Maximal Efficiencies in New Single GaAs$_{1-x}$Sb$_x$-Alloy Junction Solar Cells at 300 K

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Abstract:
In single $n^+(p^-) - p(n) \ [X(x) \equiv \text{GaAs}_{1-x}\text{Sb}_x]$-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, $\eta_{\text{Imax}}$, obtained at the open circuit voltage $V_{\text{oc}} (= V_{\text{oc}(\text{II})})$, 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 $r_{\text{Sn(Cd)}}$-radius, for example, $\eta_{\text{Imax}}(V) = 31.14\%, 28.72\%, 25.36\%$, according to $T_H(K) = 435.7, 420.9, 401.9$, at $V_{\text{oc}}(V) = 1.07, 1.09, 1.17$, respectively, while, (ii)- from Table 5, for the single $p^+ - n$ $X(x)$-alloy junction solar cell and for given $r_{\text{Cd(Sn)}}$-radius, for example, $\eta_{\text{Imax}}(V) = 33.04\%, 34.26\%, 35.47\%$, according to $T_H(K) = 448.0, 456.3, 464.9$, at $V_{\text{oc}}(V) = 1.07, 1.09, 1.17$, respectively; (iii)-Then, as given in Table 3, for $x = 0$ and for $r_{\text{Te}(\text{Mg})}$, one gets $\eta_I_{\text{m}}$ = 23.48 % and 29.71 % at $V_{\text{oc}} = 0.98$ V and 1.1727 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 $r_{\text{Sn(Cd)}}$, one gets in Table 3: $\eta_{\text{Imax}} = 25.36\%$ at $V_{\text{oc}} = 1.17$ V, and in Table 5, $\eta_{\text{Imax}} = 35.47\%$ at $V_{\text{oc}} = 1.38$ 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 $n^+(p^-) - p(n) \ [X(x) \equiv \text{GaAs}_{1-x}\text{Sb}_x]$-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, $\eta_{\text{Imax}}$, according to highest hot reservoir temperatures $T_H(K)$, obtained at the open circuit voltage: $V_{oc} = V_{oc(\text{cfl})}$ 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 $J_{d(a)}$ 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, $\eta_{(II)}$, 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 $J_{d(a)}$ and $\eta_{(II)}$ 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 $\eta_{\text{max}}$ 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 $n_{(II)}$, the maximal values of $\eta_{(II)}$ and $\eta_{(II)\text{max}}$, and the corresponding ones of the H-reservoir temperature, $T_H$, obtained at same corresponding $V_{oc} = V_{oc(\text{cfl})}$-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: $\eta_1 = 23.48\%$ and $29.71\%$ at $V_{oc} = 0.98\, \text{V}$ and $1.1272\, \text{V}$, 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: $\eta_{\text{max}} = 25.36\%$ at $V_{oc} = 1.17\, \text{V}$, and in Table 5, $\eta_{(II)\text{max}} = 35.47\%$ at $V_{oc} = 1.38\, \text{V}$, 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 $T=0\, \text{K}$, 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
\(m_v(x)/m_o = 0.300 \times x + 0.291 \times (1 - x),\) \hspace{1cm} (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:
\(\varepsilon_o(x) = 15.69 \times x + 13.13 \times (1 - x),\) \hspace{1cm} (2)

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

(iii) - Finally, the unperturbed band gap at 0 K is found to be given by:
\(E_{go}(x)\) in eV = 0.81 \(\times x + 1.52 \times (1 - x),\) \hspace{1cm} (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 \(r_{do(ao)}(x)\) in absolute values:
\(E_{do(ao)}(x) \equiv \frac{13600 \times [m_{c(v)}(x)/m_o]}{[\varepsilon_o(x)]^2}\) meV, \hspace{1cm} (4)

and then, the isothermal bulk modulus, by:
\(B_{do(ao)}(x) \equiv \frac{E_{do(ao)}(x)}{(4\pi/3)\times(r_{do(ao)})^3}.\) \hspace{1cm} (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 \(r_{d(a)} = r_{do(a)} = r_{As(Ga)} = 0.118 \) 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 \(\sigma\)-variation \(\Delta \sigma \equiv \sigma - \sigma_o = \sigma,\) are defined by: \(\frac{dp}{dV} = -\frac{B}{V}\) and \(p = -\frac{d\sigma}{dV},\) giving: \(\frac{d}{dV} \left( \frac{d\sigma}{dV} \right) = \frac{B}{V}.\) Then, by an integration, one gets:
\[ [\Delta \sigma(r_{d(a)}, x)]_n(p) = B_{d_0(a_0)}(x) \times (V - V_{d_0(a_0)}) \times \ln \left( \frac{V}{V_{d_0(a_0)}} \right) = E_{d_0(a_0)}(x) \times \left[ \left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 - 1 \right] \times \ln \left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 \geq 0. \]  

(6)

Furthermore, we also shown that, as \( r_{d(a)} > r_{d_0(a_0)} \) (\( r_{d(a)} < r_{d_0(a_0)} \)), 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: \( \pm [\Delta \sigma(r_{d(a)}, x)]_n(p) \), respectively,

\[
E_{gn(gp)}(r_{d(a)}, x) - E_{go}(x) = E_{d}(r_{d(a)}, x) - E_{d_0(a_0)}(x) = E_{d_0(a_0)}(x) \times \left[ \frac{\varepsilon_0(x)}{\varepsilon(r_{d(a)})} \right]^2 - 1 = + [\Delta \sigma(r_{d(a)}, x)]_n(p),
\]

for \( r_{d(a)} \geq r_{d_0(a_0)} \), and for \( r_{d(a)} \leq r_{d_0(a_0)} \),

\[
E_{gn(gp)}(r_{d(a)}, x) - E_{go}(x) = E_{d}(r_{d(a)}, x) - E_{d_0(a_0)}(x) = E_{d_0(a_0)}(x) \times \left[ \frac{\varepsilon_0(x)}{\varepsilon(r_{d(a)})} \right]^2 - 1 = - [\Delta \sigma(r_{d(a)}, x)]_n(p).
\]

(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 \( r_{d(a)} \geq r_{d_0(a_0)} \), since \( \varepsilon(r_{d(a)}, x) = \frac{\varepsilon_0(x)}{\sqrt{1 - \frac{(r_{d(a)})^3}{r_{d_0(a_0)}}}} \leq \varepsilon_0(x) \), according to the increase in both \( E_{gn(gp)}(r_{d(a)}, x) \) and \( E_{d}(r_{d(a)}, x) \), for a given \( x \), and

\[
E_{gn(gp)}(r_{d(a)}, x) - E_{go}(x) = E_{d}(r_{d(a)}, x) - E_{d_0(a_0)}(x) = E_{d_0(a_0)}(x) \times \left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 - 1 \times \ln \left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 \geq 0,
\]

(8a)

(ii)- for \( r_{d(a)} \leq r_{d_0(a_0)} \), since \( \varepsilon(r_{d(a)}, x) = \frac{\varepsilon_0(x)}{\sqrt{1 - \frac{(r_{d(a)})^3}{r_{d_0(a_0)}}}} \geq \varepsilon_0(x) \), with a condition, given

\[
\left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 - 1 \times \ln \left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 < 1,
\]

by: \( \left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 - 1 \times \ln \left( \frac{r_{d(a)}}{r_{d_0(a_0)}} \right)^3 < 1 \),
\[ E_{\text{gn}(gp)}(r_{d(a)}, x) - E_{\text{go}}(x) = E_{d(a)}(r_{d(a)}, x) - E_{d0(a0)}(x) = -E_{d0(a0)}(x) \times \left( \frac{r_{d(a)}}{r_{d0(a0)}} \right)^{3} \times \ln \left( \frac{r_{d(a)}}{r_{d0(a0)}} \right)^{3} \leq 0, \]  

(8.b)

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

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

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

\[ E_{\text{gin}(gip)}(r_{d(a)}, x, T) \text{ in eV} = E_{\text{gin}(gp)}(r_{d(a)}, x) - 10^{-4} \times T^{2} \times \left[ \frac{3.6773xx}{T+94 \text{ K}} + \frac{5.405\times(1-x)7}{T+204 \text{ K}} \right], \]  

(9)

which gives: \( E_{\text{gin}(gip)}(r_{d0(a0)}, x = 0, T = 0 \text{ K}) = 1.52 \text{ eV} \) and \( E_{\text{gin}(gip)}(r_{d0(a0)}, x = 1, T = 0 \text{ K}) = 0.81 \text{ eV} \), and \( E_{\text{gin}(gip)}(r_{d0(a0)}, x = 0, T = 300 \text{ K}) = 1.42 \text{ eV} \) and \( E_{\text{gin}(gip)}(r_{d0(a0)}, x = 1, T = 300 \text{ K}) = 0.73 \text{ eV} \),
suggesting that, for given \( x \) and \( r_{d(a)} \), \( E_{\text{gin}(gip)} \) decreases with an increasing \( T \).

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

\[ n_{\text{in}(ip)}^{2}(T, r_{d(a)}, x) \equiv N_{c}(T, x) \times N_{v}(T, x) \times \exp \left( \frac{E_{\text{gin}(gip)}(T, r_{d(a)}, x)}{k_{B}T} \right), \]  

(10)

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

\[ N_{c(\nu)}(T, x) = 2 \times \left( \frac{m_{c(\nu)}(x)k_{B}T^{3}}{2\pi\hbar^{2}} \right)^{3} \text{ cm}^{-3}. \]  

(11)

So, the numerical results of \( E_{d(a)}(r_{d(a)}, x) \), \( B_{d0(a0)}(x) \), \( \varepsilon(r_{d(a)}, x) \) and \( E_{\text{gin}(gip)}(r_{d(a)}, x, T) \), 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 \( E_{\text{Fp}}(-E_{\text{Fp}}) \), band gap narrowing (BGN), and apparent band gap narrowing (ABGN), are reported in the following.

First, the Fermi energy \( E_{\text{Fp}}(-E_{\text{Fp}}) \), 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:
\[
\frac{E_{Fn}(u)}{k_BT} = \frac{G(u)+Au^B}{1+Au^B}, A = 0.0005372 \text{ and } B = 4.82842262,
\] (12)

where \(u\) is the reduced electron density, \(u(N_{d(a)}, T, x) \equiv \frac{N_{d(a)}}{N_{c(\nu)}(T, x)}F(u) = au^2\left(1 + bu^{-\frac{4}{3}} + cu^{-\frac{6}{3}}\right)^2\),

\[
a = \left((3\sqrt{\pi}/4) \times u\right)^{2/3}, \quad b = \frac{1}{8}(\pi/\alpha)^2, \quad c = \frac{62.3739855}{1920}(\pi/\alpha)^4,
\]

and \(G(u) \approx Ln(u) + 2^{\frac{3}{2}} \times u \times e^{-du}; d = 2^{3/2}\left[\frac{1}{\sqrt{\pi}} - \frac{3}{16}\right] > 0\).

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) \(E_{Fn(u<<1)}\left(\frac{-E_{Fp(u<<1)}}{k_BT}\right) \ll -1\), 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:

\[
r_{sn(sp)}(N_{d(a)}, r_{d(a)}, x) = 1.1723 \times 10^8 \times \left(\frac{g_{c(\nu)}}{N_{d(a)}}\right)^{1/3} \times \frac{m_{c(\nu)}(x)}{e(r_{d(a)}-x)} \times g_{c(\nu)} = 1(1),
\] (13)

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

\[
E_{cn(cp)}(N_{d(a)}, r_{d(a)}, x) = \frac{-0.87553}{0.0908 + r_{sn(sp)}} + \frac{0.87553}{1 + 0.03847728 \times \text{r}_{sn(sp)}^{0.67378876} - 0.093288}.
\]

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):

\[
\Delta E_{gn}(N_{d}, r_{d}, x) \approx a_1 \times \frac{\epsilon_{o(x)}}{\epsilon(r_{d}, x)} \times N_r^{1/3} + a_2 \times \frac{\epsilon_{o(x)}}{\epsilon(r_{d}, x)} \times N_r^{1/2} \times (2.503 \times [-E_{cn}(r_{sn}) \times r_{sn}]) + a_3 \times \left[\frac{\epsilon_{o(x)}}{\epsilon(r_{d}, x)}\right]^{5/4} \times \frac{m_{v}}{m_{c}} \times N_r^{1/4} + a_4 \times \frac{\epsilon_{o(x)}}{\epsilon(r_{d}, x)} \times N_r^{1/2} \times 2 + a_5 \times \left[\frac{\epsilon_{o(x)}}{\epsilon(r_{d}, x)}\right]^{3/2} \times N_r^{1/5}, \quad N_r \equiv \left(\frac{N_{d}}{0.999 \times 10^{17} \text{ cm}^{-3}}\right),
\] (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:
\[ \Delta E_{gp}(N_a, r_a, x) = a_1 \times \frac{\varepsilon_{\alpha}(x)}{\varepsilon_{\alpha}(r_a, x)} \times N_r^{1/3} + a_2 \times \frac{\varepsilon_{\alpha}(x)}{\varepsilon_{\alpha}(r_a, x)} \times N_r^{1/2} + \left(2.503 \times [-E_{cp}(r_{sp}) \times r_{sp}^2]\right) + a_3 \times \left[ \frac{\varepsilon_{\alpha}(x)}{\varepsilon_{\alpha}(r_a, x)} \right]^{5/4} \times \sqrt{\frac{m_e}{m_p}} \times N_r^{1/4} + 2a_4 \times \left[ \frac{\varepsilon_{\alpha}(x)}{\varepsilon_{\alpha}(r_a, x)} \right]^{3/2} \times N_r^{1/6}, \quad N_r \equiv \left(\frac{N_a}{9.99 \times 10^{17} \text{cm}^{-3}}\right), \quad (14p) \]

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, \( n_{en(ep)}^* \), by:

\[ n_{en(ep)}^* (N_{d(a)}, T, r_{d(a)}, x) \equiv \sqrt{N_{d(a)} \times p_0(n_o)} = n_{in(ip)}(T, r_{d(a)}, x) \times \exp\left[\frac{\Delta E_{agn(agp)}}{2k_BT}\right]. \quad (15) \]

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

\[ \Delta E_{agn}(N_a, T, r_d, x) \equiv \Delta E_{gn}(N_a, r_d, x) + k_BT \times \ln\left(\frac{N_a}{N_{\epsilon(T, x)}}\right) - \Delta E_{Fn}(N_a, T, x), \quad (16n) \]

\[ \Delta E_{agp}(N_a, T, r_a, x) \equiv \Delta E_{gp}(N_a, r_a, x) + k_BT \times \ln\left(\frac{N_a}{N_{\epsilon(T, x)}}\right) + \Delta E_{pp}(N_a, T, x). \quad (16p) \]

### 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:

\[ J_{ot(ot)} \equiv J_{Eno(Epo)} + J_{Bpo(Bno)} \quad (17) \]

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 (Van Cong, 2023):

\[ J_{Bpo(Bno)}(N_{a(d)}, T, r_{a(d)}, x) = \frac{e \times n_{ip}^2(T, r_{a(d)}, x) \times \frac{D_{e(h)}(N_{a(d), T, r_{a(d)}, x})}{\tau_{eB(h)}(N_{a(d)})}}{N_{a(d)}}, \quad (18) \]
where \( n_{ip(n)}^2(T, r_{d(a)}, x) \) is determined Eq. (10), \( D_e(h)(N_{a(d)}, T, r_{d(a)}, x) \) is the minority electron (minority hole) diffusion coefficient:

\[
D_e(N_a, T, r_a, x) = \frac{k_BT}{e} \times \left[ 200 + \frac{1.3 \times 10^{14} \text{cm}^{-1}}{N_a} \right] \times \left( \frac{\varepsilon(r_a, x)}{\varepsilon_o(x)} \right)^2 \text{cm}^2\text{s}^{-1}, \tag{19a}
\]

\[
D_h(N_d, T, r_d, x) = \frac{k_BT}{e} \times \left[ 130 + \frac{8300}{N_d} \right] \times \left( \frac{\varepsilon(r_d, x)}{\varepsilon_o(x)} \right)^2 \text{cm}^2\text{s}^{-1}, \tag{19b}
\]

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

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

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

### \( J_{E|o(Epo)} \) 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):

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

\[
N_{do(ao)}(W) = 7.9 \times 10^{10} \times (2 \times 10^5) \times \exp \left\{ -\left( \frac{W}{184.2 (1) \times 10^{-7} \text{cm}} \right)^{0.66} \right\} (\text{cm}^{-3}), \tag{21}
\]

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:

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

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

\[
N_{d(a)}^*(y = W, T, r_{d(a)}, x) \equiv \frac{N_{do(ao)}(W)}{\exp \left[ \frac{\Delta E_{agp}(N_{do(ao)}W, r_{d(a)}x)}{k_BT} \right]}, \tag{22}
\]
where the apparent band gap narrowing $\Delta E_{agm(aq)}$ 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:

$$F_{h(e)}(y, N_{d(a)}, T, r_{d(a)}, x) = \frac{\frac{N_{d(a)}}{D_{h(e)}}}{\exp\left[\frac{-\Delta E_{agm(aq)}}{k_BT}\right]} (cm^{-5} \times s),$$

(23)

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

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

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 $\tau_{E}(eE)$ as:

$$\tau_{E}(eE) = \frac{1}{D_{h(e)} \times L_{h(e)}^2} = \frac{1}{D_{h(e)} \times (C \times F_{h(e)})^2}.$$

(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:

$$p_o(y|n_o(y)) = \frac{n_{in(ip)}}{N_{d(a)}(y=W, T, r_{d(a)}, x)},$$

(25)

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

$$u(y) = \frac{p(y|n(y)) - p_o(y|n_o(y))}{p_o(y|n_o(y))},$$

(26)

which must verify the two following boundary conditions as:

$$u(y = 0) = \frac{-J_n(y=0) |I_e(y=0)|}{eS \times p_o(y=0|n_o(y=0))},$$

$$u(y = W) = \exp\left(\frac{V}{n_{I(V)}(V) \times V_T}\right) - 1.$$
Here, $n_{i(I)}(V)$ is the photovoltaic conversion factor, being determined later, $S \frac{cm}{s}$ 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 (Van Cong et al., 2023; Van Cong, 2023):

\[
J_{h(e)}(y, r_{d(a)}, x) = \frac{-e(+e) \times n_{i(n,i)}^2}{F_{h(e)}(y)} \times \frac{du(y)}{dy} = \frac{-e(+e) n_{i(n,i)}^2 D_{h(e)}(N_{d(a)} r_{d(a)} x)}{N_{d(a)}^*(y, r_{d(a)} x) x} \times \frac{du(y)}{dy},
\]

(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:

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

(28)

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

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

(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:

\[
u(y) = \frac{\sinh(p(y)+1(W,S) \times \cosh(p(y))}{\sinh(p(W)+1(W,S) \times \cosh(p(W))} \times \left( \exp \left( \frac{V}{n_{i(I)}(V) x V_T} \right) - 1 \right),
\]

(30)

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

\[
I(T, r_{d(a)}, x, W, S) = \frac{D_{h(e)}(y=W, N_{d(a)}(W), T, r_{d(a)} x)}{S x L_{h(e)}(y=W, N_{d(a)}(W), T, r_{d(a)} x)}.
\]

(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:

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

(32)
where $L_{h(e)}^*$ 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:

$$
J_{h(e)}(y, W, N_d(a), T, r_d(a), x, S, V) = -J_{Eno}(y, W, N_d, T, r_d, x, S) \left[ J_{Epo}(y, W, N_a, T, r_a, x, S) \right] \times \left( \exp \left( \frac{V}{N(t)}(W) \times V_T \right) - 1 \right),
$$

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

$$
J_{Eno(Epo)}(y, W, N_d(a), T, r_d(a), x, S) = \frac{e n_{h(e)}^2 N_d(a)}{N_d(a)(y, N_d(a), T, r_d(a), x)} \times \frac{1}{\sinh(P(W)) + l \times \cosh(P(W))}
$$

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

$$
J_{Eno(Epo)}(y = 0, W, N_d(a), T, r_d(a), x, S) = \frac{e n_{h(e)}^2 N_d(a)}{N_d(a)(y = 0, N_d(a), T, r_d(a), x)} \times \frac{1}{\sinh(P(W)) + l \times \cosh(P(W))}
$$

and then,

$$
\frac{J_{h(e)}(y = 0, W, N_d(a), T, r_d(a), x, S, V)}{J_{h(e)}(y = W, W, N_d(a), T, r_d(a), x, S, V)} \equiv \frac{J_{Eno(Epo)}(y = 0, W, N_d(a), T, r_d(a), x, S)}{J_{Eno(Epo)}(y = W, W, N_d(a), T, r_d(a), x, S)} = \frac{1}{\cosh(P(W)) + l \times \sinh(P(W))}
$$

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

$$
Q_{h(e)}^*(y = W, W, N_d(a), T, r_d(a), x) \equiv \int_0^W \left[ e^2 (-e) \times u(y) \times p_o(y)[n_o(y)] \times \frac{\tau_{h(e)}^2}{\tau_{h(e)}(y, N_d(a), T, r_d(a), x)} \right] dy,
$$

and the effective minority hole (minority electron) transit time $\tau_{h(e)}(y, N_d(a), T, r_d(a), x) = Q_{h(e)}^*(y = W, W, N_d(a), T, r_d(a), x, S)$, and from Equations (24, 31), one obtains:

$$
\frac{\tau_{h(e)}^2}{\tau_{h(e)}(y, N_d(a), T, r_d(a), x, S)} \equiv 1 - \frac{J_{Eno(Epo)}(y = 0, W, N_d(a), T, r_d(a), x, S)}{J_{Eno(Epo)}(y = W, W, N_d(a), T, r_d(a), x, S)} = 1 - \frac{1}{\cosh(P(W)) + l \times \sinh(P(W))}
$$

Now, some important results can be obtained and discussed below.
As \( P \ll 1 \) (or \( W \ll L_{h(e)} \)) and \( S \to \infty \), \( I \equiv I(W, S) = \frac{D_{h(e)}(N_{do(ao)}(W), T, r_{d(a)} \times x)}{S \times L_{h(e)}(N_{do(ao)}(W), T, r_{d(a)} \times x)} \to 0 \), from Eq. (38), one has: 

\[
\frac{\tau_{ht(ee)}^{*}(y=W,W,N_{d(a)}, T, r_{d(a)} \times x, S)}{\tau_{h(ee)}} \to 0, \quad \text{suggesting a completely transparent emitter region (CTER)-case, where, from Eq. (36), one obtains:}
\]

\[
I_{Eno(Epo)}(y=W, N_{d(a)}, T, r_{d(a)} \times x, S \to \infty) \to \frac{en_{1}(p) \times D_{h(e)}}{N_{d(a)}(y=W, N_{d(a)}, T, r_{d(a)} \times x) \times L_{h(e)}} \times \frac{1}{P(W)}. \quad (39)
\]

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

\[
\frac{\tau_{ht(ee)}^{*}(y=W,W,N_{d(a)}, T, r_{d(a)} \times S)}{\tau_{h(ee)}} \to 1, \quad \text{suggesting a completely opaque emitter region (COER)-case, where, from Eq. (36), one gets:}
\]

\[
I_{Eno(Epo)}(y=W, N_{d(a)}, T, r_{d(a)} \times x, S \to 0) \to \frac{en_{1}(p) \times D_{h(e)}}{N_{d(a)}^{*}(y=W, N_{d(a)}, T, r_{d(a)} \times x) \times L_{h(e)}} \times \text{tanh}(P). \quad (40)
\]

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

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

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

**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:

\[
W = 15 \, \mu m, \quad N_{d(a)} = 10^{19} \, \text{cm}^{-3}(10^{20} \, \text{cm}^{-3}), \quad r_{d(a)} \times x, \quad S = 100 \, \text{(cm)}^{2}; \quad N_{a(d)} = 10^{17} \, \text{cm}^{-3}, \quad r_{a(d)}, \quad x, \quad (42)
\]

we propose, at given open circuit voltages \( V_{oct1(oct2)} \) and \( V_{oct1(oct2)} \), the corresponding data of the short circuit current density \( J_{sc1(II)} \), in order to formulate our following treatment method of two fix points (Green, 2022; Moon et al., 2016), as:

at \( V_{oct1(oct2)}(V) = 0.980 \, (1.1272), \quad J_{sc1(scl2)} \, \text{(mA/cm}^2 \text{)} = 27.06 \, (29.76), \)
at \( V_{oc\text{II1}(oc\text{II2})}(V) = 0.980 \) (1.03), \( J_{sc\text{II1}(sc\text{II2})}(mA/cm^2) = 24.2 \) (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:

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

where the function \( n_{II}(V) \) 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: \( J_{ph}(V = V_{oc}) \equiv J_{sc(I)}(W, N_d(a), T, r_d(a), x, S; N_a(d), T, r_a(d), x, V_{oc}) \), for \( V_{oc} \geq V_{oc\text{II1}(oc\text{II1})} \).

Therefore, the photovoltaic conversion effect occurs, according to:

\[
J_{sc(II)}(W, N_d(a), T, r_d(a), x, S; N_a(d), T, r_a(d), x, V_{oc}) \equiv J_{ol(II)}(W, N_d(a), T, r_d(a), x, S; N_a(d), T, r_a(d), x) \times (e^{X_{II}(V_{oc})} - 1), \quad (45)
\]

where \( n_{II}(V_{oc}) \equiv n_{II}(W, N_d(a), T, r_d(a), x, S; N_a(d), T, r_a(d), x, V_{oc}) \), and \( X_{II}(V_{oc}) \equiv \frac{V_{oc}}{n_{II}(V_{oc})V_T} \).

Here, one remarks that (i) for a given \( V_{oc} \), both \( n_{II}(V) \) and \( J_{ol(II)}(V) \) have the same variations, obtained in the same physical conditions, as observed in the following calculation, (ii) the function \( (e^{X_{II}(V_{oc})} - 1) \) or the PVCF, \( n_{II}(V) \), representing the photovoltaic conversion effect, converts the light, represented by \( J_{sc(II)}(W) \), into the electricity, by \( J_{ol(II)}(W) \), 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, \( n_{II}(V_{oc}) \) is determined.

Now, for \( V_{oc} \geq V_{oc\text{II1}(oc\text{II1})} \), one can propose the general expressions for the PVCF, in order to get exactly the values of \( n_{II(II1)}(V_{oc\text{II1}(oc\text{II1})}) \) and \( n_{II(II2)}(V_{oc\text{II2}(oc\text{II2})}) \), as functions of \( V_{oc} \), by:

\[
n_{II(II)}(W, N_d(a), T, r_d(a), x, S; N_a(d), T, r_a(d), x, V_{oc}) = n_{II(II1)}(V_{oc\text{II1}(oc\text{II1})}) + n_{II(II2)}(V_{oc\text{II2}(oc\text{II2})}) \times \left( \frac{V_{oc}}{V_{oc\text{II1}(oc\text{II1})}} - 1 \right)^{\alpha(\beta)}, \quad (46)
\]

where, for example, the values of \( \alpha(\beta) \), obtained for \( x = (0, 0.5, \text{and} 1) \), will be reported in Tables 3 and 5, for \( \text{GaAs}_{1-x}\text{Sb}_x \) 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:

\[
F_{II}(W, N_d(a), T, r_d(a), x, S; N_a(d), T, r_a(d), x, V_{oc}) = \frac{X_{II}(V_{oc}) - \ln[X_{II}(V_{oc}) + b]}{X_{II}(V_{oc}) + a}, \quad a = 1 \text{ and } b = 0.72. \quad (47)
\]
Finally, the efficiency $\eta_{I(II)}$ can be defined in the $n^+(p^+) - p(n)$ X(x) alloy-junction solar cells, by:

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

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

It should be noted that the maximal values of $\eta_{I(II)}$, $\eta_{I(Ill)(I(III))}$, are obtained at the corresponding ones of $V_{oc} = V_{ocI(III)},$ at which $\frac{\partial \eta_{I(II)}(W, N_{d(a)}, T, r_{d(a)}, x, S; N_{a(d)}, T, r_{a(d)}, x, V_{oc})}{\partial V_{oc}} = 0$, 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:

$$\eta_{I(III)(I(II))} = 1 - \frac{T_c}{T_H}.$$

### 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
- **HD (Mg; In; Cd) X(x) alloy ER – LD (Te; Sb; Sn) X(x) – alloy BR – case**, according to: 3

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 $\frac{J_{Bpo}}{J_{Bpo}}, J_{Eno}$ and $J_{Jot}$, are calculated, using Equations (38), (18), (36) and (41), respectively, and reported in Table 2. Further, those of $\eta_{I}, J_{scI}, F_{I}, \eta_{I(Ill)}$, 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 \( \frac{r_{\text{d(a)}}}{r_{\text{f}}}, J_{\text{Bno}}, J_{\text{Bpo}} \) and \( J_{\text{HII}} \), are calculated using Equations (38), (18), (36) and (41), respectively, and reported in Table 4. Further, those of \( \eta_{\text{II}}, J_{\text{scII}}, F_{\text{II}}, \eta_{\text{HII}}, \) and \( T_{\text{H}} \), 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 \( r_{\text{d(a)}} \)-radius, for example, one obtains: \( \eta_{\text{Imax}}(x) = 31.14\%, 28.72\%, 25.36\% \), according to \( T_{H}(K) = 435.7, 420.9, 401.9 \), at \( V_{\text{oicl}}(V) = 1.07, 1.09, 1.17 \), 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 \( r_{\text{d(a)}} \)-radius, for example, one gets: \( \eta_{\text{Imax}}(x) = 33.04\%, 34.26\%, 35.47\% \), according to \( T_{H}(K) = 448.0, 456.3, 464.9 \), at \( V_{\text{oicl}}(V) \geq V_{\text{oc}}(V) = 1.20, 1.27, 1.38 \), respectively, suggesting that such \( \eta_{\text{Imax}(\text{max})} \) and \( T_{H} \) variations depend on \( V_{\text{oicl}}(V) \geq V_{\text{oc}}(V) \) – values.

Then, as given in Table 3, for \( x = 0 \) and \( r_{\text{d(a)}} = r_{\text{Te}(\text{Mg})} \), one gets: \( \eta_{\text{I}} = 23.48 \% \) and 29.71 \% at \( V_{\text{oc}} = 0.98 \text{ V} \) and 1.1272 \text{ 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 \( r_{\text{d(a)}} = r_{\text{Sn}(\text{Cd})} \), one gets in Table 3: \( \eta_{\text{Imax}} = 25.36 \% \) at \( V_{\text{oc}} = 1.17 \text{ V} \), and in Table 5, \( \eta_{\text{Imax}} = 35.47 \% \) at \( V_{\text{oc}} = 1.38 \text{ V} \), 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 \( \text{GaAs}_{1-x}\text{Sb}_x \)-alloy junction solar cells could be chosen rather than the single crystalline [GaAs, or GaSb]-junction solar cells.

References


Van Cong, H. (2023). (14.82%, 12.16%, 26.55%, or 23.69%)-Limiting Highest Efficiencies obtained in \( n^+(p^+) - p(n) \) Crystalline (X≡Ge, GaSb, CdTe, or CdSe)-Junction Solar Cells, Due to the Effects of Impurity Size, Temperature, Heavy Doping, and Photovoltaic Conversion. SCIREA Journal of Physics, 8, 575-595. https://dx.doi.org/10.54647/physics140591

Van Cong, H., Ho-Huynh Thi, K.S., Blaise, P., Pivet, S.T., Huynh, C.V., Cayrol, M. & Munoz, S. (2023). 46 % (46 %) [48 % (49 %)]- Maximal Efficiencies \( \eta_{\text{Imax}(\text{max})} \) invested in Two New
Single $n^{+}(p^{+}) - p(n)$ X(x)- Alloy Junction Solar Cells at 300 K, $[X(x) \equiv CdS_{1-x}Te_{x}], 0 \leq x \leq 1$, According to Highest Hot Reservoir Temperatures, $T_{H}$, obtained from Carnot-Efficiency Theorem, being proved by Entropy Law. *SCIREA Journal of Physics*, 8, 596-618. [https://doi.org/10.54647/physics140600](https://doi.org/10.54647/physics140600)


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 $\epsilon(r_d(a), x)$ Decrease, while the Other Ones Increase

<table>
<thead>
<tr>
<th>Donor</th>
<th>As</th>
<th>Te</th>
<th>Sb</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_d$ (nm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>$r_{do}=0.118$</td>
<td>0.132</td>
<td>0.136</td>
<td>0.140</td>
</tr>
<tr>
<td>$r_{do}(x)$ in $10^3$ (N/m$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon(r_d, x)$</td>
<td></td>
<td>12.3, 13.5, 14.7</td>
<td>11.8, 13.0, 14.2</td>
<td>11.3, 12.4, 13.5</td>
</tr>
<tr>
<td>$E_d(r_d, x)$ mcV</td>
<td></td>
<td>5.91, 4.75, 3.94</td>
<td>4.38, 3.84, 3.35</td>
<td>3.99, 3.47, 3.09</td>
</tr>
<tr>
<td>$E_{go}(r_d, x)$ eV</td>
<td></td>
<td>1.52, 1.16, 0.81</td>
<td>1.52, 1.16, 0.81</td>
<td>1.52, 1.17, 0.81</td>
</tr>
<tr>
<td>$E_{go}(T = 300K, r_d, x)$ eV</td>
<td></td>
<td>1.42, 1.07, 0.73</td>
<td>1.42, 1.07, 0.73</td>
<td>1.42, 1.08, 0.73</td>
</tr>
<tr>
<td>Acceptor</td>
<td>Ga</td>
<td>Mg</td>
<td>In</td>
<td>Cd</td>
</tr>
<tr>
<td>$r_a$ (nm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{aa}=0.126$</td>
<td>0.140</td>
<td>0.144</td>
<td>0.148</td>
<td></td>
</tr>
<tr>
<td>$B_{aa}(x)$ in $10^3$ (N/m$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon(r_a, x)$</td>
<td></td>
<td>12.4, 13.6, 14.8</td>
<td>12.0, 13.2, 14.3</td>
<td>11.5, 12.6, 13.8</td>
</tr>
<tr>
<td>$E_d(r_a, x)$ mcV</td>
<td></td>
<td>25.7, 25.9, 26.1</td>
<td>25.7, 25.9, 26.1</td>
<td>25.7, 25.9, 26.1</td>
</tr>
<tr>
<td>$E_{go}(r_a, x)$ eV</td>
<td></td>
<td>1.52, 1.16, 0.81</td>
<td>1.52, 1.17, 0.81</td>
<td>1.52, 1.17, 0.81</td>
</tr>
<tr>
<td>$E_{go}(T = 300K, r_a, x)$ eV</td>
<td></td>
<td>1.42, 1.07, 0.73</td>
<td>1.43, 1.08, 0.73</td>
<td>1.43, 1.08, 0.73</td>
</tr>
</tbody>
</table>
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 \(\tau_{ht}\), \(J_{Bpo}\), \(J_{Eno}\) 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

<table>
<thead>
<tr>
<th>(n^*p)</th>
<th>(Te^*Mg)</th>
<th>(Sb^*In)</th>
<th>(Sn^*Cd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J_{Bpo}) in (10^{-19}) (A/cm(^2))</td>
<td>(\nabla)</td>
<td>1.0315</td>
<td>0.9965</td>
</tr>
<tr>
<td>(J_{Eno}) in (10^{-23}) (A/cm(^2))</td>
<td>(\nabla)</td>
<td>1.7830</td>
<td>1.7258</td>
</tr>
<tr>
<td>(J_{ol}) in (10^{-19}) (A/cm(^2))</td>
<td>(\nabla)</td>
<td>1.0317</td>
<td>0.9967</td>
</tr>
</tbody>
</table>

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

| \(J_{Bpo}\) in \(10^{-14}\) (A/cm\(^2\)) | \(\nabla\) | 6.1514 | 5.9426 | 5.7041 |
| \(J_{Eno}\) in \(10^{-18}\) (A/cm\(^2\)) | \(\nabla\) | 2.9271 | 2.8551 | 2.7771 |
| \(J_{ol}\) in \(10^{-14}\) (A/cm\(^2\)) | \(\nabla\) | 6.1517 | 5.9429 | 5.7044 |

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

<p>| (J_{Bpo}) in (10^{-8}) (A/cm(^2)) | (\nabla) | 3.4940 | 3.3754 | 3.2399 |
| (J_{Eno}) in (10^{-13}) (A/cm(^2)) | (\nabla) | 2.5023 | 2.4573 | 2.4108 |
| (J_{ol}) in (10^{-8}) (A/cm(^2)) | (\nabla) | 3.4940 | 3.3755 | 3.2400 |</p>
<table>
<thead>
<tr>
<th>$V_{oc}(V)$</th>
<th>$n_1$</th>
<th>$J_{sc} (\text{mA/cm}^2)$</th>
<th>$F_r(%)$</th>
<th>$\eta(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Here, $x=0.$ For the (Te$^+\text{Mg}, Sb^+\text{In}, Sn^+\text{Cd})$ junctions, the value of $\alpha$ given in Eq. (46) is 1.0822</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n&lt;p</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
</tr>
<tr>
<td>0.980</td>
<td>0.945; 0.944; 0.943</td>
<td>27.06; 27.06; 27.06</td>
<td>88.54; 88.53; 88.56</td>
<td>23.48; 23.48; 23.48</td>
</tr>
<tr>
<td>1.06</td>
<td>1.017; 1.016; 1.015</td>
<td>33.09; 33.09; 33.10</td>
<td>88.59; 88.59; 88.60</td>
<td>31.07; 31.08; 31.09</td>
</tr>
<tr>
<td>1.07</td>
<td>1.027; 1.026; 1.025</td>
<td>32.83; 32.84; 32.84</td>
<td>88.59; 88.59; 88.60</td>
<td>31.12; 31.13; 31.14</td>
</tr>
<tr>
<td>1.08</td>
<td>1.084; 1.083; 1.082</td>
<td>32.47; 32.47; 32.48</td>
<td>88.59; 88.59; 88.60</td>
<td>31.06; 31.07; 31.08</td>
</tr>
<tr>
<td>1.1272</td>
<td>1.084; 1.083; 1.082</td>
<td>29.76; 29.76; 29.76</td>
<td>88.56; 88.57; 88.58</td>
<td>29.71; 29.71; 29.72</td>
</tr>
<tr>
<td>3</td>
<td>3.317; 3.314; 3.311</td>
<td>0.160; 0.160; 0.159</td>
<td>87.28; 87.29; 87.30</td>
<td>0.420; 0.418; 0.416</td>
</tr>
<tr>
<td><strong>Here, $x=0.5.$ For the (Te$^+\text{Mg}, Sb^+\text{In}, Sn^+\text{Cd})$ junctions, the value of $\alpha$ given in Eq. (46) is 1.0866</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n&lt;p</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
</tr>
<tr>
<td>0.980</td>
<td>1.414; 1.412; 1.410</td>
<td>27.06; 27.06; 27.06</td>
<td>84.48; 84.50; 84.51</td>
<td>22.40; 22.41; 22.41</td>
</tr>
<tr>
<td>1.08</td>
<td>1.549; 1.547; 1.545</td>
<td>31.39; 31.39; 31.40</td>
<td>84.54; 84.56; 84.58</td>
<td>28.66; 28.67; 28.68</td>
</tr>
<tr>
<td>1.09</td>
<td>1.564; 1.562; 1.560</td>
<td>31.14; 31.15; 31.15</td>
<td>84.54; 84.56; 84.57</td>
<td>28.70; 28.70; 28.72</td>
</tr>
<tr>
<td>1.10</td>
<td>1.579; 1.577; 1.575</td>
<td>30.84; 30.84; 30.85</td>
<td>84.54; 84.55; 84.57</td>
<td>28.68; 28.69; 28.70</td>
</tr>
<tr>
<td>1.1272</td>
<td>1.620; 1.618; 1.616</td>
<td>29.80; 29.80; 29.80</td>
<td>84.52; 84.54; 84.56</td>
<td>28.39; 28.40; 28.41</td>
</tr>
<tr>
<td>3</td>
<td>4.970; 4.963; 4.956</td>
<td>0.849; 0.845; 0.841</td>
<td>82.83; 82.84; 82.86</td>
<td>2.110; 2.101; 2.090</td>
</tr>
<tr>
<td><strong>Here, $x=1.$ For the (Te$^+\text{Mg}, Sb^+\text{In}, Sn^+\text{Cd})$ junctions, the value of $\alpha$ given in Eq. (46) is 1.0992</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n&lt;p</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
<td>Te$^+\text{Mg}; Sb^+\text{In}; Sn^+\text{Cd}$</td>
</tr>
<tr>
<td>0.980</td>
<td>2.795; 2.788; 2.780</td>
<td>27.06; 27.06; 27.06</td>
<td>74.87; 74.91; 74.96</td>
<td>19.85; 19.87; 19.88</td>
</tr>
<tr>
<td>1.1272</td>
<td>3.193; 3.185; 3.175</td>
<td>29.78; 29.78; 29.79</td>
<td>74.99; 75.03; 75.02</td>
<td>25.17; 25.19; 25.21</td>
</tr>
<tr>
<td>1.16</td>
<td>3.291; 3.283; 3.273</td>
<td>29.11; 29.12; 29.12</td>
<td>74.96; 75.00; 75.05</td>
<td>25.31; 25.33; 25.35</td>
</tr>
<tr>
<td>1.17</td>
<td>3.321; 3.313; 3.303</td>
<td>28.88; 28.88; 28.89</td>
<td>74.95; 74.99; 75.04</td>
<td>25.32; 25.34; 25.36</td>
</tr>
<tr>
<td>1.18</td>
<td>3.352; 3.343; 3.333</td>
<td>28.63; 28.63; 28.64</td>
<td>74.94; 74.98; 75.03</td>
<td>25.31; 25.33; 25.35</td>
</tr>
</tbody>
</table>
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 $\tau_{\text{et}}$, $J_{\text{Bno}}$, $J_{\text{Epo}}$, and $J_{\text{oII}}$ areComputed, Using Equations (38), (18), (36) and (41), Respectively, Noting that $J_{\text{oII}}$ 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

<table>
<thead>
<tr>
<th>p*n</th>
<th>Mg*Te</th>
<th>In*Sb</th>
<th>Cd*Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>J_{\text{Bno}} in $10^{-20}$ (A/cm²)</td>
<td>(\n)</td>
<td>3.0094</td>
<td>2.8418</td>
</tr>
<tr>
<td>J_{\text{Epo}} in $10^{-23}$ (A/cm²)</td>
<td>(\n)</td>
<td>1.1965</td>
<td>1.1298</td>
</tr>
<tr>
<td>J_{\text{oII}} in $10^{-20}$ (A/cm²)</td>
<td>(\n)</td>
<td>3.0106</td>
<td>2.8429</td>
</tr>
</tbody>
</table>

Here, \(x=0\), and for the (Mg*Te, In*Sb, Cd*Sn)-junctions and from Eq. (34), one obtains: $\tau_{\text{et}} = (0, 0, 0)$ suggesting a completely transparent condition.

<table>
<thead>
<tr>
<th>p*n</th>
<th>Mg*Te</th>
<th>In*Sb</th>
<th>Cd*Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>J_{\text{Bno}} in $10^{-14}$ (A/cm²)</td>
<td>(\n)</td>
<td>1.7729</td>
<td>1.6831</td>
</tr>
<tr>
<td>J_{\text{Epo}} in $10^{-18}$ (A/cm²)</td>
<td>(\n)</td>
<td>7.9283</td>
<td>7.5654</td>
</tr>
<tr>
<td>J_{\text{oII}} in $10^{-14}$ (A/cm²)</td>
<td>(\n)</td>
<td>1.7737</td>
<td>1.6839</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>p*n</th>
<th>Mg*Te</th>
<th>In*Sb</th>
<th>Cd*Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>J_{\text{Bno}} in $10^{-18}$ (A/cm²)</td>
<td>(\n)</td>
<td>9.9807</td>
<td>0.9512</td>
</tr>
<tr>
<td>J_{\text{Epo}} in $10^{-12}$ (A/cm²)</td>
<td>(\n)</td>
<td>4.9874</td>
<td>4.7968</td>
</tr>
<tr>
<td>J_{\text{oII}} in $10^{-18}$ (A/cm²)</td>
<td>(\n)</td>
<td>9.9857</td>
<td>0.9517</td>
</tr>
</tbody>
</table>
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 $n_{II}$, $J_{setl}$, $F_{II}$, $\eta_{II}$, and $T_{II}$, are Computed, Using Equations (46, 45, 47, 48, 49), Respectively, Noting that Both $\eta_{II_{max}}$ and $T_{II}$, Marked in Bold, Increase with Increasing $x$ for Given $r_{a(d)}$.

<table>
<thead>
<tr>
<th>$V_{oc}(V)$</th>
<th>$n_{II}$</th>
<th>$I_{setl}$ (mA cm$^{-2}$)</th>
<th>$F_{II}(%)$</th>
<th>$\eta_{II}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>p+n</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.980</td>
<td>0.919; 0.918; 0.917</td>
<td>24.20; 24.20; 24.20</td>
<td>88.78; 88.79; 88.81</td>
<td>21.05; 21.06; 21.06</td>
</tr>
<tr>
<td>1.03</td>
<td>0.961; 0.960; 0.958</td>
<td>29.84; 29.85; 29.86</td>
<td>88.83; 88.84; 88.85</td>
<td>27.30; 27.31; 27.33</td>
</tr>
<tr>
<td>1.19</td>
<td>1.110; 1.108; 1.106</td>
<td>31.21; 31.22; 31.23</td>
<td>88.84; 88.85; 88.86</td>
<td>32.99; 33.02; 33.03</td>
</tr>
<tr>
<td>1.20</td>
<td>1.119; 1.117; 1.116</td>
<td>30.96; 30.97; 30.98</td>
<td>88.83; 88.85; 88.86</td>
<td>33.01; 33.03; 33.04</td>
</tr>
<tr>
<td>1.21</td>
<td>1.129; 1.127; 1.125</td>
<td>30.70; 30.71; 30.72</td>
<td>88.83; 88.84; 88.86</td>
<td>32.99; 33.01; 33.03</td>
</tr>
<tr>
<td>3</td>
<td>2.977; 2.973; 2.968</td>
<td>2.454; 2.456; 2.456</td>
<td>88.29; 88.30; 88.32</td>
<td>6.740; 6.719; 6.693</td>
</tr>
</tbody>
</table>

Here, $x=0$. For the (Mg$^*$Te, In$^*$Sb, Cd$^*$Sn)-junctions, the value of $\beta$ given in Eq. (46) is 1.052.

<table>
<thead>
<tr>
<th>$p^*$n</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.980</td>
<td>1.357; 1.354; 1.351</td>
<td>24.20; 24.20; 24.20</td>
<td>84.95; 84.97; 84.99</td>
<td>20.15; 20.15; 20.16</td>
</tr>
<tr>
<td>1.03</td>
<td>1.415; 1.413; 1.409</td>
<td>29.80; 29.81; 29.83</td>
<td>85.03; 85.05; 85.08</td>
<td>26.10; 26.12; 26.14</td>
</tr>
<tr>
<td>1.26</td>
<td>1.727; 1.724; 1.720</td>
<td>31.91; 31.92; 31.94</td>
<td>85.06; 85.08; 85.10</td>
<td>34.20; 34.22; 34.25</td>
</tr>
<tr>
<td>1.27</td>
<td>1.741; 1.738; 1.734</td>
<td>31.67; 31.68; 31.70</td>
<td>85.06; 85.08; 85.10</td>
<td>34.21; 34.23; 34.26</td>
</tr>
<tr>
<td>1.28</td>
<td>1.755; 1.752; 1.748</td>
<td>31.42; 31.43; 31.44</td>
<td>85.05; 85.07; 85.10</td>
<td>34.20; 34.22; 34.25</td>
</tr>
<tr>
<td>3</td>
<td>4.425; 4.417; 4.407</td>
<td>4.344; 4.329; 4.311</td>
<td>84.23; 84.25; 84.27</td>
<td>10.98; 10.94; 10.90</td>
</tr>
</tbody>
</table>

Here, $x=0.5$. For the (Mg$^*$Te, In$^*$Sb, Cd$^*$Sn)-junctions, the value of $\beta$ given in Eq. (46) is 1.0698.

<table>
<thead>
<tr>
<th>$p^*$n</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
<th>Mg$^<em>$Te; In$^</em>$Sb; Cd$^*$Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.980</td>
<td>2.578; 2.570; 2.560</td>
<td>24.20; 24.20; 24.20</td>
<td>76.20; 76.26; 76.32</td>
<td>18.07; 18.08; 18.10</td>
</tr>
<tr>
<td>1.03</td>
<td>2.672; 2.663; 2.653</td>
<td>29.80; 29.82; 29.88</td>
<td>76.43; 76.49; 76.55</td>
<td>23.46; 23.50; 23.53</td>
</tr>
<tr>
<td>1.37</td>
<td>3.525; 3.514; 3.500</td>
<td>33.69; 33.72; 33.76</td>
<td>76.56; 76.62; 76.68</td>
<td>35.34; 35.40; 35.46</td>
</tr>
<tr>
<td>1.38</td>
<td>3.553; 3.541; 3.527</td>
<td>33.46; 33.49; 33.52</td>
<td>76.56; 76.61; 76.67</td>
<td>35.35; 35.40; 35.47</td>
</tr>
<tr>
<td>1.39</td>
<td>3.580; 3.568; 3.555</td>
<td>33.22; 33.24; 33.29</td>
<td>76.53; 76.60; 76.66</td>
<td>35.34; 35.40; 35.46</td>
</tr>
<tr>
<td>3</td>
<td>8.612; 8.384; 8.351</td>
<td>7.091; 7.059; 7.022</td>
<td>74.76; 74.82; 74.88</td>
<td>13.90; 15.84; 15.77</td>
</tr>
</tbody>
</table>

Here, $x=1$. For the (Mg$^*$Te, In$^*$Sb, Cd$^*$Sn)-junctions, the value of $\beta$ given in Eq. (46) is 1.1261.