11.97% (12.12%)-Limiting Highest Efficiencies Obtained Respectively in $n^+(p^+) - p(n)$ Crystalline GaSb Junction Solar Cells at T=300K, Due to the Effects of Impurity Size, Temperature, Heavy Doping, and Photovoltaic Conversion

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Abstract:

In the $n^+(p^+) - p(n)$ crystalline GaSb-junction solar cells at 300K, due to the effects of impurity size, temperature, heavy doping, and photovoltaic conversion, we show that, with an increasing donor (acceptor)-radius $r_{d(a)}$, both the relative dielectric constant and photovoltaic conversion factor decrease, and the intrinsic band gap increases, according to the increase in photovoltaic efficiency, as observed in Tables 1, 2 and 3, being in good accordance with an important result obtained by Shockley and Queisser (1961), with the use of the second law of thermodynamics, stating that for an increasing intrinsic band gap the photovoltaic efficiency increases. Further, for highest values of $r_{d(a)}$, the limiting highest efficiencies are found to be given in Tables 2 and 3, as: 11.97 % (12.12 %), obtained in such $n^+(p^+) - p(n)$ crystalline GaSb-junction solar cells at 300 K, respectively.

Keywords: *donor (acceptor)-size effect; heavily doped emitter region; photovoltaic conversion factor; open circuit voltage; efficiency.*

Introduction

In the present work, by basing on the same energy-band-structure parameters given in d(a)-GaSb crystals and also on the same treatment method used to determine the photovoltaic conversion efficiency, as those given in our two recent papers (Van Cong et al., 2023, 2022), we will determine the limiting highest efficiencies, obtained in the heavily doped donor (acceptor)-GaSb emitter-and-lightly doped acceptor (donor)-GaSb base-regions, HD[d(a)-GaSb]ER-LD[a(d)-GaSb]BR, of $n^+(p^+) - p(n)$ junction solar cells, due to the effects of impurity size, temperature, heavy doping, and photovoltaic conversion. These two recent papers will be henceforth referred respectively to as: P1 and P2, for a simplicity of presentation, noting again that they were inspired from other works (Van Cong, 2022, 2016, 1999, 1995, 1991, 1975; Van Cong et al., 1997, 1996, 1993, 1992, 1984; Green et al., 2022, 2010; Green, 1981; Kate et al. 2013; Kharchich & Khamlichi, 2023; Kittel, 1976; Parola et al., 2019; Shockley & Queisser, 1961).

First of all, as investigated in P1, the values of the energy-band-structure parameters given in d(a)- GaSb crystals, expressed as functions of

donor (acceptor) d(a)- radius $r_{d(a)}$, and due to the effects of impurity size and temperature T, are found to be given in Table 1. Here, one notes that, with an increasing $r_{d(a)}$, both the relative dielectric constant $\varepsilon(r_{d(a)})$ and intrinsic carrier concentration $n_{in(ip)}$ decrease, while the effective donor (acceptor)-ionization energy $E_{d(a)}(r_{d(a)})$, band gap $E_{gn(gp)}(r_{d(a)})$ and intrinsic band gap $E_{gin(gip)}(T = 300, r_{d(a)})$ increase.

Then, as investigated in P2, in the present HD[d(a)-GaSb]ER-LD[a(d)-GaSb]BR, of $n^+(p^+) - p(n)$ junction solar cells at T=300 K, being due to the effects of impurity size, temperature, heavy doping, and photovoltaic conversion, the numerical results of the photovoltaic conversion factor (PVCF), n, short circuit current density, J_{sc}, fill factor, F, and finally efficiency, η, being expressed as functions of open-circuit voltage V_{oc}, and for physical conditions as: in the HDER, the emitter thickness: W=0.1 μm, high d(a)-density: $N_{d(a)} = 10^{19} (10^{20}) cm^{-3}$, hole (electron) surface recombination velocity: $S = 100 (\frac{cm}{s})$, and in the LDBR, low a(d)-density $N_{a(d)} = 10^{17} cm^{-3}$, are reported respectively in Tables 2 and 3.

Here, on remarks that, for a given V_{oc} and with an increasing $r_{d(a)}$, the intrinsic band gap $E_{gin(gip)}(T = 300, r_{d(a)})$ increase, as observed in Table 1, the function n decreases and the other functions such as: J_{sc}, F, and η increase, as seen in Tables 2 and 3, suggesting thus the new obtained results. This remark is found to be in accordance with an important result obtained by Shockley and Queisser (1961), with the use of the second law of thermodynamics, stating that for an increasing $E_{gin(gip)}$ the photovoltaic efficiency increases.

Effects of Impurity Size, Temperature and Heavy Doping

First of all, in the intrinsic GaSb crystal at T=0 K and at $r_{d(a)} = r_{Sb(Ga)} = r_{do(ao)} = 0.136 (0.126)$ nm, one has (P1; Levinshtein et al., 1999; Kittel, 1976):

the relative dielectric constant, $\varepsilon(r_{do(ao)}) = 15.69$, the relative effective electron (hole) mass in conduction (valence) bands, $(m_c/m_o) = 0.047$ and $(m_v/m_o) = 0.3$, the unperturbed intrinsic band gap, $E_{go}(r_{do(ao)}) = 0.81$ eV, and the effective d(a)-ionization energies in absolute values, $E_{do(ao)}(r_{do(ao)}) = \frac{13600 \times (m_{c(v)}/m_o)}{(\varepsilon(r_{do(ao)}))^2}$ meV = 2.5965 meV (16.57 meV).

Impurity-Size Effect

In d(a)-GaSb systems at T=0 K, since $r_{d(a)}$, in tetrahedral covalent bonds is usually either larger or smaller than $r_{do(ao)}$, a local mechanical strain (or deformation potential energy) is induced, according to a compression (dilation), for $r_{d(a)} > r_{do(ao)}$ (for $r_{d(a)} < r_{do(ao)}$), respectively, due to the d(a)-size effect, as that investigated in P1, P2 and (Van Cong, 2022, 2016). Further, in n(p)-type GaSb crystals, the band gap $E_{gn(gp)}(r_{d(a)})$ and the effective donor (acceptor)-ionization energy $E_{d(a)}(r_{d(a)})$ are expressed as:

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

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

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

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

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

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

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

Temperature Effect

Here, the intrinsic band gap in the GaSb-crystal is found to be given by:

$$E_{gin(gip)}(T, r_{d(a)}) = E_{gn(gp)}(r_{d(a)}) - \frac{3.6773 \times 10^{-4} \times T^2}{T + 94}, \tag{3}$$

being equal to 0.726 at T=300K, in good accordance with that given by Parola et al. (2019).

Further, one can here define the intrinsic carrier concentration $n_{in(ip)}$ by:

$$n_{in(ip)}^2(T, r_{d(a)}) \equiv N_c(T) \times N_v(T) \times \exp\left(\frac{-E_{gin(gip)}(T, r_{d(a)})}{k_B T} \right), \tag{4}$$

where $N_{c(v)}(T) = 2 \times \left(\frac{m_{c(v)} \times k_B T}{2\pi\hbar^2} \right)^{\frac{3}{2}}$ (cm^{-3}) are the conduction (valence)-band density of states.

The numerical results of those energy-band structure parameters are given in the following Table 1.

Table 1. From Equations (1-4), the Numerical Results of the Energy-Band-Structure Parameters, Due to the Effects of T, $r_{d!a)}$, and High $N_{d(a)}$, are Reported, Suggesting that, with an Increasing $r_{d(a)}$, Both $\varepsilon(r_d)$ and $n_{in}(T, r_d)$ Decrease, and then the Other Ones Increase

Donor (with $N_d = 10^{19}$ cm^{-3})		P	As	Sb	Sn
r_d (nm)	↗	0.110	0.118	0.136	0.140
$\varepsilon(r_d)$	↘	18.7494	16.9954	15.69	15.6284
$E_d(r_d)$ in meV	↗	1.8183	2.2130	2.5965	2.6170
$E_{gn}(r_d)$ in eV	↗	0.8092	0.8096	0.81	0.81002

$E_{gin}(T = 300K, r_d)$ in eV	↗	0.7252	0.7256	0.7260	0.72602
$n_{in}(T = 300K, r_d)$ in $10^{13} cm^{-3}$	↘	8.3297	8.2665	8.2053	8.2020
Acceptor		**B**	**Ga**	**Mg**	**In**
r_a (nm)	↗	0.088	0.126	0.140	0.144
$\varepsilon(r_a)$	↘	29.13	15.69	14.8422	14.3386
$E_a(r_a)$ in meV	↗	4.80	16.57	18.52	19.84
$E_{gp}(r_a)$ in eV	↗	0.798	0.81	0.8119	0.8133
$T = 300K, r_a)$ in eV	↗	0.7152	0,7260	0.7279	0.7293
$n_{ip}(T = 300K, r_a)$ in $10^{13} cm^{-3}$	↘	10.302	8.2054	7.9022	7.7024

Heavy Doping Effect

Here, the Fermi energy $E_{Fn}(-E_{Fp})$, band gap narrowing (BGN), and apparent band gap narrowing (ABGN), as those determined in P1and in P2, are reported in the following.

First, the Fermi energy $E_{Fn}(-E_{Fp})$, obtained for any T and any $N_{d(a)}$, being investigated in our previous paper (Van Cong and Debiais, 1993; Van Cong and Doan Khanh, 1992; Van Cong, 1991, 1975), with a precision of the order of 2.11×10^{-4} is found to be given by:

$$\frac{E_{Fn}(u)}{k_B T} \left(\frac{-E_{Fp}(u)}{k_B T} \right) = \frac{G(u) + Au^B F(u)}{1 + Au^B}, A = 0.0005372 \text{ and } B = 4.82842262, \tag{5}$$

where u is the reduced electron density,

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

Here, one notes that: (i) as $u \gg 1$, according to the HD[d(a)-GaSb]ER-case, or to the degenerate case, Eq. (5) 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)-GaSb]BR-case, or to the non-degenerate case, Eq. (5) is reduced to the function G(u).

Secondly, as given in P1 and P2, by denoting the effective Wigner-Seitz radius $r_{sn(sp)}$ characteristic of the interactions by:

$$r_{sn(sp)}(N_{d(a)}, r_{d(a)}) = 1.1723 \times 10^8 \times \left(\frac{1}{N_{d(a)}} \right)^{1/3} \times \frac{m_{cv}}{\varepsilon(r_{d(a)})},$$

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

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

Now, as given in P1 and P2, taking into account various spin-polarized chemical potential-energy contributions (Van Cong, 2016, 1975) such as: 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 heavily doped GaSb, the BGN is found to be given by:

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

$$\left[\frac{\varepsilon(r_{do})}{\varepsilon(r_d)}\right]^{5/4} \times \sqrt{\frac{m_v}{m_c}} \times N_r^{1/4} + a_4 \times \sqrt{\frac{\varepsilon(r_{do})}{\varepsilon(r_d)}} \times N_r^{1/2} \times 2 + a_5 \times \left[\frac{\varepsilon(r_{do})}{\varepsilon(r_d)}\right]^{\frac{3}{2}} \times N_r^{\frac{1}{6}}, \quad N_r \equiv \left(\frac{N_d}{9.999 \times 10^{17} \text{ cm}^{-3}}\right),$$

$$(6)$$

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 heavily doped GaSb, as:

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

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

$$(7)$$

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

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

Therefore, in the HD[d(a)-GaSb]ER, we can define the effective intrinsic carrier concentration, $n_{in(ip)}^*$, by :

$$n_{in(ip)}^* (N_{d(a)}, T, r_{d(a)}) \equiv \sqrt{N_{d(a)} \times p_o(n_o)} = n_{in(ip)} \times \exp\left[\frac{\Delta E_{agn(agp)}}{2k_B T}\right], \quad (8)$$

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

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

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

$$(9)$$

Total minority-carrier saturation current density

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

$$J_{oI(oII)} \equiv J_{Eno(Epo)} + J_{Bpo(Bno)} \tag{10}$$

where $J_{Bpo(Bno)}$ is the minority-electron (hole) saturation current density injected into the LD[a(d)-GaSb]BR,

and $J_{Eno(Epo)}$ is the minority-hole (electron) saturation-current density injected into the HD[d(a)-GaSb]ER.

$J_{Bpo(Bno)}$ in the LD[a(d)-GaSb]BR

Here, $J_{Bpo(Bno)}$ is determined by (P2; Van Cong and Debiais, 1999):

$$J_{Bpo(Bno)}\left(N_{a(d)}, r_{a(d)}\right) = \frac{e \times n_{ip(in)}^2(r_{a(d)}) \times \sqrt{\frac{D_{e(h)}(N_{a(d)}, r_{a(d)})}{\tau_{eB(hB)}(N_{a(d)})}}}{N_{a(d)}}, \tag{11}$$

where $n_{ip(in)}^2(r_{d(a)})$ is determined in Table 1, $D_{e(h)}(N_{a(d)}, r_{a(d)})$ is the minority electron (minority hole) diffusion coefficient:

$$D_e(N_a, r_a) = \frac{k_B T}{e} \times \left[850 + \frac{5750}{1 + \left(\frac{N_a}{8 \times 10^{17} \text{cm}^{-3}}\right)^{1.8}} \right] \times \left(\frac{\varepsilon(r_a)}{\varepsilon(r_{ao})}\right)^2 \ (\text{cm}^2 \text{s}^{-1}), \tag{12}$$

$$D_h(N_d, r_d) = \frac{k_B T}{e} \times \left[85 + \frac{1165}{1 + \left(\frac{N_d}{4 \times 10^{17} \text{cm}^{-3}}\right)^{0.44}} \right] \times \left(\frac{\varepsilon(r_d)}{\varepsilon(r_{do})}\right)^2 \ (\text{cm}^2 \text{s}^{-1}), \tag{13}$$

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

$$\tau_{eB}(N_a)^{-1} = \frac{1}{10^{-7}} + 3 \times 10^{-13} \times N_a + 1.83 \times 10^{-31} \times N_a^2, \tag{14}$$

$$\tau_{hB}(N_d)^{-1} = \frac{1}{10^{-7}} + 11.76 \times 10^{-13} \times N_d + 2.78 \times 10^{-31} \times N_d^2. \tag{15}$$

$J_{Eno(Epo)}$ in the HD[d(a)-GaSb]ER

In the non-uniformly and heavily doped emitter region of d(a)-GaSb devices, the effective Gaussian d(a)-density profile or the d(a) (majority-e(h)) density, is defined in such the HD[d(a)-GaSb]ER-width W, as given in P2 and also in our previous works (Van Cong, 1999, 1995; Van Cong and Debiais, 1997, 1995):

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

$$N_{do(ao)}(W) \equiv 7.9 \times 10^{17} \, (2 \times 10^5) \times \exp\left\{-\left(\frac{W}{184.2 \, (1) \times 10^{-7} \, cm}\right)^{1.066 \, (0.5)}\right\} \, (cm^{-3}), \qquad (16)$$

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

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

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

$$N_{d(a)}^*(x = W, \, r_{d(a)}) \equiv \frac{N_{do(ao)}(W)}{\exp\left[\frac{\Delta E_{agn(agp)}(N_{do(ao)}(W), r_{d(a)})}{k_B T}\right]}, \qquad (17)$$

where the apparent band gap narrowing $\Delta E_{agn(agp)}$ is determined in Eq. (9), by replacing $N_{d(a)}$ by $\rho_{d(a)}\left(x, N_{d(a)}, W\right)$. The same remark can be applied to following Equations (18-20).

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

$$F_{h(e)}(N_{d(a)}, r_{d(a)}) \equiv \frac{n_{in(ip)}^2(T, r_{d(a)})}{p_o(n_o) \times D_{h(e)}} = \frac{N_{d(a)}^*}{D_{h(e)}} \equiv \frac{N_{d(a)}}{D_{h(e)}} \times \left(\frac{n_{in(ip)}}{n_{in(ip)}^*}\right)^2 \equiv \frac{N_{d(a)}}{D_{h(e)} \times \exp\left[\frac{\Delta E_{agn(agp)}}{k_B T}\right]} \, (cm^{-5} \times s),$$
$$(18)$$

the minority hole (electron) diffusion length, $L_{h(e)}\left(N_{d(a)}, r_{d(a)}\right)$ by:

$$L_{h(e)}^{-2}\left(N_{d(a)}, r_{d(a)}\right) = \left[\tau_{hE(eE)} \times D_{h(e)}\right]^{-1} = \left(C \times F_{h(e)}\right)^2 = \left(C \times \frac{N_{d(a)}^*}{D_{h(e)}}\right)^2 = \left(C \times \frac{n_{in(ip)}^2(r_{d(a)})}{p_o(n_o) \times D_{h(e)}}\right)^2,$$
$$(19)$$

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:

$$\tau_{hE(eE)} \equiv \frac{1}{D_{h(e)} \times L_{h(e)}^{-2}} = \frac{1}{D_{h(e)} \times \left(C \times F_{e(h)}\right)^2}. \qquad (20)$$

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:

$$p_o(x)[n_o(x)] \equiv \frac{n_{in(ip)}^2}{N_{d(a)}^*(x,r_{d(a)})}, \qquad (21)$$

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

$$u(x) \equiv \frac{p(x)[n(x)]-p_o(x)[n_o(x)])}{p_o(x)[n_o(x)]}, \qquad (22)$$

which must verify the two following boundary conditions as:

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

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

Here, $n_{I(II)}(V)$ is a photovoltaic conversion factor determined latter, $S\left(\frac{cm}{s}\right)$ 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 $J_{h(e)}(x, r_{d(a)})$.

Further, as developed in P2, from the Fick's law for minority hole (electron)-diffusion equations, one has:

$$J_{h(e)}(x, r_{d(a)}) = \frac{-e(+e) \times n_{in(ip)}^2}{F_{h(e)}(x)} \times \frac{du(x)}{dx} = \frac{-e(+e) n_{in(ip)}^2 D_{h(e)}(N_{d(a)}, r_{d(a)})}{N_{d(a)}^*(x, r_{d(a)})} \times \frac{du(x)}{dx}, \qquad (23)$$

where $N_{d(a)}^*(x, r_{d(a)})$ is given in Eq. (17), $D_{h(e)}$ and $F_{h(e)}$ are determined respectively in Equations (12, 13, 18), and from the minority-hole (electron) continuity equation as:

$$\frac{dJ_{h(e)}(x, r_{d(a)})}{dx} = -e(+e) \times n_{in(p)}^2 \times \frac{u(x)}{F_{h(e)}(x) \times L_{h(e)}^2(x)} = -e(+e) \times n_{in(p)}^2 \times \frac{u(x)}{N_{d(a)}^*(x, r_{d(a)}) \times \tau_{hE(eE)}}, \qquad (24)$$

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

$$\frac{d^2 u(x)}{dx^2} - \frac{dF_{h(e)}(x)}{dx} \times \frac{du(x)}{dx} - \frac{u(x)}{L_{h(e)}^2(x)} = 0, \qquad (25)$$

Then, taking into account the two above boundary conditions given in Eq. (22), one thus gets the general solution of this Eq. (25), as:

$$u(x) = \frac{\sinh(P(x)) + I(W,S) \times \cosh(P(x))}{\sinh(P(W)) + I(W,S) \times \cosh(P(W))} \times \left(\exp\left(\frac{V}{n_{I(II)}(V) \times V_T} \right) - 1 \right), \tag{26}$$

where the factor $I(W,S)$ is determined by:

$$I(W,S) = \frac{D_{h(e)}(N_{d(a)o}(W))}{S \times L_{h(e)}(N_{do(ao)}(W))}, \tag{27}$$

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

$$P(x) \equiv \int_0^x \frac{dx}{L_{h(e)}(x)}), \; 0 \leq x \leq W, \; P(x = W) \equiv \left(\frac{1}{W} \times \int_0^W \frac{dx}{L_{h(e)}(x)} \right) \times W \equiv \frac{W}{L_{h(e)}^*(x)} = \frac{L_{h(e)}}{L_{h(e)}^*(x)} \times \frac{W}{L_{h(e)}}, \tag{28}$$

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

$$J_{h(e)}(x, W, N_{d(a)}, r_{d(a)}, S, V) = -J_{Eno}(x, W, N_d, r_d, S) [J_{Epo}(x, W, N_a, r_a, S)] \times \left(\exp\left(\frac{V}{n_{I(II)}(V) \times V_T} \right) - 1 \right), \tag{29}$$

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

$$J_{Eno(Epo)}(x, W, N_{d(a)}, r_{d(a)}, S) = \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(x, r_{d(a)}) \times L_{h(e)}} \times \frac{\cosh(P(x)) + I(W,S) \times \sinh(P(x))}{\sinh(P(W)) + I(W,S) \times \cosh(P(W))}. \tag{30}$$

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

$$J_{Eno(Epo)}(x = 0, W, N_{d(a)}, r_{d(a)}, S) = \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(x, r_{d(a)}) \times L_{h(e)}} \times \frac{1}{\sinh(P) + I \times \cosh(P)}, \tag{31}$$

$$J_{Eno(Epo)}(x = W, W, N_{d(a)}, r_{d(a)}, S) = \frac{en_{in(ip)}^2 \times D_{h(e)}}{N_{d(a)}^*(x = W, r_{d(a)}) \times L_{h(e)}} \times \frac{\cosh(P) + I \times \sinh(P)}{\sinh(P) + I \times \cosh(P)}, \tag{32}$$

and then,

$$\frac{J_{h(e)}\left(x=0,W,N_{d(a)},r_{d(a)},S,V\right)}{J_{h(e)}\left(x=W,W,N_{d(a)},r_{d(a)},S,V\right)} \equiv \frac{J_{Eno(Epo)}\left(x=0,W,N_{d(a)},r_{d(a)},S\right)}{J_{Eno(Epo)}\left(x=W,W,N_{d(a)},r_{d(a)},S\right)} = \frac{1}{\cosh(P)+I\times\sinh(P)}. \tag{33}$$

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

$$Q_{h(e)}^{*}(x=W,N_{d(a)},r_{d(a)}) \equiv \int_{0}^{W} +e(-e)\times u(x)\times p_{o}(x)[n_{o}(x)]\times\frac{\tau_{hE(eE)}(N_{d(a)},r_{d(a)})}{\tau_{hE(eE)}(\rho_{d(a)}(x),r_{d(a)})}dx,$$ and the effective minority hole (minority electron) transit time [htt(ett)] by: $\tau_{htt(ett)}^{*}(x=W,W,N_{d(a)},r_{d(a)},S) \equiv Q_{h(e)}^{*}(x=W,N_{d(a)},r_{d(a)})/J_{Eno(Epo)}\left(x=W,W,N_{d(a)},r_{d(a)},S\right),$ and from Equations (24, 31), one obtains:

$$\frac{\tau_{htt(ett)}^{*}\left(x=W,W,N_{d(a)},r_{d(a)},S\right)}{\tau_{hE(eE)}} \equiv 1 - \frac{J_{Eno(Epo)}\left(x=0,W,N_{d(a)},r_{d(a)},S\right)}{J_{Eno(Epo)}\left(x=W,W,N_{d(a)},r_{d(a)},S\right)} = 1 - \frac{1}{\cosh(P)+I\times\sinh(P)}. \tag{34}$$

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

As $P \ll 1$ (or $W \ll L_{h(e)}$) and $S \to \infty$, $I \equiv I(W,S) = \frac{D_{h(e)}(N_{do(ao)}(W))}{S\times L_{h(e)}(N_{do(ao)}(W))} \to 0$, from Eq. (34), one has: $\frac{\tau_{htt(ett)}^{*}\left(x=W,W,N_{d(a)},r_{d(a)},S\right)}{\tau_{hE(eE)}} \to 0$, suggesting a completely transparent emitter region (CTER)-case, where, from Eq. (32), one obtains:

$$J_{Eno(Epo)}\left(x=W,N_{d(a)},r_{d(a)},S\to\infty\right) \to \frac{en_{in(ip)}^{2}\times D_{h(e)}}{N_{d(a)}^{*}(x=W,r_{d(a)})\times L_{h(e)}} \times \frac{1}{P(W)}. \tag{35}$$

Further, as $P \gg 1$ (or $W \gg L_{h(e)}$) and $S \to 0$, $I \equiv I(W,S) = \frac{D_{h(e)}(N_{do(ao)}(W))}{S\times L_{h(e)}(N_{do(ao)}(W))} \to \infty$, and from Eq. (34) one has: $\frac{\tau_{htt(ett)}^{*}\left(x=W,W,N_{d(a)},r_{d(a)},S\right)}{\tau_{hE(eE)}} \to 1$, suggesting a completely opaque emitter region (COER)-case, where, from Eq. (32), one gets:

$$J_{Eno(Epo)}\left(x=W,N_{d(a)},r_{d(a)},S\to0\right) \to \frac{en_{in(ip)}^{2}\times D_{h(e)}}{N_{d(a)}^{*}(x=W,r_{d(a)})\times L_{h(e)}} \times \tanh(P). \tag{36}$$

In summary, in the two $n^{+}(p^{+}) - p(n)$ GaSb-junction solar cells, denoted respectively by I(II), the dark carrier-minority saturation current density $J_{oI(oII)}$, defined in Eq. (10), is now rewritten as:

$$J_{oI(oII)}\left(W, N_{d(a)}, r_{d(a)}, S, N_{a(d)}, r_{a(d)}\right) \equiv J_{Eno(Epo)}\left(W, N_{d(a)}, r_{d(a)}, S\right) + J_{Bpo(Bno)}\left(N_{a(d)}, r_{a(d)}\right),$$
(37)

where $J_{Eno(Epo)}$ and $J_{Bpo(Bno)}$ are determined respectively in Equations (32, 11).

Photovoltaic conversion effect at 300K

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

$$W = 0.1 \, \mu m, N_{d\equiv Sb(a\equiv Ga)} = 10^{19} \, (10^{20}) \, cm^{-3}, r_{d\equiv Sb(a\equiv Ga)}, S = 100 \, \left(\frac{cm}{s}\right), N_{a\equiv Ga(d\equiv Sb)} =$$
$$10^{17}(10^{17}) \, cm^{-3}, r_{a\equiv Ga(d\equiv Sb)},$$
(38)

we propose, at given open circuit voltages: $V_{ocI1(ocI2)}$ and $V_{ocII1(ocII2)}$, the same data of the short circuit current density $J_{scI(II)}$, in order to formulate our following treatment method of two fixe points, as developed in P2, for both $n^+(p^+) - p(n)$ GaSb junctions (Kharchich & Khamlichi, 2023; Parola et al., 2019), as:

$$V_{ocI1(ocI2)} = V_{ocII1(ocII2)} = 0.312 \, (0.374) \, V, \quad J_{scI1(scI2)} = J_{scII1(scII2)} = 0.0388 \, (0.03909) \, (A/cm^2).$$
(39)

First of all, 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 $n^+(p^+) - p(n)$ junction of GaSb solar cells, as given in P2, by:

$$J(V) \equiv J_{ph.}(V) - J_{oI(oII)} \times \left(e^{X_{I(II)}(V)} - 1\right), \quad X_{I(II)}(V) \equiv \frac{V}{n_{I(II)}(V) \times V_T}, \quad V_T \equiv \frac{k_B T}{e} = 0.02585 \, V,$$
(40)

where the function $n_{I(II)}(V)$ is the photovoltaic conversion factor (PVCF), noting that as $V = V_{oc}$, being the open circuit voltage, $J(V) = 0$, the photocurrent density is defined by: $J_{ph.}(V = V_{oc}) \equiv J_{scI(scII)}\left(W, N_{d(a)}, r_{d(a)}, S, N_{a(d)}, r_{a(d)}, V_{oc}\right)$, for $V_{oc} \geq V_{ocI1(ocII1)}$. Therefore, the photovoltaic conversion effect occurs, according to:

$$J_{scI(scII)}\left(W, N_{d(a)}, r_{d(a)}, S, N_{a(d)}, r_{a(d)}, V_{oc}\right) \equiv J_{oI(oII)}\left(W, N_{d(a)}, r_{d(a)}, S, N_{a(d)}, r_{a(d)}\right) \times$$
$$\left(e^{X_{I(II)}(V_{oc})} - 1\right),$$
(41)

where $n_{I(II)}(V_{oc}) \equiv n_{I(II)}\left(W, N_{d(a)}, r_{d(a)}, S, N_{a(d)}, r_{a(d)}, V_{oc}\right)$, 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 many cases, and (ii) the function $\left(e^{X_{I(II)}(V_{oc})} - 1\right)$ or the

PVCF, $n_{I(II)}$, representing the photovoltaic conversion effect, thus converts the light, represented by $J_{scI(scII)}$, into the electricity, by $J_{oI(oII)}$. Then, from Eq. (41), for $n^+(p^+) - p(n)$ GaSb-junction solar cells, one respectively obtained:

$$n_{I1(I2)}\big(V_{ocI1(ocI2)}, J_{scI1(scI2)}\big) = 0.8818 \quad (1.0564) \quad \text{and} \quad n_{II1(II2)}\big(V_{ocII1(ocII2)}, J_{scII1(scII2)}\big) = 0.82624$$

(0.98992), and then, for $V_{oc} \geq V_{ocI1(ocII1)}$, one can propose the general expressions for the PVCF, as:

$$n_{I(II)}\big(W, N_{d(a)}, r_{d(a)}, S, N_{a(d)}, r_{a(d)}, V_{oc}\big) = n_{I1(II1)}) + n_{I2(II2)} \times \left(\frac{V_{oc}}{V_{ocI1(ocII1)}} - 1\right)^{1.114(1.11374)} .$$

(42)

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

$$F_{I(II)}\big(W, N_{d(a)}, r_{d(a)}, S, N_{a(d)}, r_{a(d)}, V\big) = \frac{X_{I(II)}(V_{oc}) - ln\left[X_{I(II)}(V_{oc}) + 0.72\right]}{X_{I(II)}(V_{oc}) + a}, a \geq 0,$$

(43)

where a will be chosen here, as: a=1, corresponding to the ideal GaSb-junction solar cells (Green, 2022, 2010, 1981), and a=0, according to limiting highest values of $F_{I(II)}$.

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

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

(44)

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

Then, from Equations (43, 44), for ideal $n^+(p^+) - p(n)$ GaSb-junction solar cells (a=1), we get, at $V_{oc} = V_{ocI1(ocI2)} = 0.312\,V\,(0.374\,V)$, $F_I = 75.02\,\%\,(75.03\,\%)$ and $\eta_I = 9.08\,\%\,(10.97\,\%)$ for the $n^+ - p$ GaSb-junction, while at $V_{oc} = V_{ocII1(ocII2)} = 0.312\,V\,(0.374\,V)$, $F_{II} = 76.10\,\%\,(76.11\,\%)$ and $\eta_{II} = 9.21\,\%\,(11.1261\,\%)$ for the $p^+ - n$ GaSb-junction. Here, one notes that other authors (Parola & al., 2019; Kharchich & Khamlichi, 2023), respectively obtained, the corresponding values of efficiencies for the $p^+ - n$ GaSb-junction, using an AlGaAsSb window layer, as: 7.26 % (11.12 %), which can be compared with our above results, $\eta_{II} = 9.21\,\%\,(11.1261\,\%)$, giving thus the relative deviations in absolute values, equal to: 0.269 (5.5×10^{-4}). Then, our value of $\eta_{II} = 11.1261\,\%$ for the $p^+ - n$ GaSb-junction can also be compared with that, 11.2 % (Kate et al., 2013), obtained by using an ideal quantum cutting layer.

Numerical Results and Concluding Remarks

We will respectively consider the two following cases, given in the following.

HD $[(P;\ As;\ Sb;\ Sn) - GaSb]$ ER $- LD[(B;\ Ga;\ Mg;\ In) - GaSb)]$ BR $-$cases

Here, for those 4 $(n^+p) -$ junctions: $(P^+B, As^+Ga, Sb^+Mg, Sn^+In)$, respectively, we propose the following physical conditions as:

$$W = 0.1 \text{ μm}, \ N_d = 10^{19} \text{ cm}^{-3}, S = 100 \text{ (cm/s)}, \text{ and } N_a = 10^{17} \text{ cm}^{-3}. \tag{45}$$

Then, from Eq. (34), one respectively obtains: $\frac{\tau^*_{htt}}{\tau_{hE}} = (0, 0, 0, 0)$, suggesting a completely transparent.

condition, and from Eq. (32), $J_{Eno} = (9.30, 9.07, 8.92, 8.91) \times 10^{-12} \left(\frac{A}{cm^2} \right)$. Further, one respectively gets from Eq. (11), as: $J_{Bpo} = (1.29, 0.44, 0.39, 0.35) \times 10^{-7} \left(\frac{A}{cm^2} \right)$, being due to the increase in band gap with increasing r_a, obtained in the $[(B; Ga; Mg; In) - GaSb)]$ BR, $E_{gip}(T = 300K, r_a)$=(0.7142, 0.7260, 0.7279, 0.7293) in eV, as observed in Table 1. Furthermore, from Eq. (37), one obtains respectively: $J_{oI} = (1.29, 0.44, 0.39, 0.35) \times 10^{-7} \left(\frac{A}{cm^2} \right) \simeq J_{Bpo}$. Then, from the following Table 2, for example, at $V_{oc} = 0.36$ V, n_I= (1.099; 1.013; 1.003; 0.997), and, with a=1 as that given in Eq. (43) for the fill factor, η_I= (10.87; 11.13; 11.16; 11.17) %, suggesting that, with increasing r_a, or with decreasing ε_a, due to the a-size effect, both J_{oI} and n_I decrease, while both E_{gip} and η_I increase. That is found to be in good agreement with an important result, obtained by Shockley and Queisser in 1961, with the use of the second law of thermodynamics, stating that, for $E_{gip} < 1.6$ eV, η_I increases with increasing E_{gip}.

Table 2 in Appendix 1.

HD $[(B; \ Ga; \ Mg; \ In) - GaAs]$ ER $-$ LD$[(P; \ As; \ Sb; \ Sn) - GaAs]$ BR $-$cases

Here, for those 4 $(p^+n) -$ junctions: $(B^+P, Ga^+As, Mg^+Sb, In^+Sn)$, respectively, we propose the following physical conditions as:

$$W = 0.1 \text{ μm}, \ N_a = 10^{20} \text{ cm}^{-3}, S = 100 \text{ (cm/s)}, \text{ and } N_d = 10^{17} \text{ cm}^{-3}. \tag{46}$$

Then, from Eq.(34), one respectively obtains: $\frac{\tau^*_{ett}}{\tau_{eE}} = (0, 0, 0, 0)$ suggesting a completely transparent

condition, and from Eq. (30), $J_{Epo} = (2.81, 1.62, 1.52, 1.47) \times 10^{-9} \left(\frac{A}{cm^2} \right)$. Further, one respectively gets from Eq. (C1) of the Appendix C: $J_{Bno} = (1.97, 1.76, 1.60, 1.59) \times 10^{-8} \left(\frac{A}{cm^2} \right)$, being due to the increase

in band gap, with increasing r_d, obtained in the $[(P; As; Sb; Sn) - GaSb]$ BR, $E_{gin}(T = 300K, r_d)$=(0.7252, 0.7256, 0.7260, 0.72602) in eV, as observed in Table 1. Furthemore, from Eq. (37), one obtains respectively: $J_{oII} = (2.25, 1.92, 1.75, 1.74) \times 10^{-8} \left(\frac{A}{cm^2} \right) \simeq J_{Bno}$. Then, from the following Table 3, for example, at $V_{oc} = 0.355$ V, n_{II}= (0.951; 0.941; 0.935; 0.934), and, for a=1 as given in Eq. (43) for the fill factor, η_{II}= (11.29; 11.32; 11.34; 11.34) %, meaning that, with increasing r_d, or with decreasing ε_d, due to the d-size effect, both J_{oII} and n_{II} decrease, while both E_{gin} and η_{II} increase. That is found to be in good agreement with an important result, obtained by Shockley and Queisser in 1961, with the use of the second law of thermodynamics, stating that, for $E_{gin} < 1.6$ eV, η_{II} increases with increasing E_{gin}.

Table 3 in the Appendix 1.

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Appendix 1

Table 2. In the HD[(P; As; Sb; Sn)-GaAs] ER-LD[(B; Ga; Mg; In)-GaAs)] BR and for Physical Conditions Given in Eq. (45), our Numerical Results of n_I, J_{scI}, F_I, and η_I, are Computed by using Equations (42, 41, 43, 44), Respectively. Here, on Notes that, for a Given V_{oc} and with Increasing $r_{d(a)}$, the Function n_I Decreases, while Other Functions J_{scI}, F_I, and η_I Increase, Being Due to the Impurity Size $r_{d(a)}$-Effect, Suggesting thus the New Obtained Results

V_{oc}(V)	n	$J_{sc}(\frac{mA}{cm^2})$	F(%)	η(%)
In Eq. (43), obtained for the fill factor, a=1, according to an ideal solar cells				
n^+p	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In
0.312	0.957; 0.882; 0.873; 0.868	38.80; 38.80; 38.80; 38.80	73.62; 75.02; 75.18; 75.29	8.913; 9.082; 9.102; 9.114
0.35	1.067; 0.983; 0.974; 0.968	42.01; 42.29; 42.32; 42.34	3.73; 75.13; 75.29; 75.39	10.84; 11.12; 11.15; 11.17
0.36	1.099; 1.013; 1.003; 0.997	40.97; 41.15; 41.18; 41.19	73.70; 75.10; 75.26; 75.36	**10.87; 11.13; 11.16; 11.17**
0.37	1.133; 1.044; 1.034; 1.028	39.66; 39.73; 39.74; 39.74	73.65; 75.05; 75.21; 75.32	10.81; 11.03; 11.06; 11.08
0.374	1.146; 1.056; 1.046; 1.040	39.09; 39.11; 39.11; 39.11	3.63; 75.03; 75.19; 75.30	10.76; 10.97; 11.00; 11.01
0.38	1.167; 1.075; 1.065; 1.059	38.19; 38.14; 38.13; 38.12	3.60; 75.00; 75.16; 75.27	10.68; 10.87; 10.89; 10.90
0.70	2.418; 2.229; 2.207; 2.194	9.417; 8.345; 8.223; 8.144	71.48; 72.96; 73.13; 73.24	4.712; 4.262; 4.210; 4.175
1.00	3.723; 3.431; 3.399; 3.378	4.201; 3.475; 3.396; 3.345	70.08; 71.61; 71.78; 71.90	2.944; 2.489; 2.438; 2.405
In Eq. (43), obtained for the fill factor, a=0, according to highest values of this fill factor				
n^+p	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In
0.312	0.957; 0.882; 0.873; 0.868	38.80; 38.80; 38.80; 38.80	79.46; 80.51; 80.63; 80.70	9.619; 9.746; 9.760; 9.770
0.35	1.067; 0.983; 0.974; 0.968	42.01; 42.29; 42.32; 42.34	79.54; 80.59; 80.70; 80.78	11.69; 11.92; 11.95; 11.97
0.36	1.099; 1.013; 1.003; 0.997	40.97; 41.15; 41.18; 41.19	79.52; 80.56; 80.68; 80.76	**11.73; 11.93; 11.96; 11.97**
0.37	1.133; 1.044; 1.034; 1.028	39.66; 39.73; 39.74; 39.74	79.48; 80.53; 80.65; 80.72	11.66; 11.84; 11.86; 11.87
0.374	1.146; 1.056; 1.046; 1.040	39.09; 39.11; 39.11; 39.11	79.47; 80.51; 80.63; 80.71	11.62; 11.78; 11.79; 11.81
0.38	1.167; 1.075; 1.065; 1.059	38.19; 38.14; 38.13; 38.12	79.44; 80.49; 80.61; 80.69	11.53; 11.66; 11.68; 11.69
0.70	2.418; 2.229; 2.207; 2.194	9.417; 8.345; 8.223; 8.144	77.87; 78.97; 79.10; 79.18	5.133; 4.613; 4.553; 4.514
1.00	3.723; 3.431; 3.399; 3.378	4.201; 3.475; 3.396; 3.345	76.82; 77.96; 78.09; 78.17	3.227; 2.709; 2.652; 2.615

Table 3. In the HD[(B; Ga; Mg; In)-GaAs] ER-LD[(P; As; Sb; Sn)-GaAs)] BR and for Physical Conditions Given in Eq. (46), Our Numerical Results of n_{II}, J_{scII}, F_{II}, and η_{II}, are Computed by Using Equations (42, 41, 43, 44), Respectively. Here, on Notes that, for a Given V_{oc} and with Increasing $r_{a(d)}$, the Function n_{II} Decreases, while Other Functions J_{scII}, F_{II}, and η_{II} Increase, being Due to the Impurity Size $r_{a(d)}$-Effect, Suggesting thus the New Obtained Results

$V_{oc}(V)$	n	$J_{sc}(\frac{mA}{cm^2})$	F(%)	η(%)
In Eq. (43), obtained for the fill factor, a=1, according to an ideal solar cells.				
n^+p	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In
0.312	0.840; 0.831; 0.826; 0.825	38.80; 38.80; 38.80; 38.80	75.82; 76.00; 76.11; 76.11	9.179; 9.201; 9.213; 9.214
0.35	0.937; 0.927; 0.921; 0.920	42.43; 42.47; 42.50; 42.50	75.93; 76.10; 76.21; 76.22	11.28; 11.31; 11.33; 11.33
0.355	0.951; 0.941; 0.935; 0.934	41.88; 41.91; 41.93; 41.94	75.91; 76.09; 76.19; 76.20	**11.29; 11.32; 11.34; 11.34**
0.36	0.965; 0.955; 0.949; 0.948	41.23; 41.26; 41.28; 41.28	75.89; 76.07; 76.17; 76.18	11.27; 11.30; 11.32; 11.32
0.374	1.007; 0.996; 0.989; 0.989	39.08; 39.08; 39.09; 39.09	75.83; 76.01; 76.11; 76.12	11.08; 11.11; 11.17; 11.13
0.38	1.025; 1.014; 1.007; 1.007	38.06; 38.05; 38.05; 38.05	75.80; 75.98; 76.08; 76.09	10.96; 10.99; 11.00; 11.00
0.70	2.124; 2.101; 2.087; 2.086	7.738; 7.601; 7.523; 7.516	73.81; 74.00; 74.11; 74.12	3.998; 3.937; 3.903; 3.900
1.00	3.269; 3.234; 3.213; 3.212	3.090; 3.005; 2.957; 2.953	72.49; 72.69; 72.80; 72.81	2.240; 2.184; 2.152; 2.150
In Eq. (43), obtained for the fill factor, a=0, according to highest values of this fill factor.				
n^+p	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In	P^+B; As^+Ga; Sb^+Mg; Sn^+In
0.312	0.840; 0.831; 0.826; 0.825	38.80; 38.80; 38.80; 38.80	81.10; 81.24; 81.32; 81.32	9.818; 9.834; 9.844; 9.844
0.35	0.937; 0.927; 0.921; 0.920	42.43; 42.47; 42.50; 42.50	81.18; 81.31; 81.39; 81.40	12.06; 12.09; 12.10; 12.11
0.355	0.951; 0.941; 0.935; 0.934	41.88; 41.91; 41.93; 41.94	81.17; 81.30; 81.38; 81.39	**12.07; 12.10; 12.11; 12.12**
0.36	0.965; 0.955; 0.949; 0.948	41.23; 41.26; 41.28; 41.28	81.16; 81.29; 81.37; 81.37	12.05; 12.07; 12.09; 12.09
0.374	1.007; 0.996; 0.989; 0.989	39.08; 39.08; 39.09; 39.09	81.11; 81.24; 81.32; 81.33	11.86; 11.88; 11.89; 11.89
0.38	1.025; 1.014; 1.007; 1.007	38.06; 38.05; 38.05; 38.05	81.09; 81.22; 81.30; 81.31	11.73; 11.74; 11.75; 11.75
0.70	2.124; 2.101; 2.087; 2.086	7.738; 7.601; 7.523; 7.516	79.60; 79.74; 79.82; 79.83	4.312; 4.243; 4.203; 4.200
1.00	3.269; 3.234; 3.213; 3.212	3.090; 3.005; 2.957; 2.953	78.62; 78.76; 78.85; 78.85	2.429; 2.367; 2.331; 2.328