# Maximal Efficiencies in New Single $GaAs_{1-x}Sb_x$-Alloy Junction Solar Cells at 300 K

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## Abstract:

In single $n^+(p^+) - p(n)$ [$X(x) \equiv GaAs_{1-x}Sb_x$]-alloy junction solar cells at 300 K, $0 \leq x \leq 1$, by basing on the same physical model and the same treatment method, as those used in our recent work (Van Cong et al., 2023; Van Cong, 2023), we will investigate the highest (or maximal) efficiencies, $\eta_{Imax.(IImax.)}$, obtained at the open circuit voltage $V_{oc}(= V_{ocI(ocII)})$, according to highest hot reservoir temperatures $T_H(K)$, obtained from the Carnot efficiency theorem, being proved by entropy law. Here, one first remarks that, with increasing x=(0, 0.5, 1), **(i)**- from Table 3, for the single $n^+ - p$ X(x)-alloy junction solar cell and for given $r_{Sn(Cd)}$-radius, for example, $\eta_{Imax.}(\searrow)=$ **31.14%**, 28.72%, 25.36**%**, according to $T_H(K) =$ **435. 7**, 420.9, 401.9, at $V_{ocI}(V) = 1.07, 1.09, 1.17$, respectively, while, **(ii)**- from Table 5, for the single $p^+ - n$ X(x)-alloy junction solar cell and for given $r_{Cd(Sn)}$-radius, for example, $\eta_{IImax.}(\nearrow)=$ 33.04**%**, 34.26%, **35.47%**, according to $T_H(K) = 448.0, 456.3, $ **464. 9**, at $V_{ocII}(V)[> V_{ocI}(V)] = 1.20, 1.27, 1.38$, respectively, suggesting that such $\eta_{Imax.(IImax.)}$-and-$T_H$ variations depend on the $V_{ocII}(V)[> V_{ocI}(V)] - $ values. **(iii)**-Then, as given in Table 3, for $x = 0$ and for $r_{d(a)} = r_{Te(Mg)}$, one gets: $\eta_I =$ 23.48 % and 29.71 % at $V_{oc} = 0.98$ V and 1.1272 V, respectively, which can also be compared with the corresponding results, obtained by Moon et al. (2016) and Green et al. (2022) for the single-junction GaAs thin-film solar cell, 22.08 % and 29.1 %; that gives the relative deviations in absolute values, as: 6.34 % and 2.1 %. Further, for $x = 1$ and for $r_{d(a)} = r_{Sn(Cd)}$, one gets in Table 3: $\eta_{Imax.} =$ 25.36 % at $V_{oc} = 1.17$ V, and in Table 5, $\eta_{IImax.} = 35.47$ % at $V_{oc} = 1.38$ V, which can also be compared with the corresponding results, obtained for the single-junction GaSb-solar cells by Van Cong (2023), 11.17 % (12.03 %) and 11.34 % (12.16 %), respectively. As a result, in order to obtain the highest efficiencies, the single $GaAs_{1-x}Sb_x$-alloy junction solar cells could be chosen rather than the single crystalline [GaAs, or GaSb]-junction solar cells.

**Keywords:** *single $GaAs_{1-x}Sb_x$-alloy junction solar cell; single crystalline (GaAs, or GaSb)-junction solar cells; photovoltaic conversion factor; photovoltaic conversion efficiency*

## Introduction

In single $n^+(p^+) - p(n)$ [$X(x) \equiv GaAs_{1-x}Sb_x$]-alloy junction solar cells at 300 K, $0 \leq x \leq 1$, by basing on the same physical model and treatment method, as used in our recent work (Van Cong, 2023; Van Cong et al., 2023), and also other works (Green, 2022; Moon et al., 2016; Singh & Ravindra, 2012;

Van Cong & Debiais, 1997, 1993; Van Cong et al., 1984), we will investigate the highest (or maximal) efficiencies, $\eta_{Imax.(IImax.)}$, according to highest hot reservoir temperatures $T_H(K)$, obtained at the open circuit voltage: $V_{oc} = V_{ocI(ocII)}$ and from the Carnot- efficiency theorem, being proved by entropy law.

Some concluding remarks are discussed as follows.

**(i)-**As noted in Tables 2 and 4, the total (or dark) carrier-minority saturation current density $J_{oI(oII)}$ decreases slightly with increasing $r_{d(a)}$-radius for given x, and it increases with increasing x for given $r_{d(a)}$-radius. Then, as observed in Tables 3 and 5, at a same $V_{oc}$, the photovoltaic conversion factor, $n_{I(II)}(V_{oc})$, also decreases with increasing $r_{d(a)}$-radius for given x, and it increases with increasing x for given $r_{d(a)}$-radius. In other words, as discussed in Eq. (45), at a same $V_{oc}$, both $J_{oI(oII)}$ and $n_{I(II)}$ have the same variations for the same physical conditions. Further, it should be noted in the work by Singh & Ravindra (2012) that the maximal efficiency value $\eta_{max.}$ could not be obtained, since the "quality factor n" was assumed to be equal to 1.

**(ii)-** Then, as observed in Tables 3 and 5, with such variations of $n_{I(II)}(V_{oc})$, the maximal values of $\eta_{I(II)}$, $\eta_{I(II)max.}$, and the corresponding ones of the H-reservoir temperature, $T_H$, obtained at same corresponding $V_{oc} = V_{ocI(ocII)}$-values, as marked in bold, increase slightly with increasing $r_{d(a)}$-radius for a given x.

**(iii)-**Finally, as given in Table 3, for $x = 0$ and for $r_{d(a)} = r_{Te(Mg)}$, one gets: $\eta_I$ =23.48 % and 29.71 % at $V_{oc} = 0.98\ V$ and 1.1272 V, respectively, which can also be compared with the corresponding results, obtained by Moon et al. (2016) and Green et al. (2022) for the single-junction GaAs thin-film solar cell, 22.08 % and 29.1 %; that gives the relative deviations in absolute values, as: 6.34 % and 2.1 %. Further, for $x = 1$ and for $r_{d(a)} = r_{Sn(Cd)}$, one gets in Table 3: $\eta_{Imax.}$ =25.36 % at $V_{oc} = 1.17\ V$, and in Table 5, $\eta_{IImax.}$ =35.47 % at $V_{oc} = 1.38\ V$, which can also be compared with the corresponding results, obtained for the single-junction GaSb-solar cells by Van Cong (2023), 11.17 % (12.03 %) and 11.34 % (12.16 %), respectively. As a result, in order to obtain the highest efficiencies, the single $GaAs_{1-x}Sb_x$-alloy junction solar cells could be chosen rather than the single crystalline [GaAs, or GaSb]-junction solar cells.

In the following, we will show that the energy-band-structure parameters, due to the effects of x-Sb concentration, size impurity, temperature T and heavy doping, affect strongly the dark (or total) minority-carrier saturation current density and the photovoltaic conversion effect. Finally, some numerical results and concluding remarks will be also presented.

## Energy-Band-Structure Parameters and Dark Minority-Carrier Saturation Current Density, due to the Effects of x- Sb Concentration, Impurity Size, and Heavy Doping

First of all, in the single $n^+(p^+) - p(n)$ X(x)- alloy junction solar cells, $X(\equiv GaAs_{1-x}Sb_x)$, we present the effects of x-Sb concentration, donor (acceptor) [d(a)]-size, temperature T and heavy doping, affecting the energy-band-structure parameters, as those investigated in our previous works (Van Cong, 2023; Van Cong et al., 2023).

### A. Effect of x-Sb 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:

$m_c(x)/m_o = 0.047 \times x + 0.066 \times (1 - x)$, and

$m_v(x)/m_o = 0.300 \times x + 0.291 \times (1 - x)$, (1)

so that one obtains: $m_c(x = 0)/m_o = m_{c(GaAs)}/m_o = 0.066$, $m_v(x = 0)/m_o = m_{v(GaAs)}/m_o = 0.291$, and $m_c(x = 1)/m_o = m_{c(GaSb)}/m_o = 0.047$, $m_v(x = 1)/m_o = m_{v(GaSb)}/m_o = 0.300$.

**(ii)-**The unperturbed relative dielectric constant of the intrinsic of the single crystalline X- alloy is found to be defined by:

$\varepsilon_o(x) = 15.69 \times x + 13.13 \times (1 - x)$, (2)

which gives: $\varepsilon_o(x = 0) = \varepsilon_{GaAs} = 13.13 \simeq 13.1$, and $\varepsilon_o(x = 1) = \varepsilon_{GaSb} = 15.69 \simeq 15.7$.

**(iii)-**Finally, the unperturbed band gap at 0 K is found to be given by:

$E_{go}(x)$ in eV $= 0.81 \times x + 1.52 \times (1 - x)$, (3)

giving rise to: $E_{go}(x = 0) = E_{gGaAs} = 1.52$ eV, and $E_{go}(x = 1) = E_{gGaSb} = 0.81$ eV.

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

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

and then, the isothermal bulk modulus, by:

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

## B. Effects of Impurity-Size, with a Given x

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

At $r_{d(a)} = r_{do(ao)} = r_{As(Ga)} = 0.118$ nm (0.126 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 (Van Cong et al., 1984), needed to determine the σ-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:

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

$$\ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 \geq 0. \qquad (6)$$

Furthermore, we also shown that, as $r_{d(a)} > r_{do(ao)}$ ( $r_{d(a)} < r_{do(ao)}$), the compression (dilatation) gives rise to the increase (the decrease) in the energy gap $E_{gn(gp)}(r_{d(a)},x)$, and in the effective donor (acceptor)-ionization energy $E_{d(a)}(r_{d(a)},x)$ in absolute values, obtained from the effective Bohr model, and then such the compression (dilatation) is represented respectively by: $\pm\left[\Delta\sigma(r_{d(a)},x)\right]_{\mathbf{n(p)}}$, respectively,

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

$$+ \left[\Delta\sigma(r_{d(a)},x)\right]_{\mathbf{n(p)}},$$

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

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

$$- \left[\Delta\sigma(r_{d(a)},x)\right]_{\mathbf{n(p)}}. \qquad (7)$$

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

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

$$\ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 \geq 0, \qquad (8a)$$

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

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

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

$$\ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 \le 0, \tag{8.b}$$

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

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

Here, the intrinsic band gap $E_{gin(gip)}(r_{d(a)}, x, T)$ at any T is given by (Van Cong, 2023; Van Cong et al., 2023):

$$E_{gin(gip)}(r_{d(a)}, x, T) \text{ in eV} = E_{gn(gp)}(r_{d(a)}, x) - 10^{-4} \times T^2 \times \left[\frac{3.6773 \times x}{T + 94 \text{ K}} + \frac{5.405 \times (1-x)}{T + 204 \text{ K}}\right], \tag{9}$$

which gives: $E_{gin(gip)}(r_{do(ao)}, x = 0, T = 0K) = 1.52$ eV and $E_{gin(gip)}(r_{do(ao)}, x = 1, T = 0K) = 0.81$ eV, and $E_{gin(gip)}(r_{do(ao)}, x = 0, T = 300 \text{ K}) \simeq 1.42$ eV and $E_{gin(gip)}(r_{do(ao)}, x = 1, T = 300 \text{ K}) \simeq 0.73$ eV,

suggesting that, for given x and $r_{d(a)}$, $E_{gin(gip)}$ decreases with an increasing T.

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

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

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

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

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 Table 1.

Table 1 in Appendix 1.

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

Here, as given in our previous works (Van Cong, 2023; Van Cong & Debiais, 1993), 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 (Van Cong & Debiais, 1993), with a precision of the order of $2.11 \times 10^{-4}$, is found to be given by:

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

where u is the reduced electron density, $u(N_{d(a)}, T, x) \equiv \frac{N_{d(a)}}{N_{c(v)}(T,x)}$, $F(u) = au^{\frac{2}{3}}\left(1 + bu^{-\frac{4}{3}} + cu^{-\frac{8}{3}}\right)^{-\frac{2}{3}}$,

$a = \left[(3\sqrt{\pi}/4) \times u\right]^{2/3}$, $b = \frac{1}{8}\left(\frac{\pi}{a}\right)^2$, $c = \frac{62.3739855}{1920}\left(\frac{\pi}{a}\right)^4$, 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)- $CdS_{1-x}Se_x$- 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:

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

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 (Van Cong, 2023):

$$\Delta E_{gn}(N_d, r_d, x) \simeq a_1 \times \frac{\varepsilon_o(x)}{\varepsilon(r_d,x)} \times N_r^{1/3} + a_2 \times \frac{\varepsilon_o(x)}{\varepsilon(r_d,x)} \times N_r^{\frac{1}{3}} \times (2.503 \times [-E_{cn}(r_{sn}) \times r_{sn}]) + a_3 \times$$

$$\left[\frac{\varepsilon_o(x)}{\varepsilon(r_d,x)}\right]^{5/4} \times \sqrt{\frac{m_v}{m_c}} \times N_r^{1/4} + a_4 \times \sqrt{\frac{\varepsilon_o(x)}{\varepsilon(r_d,x)}} \times N_r^{1/2} \times 2 + a_5 \times \left[\frac{\varepsilon_o(x)}{\varepsilon(r_d,x)}\right]^{\frac{3}{2}} \times N_r^{\frac{1}{6}}, \qquad N_r \equiv$$

$$\left(\frac{N_d}{9.999 \times 10^{17} cm^{-3}}\right), \tag{14n}$$

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

$$\Delta E_{gp}(N_a, r_a, x) \simeq a_1 \times \frac{\varepsilon_o(x)}{\varepsilon(r_a,x)} \times N_r^{1/3} + a_2 \times \frac{\varepsilon_o(x)}{\varepsilon(r_a,x)} \times N_r^{\frac{1}{3}} \times \left(2.503 \times [-E_{cp}(r_{sp}) \times r_{sp}]\right) + a_3 \times$$

$$\left[\frac{\varepsilon_o(x)}{\varepsilon(r_a,x)}\right]^{5/4} \times \sqrt{\frac{m_c}{m_v}} \times N_r^{1/4} + 2a_4 \times \sqrt{\frac{\varepsilon_o(x)}{\varepsilon(r_a,x)}} \times N_r^{1/2} + a_5 \times \left[\frac{\varepsilon_o(x)}{\varepsilon(r_a,x)}\right]^{\frac{3}{2}} \times N_r^{\frac{1}{6}}, \quad N_r \equiv \left(\frac{N_a}{9.999 \times 10^{17}\, cm^{-3}}\right), \tag{14p}$$

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

$a_5 = 9.80 \times 10^{-5} (eV)$.

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

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

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

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

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

## 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:

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

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 (Van Cong, 2023):

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

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:

$$D_e(N_a, T, r_a, x) = \frac{k_B T}{e} \times \left[ 200 + \frac{8300}{1 + \left(\frac{N_a}{1.3 \times 10^{17} cm^{-3}}\right)^{0.91}} \right] \times \left(\frac{\varepsilon(r_a, x)}{\varepsilon_o(x)}\right)^2 \ (cm^2 s^{-1}), \tag{19a}$$

$$D_h(N_d, T, r_d, x) = \frac{k_B T}{e} \times \left[ 130 + \frac{270}{1 + \left(\frac{N_d}{8 \times 10^{17} cm^{-3}}\right)^{1.25}} \right] \times \left(\frac{\varepsilon(r_d, x)}{\varepsilon_o(x)}\right)^2 \ (cm^2 s^{-1}), \tag{19b}$$

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

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

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

## $J_{Eno(Epo)}$ 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 (Van Cong et al., 2023; Van Cong, 2023):

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

$y \le W,$

$$N_{do(ao)}(W) \equiv 7.9 \times 10^{17} \ (2 \times 10^5) \times exp\left\{-\left(\frac{W}{184.2 \ (1) \times 10^{-7} \ cm}\right)^{1.066 \ (0.5)}\right\} \ (cm^{-3}), \tag{21}$$

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:

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

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

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

where the apparent band gap narrowing $\Delta E_{agn(agp)}$ 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:

$$F_{h(e)}(y, N_{d(a)}, T, r_{d(a)}, x) \equiv \frac{n_{in(ip)}^2(T, r_{d(a)})}{p_o(n_o) \times D_{h(e)}} = \frac{N_{d(a)}^*}{D_{h(e)}} \equiv \frac{N_{d(a)}}{D_{h(e)}} \times \left(\frac{n_{in(ip)}}{n_{in(ip)}^*}\right)^2 \equiv$$

$$\frac{N_{d(a)}}{D_{h(e)} \times exp\left[\frac{\Delta E_{agn(agp)}}{k_B T}\right]} \ (cm^{-5} \times s), \tag{23}$$

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

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

$$\left.\frac{n_{in(ip)}^2(T, r_{d(a)})}{p_o(n_o) \times D_{h(e)}}\right)^2,$$

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

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

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:

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

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

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

which must verify the two following boundary conditions as:

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

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

Here, $n_{I(II)}(V)$ *is* the photovoltaic conversion factor, being determined later, $S\left(\frac{cm}{s}\right)$ 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 (Van Cong et al., 2023; Van Cong, 2023):

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

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:

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

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

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

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

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

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

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

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:

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

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:

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

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

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

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

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

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

and then,

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

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

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

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:

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

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: $\frac{\tau^*_{htt(ett)}(y=W,W,N_{d(a)},T,r_{d(a)},x,S)}{\tau_{hE(eE)}} \rightarrow 0$, suggesting a completely transparent emitter region (CTER)-case, where, from Eq. (36), one obtains:

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

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:

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

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

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

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

## 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:

$$W = 15 \text{ μm}, N_{d(a)} = 10^{19} \text{ cm}^{-3}(10^{20} \text{ cm}^{-3}), r_{d(a)}, x, S = 100 \left(\frac{cm}{s}\right); N_{a(d)} = 10^{17} \text{ cm}^{-3}, r_{a(d)}, x, \qquad (42)$$

we propose, at given open circuit voltages: $V_{ocI1(ocI2)}$ 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 (Green, 2022; Moon et al., 2016), as:

at $V_{ocI1(ocI2)}(V) = 0.980 (1.1272)$, $J_{scI1(scI2)}(\text{mA/cm}^2) = 27.06 (29.76)$,

at $V_{ocII1(ocII2)}(V) = 0.980\ (1.03)$ , $J_{scII1(scII2)}(mA/cm^2) = 24.2\ (29.84)$. (43)

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:

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

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: $J_{ph.}(V = V_{oc}) \equiv J_{scI(scII)}\left(W, N_{d(a)}, T, r_{d(a)}, x, S;\ N_{a(d)}, T, r_{a(d)}, x, V_{oc}\right)$, for $V_{oc} \geq V_{ocI1(ocII1)}$.

Therefore, the photovoltaic conversion effect occurs, according to:

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

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

Now, for $V_{oc} \geq V_{ocI1(ocII1)}$, one can propose the general expressions for the PVCF, in order to get exactly the values of $n_{I1(II1)}\left(V_{ocI1(ocII1)}\right)$ and $n_{I2(II2)}\left(V_{ocI2(ocII2)}\right)$, as functions of $V_{oc}$, by:

$$n_{I(II)}\left(W, N_{d(a)}, T, r_{d(a)}, x, S;\ N_{a(d)}, T, r_{a(d)}, x, V_{oc}\right) = n_{I1(II1)}\left(V_{ocI1(ocII1)}\right) + n_{I2(II2)}\left(V_{ocI2(ocII2)}\right) \times$$
$$\left(\frac{V_{oc}}{V_{ocI1(ocII1)}} - 1\right)^{\alpha(\beta)}, \quad (46)$$

where, for example, the values of $\alpha(\beta)$, obtained for $x = (0, 0.5,\ and\ 1)$, will be reported in Tables 3 and 5, for $GaAs_{1-x}Sb_x$ alloy junctions. 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:

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

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

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

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 $\eta_{I(II)}$, $\eta_{Imax.(IImax.)}$, are obtained at the corresponding ones of $V_{oc} = V_{ocI(ocII)}$, 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 3 and 5, 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:

$$\eta_{Imax.(IImax.)}\left(W, N_{d(a)}, T, r_{d(a)}, S, N_{a(d)}, T, r_{a(d)}, V_{ocI(ocII)}.\right) = 1 - \frac{T_C = 300 \ K}{T_H\left(W, N_{d(a)}, T, r_{d(a)}, S, N_{a(d)}, T, r_{a(d)}, V_{ocI(ocII)}.\right)}. \tag{49}$$

## Numerical Results and Concluding Remarks

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

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

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

Now, by using the physical conditions, given in Eq. (42), then, if denoting: heavily doped (HD), lightly doped (LD), emitter region (ER), and base region (BR), we can determine various photovoltaic conversion coefficients, as follows.

## Firs case: HD [ Te; Sb; Sn] X(x) $-$ Alloy ER $-$ LD [ Mg ; In ; Cd ] X(x) $-$ Alloy BR

Here, there are the 3 $(n^+p) - X(x)$ junctions, being denoted by: $(Te^+Mg, Sb^+In, Sn^+Cd)$.

Then, the numerical results of $\frac{\tau_{htt}^*}{\tau_{hE}}$, $J_{Bpo}$, $J_{Eno}$ and $J_{oI}$, are calculated, using Equations (38), (18), (36) and (41), respectively, and reported in Table 2. Further, those of $n_I$, $J_{scI}$, $F_I$, $\eta_I$, and $T_H$, are computed, using Equations (46, 45, 47, 48, 49), respectively, and reported in Table 3.

Tables 2 and 3 in Appendix 1

## Second case:  HD [ Mg ; In ; Cd] X(x) −  Alloy ER − LD [ Te; Sb, Sn ] X(x) − Alloy BR

Here, there are 3 $(p^+n) - X(x)$-junctions, being denoted by: $(Mg^+Te, In^+Sb, Cd^+Sn)$.

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 reported in Table 4. 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 Table 5.

Tables 4 and 5 in Appendix 1

Finally, some concluding remarks are obtained and discussed as follows.

(i)-First, with increasing x=(0, 0.5, 1), from Table 3, obtained for the single $n^+ - p$ $X(x)$-alloy junction solar cells, and for given $r_{Sn(Cd)}$-radius, for example, one obtains: $\eta_{Imax.}(\searrow)$= 31.14%, 28.72%, **25.36%**, according to $T_H(K) = 435.7, 420.9, \textbf{401.9}$, at $V_{ocI}(V) = 1.07, 1.09, \textbf{1.17}$, respectively.

(ii)- Secondly, with increasing x=(0, 0.5, 1), from Table 5, obtained for the single $p^+ - n$ $X(x)$-alloy junction solar cells, and for given $r_{Cd(Sn)}$-radius, for example, one gets: $\eta_{IImax.}(\nearrow)$= **33.04%**, 34.26%, 35.47%, according to $T_H(K) = \textbf{448.0}, 456.3, 464.9$, at $V_{ocII}(V)[> V_{ocI}(V)] = \textbf{1.20}, 1.27, 1.38$, respectively, suggesting that such $\eta_{Imax.(IImax.)}$-and-$T_H$ variations depend on $V_{ocII}(V)[> V_{ocI}(V)] - values$.

Then, as given in Table 3, for x = 0 and $r_{d(a)} = r_{Te(Mg)}$, one gets: $\eta_I$ =23.48 % and 29.71 % at $V_{oc}$ = 0.98 V and 1.1272 V, respectively, which can also be compared with the corresponding results, obtained for the single-junction GaAs thin-film solar cell, 22.08 % and 29.1 % by Moon et al. (2016) and Green et al. (2022), respectively, with relative deviations in absolute values, 6.34 % and 2.1 %. Further, for x = 1 and for $r_{d(a)} = r_{Sn(Cd)}$, one gets in Table 3: $\eta_{Imax.}$ =25.36 % at $V_{oc}$ = 1.17 V, and in Table 5, $\eta_{IImax.}$ =35.47 % at $V_{oc}$ = 1.38 V, which can also be compared with the corresponding results, obtained for the single-junction GaSb-solar cells by Van Cong (2023), 11.17 % (12.03 %) and 11.34 % (12.16 %), respectively. As a result, in order to obtain the highest efficiencies, the single $GaAs_{1-x}Sb_x$-alloy junction solar cells could be chosen rather than the single crystalline [GaAs, or GaSb]-junction solar cells.

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# Appendix 1

**Table 1. From Equations (5, 8a, 8b, 9) and in the n(p)-type $X(x)$-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 | | | As | Te | Sb | Sn |
|---|---|---|---|---|---|---|
| $r_d$ (nm) | | ↗ | $r_{do}$=**0.118** | 0.132 | 0.136 | 0.140 |
| x | | ↗ | 0, 0.5, 1 | 0, 0.5, 1 | 0, 0.5, 1 | 0, 0.5, 1 |
| $B_{do}(x)$ in $10^8$ $(N/m^2)$ | | ↘ | 1.21, 0.86, 0.60 | | | |
| $\varepsilon(r_d,x)$ | | ↘ | **13.1**, 14.4, **15.7** | 12.3, 13.5, 14.7 | 11.8, 13.0, 14.2 | 11.3, 12.4, 13.5 |
| $E_d(r_d,x)$ $m$eV | | ↗ | 5.21, 3.70, 2.60 | 5.91, 4.20, 2.94 | 6.38, 4.54, 3.18 | 6.99, 4.97, 3.49 |
| $E_{gn}(r_d,x)$ eV | | ↗ | **1.52**, 1.16, **0.81** | 1.52, 1.16, 0.81 | 1.52, 1.16, 0.81 | 1.52, 1.17, 0.81 |
| $E_{gin}(T=300K,r_d,x)$ eV | | ↗ | **1.42**, 1.07, **0.73** | 1.42, 1.07, 0.73 | 1.42, 1.07, 0.73 | 1.42, 1.08, 0.73 |
| Acceptor | | | **Ga** | Mg | In | Cd |
| $r_a$ (nm) | | ↗ | $r_{ao}$=**0.126** | 0.140 | 0.144 | 0.148 |
| x | | ↗ | 0, 0.5, 1 | 0, 0.5, 1 | 0, 0.5, 1 | 0, 0.5, 1 |
| $B_{ao}(x)$ in $10^8$ $(N/m^2)$ | | ↘ | 4.39, 3.70, 3.17 | | | |
| $\varepsilon(r_a,x)$ | | ↘ | **13.1**, 14.4, **15.7** | 12.4, 13.6, 14.8 | 12.0, 13.2, 14.3 | 11.5, 12.6, 13.8 |
| $E_a(r_a,x)$ $m$eV | | ↗ | 23.0, 19.4, 16.6 | 25.7, 21.6, 18.5 | 27.5, 23.2, 19.8 | 29.8, 25.2, 21.5 |
| $E_{gp}(r_a,x)$ eV | | ↗ | **1.52**, 1.16, **0.81** | 1.52, 1.17, 0.81 | 1.52, 1.17, 0.81 | 1.53, 1.17, 0.81 |
| $E_{gip}(T=300K,r_a,x)$ eV | | ↗ | **1.42**, 1.07, **0.73** | 1.43, 1.08, 0.73 | 1.43, 1.08, 0.73 | 1.43, 1.08, 0.73 |

**Table 2. In the HD [(Te; Sb; Sn)- $X(x)$-alloy] ER-LD[$(Mg; In; Cd)$-$X(x)$-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 $J_{oI}$, are Computed, Using Equations (38), (18), (36) and (41), Respectively, Noting that $J_{oI}$ 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**

| $n^+p$ | | $Te^+Mg$ | $Sb^+In$ | $Sn^+Cd$ |
|---|---|---|---|---|
| Here, **x=0,** and for the $(Te^+Mg, Sb^+In, Sn^+Cd)$-junctions and from Eq. (34), one obtains: $\frac{\tau^*_{htt}}{\tau_{hE}} = (0, 0, 0)$ suggesting a completely transparent condition. | | | | |
| $J_{Bpo}$ in $10^{-19}$ (A/cm$^2$) | ↘ | 1.0315 | 0.9965 | 0.9565 |
| $J_{Eno}$ in $10^{-23}$ (A/cm$^2$) | ↘ | 1.7830 | 1.7258 | 1.6624 |
| $J_{oI}$ in $10^{-19}$ (A/cm$^2$) | ↘ | 1.0317 | 0.9967 | 0.9567 |
| Here, **x=0.5,** and for the $(Te^+Mg, Sb^+In, Sn^+Cd)$-junctions and from Eq. (34), one obtains: $\frac{\tau^*_{htt}}{\tau_{hE}} = (0, 0, 0)$ suggesting a completely transparent condition. | | | | |
| $J_{Bpo}$ in $10^{-14}$ (A/cm$^2$) | ↘ | 6.1514 | 5.9426 | 5.7041 |
| $J_{Eno}$ in $10^{-18}$ (A/cm$^2$) | ↘ | 2.9271 | 2.8551 | 2.7771 |
| $J_{oI}$ in $10^{-14}$ (A/cm$^2$) | ↘ | 6.1517 | 5.9429 | 5.7044 |
| Here, **x=1,** and for the $(Te^+Mg, Sb^+In, Sn^+Cd)$junctions and from Eq. (34), one obtains: $\frac{\tau^*_{htt}}{\tau_{hE}} = (0, 0, 0)$ suggesting a completely transparent condition. | | | | |
| $J_{Bpo}$ in $10^{-8}$ (A/cm$^2$) | ↘ | 3.4940 | 3.3754 | 3.2399 |
| $J_{Eno}$ in $10^{-13}$ (A/cm$^2$) | ↘ | 2.5023 | 2.4573 | 2.4108 |
| $J_{oI}$ in $10^{-8}$ (A/cm$^2$) | ↘ | 3.4940 | 3.3755 | 3.2400 |

# Table 3. In the HD [(Te; Sb; Sn)- $X(x)$-alloy] ER-LD[$(Mg;\ In;\ Cd)$-$X(x)$-alloy] BR, for Physical Conditions Given in Eq. (42) and for a Given x, Our Numerical Results of $n_I$, $J_{scI}$, $F_I$, $\eta_I$, and $T_H$, are Computed, Using Equations (46, 45, 47, 48, 49), Respectively, Noting that Both $\eta_{Imax.}$ and $T_H$, Marked in Bold, Decrease with Increasing x for Given $r_{d(a)}$

| $V_{oc}(V)$ | $n_I$ | $J_{scI}(\frac{mA}{cm^2})$ | $F_I(\%)$ | $\eta_I(\%)$ |
|---|---|---|---|---|
| Here, **x=0**. For the $(Te^+Mg, Sb^+In, Sn^+Cd)$ junctions, the value of α given in Eq. (46) is 1.0822 | | | | |
| $n^+p$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ |
| **0.980** | 0.945; 0.944; 0.943 | 27.06; 27.06; 27.06 | 88.54; 88.55; 88.56 | 23.48; 23.48; 23.48 |
| 1.06 | 1.017; 1.016; 1.015 | 33.09; 33.09; 33.10 | 88.59; 88.59; 88.60 | 31.07; 31.08; 31.09 |
| **1.07** | 1.027; 1.026; 1.025 | 32.83; 32.84; 32.84 | 88.59; 88.59; 88.60 | **31.12; 31.13; 31.14** |
| | | | $V_{ocI} = 1.07\ V$ | **435.5; 435.6; 435.7=$T_H$(K)** |
| 1.08 | 1.084; 1.083; 1.082 | 32.47; 32.47; 32.48 | 88.59; 88.59; 88.60 | 31.06; 31.07; 31.08 |
| **1.1272** | 1.084; 1.083; 1.082 | 29.76; 29.76; 29.76 | 88.56; 88.57; 88.58 | 29.71; 29.71; 29.72 |
| 3 | 3.317; 3.314; 3.311 | 0.160; 0.160; 0.159 | 87.28; 87.29; 87.30 | 0.420; 0.418; 0.416 |
| Here, **x=0.5**. For the $(Te^+Mg, Sb^+In, Sn^+Cd)$ junctions, the value of α given in Eq. (46) is 1.0866 | | | | |
| $n^+p$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ |
| **0.980** | 1.414; 1.412; 1.410 | 27.06; 27.06; 27.06 | 84.48; 84.50; 84.51 | 22.40; 22.41; 22.41 |
| 1.08 | 1.549; 1.547; 1.545 | 31.39; 31.39; 31.40 | 84.54; 84.56; 84.58 | 28.66; 28.67; 28.68 |
| **1.09** | 1.564; 1.562; 1.560 | 31.14; 31.15; 31.15 | 84.54; 84.56; 84.57 | **28.70; 28.70; 28.72** |
| | | | $V_{ocI} = 1.09\ V$ | **420.7; 420.7; 420.9=$T_H$(K)** |
| 1.10 | 1.579; 1.577; 1.575 | 30.84; 30.84; 30.85 | 84.54; 84.55; 84.57 | 28.68; 28.69; 28.70 |
| **1.1272** | 1.620; 1.618; 1.616 | 29.80; 29.80; 29.80 | 84.52; 84.54; 84.56 | 28.39; 28.40; 28.41 |
| 3 | 4.970; 4.963; 4.956 | 0.849; 0.845; 0.841 | 82.83; 82.84; 82.86 | 2.110; 2.101; 2.090 |
| Here, **x=1**. For the $(Te^+Mg, Sb^+In, Sn^+Cd)$ junctions, the value of α given in Eq. (46) is 1.0992 | | | | |
| $n^+p$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ | $Te^+Mg;\ Sb^+In;\ Sn^+Cd$ |
| **0.980** | 2.795; 2.788; 2.780 | 27.06; 27.06; 27.06 | 74.87; 74.91; 74.96 | 19.85; 19.87; 19.88 |
| **1.1272** | 3.193; 3.185; 3.175 | 29.78; 29.78; 29.79 | 74.99; 75.03; 75.02 | 25.17; 25.19; 25.21 |
| 1.16 | 3.291; 3.283; 3.273 | 29.11; 29.12; 29.12 | 74.96; 75.00; 75.05 | 25.31; 25.33; 25.35 |
| **1.17** | 3.321; 3.313; 3.303 | 28.88; 28.88; 28.89 | 74.95; 74.99; 75.04 | **25.32; 25.34; 25.36** |
| | | | $V_{ocI} = 1.17\ V$ | **401.7; 401.8; 401.9=$T_H$(K)** |
| 1.18 | 3.352; 3.343; 3.333 | 28.63; 28.63; 28.64 | 74.94; 74.98; 75.03 | 25.31; 25.33; 25.35 |
| 3 | 9.866; 9.841; 9.811 | 4.480; 4.459; 4.434 | 72.38; 72.43; 72.48 | 9.928; 9.688; 9.641 |

**Table 4. In the HD [$(Mg; In; Cd)$- $X(x)$-alloy] ER-LD[(Te; Sb; Sn)-$X(x)$-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**

| $p^+n$ | | $Mg^+Te$ | $In^+Sb$ | $Cd^+Sn$ |
|---|---|---|---|---|
| Here, **x=0,** and for the ($Mg^+Te$, $In^+Sb$, $Cd^+Sn$)-junctions and from Eq. (34), one obtains: $\frac{\tau^*_{ett}}{\tau_{eE}} = (0,0,0)$ suggesting a completely transparent condition. | | | | |
| $J_{Bno}$ in $10^{-20}$ (A/cm²) | ↘ | 3.0094 | 2.8418 | 2.6512 |
| $J_{Epo}$ in $10^{-23}$ (A/cm²) | ↘ | 1.1965 | 1.1298 | 1.0513 |
| $J_{oII}$ in $10^{-20}$ (A/cm²) | ↘ | 3.0106 | 2.8429 | 2.6522 |
| Here, **x=0.5,** and for the ($Mg^+Te$, $In^+Sb$, $Cd^+Sn$)-junctions and from Eq. (34), one obtains: $\frac{\tau^*_{ett}}{\tau_{eE}} = (0,0,0)$ suggesting a completely transparent condition. | | | | |
| $J_{Bno}$ in $10^{-14}$ (A/cm²) | ↘ | 1.7729 | 1.6831 | 1.5810 |
| $J_{Epo}$ in $10^{-18}$ (A/cm²) | ↘ | 7.9283 | 7.5654 | 7.1346 |
| $J_{oII}$ in $10^{-14}$ (A/cm²) | ↘ | 1.7737 | 1.6839 | 1.5818 |
| Here, **x=1,** and for the ($Mg^+Te$, $In^+Sb$, $Cd^+Sn$)-junctions and from Eq. (34), one obtains: $\frac{\tau^*_{ett}}{\tau_{eE}} = (0,0,0)$ suggesting a completely transparent condition. | | | | |
| $J_{Bno}$ in $10^{-8}$ (A/cm²) | ↘ | 9.9807 | 0.9512 | 0.8980 |
| $J_{Epo}$ in $10^{-12}$ (A/cm²) | ↘ | 4.9874 | 4.7968 | 4.5697 |
| $J_{oII}$ in $10^{-8}$ (A/cm²) | ↘ | 9.9857 | 0.9517 | 0.8985 |

**Table 5. In the HD [($Mg$; $In$; $Cd$)- $X(x)$-alloy] ER-LD[(Te; Sb; Sn)-$X(x)$-alloy] BR, for Physical Conditions Given in Eq. (42) and for a Given x, Our Numerical Results of $n_{II}$, $J_{scII}$, $F_{II}$, $\eta_{II}$, and $T_H$, are Computed, Using Equations (46, 45, 47, 48, 49), Respectively, Noting that Both $\eta_{IImax.}$ and $T_H$, Marked in Bold, Increase with Increasing x for Given $r_{a(d)}$.**

| $V_{oc}(V)$ | $n_{II}$ | $J_{scII}(\frac{mA}{cm^2})$ | $F_{II}(\%)$ | $\eta_{II}(\%)$ |
|---|---|---|---|---|
| Here, **x=0**. For the ($Mg^+Te, In^+Sb, Cd^+Sn$)-junctions, the value of β given in Eq. (46) is 1.052. | | | | |
| $p^+n$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ |
| **0.980** | 0.919; 0.918; 0.917 | 24.20; 24.20; 24.20 | 88.78; 88.79; 88.81 | 21.05; 21.06; 21.06 |
| **1.03** | 0.961; 0.960; 0.958 | 29.84; 29.85; 29.86 | 88.83; 88.84; 88.85 | 27.30; 27.31; 27.33 |
| 1.19 | 1.110; 1.108; 1.106 | 31.21; 31.22; 31.23 | 88.84; 88.85; 88.86 | 32.99; 33.02; 33.03 |
| **1.20** | 1.119; 1.117; 1.116 | 30.96; 30.97; 30.98 | 88.83; 88.85; 88.86 | **33.01; 33.03; 33.04** |
| | | | $V_{ocII} = 1.20\ V$ | **447.8; 447.9; 448.0=$T_H(K)$** |
| 1.21 | 1.129; 1.127; 1.125 | 30.70; 30.71; 30.72 | 88.83; 88.84; 88.86 | 32.99; 33.01; 33.03 |
| 3 | 2.977; 2.973; 2.968 | 2.545; 2.536; 2.526 | 88.29; 88.30; 88.32 | 6.740; 6.719; 6.693 |
| Here, **x=0.5**. For the ($Mg^+Te, In^+Sb, Cd^+Sn$)-junctions, the value of β given in Eq. (46) is 1.0698. | | | | |
| $p^+n$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ |
| **0.980** | 1.357; 1.354; 1.351 | 24.20; 24.20; 24.20 | 84.95; 84.97; 84.99 | 20.15; 20.15; 20.16 |
| **1.03** | 1.415; 1.413; 1.409 | 29.80; 29.81; 29.83 | 85.03; 85.05; 85.08 | 26.10; 26.12; 26.14 |
| 1.26 | 1.727; 1.724; 1.720 | 31.91; 31.92; 31.94 | 85.06; 85.08; 85.10 | 34.20; 34.22; 34.25 |
| **1.27** | 1.741; 1.738; 1.734 | 31.67; 31.68; 31.70 | 85.06; 85.08; 85.10 | **34.21; 34.23; 34.26** |
| | | | $V_{ocII} = 1.27\ V$ | **456.0; 456.1; 456.3=$T_H(K)$** |
| 1.28 | 1.755; 1.752; 1.748 | 31.42; 31.43; 31.44 | 85.05; 85.07; 85.10 | 34.20; 34.22; 34.25 |
| 3 | 4.425; 4.417; 4.407 | 4.344; 4.329; 4.311 | 84.23; 84.25; 84.27 | 10.98; 10.94; 10.90 |
| Here, **x=1**. For the ($Mg^+Te, In^+Sb, Cd^+Sn$)-junctions, the value of β given in Eq. (46) is 1.1261. | | | | |
| $p^+n$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ | $Mg^+Te$; $In^+Sb$; $Cd^+Sn$ |
| **0.980** | 2.578; 2.570; 2.560 | 24.20; 24.20; 24.20 | 76.20; 76.26; 76.32 | 18.07; 18.08; 18.10 |
| **1.03** | 2.672; 2.663; 2.653 | 29.80; 29.82; 29.85 | 76.43; 76.49; 76.55 | 23.46; 23.50; 23.53 |
| 1.37 | 3.525; 3.514; 3.500 | 33.69; 33.72; 33.76 | 76.56; 76.62; 76.68 | 35.34; 35.40; 35.46 |
| **1.38** | 3.553; 3.541; 3.527 | 33.46; 33.49; 33.52 | 76.56; 76.61; 76.67 | **35.35; 35.40; 35.47** |
| | | | $V_{ocII} = 1.38$ | **464.0; 464.4; 464.9=$T_H(K)$** |
| 1.39 | 3.580; 3.568; 3.555 | 33.22; 33.24; 33.29 | 76.55; 76.60; 76.66 | 35.34; 35.40; 35.46 |
| 3 | 8.612; 8.584; 8.551 | 7.091; 7.059; 7.022 | 74.76; 74.82; 74.88 | 15.90; 15.84; 15.77 |