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THE ACOUSTOMAGNETOELECTIC FIELD IN A QUANTUM WELL WITH AN INFINITY POTENTIAL

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Abstract: The acoustomagnetoelectric (AME) field in a quantum well with an infinity potential (QWIP) has been studied in the presence of an external magnetic field. The analytic expression for the AME field in the QWIP was obtained by using the quantum kinetic equation for the distribution function of electrons interacting with the acoustic wave. The dependence of the AME field on the temperature T of the system, the frequency of the acoustic wave ω_q, the quantum well width L and the external magnetic field B for the specific QWIP AlAs/GaAs/AlAs was achieved by using a numerical method. In the case of the dependence of the electromagnetic field on the external magnetic field and the frequency of the sound waves, the calculated results showed that this dependence was non-linear. These results were compared with those for the normal bulk semiconductor to show differences.

Key words: quantum well; acoustomagnetoelectric field; electron-phonon interaction; acoustic wave; quantum kinetic equation.

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. 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 [1] and observed in bismuth by Yamada [2]. In both cases of calculations of the AME field in bulk semiconductor [3] and the Kane semiconductor [4], 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 [5-6]. Up to now, however, almost all these works have been obtained by using the Boltzmann kinetic equation method, and are, 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.

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In low-dimensional systems, the energy levels of electrons become discrete and different from other dimensionalities [7]. Under certain conditions, the decrease in dimensionality of the system for semiconductors can lead to dramatically enhanced nonlinearities [8]. Thus the nonlinear properties, especially electrical and optical properties of semiconductor quantum wells (QWs), compositional superlattices (CSLs), quantum wires, and quantum dots (QDs) have attracted much attention in the past few years. For example, calculations of the nonlinear absorption coefficients of an intense electromagnetic wave by using the quantum kinetic equation for electrons in bulk semiconductors [9], in quantum wells [10] and in quantum wires [11] have also been reported. Throughout [9-11], the quantum kinetic equation method has been regarded as a powerful tool. Hence, in a recent work [12-13] we have used this method to calculate the quantum acoustoelectric current in the QW. The present work is different from previous works [1–6] because (1) we use the quantum kinetic equation method, (2) we show that the dependence of QAME field on the frequency of external acoustic wave, the temperature T of the system, and the external magnetic field B is nonlinear. Numerical calculations are carried out for a specific quantum well AlAs/GaAs/AlAs to clarify our results. This article is organized as follows. In section 2, we calculate the AME current in a QWIP and then received analytical expressions for the AME field in the QWIP in the presence of the EMF. In Section 3 we discuss the results, and in Section 4 we come to conclusions.

2. The analytic expression for the AME field in a QWIP

We use a simple model for a QW, in which an electron gas is confined by an infinite potential along the Oz direction (along the Oz direction, the energy spectrum of the electron is quantized, or the motive direction of electron is limited); electrons are free on the (x-y) plane. When the magnetic field is applied in the y-direction, the eigenfunction and eigenvalues of an unperturbed electron is expressed as $\varepsilon_n(p_x) = (n+\frac{1}{2})\hbar\Omega_c + \frac{p_x^2}{2m}$. Let us suppose that an external acoustic wave of frequency ω_q is propagating along the quantum well axis (Oz). In the presence of an external acoustic wave with frequency ω_q, the Hamiltonian of the electron-external phonon in a QWIP in the second quantization representation can be written as

$$H = \sum_{n,\vec{p}_x} \varepsilon_{n,\vec{p}_x} a^+_{n,\vec{p}_x} a_{n,\vec{p}_x} + \sum_{\vec{k}} \hbar\omega_{\vec{k}} b^+_{\vec{k}} b_{\vec{k}} + \sum_{n,n',\vec{p}_x,\vec{q}} C_{\vec{q}} U_{n,n'}(\vec{q}) a^+_{n,\vec{p}_x+\vec{q}_\perp} a_{n,\vec{p}_x} c_{\vec{q}} \exp(-i\omega_{\vec{q}} t) \quad (1)$$

where $C_q = i\Lambda v_l^2 \sqrt{\hbar\omega_q^3/(2\rho F S)}$ is the electron - external phonon interaction factor, Λ is the deformation potential constant, $a^+_{n,\vec{p}_x}(a_{n,\vec{p}_x})$ is the creation (annihilation) operator of the electron; $b^+_{\vec{k}}(b_{\vec{k}})$ is the creation (annihilation) operator of internal phonon and $c_{\vec{q}}$ is the annihilation operator of the external phonon,

$$F = q\left[(1+\sigma_l^2)/2\sigma_t + (\sigma_l/\sigma_t - 2)(1+\sigma_t^2)/2\sigma_t\right],$$

$\sigma_l = (1-v_s^2/v_l^2)^{1/2}$, $\sigma_t = (1-v_s^2/v_t^2)^{1/2}$, v_l (v_t) is the velocity of the longitudinal (transverse) bulk acoustic wave, $U_{n,n'}(\vec{q})$ is the matrix element of the operator $U = \exp(iqy - k_l z)$ ($k_l = (q^2 - (\omega_q/v_l)^2)^{1/2}$).

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

$$i\hbar \frac{\partial \left\langle a^+_{n,\vec{p}_x} a_{n,\vec{p}_x} \right\rangle_t}{\partial t} = \left\langle \left[a^+_{n,\vec{p}_x} a_{n,\vec{p}_x}, H \right] \right\rangle_t, \quad (2)$$

where the notation $\langle X \rangle_t$ means the usual thermodynamic average of the operator X, and $\left\langle a^+_{n,p_x} a_{n,p_x} \right\rangle_t = f_{n,p_x}(t)$ is the particle number operator or the electron distribution function.

With the use of the Hamiltonian of the electron-external phonon interaction in a CQWIP in the second quantization to replace the equation of motion of statistical average value for electrons and realize operator algebraic calculations, the acoustic wave will be considered as a packet of coherent phonons. We obtained the quantum kinetic equation for electrons in the single (constant) scattering time approximation in QWIP in the presence of an EMF, and then we find the current density of the AME current in the presence of an EMF in QWIP $j_i = \sigma_{ij} E_j + \eta_{ij}\phi_j$, where σ_{ij} is the electrical conductivity tensor, η_{ij} the acoustic conductivity tensor.

$$\sigma_{ij} = \frac{e^2}{\pi}(a_1\delta_{ij} - \Omega_c a_2 \varepsilon_{ijk} h_k + \Omega_c^2 a_3 h_i h_j) \quad (3)$$

$$\eta_{ij} = b_1\delta_{ij} - \Omega_c b_2 \varepsilon_{ijk} h_k + \Omega_c^2 b_3 h_i h_j \quad (4)$$

We considered a situation whereby the sound is propagating along the Oz axis and the magnetic field B is parallel to the Oy axis and we assume that the sample is opened in all directions, so that $j_i = 0$. Therefore, we obtained the expression of the AME field, which appeared along the Oy axis of the sample

$$E_{AME} = E_y = \frac{\phi_z(\eta_{zy}\sigma_{yy} + \eta_{zz}.\sigma_{yz})}{\sigma_{yy}^{\ 2} + \sigma_{zy}^{\ 2}} \quad (5)$$

Eq. (5) is the general expression to calculate the AME field in a CQWIP in case the relaxation time of carrier $\tau(\varepsilon)$ depends on carrier energy. By using the expression of the Eqs. 3-5 and carrying out manipulations, we derived the expression for the AME field in a CQWIP in the presence of an EMF as follows:

$$E_{AME} = \frac{\pi\Omega_c}{e^2}.\frac{a_1 b_2 - b_1 a_2}{a_1^2 + \Omega_c^2 a_2^2}\Phi, \quad (6)$$

here,

$$b_1 = \tau_0 A k_B T.G_{\upsilon,2\upsilon}(z),$$

$$b_2 = \tau_0^2 A k_B T.G_{2\upsilon,2\upsilon}(z),$$

$$a_1 = \tau_0 k_B T F_{\upsilon+1,2\upsilon}(z) - \hbar\Omega_c(n' + \frac{1}{2})\tau_0 F_{\upsilon,2\upsilon}(z),$$

$$a_2 = \tau_0^2 k_B T F_{2\upsilon+1,2\upsilon}(z) - \hbar\Omega_c(n' + \frac{1}{2})\tau_0^2 F_{2\upsilon,2\upsilon}(z),$$

and

$$F_{m,n}(z) = \int_0^\infty \frac{z^m}{1+\omega_c^2\tau_0^2 z^n}.\frac{\partial f_0}{\partial z}dz,$$

$$G_{m,n}(z) = \int_0^\infty \frac{z^m}{1+\omega_c^2\tau_0^2 z^n}\frac{\partial f_0}{\partial z}(z - \frac{\Omega(N+1/2)}{k_B T})^{\frac{3}{2}} \times$$

$$\exp\left[-\frac{4\omega_c k_l}{\Omega^2 - \omega_c^2}(k_B T)^{\frac{1}{2}}(z - \frac{\Omega(N+1/2)}{k_B T})^{\frac{1}{2}}\right]dz.$$

From Eq. (6), we can see that the dependence of the AME field on the intensity B of the EMF, the temperature of the system T and the external acoustic wave of frequency is nonlinear.

3. Numerical results and discussion

In order to clarify the results that have been obtained, in this section, we considered the AME field in a QWIP. This quantity is considered as a function of the external magnetic field B, the frequency of the ultrasound, the temperature T of the system, and the parameters of the QWIP AlAs/GaAs/AlAs. The parameters used in the numerical calculations are as follows [8-10]: $\tau_0=10^{-12}$s, $\Phi=10^4$Wm^{-2}, $\rho=5,3\times10^3$kg/m^3, $\Lambda = 20,8\times10^{-19}$J, $v_l= 2,0\times10^3$ m/s, $v_t=1,8\times10^3$m/s.

Fig. 1 and Fig. 2 investigated the dependence of the AME field on the frequency of acoustic waves at different values of the external electric field and the temperature, respectively, The result showed some different behaviour from results in bulk semiconductor [1-2].

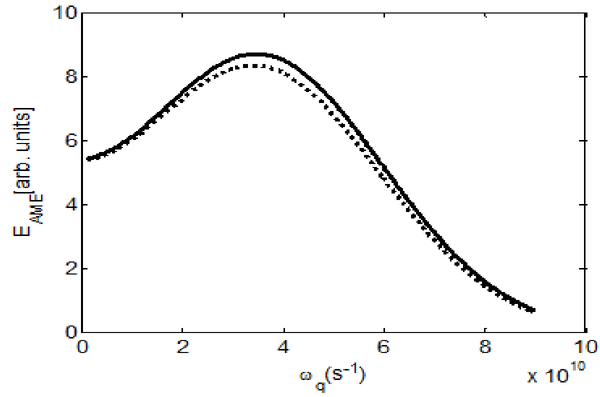

Figure 1. *Dependence of the AME field on the frequency of the acoustic wave at different values of the external magnetic field B=0.12T (dashed line), B=0.14T (solid line)*. Here T=290K.

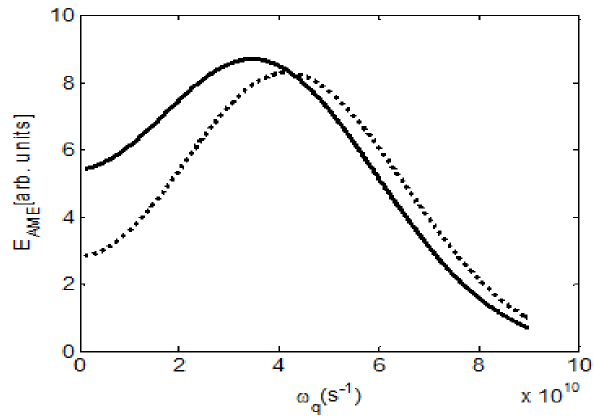

Figure 2. *Dependence of the AME field on the the frequency of the acoustic wave at different values of the temperature T=290K (dashed line), T=300K (solid line). Here B=0.14T.*

Because in the bulk semiconductor, when the frequency of acoustic waves rises up, the AME increases linearly. The cause of the difference between the bulk semiconductor and the QW, because of low-dimensional systems characteristic, means that in low-dimensional systems the energy spectrum of electron is quantized, and note that it exists even if the relaxation time τ of the carrier does not depend on the carrier energy. In addition, Fig. 2 shows that the positions of the maxima does not nearly move as the temperature of QWIP is varied. In contrast, Fig. 1 shows that the peak moves when the external magnetic field is varied, because the condition for the peak to appear does not depend on the temperature but depends on the external magnetic field. Therefore, we can use these conditions to determine the peak position at the different value of the external magnetic field or the parameters of the QWIP.

4. Conclusions

In summary, we have obtained analytical expressions for the AME field in the QWIP. There is a strong dependence of the AME field on the frequency of acoustic waves, the temperature T of the system, the cyclotron frequency of the EMF and the intensity of the EMF. The result showed that there exist peaks which disappear in bulk semiconductors [1,2]. The result of the numerical calculation was done for the QWIP AlAs/GaAs/AlAs. This result has shown that the dependence of the AME field on the frequency of acoustic waves has the peaks move when the magnetic field varies. We wish to emphasize that the condition for the position of the peak to appear does not depend on the temperature but depends on the external magnetic field. This result shows the difference from the results obtained in normal bulk semiconductors [1,2]. These are important results of the present work.

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TRƯỜNG ÂM ĐIỆN TỪ TRONG HỐ LƯỢNG TỬ VỚI THẾ CAO VÔ HẠN

Tóm tắt: Trường âm điện từ trong hố lượng tử với thế cao vô hạn được nghiên cứu khi có từ trường ngoài. Biểu thức giải tích của trường âm điện trong hố lượng tử với thế cao vô hạn đã đạt được bằng phương trình động lượng tử cho hàm phân bố của electron tương tác với sóng âm. Sự phụ thuộc của trường âm điện lên nhiệt độ T của hệ, tần số sóng âm ω_q, độ rộng của hố lượng tử L,và từ trường ngoài B trong hố lượng tử AlAs/GaAs/AlAs đã đạt được bằng phương pháp số. Trong trường hợp sự phụ thuộc của trường âm điện từ lên từ trường ngoài và tần số sóng âm, kết quả tính toán cho thấy sự phụ thuộc này là không tuyến tính. Các kết quả này được so sánh với kết quả trong bán dẫn khối để chỉ ra sự khác biệt.

Từ khóa: hố lượng tử; trường âm điện từ; tương tác electron-sóng âm; sóng âm; phương trình động lượng tử.