The Influence of the Electromagnetic Wave on the Quantum Acoustomagnetoelectric Field in a Quantum Well with a Parabolic Potential

N. Q. Bau[1] **and N. V. Hieu**[2]

[1]Faculty of Physics, Hanoi University of Science, Vietnam National University, Hanoi, Vietnam
[2]Faculty of physics, Danang University of Education, Danang, Vietnam

Abstract— The influence of the electromagnetic wave on the quantum acoustomagnetoelectric (QAME) field in a quantum well with a parabolic potential (QWPP) is investigated for an acoustic wave whose wavelength $\lambda = 2\pi/q$ is smaller than the mean free path l of the electrons and in the region $ql \gg 1$ (where q is the acoustic wave number). The dependence of the QAME field E^{QAME} on the frequency of external acoustic wave ω_q, the temperature T, the magnetic field B, the amplitude E_0 and frequency Ω of the electromagnetic wave are obtained by using the quantum kinetic equation. Numerical calculation is done, and the result is discussed for a typical AlAs/GaAs/AlAs QWPP. The computational results show that the dependence of the QAME field E^{QAME} on the external acoustic wave frequency ω_q, the frequency of electromagnetic wave Ω and the magnetic field B is non-monotonic, the cause of appearance peaks attributes the transition between mini-bands $N \to N'$. The quantum theory of the QAME current in a QW is newly developed.

1. INTRODUCTION

The acoustic waves propagate along the stress-free surface of an elastic medium has attracted much attention in the past two decades because of their utilization in acoustoelectronics. Considerable interest in such waves has also been stimulated by the possibility of their use as a powerful tool for studying the electronic properties of the surfaces and thin layers of solids.

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 acoustoelectri field. Presently this effect has been studied in detail both theoretically and experimentally and has been found in wide application in radioelectrionic systems [1–3]. The presence of an external magnetic field applied perpendicularly to the direction of the sound wave propagation in a conductor can induce another field, the so-called AME field. It was predicted by Galperin and Kagan [4] and observed in bismuth by Yamada [5]. Calculations of the AME field in bulk semiconductor [6–9] and the Kane semiconductor [10] in both cases The weak and the quantized magnetic field regions have been investigated. In recent years, the AME field in low-dimensional structures have been extensively studied [11, 12]. However, the calculation of the QAME field E^{QAME} and influence of the electromagnetic wave on QAME field in QWPP by using the quantum kinetic equation method is still open for study. In the present work, we use the quantum kinetic equation method to study the influence of the electromagnetic wave on the QAME field E^{QAME} induced by the electron-external acoustic wave interactions and the present work is different from previous works [13–18] because 1) we use the quantum kinetic equation method, 2) we calculated the influence of an electromagnetic wave on E^{QAME}. Numerical calculations are carried out for a specific quantum well AlAs/GaAs/AlAs to clarify our results. This paper is organized as follows. In Section 2, we find analytic expression for the QAME field in the QWPP, in Section 3 we discuss the results, and in Section 4 we come to a conclusion.

2. ANALYTIC EXPRESSION FOR THE AME FIELD IN THE QWPP

When the magnetic field is applied in the x-direction, in that case the vector potential is chosen as: $A = A_y = -zB$. If the confinement potential is assumed to take the form $V(z) = m\omega^2 z^2/2$ the eigenfunction of an unperturbed electron is expressed as

$$\psi_{N,\vec{p}}(r) = \left(\frac{2}{L_x L_y}\right)^{1/2} \phi_N(z - z_0) \times \exp(ip_x x)\exp(ip_y y), \tag{1}$$

where L_x and L_y are the normalization length in the x and y direction, respectively, $\phi_N(z-z_0)$ is the oscillator wavefunction centred at $z_0 = p_y\Omega_c/[m(\Omega_c^2+\omega^2)]$, m is the effective mass of a conduction electron, ω and Ω_c are the characteristic frequency of the potential and the cyclotron frequency, respectiverly, $N = 0, 1, 2, \ldots$ is the azimuthal quantum number; $\vec{p} = (p_x, p_y, 0)$ is the electron momentum vector. The electron energy spectrum takes the form

$$\varepsilon_N(\vec{p}) = \Omega_0(N+1/2) + \frac{p_x^2}{2m} + \frac{p_y^2}{2m}\left(\frac{\omega}{\Omega_0}\right)^2, \tag{2}$$

with $\Omega_0 = (\Omega_c^2+\omega^2)^{1/2}$ and $\Omega_c = eB/m$.

Let us suppose that the acoustic wave of frequency ω_q is propagated along the z QWPP axis (along the z direction, the energy spectrum of electron is quantizied or the motive direction of electron is limited) and the magnetic field is oriented along the x axis. We consider the most realistic case from the point of view of a low-temperature experiment, when $\omega_q/\eta = c_s|q|/\eta \ll 1$, $ql \gg 1$, where c_s is the velocity of the acoustic wave and q is the modulus of the acoustic wave vector and l is the electron mean free path. The compatibility of these conditions is provided by the smallness of the sound velocity in comparison with the characteristic velocity of the Fermi electrons. The acoustic wave will be considered as a packet of coherent phonons with the delta-like distribution function $N_{\vec{k}} = (2\pi)^3\Phi\delta(\vec{k}-\vec{q})/\omega_q c_s$ in the wavevector $\vec{k}$ space, Φ is the sound flux density. The Hamiltonian describing the interaction of the electron-phonon system in the QWPP, which can be written in the secondary quantization representation as

$$H = \sum_{N,\vec{k}} \varepsilon_N\left(\vec{k} - \frac{e}{c}\vec{A}(t)\right) a^+_{N,\vec{k}} a_{N,\vec{k}} + \sum_{N,\vec{k},N',\vec{q}} C_{\vec{q}} U_{N,N'}(\vec{q}) a^+_{N',\vec{k}} a_{N',\vec{k}+\vec{q}} b_{\vec{q}} \exp(-i\omega_{\vec{q}} t), \tag{3}$$

with $C_{\vec{q}}$ is the electron-phonon interaction factor and takes the form [11]

$$C_{\vec{q}} = i\Lambda c_l^2(\hbar\omega_{\vec{q}}^3/2\rho_0\Xi S)^{1/2}, \qquad \Xi = q\Big[\frac{1+\sigma_l^2}{2\sigma} + \left(\frac{\sigma_l}{\sigma_t} - 2\right)\frac{1+\sigma_t^2}{2\sigma_t}\Big], \tag{4}$$

$$\sigma_l = (1 - c_s^2/c_l^2)^{1/2} \qquad \sigma_t = (1 - c_s^2/c_t^2)^{1/2}, \tag{5}$$

Λ is the deformation potential constant; $a^+_{N,\vec{k}}$ and $a_{N,\vec{k}}$ are the creation and the annihilation operators of the electron, respectively; $b_{\vec{q}}$ is the annihilation operator of the external phonon. $|N,\vec{k}\rangle$ and $|N',\vec{k}+\vec{q}\rangle$ are electron states before and after interaction, $U_{N,N'}(\vec{q})$ is the matrix element of the operator $U = \exp(iqy - \lambda z)$, $\lambda = (q^2 - \omega_q^2/c_l^2)^{1/2}$ is the spatial attenuation factor of the potential part the displacement field; c_l and c_t are the velocities of the longitudinal and the transverse bulk acoustic wave; ρ_0 is the mass density of the medium and $S = L_xL_y$ is the surface area. $\vec{A}(t)$ is the vector potential of an external electromagnetic wave $\vec{A}(t) = \frac{e}{\Omega}\vec{E}_0\sin(\Omega t)$, Ω is the frequency of electromagnetic wave. The quantum kinetic equation of the problem which is that equation for the distribution function of electrons interacting with external phonons in the presence of an external magnetic fields in QWPP:

$$\begin{aligned}
&-\left(e\vec{E} + \Omega_c[\vec{h},\vec{p}]\right)\frac{\partial f_{N,\vec{p}}}{\partial p} \\
&= -\frac{f_{N,\vec{p}} - f_0}{\tau} + \sum_{N',\vec{k}} |C_{\vec{k}}|^2 |U_{N,N'}|^2 \sum_{l,s} J_l\left(\frac{e\vec{E}_0\vec{k}_\perp}{m\Omega^2}\right) J_{l+s}\left(\frac{e\vec{E}_0\vec{k}_\perp}{m\Omega^2}\right)\exp(-is\Omega t) \\
&\times\Big(\Big[f_{N',\vec{p}+\vec{k}}(N_{\vec{k}}+1) - f_{N,\vec{p}}N_{\vec{k}}\Big]\delta(\varepsilon_{N',\vec{p}+\vec{k}} - \varepsilon_{N,\vec{p}} - \omega_{\vec{k}} - l\Omega) \\
&+[f_{N',\vec{p}-\vec{k}}N_{\vec{k}} - f_{N,\vec{p}}(N_{\vec{k}}+1)]\delta(\varepsilon_{N',\vec{p}-\vec{k}} - \varepsilon_{N,\vec{p}} + \omega_{\vec{k}} - l\Omega)\Big),
\end{aligned} \tag{6}$$

Multiply both sides of Eq. (6) by $(e/m)\vec{p}\delta(\varepsilon - \varepsilon_{N,\vec{p}})$ and carry out the summation over N and $\vec{p}$, we have the equation for the partial current density $\vec{R}_{N,N'}(\varepsilon)$ (the current caused by electrons which have energy of ε):

$$\frac{\vec{R}_{N,N'}(\varepsilon)}{\tau(\varepsilon)} + \Omega_c[\vec{h}, \vec{R}_{N,N'}(\varepsilon)] = \vec{Q}_N(\varepsilon) + \vec{S}_{N,N'}(\varepsilon), \tag{7}$$

where

$$\vec{Q}_N(\varepsilon) = -\sum_{N,\vec{p}} e\frac{\vec{p}}{m}\left(\vec{E}, \frac{\partial f_{N',\vec{p}}}{\partial \vec{p}}\right)\delta(\varepsilon - \varepsilon_{N,\vec{p}}),$$

$$\vec{S}_{N,N'}(\varepsilon) = \frac{(2\pi)^3|C_{\vec{q}}|^2\Phi}{\omega_{\vec{q}}c_s}\sum_{N,N',\vec{p},\vec{k}}|U_{N,N'}|^2\sum_{l,s}J_l\left(\frac{e\vec{E}_0\vec{k}_\perp}{m\Omega^2}\right)J_{l+s}\left(\frac{e\vec{E}_0\vec{k}_\perp}{m\Omega^2}\right)\exp(-is\Omega t)\frac{\vec{p}}{m}\delta(\varepsilon - \varepsilon_{N,\vec{p}})$$
$$\times\delta(\vec{k}-\vec{q})\Big((f_{N',\vec{p}+\vec{k}} - f_{N,\vec{p}})\delta(\varepsilon_{N',\vec{p}+\vec{k}} - \varepsilon_{N,\vec{p}} - \omega_{\vec{k}} - l\Omega) + (f_{N',\vec{p}-\vec{k}} - f_{N,\vec{p}})\delta(\varepsilon_{N',\vec{p}-\vec{k}} - \varepsilon_{N,\vec{p}} + \omega_{\vec{k}} - l\Omega)\Big).$$

Solving the Eq. (7), we obtained the partial current $\vec{R}_{N,N'}(\varepsilon)$

$$\begin{aligned}\vec{R}_{N,N'}(\varepsilon) \;=\; & \frac{\tau(\varepsilon)}{1+\Omega_c^2\tau^2(\varepsilon)}\Big\{\left(\vec{Q}_N(\varepsilon)+\vec{S}_{N,N'}(\varepsilon)\right)\tau(\varepsilon) \\ & -\Omega_c\tau(\varepsilon)\left([\vec{h},\vec{Q}_N(\varepsilon)]+[\vec{h},\vec{S}_{N,N'}(\varepsilon)]\right)+\Omega_c^2\tau^2(\varepsilon)\left(\vec{Q}_N(\varepsilon)+\vec{S}_{N,N'}(\varepsilon),\vec{h}\right)\vec{h}\Big\},\end{aligned} \quad (8)$$

the total current density is generally expressed as

$$\vec{j} = \int_0^\infty \vec{R}_{N,N'}(\varepsilon)d\varepsilon, \quad (9)$$

we find the current density

$$j_i = \alpha_{ij}E_j + \beta_{ij}\Phi_j, \quad (10)$$

where α_{ij} and β_{ij} are the electrical conductivity and the acoustic conductivity tensors, respectively

$$\alpha_{ij} = \frac{e^2n_0}{m}\Big\{a_1\delta_{ij} - \Omega_c a_2\epsilon_{ijk}h_k + \Omega_c^2 a_3 h_i h_j\Big\}; \qquad \beta_{ij} = A\Big\{b_1\delta_{ij} - \Omega_c b_2\epsilon_{ijk}h_k + \Omega_c^2 b_3 h_i h_j\Big\}, \quad (11)$$

here ϵ_{ijk} is the unit antisymmetric tensor of third order, n_0 is the carrier concentration, and a_x, b_x $(x = 1, 2, 3)$ are given as

$$\begin{aligned} a_x \;=\; & \frac{m^2}{\pi n_0}\int_0^\infty \frac{\tau^x(\varepsilon)}{1+\Omega_c^2\tau^2(\varepsilon)}\left(\varepsilon - \Omega_0(N+1/2)\right)\frac{\partial f_0}{\partial\varepsilon}d\varepsilon; \qquad b_x = \int_0^\infty \frac{\tau^x(\varepsilon)}{1+\Omega_c^2\tau^2(\varepsilon)}\frac{\partial f_0}{\partial\varepsilon}d\varepsilon, \\ A \;=\; & \frac{8e\pi^3|C_q|^2E_0}{\omega_q c_s\Omega^3}\sum_l\frac{1}{l\Big[(l\Omega\tau)^2+1\Big]}\sum_{N,N'}\frac{4}{(L_yL_x)^2}(2\pi)^4\Big[L_N^0\left(\frac{-\lambda^2}{m\Omega_0}\right)\Big]^2\frac{q}{m(2\pi)^2} \\ & \times\exp\left(-\frac{\lambda^2}{4m\Omega_0} - \frac{2\lambda\Omega_c^2}{m\Omega_0^3}q\right)\Big\{\delta\left((N'-N)\Omega_0 - \omega_q - l\Omega\right) - \delta\left((N'-N)\Omega_0 + \omega_q - l\Omega\right)\Big\}.\end{aligned}$$

We considered a situation whereby the sound is propagating along the x axis and the magnetic field B is parallel to the z axis and we assume that the sample is opened in all directions, so that $j_i = 0$. Therefore, from Eq. (10) we obtained the expression of the AME field E_{AME}, which appeared along the y axis of the sample

$$\begin{aligned} E_y \;=\; & E_{AME} = \frac{\beta_{zz}\alpha_{yz} - \beta_{yz}\alpha_{yy}}{\alpha_{yy}^2+\alpha_{yz}^2}\Phi = \frac{\pi\Omega_c A\tau_0\Phi}{e^2mk_BT}.\Big\{F_{2\nu,2\nu}F_{\nu+1,2\nu} - F_{\nu,2\nu}F_{2\nu+1,2\nu}\Big\} \\ & \times\left\{\left(F_{\nu+1,2\nu} - \frac{\Omega_0(N+1/2)}{k_BT}F_{\nu,2\nu}\right)^2 + \Omega_c^2\tau_0^2\left(F_{2\nu+1,2\nu} - \frac{\Omega_0(N+1/2)}{k_BT}F_{2\nu,2\nu}\right)^2\right\}^{-1}\end{aligned} \quad (12)$$

where $F_{\nu,\nu'} = \int_0^\infty \frac{x^\nu}{1+\Omega_c^2\tau_0^2x^{\nu'}}\frac{\partial f_0}{\partial x}dx$. The Eq. (12) is the AME field in the QWPP in the case of the external magnetic field and electromagnetic wave. We can see that the dependence of the AME field on the external magnetic field, the frequency $\omega_{\vec{q}}$ and the frequency of electromagnetic wave is nonlinear. We will carry out further analysis of the Eq. (12) separately for the two limiting cases: the weak magnetic field region and the case of quantized one.

2.1. The Case of Weak Magnetic Field Region

In the case of the weak magnetic field

$$\Omega_c \ll k_B T; \qquad \Omega_c \ll \eta, \tag{13}$$

in this case, the expression of E_{AME} in the Eq. (12) takes the form

$$E_{AME} = \frac{\pi\Omega_c A\tau_0\Phi}{e^2 m k_B T}\left\{F_{2\nu,2\nu}F_{\nu+1,2\nu} - F_{\nu,2\nu}F_{2\nu+1,2\nu}\right\}\left\{F^2_{\nu+1,2\nu} + \Omega_c^2\tau_0^2 F^2_{2\nu+1,2\nu}\right\}^{-1}, \tag{14}$$

2.2. The Case of Quantized Magnetic Field Region

In the case of quantized magnetic field region

$$\Omega_c \gg k_B T, \qquad \Omega_c \gg \eta, \tag{15}$$

in this case, the expression of E_{AME} in Eq. (12) takes the form

$$E_{AME} = \frac{\pi\Omega_c A\tau_0 k_B T\Phi}{e^2 m\Omega_0^2 (N+1/2)^2}\left\{F_{2\nu,2\nu}F_{\nu+1,2\nu} - F_{\nu,2\nu}F_{2\nu+1,2\nu}\right\}\left\{F^2_{\nu,2\nu} + \Omega_c^2\tau_0^2 F^2_{2\nu,2\nu}\right\}^{-1}, \tag{16}$$

From Eq. (14) and Eq. (16), we see that in both cases, the weak magnetic field and the quantized magnetic field, the dependence of AME field on external magnetic field B is nonlinear.

3. NUMERICAL RESULTS AND DISCUSSIONS

To clarify the results that have been obtained, in this section, we considered the AME field in two limited cases weak magnetic field region and the case of quantized magnetic field region in QWPP. This quantity is considered as a function of an external magnetic field B, the frequency ω_q of ultrasound, the temperature T of system, and the parameters of the AlAs/GaAs/AlAs quantum well. The parameters used in the numerical calculations are as follow: $\tau_0 = 10^{-12}$ s, $\Phi = 10^4\,\mathrm{Wm}^{-2}$, $m = 0.067m_0$, m_0 being the mass of free electron, $\rho_0 = 5320\,\mathrm{kg\ m}^{-3}$, $c_l = 2\times10^3\,\mathrm{m\ s}^{-1}$, $c_t = 18\times10^2\,\mathrm{m\ s}^{-1}$, $c_s = 8\times10^2\,\mathrm{m\ s}^{-1}$, $\Lambda = 13.5\,\mathrm{eV}$, $\omega_q = 10^9\,\mathrm{s}^{-1}$.

Figure 1 present The dependence of the QAME field on the magnetic field at different values of the frequency of electromagnetic wave shows that when magnetic field rises up, the QAME field increases monotonically. However, it reached a maximum value at B is about 0.12 T, and decreased again above 0.12 T. On the other hand, E^{QAME} increases nonlinearly with the magnetic field. This result is different from those for bulk semiconductor [11-14] and the Kane semiconductor [15] under condition $ql \gg 1$, and the weak magnetic field region. Because the QAME field expression E_{AME} in bulk semiconductor [11–14] and the Kane semiconductor [15] is proportional to B. In other words, E^{QAME} increases linearly with the magnetic field. Our result indicates that the dominant mechanism for such a behaviour is attributed to the electron confinement in the QWPP. From Figure 1, we see that the E^{QAME} depends significantly on the frequency of electromagnetic wave, when the frequency of electromagnetic wave increase the position of the peaks change.

Figure 2 investigated the dependence of QAME field on the magnetic field in the quantized magnetic field region which have many distinct maxima. The result showed the different behaviour from results in bulk semiconductor [11–14] and the Kane semiconductor [15]. Different from the bulk semiconductor, these peaks in this case are much sharper. According to the result in the bulk semiconductor [11–14] and the Kane semiconductor [15] in the case of strong magnetic field E^{QAME} which is proportional to $\frac{1}{B}$. 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 QWPP, that means above $B > 1.8T$ and below 4 K, carriers in the samples satisfy the quantum limit conditions: $\Omega_c \gg k_B T$ and $\Omega_c\tau \gg 1$, and in the QWPP the energy spectrum of electron is quantized. Also, the result is different from those in superlattice [16, 17]. In [16, 17] by using the Boltzmann kinetic equation, QAME field is proportional to B with all regions of temperature. By using the quantum kinetic equation method, our result indicate that it is only linear to B in case of the weak magnetic field and higher temperature, while in case of the strong magnetic field and low temperature QAME field is not proportional to B, but there are many peaks in Figure 2. This is our new development.

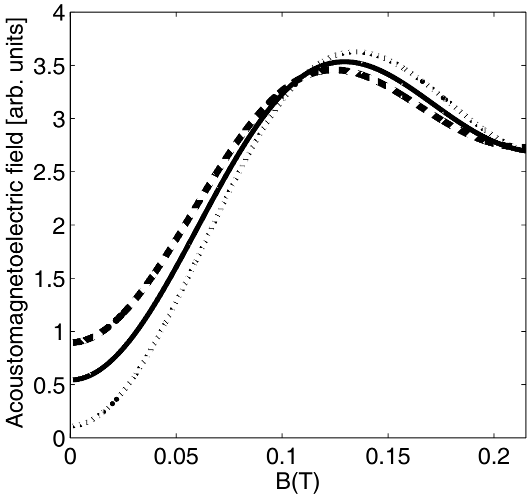

Figure 1: Dependence of the E^{QAME} field QAME on the magnetic field B at different values of the frequency of electromagnetic wave $\Omega = 8\times10^{13}\,\mathrm{s}^{-1}$ (dot line), $\Omega = 9\times10^{13}\,\mathrm{s}^{-1}$ (solid line), $\Omega = 10\times10^{13}\,\mathrm{s}^{-1}$ (dashed line). Here $T = 280\,\mathrm{K}$.

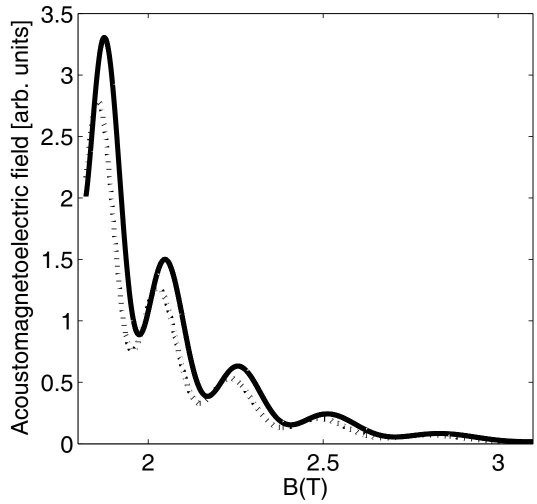

Figure 2: Dependence of the E^{QAME} field QAME on the magnetic field B at different values of the frequency of electromagnetic wave $\Omega = 8\times10^{13}\,\mathrm{s}^{-1}$ (solid line), $\Omega = 9\times10^{13}\,\mathrm{s}^{-1}$ (dot line). Here $T = 4\,\mathrm{K}$.

4. CONCLUSION

In this paper, we have obtained analytical expressions for the QAME field in presence of the external electromagnetic wave in a QWPP for both the case of quantized magnetic field and the weak magnetic field region. There is a strong dependence of QAME field on the cyclotron frequency Ω_c of the magnetic field, $\omega_{\vec{q}}$ of the acoustic wave, and the temperature T of system. The numerical result obtained for AlAs/GaAs/AlAs QWPP shows that in the quantized magnetic field region, the dependence of QAME field on the magnetic B is nonlinear, and there are many distinct maxima. This dependence has differences in comparison with that in normal bulk semiconductors [12–14] and the Kane semiconductor [15].

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