Influence of an External Magnetic Field on the Acoustomagnetoelectric Field in a Rectangular Quantum Wire with an Infinite Potential by Using a Quantum Kinetic Equation

N. Q. Bau, N. V. Nghia

***Abstract*—**The acoustomagnetoelectric (AME) field in a rectangular quantum wire with an infinite potential (RQWIP) is calculated in the presence of an external magnetic field (EMF) by using the quantum kinetic equation for the distribution function of electrons system interacting with external phonons and electrons scattering with internal acoustic phonon in a RQWIP. We obtained ananalytic expression for the AME field in the RQWIP in the presence of the EMF. The dependence of AME field on the frequency of external acoustic wave, the temperature T of system, the cyclotron frequency of the EMF and the intensity of the EMF is obtained. Theoretical results for the AME field are numerically evaluated, plotted and discussed for a specific RQWIP *GaAs/GaAsAl*. This result has shown that the dependence of the AME field on intensity of the EMF is nonlinearly and it is many distinct maxima in the quantized magnetic region. We also compared received fields with those for normal bulk semiconductors, quantum well and quantum wire to show the difference. The influence of an EMF on AME field in a RQWIP is newly developed.

***Keywords*—**Rectangular quantum wire, acoustomagnetoelectric field, electron-phonon interaction, kinetic equation method.

I. Introduction

THE propagation of the acoustic wave in conductors in the presence of an external magnetic field (EMF) is accompanied by the transfer of the energy and momentum to conduction electrons which may give rise to a current usually called the acoustomagnetoelectric (AME) current, in the case of an open circuit called AME field. The AME field is similar to the Hall field in the bulk semiconductor where the sound flux ϕ plays the role of electric current. The essence of the AME effect is due to the existence of partial current generated by the different energy groups of electrons, when the total AME current in specimen is equal to zero. When this happens, the energy dependence of the electron momentum relaxation time causes average mobility of the electrons in the partial current, in general, to differ, if an EMF is perpendicular to the direction of the sound flux, the Hall currents generated by these groups will not compensate one another, and a non-zero AME effect will result. The AME effect was predicted in [1] and observed in bismuth [2]. Calculations of the AME field in bulk semiconductor [3]-[5] in the case the weak magnetic field region have been investigated. The quantum AME effect due to the Rayleigh sound waves was investigated in a bulk semiconductor [6], [7]. In recent years, the AME field in super lattice has been extensively studied [8]. So far, almost all these works obtained by using the Boltzmann kinetic equation method, thus, limited to the case of the weak magnetic field region. In the case of the quantized magnetic field (strong magnetic field) region using the Boltzmann kinetic equation is invalid. Therefore, we use quantum theory to investigate both the weak magnetic field and the quantized magnetic field region.

In low dimensional systems, the energy levels of electrons become discrete and different from those in bulk semiconductors [9]. Under certain conditions, the decrease in dimensionality of the system for semiconductors can lead to dramatically enhanced nonlinearities [10]. Thus, the nonlinear properties, especially electrical and optical properties of semiconductor quantum wells, superlattices, quantum wires, and quantum dots have attracted much attention in the past few years. In low-dimensional systems, the quantum kinetic equation method has been seen as a powerful tool. So, in a recent work, we have used this method to calculate the quantum acoustoelectric current in the cylindrical quantum wire with an infinite potential [11] and the AME field in the quantum well [12] and the RQWIP [13] when taking only into account the interaction between electrons and external acoustic phonons. However, in the RQWIP is not only the electron-external acoustic wave interaction but also the electron-acoustic phonon scattering. Therefore, the purpose of this work is to examine the influence of an external magnetic field on the AME field in the RQWIP by using the quantum kinetic equation for the distribution function of electrons interacting with external phonon and electron - internal phonon scattering.

The new things obtained in this work are:

1) We show that the AME field is not only a result of the electron-external acoustic wave interaction but also the electron-acoustic phonon scattering in the sample;
2) We use the quantum kinetic equation method;

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3) We calculate the AME field in a RQWIP GaAs/GaAsAl in the presence of EMF for both cases: the weak magnetic field region and the quantized magnetic field region;
4) We show that the dependence of AME field on the EMF in RQWIP is nonlinear;
5) We indicate that the condition to appear the positions of the peaks is not dependent on the temperature systems.

This paper is organized as follows: In Section II, starting from the Hamiltonian of the electron-external phonon interaction and electrons-acoustic phonon scattering system in RQWIP, we built from the quantum kinetic equation for electron in RQWIP in the presence of an EMF. We calculate the AME current in a RQWIP and then received analytical expressions for the AME field in the RQWIP *GaAs/GaAsAl*in the presence of the EMF. Numerical results and discussion are given in Section III. Finally, remarks and conclusions are shown in Section IV.

II. Analytic Expression for the AME Field in the RQWIP

We consider a RQWIP structure of the length L with an EMF assumed to be in the Oz direction. Due to the confinement potential, the motion of electrons in the Oz direction is free, while the motion in the $(x - y)$ plane quantized into discrete energy levels called sub-bands. Then the eigen-function of an unperturbed electron in the RQWIP is expressed as [14], [15]:

$$\psi_{n,l,N}(\vec r)=\frac{1}{\sqrt{L}}e^{i\frac{p_z}{\hbar}z}\sqrt{\frac{2}{L_x}}\,sin(\frac{n\pi}{L_x}x)\sqrt{\frac{2}{L_y}}\,sin(\frac{l\pi}{L_y}y), \quad (1)$$

where L_x and L_y are, respectively, the cross-sectional dimensions along x- and y-directions, n, l are the subband indexes, $N = 0,1,2,\ldots$ is the index of the Landau, and $\vec p_z$ is the electron momentum vector along z-direction. The electron energy spectrum takes the form:

$$\varepsilon^B_{n,l,N,p_z}=\frac{p_z^2}{2m}+A_N^{n,l}\ ;\ A_N^{n,l}=\omega_c\left(N+\frac{1}{2}\right)+\frac{\pi^2}{2m}\left(\frac{n^2}{L_x^2}+\frac{l^2}{L_y^2}\right),$$

where m is the effective mass of the electron, ω_c is the cyclotron frequency.

We assume that an external acoustic wave of frequency ω_q is propagating along the RQWIP axis in the EMF. We consider the most realistic case from the point of view of a low-temperature experiment, when $\omega_q/\eta = v_s|q|/\eta << 1$ and $qd >> 1$, where v_s is the velocity of the acoustic wave, q is the acoustic wave number, d is the electron mean free path and η is the frequency of the electron collisions. The compatibility of these conditions is provided by the smallness of the sound velocity in comparison with the characteristic velocity of the Fermi electrons. We also suppose that inequalities $v_s|q|/\eta << 1$ and $qd >> 1$ hold, i.e. the quantization of the electron motion in the EMF is essential. If the conditions $v_s|q|/\eta << 1$ and $qd >> 1$ are satisfied, a macroscopic approach to the description of the AME effect is inapplicable and the problem should be treated by using quantum mechanical methods. We also consider the acoustic wave as a packet of coherent phonons. Therefore, we have to first find the Hamiltonian describing the interaction of the electron-internal and external acoustic phonon system in the RQWIP in the presence of the EMF, which can be written as:

$$\begin{aligned}H=&\sum_{n,l,N,\vec p_z}\varepsilon^B_{n,l,N,\vec p_z}a^+_{n,l,N,\vec p_z}a_{n,l,N,\vec p_z}+\sum_{\vec k}\hbar\omega_{\vec k}b^+_{\vec k}b_{\vec k}\\&+\sum_{n,l,N,n',l',N',\vec k}I^{n',l'}_{n,l}C_{\vec k}J^{N'}_N(u)a^+_{n',l',N',\vec p_z+\vec k}a_{n',l',N',\vec p_z'}(b_{\vec k}+b^+_{-\vec k})\\&+\sum_{n,l,N,n,N',l',\vec q}C_{\vec q}U^{n',l',N'}_{n,l,N}a^+_{n',l',N',\vec p_z+\vec q}a_{n',l',N',\vec p_z'}b_{\vec q}\,exp(-i\omega_{\vec q}t)\end{aligned} \quad (2)$$

where $\varepsilon^B_{n,l,N,\vec p_z}$ is the electron energy spectrum in the presence of the EMF, ω_k is the internal phonon frequency, $C_{\vec k}=\Lambda\sqrt{k/(2\rho v_s SL)}$ is the electron-internal phonon interaction factor, ρ is the mass density of the medium, Λ is the deformation potential constant, $C_{\vec q}$ is the electron-external phonon interaction factor

$$C_{\vec q}=\frac{i\Lambda v_l^2}{q}\left(\frac{\hbar\omega^3_{\vec q}}{2\rho S}\right)^{\frac{1}{2}}\left[\frac{1+\sigma_l^2}{2\sigma_t}+\left(\frac{\sigma_l}{\sigma_t}-2\right)\frac{1+\sigma_t^2}{2\sigma_t}\right]^{-1}, \quad (3)$$

where $\sigma_l=(1-v_s^2/v_l^2)^{1/2}$, $\sigma_t=(1-v_s^2/v_t^2)^{1/2}$, S is the surface area, $v_l(v_t)$ is the velocity of the longitudinal (transverse) bulk acoustic wave, $a^+_{n,l,N,\vec p_z}$ ($a_{n,l,N,\vec p_z}$) is the electron creation (annihilation) operator; $b^+_{\vec k}$ ($b_{\vec k}$) is the creation (annihilation) operator of internal phonon and $b_{\vec q}$ is the annihilation operator of the external phonon; $U^{n',l',N'}_{n,l,N}$ is the matrix element:

$$U^{n',l',N'}_{n,l,N}=\frac{2\,exp(-k_lL)}{R^2L}\int_0^R\psi^*_{n',l',N'}(\vec r)\psi_{n,l,N}(\vec r)\,exp(iq_\perp r)dr, \quad (4)$$

$I^{n',l'}_{n,l}$ is the electronic form factor:

$$I^{n',l'}_{n,l}=\frac{2}{R^2}\int_0^R J_{|n-n'|}(q_\perp R)\psi^*_{n',l',N'}(\vec r)\psi_{n,l,N}(\vec r)rdr, \quad (5)$$

and

$$J^{N'}_N(u)=\int_{-\infty}^{\infty}\psi^*_{n,l,N'}(\vec r_\perp-a_c^2(\vec p_z-\vec k))e^{iq_\perp p_z}\psi_{n,l,N}(\vec r_\perp-a_c^2\vec p_z)dr,$$

where $u=a_cq_\perp^2/2$; $r_\perp$ is the position of the electron cyclotron orbit, $q_\perp$ is the wave vector in the plane Oxy.

To set up the quantum kinetic equation for electrons in the presence of an ultrasound, we use equation of motion of statistical average value for electrons

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$$i\hbar \frac{\partial \left\langle a^{+}_{n,l,N,\vec{p}_z} a_{n,l,N,\vec{p}_z} \right\rangle_t}{\partial t} = \left\langle a^{+}_{n,l,N,\vec{p}_z} a_{n,l,N,\vec{p}_z}, H \right\rangle_t , \tag{6}$$

where the notation $\left\langle X \right\rangle_t$ is mean the usual thermodynamic average of the operator X and $f^{n,l,N}_{\vec{p}_z} = \left\langle a^{+}_{n,l,N,\vec{p}_z} a_{n,l,N,\vec{p}_z} \right\rangle_t$ is the particle number operator or the electron distribution function. Substituting (2) into (6) and realizing operator algebraic calculations, we obtained.

$$\begin{aligned}\frac{\partial f^{n,l,N}_{\vec{p}_z}}{\partial t} &= \frac{\pi}{\hbar^2} \sum_{n,l,N,n',l',N',\vec{p}_z,\vec{k}} \left|C_k\right|^2 \left|I^{n',l'}_{n,l}\right|^2 \left|J^{N'}_{N}(u)\right|^2 N_k \\ &.\Big\{\Big[f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{k}}\Big]\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} - \varepsilon^{B}_{n,l,N\vec{p}_z} - \hbar\omega_k\Big) + \\ &+ \Big(f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{k}}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z+\vec{k}} - \varepsilon^{B}_{n,l,N,\vec{p}_z} + \hbar\omega_k\Big) - \\ &- \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{k}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z} - \varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} - \hbar\omega_k\Big) - \\ &- \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{k}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z} - \varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} + \hbar\omega_k\Big)\Big\} + \\ &+ \frac{\pi}{\hbar^2} \sum_{n,l,N,n',l',N',\vec{p}_z,\vec{q}} \left|C_q\right|^2 \left|U^{n',l',N'}_{n,l,N}\right|^2 N_q \\ &.\Big\{\Big(f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{q}}\Big)\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{q}} - \varepsilon^{\boldsymbol{B}}_{n,l,N,\vec{p}_z} + \hbar\omega_q - \hbar\omega_k\Big) \\ &- \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{q}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z-\vec{q}} - \varepsilon^{B}_{n,l,N,\vec{p}_z} + \hbar\omega_k - \hbar\omega_q\Big)\Big\}\end{aligned} \tag{7}$$

The acoustic wave will be considered as a packet of coherent phonons with the delta-like distribution function $N(\vec{k}) = (2\pi)^3 \phi\delta(\vec{k} - \vec{q})/(\hbar\omega_{\vec{q}} v_s)$ in the wave vector $\vec{k}$ space, ϕ is the sound flux density. The quantum kinetic equation for electrons in the single (constant) scattering time approximation takes the form [12], [13].

$$\begin{aligned}&\left(e\vec{E} + \omega_c\left[\vec{p},\vec{h}\right], \frac{\partial f^{n,l,N}_{\vec{p}_z}}{\partial p_z}\right) = \frac{f^{n,l,N}_{\vec{p}_z} - f_0}{\tau(\vec{p}_z)} - \\ &- \frac{\pi}{\hbar^2} \sum_{n,l,N,n',l',N',\vec{p}_z,\vec{k}} \left|C_k\right|^2 \left|I^{n',l'}_{n,l}\right|^2 \left|J^{N'}_{N}(u)\right|^2 N_k \\ &\quad .\Big\{\Big[f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{k}}\Big]\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} - \varepsilon^{B}_{n,l,N\vec{p}_z} - \hbar\omega_k\Big) + \\ &\quad + \Big(f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{k}}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z+\vec{k}} - \varepsilon^{B}_{n,l,N,\vec{p}_z} + \hbar\omega_k\Big) - \\ &\quad - \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{k}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z} - \varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} - \hbar\omega_k\Big) - \\ &\quad - \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{k}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z} - \varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} + \hbar\omega_k\Big)\Big\} \\ &- \frac{\pi}{\hbar^2} \sum_{n,l,N,n',l',N',\vec{p}_z,\vec{q}} \left|C_q\right|^2 \left|U^{n',l',N'}_{n,l,N}\right|^2 N_q \\ &.\Big\{\Big(f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{q}}\Big)\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{q}} - \varepsilon^{\boldsymbol{B}}_{n,l,N,\vec{p}_z} + \hbar\omega_q - \hbar\omega_k\Big) \\ &- \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{q}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z-\vec{q}} - \varepsilon^{B}_{n,l,N,\vec{p}_z} + \hbar\omega_k - \hbar\omega_q\Big)\Big\}\end{aligned} \tag{8}$$

where $\vec{h} = \vec{B}/B$ is unit vector along the direction of the EMF, f_0 is the equilibrium electron distribution function, $f^{n,l,N}_{\vec{p}_z}$ is an unknown distribution function perturbed due to the external fields.

Multiply both sides of (7) by $(e/m)\vec{p}\delta\left(\varepsilon - \varepsilon^{B}_{n',l',N',\vec{p}_z}\right)$ and carry out the summation over *n, l* and $\vec{p}$, we have the equation for the partial current density $\vec{j}^{\,n',l',N'}_{n,l,N}(\varepsilon)$ (the current caused by electrons which have energy of ε)

$$\frac{\vec{j}^{\,n',l',N'}_{n,l,N}(\varepsilon)}{\tau(\varepsilon)} + \omega_c[\vec{h}, \vec{j}^{\,n',l',N'}_{n,l,N}(\varepsilon)] = \vec{Q}^{n',l',N'}_{n,l,N}(\varepsilon) + \vec{S}^{n',l',N'}_{n,l,N}(\varepsilon), \tag{9}$$

with

$$\vec{j}^{\,n',l',N'}_{n,l,N}(\varepsilon) = \sum_{n',l',N',\vec{p}_z} e\frac{\vec{p}_z}{m} f^{n',l',N'}_{\vec{p}_z} \delta(\varepsilon - \varepsilon^{B}_{n',l',N',\vec{p}_z}), \tag{10}$$

$$\vec{Q}^{n',l',N'}_{n,l,N}(\varepsilon) = -e^2 \sum_{n',l',N',\vec{p}_z} \frac{\vec{p}_z}{m}\left(\vec{E}, \frac{\partial f^{n',l',N'}_{\vec{p}_z}}{\partial \vec{p}_z}\right)\delta(\varepsilon - \varepsilon^{B}_{n',l',N',\vec{p}_z}) \tag{11}$$

$$\begin{aligned}\vec{S}^{n',l',N'}_{n,l,N}(\varepsilon) &= \frac{(2\pi)^3 \left|C_{\vec{q}}\right|^2 \phi}{\hbar^3 \omega_{\vec{q}} v_s} \sum_{n,l,N,n',l',N',\vec{p}_z} \frac{\vec{p}}{m}\delta(\varepsilon - \varepsilon^{B}_{n',l',N',\vec{p}_z}) \\ &.\Big\{\frac{\pi}{\hbar^2} \sum_{n,l,N,n',l',N',\vec{p}_z,\vec{k}} \left|C_k\right|^2 \left|I^{n',l'}_{n,l}\right|^2 \left|J^{N'}_{N}(u)\right|^2 N_k \\ &\quad .\Big\{\Big[f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{k}}\Big]\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} - \varepsilon^{B}_{n,l,N\vec{p}_z} - \hbar\omega_k\Big) + \\ &\quad + \Big(f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{k}}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z+\vec{k}} - \varepsilon^{B}_{n,l,N,\vec{p}_z} + \hbar\omega_k\Big) - \\ &\quad - \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{k}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z} - \varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} - \hbar\omega_k\Big) - \\ &\quad - \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{k}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n,l,N,\vec{p}_z} - \varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{k}} + \hbar\omega_k\Big)\Big\} + \\ &+ \frac{\pi}{\hbar^2} \sum_{n,l,N,n',l',N',\vec{p}_z,\vec{q}} \left|C_q\right|^2 \left|U^{n',l',N'}_{n,l,N}\right|^2 N_q \\ &.\Big\{\Big(f^{n,l,N}_{\vec{p}_z} - f^{n',l',N'}_{,\vec{p}_z+\vec{q}}\Big)\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z+\vec{q}} - \varepsilon^{\boldsymbol{B}}_{n,l,N,\vec{p}_z} + \hbar\omega_q - \hbar\omega_k\Big) \\ &- \Big(f^{n',l',N'}_{,\vec{p}_z-\vec{q}} - f^{n,l,N}_{\vec{p}_z}\Big)\delta\Big(\varepsilon^{B}_{n',l',N',\vec{p}_z-\vec{q}} - \varepsilon^{B}_{n,l,N,\vec{p}_z} + \hbar\omega_k - \hbar\omega_q\Big)\Big\}\Big\}\end{aligned} \tag{12}$$

Equation (9) is the basic equation of the problem which is that the quantum kinetic equation for electrons with internal acoustic phonons and external acoustic phonons interaction in the presence of an EMF. Equation (9) is completely different from that in the work reported by [13] because they only consider the interaction between the electron with external acoustic wave.

Solving (9), we obtained the partial current density

$$\begin{aligned}\vec{j}^{\,n',l',N'}_{n,l,N}(\varepsilon) &= \frac{\tau(\varepsilon)}{1 + \omega_c^2\tau^2(\varepsilon)}\Big\{\Big(\vec{Q}^{n',l',N'}_{n,l,N}(\varepsilon) + \vec{S}^{n',l',N'}_{n,l,N}(\varepsilon)\Big) - \\ &- \omega_c\tau(\varepsilon)\Big([\vec{h}, \vec{Q}^{n',l',N'}_{n,l,N}(\varepsilon)] + [\vec{h}, \vec{S}^{n',l',N'}_{n,l,N}(\varepsilon)]\Big) \\ &+ \omega_c^2\tau^2(\varepsilon)\Big([\vec{Q}^{n',l',N'}_{n,l,N}(\varepsilon), \vec{h}]\vec{h} + [\vec{S}^{n',l',N'}_{n,l,N}(\varepsilon), \vec{h}]\vec{h}\Big)\Big\}\end{aligned} \tag{13}$$

The total AME current density is generally expressed as

$$\vec{j} = \int_0^\infty \vec{j}^{\,n',l',N'}_{n,l,N}(\varepsilon)d\varepsilon, \tag{14}$$

Substituting (13) into (14) and realizing calculations, we obtained the equation for the AME current density:

$$j_i = \alpha_{ij} E_j + \left(\eta_{ij} + \beta_{ij}\right)\phi_j , \tag{15}$$

where α_{ij} is the electrical conductivity tensor, η_{ij} and β_{ij} are the internal and external acoustic conductivity tensors, respectively

$$\alpha_{ij} = (e^2 n_0 / m\hbar)\{ a_1\delta_{ij} - \omega_c a_2 \varepsilon_{ijk} h_k + \omega_c^2 a_3 h_i h_j \}, \tag{16}$$

$$\eta_{ij} = \{ b_1\delta_{ij} - \omega_c b_2 \varepsilon_{ijk} h_k + \omega_c^2 b_3 h_i h_j \}, \tag{17}$$

$$\beta_{ij} = \{ c_1\delta_{ij} - \omega_c c_2 \varepsilon_{ijk} h_k + \omega_c^2 c_3 h_i h_j \}. \tag{18}$$

Here ε_{ijk} is the unit anti-symmetric tensor of third order, n_0 is the carrier concentration and a_g, b_g, c_g (g=1,2,3) are given as

$$a_g = \frac{m}{\pi}\int_0^\infty \frac{\tau^g(\varepsilon)(\varepsilon - A_N^{n,l})}{1+\omega_c^2\tau^2(\varepsilon)}\frac{\partial f_0}{\partial\varepsilon}d\varepsilon , \tag{19}$$

$$b_g = \int_0^\infty \frac{\tau^g(\varepsilon)A_1}{1+\omega_c^2\tau^2(\varepsilon)}\frac{\partial f_0}{\partial\varepsilon}d\varepsilon \, ; c_g = \int_0^\infty \frac{\tau^g(\varepsilon)A_2}{1+\omega_c^2\tau^2(\varepsilon)}\frac{\partial f_0}{\partial\varepsilon}d\varepsilon , \tag{20}$$

$$\Delta_{n,l,n',l'}^{N,N'} = A_N^{n,l} - A_{N'}^{n',l'} \tag{21}$$

$$\begin{aligned} A_1 = {} & \frac{e|\Lambda|^2 k_B T}{8\pi\omega_k \rho v_s LS\phi} \sum_{n,l,n',l',N,N'} \left|I_{n,l}^{n',l'}\right|^2 \left|J_N^{N'}(u)\right|^2 \left(\varepsilon - A_N^{n,l}\right)^{\frac{3}{2}} \\ & .\Big\{ \Big(\sqrt{\Delta_{n,l,n',l'}^{N,N'} + A_N^{n,l} - \hbar\omega_k - \varepsilon} + \sqrt{\varepsilon - A_N^{n,l}} \Big)^3 + \\ & + \Big(\sqrt{\Delta_{n,l,n',l'}^{N,N'} + A_N^{n,l} + \hbar\omega_k - \varepsilon} + \sqrt{\varepsilon - A_N^{n,l}} \Big)^3 \\ & - \Big(\sqrt{\Delta_{n,l,n',l'}^{N,N'} - A_N^{n,l} + \hbar\omega_k + \varepsilon} - \sqrt{\varepsilon - A_N^{n,l}} \Big)^3 \\ & - \Big(\sqrt{\Delta_{n,l,n',l'}^{N,N'} - A_N^{n,l} - \hbar\omega_k + \varepsilon} - \sqrt{\varepsilon - A_N^{n,l}} \Big)^3 \Big\} \end{aligned} \tag{22}$$

$$\begin{aligned} A_2 = {} & \frac{e(2\pi\hbar v_s)^3 |C_q|^2 \phi\sqrt{2m}}{\pi\hbar\omega_q^2 v_l^4} \sum_{n,l,n',l',N,N'} \left|U_{n,l}^{n',l'}\right|^2 \left(\varepsilon - A_N^{n,l}\right)^{\frac{3}{2}} \\ & .\sum_q q^3 \{ \delta(q^2 - 2m(\Delta_{n,l,n',l'}^{N,N'} + \hbar\omega_k - \hbar\omega_q)) \\ & - \delta(q^2 - 2m(\Delta_{n,l,n',l'}^{N,N'} - \hbar\omega_k + \hbar\omega_q))\} \end{aligned} \tag{23}$$

We considered a situation whereby the sound is propagating along the Ox axis in the EMF and we assume that the sample be opened in all directions, so that j_i= 0. Therefore, from (15) we obtained the expression of the AME field E_{AME}, which appeared along the Oy axis of the sample.

$$E_y = E_{AME} = \frac{\left(\eta_{zz} + \beta_{zz}\right)\alpha_{zy} - \left(\eta_{yz} + \beta_{yz}\right)\alpha_{yy}}{\alpha_{yy}^2 + \alpha_{zy}^2}\phi . \tag{24}$$

We can see that (24) in the general case is very complicated, so that we only examined the relaxation time of carrier $\tau(\varepsilon)$ depending on carrier energy as follows $\tau(\varepsilon) = \tau_0(\varepsilon / k_B T)^v$, with τ_0 is constant, k_B is Boltzmann constant and T is the temperature of the system. We also calculated for $f_0 = [1 - \exp(\beta(\varepsilon - \varepsilon_F))]^{-1}$ the Fermi-Dirac distribution function, $\beta = 1/k_B T$, ε_F is the Fermi energy. By using (16)-(18) and carrying out manipulations, we obtained an analysis expression for the AME field in a RQWIP as follows:

$$\begin{aligned} E_{AME} = {} & \frac{\hbar\phi\omega_c\tau_0(A_1 + A_2)}{2e^2 m} \Big\{ \Big(F_{v,2v}(x) + \tau_0^2\omega_c^2 F_{3v,2v}(x) \Big) \\ & .[k_B T \Big(F_{2v+1,2v}(x)\cos\varphi + \tau_0\omega_c \sin\varphi F_{3v+1,2v}(x) \Big) \\ & - A_N^{n,l} \Big(F_{2v,2v}(x)\cos\varphi + \tau_0\omega_c \sin\varphi F_{3v,2v}(x) \Big)] \\ & - F_{2v,2v}(x) [k_B T \Big(F_{v+1,2v}(x) + \tau_0^2\omega_c^2 \sin^2\varphi F_{3v+1,2v}(x) \Big) \\ & - A_N^{n,l} \Big(F_{v,2v}(x) + \tau_0^2\omega_c^2 \sin^2\varphi F_{3v,2v}(x) \Big)] \Big\} \\ & .\Big\{ [k_B T \Big(F_{v+1,2v}(x) + \tau_0^2\omega_c^2 \sin^2\varphi F_{3v+1,2v}(x) \Big) - \\ & - A_N^{n,l} \Big(F_{v,2v}(x) - \tau_0^2\omega_c^2 \sin^2\varphi F_{3v,2v}(x) \Big)]^2 + \\ & + \tau_0^2\omega_c^2 [k_B T \Big(F_{2v+1,2v}(x)\cos\varphi + \tau_0\omega_c \sin\varphi F_{3v+1,2v}(x) \Big) \\ & - A_N^{n,l} \Big(F_{2v,2v}(x)\cos\varphi + \tau_0\omega_c \sin\varphi F_{3v,2v}(x) \Big)]^2 \Big\}^{-1} \end{aligned} \tag{25}$$

where φ is the angle between the direction of propagation of sound waves and EMF, $F_{\mu,\gamma}(x) = \int_0^\infty \frac{x^\mu}{1+\omega_c^2\tau_0^2 x^\gamma}\frac{\partial f_0}{\partial x}dx$ and $x = 1/\tau_0\omega_c$.

Choose v = 1, the relaxation time of carrier $\tau(\varepsilon)$ depending on carrier energy as follows $\tau(\varepsilon) = \tau_0\varepsilon / k_B T$ and the realizing calculations, we have the expression for the AME field in a RQWIP as:

$$\begin{aligned} E_{AME} = {} & \frac{\hbar\phi\tau_0\omega_c \sin\varphi}{2e^2 m} \sum_{n,n',l,l'N,N'} (A_1 + A_2) \\ & .\{ A_N^{n,l} \cos^2\varphi F_{1,2}(x) F_{2,2}(x) - k_B T(1+\sin^2\varphi) F_{2,2}^2(x) \} \\ & .\{ (1+\sin^2\varphi)^2 [((k_B T)^2 + (A_N^{n,l})^2) F_{1,2}^2(x) - \\ & - 2k_B T A_N^{n,l} F_{1,2}(x) F_{2,2}(x)] + \\ & + [(x k_B T\cos\varphi - A_N^{n,l} \sin\varphi)^2 F_{1,2}^2(x) + \\ & + (k_B T\sin\varphi - A_N^{n,l}\tau_0\omega_c \cos\varphi)^2 F_{2,2}^2(x)] - \\ & - 2(x k_B T\cos\varphi - A_N^{n,l} \sin\varphi) \\ & .(k_B T\sin\varphi - A_N^{n,l}\tau_0\omega_c \cos\varphi) F_{1,2}(x) F_{2,2}(x) \}^{-1} \end{aligned} \tag{26}$$

We will carry out further analysis of (26) separately for the two limiting cases: the case of the weak magnetic field region and the case of quantized magnetic field region. In the case of the weak magnetic field region and high temperature $\omega_c << k_B T$, $\omega_c << \eta$, the expression of E_{AME} in (26) takes the form:

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$$\begin{aligned} E_{AME} = & -\frac{\hbar\phi \sin\varphi}{2e^2 m} x k_B T \sum_{n,n,l.l',N,N'} (A_1 + A_2)(ci^2(x) + si^2(x)) \\ & .\{[(xk_BT)^2 + (A_N^{n,l})^2][ci^2(x) + si^2(x)] - \\ & - \sin(2x)[(xk_BT)^2 - (A_N^{n,l})^2] ci(x) si(x) + 2xk_BTA_N^{n,l} \\ & .[\sin(2x)(ci^2(x) - si^2(x)) + \cos(2x) ci(x) si(x)]\}^{-1} \end{aligned} \tag{27}$$

where

$$si(x) = -\frac{\pi}{2} + \sum_{k=1}^{\infty} \frac{(-1)^k x^{2k-1}}{(2k-1)(2k-1)!}, \quad ci(x) = -\ln(x) + \sum_{k=1}^{\infty} \frac{(-1)^k x^{2k}}{2k(2k)!} \cdot$$

In the case of quantized magnetic field region and low temperature $\omega_c >> k_B T, \omega_c >> \eta$, the expression of E_{AME} in (26) takes the form:

$$\begin{aligned} E_{AME} = & -\frac{\hbar\phi\tau_0}{2e^2 m\omega_c} \sum_{n,n',l,l',N,N'} (A_1 + A_2) \\ & .\{[x^2G_1 - G_2][ci^2(x) + si^2(x)] - \\ & \quad - xG_3 \cos(x)\sin(x)[ci^2(x) - si^2(x)] \\ & \quad + [(x^2G_1 + G_2)\sin(2x) + xG_3\cos(2x)] ci(x) si(x)\} \\ & .\{[G_{m1} + x^2 G_{m3} + xG_{m2}\cos(x)\sin(x)][ci^2(x) + si^2(x)] \\ & - [(G_{m1} - x^2G_{m3})\sin(2x) - xG_{m2}\cos(2x)] ci(x) si(x)\}^{-1} \end{aligned} \tag{28}$$

where

$$G_1 = k_B T\cos\varphi + A_N^{n,l}\tau_0\omega_c \sin\varphi \,; G_2 = x^2 k_B T \sin^2\varphi \cos\varphi \,;$$

$$G_3 = xk_BT\sin\varphi - A_N^{n,l}\cos^3\varphi \,;$$

$$\begin{aligned} G_{m1} = & (1+\sin^2\varphi)^2 (xk_BT\sin\varphi)^2 \\ & + A_N^{n,l}\cos\varphi(A_N^{n,l} - 2xk_BT\sin\varphi) \end{aligned}$$

$$\begin{aligned} G_{m2} = & \tau_0\omega_c[(xk_BT)^2 + (A_N^{n,l})^2]\sin(2\varphi) \\ & - 2k_BTA_N^{n,l}(1+\sin^4\varphi) \end{aligned}$$

$$\begin{aligned} G_{m3} = & (\tau_0\omega_c A_N^{n,l}\sin\varphi)^2(1+\sin^2\varphi) \\ & + (k_BT\cos\varphi)^2 - \tau_0\omega_c k_B T A_N^{n,l}\sin 2\varphi \end{aligned}$$

From (27) and (28) we see that, the dependence of AME field on the temperature T of system, the cyclotron frequency ω_c of the EMF and the intensity B of the EMF is quite different from the results received in bulk semiconductor [3]-[6], the quantum well [12] and RQWIP [13].

III. Numerical Results and Discussion

To clarify the results that have been obtained, in this section, we considered the AME field in a RQWIP *GaAs/GaAsAl*. The parameters used in the numerical calculations are as follow [12]-[15]: $\tau_0 = 10^{-12}$s, $\phi = 10^4$ Wm^{-2}, L = 120nm, L_x = 30nm, L_y = 28nm, $\varphi = \pi/2$, $m = 0.067m_e$, m_e being the mass of free electron, ρ = 5320kgm^{-3}, $v_l = 2\times10^3$ms^{-1}, $v_t = 18\times10^2$ ms^{-1}, v_s = 5370 ms^{-1}, Λ = 13.5eV, $\omega_k = 9\times10^9$ s^{-1}.

Fig. 1 shows the dependence of AME field in RQWIP on the intensity B of the EMF for the weak magnetic field region with high temperature T = 250K (dashed line) and T = 200K (solid line) is nonlinearly with the intensity B of the EMF. The dependence of the AME field on the intensity B of the EMF at different values of the temperature shows that when magnetic field rises up, the AME field increases monotonically and it reached a maximum value at B=0.13T. The maximum value of AME field is approximates 2.5x10^{-4} V/m at T = 200K and 2.1x10^{-4} V/m at T = 250K.In addition, Fig. 1 shows that the positions of the maxima are not move as the temperature is varied, because the conditions to appear peak do not depend on the temperature but depend on the external magnetic field. This means that the condition is determined mainly by the electrons energy. This result is different from those for the bulk semiconductor [3]-[6] under condition qd>> 1 and the weak magnetic field region, because the AME field expression in the bulk semiconductor [3]-[6] is proportional to the intensity B of the EMF. In other words, AME field increases linearly with the magnetic field. This result is similar to the results received in QW [12] but the value of the AME field in RQWIP is greater the value of this field in QW [12]. Our result indicates that the dominant mechanism for such a behavior is attributed to the electron confinement in the RQWIP.

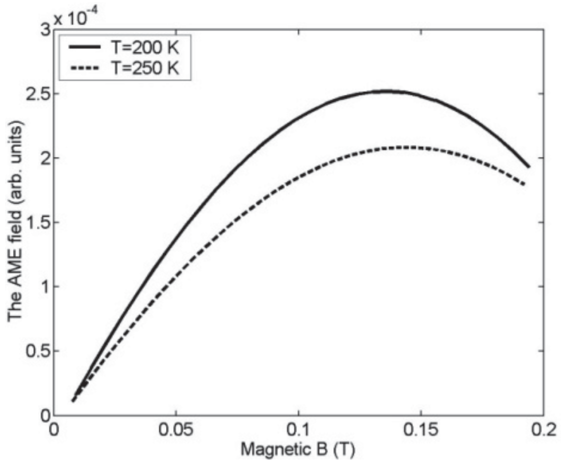

Fig. 1 The dependence of the AME field in RQWIP on the intensity B of the EMF for the weak magnetic field region with T = 250K (dashed line) and T = 200K (solid line). Here $\omega_q = 2\times10^{10}$ s^{-1}, *n=0, ±1; n'=0, ±1; l=0,±1; l'=0,±1;N=0,1,2,3; N'=0,1,2,3*

Fig. 2 shows the dependence of AME field in RQWIP on the intensity B of the EMF in the quantized magnetic field region which has many distinct maxima. The result showed the different behavior from results in bulk semiconductor [3]-[6]. According to the result in the bulk semiconductor [3]-[6] in the case of strong magnetic field, AME field is proportional to 1/B. Different from [3]-[6], these peaks in this case are much sharper. There are two reasons for the difference between our result and other results: one is that in the presence of the quantum magnetic field, the electron energy spectrum was affected by quantized magnetic field and the other is the effect of the electrons confinement in the RQWIP. This result is similar to the results received in QW [12] but the value of the AME field in RQWIP is greater the value of this field in QW [12]. According to the result in QW [12] is about E_{AME}=3.2x10^{-3} V/m at B = 1.9 (T), T = 4.0K and the results of the AME field in Fig. 2 is about E_{AME}=0.014 V/m at B= 1.82 (T), T = 5.0K (dashed line) and E_{AME}=0.029 V/m at B= 1.82 (T), T = 4.0K (solid line). The value of the AME field rise because the AME field in [12] is obtained when taking into account the interaction between electrons and external acoustic phonons, but in this paper has been considered when including the interaction between electrons and internal acoustic phonons and the electron-acoustic phonon scattering in the sample. In addition, from the result of the numerical calculation, if ignored the interaction between electrons and internal acoustic phonons, this result returns similar to [13]. In this work we have shown the dependence of AME field on confinement of electrons in one-dimensional systems, in particular on the wave function, energy spectrum and the potential form of different confinement of electrons. Additionally, we also show that the AME field does not exist when the sound waves travel parallel to the EMF and it reaches the maximum value when the sound waves travel perpendicular to the EMF.

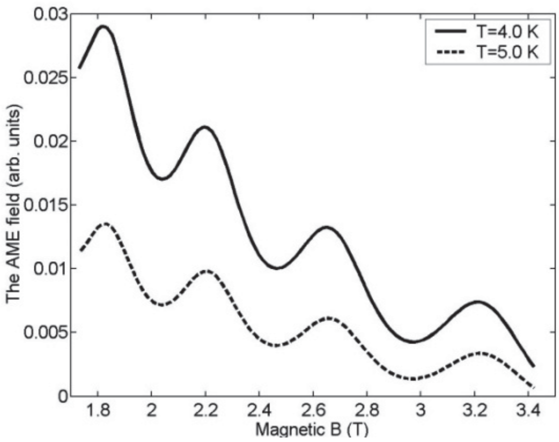

Fig. 2 The dependence of the AME field in RQWIP on the intensity B of the EMF for the quantized magnetic field region with$T$ = 5K (dashed line) and T = 4K (solid line). Here $\omega_q = 2\times10^{10}\ s^{-1}$, *n=0,±1;n'=0,±1; l=0,±1; l'=0,±1;N=0,1,2,3; N'=0,1,2,3*

Fig. 3 shows the dependence of AME field in RQWIP on the intensity B of the EMF in the quantized magnetic field region at T = 4K with two different values of the external acoustic wave of frequency $\omega_q = 2.5\times10^{11}\ s^{-1}$ (dashed line) and $\omega_q = 2.0\times10^{11}\ s^{-1}$ (solid line). The curves have many distinct maxima when the condition $\omega_{\vec q} = \omega_{\vec k} \pm \Delta^{N,N'}_{n,l,n',l'}$ ($n\neq n'$, $l\neq l'$, $N\neq N'$) is satisfied. From the results in Fig. 3, we can see the width of the peaks increases when the intensity B of the EMF rises up. The maximum value of the AME field increases the frequency of sound waves large. In addition, the positions of the maxima are not move. By using the quantum kinetic equation method, our result indicate that it is only linear to intensity B of the EMF in case of the weak magnetic field and higher temperature, while in case of the quantized magnetic field and low temperature AME field is not proportional to 1/B, but there are many peaks in Fig. 2.

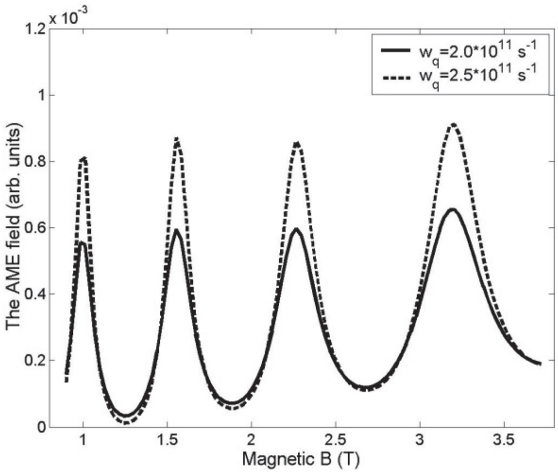

Fig. 3 The dependence of the AME field in RQWIP on the intensity B of the EMF for the quantized magnetic field region with ω_q = $2.5\times10^{11} s^{-1}$ (dashed line) and $\omega_q = 2.0\times10^{11} s^{-1}$ (solid line). Here T = 4K, *n=0, ±1; n'=0,±1; l=0,±1; l'=0,±1;N=0,1,2,3; N'=0,1,2,3*

IV. Conclusion

In summary, we have theoretically investigated the influence of an external magnetic field on the AME field in the RQWIP *GaAs/GaAsAl* by using the quantum kinetic equation for the distribution function of electrons interacting with external phonon and electron - internal phonon scattering. We have obtained analytical expressions for the AME field in the RQWIP for both cases: the weak magnetic field region and the quantized magnetic field region. There is a strong dependence of AME field on the intensity of the EMF. The result showed that there are many distinct maxima in the quantized magnetic field region and the AME field is only linear to intensity B of the EMF in case of the weak magnetic field and higher temperature. In addition, the AME field is not exist when the sound waves traveling in parallel to the EMF and it reaches the maximum value when the sound waves traveling perpendicular to the EMF.

The result of the numerical calculation was done for the RQWIP *GaAs/GaAsAl*. This result has shown that, the positions of the maxima of the AME field are not move as the temperature of system is varied. We want to emphasized that, there is a strong the influence of an external magnetic field on the AME field in the RQWIP and the condition to appear the positions of the peaks in the dependence of AME field on the intensity of the EMF in RQWIP *GaAs/GaAsAl* is not dependent the temperature. This result shows the difference from the results obtained in normal bulk semiconductors [3]-[6]. These are importance results of the present work.

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References

[1] M. Y. Galperin and V. D. Kagan, "On the acoustoelectric effect in a strong magnetic field,"", *Fiz. Tverd.Tela (Sov. Phys. Solid. State).*,10, 1968, pp. 2038-2045.
[2] T. Yamada, "Acoustomagnetoelectric Effect in Bismuth", *J. Phys. Soc. Japan.*, 20, 1965, pp. 1424-1437.
[3] G. M. Shmelev, G. I. Tsurkan and N. Q. Anh, "Photostimulated planar acoustomagnetoelectric effect in semiconductors", *Phys. Stat. Sol.*, 121, No. 1, 1984, pp. 97-102.
[4] E. M. Epshtein, "Photostimulated Acoustomagnetoelectric effect in semiconductor", *JETP Lett.*, 19, 1974, pp. 332.
[5] W. Salaneck, Y. Sawada and E. Burstein, "The magneto-quantum-electric effect", *J. Phys. Chem. Solids*., 32, No. 10, 1971, pp. 2285-2300.
[6] M. Kogami and S. Tanaka, "Acoustomagnetoelectric and acoustoelectric effects in n-InSb at low temperatures", *J. Phys. Soc. Japan.*, 30, 1971, pp. 775-784.
[7] A. D. Margulisand V. A. Margulis, "The quantum acoustomagnetoelectric effect due to Rayleigh sound waves", *J. Phys.*, 6, No. 31, 1994, pp. 6139-6150.
[8] S. Y. Mensah, F. K. A. Alloteyand S. K. Adjepong, "Acoustomagnetoelectric effect in a superlattice", *J. Phys. Condens.Matter.*,8, No. 9,1996, pp. 1235-1239.
[9] Y. Zhang, K. Suenaga, C. Colliex, S. Iijima, "Coaxial Nanocable: Silicon Carbide and Silicon Oxide Sheathed with Boron Nitride and Carbon", *Science*.,281, 1998, pp. 973-975.
[10] S. S. Rink, D. S. Chemla and D. A. B. Miller, "Linear and nonlinear optical properties of semiconductor quantum wells", *Adv. Phys.*, 38, 1989, pp. 89-188.
[11] N. V. Nhan, N. V. Nghia and N. V. Hieu, "The dependence of a quantum acoustoelectric current on some qualities in a cylindrical quantum wire with an infinite potential GaAs/GaAsAl", *Materials Transactions*, 56, No.09, 2015, pp.1408-1411.
[12] N. Q. Bau, N. V. Hieu, N. V. Nhan, "The quantum acoustomagnetoelectric field in a quantum well with a parabolic potential", *Superlatt. Microstruct.*, 52, 2012, pp. 921-930.
[13] N. V. Nghia, N. Q. Bau, N. V. Nhan and D. Q. Vuong, "Calculation of the acoustomagnetoelectric field in a rectangular quantum wire with an infinite potential in the presence of an external magnetic field", *PIERS Proceedings*, Malaysia, March 27-30, 2012, pp. 772-777.
[14] R. Mickevicius and V. Mitin, "Acoustic-phonon scattering in a rectangular quantum wire", *Phys. Rev. B*, 48, 1993, pp. 17194-171201.
[15] K. W. Kim, M. A. Stroscio, A. Bhatt, R. Mickevicius, V. V. Mitin, "Electron-optical-phonon scattering rates in a rectangular semiconductor quantum wire", *J. Appl. Phys*., 70, 1991, pp. 319-327.