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THE ACOUSTOMAGNETOELECTRIC CURRENT OF A RECTANGULAR QUANTUM WIRE WITH AN INFINITE POTENTIAL IN THE PRESENCE OF AN EXTERNAL MAGNETIC FIELD

NGUYEN VAN NGHIA
Department of Physics, Water Resources University
DINH QUOC VUONG
Quangninh Department of Education and Training
NGUYEN QUANG BAU
Department of Physics, College of Natural Sciences, Hanoi National University

Abstract. *The acoustomagnetoelectric effect in a rectangular quantum wire with an infinite potential in the presence of an external magnetic field is investigated by using Boltzmann kinetic equation for an acoustic wave whose wavelength $\lambda = 2\pi/q_z$ is smaller than the mean free path l of the electrons and hypersound in the region $q_z l \gg 1$, (where q_z is the acoustic wave number). The analytic expression for the acoustomagnetoelectric current I is calculated in the case: relaxation time of momentum τ is constant approximation and non-degenerate electron gas. The dependence of the expression for the acoustomagnetoelectric current I on the acoustic wave numbers q_z and on the parameters of the rectangular quantum wires is obtained. Numerical calculations have been done and result is analysed for GaAs rectangular quantum wire with an infinite potential. This result is also compared with the result of the experiment in the normal bulk semiconductors, the superlattices and the cylindrical quantum wire to show the different.*

I. INTRODUCTION

In recent times, there has been more and more interests in studying and discovering the behavior of low-dimensional system, in particular, one-dimensional systems, such as quantum wire. In quantum wires, the motion of electrons is restricted in two dimensions, so that can flow freely in one dimension. The confinement of electron in these systems has changed the electron mobility remarkably. This has resulted in a number of new phenomena, which concern a reduction of sample dimensions. These effects differ from those in bulk semiconductors, for example, electron-phonon interaction and scattering rates [1, 2] and acoustic-electromagnetic wave interaction [3].

It is well known that, when an acoustic wave propagates through a conductor, it is accompanied by a transfer of energy and momentum to the conducting electrons. This gives rise to what is called the acoustoelectric effect [4 - 6]. Recently, the acoustoelectric effect have investigated this effect in superlattices [7 - 9]. However, in the presence of a magnetic field the acoustic wave is propagated in the conductor can produce another effect called the acoustomagnetoelectric (AME) effect. The AME effect is creating an AME current (if the sample is short circuited in the Hall direction), or an AME field (if the sample is open) when a sample placed in a magnetic field $\vec{H}$ carried an acoustic wave propagating in a direction perpendicular to the magnetic field $\vec{H}$. The AME effect was studied first for bipolar semiconductors [10] and was observed experimentally in bismuth [11]. In past times, there are more and more interests in studying and discovering this effect in a bulk monopolar semiconductor [12], in a bulk semiconductor n-InSb [13]. In this specimen they observed that the AME effect occurs mainly because of the dependence of the electron relaxation time on the energy and when $\tau = constant$ the effect vanishes. Like the classical magnetic field, the effect also exists in the case of a quantized magnetic field, and the quantum acoustomagnetoelectric effects due to Rayleigh sound waves have investigated [14]. The AME effect problems in the bulk semiconductors [12, 13]; in superlattices [15] in the case non-degenerate electron gas and in superlattices [16] in the case degenerate electron gas have been investigated. However, the AME effect in the quantum wires has not been studied yet. Therefore, the purpose of this work is to examine this effect in the rectangular quantum wire (RQW) with an infinite potential for the case electron relaxation time which is not dependent on the energy and non-degenerate electron gas. Furthermore, we think the research of this effect may help us to understand the properties of quantum wire material. We have obtained the AME current I in the RQW with an infinite potential in the presence of an external magnetic field. The dependence of the expression for the AME current I on acoustic wave numbers q_z and on the parameters of the RQW with an infinite potential has been shown. Numerical calculations are carried out with a specific GaAs rectangular quantum wire to clarify our results.

II. ANALYTIC EXPRESSION FOR THE ACOUSTOMAGNETOELECTRIC CURRENT

It is well known that, when the wavelength $\lambda = \frac{2\pi}{q_z}$ of the acoustic wave will be considered shorter than the electron mean free path l (where $q_z l >> 1$), the sound wave can be treated as a packet of coherent phonons (monochromatic phonon) having a function distribution $N(\vec{k}) = \frac{(2\pi)^3}{\hbar\omega_{\vec{q}_z} v_s}\phi\delta(\vec{k} - \vec{q}_z)$. Where $\hbar = 1$, $\vec{k}$ is the current phonon wave vector, ϕ is the sound flux density, $\omega_{\vec{q}_z}$ and v_s are the frequency and the group velocity of sound wave with the wave vector $\vec{q}_z$, respectively. The problem will be solved in the quasi-classical case. The magnetic field will also be considered classically, and weak thus limiting ourselves to the linear approximation of magnetic field $\vec{H}$.

We shall consider a situation whereby the sound is propagating along the quantum wire axis (Oz), the magnetic field $\vec{H}$ is parallel to the (Ox) axis and the AME current appears parallel to the (Oy) axis. The electron energy spectrum $\varepsilon_{n,l,\vec{p}_z}$ of the RQW with an infinite potential is given by [17]

$$\varepsilon_{n,l,\vec{p}_z} = \frac{\vec{p}_z^2}{2m} + \frac{\pi^2\hbar^2}{2m}\left(\frac{n^2}{a^2} + \frac{l^2}{b^2}\right). \quad (1)$$

Here a and b are, respectively, the cross-sectional dimensional along x- and y-directions, n, l are the subband indexes, m is the electron effective mass, and p_z is the longitudinal (relative to the quantum wire axis) component of the quasi-momentum.

The density of the acoustoelectric current in the presence of magnetic field can be written in the form [15]

$$j^{AE} = \frac{2e}{(2\pi)^3}\int U^{AE}\psi_i d^3p, \tag{2}$$

with

$$U^{AE} = \frac{2\pi\phi}{\omega_{\vec{q}_z} v_s}\{|G_{\vec{p}_z-\vec{q}_z,\vec{p}_z}|^2[f_{\alpha'}(\vec{p}_z-\vec{q}_z)-f_\alpha(\vec{p}_z)]\delta(\varepsilon_{n,l,\vec{p}_z-\vec{q}_z}-\varepsilon_{n,l,\vec{p}_z}+\omega_{\vec{q}_z})$$
$$+|G_{\vec{p}_z+\vec{q}_z,\vec{p}_z}|^2[f_{\alpha'}(\vec{p}_z+\vec{q}_z)-f_\alpha(\vec{p}_z)]\delta(\varepsilon_{n,l,\vec{p}_z+\vec{q}_z}-\varepsilon_{n,l,\vec{p}_z}-\omega_{\vec{q}_z})\}. \tag{3}$$

Here $f_\alpha(\vec{p}_z)$ is the distribution function, α (α') characterizing the states of electron in the quantum wire before (after) scattering with phonon, $G_{\vec{p}_z-\vec{q}_z,\vec{p}_z}$ is the matrix element of the electron-phonon interaction and ψ_i $(i = x, y, z)$ is the root of the kinetic equation given by [15]

$$\frac{e}{c}(\vec{V}\times\vec{H})\frac{\partial\psi_i}{\partial p}+\widehat{W}_{\vec{p}}\{\psi_i\} = \vec{V}_i, \tag{4}$$

here $\vec{V}_i$ is the electron velocity, $\vec{V}$ is the average drift velocity of the moving charges and $\widehat{W}_{\vec{p}}\{...\} = (\partial f/\partial\varepsilon)^{-1}\widehat{W}\{(\partial f/\partial\varepsilon)...\}$. The operator $\widehat{W}$ is assumed to be Hermitian [18]. In the case of the relaxation time of momentum τ is approximately constant, the collision operator has form $\widehat{W}_{\vec{p}} = 1/\tau$. Solving Eq.(4) by the method of iteration, we get for the zero and the first approximation with $\psi_i = \psi_i^{(0)} + \psi_i^{(1)} + ...$ Inserting into Eq.(2) and taking into account the fact that $|G_{\vec{p}_z,\vec{p'}_z}|^2 = |G_{\vec{p'}_z,\vec{p}_z}|^2$, we obtain for the density of the acoustoelectric current the expression

$$j_i^{AE} = -\frac{e\phi}{2\pi^2 v_s\omega_{\vec{q}_z}}\int|G_{\vec{p}_z+\vec{q}_z,\vec{p}_z}|^2[f_{\alpha'}(\vec{p}_z+\vec{q}_z)-f_\alpha(\vec{p}_z)]\times$$
$$\times[V_i(\vec{p}_z+\vec{q}_z)\tau - V_i(\vec{p}_z)\tau]\delta(\varepsilon_{n,l,\vec{p}_z+\vec{q}_z}-\varepsilon_{n,l,\vec{p}_z}-\omega_{\vec{q}_z})d^3p-$$
$$-\frac{e^2\phi\tau^2}{2\pi^2 mcv_s\omega_{\vec{q}_z}}\int|G_{\vec{p}_z+\vec{q}_z,\vec{p}_z}|^2[f_{\alpha'}(\vec{p}_z+\vec{q}_z)-f_\alpha(\vec{p}_z)]\times$$
$$\times[(\vec{V}(\vec{p}_z+\vec{q}_z)\times\vec{H})_i-(\vec{V}(\vec{p}_z)\times\vec{H})_i]\delta(\varepsilon_{n,l,\vec{p}_z+\vec{q}_z}-\varepsilon_{n,l,\vec{p}_z}-\omega_{\vec{q}_z})d^3p. \tag{5}$$

The matrix element of the electron-phonon interaction [7, 15] is given $|G_{\vec{p}_z,\vec{q}_z}|^2 = \frac{|\Lambda|^2|\vec{q}_z|^2}{2\rho\omega_{\vec{q}_z}}$. Where Λ is the deformation potential constant and ρ is the crystal density of the RQW.

In Eq.(5), the first term is the expression of the density of the acoustoelectric current and the second term is the expression of the density of the AME current. If the external magnetic field does not exist, then the second term will not exist. Thus, the density of the AME current is expressed as

$$j_y^{AME} = -\frac{e\phi\vec{q}_z^2\tau^2|\Lambda|^2\Omega}{4\pi v_s\omega_{\vec{q}_z}^2\rho}\int[f_{\alpha'}(\vec{p}_z+\vec{q}_z)-f_\alpha(\vec{p}_z)][V_z(\vec{p}_z+\vec{q}_z)-V_z(\vec{p}_z)]\times$$
$$\times\delta(\varepsilon_{n,l,\vec{p}_z+\vec{q}_z}-\varepsilon_{n,l,\vec{p}_z}-\omega_{\vec{q}_z})d^3p, \tag{6}$$

where $\Omega = \frac{eH}{mc}$ is the cyclotron frequency and the Fermi-Dirac distribution function $f_\alpha(\vec{p}_z)$ in the usual form is given by

$$f_\alpha(\vec{p}_z) = \frac{1}{exp(\beta(\varepsilon_{n,l,\vec{p}_z} - \mu)) + 1}, \tag{7}$$

with $\beta = 1/k_bT$, k_b is the Boltzmann constant, T is the temperature of the RQW and μ is the chemical potential.

In the case a one-dimensional wire, for a non-degenerate electrons gas, the equilibrium electron distribution is described by the one-dimensional Maxwellian function and it is given by [17]

$$f_\alpha(\vec{p}_z) = n_L \left(\frac{\pi\hbar^2}{2mk_bT}\right)^{1/2} exp\left(-\frac{p_z^2}{2mk_bT}\right). \tag{8}$$

Substituting Eqs.(1) and (8) into Eq.(6) and taking into account the fact that $V_z(\vec{p}_z) = \frac{\partial\varepsilon_{n,l,\vec{p}_z}}{\partial p_z}$, we obtain for the AME current with the condition is satisfied then:

$$\varepsilon_F > \frac{\vec{p}_z^2}{2m} + \frac{\pi^2\hbar^2}{2m}\left(\frac{n^2}{a^2} + \frac{l^2}{b^2}\right) + \hbar\omega_{\vec{q}_z}. \tag{9}$$

Where ε_F is the Fermi energy and the inequalities in Eq.(9) is condition acoustic wave vector $\vec{q}_z$ to the AME effect exists. Therefor, we have obtained the expression AME current

$$I = \frac{e\phi|\Lambda|^2 q_z^3\tau^2\Omega abn_L}{4v_s\omega_{\vec{q}_z}^2\rho\hbar^2 m}\sum_{n,n',l,l'}\left[1 - exp\left[\frac{\pi^2\hbar^2}{2mk_bT}\left(\left(\frac{n'^2-n^2}{a}\right) + \left(\frac{l'^2-l^2}{b}\right)\right) + \frac{\hbar\omega_{\vec{q}_z}}{k_bT}\right]\right]. \tag{10}$$

Eq.(10) is the AME current in the RQW with an infinite potential in the case non-degenerate electron gas, the expression only obtained if the condition in Eq.(9) is satisfied.

III. NUMERICAL RESULTS AND DISCUSSION

In the paper, we consider a $GaAs$ quantum wire. The parameters used in the calculations are as follows [14, 16, 17]: $\tau = 10^{-12}s; \Lambda = 8eV; a = b = 100\mathring{A}; n_L = 1.0 \times 10^6 m^{-1}; \phi = 10^{14}Wm^{-2}; H = 2\times10^3 Am^{-1}; \rho = 2\times10^{13}kgm^{-3}; v_s = 5370ms^{-1}; \omega_{\vec{q}_z} = 10^{10}s^{-1}; m = 0.067m_e$, m_e being the mass of free electron.

In the figure 1, we show the dependence of the AME current on the acoustic wave number q_z with the area of cross-sectional $a = b = 100\mathring{A}$, the intensity of the magnetic field $H = 2\times10^3Am^{-1}$ and the temperature $T = 77$K, $T = 100$K and $T = 300$K. The curve of the AME current I strongly increases when the large value range of the acoustic wave number q_z and this value decreases when the temperature increases. Unlike the normal bulk semiconductors [12, 13], in the quantum wire the AME current is non-linear with the acoustic wave number q_z. These results are compared with those obtained in the superlattices [15, 16], the AME current have a non-linear with the acoustic wave number q_z. It is very different between the superlattices and the RQW with an infinite potential.

In the figure 2, we show the dependence of the AME current on the temperature T of the RQW with the acoustic wave number $q_z = 1.00\times10^6cm^{-1}$, $q_z = 1.68\times10^6cm^{-1}$ and $q_z = 1.80\times10^6cm^{-1}$. The value of the AME current strongly decreases with the

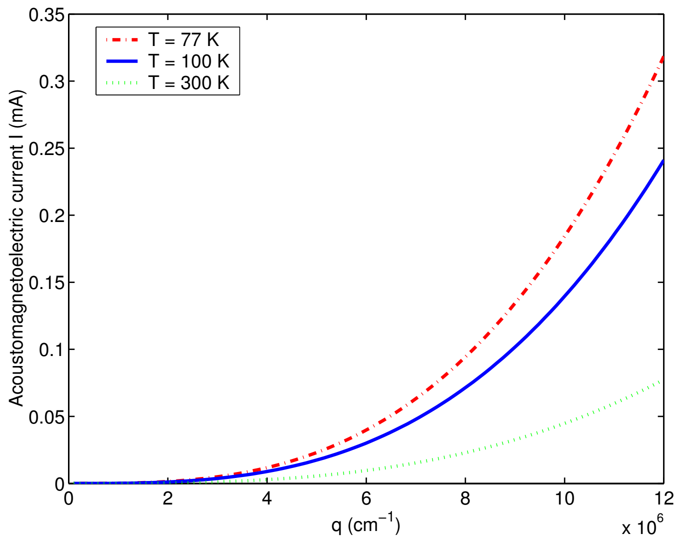

Fig. 1. The dependence of the AME current on the acoustic wave number q_z.

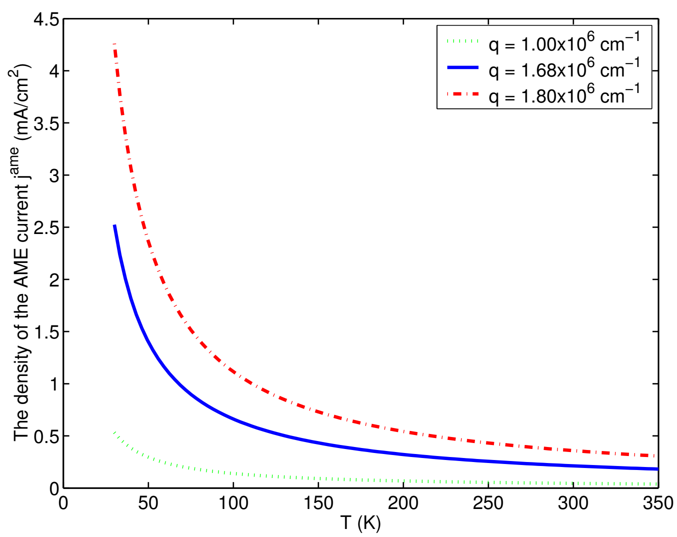

Fig. 2. The dependence of the AME current on the temperature T.

temperature when the temperature increases in the small value range the low temperature. This value is approximation constant in the high temperatures T.

In the figure 3, we show the dependence of the AME current on the cyclotron frequency Ω with the area of cross-sectional $a = b = 100\mathring{A}$, the acoustic wave number $q_z = 1.68 \times 10^6 cm^{-1}$ and the temperature $T = 77$K, $T = 100$K and $T = 300$K. When the intensity of the magnetic field rises up, the AME current I increases linearly with the

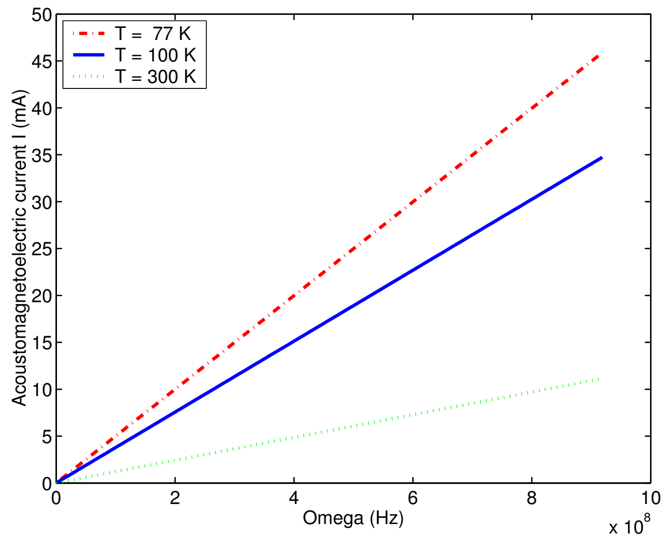

Fig. 3. The dependence of the AME current on the cyclotron frequency Ω.

cyclotron frequency Ω. This value also decreases when the temperature T of the RQW increases.

IV. CONCLUSION

In this paper, we have analytically investigated the possibility of the AME effect in the RQW with an infinite potential. We have obtained analytically expressions for the AME effect in the RQW with an infinite potential for the case non-degenerate electron gas. The dependences of the expression for the AME current I on the cyclotron frequency Ω, the frequency $\omega_{\vec{q}_z}$ of the acoustic wave, the temperature T and the cross-sectional area of the RQW are obtained. The result is different compared to those obtained in the normal bulk semiconductors [12, 13] and the superlattices [15, 16].

The numerical results have expressed the dependence of the AME current I on the acoustic wave number q, the cross-sectional area and the temperature of the RQW are performed for GaAs rectangular quantum wire with an infinite potential. The result shows that, the AME effect exists when the acoustic wave vector $\vec{q}_z$ complies with specific conditions in Eq.(9) which condition dependences on the frequency $\omega_{\vec{q}_z}$ of the acoustic wave, the mass of electrons, the temperature and the cross-sectional area of the RQW. The curve of the AME current I strongly increases when the low temperature and the large value range of the acoustic wave number q_z. The value of the AME current I is zero (the effect is not appear) when the small value range of the acoustic wave number q_z and the cross-sectional area of the RQW. That is mean to have AME current I, the acoustic phonons energy is high enough and satisfied in the some interval to impact much momentum to the conduction electrons.

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