World Journal of Engineering Research and Technology

www.wjert.org

Impact Factor: 7.029 Coden USA: WJERA4

# OUR NEW DIFFUSION-MOBILITY-VISCOSITY-ACTIVATION ENERGY-FERMI ENERGY RELATIONS, INVESTIGATED IN N(P)-TYPE DEGENERATE (OR VISCOUS) GATE(1-X) AS(X)-CRYSTALLINE ALLOY, SUGGESTING A DEGENERACY-AND-VISCOSITY EQUIVALENCE CONCEPT (XV)

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**Article Received on 22/12/2025** **Article Revised on 12/01/2026** **Article Published on 01/02/2026**

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https://doi.org/10.5281/zenodo.18441162

**How to cite this Article:** Prof. Dr. Huynh Van Cong*. (2026). Our New Diffusion-Mobility-Viscosity-Activation Energy-Fermi Energy Relations, Investigated In N(P)-Type Degenerate (Or Viscous) Gate(1-X) As(X)-Crystalline Alloy, Suggesting A Degeneracy-And-Viscosity Equivalence Concept (Xv). World Journal of Engineering Research and Technology, 12(2), 105–139.

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## ABSTRACT

In degenerate $\mathbf{n^+(p^+) - p(n) - X(x) \equiv GaTe(1-x)As(x)}$ - crystalline alloy, $0 \leq x \leq 1$ , various optical, electrical and thermoelectric laws and Stokes-Einstein-Sutherland-Reynolds-Van Cong relations, enhanced by: the optico-electrical phenomenon (O-EP) and the electro-optical phenomenon (E-OP), our static dielectric constant law given in Equations (1a, 1b), our accurate Fermi energy expression given in Eq. (11), and finally our conductivity model given in Eq. (18), are now investigated, by basing on the same physical model and the mathematical treatment method, as those used in our recent works.[1-5] One notes that, for x=0, this crystalline alloy is reduced to the n(p)-type degenerate **GaTe -crystal**. For the physical conditions, as those given in Eq. (15), one remarks that the optical conductivity, $\sigma_O$, obtained from the O-EP, has a same form with that of the electrical conductivity, given from the E-OP, $\sigma_E$, as those determined in Eq. (20a), but $\sigma_O > \sigma_E$ since $m_r(x) < m_{c(v)}(x)$, $m_{c(v)}$ and $m_r$, being the unperturbed reduced effective electron (hole) mass in conduction (valence) bands and the relative carrier mass, respectively. Then, by basing on our optical [electrical]

conductivity models, $\sigma_{O[E]}$, given in Eq. (18), the diffusion-mobility-viscosity-activation energy-Fermi energy relations are determined, and their numerical results are reported in Tables 3n(p), 4n(p), 5n(p) and 6n(p), suggesting an equivalence between the degeneracy-and-viscosity concept in this X(x)-degenerate (viscous) crystalline alloy.

**KEYWORDS**: Conductivity, Mobility, Viscosity coefficient, Diffusion coefficient, Activation energy, Fermi energy

## INTRODUCTION

In the $\mathbf{n^+(p^+) - X(x) \equiv GaTe(1-x)As(x)}$ -crystalline alloy, $0 \leq x \leq 1$, x being the concentration, the optical, electrical and thermoelectric coefficients, enhanced by : (i) the optico-electrical phenomenon (O-EP) and the electro-optical phenomenon (E-OP), (ii) our static dielectric constant law, $\varepsilon(r_{d(a)}, x)$, $r_{d(a)}$ being the donor (acceptor) d(a)-radius, given in Equations (1a, 1b), (iii) our accurate reduced Fermi energy, $\xi_{n(p)}$, given in Eq. (11), accurate with a precision of the order of $2.11 \times 10^{-4}$ [9] affecting all the expressions of optical, electrical and thermoelectric coefficients, and (iv) our optical-and-electrical conductivity models, given in Eq. (18, 20a), are now investigated by basing on our physical model and Fermi-Dirac distribution function, as those given in our recent works.[1,5] It should be noted here that for x=0, the present obtained numerical results are reduced to those given in the n(p)-type degenerate **GaTe**-crystal.[1,6,18]

Then, some important remarks can be reported as follows.

**(1)** As observed in Equations (3, 5, 6a, 6b), the critical impurity density $N_{CDn(CDp)}$, defined by the generalized Mott criterium in the metal-insulator transition (**MIT**), is just the density of electrons (holes), localized in the exponential conduction (valence)-band tail (**EBT**), $N^{EBT}_{CDn(CDp)}$, being obtained with a precision of the order of $\mathbf{2.91 \times 10^{-7}}$, as given in our recent work.[3] Therefore, the effective electron (hole)-density can be defined as: $N^* \equiv N - N_{CDn(CDp)} \simeq N - N^{EBT}_{CDn(CDp)}$, N being the total impurity density, as that observed in the compensated crystals.

**(2)** The ratio of the inverse effective screening length $k_{sn(sp)}$ to Fermi wave number $k_{Fn(kp)}$ at 0 K, $R_{sn(sp)}(N^*)$, defined in Eq. (7), is valid at any $N^*$.

**(3)** For given $[N, r_{d(a)}, x, T]$, the coefficients: $\sigma_{O[E]}(E)$, $\kappa_{O[E]}(E)$, $\varepsilon_{2\,O[E]}(E)$, and $\propto_{O[E]}(E)$, are determined in Equations (18, 19b-19d), as functions of the photon energy E, and then their numerical results are reported in Tables 3-8, being new ones.

**(4)** Finally, for particular physical conditions, as those given in Eq. (15), one observes that the optical conductivity $\sigma_O$ has a same form with that of the electrical conductivity, $\sigma_E$, as those given in Eq. (20a), but $\sigma_O > \sigma_E$ since $m_r(x) < m_{c(v)}(x)$, $m_{c(v)}$ and $m_r$, being the unperturbed reduced effective electron (hole) mass in conduction (valence) bands and the relative carrier mass, respectively. Then, by basing on those $\sigma_{O[E]}$-expressions, the diffusion-mobility-viscosity-activation energy-Fermi energy relations are determined, and their numerical results are reported in Tables 3n(p), 4n(p), 5n(p) and 6n(p), suggesting an equivalence between the degeneracy-and-viscosity concept in this X(x)-degenerate (viscous) crystalline alloy.

In the following, various Sections are presented in order to investigate the conductivity, the mobility, the viscosity coefficient, and the activation energy, expressed as functions of the Fermi energy, given in the degenerate (viscous) $n^+(p^+) - \mathbf{X(x)}$- crystalline alloy.

## OUR STATIC DIELECTRIC CONSTANT LAW AND GENERALIZED MOTT CRITERIUM IN THE METAL-INSULATOR TRANSITION

First of all, in the degenerate $n^+(p^+) - \mathbf{X(x)}$- crystalline alloy, at T=0 K [1-5], we denote : the donor (acceptor) d(a)-radius by $r_{d(a)}$, the corresponding intrinsic one by: $\mathbf{r_{do(ao)}}$=$\mathbf{r_{Te(Ga)}}$, respectively, the effective averaged numbers of equivalent conduction (valence)-bands by: $g_{c(v)}$ , the unperturbed reduced effective electron (hole) mass in conduction (valence) bands by $m_{c(v)}(x)/m_o$, $m_o$ being the free electron mass, the relative carrier mass by: $m_r(x) \equiv \frac{m_c(x) \times m_v(x)}{m_c(x)+m_v(x)} < m_{c(v)}(x)$ for given x , the unperturbed static dielectric constant by: $\varepsilon_o(x)$, and the intrinsic band gap by: $E_{go}(x)$, as those given in **Table 1, reported in Appendix 1**.

Here, the effective carrier mass $m^*_{n(p)}(x)$ is equal to $m_{c(v)}(x)$. Therefore, we can define the effective donor (acceptor)-ionization energy in absolute values as:

$E_{do(ao)}(x) = \frac{13600 \times [m_{c(v)}(x)/m_o]}{[\varepsilon_o(x)]^2}$ meV , and then, the isothermal bulk modulus, by : $B_{do(ao)}(x) \equiv \frac{E_{do(ao)}(x)}{\left(\frac{4\pi}{3}\right) \times (r_{do(ao)})^3}$ .

**Our Static Dielectric Constant Law** $\left[m^{*}_{n(p)}(x) \equiv m_{c(v)}(x)\right]$

Here, the changes in all the energy-band-structure parameters, expressed in terms of the effective dielectric constant $\varepsilon(r_{d(a)}, x)$, are developed as follows.

At $r_{d(a)} = r_{do(ao)}$, the needed boundary conditions are found to be, for the impurity-atom volumes : $V = (4\pi/3) \times \left(r_{d(a)}\right)^3$ and $V_{do(ao)} = (4\pi/3) \times \left(r_{do(ao)}\right)^3$, according to the pressures : p, $p_o = 0$, and to the deformation potential energies (or the strain energies) : $\alpha$, $\alpha_o = 0$. Further, the two important equations, used to determine the $\alpha$ -variation, $\Delta\alpha \equiv \alpha - \alpha_o = \alpha$, are defined by : $\frac{dp}{dV} = -\frac{B_{do(ao)}(x)}{V}$ and $p = -\frac{d\alpha}{dV}$, giving rise to : $\frac{d}{dV}\left(\frac{d\alpha}{dV}\right) = \frac{B_{do(ao)}(x)}{V}$.

Then, by an integration, one gets

$$\left[\Delta\alpha(r_{d(a)}, x)\right]_{n(p)} = B_{do(ao)}(x) \times (V - V_{do(ao)}) \times \ln\left(\frac{V}{V_{do(ao)}}\right) = E_{do(ao)}(x) \times \left[\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 - 1\right] \times \ln\left(\frac{r_{d(a)}}{r_{do(ao)}}\right)^3 \geq 0.$$

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

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

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

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

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

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

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

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

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

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

It should be noted that, in the following, all the optical, electrical and thermoelectric properties strongly depend on this **new $\varepsilon(r_{d(a)},x)$-law.**

Furthermore, the effective Bohr radius $a_{Bn(Bp)}(r_{d(a)},x)$ is defined by:

$$a_{Bn(Bp)}(r_{d(a)},x)\equiv\frac{\varepsilon(r_{d(a)},x)\times\hbar^2}{m^*_{n(p)}(x)\times m_o\times q^2}=0.53\times10^{-8}\text{ cm}\times\frac{\varepsilon(r_{d(a)},x)}{m^*_{n(p)}(x)}, \text{ (2)}$$

where q=e, according to an electron charge equal to : -e.

**Generalized Mott Criterium in the MIT** $\left[m^*_{n(p)}(x)\equiv m_{c(v)}(x)\right]$

Now, it is interesting to remark that the critical total donor (acceptor)-density in the MIT at T=0 K, $N_{CDn(NDp)}(r_{d(a)},x)$, was given by the Mott's criterium, with an empirical parameter, $M_{n(p)}$, as [3] :

$$N_{CDn(CDp)}(r_{d(a)},x)^{1/3}\times a_{Bn(Bp)}(r_{d(a)},x)=M_{n(p)},\ M_{n(p)}=0.25, \text{ (3)}$$

depending thus on our **new $\varepsilon(r_{d(a)},x)$-law**.

This excellent one can be explained from the definition of the reduced effective Wigner-Seitz (**WS**) radius $r_{sn(sp),M}$, in the Mott's criterium, being characteristic of interactions, by :

$$r_{sn(sp),M}\left(N = N_{CDn(CDp)}(r_{d(a)}, x), r_{d(a)}, x\right) \equiv \left(\frac{3}{4\pi N_{CDn(CDp)}(r_{d(a)},x)}\right)^{\frac{1}{3}} \times \frac{1}{a_{Bn(Bp)}(r_{d(a)},x)} = \mathbf{2.4813963}, \quad (4)$$

for any $(r_{d(a)}, x)$-values. Then, from Eq. (4), one also has :

$$N_{CDn(CDp)}(r_{d(a)}, x)^{1/3} \times a_{Bn(Bp)}(r_{d(a)}, x) = \left(\frac{3}{4\pi}\right)^{\frac{1}{3}} \times \frac{1}{\mathbf{2.4813963}} = \mathbf{0.25} = \mathbf{M_{n(p)}}, \quad (5)$$

**explaining thus the existence of the Mott's criterium**.

Furthermore, by using $M_{n(p)} = 0.25$, according to the empirical Heisenberg parameter $\mathcal{H}_{\mathbf{n(p)}} = \mathbf{0.47137}$, as those given in our previous work.[3] we have also showed that $N_{CDn(CDp)}$ is just **the density of electrons (holes) localized in the exponential conduction (valence)-band tai** , $\mathbf{N^{EBT}_{CDn(CDp)}}$ , with a precision of the order of $\mathbf{2.91 \times 10^{-7}}$ , respectively [3]. So,

$$N_{CDn(NDp)}(r_{d(a)}, x) \cong N^{EBT}_{CDn(CDp)}(r_{d(a)}, x). \quad (6a)$$

It shoud be noted that the values of $M_{n(p)}$ and $\mathcal{H}_{n(p)}$ could be chosen so that those of $N_{CDn(CDp)}$ and $N^{EBT}_{CDn(CDp)}$ are found to be in good agreement with their experimental results.

There Fore, the effective density of electrons (holes) given in parabolic conduction (valence) bands, $N^*$, can be defined, as that given in compensated materials:

$$N^*(N, r_{d(a)}, x) \equiv N - N_{CDn(NDp)}(r_{d(a)}, x) \cong N - N^{EBT}_{CDn(CDp)}(r_{d(a)}, x) \geq 0. \quad (6b)$$

In summary, as observed in our previous paper [3], for a given x and an increasing $r_{d(a)}$, $\varepsilon(r_{d(a)}, x)$ decreases, while $E_{gno(gpo)}(r_{d(a)}, x)$, $N_{CDn(NDp)}(r_{d(a)}, x)$ and $N^{EBT}_{CDn(CDp)}(r_{d(a)}, x)$ increase, affecting strongly all the optical, electrical, and thermoelectric coefficients, as those observed in following Sections.

## PHYSICAL MODEL

In the degenerate $n^+(p^+) - \mathbf{X(x)}$ -crystalline alloy, the reduced effective Wigner-Seitz (**WS**) radius $r_{sn(sp)}$, characteristic of interactions, being given in Eq. (4), in which N is replaced by $N^*$, is now defined by:

$\gamma \times r_{sn(sp)}(N^*, r_{d(a)}, x) \equiv \frac{k_{Fn(Fp)}^{-1}}{a_{Bn(Bp)}} < 1$ , $r_{sn(sp)}(N^*, r_{d(a)}, x) \equiv \left(\frac{3g_{c(v)}}{4\pi N^*}\right)^{1/3} \times \frac{1}{a_{Bn(Bp)}(r_{d(a)}, x)}$ ,

being proportional to $N^{*-1/3}$. Here, $\gamma = (4/9\pi)^{1/3}$, $k_{Fn(Fp)}(N^*) \equiv \left(\frac{3\pi^2 N^*}{g_{c(v)}}\right)^{\frac{1}{3}}$ is the Fermi wave.

Then, the ratio of the inverse effective screening length $k_{sn(sp)}$ to Fermi wave number $k_{Fn(kp)}$ is defined by:

$$R_{sn(sp)}(N^*) \equiv \frac{k_{sn(sp)}}{k_{Fn(Fp)}} = \frac{k_{Fn(Fp)}^{-1}}{k_{sn(sp)}^{-1}} = R_{snWS(spWS)} + \left[R_{snTF(spTF)} - R_{snWS(spWS)}\right] e^{-r_{sn(sp)}} < 1, \quad (7)$$

**being valid at any $N^*$.**

Here, these ratios, $R_{snTF(spTF)}$ and $R_{snWS(spWS)}$, can be determined as follows.

First, for $N \gg N_{CDn(NDp)}(r_{d(a)}, x)$ , according to the **Thomas-Fermi (TF)-approximation**, the ratio $R_{snTF(spTF)}(N^*)$ is reduced to

$$R_{snTF(spTF)}(N^*) \equiv \frac{k_{snTF(spTF)}}{k_{Fn(Fp)}} = \frac{k_{Fn(Fp)}^{-1}}{k_{snTF(spTF)}^{-1}} = \sqrt{\frac{4\gamma r_{sn(sp)}}{\pi}} \ll 1, \quad (8)$$

being proportional to $N^{*-1/6}$.

Secondly, for $N \ll N_{CDn(NDp)}(r_{d(a)})$, according to the **Wigner-Seitz (WS)-approximation**, the ratio $R_{snWS(snWS)}$ is respectively reduced to

$$R_{sn(sp)WS}(N^*) \equiv \frac{k_{sn(sp)WS}}{k_{Fn}} = 0.5 \times \left(\frac{3}{2\pi} - \gamma \frac{d\left[r_{sn(sp)}^2 \times E_{CE}(N^*)\right]}{dr_{sn(sp)}}\right), \quad (9a)$$

where $E_{CE}(N^*)$ is the majority-carrier correlation energy (CE), being determined by:

$$E_{CE}(N^*) = \frac{-0.87553}{0.0908 + r_{sn(sp)}} + \frac{\frac{0.87553}{0.0908 + r_{sn(sp)}} + \left(\frac{2[1 - \ln(2)]}{\pi^2}\right) \times \ln(r_{sn(sp)}) - 0.093288}{1 + 0.03847728 \times r_{sn(sp)}^{1.67378876}}.$$

Furthermore, in the highly degenerate case, the physical conditions are found to be given by:

$$\frac{k_{Fn(Fp)}^{-1}}{a_{Bn(Bp)}} < \frac{\sigma_{n(p)}}{E_{Fno(Fpo)}} \equiv \frac{1}{A_{n(p)}} < \frac{k_{Fn(Fp)}^{-1}}{k_{sn(sp)}^{-1}} \equiv R_{sn(sp)} < 1, \ \sigma_{n(p)}(N^*) \equiv \frac{\sqrt{2\pi \times \left(\frac{N^*}{g_{c(v)}}\right)}}{\varepsilon(r_{d(a)})} \times q^2 k_{sn(sp)}^{-1/2}, \quad (9b)$$

which gives: $A_{n(p)}(N^*) = \frac{E_{Fno(Fpo)}(N^*)}{\sigma_{n(p)}(N^*)}$, $E_{Fno(Fpo)}(N^*, r_{d(a)}, x) \equiv \frac{\hbar^2 \times k_{Fn(Fp)}^2(N^*)}{2 \times m_{n(p)}^*(x) \times m_o}$.

**BAND GAP NARROWING (BGN)**

First, the BGN is found to be given by

$$\Delta E_{gn(gp)}\left(N^{*}, r_{d(a)}, x\right) \simeq$$

$$a_1 + \frac{\varepsilon_o(x)}{\varepsilon\left(r_{d(a)},x\right)} \times N_r^{\frac{1}{3}} + a_2 \times \frac{\varepsilon_o(x)}{\varepsilon\left(r_{d(a)},x\right)} \times N_r^{\frac{1}{3}} \times \left(2.503 \times \left[-E_{CE}\left(r_{sn(sp)}\right)\right] \times r_{sn(sp)}\right) + a_3 \times$$

$$\left[\frac{\varepsilon_o(x)}{\varepsilon\left(r_{d(a)},x\right)}\right]^{\frac{5}{4}} \times \sqrt{\frac{m_{v(c)}}{m^{*}_{n(p)}(x)}} \times N_r^{\frac{1}{4}} + 2a_4 \times \left[\frac{\varepsilon_o(x)}{\varepsilon\left(r_{d(a)},x\right)}\right]^{\frac{1}{2}} \times N_r^{\frac{1}{2}} + 2a_5 \times \left[\frac{\varepsilon_o(x)}{\varepsilon\left(r_{d(a)},x\right)}\right]^{\frac{3}{2}} \times N_r^{\frac{1}{6}},\ N_r =$$

$$\frac{N^{*}}{9.999\times10^{17}cm^{-3}}, \text{ (10a)}$$

Here, for $\Delta E_{gn;N}(N^{*}, r_d, x)$, one has: $a_1 = 3.8 \times 10^{-3}(eV)$, $a_2 = 6.5 \times 10^{-4}(eV)$, $a_3 = 2.8 \times 10^{-3}(eV)$, $a_4 = 5.597 \times 10^{-3}(eV)$, and $a_5 = 8.1 \times 10^{-4}(eV)$, and for $\Delta E_{gp;N}(N^{*}, r_a, x)$, one has: $a_1 = 3.15 \times 10^{-3}(eV)$, $a_2 = 5.41 \times 10^{-4}(eV)$, $a_3 = 2.32 \times 10^{-3}(eV)$, $a_4 = 4.12 \times 10^{-3}(eV)$, and $a_5 = 9.8 \times 10^{-5}(eV)$.

Therefore, at T=0 K and $N^{*} = 0$, and for any x and $r_{d(a)}$, one gets: $\Delta E_{gn(gp)} = 0$, according to the metal-insulator transition (MIT).

Secondly, one has:

$$\Delta E_{gn(gp)}(T, x) = 10^{-4}T^2 \times \left[\frac{7.205\times x}{T+94} + \frac{5.405\times(1-x)}{T+204}\right] (eV). \text{ (10b)}$$

**FERMI ENERGY AND FERMI-DIRAC DISTRIBUTION FUNCTION**

**Fermi Energy**

Here, for a presentation simplicity, we change all the sign of various parameters, given in the degenerate $p^{+} - \mathbf{X}(\mathbf{x})$-crystalline alloy, in order to obtain the same one, as given in the degenerate $n^{+} - \mathbf{X}(\mathbf{x})$ - crystalline alloy, according to the reduced Fermi energy $E_{Fn(Fp)}$, $\xi_{n(p)}(N^{*}, r_{d(a)}, x, T) \equiv \frac{E_{Fn(Fp)}(N^{*}, r_{d(a)}, x, T)}{k_B T} > 0 (< 0)$, obtained respectively in the degenerate (non-degenerate) case.

For any $(N^{*}, r_{d(a)}, x, T)$, the reduced Fermi energy $\xi_{n(p)}(N^{*}, r_{d(a)}, x, T)$ or the Fermi energy $E_{Fn(Fp)}(N^{*}, r_{d(a)}, x, T)$, obtained in our previous paper[9], obtained with a precision of the order of $\mathbf{2.11 \times 10^{-4}}$, is found to be given by:

$$\xi_{n(p)}(u) \equiv \frac{E_{Fn(Fp)}(u)}{k_B T} = \frac{G(u)+Au^{B}F(u)}{1+Au^{B}} \equiv \frac{V(u)}{W(u)}, A = 0.0005372 \text{ and } B = 4.82842262, \text{ (11)}$$

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

So, in the non-degenerate case ($u \ll 1$), one has: $E_{Fn(Fp)}(u) = k_B T \times G(u) \simeq k_B T \times Ln(u)$ as **$u \longrightarrow 0$, the limiting non-degenerate condition**, and in the very degenerate case ($u \gg 1$), one gets: $E_{Fn(Fp)}(u \gg 1) = k_B T \times F(u) = k_B T \times au^{\frac{2}{3}}\left(1 + bu^{-\frac{4}{3}} + cu^{-\frac{8}{3}}\right)^{-\frac{2}{3}} \simeq \frac{\hbar^2 \times k^2_{Fn(Fp)}(N^*)}{2 \times m^*_{n(p)}(x) \times m_o}$ as **$u \longrightarrow \infty$, the limiting degenerate condition**. In other words, $\xi_{n(p)} \equiv \frac{E_{Fn(Fp)}}{k_B T}$ is accurate, and it also verifies the correct limiting conditions.

In particular, as $T \to 0\ K$, since $u^{-1} \to 0$, Eq. (11) is reduced to: $E_{Fno(Fpo)}(N^*) \equiv \frac{\hbar^2 \times k^2_{Fn(Fp)}(N^*)}{2 \times m^*_{n(p)}(x) \times m_o}$, proportional to $(N^*)^{2/3}$, noting that, for a given $N^*$, $E_{Fno(Fpo)}\left(m^*_{n(p)}(x) = m_r(x)\right) > E_{Fno(Fpo)}\left(m^*_{n(p)}(x) = m_{c(v)}(x)\right)$ since $m_r(x) < m_{c(v)}(x)$ for given x. Further, at T=0 K and $N^* = 0$, being the physical conditions, given for the metal-insulator transition (MIT).

In the following, it should be noted that all the optical and electrical-and-thermoelectric properties strongly depend on such the accurate expression of $\xi_{n(p)}(N^*, r_{d(a)}, x, T)$.[9]

**Fermi-Dirac Distribution Function (FDDF)**

The Fermi-Dirac distribution function (FDDF) is given by: $f(E) \equiv (1 + e^{\gamma})^{-1}$, $\gamma \equiv (E - E_{Fn(Fp)})/(k_B T)$.

So, the average of $E^p$, calculated using the FDDF-method, as developed in our previous works.[1,6] is found to be given by:

$\langle E^p \rangle_{FDDF} \equiv G_p(E_{Fn(Fp)}) \times E^p_{Fn(Fp)} \equiv \int_{-\infty}^{\infty} E^p \times \left(-\frac{\partial f}{\partial E}\right) dE$, $-\frac{\partial f}{\partial E} = \frac{1}{k_B T} \times \frac{e^{\gamma}}{(1+e^{\gamma})^2}$.

Further, one notes that, at 0 K, $-\frac{\partial f}{\partial E} = \delta(E - E_{Fno(Fpo)})$, $\delta(E - E_{Fno(Fpo)})$ being the Dirac delta ($\delta$)-function. Therefore, $G_p(E_{Fno(Fpo)}) = 1$.

Then, at low T, by a variable change $\gamma \equiv (E - E_{Fn(Fp)})/(k_B T)$, one has:

$G_p(E_{Fn(Fp)}) \equiv 1 + E_{Fn(Fp)}^{-p} \times \int_{-\infty}^{\infty} \frac{e^{\gamma}}{(1+e^{\gamma})^2} \times (k_B T\gamma + E_{Fn(Fp)})^p d\gamma = 1 + \sum_{\mu=1,2,...}^{p} C_p^{\beta} \times (k_B T)^{\beta} \times E_{Fn(Fp)}^{-\beta} \times I_{\beta}$, where $C_p^{\beta} \equiv p(p-1)...(p-\beta+1)/\beta!$ and the integral $I_{\beta}$ is given by:

$I_{\beta} = \int_{-\infty}^{\infty} \frac{\gamma^{\beta} \times e^{\gamma}}{(1+e^{\gamma})^2} d\gamma = \int_{-\infty}^{\infty} \frac{\gamma^{\beta}}{(e^{\gamma/2}+e^{-\gamma/2})^2} d\gamma$, vanishing for old values of $\beta$. Then, for even values of $\beta = 2n$, with n=1, 2, …, one obtains:.

$I_{2n} = 2\int_{0}^{\infty} \frac{\gamma^{2n} \times e^{\gamma}}{(1+e^{\gamma})^2} d\gamma$ .

Now, using an identity $(1 + e^{\gamma})^{-2} \equiv \sum_{s=1}^{\infty} (-1)^{s+1} s \times e^{\gamma(s-1)}$, a variable change: $s\gamma = -t$, the Gamma function: $\int_0^{\infty} t^{2n} e^{-t} dt \equiv \Gamma(2n+1) = (2n)!$, and also the definition of the Riemann's zeta function: $\zeta(2n) \equiv 2^{2n-1}\pi^{2n}|B_{2n}|/(2n)!$, $B_{2n}$ being the Bernoulli numbers, one finally gets: $I_{2n} = (2^{2n} - 2) \times \pi^{2n} \times |B_{2n}|$. So, from above Eq. of $\langle E^p \rangle_{FDDF}$, we get in the degenerate case the following ratio:

$G_p(E_{Fn(Fp)}) \equiv \frac{\langle E^p \rangle_{FDDF}}{E_{Fn(Fp)}^p} = 1 + \sum_{n=1}^{p} \frac{p(p-1)...(p-2n+1)}{(2n)!} \times (2^{2n} - 2) \times |B_{2n}| \times y^{2n} \equiv G_{p\geq 1}(y)$,(12)

where $y \equiv \frac{\pi}{\xi_{n(p)}(N^*, r_{d(a)}, x, T)} = \frac{\pi k_B T}{E_{Fn(Fp)}(N^*, r_{d(a)}, x, T)}$, noting that $G_{p=1}(y \equiv \frac{\pi k_B T}{E_{Fn(Fp)}} = \frac{\pi}{\xi_{n(p)}}) = 1$ , and as T→ 0 K, $G_{p>1}(y \to 0) \to 1$.

Then, some usual results of $G_{p\geq 1}(y)$ are given in the **Table 2, reported in Appendix 1**, being needed to determine all the following optical, electrical and thermoelectric properties.

## OPTICAL-AND-ELECTRICAL PROPERTIES

### Optico-Electrical Phenomenon (O-EP) and Electro-Optical Phenomenon (E-OP)

In the degenerate $n^+(p^+) - \mathbf{X}(\mathbf{x})$-crystalline alloy, one has

(i) in the **E-OP**, the reduced band gap is defined by:

$E_{gn2(gp2)} \equiv E_{gn(gp)} - \Delta E_{gn(gp)}(N^*, r_{d(a)}, x) - \Delta E_{gn(gp)}(T, x)$, (13)

where the intrinsic band gap $E_{gn(gp)}$ is defined in Equations (1a, 1b), $\Delta E_{gn(gp)}(N^*, r_{d(a)}, x)$ and $\Delta E_{gn(gp)}(T, x)$ are respectively determined in Equations (10a, 10b), and

(ii) in the (**O-EP**), the photon energy is defined by: $E \equiv \hbar\omega$, and the optical band gap, as: $E_{gn1(gp1)} \equiv E_{gn2(gp2)} + E_{Fn(Fp)}$.

Therefore, for $E \geq E_{gn1(gp1)}(E_{gn2(gp2)})$, the effective photon energy $E^*$ is found to be given by:

$$E^* \equiv E - E_{gn1(gp1)}(E_{gn2(gp2)}) \geq 0. \quad (14)$$

From above Equations, one notes that: $E^* \equiv [E - E_{gn1(gp1)}] = E_{Fn(Fp)}$, given in the O-EP, if $E = [E_{gn1(gp1)} + E_{Fn(Fp)}] \equiv E_{gn(gp)O}$ and $m^*_{n(p)}(x) = m_r(x)$, and $E^* \equiv E - E_{gn2(gp2)} = E_{Fn(Fp)}$, given in the E-OP, if $E = [E_{gn2(gp2)} + E_{Fn(Fp)}] \equiv E_{gn(gp)E}$ and $m^*_{n(p)}(x) = m_{c(v)}(x)$, noting that $E_{Fn(Fp)}(m_r(x)) > E_{Fn(Fp)}(m_{c(v)}(x))$, since $m_r(x) < m_{c(v)}(x)$, for a given x. (15)

Eq. (15) thus shows that, in both O-EP and E-OP, the Fermi energy-level penetrations into conduction (valence)-bands, observed in the $n^+(p^+) -$ type degenerate $n^+(p^+) - \mathbf{X(x)}$-crystalline alloy, $E_{Fn(Fp)}$, are well defined.

**Optical Coefficients**

The optical properties for any medium, defined in the O-EP and E-OP, respectively, according to: $[m^*_{n(p)} \equiv m_r(x)[m_{c(v)}(x)]]$, can be described by the complex refraction: $\mathbb{N}_{O[E]} \equiv n_{O[E]} - i\kappa_{O[E]}$, $n_{O[E]}$ and $\kappa_{O[E]}$ being the refraction index and the extinction coefficient, the complex dielectric function: $\mathcal{E}_{O[E]} = \varepsilon_{1\,O[E]} - i\varepsilon_{2\,O[E]}$, where $i^2 = -1$, and $\mathcal{E}_{O[E]} = \mathbb{N}_{O[E]}{}^2$. Further, if denoting the normal-incidence reflectance and the optical absorption by $R_{O[E]}$ and $\propto_{O[E]}$, and the effective joint parabolic conduction (parabolic valence)-band density of states by:

$$JDOS_{n(p)\,O[E]}(E, N^*, r_{d(a)}, x, T) \equiv$$

$$\frac{1}{2\pi^2} \times \left(\frac{2m^*_{n(p)}(x)}{\hbar^2}\right)^{3/2} \times \sqrt{E_{Fno(Fpo)}(N^*)} \times \left[\frac{E - E_{gn1(gp1)}(E_{gn2(gp2)})}{E - [E_{gn1(gp1)}(E_{gn2(gp2)}) + E_{Fn(Fp)} - E_{Fno(Fpo)}]}\right]^2 \quad , \quad \text{and}$$

$F_{O[E]}(E) \equiv \frac{\hbar q^2 \times |v(E)|^2}{n_{O[E]}(E) \times cE \times \varepsilon(r_{d(a)}, x) \times \varepsilon_{free\ space}}$, one gets [2]:

$$\propto_{O[E]}(E) = JDOS_{n(p)\,O[E]}(E) \times F_{O[E]}(E) = \frac{E \times \varepsilon_{2\,O[E]}(E)}{\hbar c\, n_{O[E]}(E)} = \frac{2E \times \kappa_{O[E]}(E)}{\hbar c} =$$

$$\frac{4\pi\sigma_{O[E]}(E)}{cn_{O[E]}(E) \times \varepsilon(r_{d(a)}, x) \times \varepsilon_{free\ space}},$$

$\varepsilon_{1\,O[E]}(E) \equiv {n_{O[E]}}^2 - {\kappa_{O[E]}}^2$, $\varepsilon_{2\,O[E]}(E) \equiv 2\kappa_{O[E]}n_{O[E]}$, and $R_{O[E]}(E) \equiv \frac{{[n_{O[E]}-1]}^2+{\kappa_{O[E]}}^2}{{[n_{O[E]}+1]}^2+{\kappa_{O[E]}}^2}$. (16a)

One notes here that, at the MIT-conditions : $N^* = 0$, both $E_{gn1(gp1)}(E_{gn2(gp2)}) = E_{gn(gp)}$, according to :

$\left[\frac{E-E_{gn1(gp1)}(E_{gn2(gp2)})}{E-[E_{gn1(gp1)}(E_{gn2(gp2)})+E_{Fn(Fp)}-E_{Fno(Fpo)}]}\right]^2 = \frac{0}{0}$ for $E=E_{gn(gp)}$,

$\left[\frac{E-E_{gn1(gp1)}(E_{gn2(gp2)})}{E-[E_{gn1(gp1)}(E_{gn2(gp2)})+E_{Fn(Fp)}-E_{Fno(Fpo)}]}\right]^2 = 1$ for $E \gtrsim E_{gn(gp)}$, so that, in such the MIT,

$JDOS_{n(p)\,O[E]}(E, N^*, r_{d(a)}, x, T) \equiv \frac{1}{2\pi^2} \times \left(\frac{2m^*_{n(p)}(x)}{\hbar^2}\right)^{\frac{3}{2}} \times \sqrt{E_{Fno(Fpo)}(N^* = 0)} = 0$, for $E \gtrsim E_{gn(gp)}$, which is largely verified since $N_{CDn(NDp)}(r_{d(a)}, x) \cong N^{EBT}_{CDn(CDp)}(r_{d(a)}, x)$ or $E_{gn2(gp2)}(N_{CDn(NDp)}, T = 0K) \cong E_{gn2(gp2)}(N^{EBT}_{CDn(CDp)}, T = 0K) \cong E_{gn(gp)}$, as those given in Equations (6a, 6b). In other words, the critical photon energy can be defined by: $E \cong E_{gn(gp)}$.

Then, Eq. (6a) states that $N_{CDn(CDp)}$, given in parabolic conduction (parabolic valence)-band density of states, is just the density of electrons (holes) localized in the exponential conduction (valence)-band tail, $N^{EBT}_{CDn(CDp)}$, with a precision of the order of $\mathbf{2.91 \times 10^{-7}}$, respectively .[3]

Therefore, for $E \cong E_{gn(gp)}$, the exponential conduction (valence)-band tail states can be approximated with a same precision to: <

$JDOS^{EBT}_{n(p)O[E]}(E, N^*, r_{d(a)}, x, T) \equiv \frac{1}{2\pi^2} \times \left(\frac{2m^*_{n(p)}(x)}{\hbar^2}\right)^{\frac{3}{2}} \times \sqrt{E_{Fno(Fpo)}(N^* = N_{CDn(NDp)})}$. (16b)

Here, $\varepsilon_{free\ space} = 8.854187817 \times 10^{-12}\left(\frac{C^2}{N \times m^2}\right)$ is the permittivity of the free space, -q (<0) is the charge of the electron, $|v_{O[E]}(E)|$ is the matrix elements of the velocity operator between valence (conduction)-and-conduction (valence) bands, and our approximate expression for the refraction index $n_{O[E]}$ is found to be defined by:

$n_{O[E]}(E, N^*, r_{d(a)}, x, T) = n_\infty(r_{d(a)}, x) + \sum_{i=1}^{4} \frac{X_i(E_{gn1(gp1)}) \times E + Y_i(E_{gn1(gp1)})}{E^2 - B_i E + C_i}$, (17)

going to a constant as $E \to \infty$, since $n(E \to \infty, r_{d(a)}, x) \to n_\infty(r_{d(a)}, x) = \sqrt{\varepsilon(r_{d(a)}, x)} \times \frac{\omega_T}{\omega_L}$, given in the well-known Lyddane-Sachs-Teller relation, in which $\omega_T \simeq 5.1 \times 10^{13}\ s^{-1}$ and

$\omega_L \simeq 8.9755 \times 10^{13}\ s^{-1}$ are the transverse (longitudinal) optical phonon frequencies, giving rise to: $n_\infty(r_{d(a)}, x) \simeq \sqrt{\varepsilon(r_{d(a)}, x)} \times 0.568$.

Here, the other parameters are determined by: $X_i(E_{gn1(gp1)}) = \frac{A_i}{Q_i} \times \left[-\frac{B_i^2}{2} + E_{gn1(gp1)}B_i - E_{gn1(gp1)}^2 + C_i\right]$, $Y_i(E_{gn1(gp1)}) = \frac{A_i}{Q_i} \times \left[\frac{B_i \times (E_{gn1(gp1)}^2 + C_i)}{2} - 2E_{gn1(gp1)}C_i\right]$, $Q_i = \frac{\sqrt{4C_i - B_i^2}}{2}$, where, for i=(1, 2, 3, and 4),

$A_i = 4.7314 \times 10^{-4},\ 0.2313655, 0.1117995, 0.0116323$ , $B_i = 5.871, 6.154, 9.679$ , 13.232, and $C_i = 8.619, 9.784, 23.803, 44.119$.

Now, the optical [electrical] conductivity $\sigma_{O[E]}$ can be defined and expressed in terms of the kinetic energy of the electron (hole), $E_k \equiv \frac{\hbar^2 \times k^2}{2 \times m^*_{n(p)}(x) \times m_o}$, k being the wave number, as:

$\sigma_{O[E]}(k) \equiv \frac{q^2 \times k}{\pi \times \hbar} \times \frac{k}{k_{sn(sp)}} \times \left[k \times a_{Bn(Bp)}\right] \times \left(\frac{E_k}{\sigma_{n(p)}}\right)^{\frac{1}{2}}$ $(\frac{1}{\Omega \times cm})$, which is thus proportional to $E_k{}^2$,

where $\frac{q^2}{\pi \times \hbar} = 7.7480735 \times 10^{-5}\ ohm^{-1}$ and $\sigma_{n(p)}(N^*)$ is determined in Eq. Eq. (9b).

Then, we obtain: $\langle E^2 \rangle_{FDDF} \equiv G_2(y = \frac{\pi k_B T}{E_{Fn(Fp)}}) \times E_{Fn(Fp)}^2$ , and $G_2(y) = \left(1 + \frac{y^2}{3}\right) \equiv G_2(N, r_{d(a)}, x, T)$, with $y \equiv \frac{\pi}{\xi_{n(p)}}$, $\xi_{n(p)} = \xi_{n(p)}(N^*, r_{d(a)}, x, T)$ for a presentation simplicity.

There Fore, from above equations (16, 17), if denoting the function $H(N, r_{d(a)}, x, T)$ by:

$H(N^*, r_{d(a)}, x, T) =$

$\left[\frac{k_{Fn(Fp)}(N^*)}{R_{sn(sp)}(N^*)} \times \left[k_{Fn(Fp)}(N^*) \times a_{Bn(Bp)}(r_{d(a)}, x)\right] \times \sqrt{A_{n(p)}(N^*) = \frac{E_{Fno(Fpo)}(N^*)}{\sigma_{n(p)}(N^*)}}\right] \times$

$G_2(N^*, r_{d(a)}, x, T)$, being expressed in terms of $E_{Fno(Fpo)}^2$. Here, $R_{sn(sp)}(N^*) \equiv \frac{k_{sn(sp)}}{k_{Fn(Fp)}}$ is defined in Eq. (7). Then, our optical [electrical] conductivity models, defined in the O-EP and E-OP, respectively, for a simply representation, can thus be assumed to be as:

$\sigma_O(E, N^*, r_{d(a)}, x, T) =$

$\frac{q^2}{\pi \times \hbar} \times H(N^*, r_{d(a)}, x, T) \times \left[\frac{E - E_{gn1(gp1)}}{E - [E_{gn1(gp1)} + E_{Fn(Fp)} - E_{Fno(Fpo)}]}\right]^2$ $(\frac{1}{\Omega \times cm})$, and

$$\sigma_E\left(E, N, r_{d(a)}, x, T\right) =$$

$$\frac{q^2}{\pi\times\hbar} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left[\frac{E-E_{gn2(gp2)}}{E-\left[\left(E_{gn2(gp2)}+E_{Fn(Fp)}-E_{Fno(Fpo)}\right)\right]}\right]^2 \left(\frac{1}{\Omega\times cm}\right). \quad (18)$$

It should be noted here that:

(i) $\sigma_{O[E]}\left(E = E_{gn1(gp1)}[E_{gn2(gp2)}]\right) = 0$ , and $\sigma_{O[E]}(E \to \infty) \to$ Constant for given $\left(N, r_{d(a)}, x, T\right)$ −physical conditions, and

(ii) as $T \to 0$ K and $N^* = 0$ [or $E_{Fno(Fpo)}(N^*) = 0$], according to: $H\left(N^*, r_{d(a)}, x, T\right) = 0$, and for a given E, $\left[E - E_{gn1(gp1)}\right] = \left[E - E_{gn(gp)}\right]$=Constant, then from Equations (16-18), $n_{O[E]}$ (E)= Constant, $\sigma_{O[E]}(E) = 0$, $\kappa_{O-EP[E-OP]}(E) = 0$, $\varepsilon_{1\,O[E]}(E) = (n_\infty)^2 =$ Constant, $\varepsilon_2(E) = 0$, and $\propto_{O[E]}(E) = 0$.

This result (18) should be new, in comparison with that, obtained from an improved Forouhi-Bloomer parameterization, as given in our previous work.[2]

Using Equations (16-18), one obtains all the analytically results as:

$$\frac{|v(E)|^2}{E} = \frac{8\pi^2\hbar}{(2m_r)^{\frac{3}{2}}\times\sqrt{\sigma_{n(p)}(N^*)}} \times \left[\frac{k_{Fn(Fp)}(N^*)}{R_{sn(sp)}(N^*)} \times \left[k_{Fn(Fp)}(N^*) \times a_{Bn(Bp)}\left(r_{d(a)}, x\right)\right]\right] \times$$

$$G_2\left(N^*, r_{d(a)}, x, T\right), \quad (19a)$$

$$\kappa_O(E) = \frac{2q^2}{n(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}\times E} \times H\left(N^*, r_{d(a)}, x, T\right) \times$$

$$\left[\frac{E-E_{gn1(gp1)}}{E-\left[E_{gn1(gp1)}+E_{Fn(Fp)}-E_{Fno(Fpo)}\right]}\right]^2 \quad \text{and}$$

$$\kappa_E(E) = \frac{2q^2}{n(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}\times E} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left[\frac{E-E_{gn2(gp2)}}{E-\left[\left(E_{gn2(gp2)}+E_{Fn(Fp)}-E_{Fno(Fpo)}\right)\right]}\right]^2 ,$$

(19b)

which gives: $\kappa_{O[E]}\left(E = E_{gn1(gp1)}[E_{gn2(gp2)}]\right) = 0$, and $\kappa_{O[E]}(E \to \infty) \to 0$, as those given in Ref. [2],

$$\varepsilon_{2\,O}(E) = \frac{4q^2}{\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}\times E} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left[\frac{E-E_{gn1(gp1)}}{E-\left[E_{gn1(gp1)}+E_{Fn(Fp)}-E_{Fno(Fpo)}\right]}\right]^2 \text{ and}$$

$$\varepsilon_{2\,E}(E) = \frac{4q^2}{\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}\times E} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left[\frac{E-E_{gn2(gp2)}}{E-\left[\left(E_{gn2(gp2)}+E_{Fn(Fp)}-E_{Fno(Fpo)}\right)\right]}\right]^2 ,$$

(19c)

which gives: $\varepsilon_{2O-EP[2E-OP]}\left(E = E_{gn1(gp1)}[E_{gn2(gp2)}]\right) = 0$, and $\varepsilon_{2O-EP[2E-OP]}(E \to \infty) \to 0$, as those given in Ref. [2],

$$\propto_O (E) = \frac{4q^2}{\hbar cn(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left[\frac{E-E_{gn1(gp1)}}{E-[E_{gn1(gp1)}+E_{Fn(Fp)}-E_{Fno(Fpo)}]}\right]^2 \left(\frac{1}{cm}\right)$$ and

$$\propto_E (E) = \frac{4q^2}{\hbar cn(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left[\frac{E-E_{gn2(gp2)}}{E-[(E_{gn2(gp2)}+E_{Fn(Fp)}-E_{Fno(Fpo)}]}\right]^2 \left(\frac{1}{cm}\right), \quad (19d)$$

which gives: $\propto_{O[E]} \left(E = E_{gn1(gp1)}[E_{gn2(gp2)}]\right) = 0$, and $\propto_{O[E]} (E \to \infty) \to$ Constant.

Furthermore, from Equations (16, 17, 19b), we can also determine $\varepsilon_{1\,O[E]}(E)$ and $R_{O[E]}(E)$.

Now, from Equations (18, 19b, 19c, 19d), using Eq. (15) as $E \equiv E_{gn(gp)O[E]}$, one obtains respectively, as:

$$\sigma_O\left(N^*, r_{d(a)}, x, T\right) = \frac{q^2}{\pi\times\hbar} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2 \left(\frac{1}{\Omega\times cm}\right),$$

having the same form with that of $\sigma_E\left(N, r_{d(a)}, x, T\right)$ [1], as:

$$\sigma_E\left(N^*, r_{d(a)}, x, T\right) = \frac{q^2}{\pi\times\hbar} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2 \left(\frac{1}{\Omega\times cm}\right), \quad (20a)$$

noting here that for given $\left(N^*, r_{d(a)}, x, T\right)$ -physical conditions we obtain: $\sigma_O > \sigma_E$ since $m_r(x) < m_{c(v)}(x)$,

$$\kappa_O\left(N^*, r_{d(a)}, x, T\right) = \frac{2q^2}{n(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}\times(E_{gn1(gp1)}+E_{Fn(Fp)})} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2$$ and

$$\kappa_E\left(N^*, r_{d(a)}, x, T\right) = \frac{2q^2}{n(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}\times(E_{gn2(gp2)}+E_{Fn(Fp)})} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2, \quad (20b)$$

$$\varepsilon_{2\,O}\left(N^*, r_{d(a)}, x, T\right) = \frac{4q^2}{\varepsilon(r_{d(a)},x)\times\varepsilon_{free\ space}\times(E_{gn1(gp1)}+E_{Fn(Fp)})} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2$$

and

$$\varepsilon_{2\,E}\left(N^*, r_{d(a)}, x, T\right) = \frac{4q^2}{\varepsilon(r_{d(a)},x)\times\varepsilon_{\text{free space}}\times(E_{gn2(gp2)}+E_{Fn(Fp)})} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2 ,$$

(20c)

$$\propto_O \left(N^*, r_{d(a)}, x, T\right) =$$

$$\frac{4q^2}{\hbar cn(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{\text{free space}}} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2 \left(\frac{1}{cm}\right) \quad \text{and}$$

$$\propto_E \left(N^*, r_{d(a)}, x, T\right) = \frac{4q^2}{\hbar cn(E)\times\varepsilon(r_{d(a)},x)\times\varepsilon_{\text{free space}}} \times H\left(N^*, r_{d(a)}, x, T\right) \times \left(\frac{E_{Fn(Fp)}}{E_{Fno(Fpo)}}\right)^2 \left(\frac{1}{cm}\right). \quad (20d)$$

Further, from Equations (16, 17, 20b), we can also determine $\varepsilon_{1\,O[E]}(E)$ and $R_{O[E]}(E)$.

**OPTICAL [ELECTRICAL] PROPERTIES** $\left[m^*_{n(p)} \equiv m_r(x)[m_{c(v)}(x)]\right]$

Here, if denoting, for majority electrons (holes), the thermal conductivity by: $\sigma_{Th.\ O[E]}(N^*, r_{d(a)}, x, T)$ in $\frac{W}{cm\times K}$, and the Lorenz number L by: $L = \frac{\pi^2}{3} \times \left(\frac{k_B}{q}\right)^2 = 2.4429637 \left(\frac{W\times ohm}{K^2}\right) = 2.4429637 \times 10^{-8}\ (V^2 \times K^{-2})$, then the well-known Wiedemann-Frank law states that the ratio, $\frac{\sigma_{Th.O[E]}}{\sigma_{O[E]]}}$, due to the O-EP [E-OP], is proportional to the temperature T(K), as: $\frac{\sigma_{Th.O[E]}(N^*, r_{d(a)}, x, T)}{\sigma_{O[E]}(N^*, r_{d(a)}, x, T)} = L \times T.$ (21)

Further, the resistivity is found to be given by: $\rho_{O[E]}(N^*, r_{d(a)}, x, T) \equiv 1/\sigma_{O[E]}(N^*, r_{d(a)}, x, T)$, noting again that $N^* \equiv N - N_{CDn(NDp)}(r_{d(a)}, x)$.

In Eq. (20a), one notes that at T= 0 K, $\sigma_{O[E]}(N^*, r_{d(a)}, x, T)$ is proportional to $E^2_{Fno(Fpo)}$, or to $(N^*)^{\frac{4}{3}}$. Thus, from Eq. (21), one has: $\sigma_{O[E]}(N^* = 0, r_{d(a)}, x, T = 0K) = 0$ and also $\sigma_{Th.\ O[E]}(N^* = 0, r_{d(a)}, x, T = 0K) = 0$ at $N^* = 0$, at which the MIT occurs.

**New Optical [Electrical] Coefficients**

The relaxation time $\tau_{O[E]}$ is related to $\sigma_{O[E]}$ by [1]:

$\tau_{O[E]}(N^*, r_{d(a)}, x, T) \equiv \sigma_{O[E]}(N^*, r_{d(a)}, x, T) \times \frac{m^*_{n(p)}(x)\times m_o}{q^2\times(N^*/g_{c(v)})}$. Therefore, the mobility $\mu_{O[E]}$ is given by:

$$\mu_{O[E]]}\left(N^*, r_{d(a)}, x, T\right) = \frac{q\times\tau_{O[E]}(N^*, r_{d(a)}, x, T)}{m^*_{n(p)}(x)\times m_o} = \frac{\sigma_{O[E]}(N^*, r_{d(a)}, x, T)}{q\times(N^*/g_{c(v)})} \left(\frac{cm^2}{V\times s}\right). \quad (22a)$$

Here, for $T \geq 0$ K, one notes that, as given in Eq. (18), both $\mu_{O[E]]}$ and $\sigma_{O[E]}$, expressed in terms of $G_2(y) = \left(1 + \frac{y^2}{3}\right) \equiv G_2(N, r_{d(a)}, x, T)$, with $y \equiv \frac{\pi}{\xi_{n(p)}}$, $\xi_{n(p)} = \xi_{n(p)}\left(N^*, r_{d(a)}, x, T\right)$, thus increase (or decrease), **with increasing T (or decreasing T)**, respectively, for given $(N, r_{d(a)}, x)$, since the reduced Fermi energy $\xi_{n(p)}$ **decreases (or increases)**.

Then, from the idea of Stokes, Einstein, Sutherland and Reynolds, we can define our viscosity coefficient, $\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$, and its reduced one, $R\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$, by:

$$\frac{\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)}{q} \equiv \frac{1}{6\pi \times \mu_{O[E]]}(N^*, r_{d(a)}, x, T) \times R_{WS}(N^*, x)} \left(\frac{V}{cm} \times \frac{s}{cm^2}\right) \quad , \quad R\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T) \equiv \frac{\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)}{\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T=0K)}, \quad (22b)$$

where $R_{WS}(N^*, x) \equiv \left(\frac{3g_{c(v)}(x)}{4\pi N^*}\right)^{1/3}$ is the effective Wigner-Seitz radius. Therefore, as noted above, for given $(N, r_{d(a)}, x)$, and **with increasing T (or decreasing T)**, $\mathbb{V}_{O[E]}$ thus decreases (or increases), since $\mu_{O[E]]}$ increases (or decreases), giving raise to: $\mathbf{R\mathbb{V}_{O[E]} \leq 1}$, in good agreement with observed results, obtained in liquids by Ewell and Eyring.[17] and in complex fluids by Wenhao.[18]

Then, taking into account above remarks, it is interesting to define the activation energy, $AE_{O[E]}(N^*, r_{d(a)}, x, T)$, as.[17] by:

$$AE_{O[E]}\left(N^*, r_{d(a)}, x, T\right) \equiv k_B T \times Ln\left(R\mathbb{V}_{O[E]}\left(N^*, r_{d(a)}, x, T\right)\right) \leq 0 \text{ eV}, \quad (22c)$$

according to the reduced activation energy, $RAE_{O[E]}\left(N^*, r_{d(a)}, x, T\right)$, defined by:

$$RAE_{O[E]}\left(N^*, r_{d(a)}, x, T\right) \equiv \frac{AE_{O[E]}(N^*, r_{d(a)}, x, T)}{k_B T} \equiv Ln\left(R\mathbb{V}_{O[E]}\left(N^*, r_{d(a)}, x, T\right)\right) \leq 0.$$

Furthermore, the Hall factor is defined by:

$$r_{HO[HE]}(N^*, r_{d(a)}, x, T) \equiv \frac{\langle \tau_{O[E]}{}^2 \rangle_{FDDF}}{\left[\langle \tau_{O[E]} \rangle_{FDDF}\right]^2} = \frac{G_4(y)}{[G_2(y)]^2}, \; y \equiv \frac{\pi}{\xi_{n(p)}(N^*, r_{d(a)}, x, T)} = \frac{\pi k_B T}{E_{Fn(Fp)}(N^*, r_{d(a)}, x, T)}, \text{ and}$$

therefore, the Hall mobility yields:

$$\mu_{HO[HE]}\left(N^*, r_{d(a)}, x, T\right) \equiv \mu_{O[E]}\left(N^*, r_{d(a)}, x, T\right) \times r_{HO[HE]}\left(N^*, r_{d(a)}, x, T\right) \left(\frac{cm^2}{V \times s}\right), \quad (23)$$

noting that, at T=0K, since $r_{HE[HO]}(N^*, r_{d(a)}, x, T) = 1$, one therefore gets: $\mu_{HO[HE]}(N^*, r_{d(a)}, x, T) \equiv \mu_{O[E]}(N^*, r_{d(a)}, x, T)$.

**Our relation between the diffusion, mobility, and viscosity**

By taking into account Equations (22a, 22b), our relation is found to be defined by [1]:

$$\mathbb{R}_{E[O]}\left(N^*, r_{d(a)}, x, T\right) \equiv \frac{D_{O[E]}\left(N^*, r_{d(a)}, x, T\right)}{\mu_{O[E]}\left(N^*, r_{d(a)}, x, T\right)} \equiv D_{O[E]}\left(N^*, r_{d(a)}, x, T\right) \times \frac{\mathbb{V}_{O[E]}\left(N^*, r_{d(a)}, x, T\right)}{q} \times$$

$$6\pi \times R_{WS}(N^*, x) \equiv \frac{N^*}{q} \times \frac{dE_{Fn(Fp)}}{dN^*} \equiv \frac{k_B \times T}{q} \times \left(u \frac{d\xi_{n(p)}(u)}{du}\right) = \sqrt{\frac{3 \times L}{\pi^2}} \times T \times \left(u \frac{d\xi_{n(p)}(u)}{du}\right),$$

$$\frac{k_B}{q} = \sqrt{\frac{3 \times L}{\pi^2}}, \quad (24)$$

where $D_{E[O]}\left(N^*, r_{d(a)}, x, T\right)$ is the diffusion coefficient, $\xi_{n(p)}(u)$ is defined in Eq. (11), the mobility $\mu_{O[E]}\left(N^*, r_{d(a)}, x, T\right)$ is determined in Eq. (22a), and finally the viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$ is defined in Eq. (22b). Then, by differentiating this function $\xi_{n(p)}(u) \equiv \frac{E_{Fn(Fp)}(u)}{k_B T} = \frac{G(u)+Au^B F(u)}{1+Au^B} \equiv \frac{V(u)}{W(u)}$, with respect to u, being defined in Eq. (11), one thus obtains $\frac{d\xi_{n(p)}(u)}{du}$.

Therefore, Eq. (24) can also be rewritten as: $\mathbb{R}_{E[O]}(u) = \frac{k_B \times T}{q} \times u \frac{V'(u) \times W(u) - V(u) \times W'(u)}{W^2(u)}$

where $W'(u) = ABu^{B-1}$ and $V'(u) = u^{-1} + 2^{-\frac{3}{2}} e^{-du}(1 - du) + \frac{2}{3} Au^{B-1} F(u) \left[\left(1 + \frac{3B}{2}\right) + \frac{4}{3} \times \frac{bu^{-\frac{4}{3}} + 2cu^{-\frac{8}{3}}}{1 + bu^{-\frac{4}{3}} + cu^{-\frac{8}{3}}}\right]$.

One remarks that: (i) as $u \to 0$, one has: $W^2 \simeq 1$ and $u[V' \times W - V \times W'] \simeq 1$, and therefore: $\mathbb{R}_{E[O]}(u \to 0) \simeq \frac{k_B \times T}{q}$, being a well-known relation given by Stokes, Einstein, Sutherland and Reynolds, and (ii) as $u \to \infty$, one has: $W^2 \approx A^2 u^{2B}$ and $u[V' \times W - V \times W'] \approx \frac{2}{3} a u^{2/3} A^2 u^{2B}$, and therefore, in this **highly degenerate case** and at T=0K, our relation (24) is reduced to: $\mathbb{R}_{E[O]}\left(N^*, r_{d(a)}, x, T = 0K\right) \approx \frac{2}{3} E_{Fno(Fpo)}(N^*)/q$. In other words, **Eq. (24) verifies all the correct limiting conditions**.

Furthermore, in the present degenerate case ($u \gg 1$), Eq. (24) can be rewritten as:

$$\mathbb{R}_{E[O](VC)}\left(N^*, r_{d(a)}, x, T = 0K\right) \simeq \frac{2}{3} \times \frac{E_{Fno(Fpo)}(u)}{q} \times \left[1 + \frac{4}{3} \times \frac{\left(bu^{-\frac{4}{3}} + 2cu^{-\frac{8}{3}}\right)}{\left(1 + bu^{-\frac{4}{3}} + cu^{-\frac{8}{3}}\right)}\right],$$

where $a = \left[3\sqrt{\pi}/4\right]^{2/3}$, $b = \frac{1}{8}\left(\frac{\pi}{a}\right)^2$ and $c = \frac{62.3739855}{1920}\left(\frac{\pi}{a}\right)^4$.

Then, in Tables 3n and 3p, reported in Appendix 1, for given ($r_d$, x and T), the numerical results of $\mathbb{V}_{O[E]}$, $\mu_{O[E]}$ and $D_{O[E]}$, expressed respectively in $\left(\frac{eV}{cm}\times\frac{s}{cm^2},\frac{10^{3[4]}\times cm^2}{V\times s},\frac{10^3\times cm^2}{s}\right)$, as functions of N, are obtained by using Equations (22b, 22a and 24).

In Tables 4n and 4p, reported in Appendix 1, the numerical results of the viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$, expressed in $\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$, are obtained by using Eq. (22b).

In Tables 5n and 5p, reported in Appendix 1, the numerical results of reduced Fermi energy $\xi_{nO[E]}(N^*, r_{d(a)}, x, T)$, mobility $\mu_{O[E]}(N^*, r_{d(a)}, x, T$, diffusion coefficient $D_{O[E]}(N^*, r_{d(a)}, x, T$, viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$, and activation energy $AE_{O[E]}(N^*, r_{d(a)}, x, T)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively.

Finally, in Tables 6n and 6p, For given x, $r_a$, T and N, the numerical results of reduced Fermi energy $\xi_{pO[E]}(N^*, r_{d(a)}, x, T)$, mobility $\mu_{O[E]}(N^*, r_{d(a)}, x, T)$, diffusion coefficient $D_{O[E]}(N^*, r_{d(a)}, x, T)$, viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$, and activation energy $AE_{O[E]}(N^*, r_{d(a)}, x, T)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively.

## CONCLUDING REMARKS

In the $\mathbf{n^+(p^+)-X(x)}$-crystalline alloy, $0 \le x \le 1$, x being the concentration, the diffusion-mobility-activation energy-Fermi energy relations, enhanced by: **(i)** the optico-electrical phenomenon (O-EP) and the electro-optical phenomenon (E-OP), **(ii)** our static dielectric constant law, $\varepsilon(r_{d(a)}, x)$, $r_{d(a)}$ being the donor (acceptor) d(a)-radius, given in Equations (1a, 1b), **(iii)** our accurate reduced Fermi energy, $\xi_{n(p)}$, given in Eq. (11), accurate with a precision of the order of $\mathbf{2.11\times10^{-4}}$ [9] and finally **(iv)** our optical-and-electrical conductivity models, given in Eq. (18, 20a), are now investigated by basing on our physical model and Fermi-Dirac distribution function, as those given in our recent works.[1,5]

Some important concluding remarks can be given and discussed as follows.

**(I)**- Then, in Tables 3n and 3p, reported in Appendix 1, for given x, $r_{d(a)}$, and T=(4.2 K and 77 K [300K]), the numerical results of $\mathbb{V}_{O[E]}$, $\mu_{O[E]}$ and $D_{O[E]}$, expressed respectively in $\left(\frac{eV}{cm}\times\frac{s}{cm^2},\frac{10^{3[4]}\times cm^2}{V\times s},\frac{10^3\times cm^2}{s}\right)$, as functions of N, are obtained by using Equations (22b, 22a and 24). In particular, for given (x, $r_{d(a)}$ and N), those of $\mu_{O[E]}(T)$ decrease [decrease] with decreasing T, due to the increasing reduced Fermi energy $\xi_{nO[E]}$. Further, for given (x, $r_{d(a)}$

and N) the numerical results of $\mathbb{V}_{O[E]}$ increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao,[18] and for given (x, T and $r_{d(a)}$) they increase with increasing N, in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, with increasing degeneracy (or with decreasing T and increasing N), both the reduced Fermi energy $\xi_{nO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

In Tables 4n and 4p, the numerical results of the viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$, expressed in $\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$, are obtained by using Eq. (22b), suggesting that: (i) for given (x, T and N), they increase with increasing $r_{d(a)}$, (ii) for given (x, $r_{d(a)}$ and N) the numerical results of $\mathbb{V}_{O[E]}$ increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao.[18] and (iii) for given (x, T and $r_{d(a)}$) they increase with increasing N, in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, with increasing degeneracy (or with decreasing T and increasing N), both the reduced Fermi energy $\xi_{n(p)O[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

In Tables 5n and 5p, reported in Appendix 1, the numerical results of reduced Fermi energy $\xi_{nO[E]}(N^*, r_{d(a)}, x, T)$, mobility $\mu_{O[E]}(N^*, r_{r_{d(a)}}, x, T)$, diffusion coefficient $D_{O[E]}(N^*, r_{d(a)}, x, T)$, viscosity coefficient $\mathbb{V}_{O[E]}\left(N^*, r_{d(a)}, x, T\right)$, and activation energy $AE_{O[E]}\left(N^*, r_{r_{d(a)}}, x, T\right)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively. In particular, from the numerical results of $\mathbb{V}_{O[E]}$, one notes that, for given (x, $r_{d(a)}$ and N), they increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao.[18] In other words, with increasing degeneracy, both the reduced Fermi energy $\xi_{nO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

Finally, in Tables 6n and 6p, For given x, $r_a$, T and N, the numerical results of reduced Fermi energy $\xi_{pO[E]}(N^*, r_{d(a)}, x, T)$, mobility $\mu_{O[E]}(N^*, r_{d(a)}, x, T)$, diffusion coefficient $D_{O[E]}(N^*, r_{d(a)}, x, T)$, viscosity coefficient $\mathbb{V}_{O[E]}\left(N^*, r_{d(a)}, x, T\right)$, and activation energy $AE_{O[E]}\left(N^*, r_{d(a)}, x, T\right)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively.

In particular, from the numerical results of $\mathbb{V}_{O[E]}(N^*, r_{d(a)}, x, T)$, one observes that, for given (x, $r_{d(a)}$ and T), they increase with increasing N, in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, with increasing degeneracy, both the reduced Fermi energy $\xi_{n(p)O[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

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## APPENDIX 1

**Table 1:** In the $\boldsymbol{X(x) \equiv GaTe_{1-x}As_x}$-crystalline alloy, the different values of energy-band-structure parameters, for a given x, are given in the following.[3]

In the **X(x)-crystalline alloy**, in which $r_{do(ao)} = r_{\mathbf{Te(Ga)}} = 0.132$ nm (0.126 nm), we have [3]: $g_{c(v)}(x) = 1 \times x + 1 \times (1 - x) = 1$ , $m_{c(v)}(x)/m_o = 0.066\ (0.291) \times x + 0.209\ (0.4) \times (1 - x)$ , $\varepsilon_o(x) = 13.13 \times x + 12.3 \times (1 - x)$, $E_{go}(x) = 1.52 \times x + 1.796 \times (1 - x)$.

**Table 2:** Expressions for $G_{p>1}(y \equiv \frac{\pi}{\xi_{n(p)}})$, due to the Fermi-Dirac distribution function, are used to determine the electrical-and-thermoelectric coefficients, suggesting that, for given $(N^*, r_d, x)$, since $\xi_{n(p)}(N^*, r_d, x, T)$ decreases with increasing T, $G_{p>1}(T)$ increases.

| $G_{3/2}(y)$ | $G_2(y)$ | $G_{5/2}(y)$ | $G_3(y)$ | $G_{7/2}(y)$ | $G_4(y)$ | $G_{9/2}(y)$ |
|---|---|---|---|---|---|---|
| $\left(1 + \frac{y^2}{8} + \frac{7y^4}{640}\right)$ | $\left(1 + \frac{y^2}{3}\right)$ | $\left(1 + \frac{5y^2}{8} - \frac{7y^4}{384}\right)$ | $(1 + y^2)$ | $\left(1 + \frac{35y^2}{24} + \frac{49y^4}{384}\right)$ | $\left(1 + 2y^2 + \frac{7y^4}{15}\right)$ | $\left(1 + \frac{21y^2}{8} + \frac{147y^4}{128}\right)$ |

**Table 3n:** For given x, $r_d$, and T=(4.2 K and 77 K), the numerical results of $\mathbb{V}_{O[E]}$, $\mu_{O[E]}$ and $D_{O[E]}$, expressed respectively in $\left(\frac{eV}{cm} \times \frac{s}{cm^2}, \frac{10^3 \times cm^2}{V \times s}, \frac{10^3 \times cm^2}{s}\right)$, as functions of N, are obtained by using Equations (22b, 22a and 24). In particular, for given (x, $r_d$ and N), those of $\mu_{O[E]}(T)$ decrease [decrease] with decreasing T, due to the increasing reduced Fermi energy $\xi_{nO[E]}$ (or with increasing degeneracy), and therefore, those of the viscosity coefficient $\mathbb{V}_{O[E]}$ increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao.[18] Further, for given (x, T and $r_d$), those of $\mathbb{V}_{O[E]}$ increase with increasing N, due to the increasing reduced Fermi energy $\xi_{nO[E]}$ (or with increasing degeneracy), in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, with increasing degeneracy (or with decreasing T and increasing N), both $\xi_{nO[E]}$ and $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| Donor | **Te** | Sb |
|---|---|---|
| $r_d$ (nm) ↗ | **0.132** | 0.136 |
| For x=0 and at T=4.2 K | | |
| N ($10^{19}$ $cm^{-3}$) | | |
| 3 | 90.54 [180.3], 2.918 [1.466], 0.493 [0.163] | 91.17 [181.4], 2.897 [1.456], 0.489 [0.161] |
| 7 | 130.9 [267.2], 2.685 [1.316], 0.803 [0.259] | 131.9 [269.0], 2.666 [1.307], 0.798 [0.257] |
| 10 | 152.2 [313.3], 2.604 [1.265], 0.990 [0.316] | 153.3 [315.5], 2.585 [1.256], 0.982 [0.313] |
| For x=0 and at T=77 K | | |
| N ($10^{19}$ $cm^{-3}$) | | |
| 3 | 25.65 [12.01], 10.30 [22.00], 1.739 [2.437] | 25.83 [12.08], 10.23 [21.86], 1.727 [2.421] |

| | | |
|---|---|---|
| 7 | 72.51 [48.97], 4.849 [7.180], 1.450 [1.410] | 73.03 [49.30], 4.814 [7.131], 1.440 [1.401] |
| 10 | 101.5 [83.32], 3.903 [4.756], 1.483 [1.187] | 102.2 [83.90], 3.875 [4.723], 1.473 [1.179] |
| For x=0.5 and at T=4.2 K | | |
| N ($10^{19}$ $cm^{-3}$) | | |
| 3 | 48.53 [86.33], 5.467 [3.073], 1.300 [0.523] | 48.89 [86.94], 5.427 [3.052], 1.291 [0.519] |
| 7 | 68.88 [124.2], 5.114 [2.835], 2.143 [0.850] | 69.39 [125.1], 5.076 [2.815], 2.128 [0.844] |
| 10 | 79.58 [144.2], 4.986 [2.751], 2.652 [1.047] | 80.17 [145.3], 4.949 [2.731], 2.632 [1.039] |
| For x=0.5 and at T=77 K | | |
| N ($10^{19}$ $cm^{-3}$) | | |
| 3 | 13.93 [5.857], 19.04 [45.30], 4.528 [7.702] | 14.03 [5.898], 18.91 [44.98], 4.496 [7.648] |
| 7 | 38.28 [22.92], 9.202 [15.36], 3.856 [4.606] | 38.56 [23.09], 9.133 [15.25], 3.828 [4.573] |
| 10 | 53.18 [38.52], 7.461 [10.30], 3.968 [3.918] | 53.58 [38.80], 7.405 [10.22], 3.938 [3.890] |
| For x=1 and at T=4.2 K | | |
| N ($10^{19}$ $cm^{-3}$) | | |
| 3 | 15.65 [22.64], 16.97 [11.73], 7.401 [4.171] | 15.77 [22.81], 16.84 [11.65], 7.345 [4.140] |
| 7 | 21.83 [31.70], 16.15 [11.12], 12.39 [6.952] | 21.99 [31.94], 16.03 [11.03], 12.29 [6.899] |
| 10 | 25.07 [36.46], 15.83 [10.88], 15.41 [8.635] | 25.26 [36.74], 15.71 [10.80], 15.29 [8.570] |
| For x=1 and at T=77 K | | |
| N ($10^{19}$ $cm^{-3}$) | | |
| 3 | 4.513 [1.545], 58.87 [171.9], 25.66 [61.09] | 4.548 [1.557], 58.42 [170.6], 25.47 [60.63] |
| 7 | 12.14 [5.863], 29.02 [60.11], 22.26 [37.59] | 12.24 [5.907], 28.80 [59.66], 22.09 [37.31] |
| 10 | 16.76 [9.752], 23.68 [40.70], 23.04 [32.29] | 16.89 [9.827], 23.50 [40.39], 22.87 [32.04] |

**Table 3p:** For given x, $r_a$, and T=(4.2 K and 300 K), the numerical results of $\mathbb{V}_{O[E]}$, $\mu_{O[E]}$ and $D_{O[E]}$, expressed respectively in $\left(\frac{eV}{cm}\times\frac{s}{cm^2},\frac{10^4\times cm^2}{V\times s},\frac{10^3\times cm^2}{s}\right)$, as functions of N, are obtained by using Equations (22b, 22a and 24). In particular, for given (x, $r_a$ and N), those of $\mu_{O[E]}(T)$ decrease [decrease] with decreasing T, due to the increasing reduced Fermi energy $\xi_{pO[E]}$ (or with increasing degeneracy), and therefore, those of the viscosity coefficient $\mathbb{V}_{O[E]}$ increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao.[18] Further, for given (x, T and $r_a$), those of $\mathbb{V}_{O[E]}$ increase with increasing N, due to the increasing reduced Fermi energy $\xi_{pO[E]}$ (or with increasing degeneracy), in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, with increasing degeneracy (or with decreasing T and increasing N), both $\xi_{pO[E]}$ and $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| Acceptor | Mg | In |
|---|---|---|
| $r_a$ (nm) ↗ | 0.140 | 0.144 |

For x=0 and at T=4.2 K

| N ($10^{19}$ $cm^{-3}$) | | |
|---|---|---|
| 3 | 93.53 [477.2], 0.270 [0.053], 0.417 [0.028] | 98.24 [495.2], 0.255 [0.051], 0.389 [0.026] |
| 5 | 120.4 [648.9], 0.254 [0.047], 0.575 [0.037] | 127.1 [677.8], 0.240 [0.045], 0.539 [0.035] |
| 10 | 164.9 [947.6], 0.237 [0.041], 0.879 [0.052] | 174.8 [995.3], 0.223 [0.039], 0.825 [0.050] |

For x=0 and at T=300 K

| N ($10^{19}$ $cm^{-3}$) | | |
|---|---|---|
| 3 | 87.18 [364.0], 0.290 [0.069], 0.439 [0.052] | 91.41 [378.3], 0.274 [0.066], 0.411 [0.049] |
| 5 | 116.5 [509.8], 0.262 [0.060], 0.590 [0.047] | 122.9 [531.4], 0.248 [0.057], 0.553 [0.045] |
| 10 | 162.9 [855.3], 0.240 [0.046], 0.887 [0.057] | 172.6 [897.8], 0.226 [0.043], 0.833 [0.054] |

For x=0.5 and at T=4.2 K

| N ($10^{19}$ $cm^{-3}$) | | |
|---|---|---|
| 3 | 51.62 [384.7], 0.500 [0.067], 1.126 [0.043] | 54.57 [401.9], 0.471 [0.064], 1.055 [0.041] |
| 5 | 64.86 [509.6], 0.477 [0.061], 1.548 [0.056] | 68.75 [534.7], 0.450 [0.058], 1.452 [0.053] |
| 10 | 87.02 [726.8], 0.452 [0.054], 2.368 [0.081] | 92.45 [765.7], 0.425 [0.051], 2.223 [0.076] |

For x=0.5 and at T=300 K

| N ($10^{19}$ $cm^{-3}$) | | |
|---|---|---|
| 3 | 49.93 [290.0], 0.517 [0.089], 1.156 [0.070] | 52.76 [302.9], 0.488 [0.085], 1.083 [0.067] |
| 5 | 63.82 [423.4], 0.485 [0.073], 1.568 [0.065] | 67.64 [443.7], 0.457 [0.070], 1.470 [0.062] |
| 10 | 86.48 [674.1], 0.455 [0.058], 2.379 [0.085] | 91.87 [709.9], 0.428 [0.055], 2.233 [0.081] |

For x=1 and at T=4.2 K

| N ($10^{19}$ $cm^{-3}$) | | |
|---|---|---|
| 3 | 16.99 [291.6], 1.540 [0.090], 6.513 [0.070] | 18.05 [306.2], 1.447 [0.085], 6.100 [0.066] |
| 5 | 20.95 [378.7], 1.490 [0.082], 8.972 [0.092] | 22.28 [398.8], 1.400 [0.078], 8.410 [0.087] |
| 10 | 27.61 [529.4], 1.431 [0.075], 13.80 [0.133] | 29.39 [559.2], 1.343 [0.071], 12.95 [0.126] |

For x=1 and at T=300 K

| N ($10^{19}$ $cm^{-3}$) | | |
|---|---|---|
| 3 | 16.83 [229.5], 1.554 [0.114], 6.562 [0.090] | 17.88 [240.8], 1.461 [0.108], 6.146 [0.086] |
| 5 | 20.85 [331.8], 1.497 [0.094], 9.005 [0.101] | 22.17 [349.3], 1.406 [0.089], 8.441 [0.096] |
| 10 | 27.56 [502.1], 1.434 [0.079], 13.82 [0.139] | 29.34 [530.3], 1.346 [0.074], 12.96 [0.131] |

**Table 4n:** The numerical results of the viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_d, x, T)$, expressed in $\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$, are obtained by using Eq. (22b), suggesting that: (i) for given (x, T and N), they increase with increasing $r_d$, (ii) for given (x, $r_d$ and N) the numerical results of $\mathbb{V}_{O[E]}$ increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao,[18] and (iii) for given (x, T and $r_d$) they increase with increasing N, in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, as discussed in above Table 3n, with increasing degeneracy (or with decreasing T and increasing N), both the reduced Fermi energy $\xi_{nO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| Donor | P | **Te** | Sb | Sn |
|---|---|---|---|---|
| $r_d$ (nm) [4] ↗ | 0.110 | **0.132** | 0.136 | 0.140 |
| For x=0 and at T=4.2 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 72.69 [146.5] | 90.54 [180.2] | 91.17 [181.4] | 93.10 [185.0] |
| 7 | 104.3 [214.9] | 130.9 [267.2] | 131.9 [269.0] | 134. 7 [274.6] |
| 10 | 120.9 [251.2] | 152.2 [313.3] | 153.3 [315.5] | 156.7 [322.2] |
| For x=0 and at T=77 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 20.70 [9.826] | 25.65 [12.01] | 25.83 [12.08] | 26.35 [12.31] |
| 7 | 57.85 [39.49] | 72.51 [48.97] | 73.03 [49.30] | 74.61 [50.31] |
| 10 | 80.74 [66.91] | 101.5 [83.32] | 102.2 [83.90] | 104.5 [85.66] |
| For x=0.5 and at T=4.2 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 38.59 [69.12] | 48.53 [86.33] | 48.89 [86.94] | 49.97 [88.80] |
| 7 | 54.51 [98.85] | 68.88 [124.2] | 69.39 [125.1] | 70.96 [127.9] |
| 10 | 62.88 [114.5] | 79.58 [144.2] | 80.17 [145.3] | 82.00 [148.5] |
| For x=0.5 and at T=77 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 11.09 [4.698] | 13.93 [5.857] | 14.03 [5.898] | 14.34 [6.023] |
| 7 | 30.31 [18.25] | 38.28 [22.92] | 38.56 [23.09] | 39.43 [23.59] |
| 10 | 42.03 [30.59] | 53.18 [38.52] | 53.58 [38.80] | 54.80 [39.66] |
| For x=1 and at T=4.2 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 12.34 [17.88] | 15.65 [22.64] | 15.77 [22.81] | 16.14 [23.33] |
| 7 | 17.16 [24.97] | 21.83 [31.70] | 21.99 [31.94] | 22.51 [32.68] |
| 10 | 19.69 [28.69] | 25.07 [36.46] | 25.26 [36.74] | 25.85 [37.60] |

For x=1 and at T=77 K

| N ($10^{19}$ $cm^{-3}$) | | | | |
|---|---|---|---|---|
| 3 | 3.558 [1.221] | 4.513 [1.545] | 4.548 [1.557] | 4.652 [1.593] |
| 7 | 9.550 [4.617] | 12.14 [5.863] | 12.24 [5.907] | 12.52 [6.044] |
| 10 | 13.17 [7.673] | 16.76 [9.752] | 16.89 [9.827] | 17.29 [10.05] |

**Table 4p:** The numerical results of the viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_a, x, T)$, expressed in $\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$, are obtained by using Eq. (22b), suggesting that: (i) for given (x, T and N), they increase with increasing $r_a$, (ii) for given (x, $r_a$ and N) the numerical results of $\mathbb{V}_{O[E]}$ increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao.[18] and (iii) for given (x, T and $r_a$) they increase with increasing N, in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, as discussed in above Table 3p, with increasing degeneracy (or with decreasing T and increasing N), both the reduced Fermi energy $\xi_{pO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| **Acceptor** | **Ga** | Mg | In | Cd |
|---|---|---|---|---|
| $r_a$ (nm) ↗ | **0.126** | 0.140 | 0.144 | 0.148 |
| For x=0 and at T=4.2 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 86.20 [448.1] | 93.53 [477.2] | 98.24 [495.2] | 103.9 [516.4] |
| 5 | 110.2 [603.7] | 120.4 [648.9] | 127.1 [677.8] | 135.4 [712.8] |
| 10 | 150.1 [874.4] | 164.9 [947.6] | 174.8 [995.3] | 187.1 [1054] |
| For x=0 and at T=300 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 80.53 [341.0] | 87.18 [364.0] | 91.41 [378.3] | 96.49 [395.3] |
| 5 | 106.7 [475.7] | 116.5 [509.8] | 122.9 [531.4] | 130.8 [557.3] |
| 10 | 148.3 [789.9] | 162.9 [855.3] | 172.6 [897.8] | 184.8 [950.1] |
| For x=0.5 and at T=4.2 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 47.15 [357.7] | 51.62 [384.7] | 54.57 [401.9] | 58.24 [422.8] |
| 5 | 59.01 [471.0] | 64.86 [509.6] | 68.75 [534.7] | 73.63 [565.6] |
| 10 | 78.91 [667.6] | 87.02 [726.8] | 92.45 [765.7] | 99.30 [814.0] |
| For x=0.5 and at T=300 K | | | | |
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 45.62 [269.9] | 49.93 [290.0] | 52.76 [302.9] | 56.26 [318.5] |
| 5 | 58.07 [391.9] | 63.82 [423.4] | 67.64 [443.7] | 72.43 [468.6] |
| 10 | 78.42 [619.4] | 86.48 [674.1] | 91.87 [709.9] | 98.68 [754.4] |

| For x=1 and at T=4.2 K | | | | |
|---|---|---|---|---|
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 15.41 [269.2] | 16.99 [291.6] | 18.05 [306.2] | 19.38 [324.2] |
| 5 | 18.96 [348.1] | 20.95 [378.7] | 22.28 [398.8] | 23.96 [423.7] |
| 10 | 24.95 [484.4] | 27.61 [529.4] | 29.39 [559.2] | 31.66 [596.4] |

| For x=1 and at T=300 K | | | | |
|---|---|---|---|---|
| N ($10^{19}$ $cm^{-3}$) | | | | |
| 3 | 15.27 [212.2] | 16.83 [229.5] | 17.88 [240.8] | 19.19 [254.5] |
| 5 | 18.87 [305.2] | 20.85 [331.8] | 22.17 [349.3] | 23.85 [370.9] |
| 10 | 24.90 [459.5] | 27.56 [502.1] | 29.34 [530.3] | 31.60 [565.5] |

**Table 5n:** For given x, $r_d$ , T=[3K, 80K, 300K] and N= [N1= $9.4754 \times 10^{18}$ $cm^{-3}$, N2 = $5.5834 \times 10^{18}$ $cm^{-3}$, N3 = $2.215085 \times 10^{18}$ $cm^{-3}$], the numerical results of reduced Fermi energy $\xi_{nO[E]}(N^*, r_d, x, T)$, mobility $\mu_{O[E]}(N^*, r_d, x, T)$ , diffusion coefficient $D_{O[E]}(N^*, r_d, x, T)$ , viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_d, x, T)$, and activation energy $AE_{O[E]}(N^*, r_d, x, T)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively. In particular, from the numerical results of $\mathbb{V}_{O[E]}(N^*, r_d, x, T)$, one observes that, for given (x, $r_d$ and N), they increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao.[18] In other words, as discussed in above Table 3n, with increasing degeneracy, both the reduced Fermi energy $\xi_{nO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| Donor | | Te | Sb | Sn |
|---|---|---|---|---|
| For **x=0** and **N=N1=$9.4754 \times 10^{18}$ $cm^{-3}$**, | | | | |
| $\xi_{nO[E](T=3K)}$ | ↘ | **443.181 [291.090]** | **442.967 [290.950]** | **442.306 [290.515]** |
| $\xi_{nO[E](T=80K)}$ | ↘ | 16.694 [11.031] | 16.686 [11.026] | 16.661 [11.009] |
| $\xi_{nO[E](T=300K)}$ | ↘ | 4.6738 [2.783] | 4.6716 [2.781] | 4.6648 [2.775] |
| $\mu_{O[E](3K)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ | ↘ | 0.0336 [0.0176] | 0.0334 [0.0175] | 0.0328 [0.0172] |
| $\mu_{O[E](80K)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ | ↘ | 0.5240 [1.4540] | 0.5210 [1.4467] | 0.5123 [1.4250] |
| $\mu_{O[E](300K)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ | ↘ | 112.46 [261.26] | 111.84 [259.82] | 109.99 [255.54] |
| $D_{O[E](3K)}\left(\frac{10^4 \times cm^2}{s}\right)$ | ↘ | 0.0257 [0.00885] | 0.0255 [0.00879] | 0.0250 [0.00862] |
| $D_{O[E](80K)}\left(\frac{10^4 \times cm^2}{s}\right)$ | ↘ | 0.3984 [0.7215] | 0.3959 [0.7175] | 0.3887 [0.7057] |
| $D_{O[E](300K)}\left(\frac{10^4 \times cm^2}{s}\right)$ | ↘ | 88.524 [187.83] | 88.017 [186.70] | 86.519 [183.34] |
| $\mathbb{V}_{O[E]\,(3K)}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ | ↗ | **52.786 [100.66]** | **53.120 [101.24]** | **54.137 [103.01]** |
| $\mathbb{V}_{O[E]\,(80K)}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ | ↗ | 3.3900 [1.2216] | 3.4084 [1.2275] | 3.4638 [1.2452] |
| $\mathbb{V}_{O[E]\,(300K)}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ | ↗ | 0.0158 [0.006799] | 0.0159 [0.00683] | 0.0161 [0.00694] |
| $-AE_{O[E](3K)}$ (meV$\times 10^{-6}$) | ↗ | 5.989 [18.645] | 5.995 [18.663] | 6.013 [18.719] |

| | | | |
|---|---|---|---|
| $-AE_{O[E](80K)}$ (meV) ↗ | 18.9266 [30.413] | 18.9329 [30.420] | 18.9524 [30.441] |
| $-AE_{O[E](300K)}$ (meV) ↗ | 209.773 [248.25] | 209.798 [248.26] | 209.877 [248.30] |

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For **x=0.5** and **N=N2=5.5834 × $10^{18}$ $cm^{-3}$**, one has:

| | | | |
|---|---|---|---|
| $\xi_{nO[E](T=3K)}$ ↘ | **444.064 [317.65]** | **443.973 [317.58]** | **443.692 [317.38]** |
| $\xi_{nO[E](T=80K)}$ ↘ | 16.727 [12.017] | 16.724 [12.014] | 16.713 [12.007] |
| $\xi_{nO[E](T=300K)}$ ↘ | 4.6829 [3.162] | 4.6819 [3.161] | 4.6790 [3.158] |
| $\mu_{O[E](3K)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 0.0649 [0.0379] | 0.0644 [0.0377] | 0.0631 [0.0370] |
| $\mu_{O[E](80K)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 1.8985 [6.0085] | 1.886 [5.9723] | 1.850 [5.8649] |
| $\mu_{O[E](300K)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 420.60 [1181.01] | 417.92 [1173.7] | 409.96 [1152.0] |
| $D_{O[E](3K)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 0.0496 [0.0208] | 0.0493 [0.0206] | 0.0483 [0.0202] |
| $D_{O[E](80K)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 1.4463 [3.2594] | 1.4368 [3.2391] | 1.4084 [3.1788] |
| $D_{O[E](300K)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 331.30 [910.14] | 329.17 [904.40] | 322.83 [887.35] |
| $\mathbb{V}_{O[E]\,(3K)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | **23.196 [39.667]** | **23.353 [39.920]** | **23.829 [40.690]** |
| $\mathbb{V}_{O[E]\,(80K)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 0.7927 [0.2505] | 0.7978 [0.2519] | 0.8130 [0.2565] |
| $\mathbb{V}_{O[E]\,(300K)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 0.0035 [0.00127] | 0.0036 [0.00128] | 0.0037 [0.0013] |
| $-AE_{O[E](3K)}$ (meV× $10^{-6}$) ↗ | 8.554 [27.890] | 8.557 [27.901] | 8.568 [27.936] |
| $-AE_{O[E](80K)}$ (meV) ↗ | 23.275 [34.917] | 23.278 [34.920] | 23.287 [34.929] |
| $-AE_{O[E](300K)}$ (meV) ↗ | 226.900 [267.46] | 226.911 [267.47] | 226.945 [267.49] |

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For **x=1** and **N=N3=2.215085 × $10^{18}$ $cm^{-3}$**, one has:

| | | | |
|---|---|---|---|
| $\xi_{nO[E](T=3K)}$ ↘ | **443.635 [361.620]** | **443.613 [361.601]** | **443.543 [361.544]** |
| $\xi_{nO[E](T=80K)}$ ↘ | 16.71102 [13.6527] | 16.71018 [13.6521] | 16.70757 [13.6499] |
| $\xi_{nO[E](T=300K)}$ ↘ | 4.6785 [3.7525] | 4.67824 [3.7522] | 4.67752 [3.7515] |
| $\mu_{O[E](3K)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 0.2077 [0.1470] | 0.2062 [0.1460] | 0.2018 [0.1430] |
| $\mu_{O[E](80K)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 19.857 [77.302] | 19.718 [76.773] | 19.306 [75.205] |
| $\mu_{O[E](300K)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 4507.9 [16654] | 4476.4 [16539] | 4382.8 [16200] |
| $D_{O[E](3K)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 0.1588 [0.0916] | 0.1576 [0.0910] | 0.1543 [0.0891] |
| $D_{O[E](80K)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 15.113 [47.842] | 15.007 [47.512] | 14.690 [46.534] |
| $D_{O[E](300K)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 3549.6 [13124] | 3524.7 [13034] | 3450.9 [12767] |
| $\mathbb{V}_{O[E]\,(3K)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | **5.3572 [7.5663]** | **5.3954 [7.6190]** | **5.5120 [7.7798]** |
| $\mathbb{V}_{O[E]\,(80K)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 0.0560 [0.0144] | 0.0564 [0.0145] | 0.0676 [0.0148] |
| $\mathbb{V}_{O[E]\,(300K)}\left(\frac{eV}{cm}\times\frac{s\times10^{-5}}{cm^2}\right)$ ↗ | 24.68 [6.68] | 24.85 [6.73] | 25.38 [6.87] |
| $-AE_{O[E](3K)}$ (meV× $10^{-6}$) ↗ | 21.054 [77.1003] | 21.056 [77.1082] | 21.062 [77.1324] |

| | | | |
|---|---|---|---|
| $-AE_{O[E](80K)}$ (meV) ↗ | 31.43915 [43.1906] | 31.43985 [43.1913] | 31.4420 [43.1935] |
| $-AE_{O[E](300K)}$ (meV) ↗ | 258.14445 [300.859] | 258.14715 [300.861] | 258.1555 [300.867] |

**Table 5p:** For given x, $r_a$, T=[3K, 80K, 300K] and N= [N1= $6.85437 \times 10^{19}$ $cm^{-3}$, N2 = $4.14873 \times 10^{19}$ $cm^{-3}$, N3 = $1.70735 \times 10^{19}$ $cm^{-3}$], the numerical results of reduced Fermi energy $\xi_{pO[E]}(N^*, r_a, x, T)$, mobility $\mu_{O[E]}(N^*, r_a, x, T)$, diffusion coefficient $D_{O[E]}(N^*, r_a, x, T)$, viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_a, x, T)$, and activation energy $AE_{O[E]}(N^*, r_a, x, T)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively. In particular, from the numerical results of $\mathbb{V}_{O[E]}(N^*, r_a, x, T)$, one observes that, for given (x, $r_a$ and N), they increase with decreasing T, in good agreement with those, obtained in liquids by Ewell and Eyring.[17] and complex fluids by Wenhao.[18] In other words, as discussed in above Table 3p, with increasing degeneracy, both the reduced Fermi energy $\xi_{pO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| Acceptor | Ga | Mg | In |
|---|---|---|---|
| **For x=0** and **N=N1=$6.85437 \times 10^{19}$ $cm^{-3}$** one has: | | | |
| $\xi_{pO[E](T=3K)}$ ↘ | **1659.6 [569.556]** | **1648.4 [565.722]** | **1640.5 [562.989]** |
| $\xi_{pO[E](T=80K)}$ ↘ | 62.255 [21.416] | 61.836 [21.273] | 61.538 [21.171] |
| $\xi_{nO[E](T=300K)}$ ↘ | 16.671 [5.918] | 16.560 [5.881] | 16.481 [5.854] |
| $\mu_{O[E](3K)}\left(\frac{10^3 \times cm^2}{V \times s}\right)$ ↘ | 2.7026 [0.4791] | 2.4579 [0.4424] | 2.3181 [0.4213] |
| $\mu_{O[E](80K)}\left(\frac{10^3 \times cm^2}{V \times s}\right)$ ↘ | 2.7066 [0.4852] | 2.4616 [0.4480] | 2.3216 [0.4267] |
| $\mu_{O[E](300K)}\left(\frac{10^3 \times cm^2}{V \times s}\right)$ ↘ | 2.7594 [0.5658] | 2.5103 [0.5235] | 2.3679 [0.4992] |
| $D_{O[E](3K)}\left(\frac{10^2 \times cm^2}{s}\right)$ ↘ | 7.7302 [0.4703] | 6.9831 [0.4313] | 6.5539 [0.4087] |
| $D_{O[E](80K)}\left(\frac{10^2 \times cm^2}{s}\right)$ ↘ | 7.7392 [0.4749] | 6.9913 [0.4356] | 6.5617 [0.4129] |
| $D_{O[E](300K)}\left(\frac{10^2 \times cm^2}{s}\right)$ ↘ | 7.8563 [0.5374] | 7.0985 [0.4939] | 6.6633 [0.4688] |
| $\mathbb{V}_{O[E]_{O[E]\,(3K)}}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ ↗ | **127.18 [717.43]** | **139.37 [774.40]** | **147.42 [811.21]** |
| $\mathbb{V}_{O[E]_{O[E]\,(80K)}}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ ↗ | 126.99 [708.48] | 139.16 [764.60] | 147.20 [800.85] |
| $\mathbb{V}_{O[E]_{O[E]\,(300K)}}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ ↗ | 124.5689 [607.49] | 136.4682 [654.40] | 144.3236 [684.51] |
| $-AE_{O[E]_{O[E]\,(3K)}}$ (meV× $10^{-9}$) ↗ | 0.540 [4.588] | 0.548 [4.650] | 0.553 [4.696] |
| $-AE_{O[E]_{O[E]\,(80K)}}$ (meV) ↗ | 0.01024 [0.087] | 0.01038 [0.088] | 0.01048 [0.089] |
| $-AE_{O[E]_{O[E]\,(300K)}}$ (meV) ↗ | 0.53731 [4.301] | 0.5446 [4.353] | 0.5498 [4.391] |
| **For x=0.5** and **N=N2=$4.14873 \times 10^{19}$ $cm^{-3}$** one has: | | | |
| **$\xi_{pO[E](T=3K)}$** ↘ | **1659.6 [472.457]** | **1648.9 [469.399]** | **1641.2 [467.218]** |
| $\xi_{pO[E](T=80K)}$ ↘ | 62.255 [17.787] | 61.852 [17.673] | 61.565 [17.591] |
| $\xi_{nO[E](T=300K)}$ ↘ | 16.671 [4.970] | 16.564 [4.939] | 16.488 [4.918] |
| $\mu_{O[E](3K)}\left(\frac{10^3 \times cm^2}{V \times s}\right)$ ↘ | 5.3455 [0.682] | 4.8530 [0.629] | 4.5716 [0.599] |

| | | | | |
|---|---|---|---|---|
| $\mu_{O[E](80K)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ | ↘ | 5.3534 [0.694] | 4.8603 [0.6409] | 4.5785 [0.6103] |
| $\mu_{O[E](300K)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ | ↘ | 5.4578 [0.8548] | 4.9563 [0.7907] | 4.6698 [0.7539] |
| $D_{O[E](3K)}\left(\frac{10^2\times cm^2}{s}\right)$ | ↘ | 15.2896 [0.5550] | 13.7912 [0.5090] | 12.931 [0.4824] |
| $D_{O[E](80K)}\left(\frac{10^2\times cm^2}{s}\right)$ | ↘ | 15.3075 [0.5630] | 13.8075 [0.5164] | 12.946 [0.4894] |
| $D_{O[E](300K)}\left(\frac{10^2\times cm^2}{s}\right)$ | ↘ | 15.5390 [0.6939] | 14.019 [0.6394] | 13.147 [0.6080] |
| $\mathbb{V}_{O[E]_{O[E]\,(3K)}}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ | ↗ | **54.430 [426.84]** | **59.759 [460.9]** | **63.290 [482.99]** |
| $\mathbb{V}_{O[E]_{O[E]\,(80K)}}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ | ↗ | 54.349 [419.14] | 59.669 [452.5] | 63.194 [474.07] |
| $\mathbb{V}_{O[E]_{O[E]\,(300K)}}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ | ↗ | 53.310 [340.39] | 58.514 [366.8] | 61.960 [383.8] |
| $-AE_{O[E]_{O[E]\,(3K)}}$ (meV$\times 10^{-6}$) | ↗ | 0.540 [6.668] | 0.547 [6.755] | 0.552 [6.818] |
| $-AE_{O[E]_{O[E]\,(80K)}}$ (meV) | ↗ | 0.0102 [0.1258] | 0.0104 [0.1274] | 0.0105 [0.1286] |
| $-AE_{O[E]_{O[E]\,(300K)}}$ (meV) | ↗ | 0.53731 [5.852] | 0.5443 [5.907] | 0.5494 [5.946] |

**For x=1** and **N=N3=$1.70735\times10^{19}$ cm$^{-3}$**, one has:

| | | | | |
|---|---|---|---|---|
| $\xi_{pO[E](T=3K)}$ | ↘ | **1659.6 [306.822]** | **1645.2 [304.156]** | **1634.9 [302.254]** |
| $\xi_{pO[E](T=80K)}$ | ↘ | 62.255 [11.615] | 61.714 [11.516] | 61.329 [11.445] |
| $\xi_{nO[E](T=300K)}$ | ↘ | 16.671 [3.008] | 16.527 [2.970] | 16.425 [2.943] |
| $\mu_{O[E](3K)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ | ↘ | 17.691 [1.0796] | 16.029 [0.9989] | 15.080 [0.9526] |
| $\mu_{O[E](80K)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ | ↘ | 17.717 [1.1269] | 16.053 [1.0434] | 15.103 [0.9956] |
| $\mu_{O[E](300K)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ | ↘ | 18.063 [1.4152] | 16.371 [1.3079] | 15.406 [1.2462] |
| $D_{O[E](3K)}\left(\frac{10^2\times cm^2}{s}\right)$ | ↘ | 50.602 [0.5709] | 45.449 [0.5236] | 42.490 [0.4962] |
| $D_{O[E](80K)}\left(\frac{10^2\times cm^2}{s}\right)$ | ↘ | 50.661 [0.5901] | 45.503 [0.5415] | 42.541 [0.5134] |
| $D_{O[E](300K)}\left(\frac{10^2\times cm^2}{s}\right)$ | ↘ | 51.427 [1.0663] | 46.203 [0.9788] | 43.204 [0.9278] |
| $\mathbb{V}_{O[E]_{O[E]\,(3K)}}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ | ↗ | **12.163 [199.32]** | **13.366 [214.49]** | **14.163 [224.21]** |
| $\mathbb{V}_{O[E]_{O[E]\,(80K)}}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ | ↗ | 12.145 [190.95] | 13.346 [205.32] | 14.141 [214.52] |
| $\mathbb{V}_{O[E]_{O[E]\,(300K)}}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ | ↗ | 11.913 [152.05] | 13.086 [163.81] | 13.863 [171.38] |
| $-AE_{O[E]_{O[E]\,(3K)}}$ (meV$\times 10^{-6}$) | ↗ | 0.540 [15.81039] | 0.550 [16.0887] | 0.557 [16.2919] |
| $-AE_{O[E]_{O[E]\,(80K)}}$ (meV) | ↗ | 0.01024 [0.29622] | 0.01042 [0.3014] | 0.01055 [0.3051] |
| $-AE_{O[E]_{O[E]\,(300K)}}$ (meV) | ↗ | 0.53731 [6.99926] | 0.5467 [6.9698] | 0.5536 [6.9489] |

**Table 6n:** For given x, $r_d$, T=(50K, 100K, 150K) and N=[N1= $10^{19}$ $cm^{-3}$, N2= $5 \times 10^{19}$ $cm^{-3}$, N3=$10^{20}$ $cm^{-3}$], the numerical results of reduced Fermi energy $\xi_{nO[E]}(N^*, r_d, x, T)$, mobility $\mu_{O[E]}(N^*, r_d, x, T)$, diffusion coefficient $D_{O[E]}(N^*, r_d, x, T)$, viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_d, x, T)$, and activation energy $AE_{O[E]}(N^*, r_d, x, T)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively. In particular, from the numerical results of $\mathbb{V}_{O[E]}(N^*, r_d, x, T)$, one observes that, for given (x, $r_d$ and T), they increase with increasing N, in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, as discussed in above Table 3n, with increasing degeneracy, both the reduced Fermi energy $\xi_{nO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| Donor | Te | Sb | Sn |
|---|---|---|---|
| For **x=0** and **T=50 K** | | | |
| $\xi_{nO[E](N1)}$ ↘ | 27.663 [18.209] | 27.651 [18.201] | 27.612 [18.175] |
| $\xi_{nO[E](N2)}$ ↘ | 83.094 [54.590] | 83.086 [54.585] | 83.064 [54.571] |
| $\xi_{nO[E](N3)}$ ↘ | **132.35 [86.935]** | **132.34 [86.931]** | **132.32 [86.919]** |
| $\mu_{O[E](N1)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ ↘ | 0.0990 [0.2116] | 0.0984 [0.2105] | 0.0966 [0.2072] |
| $\mu_{O[E](N2)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ ↘ | 0.0337 [0.0304] | 0.0335 [0.0302] | 0.0327 [0.0296] |
| $\mu_{O[E](N3)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ ↘ | 0.0282 [0.0187] | 0.0280 [0.0186] | 0.0274 [0.0182] |
| $D_{O[E](N1)}\left(\frac{10^4 \times cm^2}{s}\right)$ ↘ | 0.0784 [0.1098] | 0.0779 [0.1092] | 0.0764 [0.1074] |
| $D_{O[E](N2)}\left(\frac{10^4 \times cm^2}{s}\right)$ ↘ | 0.0804 [0.0476] | 0.0798 [0.0473] | 0.0781 [0.0464] |
| $D_{O[E](N3)}\left(\frac{10^4 \times cm^2}{s}\right)$ ↘ | 0.1074 [0.0467] | 0.1066 [0.0464] | 0.1043 [0.0454] |
| $\mathbb{V}_{O[E](N1)}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ ↗ | 18.287 [8.5546] | 18.393 [8.5974] | 18.712 [8.7263] |
| $\mathbb{V}_{O[E](N2)}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ ↗ | 93.161 [103.23] | 93.822 [103.92] | 95.840 [106.02] |
| $\mathbb{V}_{O[E](N3)}\left(\frac{eV}{cm} \times \frac{s}{cm^2}\right)$ ↗ | **140.23 [211.62]** | **141.25 [213.09]** | **144.38 [217.60]** |
| $-AE_{O[E](N1)}$ (meV) ↗ | 4.6421 [10.747] | 4.6848 [10.750] | 4.6929 [10.762] |
| $-AE_{O[E](N2)}$ (meV) ↗ | 0.8443 [3.4359] | 0.8444 [3.4364] | 0.8448 [3.4376] |
| $-AE_{O[E](N3)}$ (meV) ↗ | 0.35268 [1.6907] | 0.35271 [1.6908] | 0.35280 [1.6912] |
| For **x=0.5** and **T=100 K**, one has: | | | |
| $\xi_{nO[E](N1)}$ ↘ | 19.850 [14.243] | 19.848 [14.241] | 19.841 [14.236] |
| $\xi_{nO[E](N2)}$ ↘ | 58.295 [41.714] | 58.294 [41.713] | 58.290 [41.710] |
| $\xi_{nO[E](N3)}$ ↘ | **92.599 [66.247]** | **92.598 [66.246]** | **92.595 [66.244]** |
| $\mu_{O[E](N1)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ ↘ | 1.9809 [6.1339] | 1.9675 [6.0943] | 1.9277 [5.9770] |
| $\mu_{O[E](N2)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ ↘ | 0.2427 [0.6109] | 0.2409 [0.6066] | 0.2356 [0.5937] |
| $\mu_{O[E](N3)}\left(\frac{10^5 \times cm^2}{V \times s}\right)$ ↘ | 0.1215 [0.2442] | 0.1206 [0.2424] | 0.1179 [0.2372] |
| $D_{O[E](N1)}\left(\frac{10^4 \times cm^2}{s}\right)$ ↘ | 2.2446 [4.9561] | 2.2291 [4.9236] | 2.1834 [4.8270] |

| | | | |
|---|---|---|---|
| $D_{O[E](N2)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 0.8121 [1.4620] | 0.8062 [1.4516] | 0.7885 [1.4206] |
| $D_{O[E](N3)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 0.6460 [0.9290] | 0.6411 [0.9222] | 0.6269 [0.9021] |
| $\mathbb{V}_{O[E]\,(N1)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 0.9260 [0.2990] | 0.9322 [0.3009] | 0.9513 [0.3068] |
| $\mathbb{V}_{O[E]\,(N2)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 12.971 [5.1522] | 13.066 [5.1891] | 13.358 [5.3015] |
| $\mathbb{V}_{O[E]\,(N3)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | **32.665 [16.246]** | **32.910 [16.365]** | **33.658 [16.728]** |
| $-AE_{O[E](N1)}$ (meV) ↗ | 30.034 [44.533] | 30.036 [44.535] | 30.042 [44.541] |
| $-AE_{O[E](N2)}$ (meV) ↗ | 13.200 [26.196] | 13.201 [26.1968] | 13.202 [26.1979] |
| $-AE_{O[E](N3)}$ (meV) ↗ | 7.6730 [18.8170] | 7.6731 [18.8171] | 7.6735 [18.8177] |

For **x=1** and **T=150 K**, one has:

| | | | |
|---|---|---|---|
| $\xi_{nO[E](N1)}$ ↘ | 24.3630 [19.8800] | 24.3627 [19.8798] | 24.3619 [19.8791] |
| $\xi_{nO[E](N2)}$ ↘ | 71.1567 [58.0088] | 71.1566 [58.0087] | 71.1561 [58.0083] |
| $\xi_{nO[E](N3)}$ ↘ | **112.948 [92.0711]** | **112.947 [92.0710]** | **112.947 [92.0707]** |
| $\mu_{O[E](N1)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 29.463 [111.28] | 29.245 [110.47] | 28.601 [108.07] |
| $\mu_{O[E](N2)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 3.2325 [11.618] | 3.2079 [11.530] | 3.1352 [11.271] |
| $\mu_{O[E](N3)}\left(\frac{10^5\times cm^2}{V\times s}\right)$ ↘ | 1.3290 [4.4850] | 1.3189 [4.4509] | 1.2887 [4.3498] |
| $D_{O[E](N1)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 61.596 [189.43] | 61.140 [188.05] | 59.790 [183.95] |
| $D_{O[E](N2)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 19.811 [58.032] | 19.661 [57.595] | 19.215 [56.299] |
| $D_{O[E](N3)}\left(\frac{10^4\times cm^2}{s}\right)$ ↘ | 12.933 [35.574] | 12.834 [35.303] | 12.541 [34.502] |
| $\mathbb{V}_{O[E]\,(N1)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 0.0625 [0.0165] | 0.0630 [0.0167] | 0.0644 [0.0170] |
| $\mathbb{V}_{O[E]\,(N2)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 0.9746 [0.2711] | 0.9820 [0.2732] | 1.0048 [0.2795] |
| $\mathbb{V}_{O[E]\,(N3)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | **2.9865 [0.8850]** | **3.0096 [0.8918]** | **3.0799 [0.9125]** |
| $-AE_{O[E](N1)}$ (meV) ↗ | 65.6971 [87.5452] | 65.6974 [87.5455] | 65.6983 [87.5464] |
| $-AE_{O[E](N2)}$ (meV) ↗ | 38.48782 [59.8286] | 38.48787 [59.8287] | 38.48804 [59.8289] |
| $-AE_{O[E](N3)}$ (meV) ↗ | 27.49976 [48.06517] | 27.49979 [48.0652] | 27.49987 [48.0653] |

**Table 6p:** For given x, $r_a$, T=(50K, 100K, 150K) and N=[N1= $3\times10^{19}$ $cm^{-3}$, N2= $5\times10^{19}$ $cm^{-3}$, N3=$10^{20}$ $cm^{-3}$], the numerical results of reduced Fermi energy $\xi_{pO[E]}(N^*, r_a, x, T)$, mobility $\mu_{O[E]}(N^*, r_a, x, T)$, diffusion coefficient $D_{O[E]}(N^*, r_a, x, T)$, viscosity coefficient $\mathbb{V}_{O[E]}(N^*, r_a, x, T)$, and activation energy $AE_{O[E]}(N^*, r_a, x, T)$, are obtained by using Equations (11, 22a, 24, 22b, 22c), respectively. In particular, from the numerical results of $\mathbb{V}_{O[E]}(N^*, r_a, x, T)$, one observes that, for given (x, $r_a$ and T), they increase with increasing N, in good agreement with those, obtained in complex fluids by Wenhao.[18] In other words, as discussed in above Table 3p, with increasing degeneracy, both the reduced Fermi energy $\xi_{pO[E]}$ and the viscosity coefficient $\mathbb{V}_{O[E]}$ increase, according to **an equivalence between the degeneracy-and-viscosity concept**.

| Acceptor | Ga | Mg | In |
|---|---|---|---|
| For **x=0** and **T=50 K** | | | |
| $\xi_{pO[E](N1)}$ ↘ | 54.658 [18.816] | 53.751 [18.506] | 53.102 [18.284] |
| $\xi_{pO[E](N2)}$ ↘ | 79.594 [27.355] | 78.843 [27.098] | 78.308 [26.915] |
| $\xi_{pO[E](N3)}$ ↘ | **129.59 [44.497]** | **129.00 [44.296]** | **128.58 [44.152]** |
| $\mu_{O[E](N1)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 2.9593 [0.5775] | 2.7048 [0.5380] | 2.5596 [0.5155] |
| $\mu_{O[E](N2)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 2.7911 [0.5129] | 2.5423 [0.4750] | 2.4002 [0.4532] |
| $\mu_{O[E](N3)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 2.6124 [0.4497] | 2.3724 [0.4140] | 2.2352 [0.3936] |
| $D_{O[E](N1)}\left(\frac{10^2\times cm^2}{s}\right)$ ↘ | 4.6422 [0.3099] | 4.1725 [0.2839] | 3.9009 [0.2687] |
| $D_{O[E](N2)}\left(\frac{10^2\times cm^2}{s}\right)$ ↘ | 6.3788 [0.4017] | 5.7554 [0.3684] | 5.3967 [0.3492] |
| $D_{O[E](N3)}\left(\frac{10^3\times cm^2}{s}\right)$ ↘ | 9.7227 [0.5741] | 8.7897 [0.5261] | 8.2545 [0.4985] |
| $\mathbb{V}_{O[E](N1)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 86.038 [440.89] | 93.349 [469.29] | 98.043 [486.84] |
| $\mathbb{V}_{O[E](N2)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 110.09 [599.10] | 120.29 [643.89] | 126.99 [672.51] |
| $\mathbb{V}_{O[E](N3)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | **150.09 [871.88]** | **164.90 [944.85]** | **174.74 [992.42]** |
| $-AE_{O[E](N1)}$ ($eV\times10^{-6}$) ↗ | 8.3060 [70.25] | 8.5887 [72.63] | 8.8001 [74.41] |
| $-AE_{O[E](N2)}$ ($eV\times10^{-6}$) ↗ | 3.9162 [33.19] | 3.9911 [33.82] | 4.0459 [34.29] |
| $-AE_{O[E](N3)}$ ($eV\times10^{-6}$) ↗ | 1.4773 [12.53] | 1.4907 [12.65] | 1.5005 [12.73] |
| For **x=0.5** and **T=100 K**, one has: | | | |
| $\xi_{pO[E](N1)}$ ↘ | 39.593 [11.374] | 39.231 [11.272] | 38.973 [11.199] |
| $\xi_{pO[E](N2)}$ ↘ | 56.748 [16.226] | 56.446 [16.140] | 56.231 [16.079] |
| $\xi_{pO[E](N3)}$ ↘ | **91.376 [26.057]** | **91.138 [25.989]** | **90.969 [25.941]** |
| $\mu_{O[E](N1)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 5.5213 [0.7582] | 5.0196 [0.7024] | 4.7329 [0.6704] |
| $\mu_{O[E](N2)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 5.2727 [0.6740] | 4.7840 [0.6214] | 4.5046 [0.5911] |
| $\mu_{O[E](N3)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 4.9980 [0.5954] | 4.5262 [0.5462] | 4.2566 [0.5180] |
| $D_{O[E](N1)}\left(\frac{10^2\times cm^2}{s}\right)$ ↘ | 12.539 [0.4855] | 11.295 [0.4456] | 10.580 [0.4224] |

| | | | |
|---|---|---|---|
| $D_{O[E](N2)}\left(\frac{10^2\times cm^2}{s}\right)$ ↘ | 17.176 [0.6223] | 15.501 [0.5706] | 14.541 [0.5407] |
| $D_{O[E](N3)}\left(\frac{10^3\times cm^2}{s}\right)$ ↘ | 26.229 [0.8879] | 23.691 [0.8125] | 22.239 [0.7691] |
| $\mathbb{V}_{O[E]\,(N1)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 46.974 [342.08] | 51.432 [367.56] | 54.367 [383.81] |
| $\mathbb{V}_{O[E]\,(N2)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 58.901 [460.81] | 64.745 [498.48] | 68.629 [523.0] |
| $\mathbb{V}_{O[E]\,(N3)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | **78.859 [662.0]** | **86.965 [720.62]** | **92.387 [759.14]** |
| $-AE_{O[E](N1)}\,(eV\times 10^{-6})$ ↗ | 31.668 [386.2] | 32.254 [393.3] | 32.683 [398.5] |
| $-AE_{O[E](N2)}\,(eV\times 10^{-6})$ ↗ | 15.410 [189.1] | 15.575 [191.1] | 15.695 [192.6] |
| $-AE_{O[E](N3)}\,(eV\times 10^{-6})$ ↗ | 5.9425 [73.173] | 5.9736 [73.554] | 5.9958 [73.828] |

For **x=1** and **T=150 K**, one has:

| | | | |
|---|---|---|---|
| $\xi_{pO[E](N1)}$ ↘ | 49.348 [9.2573] | 49.111 [9.2143] | 48.943 [9.1837] |
| $\xi_{pO[E](N2)}$ ↘ | 70.081 [13.049] | 69.883 [13.013] | 69.742 [12.987] |
| $\xi_{pO[E](N3)}$ ↘ | **112.09 [20.781]** | **111.94 [20.752]** | **111.83 [20.732]** |
| $\mu_{O[E](N1)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 17.059 [1.0427] | 15.434 [0.9609] | 14.506 [0.9140] |
| $\mu_{O[E](N2)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 16.506 [0.9292] | 14.920 [0.8531] | 14.014 [0.8094] |
| $\mu_{O[E](N3)}\left(\frac{10^3\times cm^2}{V\times s}\right)$ ↘ | 15.856 [0.8272] | 14.320 [0.7564] | 13.442 [0.7158] |
| $D_{O[E](N1)}\left(\frac{10^2\times cm^2}{s}\right)$ ↘ | 72.469 [0.8063] | 65.253 [0.7394] | 61.119 [0.7008] |
| $D_{O[E](N2)}\left(\frac{10^2\times cm^2}{s}\right)$ ↘ | 99.632 [1.0293] | 89.805 [0.9422] | 84.181 [0.8921] |
| $D_{O[E](N3)}\left(\frac{10^3\times cm^2}{s}\right)$ ↘ | 153.14 [1.4728] | 138.10 [1.3449] | 129.51 [1.2714] |
| $\mathbb{V}_{O[E]\,(N1)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 15.376 [251.58] | 16.954 [272.32] | 18.008 [285.81] |
| $\mathbb{V}_{O[E]\,(N2)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | 18.941 [336.45] | 20.924 [365.95] | 22.254 [385.32] |
| $\mathbb{V}_{O[E]\,(N3)}\left(\frac{eV}{cm}\times\frac{s}{cm^2}\right)$ ↗ | **24.938 [478.03]** | **27.595 [522.38]** | **29.382 [551.73]** |
| $-AE_{O[E](N1)}\,(eV\times 10^{-6})$ ↗ | 30.571 [877.64] | 30.866 [885.9] | 31.079 [891.9] |
| $-AE_{O[E](N2)}\,(eV\times 10^{-6})$ ↗ | 15.155 [439.37] | 15.241 [441.8] | 15.303 [443.6] |
| $-AE_{O[E](N3)}\,(eV\times 10^{6})$ ↗ | 5.9229 [172.69] | 5.9395 [173.17] | 5.9513 [173.51] |