

Relaxation Time of Electron – Polar Optical Phonon Field-Induced Tunnel Scattering

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Abstract. Theory of electron-polar optical single phonon field-induced tunnel scattering under the influence of an electric field is considered. It is assumed that the non-degenerate polar semiconductor has a spherical parabolic band structure. In low-field regime, an expression for the scattering time is obtained. Dependence of the scattering time (the scattering rate) on the electron energy is analyzed. The results of corresponding numerical computations for an n-GaAs at 300 K are presented. It is established that there is no fracture on the curve of electron scattering time (scattering rate) dependence on the electron energy.

Keywords: electron-polar optical phonon scattering, field-induced tunnel scattering, tilted band semiconductor, scattering time, scattering rate.

1. Introduction

As shown in a series of publications [1-8] in the theory of semiconductors and semiconductor devices to study mechanisms of various physical phenomena, particularly low-frequency $1/f$ -noise, it is important to investigate carrier mobility fluctuations. The results of various experimental studies (see, e.g., [9, 10]) are a good basis for the further research.

The study and analysis of mechanisms of carrier mobility fluctuations in semiconductors were done in the works [1-3]. The main sources of carrier mobility fluctuations are random intraband scattering, generation-recombination transitions, and the shot effect [1].

In the theory of low-frequency noise in semiconductors, it is of basic interest is the study of carrier-phonon scattering under the influence of an electric field. Particularly, in [4] electron mobility variance in the presence of an electric field was studied and a new mechanism of electron-phonon scattering under the influence of an electric field was proposed: electron-phonon field-induced tunnel (FIT) scattering. Within the framework of FIT-scattering electron-acoustic phonon scattering [6] and electron-non-polar optical phonon scattering [4] were studied in details and partially the electron-polar optical phonon scattering [7].

As it is well known from the theory of fluctuations and noises, the study of the variance of the given quantity is of great importance to the study of the given fluctuating quantity. In general cases electron mobility fluctuation $\tilde{\mu}$ is the result of the fluctuations of the electron quasi-momentum relaxation time τ_k ($\tilde{\tau}_k$ -source) and the occupancy of energy levels of the conduction band n_k ($\tilde{n}_k$ -source) [3]. For the theory of $1/f$ -noise, the $\tilde{n}_k$ component of the mobility fluctuations is of basic interest [3].

In [3], for the electron mobility variance σ_μ^2 in non-degenerate n-type semiconductor, the following expression was obtained:

$$\sigma_\mu^2 = \frac{\bar{\mu}^2}{N} \rho, \quad (1)$$

where

$$\rho \equiv \frac{\langle \bar{\tau}_{\mathbf{k},char}^2 \rangle}{\langle \bar{\tau}_{\mathbf{k},char} \rangle^2} - 1, \quad (2)$$

$$\bar{\tau}_{\mathbf{k},char} \equiv \bar{\tau}_{\mathbf{k}} + \frac{k}{3} \frac{d\bar{\tau}_{\mathbf{k}}}{dk}, \quad (3)$$

μ is the electron mobility, N is the number of conduction electrons, $\tau_{\mathbf{k}}$ is the electron quasi-momentum relaxation time, the bolded symbol $\mathbf{k}$ is the electron quasi-wave vector, and the non-bolded symbol k is the magnitude of $\mathbf{k}$, “ $\bar{}$ ” is the symbol of averaging over statistical ensemble and $\langle \dots \rangle$ is the symbol of $\mathbf{k}$ -averaging (averaging via quantum states of the conduction band).

The theoretical and experimental importance of the study of electron mobility variance and mobility fluctuations is given, for example, in [5] and [8]. For the non-polar semiconductors in the framework of electron-phonon FIT-scattering, a good agreement was established between the electron mobility noise (fluctuations) coefficient (and its temperature dependence) and experimental data for the Hooke’s well-known [11] coefficient for $1/f$ -noise (and its temperature dependence) [5]. In [8] fluctuations of electron system from equilibrium state due to electron-acoustic phonon random scattering is analyzed. Via linearization of the Boltzmann equation, the time dependence of the electrons lattice mobility fluctuations was obtained. It was shown that in the Boltzmann equation linearization approximation, lattice mobility fluctuations do not decay over time [8].

One can notice that for the study of electron mobility variance it is necessary to calculate the electron quasi-momentum relaxation time for different scattering mechanisms. Calculation of electron-polar optical phonon scattering relaxation time is given below.

2. Electron-polar optical phonon FIT transition probability

The interaction of electrons with polar optical phonons is the dominant scattering mechanism at room temperature in polar semiconductors. The standard theory of electron-polar optical phonon scattering is well known from the literature [12-14]. One should notice that the influence of an electric field on the scattering phenomena is not studied sufficiently. By above-mentioned reasons, it is of high interest to discuss electron-polar optical phonon interaction under the influence of an electric field.

The scattering time (the relaxation time or the scattering rate) is defined as [12-14]:

$$\frac{1}{\bar{\tau}_{\mathbf{k}}} = \sum_{\mathbf{k}'} W(\mathbf{k}, \mathbf{k}'), \quad (4)$$

where $W(\mathbf{k}, \mathbf{k}')$ is the transition probability per unit time for an electron scattered from an initial state $|\mathbf{k}\rangle$ to a final state $|\mathbf{k}'\rangle$, and the summation is done over all possible final states of electron. The transition from an initial state to a final state can be realized by both absorption and emission of a phonon by electron.

In [7] within the framework of electron-phonon FIT-scattering theory, electron-polar optical phonon scattering was studied. A non-degenerate n-type semiconductor with a spherical-parabolic conduction band and electron scalar effective mass m was considered. A uniform electric field with magnitude F is assumed to be parallel to the z-direction. Using theoretical methods developed on [4, 6] for $W(\mathbf{k}, \mathbf{k}')$, the following expression was obtained:

$$W(\mathbf{k}, \mathbf{k}') = \frac{4\pi e^2 \omega_0}{V \varepsilon_0 \varepsilon_r^*} \left(N_0 + \frac{1}{2} \mp \frac{1}{2} \right) \delta(\varepsilon_{\mathbf{k}'} - \varepsilon_{\mathbf{k}} \mp \hbar \omega_0) \times \sum_{\substack{q_x, q_y, \\ q_z \geq 0}} \frac{1}{q^2} \delta_{k'_x, k_x \pm q_x} \delta_{k'_y, k_y \pm q_y} \left[\operatorname{Re} \int_{-L_z/2}^{L_z/2} dz \chi_n^*(z) \chi_n(z) e^{\pm i q_z z} \right]^2. \quad (5)$$

Here e -is the elementary charge, ω_0 -is the longitudinal polar optical phonon frequency which for the long-wavelength range is assumed to be constant and independent of the phonon wave vector $\mathbf{q}$ ($q^2 = q_x^2 + q_y^2 + q_z^2$) in the first order approximation. $V = L_x L_y L_z$ - is the semiconductor volume, ε_0 -is the permittivity of a vacuum, $1/\varepsilon_r^* \equiv 1/\varepsilon_r^\infty - 1/\varepsilon_r^0$, ε_r^∞ and ε_r^0 are high- and low-frequency relative dielectric constants respectively. N_0 is the occupation number of the equilibrium phonons which is assumed to be $\mathbf{q}$ -independent by the same approximation as ω_0 and is given by the Bose-Einstein distribution function:

$$N_0 = \frac{1}{\exp(\hbar \omega_0 / k_B T) - 1}. \quad (6)$$

$\hbar$ -is the Planck reduced constant, k_B -is the Boltzmann constant, T -is the absolute temperature. In the presence of an electric field a conduction electron initial state $\mathbf{k}$ with energy $\varepsilon_{\mathbf{k}}$ is characterized by $(\mathbf{k}_\perp, k_n)$ (or (k_x, k_y, k_n)) quantum numbers, and final state $\mathbf{k}'$ with energy $\varepsilon_{\mathbf{k}'}$ is characterized by the $(\mathbf{k}'_\perp, k'_n)$ (or (k'_x, k'_y, k'_n)) quantum numbers [4, 6]. $\mathbf{k}_\perp$ -is the electron wave-vector perpendicular to the electric field ($k_\perp^2 = k_x^2 + k_y^2$). Electron energy eigenvalues $\varepsilon_{\mathbf{k}}$ are determined as

$$\varepsilon_{\mathbf{k}} = \frac{\hbar^2 k_\perp^2}{2m} + \varepsilon_n, \quad (7)$$

where $\varepsilon_n \equiv \hbar^2 k_n^2 / 2m$, and the index n identifies electron energy eigenvalues. $\hbar \omega_0$ -is the phonon energy. In (5), Dirac δ -function expresses the energy conservation law, and Kronecker δ -functions express the laws of conservation of quasi-momentum x, y components perpendicular to the electric field. In (5) the upper sign corresponds to the phonon absorption and the lower sign corresponds to the phonon emission.

In the presence of an electric field parallel to the z -axis, the electron wave function is determined by the stationary Schrödinger equation the solution of which is given as [4, 12-14]

$$\psi_{\mathbf{k}}(\mathbf{r}) = \frac{1}{\sqrt{L_x L_y}} \exp[i(k_x x + k_y y)] \chi_n(z), \quad (8)$$

and

$$\chi_n(z) = C_n \operatorname{Ai}\left(\frac{z}{l} - (k_n l)^2\right). \quad (9)$$

Here C_n -is the normalization constant, $\operatorname{Ai}(\dots)$ is the Airy function [16]:

$$\text{Ai}(s) = \frac{1}{\pi} \int_0^{\infty} du \cos\left(\frac{u^3}{3} + us\right),$$

and the notation

$$l \equiv \left(\frac{\hbar^2}{2emF} \right)^{\frac{1}{3}} \quad (10)$$

was used.

One should notice that for simplicity in (5), the screening effect (static screening) is neglected.

The main contribution of FIT scattering is that for an electron with energy $\varepsilon_{\mathbf{k}} < \hbar\omega_0$ the probability of phonon emission is not zero.

3. Electron-polar optical phonon FIT scattering relaxation time

Now inserting the expression (5) for transition probability into the expression (4) we can calculate the relaxation time (the scattering rate) of electron-polar optical phonon scattering.

For the calculation of the sum in (4), the following transition can be used:

$$\sum_{\mathbf{k}'} \rightarrow \frac{L_x L_y}{(2\pi)^2} \int_{\text{BZ}} dk'_x dk'_y \sum_{n'} . \quad (11)$$

Here, we are interested in a large length semiconductor in z -direction ($-L_z/2 \leq z \leq L_z/2$). The allowed values of k_n (or ε_n) are computed from the boundary condition $\chi_n(z = -L_z/2) = 0$ as [4, 6]

$$\frac{L_z}{2l} + (k_n l)^2 = -a_n. \quad (12)$$

Here a_n are the zeroes of the Airy function [16]: $-a_n \equiv -(3\pi[4n-1]/8)^{2/3}$, $n = 1, 2, \dots$. Hence, from (12) one obtains:

$$k_n^2 = -\frac{L_z}{2l^3} + \frac{1}{l^2} \left[\frac{3\pi}{2} \left(n - \frac{1}{4} \right) \right]^{2/3}, \quad (13)$$

and

$$\varepsilon_{\mathbf{k}} = \frac{\hbar^2}{2m} \left\{ k_{\perp}^2 - \frac{L_z}{2l^3} + \frac{1}{l^2} \left[\frac{3\pi}{2} \left(n - \frac{1}{4} \right) \right]^{2/3} \right\}. \quad (14)$$

For further calculations let us use the following notation:

$$s_n^2 \equiv \frac{1}{l^2} \left[\frac{3\pi}{2} \left(n - \frac{1}{4} \right) \right]^{2/3}, \quad s_{n'}^2 \equiv \frac{1}{l^2} \left[\frac{3\pi}{2} \left(n' - \frac{1}{4} \right) \right]^{2/3}. \quad (15)$$

From (12) it follows $k_{n+1}^2 - k_n^2 \sim 1/l^2$. The distance between k_n and k_{n+1} depends on n and it is very small for large l . This means that one can change the summation of n' in (11) by an integral over $s_{n'}$:

$$\sum_{n'} \rightarrow \int ds_{n'} \frac{dn'}{ds_{n'}}. \quad (16)$$

From (15):

$$\frac{dn'}{ds_{n'}} = \frac{2l^3 s_{n'}^2}{\pi}. \quad (17)$$

Now inserting (17) into (16), using transition (11) and taking into account properties of Kronecker δ -s in (5), it is easy to show that inserting (5) into (4) one obtains the following expression for relaxation time:

$$\begin{aligned} \frac{1}{\bar{\tau}_k} = & \int ds_{n'} \frac{2l^3 s_{n'}^2}{\pi} \frac{4\pi e^2 \omega_0}{V \varepsilon_0 \varepsilon_r^*} \left(N_0 + \frac{1}{2} \mp \frac{1}{2} \right) \delta \left(\frac{\hbar^2 (\mathbf{k}_\perp \pm \mathbf{q}_\perp)^2}{2m} + \varepsilon_{n'} - \frac{\hbar^2 k_\perp^2}{2m} - \varepsilon_n \mp \hbar \omega_0 \right) \\ & \times \sum_{\substack{q_x, q_y, \\ q_z \geq 0}} \frac{1}{q^2} \left[\operatorname{Re} \int_{-L_z/2}^{L_z/2} dz \chi_{n'}^*(z) \chi_n(z) e^{\pm i q_z z} \right]^2. \end{aligned} \quad (18)$$

For normalization constant C_n we have [4, 6]

$$C_n^2 = \pi / l \sqrt{-a_n}. \quad (19)$$

Using (12), (13) and (15), (19) can be rewritten as

$$C_n^2 = \frac{\pi}{l^2 s_n}; \quad C_{n'}^2 = \frac{\pi}{l^2 s_{n'}}, \quad (20)$$

Inserting (20) into (9) and using (15) one obtains:

$$\chi_n(z) = \sqrt{\frac{\pi}{l^2 s_n}} \operatorname{Ai} \left(\frac{z + \frac{L_z}{2} - s_n^2 l^3}{l} \right); \quad \chi_{n'}^*(z) = \sqrt{\frac{\pi}{l^2 s_{n'}}} \operatorname{Ai}^* \left(\frac{z + \frac{L_z}{2} - s_{n'}^2 l^3}{l} \right). \quad (21)$$

Now using the obvious transition $\int ds_{n'} s_{n'} = \frac{1}{2} \int ds_{n'}^2$ and (21), one can rewrite (18) as

$$\begin{aligned} \frac{1}{\bar{\tau}_k} = & \frac{8\pi^2 m e^2 \omega_0}{V \varepsilon_0 \varepsilon_r^* \hbar^2 l} \left(N_0 + \frac{1}{2} \mp \frac{1}{2} \right) \int ds_{n'}^2 \frac{1}{s_n} \delta \left((\mathbf{k}_\perp \pm \mathbf{q}_\perp)^2 + k_{n'}^2 - k_\perp^2 - k_n^2 \mp \frac{2m}{\hbar^2} \hbar \omega_0 \right) \\ & \times \sum_{\substack{q_x, q_y, \\ q_z \geq 0}} \frac{1}{q^2} \left[\operatorname{Re} \int_{-L_z/2}^{L_z/2} dz \operatorname{Ai}^* \left(\frac{z + \frac{L_z}{2} - s_{n'}^2 l^3}{l} \right) \operatorname{Ai} \left(\frac{z + \frac{L_z}{2} - s_n^2 l^3}{l} \right) e^{\pm i q_z z} \right]^2. \end{aligned}$$

(22)

Inserting (15) into (14) the argument of δ function in (22) can be modified as

$$\delta\left((\mathbf{k}_\perp \pm \mathbf{q}_\perp)^2 + k_{n'}^2 - k_\perp^2 - k_n^2 \mp \frac{2m}{\hbar^2} \hbar \omega_0\right) = \delta\left(q_x^2 + q_y^2 \pm 2k_x q_x \pm 2k_y q_y + s_{n'}^2 - s_n^2 \mp \frac{2m}{\hbar^2} \hbar \omega_0\right).$$

Then, after δ -integration in (22) we obtain

$$\begin{aligned} \frac{1}{\bar{\tau}_k} &= \frac{8\pi^2 m e^2 \omega_0}{V \varepsilon_0 \varepsilon_r^* \hbar^2 l} \left(N_0 + \frac{1}{2} \mp \frac{1}{2}\right) \frac{1}{s_n} \\ &\times \sum_{\substack{q_x, q_y, \\ q_z \geq 0}} \frac{1}{q^2} \left[\operatorname{Re} \int_{-L_z/2}^{L_z/2} dz \operatorname{Ai}^* \left(\frac{z + \frac{L_z}{2} - s_n^2 l^3}{l} \right) \operatorname{Ai} \left(\frac{z + \frac{L_z}{2} - s_n^2 l^3}{l} \right) e^{\pm i q_z z} \right]^2 \Bigg|_{s_n^2 = s_{n'}^2 - q_x^2 - q_y^2 \mp 2k_x q_x \mp 2k_y q_y \pm \frac{2m}{\hbar^2} \hbar \omega_0} \end{aligned}$$

We can assume that $L_z \rightarrow \infty$, and using the following expression [16]

$$\begin{aligned} I_\lambda &= \frac{1}{|\alpha^2|} \int_{-\infty}^{+\infty} \operatorname{Ai} \left[\frac{x+a}{\alpha} \right] \operatorname{Ai} \left[\frac{x+b}{\alpha} \right] \exp[i\lambda x] dx \\ &= \frac{1}{2\sqrt{\pi} |\lambda|^{\frac{1}{2}} |\alpha|^{\frac{3}{2}}} \times \exp \left\{ -i \left[\frac{\alpha^3 \lambda^3}{12} - \frac{(a-b)^2}{4\alpha^3 \lambda} + \frac{\lambda(a+b)}{2} + \frac{\pi}{4} \operatorname{sgn}(\alpha \lambda) \right] \right\}, \end{aligned}$$

one can obtain the following transition:

$$\begin{aligned} &\left[\operatorname{Re} \int_{-L_z/2}^{L_z/2} dz \operatorname{Ai}^* \left(\frac{z + \frac{L_z}{2} - s_n^2 l^3}{l} \right) \operatorname{Ai} \left(\frac{z + \frac{L_z}{2} - s_n^2 l^3}{l} \right) e^{\pm i q_z z} \right]^2 \\ &= \frac{l}{4\pi q_z} \cos^2 \left[\frac{l^3 (\pm q_z)^3}{12} - \frac{l^3 (-s_{n'}^2 + s_n^2)^2}{4(\pm q_z)} + \frac{(\pm q_z) l^3 \left(\frac{L_z}{l^3} - s_{n'}^2 - s_n^2 \right)}{2} \pm \frac{\pi}{4} \right]. \end{aligned} \quad (23)$$

Then one can use the following transition [12-14]:

$$\sum_{\substack{q_x, q_y, \\ q_z \geq 0}} \rightarrow \frac{V}{(2\pi)^3} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_0^{\infty} dq_z dq_y dq_x. \quad (24)$$

Here we need to change the integration boundaries because of δ function. From the δ

function argument, we have the following relation

$$s_n^2 = s_n^2 - q_x^2 - q_y^2 \mp 2k_x q_x \mp 2k_y q_y \pm \frac{2m}{\hbar^2} \hbar \omega_0. \quad (25)$$

From (15) one can notice that $s_n^2 \geq 0$. For phonon absorption we have

$$s_n^2 - q_x^2 - q_y^2 - 2k_x q_x - 2k_y q_y + \frac{2m}{\hbar^2} \hbar \omega_0 \geq 0, \quad (26)$$

and for phonon emission:

$$s_n^2 - q_x^2 - q_y^2 + 2k_x q_x + 2k_y q_y - \frac{2m}{\hbar^2} \hbar \omega_0 \geq 0. \quad (27)$$

From relations (26) and (27) one can find out the integration boundaries

$$\begin{aligned} q_{x,a,\min} &= -k_x - \sqrt{k_x^2 + k_y^2 + s_n^2 + H} & q_{x,e,\min} &= k_x - \sqrt{k_x^2 + k_y^2 + s_n^2 - H} \\ q_{x,a,\max} &= -k_x + \sqrt{k_x^2 + k_y^2 + s_n^2 + H} & q_{x,e,\max} &= k_x + \sqrt{k_x^2 + k_y^2 + s_n^2 - H} \\ q_{y,a,\min} &= -k_y - \sqrt{k_y^2 - q_x^2 - 2k_x q_x + s_n^2 + H} & q_{y,e,\min} &= k_y - \sqrt{k_y^2 - q_x^2 + 2k_x q_x + s_n^2 - H} \\ q_{y,a,\max} &= -k_y + \sqrt{k_y^2 - q_x^2 - 2k_x q_x + s_n^2 + H} & q_{y,e,\max} &= k_y + \sqrt{k_y^2 - q_x^2 + 2k_x q_x + s_n^2 - H} \end{aligned} \quad (28)$$

Here the index a indicates phonon absorption and the index e indicates phonon emission. In (28) we have used the notation

$$H \equiv \frac{2m}{\hbar^2} \hbar \omega_0. \quad (29)$$

The relaxation time can be represented in a more convenient form:

$$\frac{1}{\bar{\tau}_{\mathbf{k}}} = \frac{1}{\bar{\tau}_{\mathbf{k},a}} + \frac{1}{\bar{\tau}_{\mathbf{k},e}}. \quad (30)$$

Here $\bar{\tau}_{\mathbf{k},a}$ and $\bar{\tau}_{\mathbf{k},e}$ are the components of relaxation time associated with the phonon absorption and emission processes, respectively.

Now taking into account the transition (24) and relations (23), (25), (28) one can write down the following expressions for relaxation time absorption and emission components:

$$\begin{aligned} \frac{1}{\bar{\tau}_{\mathbf{k},a}} &= GN_0 \times \int_{q_{x,a,\min}}^{q_{x,a,\max}} \int_{q_{y,a,\min}}^{q_{y,a,\max}} \int_0^\infty \frac{1}{q_z (q_x^2 + q_y^2 + q_z^2)} \cos^2[f_a] dq_z dq_y dq_x \\ f_a &\equiv -\frac{l^3 q_z \left(2s_n^2 - q_x^2 - q_y^2 - 2k_x q_x - 2k_y q_y - \frac{L_z}{l^3} + H \right)}{2} - \\ &\quad - \frac{l^3 (q_x^2 + q_y^2 + 2k_y q_y + 2k_x q_x - H)^2}{4q_z} + \frac{l^3 q_z^3}{12} + \frac{\pi}{4} \end{aligned} \quad (31)$$

and

$$\frac{1}{\bar{\tau}_{\mathbf{k},c}} = G(N_0 + 1) \times \int_{q_{x,e,\min}}^{q_{x,e,\max}} \int_{q_{y,e,\min}}^{q_{y,e,\max}} \int_0^\infty \frac{1}{q_z(q_x^2 + q_y^2 + q_z^2)} \cos^2[f_e] dq_z dq_y dq_x$$

$$f_e \equiv \frac{l^3 q_z \left(2s_n^2 - q_x^2 - q_y^2 + 2k_y q_y + 2k_x q_x - \frac{L_z}{l^3} - H \right)}{2} +$$

$$+ \frac{l^3 (q_x^2 + q_y^2 - 2k_y q_y - 2k_x q_x + H)^2}{4q_z} - \frac{l^3 q_z^3}{12} - \frac{\pi}{4} \quad (32)$$

Here we used the notation

$$G \equiv \frac{me^2 \omega_0}{4\pi^2 \hbar^2 \epsilon_0 \epsilon_r^* s_n} \quad (33)$$

The relaxation time (scattering rate) of electron-polar optical phonon FIT-scattering is given by the expression (30) with (31) and (32). These expressions give a quasi-momentum (hence energy) dependence of relaxation time. Moreover, one can notice that electron-polar optical phonon FIT-scattering relaxation time is a function of electric field (see (15) and (10)).

4. Numerical calculations and discussions

To calculate integrals in expressions (31) and (32) we had to use numerical methods because the study of literature on mathematics shows that there are no analytic forms of integrals (31) and (32). For numerical calculations, we use the *Wolfram Mathematica* program package. Furthermore, without powerful processing systems some more technical transformations and assumptions were done to make possible to do appropriate numerical calculations in a convenient time interval.

For simplicity as a polar semiconductor we considered a GaAs at temperature $T = 300\text{K}$ with the following parameters [15]: $m = 0.067m_0$, $\hbar\omega_0 = 35.3\text{meV}$, $\epsilon_r^0 = 12.9$; $\epsilon_r^\infty = 10.86$, $L_z = 1\text{cm}$, and the value of the homogeneous electric field [4, 6] $F = 800\text{V/cm}$. Figure 1 shows the preliminary numerical calculation results for the electron-polar optical phonon FIT-

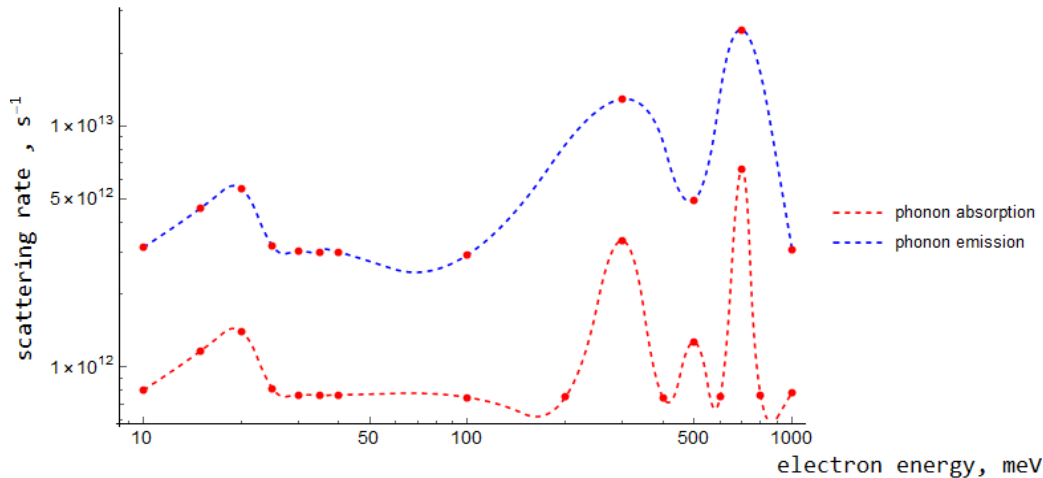


Figure 1. The electron-polar optical phonon FIT-scattering relaxation time (scattering rate) versus the electron energy (in the range of positive energy)

scattering relaxation time (scattering rate) dependence on the electron energy (in the range of positive energy). Here scattering rate values for the respective energy values are given by the red points, and dashed curves were used to make the illustration more clear. The red curve corresponds to the phonon absorption and the blue curve corresponds to the phonon emission.

For further discussions, one needs to compare the given numerical calculation results to the energy dependence of the electron-polar optical phonon scattering rate calculated for the bulk semiconductor when there is no external electric field. *Figure 2* gives integrated scattering rates as a function of energy at room temperature for polar optical phonon scattering [14]. Here the model used refers to electrons in GaAs.

Comparing *Figure 1* and *Figure 2* one can notice the good agreement of the scattering rate approximate numerical values in both models. There are obvious differences too. First, in *Figure 2* there is a fracture, which is connected to the fact that in the standard theory, when no field influence is discussed, for an electron with energy $\varepsilon_k < \hbar\omega_0$ the probability of phonon

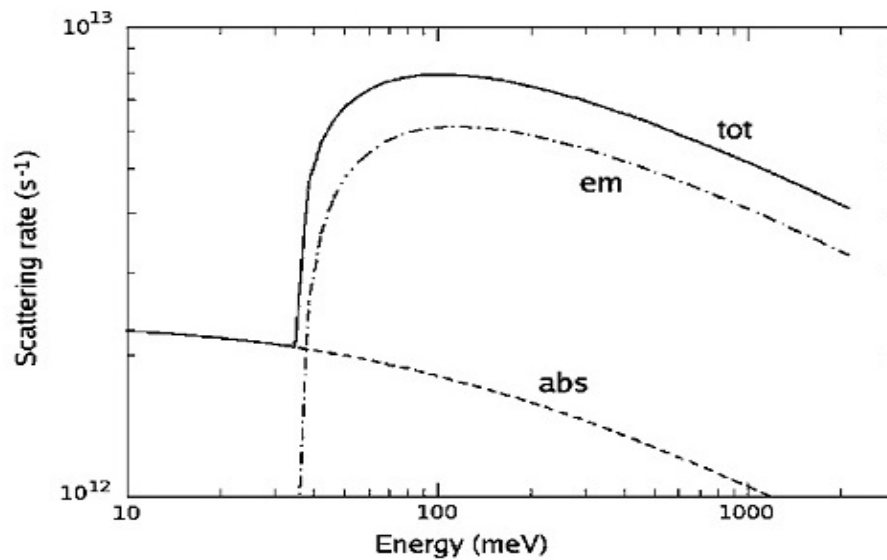


Figure 2. Integrated scattering rates as a function of energy at room temperature for polar optical phonon scattering (refers to electrons in GaAs).

emission is zero. Our calculations show that when the influence of the external electric field is considered, there is no fracture. This peculiarity is of high interest in the theory of electron mobility fluctuations [1-8]. Second, as it is shown in *Figure 1* the curves have an oscillation character.

It should be noted that for further research we need not only more precise results of numerical calculations for energy dependence, but also detailed results of field dependence of the scattering rate. This is a subject for separate research.

5. Conclusions

Thus, the relaxation time (scattering rate) of electron-polar optical phonon FIT-scattering is given by the expression (30) with (31) and (32). These expressions give a quasi-momentum (hence energy) dependence of the relaxation time. The results of corresponding numerical computations for n-GaAs at 300 K are presented in *Figure 1*. Our calculations show that when the influence of the external electric field is considered, there is no fracture on the curve on the contrary to the well-known standard model when no electric field is considered. These results could be a good basis for further research.

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References

- [1] S.V. Melkonyan, *Physica B* **405** (2010) 379.
- [2] S.V. Melkonyan, V.M. Aroutiounian, F.V. Gasparyan, H.V. Asriyan, *Physica B* **382** (2006) 65.
- [3] S.V. Melkonyan, H.V. Asriyan, Ash.V. Surmalyan, J.M. Smulko, *Arm. J.Phys.* **4** (2011) 62.
- [4] S.V. Melkonyan, *Physica B* **407** (2012) 4804.
- [5] S.V. Melkonyan, T.A. Zalinyan, and A.L. Harutyunyan, *Arm. J.Phys.* **7** (2014) 224.
- [6] S.V. Melkonyan, A.L. Harutyunyan, T.A. Zalinyan, *Condensed Matter Physics* **18** (2014) 23702.
- [7] A.L. Harutyunyan, *Arm. J.Phys.* **8** (2015) 38.
- [8] S.V. Melkonyan, T.A. Zalinyan, S.S. Melkonyan, *Fluctuation and Noise Letters* **17** (2018) 1850018.
- [9] T. Kang. Optimization of Signal-to-Noise Ratio in Semiconductor Sensors via On-Chip Signal Amplification and Interface-Induced Noise Suppression, PHD, (The University of Michigan, 2015) .
- [10] M.D. Hammig, T. Kang, M. Jeong, M. Jarrett, *IEEE T NUCL SCI*, **60** (2013) 2831.
- [11] L.K.J. Vandamme, F.N. Hooge, *IEER Trans. Electron. Devices* **55** (2008) 3070.
- [12] B.M. Askerov, *Electron Transport Phenomena in Semiconductors* (World Scientific Publishers Co. Inc, 1994).
- [13] Ch. Hamaguchi, *Basic Semiconductor Physics*, 2nd Edition (Springer, 2010).
- [14] Jacoboni C., *Theory of Electron Transport in Semiconductors*, (Springer, 2010).
- [15] Sadao Adachi, *Properties of Group-IV, III-V and II-VI Semiconductors*, (John Wiley & Sons, Ltd, 2005).
- [16] O. Vallee, M. Soares, *Airy Functions and Applications to Physics* (Imperial College Press, London, 2004).