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Rectangular quantum wire with an infinite potential GaAs/AlGaAs: Quantum theory of acoustomagnetolectric effect in the presence of electromagnetic wave

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Abstract. The acoustomagnetolectric (AME) effect in an GaAs/AlGaAs rectangular quantum wire with infinite potential (RQWIP) is investigated under the influence of electromagnetic wave (EMW) by using quantum kinetic equation (QKE) method. We obtain the electron distribution function in the interaction with internal and external phonon. By solving the inhomogeneous differential equation, the current density \vec{J} and the acoustomagnetolectric field (E_{AME}) are obtained in the dependence on the EMW amplitude, external acoustic wave frequency, the system temperature and the RQWIP length. The results are numerically evaluated for GaAs/AlGaAs quantum wire. We compares it to the result obtained in case of the bulk semiconductors and others low-dimension system in order to show the difference and the novelty of the results. The E_{AME} depends non-linearly on the wire length L_z and exhibits an oscillatory behavior as the function of wire length, although the stability period in long wire length condition. Moreover, we survey the impact of EMW on E_{AME} with the dependence on the external acoustic wave frequency $\omega_{\vec{q}}$. The result also indicates that the current density \vec{J} amplifies exponentially as the temperature increases.

1. Introduction

It is well known that the propagation of the acoustic wave in conductors is accompanied by the transfer of the energy and momentum to conduction electrons which may give rise to a current usually called the acoustoelectric current, in the case of an open circuit called acoustoelectric field. The presence of an external magnetic field (B) applied perpendicularly to the direction of the sound wave propagation in a conductor can induce another field, the so-called AME field. The study of the AME in bulk materials have received a lot of attentions. In recent years, the AME field in the low-dimensional structures have been carefully studied by using the Boltzmann classical kinetic equation [1, 2, 3, 4, 5, 6, 7] and [8].

In addition, the acoustoelectric (AE) effect has been studied experimentally in a composition superlattices [9] and in a quantum well, superlattices [10], [11]. The AE effect under the presence of a strong electromagnetic wave becomes the AME effect due to the appearance of B . That's



why the AME field is similar to the Hall field in the bulk semiconductor where the sound flux Θ 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 acoustoelectric (longitudinal) current in specimen is equal to zero. When this effect 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 external magnetic field 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 QKE method has been seen as a powerful tool in the low-dimensional structures [12, 13, 14, 15] since the Boltzmann kinetic equation temperature limitation condition is bland. On the other hand, QKE method is unoccupied by temperature condition restrict. Accordingly, in term of QKE approach, the quantum theory of low dimensional system in both low and high temperature is unveiled. As a consequence, we have used this method to calculate the AME field and influence of the EMW in the doped semiconductors superlattices [16] and in two-dimension systems [17].

Hence, the AME field under the influence of EMW on AME field in one-dimension systems becomes a fresh topic for researches. In this paper, we investigate the AME effect on GaAs/AlGaAs RQWIP under the photo-stimulation. The goal of present work is the analytical presentation of both current density and AME field in the company of numerical calculation for GaAs/AlGaAs nanowire model. To do this, in Sec.2, we briefly indicate the electron distribution by using QKE method due to the advantage mentioned above. The representation is taken place in Sec.3 in order to graphing and explaining the results. Finally, we showed our conclusion in Sec.4.

2. Acoustomagnetolectric effect in a rectangular quantum wire with an infinite potential in the presence of laser radiation

2.1. Electronic structure in a rectangular quantum wire (RQW)

Consider a perfect RQWIP structure subjected to a crossed electric field $\vec{E}_1 = (0, 0, \vec{E}_1)$, a magnetic field $\vec{B} = (0, \vec{B}, 0)$ and a strong laser radiation characterized by electric field $\vec{E} = (0, 0, \vec{E}_o \sin \Omega t)$ with the laser field potential vector $\vec{A}(t) = \frac{c}{\Omega} \vec{E}_o \cos \Omega t = \vec{A}_o \cos \Omega t$. If the confinement potential is assumed to take the form $V(x, y)$ of a square well along the x, y direction ($V = 0$ if $0 \leq r \leq R$ and $V = \infty$ if $r < 0 \cup r > R$). The electrons are only free on the z plane. In this RQWIP the motion of carriers are restricted, the electron eigenfunction and eigenstate are given by:

$$\psi_{n,l,\vec{p}_z} = \frac{2}{\sqrt{L_x L_y L_z}} e^{i(\vec{p}_z - \frac{e}{\hbar c} \vec{A}(t))z/\hbar} \phi_n(x) \phi_l(y) \quad (1)$$

$$\xi_{N,n,l,\vec{p}_z} = \frac{\hbar^2}{2m^*} \left(\vec{p}_z - \frac{e}{\hbar c} \vec{A}(t) \right)^2 - \hbar v_d \vec{p}_z + \xi_N + \frac{\pi^2 \hbar^2}{2m^*} \left(\frac{n^2}{L_x^2} + \frac{l^2}{L_y^2} \right) \quad (2)$$

in which

$$\phi_n(x) = \sin \left(\frac{n\pi x}{L_x} \right); \phi_l(y) = \sin \left(\frac{l\pi y}{L_y} \right)$$

$$\xi_N = \hbar \omega_c \left(N + \frac{1}{2} \right)$$

where m^* and e are the effective mass and the charge of a conduction electron, respectively; $\vec{p}_z = (0, 0, \vec{p}_z)$ is the total wave vector of electron (along the z axis); L_x and L_y are the effective

length of RQW long x -axis and y -axis; $n, l = 1, 2, \dots$ denote the quantization of the energy spectrum and embody the 2-direction quantization of one-dimensional systems. $N = 1, 2, \dots$ is the Landau quantized level, $\omega_c = eB/m^*$ is the cyclotron frequency and $v_d = \frac{E_1}{b}$ is the drift velocity. The wave function takes the form (1) with $0 \leq x \leq L_x$, $0 \leq y \leq L_y$ and becomes zero if $x > L_x$, $y > L_y$.

2.2. Quantum kinetic equation for confined electrons in a rectangular quantum wire with an infinite potential

The Hamiltonian of the electron-phonon system in RQWIP in the second quantization representation can be written as:

$$\begin{aligned}
 H = & \sum_{N,n,l,\vec{p}_z} \epsilon_{N,n,l} \left(\vec{p}_z - \frac{e}{\hbar c} \vec{A}(t) \right) a_{Nn,l,\vec{p}_z}^+ a_{Nn,l,\vec{p}_z} + \sum_{\vec{k}} \hbar \omega_{\vec{k}} b_{\vec{k}}^+ b_{\vec{k}} \\
 & + \sum_{N,n,l,N',n',l'} \sum_{\vec{p}_z \vec{k}} C_{\vec{k}} I_{n,l,n',l'}(\vec{k}) J_{N,N'}(u) a_{N',n',l',\vec{p}_z+\vec{k}}^+ a_{N,n,l,\vec{p}_z} (b_{\vec{k}} + b_{-\vec{k}}) \\
 & + \sum_{N,n,l,N',n',l'} \sum_{\vec{p}_z \vec{q}} C_{\vec{q}} U_{n,n'}(\vec{q}) a_{N',n',l',\vec{p}_z+\vec{q}}^+ a_{N,n,l,\vec{p}_z} b_{\vec{q}} \exp(-i\omega_{\vec{q}} t)
 \end{aligned} \quad (3)$$

where (N, n, l, \vec{p}_z) and $(N', n', l', \vec{p}_z + \vec{k})$ or $(N', n', l', \vec{p}_z + \vec{q})$ are electron states before and after scattering; $\hbar \omega_{\vec{k}}$ is the energy of a phonon with the wave vector \vec{k} ; a_{N,n,l,\vec{p}_z}^+ and a_{N,n,l,\vec{p}_z} ($b_{\vec{q}}^+$ and $b_{\vec{q}}$) are the creation and annihilation operators of electron (phonon), respectively.

In this case, we consider acoustic phonon for the internal scattering. So, the electron - phonon scattering constant takes the form as: $|C_{\vec{k}}|^2 = \frac{\hbar E_d^2 \vec{k}}{2\rho v_s V_0}$ with V_0 is the normalization volume and E_d is the deformation potential constant [16]. And also, the RQW form factor can be formulated as follows:

$$\begin{aligned}
 I_{n,l,n',l'}(\vec{k}) = & \frac{32(k_x L_x n n')^2 \left[1 - (-1)^{n+n'} \cos(k_x L_x) \right]}{[(k_x L_x)^4 - 2\pi^2 (k_x L_x)^2 (n^2 + n'^2) + \pi^4 (n^2 + n'^2)^2]^2} \\
 & \times \frac{32(k_y L_y l l')^2 \left[1 - (-1)^{l+l'} \cos(k_y L_y) \right]}{[(k_y L_y)^4 - 2\pi^2 (k_y L_y)^2 (l^2 + l'^2) + \pi^4 (l^2 + l'^2)^2]^2}
 \end{aligned} \quad (4)$$

The electron-external phonon interaction factor is: $C_{\vec{q}}^2 = \frac{E_d^2 v_l^4 \hbar \omega_{\vec{q}}^3}{2\rho q S} \left[\frac{1+\sigma_l^2}{2\sigma_l} + \left(\frac{\sigma_l}{\sigma_t} + 2 \right) \frac{1+\sigma_t^2}{\sigma_t} \right]^{-1}$

with $\sigma_l = \sqrt{1 - \frac{v_s^2}{v_l^2}}$ and $\sigma_t = \sqrt{1 - \frac{v_s^2}{v_t^2}}$. Here, v_l, v_t, v_s are the velocities of longitudinal, the transverse bulk acoustic wave and acoustic wave, respectively. ρ is the mass density and S is the surface area ($S = L_x L_y$). $U_{n,n'}(\vec{q}) = 4 \exp(-\lambda_l L_z) / L_z$ is the matrix element of the operator $U = \exp(iqy - \lambda_l z)$ with $\lambda_l = \sqrt{q^2 - \frac{\omega_q^2}{v_l^2}}$ is the spatial attenuation factor of the potential part of the displacement field. $J_{N,N'}(u) = \int_{-\infty}^{\infty} dz \phi_{N'}(z - r_c^2(p_z - k_{\perp})) e^{ik_{\perp} p_z} \phi_N(z - r_c^2 p_z)$ with $u = r_c k_{\perp}^2 / 2$, $k_{\perp}^2 = k_x^2 + k_y^2$ and $r_c = m^* c / (eB)$ is Landau radius.

The QKE of average number of electron $f_{N,n,l,\vec{p}_z} = \langle a_{N,n,l,\vec{p}_z}^+ a_{N,n,l,\vec{p}_z} \rangle_t$ is:

$$\frac{\partial f_{N,n,l,\vec{p}_z}}{\partial t} = \frac{1}{i\hbar} \left\langle \left[a_{N,n,l,\vec{p}_z}^+ a_{N,n,l,\vec{p}_z}, H \right] \right\rangle_t \quad (5)$$

Using Hamiltonian (3), we evaluate (5) to obtain the equation below:

$$\begin{aligned}
& \frac{\partial f_{N,n,\vec{p}_z}}{\partial t} + \left(\frac{e\vec{E}_1}{\hbar} + \frac{\omega_c}{\hbar} [\vec{p}_z \times \vec{h}] \right) \frac{\partial f_{N,n,\vec{p}_y}}{\partial \vec{k}_y} = \frac{4\pi}{\hbar} \sum_{N,n,l,N',n',l'} \sum_{\vec{p}_z, \vec{k}} C_k^2 I_{n,l,N',l'}^2(\vec{k}) N_{\vec{k}} \\
& \times \left(f_{N',n',l',\vec{p}_z+\vec{k}} - f_{N,n,l,\vec{p}_z} \right) \left\{ \left(1 - \frac{\alpha^2 \vec{k}^2}{2} \right) \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{k}} - \varepsilon_{N,n,l,\vec{p}_z} \right) \right. \\
& + \frac{\alpha^2 \vec{q}^2}{4} \left[\delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{k}} - \varepsilon_{N,n,l,\vec{p}_z} - \hbar\Omega \right) + \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{k}} - \varepsilon_{N,n,l,\vec{p}_z} + \hbar\Omega \right) \right] \left. \right\} \\
& - \frac{2\pi}{\hbar} \sum_{N,n,l,N',n',l'} \sum_{\vec{p}_z, \vec{q}} C_q^2 U_{n,n'}^2(\vec{q}) N_{\vec{q}} \left(f_{N',n',l',\vec{p}_z+\vec{q}} - f_{N,n,l,\vec{p}_z} \right) \\
& \times \left\{ \left(1 - \frac{\alpha^2 \vec{q}^2}{2} \right) \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{q}} - \varepsilon_{N,n,l,\vec{p}_z} - \hbar\omega_{\vec{q}} \right) + \frac{\alpha^2 \vec{q}^2}{4} \right. \\
& \times \left. \left[\delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{q}} - \varepsilon_{N,n,l,\vec{p}_z} - \hbar\Omega - \hbar\omega_{\vec{q}} \right) + \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{q}} - \varepsilon_{N,n,l,\vec{p}_z} + \hbar\Omega - \hbar\omega_{\vec{q}} \right) \right] \right\}
\end{aligned} \tag{6}$$

where $\vec{h} = \frac{\vec{B}}{B}$; $N_{\vec{k}}$ and $N_{\vec{q}}$ is the equilibrium phonon and external phonon distribution function; $\delta(x)$ is the Dirac delta function and $\vec{\alpha} = e\vec{E}_0/(m^*\Omega^2)$. Multiplying both sides of (6) by $(e/m^*)\vec{p}_z\delta(\varepsilon - \varepsilon_{N,n,l}(\vec{p}_z))$ we get the following equation:

$$\frac{\vec{R}(\varepsilon)}{\tau(\varepsilon)} + \omega_c [\vec{p}_z \times \vec{R}(\varepsilon)] = \vec{Q}(\varepsilon) + \vec{S}(\varepsilon) \tag{7}$$

where

$$\vec{Q}(\varepsilon) = -\frac{e}{m^*} \sum_{N,n,l,\vec{p}_z} \vec{p}_z \left(e\vec{E}_1, \frac{\partial f_{N,n,l,\vec{p}_z}}{\partial \vec{p}_z} \right) \delta(\varepsilon - \varepsilon_{N,n,l,\vec{p}_z}) \tag{8}$$

$$\begin{aligned}
\vec{S}(\varepsilon) &= \frac{4\pi e}{m^* \hbar} \sum_{N,n,l,N',n',l'} \sum_{\vec{p}_z, \vec{k}} C_k^2 I_{N,n,l,N',n',l'}^2(\vec{k}) N_{\vec{k}} \vec{p}_z \left(f_{N',n',l',\vec{p}_z+\vec{k}} - f_{N,n,l,\vec{p}_z} \right) \\
& \times \delta(\varepsilon - \varepsilon_{N,n,l,\vec{p}_z}) \left\{ \left(1 - \frac{\alpha^2 \vec{k}^2}{2} \right) \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{k}} - \varepsilon_{N,n,l,\vec{p}_z} \right) + \frac{\alpha^2 \vec{q}^2}{4} \right. \\
& \times \left. \left[\delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{k}} - \varepsilon_{N,n,l,\vec{p}_z} - \hbar\Omega \right) + \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{k}} - \varepsilon_{N,n,l,\vec{p}_z} + \hbar\Omega \right) \right] \right\} \\
& - \frac{2\pi}{\hbar} \sum_{N,n,l,N',n',l'} \sum_{\vec{p}_z, \vec{q}} C_q^2 U_{n,n'}^2(\vec{q}) N_{\vec{q}} \vec{p}_z \left(f_{N',n',l',\vec{p}_z+\vec{q}} - f_{N,n,l,\vec{p}_z} \right) \\
& \times \delta(\varepsilon - \varepsilon_{N,n,l,\vec{p}_z}) \left\{ \left(1 - \frac{\alpha^2 \vec{q}^2}{2} \right) \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{q}} - \varepsilon_{N,n,l,\vec{p}_z} - \hbar\omega_{\vec{q}} \right) + \frac{\alpha^2 \vec{q}^2}{4} \right. \\
& \times \left. \left[\delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{q}} - \varepsilon_{N,n,l,\vec{p}_z} - \hbar\Omega - \hbar\omega_{\vec{q}} \right) + \delta \left(\varepsilon_{N',n',l',\vec{p}_z+\vec{q}} - \varepsilon_{N,n,l,\vec{p}_z} + \hbar\Omega - \hbar\omega_{\vec{q}} \right) \right] \right\}
\end{aligned} \tag{9}$$

(7) is the inhomogeneous differential equation of $\vec{R}(\varepsilon)$ variable. Solving (7), we obtain the representation of $\vec{R}(\varepsilon)$ as:

$$\begin{aligned}
\vec{R}(\varepsilon) &= \frac{\tau}{1 + \omega_c^2 \tau^2} \\
& \times \left[(\vec{Q}(\varepsilon) + \vec{S}(\varepsilon)) - \omega_c \tau \left([\vec{h} \times \vec{Q}(\varepsilon)] + [\vec{h} \times \vec{S}(\varepsilon)] \right) + \omega_c^2 \tau^2 \left(\vec{Q}(\varepsilon) \vec{h} + \vec{S}(\varepsilon) \vec{h} \right) \vec{h} \right]
\end{aligned} \tag{10}$$

As can be seen from (10), we have to evaluate both $\vec{Q}(\varepsilon)$ and $\vec{S}(\varepsilon)$ from (8) and (7) to obtain the clarified analytical form of $\vec{R}(\varepsilon)$. Besides, $\vec{R}(\varepsilon)$ has the meaning of partial current density which caused by electrons with ε energy level motions in RQW. Thus, we will calculate the integral of $\vec{R}(\varepsilon)$ in order to find out the current density due to the AME effect in the following part.

2.3. Analytical expression for the acoustomagnetolectric field

The current density \vec{J} is given by

$$\vec{J} = \int_0^\infty \vec{R}(\varepsilon) d\varepsilon \quad (11)$$

We also have

$$\begin{aligned} J_i &= \sigma_{(N,n,l)ij} E_j + \eta_{(N,n,l)ij} \Theta_j \\ (E_{AME})_z &= \frac{\sigma_{(N,n,l)yx} \eta_{(N,n,l)xx} + \sigma_{(N,n,l)yy} \eta_{(N,n,l)yx}}{\sigma_{(N,n,l)yx}^2 + \sigma_{(N,n,l)yy}^2} \Theta_x \end{aligned} \quad (12)$$

here ε_F is the Fermi energy level; $\sigma_{(N,n,l)ik}$, $\eta_{(N,n,l)ik}$ are electrical and sound conductivity tensors in one-dimensional systems; i, j, k stand for the unit vectors in Cartesian coordinate system. (12) is the general expression of the E_{AME} for one-dimension semiconductor systems.

$$\begin{aligned} \sigma_{(N,n,l)ij} &= \left\{ \frac{e^2 L_z^2 \hbar^4}{8\pi m^{*3}} \sum_{n,l} \sqrt{\Delta_{n,l}} + \frac{e^2 L_z \hbar^4 E_d^2 N_{\vec{k}}}{64\pi^2 m^{*3} \rho v_s} \sum_{n,l,n',l'} I_{n,l,n',l'}^2(\vec{k})(SH1a + SH1b) \right. \\ &\quad \left. + \frac{e^2 L_z \hbar^4 E_d^2 \alpha^2 N_{\vec{k}}}{256\pi^2 m^{*3} \rho v_s} \sum_{N,n,l,N',n',l'} I_{n,l,n',l'}^2(\vec{k})(SH2 + SH3) \right\} \\ &\quad \times \frac{\tau(\varepsilon_F)}{1 + \omega_c^2 \tau^2(\varepsilon_F)} [\delta_{ik} + \omega_c \tau(\varepsilon_F) \epsilon_{ikj} + \omega_c^2 \tau^2(\varepsilon_F) h_j h_k] \end{aligned} \quad (13)$$

$$\begin{aligned} \eta_{(N,n,l)ij} &= \left\{ \frac{e L_z \hbar^4 E_d v_l^4 \omega_{\vec{q}} V_o N_{\vec{q}}}{128\pi^2 m^{*3} \rho F S} \sum_{N,n,l,N',n',l'} U_{n,l,n',l'}^2(\vec{q})(SH4a + SH4b) \right. \\ &\quad \left. + \frac{e L_z \hbar^4 E_d v_l^4 \omega_{\vec{q}} \alpha^2 N_{\vec{q}}}{512\pi^2 m^{*3} \rho F S} \sum_{N,n,l,N',n',l'} U_{n,l,n',l'}^2(\vec{q})(SH5 + SH6) \right\} \\ &\quad \times \frac{\tau(\varepsilon_F)}{1 + \omega_c^2 \tau^2(\varepsilon_F)} [\delta_{ik} + \omega_c \tau(\varepsilon_F) \epsilon_{ikj} + \omega_c^2 \tau^2(\varepsilon_F) h_j h_k] \end{aligned} \quad (14)$$

here, τ is the momentum relaxation time, δ_{ik} is the Kronecker delta, ξ_{ijk} is the asymmetric Levi - Civita tensor.

$$\begin{aligned} SH1a &= -\frac{x_1^2}{\sqrt{\Delta_{11} \Delta_{n,l}}} \left(c_1^2 + d_1^2 - \frac{\alpha^2}{2} (c_1^4 + d_1^4) \right) + \frac{x_2^2}{\sqrt{\Delta_{12} \Delta_{n,l}}} \left(c_2^2 + d_2^2 - \frac{\alpha^2}{2} (c_2^4 + d_2^4) \right) \\ SH1b &= \frac{y_1}{\sqrt{\Delta_{I1} \Delta_{n',l'}}} \left[C_1^2 (y_1 - C_1) \left(1 - \frac{\alpha^2}{2} C_1^2 \right) + D_1^2 (y_1 - D_1) \left(1 - \frac{\alpha^2}{2} D_1^2 \right) \right] \\ &\quad + \frac{y_2}{\sqrt{\Delta_{I2} \Delta_{n',l'}}} \left[C_2^2 (y_2 - C_2) \left(1 - \frac{\alpha^2}{2} C_2^2 \right) + D_2^2 (y_2 - D_2) \left(1 - \frac{\alpha^2}{2} D_2^2 \right) \right] \\ SH2 &= -\frac{x_1^2}{\sqrt{\Delta_{21} \Delta_{n,l}}} (g_1^3 + h_1^3) - \frac{x_2^2}{\sqrt{\Delta_{22} \Delta_{n,l}}} (g_2^3 + h_2^3) + \frac{y_1}{\sqrt{\Delta_{II1} \Delta_{n',l'}}} \end{aligned}$$

$$\begin{aligned}
& \times [(y_1 - G_1)G_1^3 + (y_1 - H_1)H_1^3] + \frac{y_2}{\sqrt{\Delta_{II2}\Delta_{n',l'}}} [(y_2 - G_2)G_2^3 + (y_2 - H_2)H_2^3] \\
SH4a = & -\frac{x_1^2}{\sqrt{\Delta_{41}\Delta_{n,l}}} \left(2 - \frac{\alpha^2}{2}(c_1^2 + d_1^2)\right) + \frac{x_2^2}{\sqrt{\Delta_{42}\Delta_{n,l}}} \left(2 - \frac{\alpha^2}{2}(c_2^2 + d_2^2)\right) \\
SH4b = & \frac{y_1}{\sqrt{\Delta_{IV1}\Delta_{n',l'}}} \left[(y_1 - C_1) \left(1 - \frac{\alpha^2}{2}C_1^2\right) + (y_1 - D_1) \left(1 - \frac{\alpha^2}{2}D_1^2\right) \right] \\
& + \frac{y_2}{\sqrt{\Delta_{IV2}\Delta_{n',l'}}} \left[(y_2 - C_2) \left(1 - \frac{\alpha^2}{2}C_2^2\right) + (y_2 - D_2) \left(1 - \frac{\alpha^2}{2}D_2^2\right) \right] \\
SH5 = & -\frac{x_1^2}{\sqrt{\Delta_{51}\Delta_{n,l}}} (g_1^2 + h_1^2) - \frac{x_2^2}{\sqrt{\Delta_{52}\Delta_{n,l}}} (g_2^2 + h_2^2) + \frac{y_1}{\sqrt{\Delta_{V1}\Delta_{n',l'}}} \\
& \times [(y_1 - G_1)G_1^2 + (y_1 - H_1)H_1^2] + \frac{y_2}{\sqrt{\Delta_{V2}\Delta_{n',l'}}} [(y_2 - G_2)G_2^2 + (y_2 - H_2)H_2^2] \\
\Delta_{n,l} = & \frac{2m^*}{\hbar^2} \left(\varepsilon_F + \frac{1}{2} \left(\frac{eE_1}{\omega_c} \right)^2 - \omega_c \left(N + \frac{1}{2} \right) \right) - \pi^2 \left(\frac{n^2}{L_x^2} + \frac{l^2}{L_y^2} \right) \\
x_1 = & \sqrt{\Delta_{n,l}}; x_2 = -\sqrt{\Delta_{n,l}} \\
\Delta_{11} = & x_1^2 - \pi^2 \left(\frac{n'^2 - n^2}{L_x^2} + \frac{l'^2 - l^2}{L_y^2} \right) + \frac{2m^*\Omega}{\hbar} \\
c_1 = & x_1 + \sqrt{\Delta_{11}}; d_1 = x_1 - \sqrt{\Delta_{11}}
\end{aligned} \tag{15}$$

In the above analytical expressions, by replacing n, l with n', l' , the expression of $\Delta_{n,l}, \Delta_1, x, c, d, \dots$ become $\Delta_{n',l'}, \Delta_I, y, C, D, \dots$, respectively. Then, by replacing the index number 1 with 2, the expression of $(eq)_1$ become $(eq)_2$. We using these presentations to mathematically express the symbols in each SH . The main different point between SHs is the last term in [...] of Δ_{aa} in (15). By adding $\frac{2m^*}{\hbar}\Omega$, $-\frac{2m^*}{\hbar}\Omega$, $\frac{2m^*}{\hbar}\omega_{\vec{q}}$, $\frac{2m^*}{\hbar}(\Omega + \omega_{\vec{q}})$ and $\frac{2m^*}{\hbar}(-\Omega + \omega_{\vec{q}})$ to be the last term of Δ_1 , we obtain the analytical expression of $\Delta_2, \Delta_3, \Delta_4, \Delta_5$ and Δ_6 , respectively. Using these relative evaluations for c_1 and d_1 , we also obtain the explicit expressions of $SH3$ from $SH2$ and $SH6$ from $SH5$. Take a look at (13) and (14), we could realize that 6-term in above expression stands for 6-root of the delta function with the argument of energy level. 6-term is calculated from delta function is the main different point compares to others low-dimensional system since the difference in expression of eigenfunction and eigenstate.

We use these above tensor expressions and the assumption of \vec{E}_1, \vec{B} and \vec{E} to calculate the 6-tensor appears in (12). So that, we obtain the physical expressions of AME field E_{AME} which is totally new finding and embodied for the AME effect in RQWIP. Later, we can use this E_{AME} expression to compared with other low dimension systems in analytical point of views.

3. Numerical results and discussion

In order to clarify the results obtained, in this section, we numerically calculate the AME field in a RQWIP subjected to the uniform crossed magnetic field and electric field in the presence of a strong EMW. For the numerical evaluation, we consider the GaAs/AlGaAs RQWIP with the parameters [18, 19]: $\rho = 5300 kg.m^{-3}$, $m^* = 0.067m_e$, m_e being the mass of free electron, $\Theta = 10^4 Wm^{-2}$, $v_s = 5370 m/s$, $e = 1.60219.10^{-19}$, $\tau_0 = 10^{-12} s$, $L_x = L_y = 100 nm$.

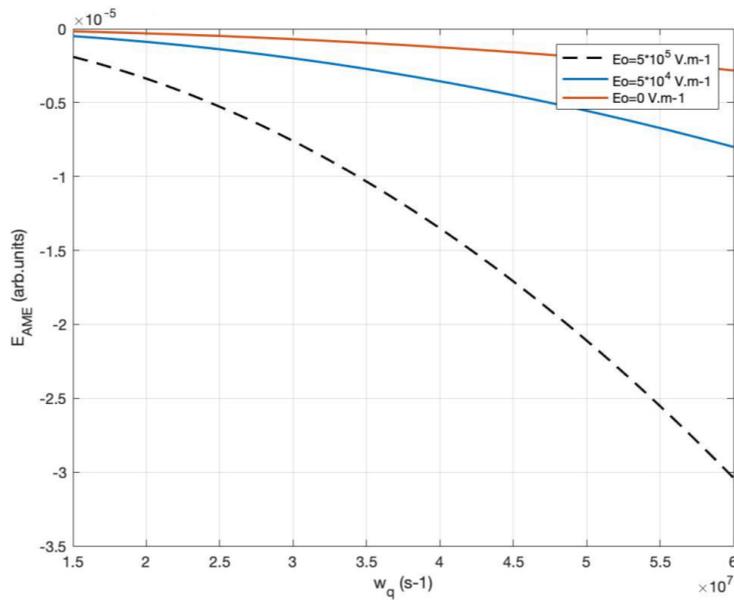


Figure 1: The dependence of the AME field on the external acoustic wave frequency

The Fig.1 shows the dependence of the AME field on external phonon frequency value in two cases: with and without electromagnetic wave. From the graph, we see that, without the presence of an EMW, the AME field magnitude is small and almost stable when the phonon frequency changes. Then, in the appearance of EMW, the AME field value is much bigger than the former case. It can be seen easily that the stronger EMW is, the bigger AME value. Moreover, we can also note that the AME field magnitude increases almost linearly in the weak frequency domain ($\omega_q \leq 3.5 \times 10^{-7} s$) and the E_{AME} values are almost the same in both cases of EMW. On the other hand, in strong frequency domain ($\omega_q \geq 3.5 \times 10^{-7} s$), the E_{AME} raises significantly as an exponential function and we can clearly observe three separate lines. This can be explained by the analytical contribution of ω_q in Delta functions in the expression of E_{AME} . This result brings us to the conclusion that EMW impacts strongly on the AME effect. In particular, the presence of EMW increases the value of E_{AME} and the E_{AME} growth rate especially in strong phonon frequency domain. Compare with our previous research about the AE field on quantum wells [17] and in bulk semiconductors [20, 21, 22, 23], the dependence of E_{AME} on ω_q is different. It can be explained that the single wave function and the energy spectrum are quantized differently compared to other low-dimensional systems, also the confined potential which is considered now is infinite potential and we also put our system in a strong EMW.

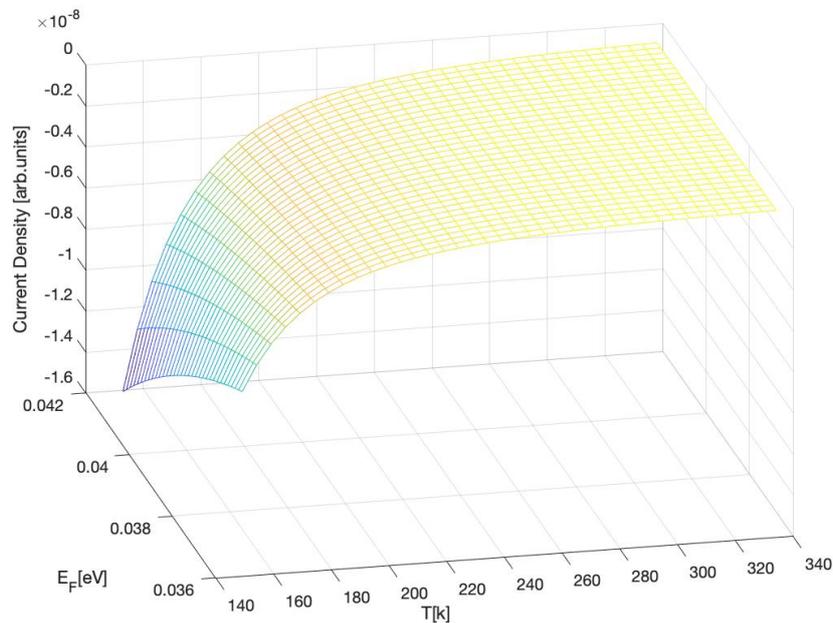


Figure 2: The dependence of the current density on the Fermi energy level and temperature

Fig.2, indicates the dependence of the current density on the Fermi energy level and temperature. As can be seen from the graph, the Fermi energy value impacts clearly on J in low temperature condition ($T \leq 180K$) and in high temperature condition, ($T \geq 180K$) J remains constant. Moreover, also in consideration of high temperature, the magnitude of J steadies a stable at a small value ($\approx 0.2 \times 10^{-8} eV$), this is about consistent to our previous research without the presence of EMW [24]. The influence of temperature in AME effect is quite delicate since the complication in analysis and the high temperature limitation of Boltzmann kinetic equation method. We use the QKE method to overcome the limitation so that the result about temperature is specially new in low-temperature domain. In term of Fermi level, we just consider low temperature condition as mentioned above, J depends on ε_F as a parabolic curve and tends to be asymptotic when ε_F reaches high value. This can be explained as the fact that when ε_F is big, the impact of EMW and size-reduction effect on Delta term in J expression are bland. The results now become to the bulk semiconductor cases.

The Fig. 3 shows the dependence of AME field on the length of the QW L_z in two cases: with and without EMW. From graph, we observe that the oscillation appears in short length L_z condition ($\leq 0.1nm$). The E_{AME} fluctuates wildly and reach a peak of $L_z \approx 0.012nm$ and this point seem to be constant when EMW changes. The difference is the E_{AME} peaks at diverse value depends on how strong EMW is. In particular, without EMW ($E_o = 0 Vm^{-1}$) the E_{AME} peak is roughly -0.5×10^{-8} and approximately -2.8×10^{-8} with strong EMW condition ($E_o = 4 \times 10^5 Vm^{-1}$). This oscillation could be explained as the contribution of RQWIP form factor and we can use this to discriminate RQWIP from other low-dimension systems. This leads to the same conclusion from figure 1 that the impact of EMW on AME effect in general and E_{AME} in particular is value booster and it does not change the analytic influence of other system parameters on effect. Furthermore, in long length condition, this means the size-reduction effect might disappear and the magnitude of E_{AME} is a straight line and about (0 arb.units) as obvious. The accuracy of our calculations is verified and we could use the above results to apply on reality RQW construction processing.

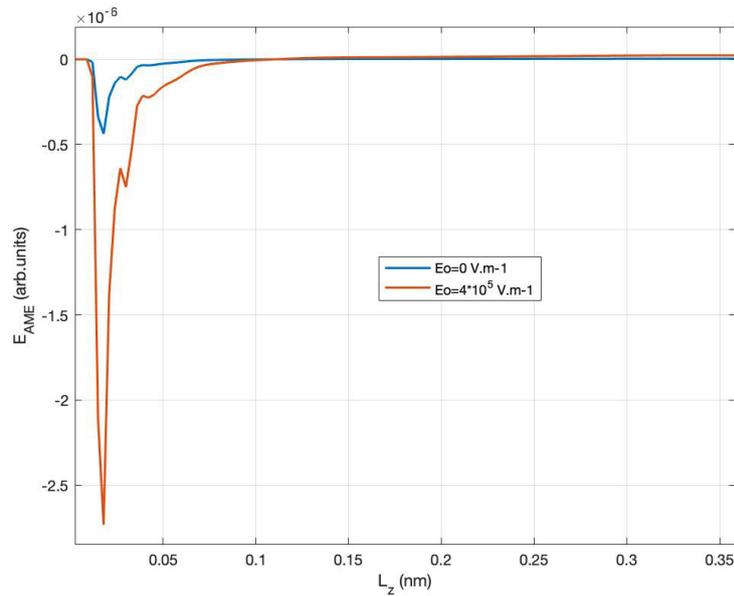
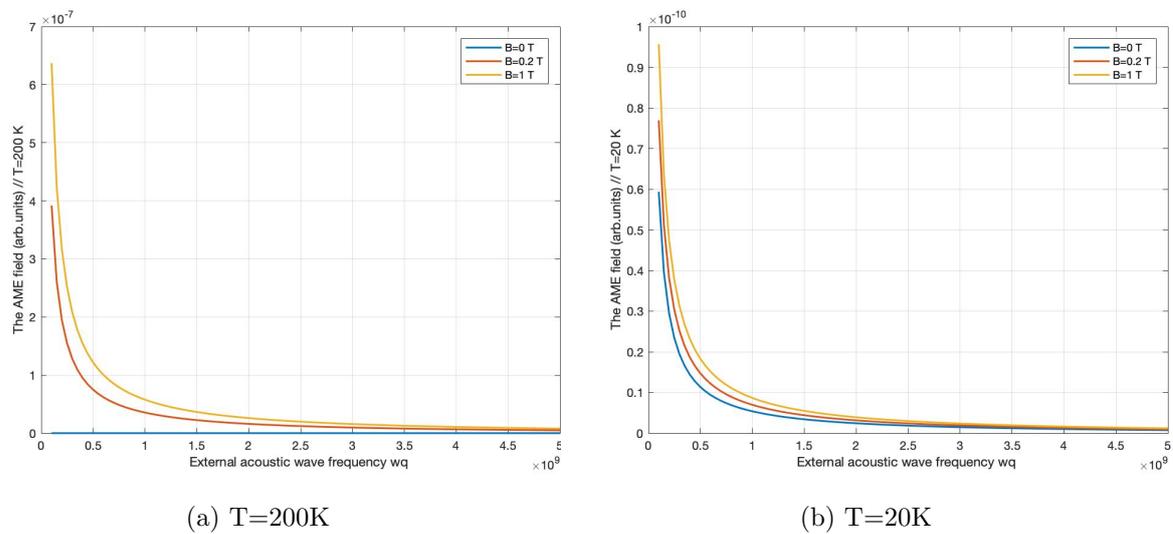


Figure 3: The dependence of the AME field on the length of the QW



(a) $T=200\text{K}$

(b) $T=20\text{K}$

Figure 4: The dependence of the AME field on the external acoustic wave frequency

The Fig.4 describes the influence of AME field value on the external acoustic wave frequency $w_{\vec{q}}$ in low and high temperature condition ($T = 20\text{ K}$ and $T = 200\text{ K}$). Initially, the 200K temperature RQWIP graph shows that, the AME field is much stronger compared to the 20K temperature case. Perhaps due to the quantum effect that in high temperature condition, the phonon which is calculated as Bose-Einstein condensed state distribution function will move as simple harmonic oscillator. When the acoustic wave frequency changes, the cycle of oscillation also changes. The energy levels of phonon are separated into Landau levels, with each Landau level, cyclotron energy and the phonon energy linearly increase with the magnetic field. When the energy level of Landau levels exceeds the value of Fermi level, the phonon can move up

freely. It also give us the reason why the magnetic field impact a lot on the AME field. Then, in low temperature condition, as considered above, we can only calculate the AME field in low temperature case by using QKE. The result is basically similar to the case of high temperature with the same parabolic curved but much smaller value. The impact of magnetic field on AME field in this case is tiny and could be considered as no impact since the value of AME field almost the same in three different magnetic B value. The resonance in low temperature and strong magnetic field which often appears in other quantum kinetic effects also vanished. This might due to the different in the physical expression of AME field and acoustomagnetolectric effect compared to other specific effects. This is the new finding of our research and affirm the efficiency and effectiveness of QKE method in solving kinetic quantum effects.

4. Conclusions

In summary, we manipulate the QKE to calculate the current density and the AME field analytical representation in presence of a strong EMW in GaAs/AlGaAs RQWIP. We have expressed the dependence of \vec{J} and E_{AME} on the amplitude of a EMW, the frequency of acoustic wave ω_q , Fermi energy level ε_F , system temperature T and the length of the RQWIP L_z . The result shows that E_{AME} and J depends exponentially on ω_q , ε_F and T but different value and tendency. This result obtained due to the complication in analytical expression of E_{AME} on these above parameters. Surveying the influence of L_z on E_{AME} , we find out that the oscillation appears wildly in short L_z period and a steady level in the remained domain. The impact of EMW is crucial as the E_{AME} value booster, it makes the magnitude of E_{AME} becomes higher and does not change the dependence of the AME field on other parameters also the peak positions, particularly. Also, the effect of low temperature to the AME field is revealed in this paper. The E_{AME} in high temperature is much stronger than the case of low temperature even with different magnetic field values. Our results we obtained from research is new and contribute to the theoretical quantum AME effect in low-dimensional semiconductor system. We expect it to become an useful data source for the future experimental observation and fabrication.

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