l$ ,  $J_{scl}$ ,  $F_l$ ,  $\eta_l$  and  $T_H$  are computed, using Equations (46, 45, 47, 48, 49), respectively, and reported in the following Table 4.2.

**Table 4.1.** In the HD [(Se; Te; Sn)-  $CdS_{1-x}Te_x$ -alloy] ER-LD[(Mg; In; Cd)- $CdS_{1-x}Te_x$ -alloy] BR and for physical conditions given in Eq. (42) and for a given x, our numerical results of  $\frac{\tau_{htt}^*}{\tau_{hE}}$ ,  $J_{Bpo}$ ,  $J_{Eno}$ , and  $J_{ol}$  are computed, using Equations (38), (18), (36) and (41), respectively, noting that  $J_{ol}$  decreases slightly for given x with increasing  $r_{d(a)}$ -radius for given x, but it increases strongly with increasing x for given  $r_{d(a)}$ -radius, being new results.

$n^+p$	Se <sup>+</sup> Mg	Te <sup>+</sup> In	Sn <sup>+</sup> Cd
Here, $x=0$ , and for the $(Se^+Mg, Te^+In, Sn^+Cd)$ -junctions and from Eq. (34), one obtains: $\frac{\tau_{htt}^*}{\tau_{hE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bpo}$ in $10^{-35} \text{ (A/cm}^2\text{)} \searrow$	5.8715	5.8148	5.7959
$J_{Eno}$ in $10^{-39} \text{ (A/cm}^2\text{)} \searrow$	9.8161	6.5403	4.4542
$J_{ol}$ in $10^{-35} \text{ (A/cm}^2\text{)} \searrow$	5.8725	5.8154	5.7963
Here, $x=0.5$ , and for the $(Se^+Mg, Te^+In, Sn^+Cd)$ -junctions and from Eq. (34), one obtains: $\frac{\tau_{htt}^*}{\tau_{hE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bpo}$ in $10^{-27} \text{ (A/cm}^2\text{)} \searrow$	1.3814	1.3680	1.3636
$J_{Eno}$ in $10^{-33} \text{ (A/cm}^2\text{)} \nearrow$	3.0406	3.1481	3.0927
$J_{ol}$ in $10^{-27} \text{ (A/cm}^2\text{)} \searrow$	1.3814	1.3640	1.3636
Here, $x=0.75$ , and for the $(Se^+Mg, Te^+In, Sn^+Cd)$ -junctions and from Eq. (34), one obtains: $\frac{\tau_{htt}^*}{\tau_{hE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bpo}$ in $10^{-24} \text{ (A/cm}^2\text{)} \searrow$	6.2893	6.2285	6.2083

$J_{\text{Eno}}$ in $10^{-31}$ (A/cm <sup>2</sup> ) ↗	2.8584	3.4715	3.8702
$J_{\text{ol}}$ in $10^{-24}$ (A/cm <sup>2</sup> ) ↘	6.2893	6.2285	6.2083

Here,  $x=1$ , and for the (Se<sup>+</sup>Mg, Te<sup>+</sup>In, Sn<sup>+</sup>Cd)-junctions and from Eq. (34), one obtains:  $\frac{\tau_{\text{ht}}^*}{\tau_{\text{HE}}} = (0, 0, 0)$  suggesting a completely transparent condition.

$J_{\text{Bpo}}$ in $10^{-20}$ (A/cm <sup>2</sup> ) ↘	2.6721	2.6473	2.6387
$J_{\text{Eno}}$ in $10^{-30}$ (A/cm <sup>2</sup> ) ↗	2.6574	3.7678	4.7414
$J_{\text{ol}}$ in $10^{-20}$ (A/cm <sup>2</sup> ) ↘	2.6721	2.6473	2.6387

**Table 4.2.** In the HD [(Se; Te; Sn)-  $\text{CdS}_{1-x}\text{Te}_x$ -alloy] ER-LD[(*Mg; In; Cd*)- $\text{CdS}_{1-x}\text{Te}_x$ -alloy] BR, for physical conditions given in Eq. (42) and for a given  $x$ , our numerical results of  $n_I$ ,  $J_{\text{scl}}$ ,  $F_I$ ,  $\eta_I$ , and  $T_H$ , are computed, using Equations (46, 45, 47, 48, 49), respectively, noting that both  $\eta_{I\text{max}}$  and  $T_H$ , marked in bold, increase with increasing  $x$  for given  $r_{d(a)}$ , being new results.

$V_{\text{oc}}(\text{V})$	$n_I$	$J_{\text{scl}}(\frac{\text{mA}}{\text{cm}^2})$	$F_I(\%)$	$\eta_I(\%)$
Here, $x=0$ . For the (Se <sup>+</sup> Mg, Te <sup>+</sup> In, Sn <sup>+</sup> Cd)-junctions, the value of $\alpha$ given in Eq. (46) is: $\alpha = 1.052$ .				
$n^+p$	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd
<b>2.041</b>	1.068; 1.068; 1.068	7.490; 7.490; 7.490	92.91; 92.91; 92.91	14.20; 14.20; 14.20
<b>2.076</b>	1.083; 1.083; 1.083	9.371; 9.371; 9.371	92.93; 92.93; 92.93	18.08; 18.08; 18.08
2.65	1.371; 1.371; 1.371	17.01; 17.01; 17.01	92.97; 92.97; 92.97	41.91; 41.92; 41.92
<b>2.66</b>	1.376; 1.376; 1.376	16.95; 16.95; 16.95	92.97; 92.97; 92.97	<b>41.92; 41.92; 41.92</b>
<b><math>V_{\text{oc,max}} = 2.66 \text{ V}</math></b>		<b><math>T_H(\text{K}) = 516.5; 516.5; 516.5</math></b>		
2.67	1.381; 1.381; 1.381	16.88; 16.88; 16.88	92.97; 92.97; 92.97	41.91; 41.91; 41.91
3	1.557; 1.557; 1.557	13.51; 13.59; 13.59	92.95; 92.95; 92.95	37.90; 37.90; 37.90
Here, $x=0.5$ . For the (Se <sup>+</sup> Mg, Te <sup>+</sup> In, Sn <sup>+</sup> Cd)-junctions, the value of $\alpha$ given in Eq. (46) is: $\alpha = 1.069$ .				
$n^+p$	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd
2.041	1.386; 1.386; 1.386	7.490; 7.490; 7.490	91.28; 91.28; 91.28	13.95; 13.95; 13.95
2.076	1.404; 1.404; 1.404	9.392; 9.392; 9.392	91.30; 91.31; 91.31	17.80; 17.80; 17.80
2.69	1.799; 1.798; 1.798	18.27; 18.27; 18.27	91.38; 91.38; 91.38	44.90; 44.91; 44.91
<b>2.70</b>	1.805; 1.805; 1.805	18.20; 18.20; 18.20	91.38; 91.38; 91.38	<b>44.91; 44.92; 44.92</b>
<b><math>V_{\text{oc,max}} = 2.70 \text{ V}</math></b>		<b><math>T_H(\text{K}) = 544.6; 544.7; 544.7</math></b>		
2.71	1.812; 1.812; 1.812	18.13; 18.13; 18.13	91.38; 91.38; 91.38	44.90; 44.91; 44.91
3	2.012; 2.012; 2.012	15.18; 15.18; 15.18	91.36; 91.36; 91.36	41.60; 41.61; 41.61
Here, $x=0.75$ . For the (Se <sup>+</sup> Mg, Te <sup>+</sup> In, Sn <sup>+</sup> Cd)-junctions, the value of $\alpha$ given in Eq. (46) is: $\alpha = 1.083$ .				
$n^+p$	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd
2.041	1.627; 1.626; 1.626	7.490; 7.490; 7.490	90.11; 90.11; 90.11	13.77; 13.77; 13.78

2.076	1.647; 1.646; 1.646	9.409; 9.410; 9.410	90.15; 90.15; 90.15	17.61; 17.61; 17.61
2.71	2.119; 2.118; 2.118	19.20; 19.20; 19.21	90.26; 90.26; 90.26	46.97; 46.97; 46.98
<b>2.72</b>	2.127; 2.126; 2.126	19.13; 19.14; 19.14	90.26; 90.26; 90.26	<b>46.98; 46.98; 46.99</b>
<b>V<sub>oc,max</sub> = 2.72 V</b>		<b>T<sub>H</sub>(K) = 565.8; 565.8; 565.9</b>		
2.73	2.135; 2.134; 2.134	19.06; 19.06; 19.07	90.26; 90.26; 90.26	46.97; 46.98; 46.98
3	2.353; 2.353; 2.353	16.24; 16.24; 16.24	90.23; 90.23; 90.24	43.95; 43.96; 43.96

Here,  $x=1$ . For the (Se<sup>+</sup>Mg, Te<sup>+</sup>In, Sn<sup>+</sup>Cd)-junctions, the value of  $\alpha$  given in Eq. (46) is:  $\alpha = 1.102$ .

n <sup>+</sup> p	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd	Se <sup>+</sup> Mg; Te <sup>+</sup> In; Sn <sup>+</sup> Cd
2.041	1.965; 1.964; 1.964	7.490; 7.490; 7.490	88.56; 88.56; 88.56	13.54; 13.54; 13.54
2.076	1.987; 1.987; 1.987	9.390; 9.390; 9.391	88.61; 88.61; 88.61	17.27; 17.27; 17.27
2.73	2.566; 2.565; 2.565	20.01; 20.01; 20.01	88.77; 88.77; 88.77	48.49; 48.50; 48.50
<b>2.74</b>	2.575; 2.575; 2.574	19.94; 19.94; 19.95	88.77; 88.77; 88.77	<b>48.50; 48.51; 48.51</b>
<b>V<sub>oc,max</sub> = 2.74 V</b>		<b>T<sub>H</sub>(K) = 582.5; 582.6; 582.6</b>		
2.75	2.585; 2.584; 2.584	19.87; 19.87; 19.87	88.77; 88.77; 88.77	48.50; 48.51; 48.51
3	2.830; 2.829; 2.829	17.23; 17.23; 17.23	88.74; 88.74; 88.74	45.86; 45.87; 45.87

### **Second case: HD [Mg; In; Cd] CdS<sub>1-x</sub>Te<sub>x</sub> Alloy ER – LD [Se; Te; Sn] CdS<sub>1-x</sub>Te<sub>x</sub> Alloy BR**

Here, there are 3 ( $p^+n$ ) – CdS<sub>1-x</sub>Te<sub>x</sub> junctions, being denoted by: (Mg<sup>+</sup>Se, In<sup>+</sup>Te, Cd<sup>+</sup>Sn).

Then, from above physical conditions, the numerical results of  $\frac{\tau_{ett}^*}{\tau_{eE}}$ ,  $J_{Bno}$ ,  $J_{Epo}$  and  $J_{oII}$ , are calculated using Equations (38), (18), (36) and (41), respectively, and obtained, as those given in Table 5.1. Further, those of  $n_{II}$ ,  $J_{scII}$ ,  $F_{II}$ ,  $\eta_I$  and  $T_H$  are computed, using Equations (46, 45, 47, 48, 49), respectively, and reported in the following Table 5.2.

**Table 5.1.** In the HD [(Mg; In; Cd)– CdS<sub>1-x</sub>Te<sub>x</sub> -alloy] ER-LD[(Se; Te; Sn)- CdS<sub>1-x</sub>Te<sub>x</sub> -alloy] BR, for physical conditions given in Eq. (42) and for a given  $x$ , our numerical results of  $\frac{\tau_{ett}^*}{\tau_{eE}}$ ,  $J_{Bno}$ ,  $J_{Epo}$ , and  $J_{oII}$  are computed, using Equations (38), (18), (36) and (41), respectively, noting that  $J_{oII}$  decreases slightly with increasing  $r_{a(d)}$ -radius for given  $x$ , but it increases strongly with increasing  $x$  for given  $r_{a(d)}$ -radius, being new results.

p <sup>+</sup> n	Mg <sup>+</sup> Se	In <sup>+</sup> Te	Cd <sup>+</sup> Sn
Here, $x=0$ , and for the (Mg <sup>+</sup> Se, In <sup>+</sup> Te, Cd <sup>+</sup> Sn )-junctions and from Eq. (34), one obtains: $\frac{\tau_{ett}^*}{\tau_{eE}} = (0, 0, 0)$ suggesting a completely transparent condition.			
$J_{Bno}$ in $10^{-35}$ (A/cm <sup>2</sup> ) $\searrow$	1.7992	0.6102	0.1643
$J_{Epo}$ in $10^{-34}$ (A/cm <sup>2</sup> ) $\searrow$	1.5401	1.3943	1.3480
$J_{oII}$ in $10^{-34}$ (A/cm <sup>2</sup> ) $\searrow$	1.7200	1.4553	1.3645

Here,  $x=0.5$ , and for the (Mg<sup>+</sup>Se, In<sup>+</sup>Te, Cd<sup>+</sup>Sn )-junctions and from Eq. (34), one obtains:  $\frac{\tau_{ett}^*}{\tau_{eE}} = (0, 0, 0)$  suggesting a completely transparent condition.

$J_{\text{Bno}}$ in $10^{-28}$ (A/cm <sup>2</sup> ) $\searrow$	4.4047	2.0176	1.1344
$J_{\text{Epo}}$ in $10^{-27}$ (A/cm <sup>2</sup> ) $\searrow$	3.5960	3.2941	3.1975
$J_{\text{oll}}$ in $10^{-27}$ (A/cm <sup>2</sup> ) $\searrow$	4.0365	3.4958	3.3110

Here,  $\mathbf{x=0.75}$ , and for th (Mg<sup>+</sup>Se, In<sup>+</sup>Te, Cd<sup>+</sup>Sn )-junctions and from Eq. (34), one obtains:  $\frac{\tau_{\text{ett}}^*}{\tau_{\text{eE}}} = (0, 0, 0)$  suggesting a completely transparent condition.

$J_{\text{Bno}}$ in $10^{-24}$ (A/cm <sup>2</sup> ) $\searrow$	2.0386	1.0570	0.6572
$J_{\text{Epo}}$ in $10^{-23}$ (A/cm <sup>2</sup> ) $\searrow$	1.6309	1.5015	1.4600
$J_{\text{oll}}$ in $10^{-23}$ (A/cm <sup>2</sup> ) $\searrow$	1.8348	1.6072	1.5257

Here,  $\mathbf{x=1}$ , and for the (Mg<sup>+</sup>Se, In<sup>+</sup>Te, Cd<sup>+</sup>Sn )-junctions and from Eq. (34), one obtains:  $\frac{\tau_{\text{ett}}^*}{\tau_{\text{eE}}} = (0, 0, 0)$  suggesting a completely transparent condition.

$J_{\text{Bno}}$ in $10^{-21}$ (A/cm <sup>2</sup> ) $\searrow$	8.7909	5.0854	3.4567
$J_{\text{Epo}}$ in $10^{-20}$ (A/cm <sup>2</sup> ) $\searrow$	6.9019	6.3830	6.2160
$J_{\text{oll}}$ in $10^{-20}$ (A/cm <sup>2</sup> ) $\searrow$	7.7810	6.8915	6.5617

**Table 5.2.** In the HD [(Mg; In; Cd)- CdS<sub>1-x</sub>Te<sub>x</sub>-alloy] ER-LD[(Se; Te; Sn)-CdS<sub>1-x</sub>Te<sub>x</sub>-alloy] BR, for physical conditions given in Eq. (42) and for a given x, our numerical results of  $n_{\text{II}}$ ,  $J_{\text{scII}}$ ,  $F_{\text{II}}$ ,  $\eta_{\text{II}}$ , and  $T_{\text{H}}$ , are computed, using Equations (46, 45, 47, 48, 49), respectively, noting that both  $\eta_{\text{II}max.}$  and  $T_{\text{H}}$ , marked in bold, increase with increasing x for given  $r_{a(d)}$ , being new results.

$V_{\text{oc}}(\text{V})$	$n_{\text{II}}$	$J_{\text{scII}}(\frac{\text{mA}}{\text{cm}^2})$	$F_{\text{II}}(\%)$	$\eta_{\text{II}}(\%)$
Here, $\mathbf{x=0}$ . For the (Mg <sup>+</sup> Se, In <sup>+</sup> Te, Cd <sup>+</sup> Sn)-junctions, the value of $\alpha$ given in Eq. (46) is: $\beta = 1.0533$ .				
$p^+n$	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn
2.041	1.084; 1.081; 1.080	7.490; 7.490; 7.490	92.82; 92.84; 92.84	14.19; 14.19; 14.19
2.076	1.099; 1.096; 1.095	9.391; 9.396; 9.397	92.84; 92.86; 92.86	18.10; 18.11; 18.12
2.65	1.391; 1.388; 1.387	17.26; 17.29; 17.30	92.89; 92.90; 92.91	42.49; 42.57; 42.60
<b>2.66</b>	1.396; 1.393; 1.392	17.20; 17.23; 17.24	92.89; 92.90; 92.91	<b>42.49; 42.57; 42.60</b>
<b><math>V_{\text{oc;max}} = 2.66 \text{ V}</math></b>		<b><math>T_{\text{H}}(\text{K}) = 521.6; 522.4; 522.6</math></b>		
2.67	1.402; 1.398; 1.397	17.13; 17.16; 17.17	92.89; 92.90; 92.91	42.48; 42.57; 42.59
3	1.579; 1.576; 1.575	13.79; 13.81; 13.82	92.87; 92.89; 92.89	38.44; 38.49; 38.51
Here, $\mathbf{x=0.5}$ . For the (Mg <sup>+</sup> Se, In <sup>+</sup> Te, Cd <sup>+</sup> Sn)-junctions, the value of $\alpha$ given in Eq. (46) is: $\beta = 1.071$ .				
$p^+n$	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn
2.041	1.413; 1.409; 1.408	7.490; 7.490; 7.490	91.15; 91.16; 91.17	13.93; 13.94; 13.94
2.076	1.431; 1.427; 1.426	9.407; 9.413; 9.415	91.17; 91.19; 91.20	17.81; 17.82; 17.82

2.69	1.832; 1.827; 1.826	18.52; 18.57; 18.58	91.26; 91.27; 91.28	45.48; 45.58; 45.63
<b>2.70</b>	1.839; 1.834; 1.833	18.46; 18.50; 18.51	91.26; 91.27; 91.28	<b>45.48; 45.59; 45.63</b>
<b><math>V_{oc,max.} = 2.70 \text{ V}</math></b>		<b><math>T_H(K) = 550.2; 551.4; 551.8</math></b>		
2.71	1.846; 1.841; 1.840	18.39; 18.43; 18.44	91.26; 91.27; 91.28	45.47; 45.58; 45.62
3	2.050; 2.045; 2.043	15.40; 15.43; 15.44	91.23; 91.25; 91.26	42.16; 42.23; 42.26

Here,  $x=0.75$ . For the (Mg<sup>+</sup>Se, In<sup>+</sup>Te, Cd<sup>+</sup>Sn)-junctions, the value of  $\alpha$  given in Eq. (46) is:  $\beta = 1.084$ .

$p^+n$	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn
2.041	1.663; 1.659; 1.657	7.490; 7.490; 7.490	89.94; 89.96; 89.97	13.75; 13.75; 13.75
2.076	1.684; 1.679; 1.677	9.385; 9.391; 9.393	89.98; 90.00; 90.01	17.53; 17.54; 17.55
2.71	2.166; 2.160; 2.158	19.07; 19.11; 19.13	90.09; 90.11; 90.12	46.55; 46.68; 46.73
<b>2.72</b>	2.174; 2.168; 2.166	19.00; 19.05; 19.06	90.09; 90.11; 90.12	<b>46.56; 46.69; 46.74</b>
<b><math>V_{oc,max.} = 2.72 \text{ V}</math></b>		<b><math>T_H(K) = 561.4; 562.7; 563.3</math></b>		
2.73	2.182; 2.176; 2.174	18.93; 18.98; 18.99	90.09; 90.11; 90.12	46.56; 46.68; 46.73
3	2.406; 2.399; 2.397	16.17; 16.20; 16.21	90.06; 90.08; 90.09	43.68; 43.78; 43.81

Here,  $x=1$ . For the (Mg<sup>+</sup>Se, In<sup>+</sup>Te, Cd<sup>+</sup>Sn)-junctions, the value of  $\alpha$  given in Eq. (46) is:  $\beta = 1.105$ .

$p^+n$	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn	Mg <sup>+</sup> Se; In <sup>+</sup> Te; Cd <sup>+</sup> Sn
2.041	2.019; 2.012; 2.010	7.490; 7.490; 7.490	88.32; 88.35; 88.36	13.50; 13.50; 13.51
2.076	2.076; 2.035; 2.033	9.385; 9.391; 9.394	88.37; 88.40; 88.41	17.22; 17.23; 17.24
2.74	2.643; 2.635; 2.632	20.06; 20.12; 20.14	88.54; 88.57; 88.58	48.66; 48.82; 48.88
<b>2.75</b>	2.653; 2.645; 2.642	19.99; 20.04; 20.07	88.54; 88.57; 88.58	<b>48.66; 48.82; 48.88</b>
<b><math>V_{oc,max.} = 2.75 \text{ V}</math></b>		<b><math>T_H(K) = 584.3; 586.2; 586.8</math></b>		
2.76	2.663; 2.655; 2.652	19.81; 19.97; 19.99	88.54; 88.56; 88.58	48.65; 48.81; 48.87
3	2.905; 2.896; 2.892	17.35; 17.39; 17.41	88.51; 88.53; 88.55	46.08; 46.20; 46.25

Finally, some concluding remarks, obtained from those numerical results reported in above Tables 2.2, 3.2, 4.2 and 5.2, are discussed as follows.

(i)-As noted in Tables 2.1, 3.1, 4.1 and 5.1, the dark carrier-minority saturation current density  $J_{ol(ol)}$  decrease slightly with increasing  $r_{d(a)}$ -radius for given  $x$ , but it increases strongly with increasing  $x$  for given  $r_{d(a)}$ -radius. Then, as remarked in Tables 2.2, 3.2, 4.2 and 5.2, at a same  $V_{oc}$ , the photovoltaic conversion factor,  $n_{I(II)}(V_{oc})$ , also decrease slightly with increasing  $r_{d(a)}$ -radius for given  $x$ , but it also increases strongly with increasing  $x$  for given  $r_{d(a)}$ -radius. In other words, as discussed in Eq. (45), at a same  $V_{oc}$ , both  $J_{ol(ol)}$  and  $n_{I(II)}$  have the same variations for the same physical conditions, noting here that in Ref. [6] the quality factor  $n$  was assumed to be equal to 1.

(ii)-With such variations of  $n_{I(II)}(V_{oc})$ , as observed in Tables 2.2, 3.2, 4.2 and 5.2, the maximal values of  $\eta_{I(II)}$ ,  $\eta_{I(II)max.}$ , and the corresponding ones of the H-reservoir temperature,  $T_H$ , are obtained at  $V_{oc} = V_{oc,max.}$ , being marked in bold, increase with increasing  $x$  for given  $r_{d(a)}$ -radius.

(iii)-In particular, we obtain: (a) in the  $n^+(p^+) - p(n)$   $CdS_{1-x}Se_x$  alloy-junction solar cells, at  $x=0$  and for  $Sn^+Cd$  ( $Cd^+Sn$ ),  $\eta_{I_{max.}(II_{max.})}=42.24$  % (42.60 %), as those given in Tables 2.2 (3.2), and (b) in the  $n^+(p^+) - p(n)$   $CdS_{1-x}Te_x$  alloy-junction solar cells, at  $x=0$  and for  $Sn^+Cd$  ( $Cd^+Sn$ ),  $\eta_{I_{max.}(II_{max.})}=41.92$  % (42.60 %), as those given in Tables 4.2 (5.2). These results can be compared with the corresponding ones given in the  $n^+(p^+) - p(n)$  crystalline CdS-junction solar cells [1], as:  $\eta_{I_{max.}(II_{max.})} = 43.22$  % (43.40 %).

(iv)-Finally, we obtain: (a) in the  $n^+(p^+) - p(n)$   $CdS_{1-x}Se_x$  alloy-junction solar cells, at  $x=1$  and for  $Sn^+Cd$  ( $Cd^+Sn$ ),  $\eta_{I_{max.}(II_{max.})}=46.07$  % (46.59 %) and  $T_H=556.3$  K (561.7 K), as those given in Tables 2.2 (3.2), and (b) in the  $n^+(p^+) - p(n)$   $CdS_{1-x}Te_x$  alloy-junction solar cells, at  $x=1$  and for  $Sn^+Cd$  ( $Cd^+Sn$ ),  $\eta_{I_{max.}(II_{max.})}=48.51$  % (48.88 %) and  $T_H=582.6$  K (586.8 K), as those given in Tables 4.2 (5.2), suggesting that in order to obtain the highest efficiencies, the  $(CdS_{1-x}Se_x, CdS_{1-x}Te_x)$ -alloy junctions could be chosen rather than the crystalline CdS-junctions [1].

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