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Acoustomagnetoelectric effect in a superlattice

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Abstract. The acoustomagnetoelectric (AME) effect in a semiconductor superlattice (SL) has been studied for a hypersound in the region $ql \gg 1$. The expression for the AME current j^{AME} was calculated in the $\tau =$ constant approximation. The result indicates that the existence of j^{AME} in a SL may be due to the finite gap band and the periodicity of the electron spectrum. It is shown in particular that when $\omega_q > \Delta$ and $\Delta \gg T$ (ω_q is the frequency of the acoustic phonons, 2Δ is the miniband width of the SL and T is the temperature measured in energy units), the SL behaves as a monopolar semiconductor bulk material and in that case $j^{AME} \to 0$.

1. Introduction

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 [1, 2]. Recently, Mensah *et al* [3] have studied this effect in a superlattice.

However, in the presence of a magnetic field the acoustic wave propagating in the conductor can induce another effect called the acoustomagnetoelectric (AME) effect. The AME effect is actually the generation of 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 H carries an acoustic wave propagating in a direction perpendicular to H.

The AME effect was first predicted theoretically by Grinberg and Kramer [4] for bipolar semiconductors and was observed experimentally in bismuth by Yamada [5]. The explanation given to the effect in [4] was that, when an acoustic wave is propagating through a conductor having a bipolar conduction immersed in a magnetic field with the direction of propagation perpendicular to the field, a potential difference (or a short-circuit current) will appear in the third direction. This is because the absorption of the acoustic wave causes equal fluxes of electrons and holes in the direction of propagation of the acoustic wave. The magnetic field then deflects these fluxes in the opposite direction, thus giving rise to the onset of the AME field.

Epshtein and Gulyaev [6] later studied this effect in a monopolar semiconductor. In this specimen they observed that the AME effect occurs mainly because of the dependence of the electron relaxation time on the energy, i.e. $\tau(\epsilon_p)$ and that, when $\tau =$ constant, the effect vanishes. The physics behind the existence of this effect is that the perturbation of the

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electron distribution function under the influence of the sound flux differs significantly from the perturbation that is caused by the electric field so that, depending on their energy, the effect of the sound flux will prevail for some electrons while the effect of the compensating electric field will prevail for others. As a result when the total acoustoelectric (longitudinal) current is equal to zero, the specimen will manifest mutually compensating 'partial' currents generated by different energy groups of electrons. When this happens, the energy dependence of the electron momentum relaxation time will cause the average mobilities of the electrons in these partial currents, in general, to differ. If an external magnetic field is applied perpendicular to the direction of the sound flux, the Hall currents generated by these groups will not, in general, compensate one another, and a non-zero AME effect will result.

Kaganov *et al* [7], upon studying this effect in a metal with an arbitrary conduction-electron dispersion law, found that the effect is very sensitive to the structure of the electron spectrum. As a result it can even exist at $\tau =$ constant.

It is necessary to note that, like the classical magnetic field, this effect also exists in the case of a quantized magnetic field. Galperin and Kagan [8] were the first to note this and later it was observed by Salaneck *et al* [9] in bismuth. Recently, Margulis and Margulis [10] have studied the quantum acoustomagnetoelectric (QAME) effect due to Rayleigh sound waves. They suggested in their study that the ratio of AME current j^{AME} to that of the acoustoelectric current j^{AE} will be of the order of the ratio σ_{xy}/σ_{yy} of conductivities, which is large for a degenerate electron gas because of the parameter Ω/ν (Ω is the cyclotron frequency; ν is the frequency of electron collisions).

We present in this paper the AME effect in a semiconductor SL on which, in our opinion, no work has been done. Furthermore, we think that the study of this effect may present itself as interesting in the field of radioelectronics [10]. It may also help us to understand the properties of SL material. It will be seen that, due to the anisotropic nature of the dispersion law, the AME effect is observed at $\tau =$ constant. It is also dependent non-linearly on the SL parameters Δ and d. (2Δ is the miniband width; d is the period of the SL) the temperature T and the frequency ω_q (ω_q is the frequency of acoustic phonons and q is its wavenumber).

Finally, it depends substantially on the field H; the quantity $\Omega\tau$ which is equal to the ratio j^{AME}/j^{AE} serves as a measure of the magnetic field strength. It will also be noted that, as $\omega_q > \Delta \gg kT$, the SL behaves as a bulk monopolar semiconductor and $j^{AME} \to 0$ as expected [6].

The paper is organized as follows. In section 2 we outline the theory and conditions necessary to solve the problem and in section 3 we discuss the results and draw some conclusions.

2. Theory

Following the method developed in [3] we calculate the AME current in a SL. The acoustic wave will be considered as a hypersound in the region $ql \gg 1$ (l is the electron mean free path) and then treated as monochromatic phonons (frequency ω_q). The problem will be solved in the quasi-classical case, i.e. $2\Delta \gg \tau^{-1}$ ($\hbar = 1$). The magnetic field will also be considered classically, i.e. $\Omega < \nu$, $\Omega \ll T$ (T is the temperature in energy unit), and weak, thus limiting ourselves to the linear approximation of H.

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

$$j^{AE} = \frac{2e}{(2\pi)^3} \int U^{AE} \psi_i(\boldsymbol{P}, -\boldsymbol{H})\, \mathrm{d}^3 p \qquad (1)$$

where

$$U^{AE} = \frac{2\pi\phi}{\omega_q s} |G_{p-q,p}|^2 [f(\epsilon_{p-q}) - f(\epsilon_p)] \delta(\epsilon_{p-q} - \epsilon_p + \omega_q) + |G_{p+q,p}|^2 [f(\epsilon_{p+q}) - f(\epsilon_p)] \delta(\epsilon_{p+q} - \epsilon_p - \omega_q). \qquad (2)$$

Here ϕ is the sound flux, s is the velocity sound, $f(\epsilon_p)$ is the distribution function, $G_{p+q,p}$ is the matrix element of the electron–phonon interaction and $\psi_i(\boldsymbol{P}, -\boldsymbol{H})$ is the solution of the kinetic equation given by

$$\frac{e}{c}(\boldsymbol{V} \times \boldsymbol{H}) \frac{\partial \psi_i}{\partial p} + \widehat{W}_p\{\psi_i\} = V_i. \qquad (3)$$

V_i is the electron velocity and $\widehat{W}_p\{\ldots\} = (\partial f/\partial\epsilon)^{-1} \widehat{W}(\partial f/\partial\epsilon \ldots)$. The operator $\widehat{W}$ is assumed to be Hermitian [7]. In the τ approximation, $\widehat{W}_p = 1/\tau$. Furthermore, $\tau =$ constant. We shall seek the solution of equation (3) as

$$\psi_i = \psi_i^{(0)} + \psi_i^{(1)} + \cdots. \qquad (4)$$

Substituting equation (4) into equation (3) and solving by the method of iteration, we get for the zero approximation, i.e. in the absence of magnetic field ($H = 0$),

$$\psi_i^{(0)} = V_i \tau \qquad (5)$$

and for the first approximation

$$\psi_i^{(1)} = -\frac{\tau^2 e}{mc} (\boldsymbol{V} \times \boldsymbol{H})_i \qquad (6)$$

where $i = x, y, z$.

Inserting (5) and (6) into (1) and taking into account the fact that

$$|G_{p'p}|^2 = |G_{pp'}|^2$$

we obtain for the acoustoelectric current the expression

$$j_i^{AE} = -\frac{e\phi}{2\pi^2 s\omega_q} \int |G_{p+q,p}|^2 [f(\epsilon_{p+q}) - f(\epsilon_p)] \times \{V_i(p+q)\tau - V_i(p)\tau\} \delta(\epsilon_{p+q} - \epsilon_p - \omega_q)\, \mathrm{d}^3 p - \frac{e^2\phi\tau^2}{2\pi^2 mc\omega_q s} \int |G_{p+q,p}|^2 [f(\epsilon_{p+q}) - f(\epsilon_p)] \times \{(\boldsymbol{V}(p+q) \times \boldsymbol{H})_i - (\boldsymbol{V}(p) \times \boldsymbol{H})_i\} \delta(\epsilon_{p+q} - \epsilon_p - \omega_q)\, \mathrm{d}^3 p. \qquad (7)$$

The matrix element of the electron–phonon interaction for $qd \ll 1$ is given as

$$|G_{p,q}|^2 = \frac{|\Lambda|^2 q^2}{2\sigma\omega_q} \qquad (8)$$

where Λ is the deformation potential constant and σ is the density of the SL.

In solving equation (7) we shall consider a situation whereby the sound is propagating along the SL axis (Ox) and the magnetic field H is parallel to the Oz axis. Under such orientation the first term in equation (7) is responsible for the acoustoelectric current and the solution is found in [3].

The second term is the AME current and is expressed as

$$j_y^{AME} = -\frac{e\phi|\Lambda|^2 q^2\tau^2\Omega}{4\pi s\omega_q^2\rho}\int [f(\epsilon_{p+q}) - f(\epsilon_p)]\{V_x(p+q) - V_x(p)\}\delta(\epsilon_{p+q} - \epsilon_p - \omega_q)\,\mathrm{d}^3p \tag{9}$$

where $\Omega = eH/mc$.

The distribution function $f(\epsilon_p)$ in the usual form is given by

$$f(\epsilon_p) = \frac{\pi dn}{mTI_0(\Delta/T)}\exp\left(-\frac{\epsilon_p}{T}\right) \tag{10}$$

where n is the electron density, m is the mass of electron and $I_0(X)$ is the modified Bessel function of the zero order.

The energy $\epsilon(p)$ of the SL in the lowest miniband is given using the usual notation by

$$\epsilon(p) = \frac{P_1^2}{2m} + \Delta[1 - \cos(P_x d)]. \tag{11}$$

Hence

$$\frac{\partial\epsilon}{\partial p} = V_x(p) = \Delta d\sin(P_x d). \tag{12}$$

Substituting (10), (11) and (12) into (9) and after cumbersome calculation we obtain for non-degenerate electron gas the following expression:

$$j_y^{AME} = \frac{e|\Lambda|^2 nq^2\phi\tau^2\Omega d}{s\omega_q^2\sigma}\Theta(1-b^2)\sinh\left(\frac{\omega_q}{2T}\right)\sinh\left[\frac{\Delta}{T}\cos\left(\frac{qd}{2}\right)\sqrt{1-b^2}\right] \tag{13}$$

where

$$b = \omega_q/[2\Delta\sin(qd/2)].$$

3. Discussion and conclusion

The result in equation (13) can be written in terms of the acoustoelectric current as

$$j_y^{AME} = j_x^{AE}\Omega\tau. \tag{14}$$

The AME current depends on the magnetic field H, the quantity $\Omega\tau$ serving as a measure of the magnetic strength. The ratio of j^{AME}/j^{AE} is equal to $\Omega\tau$. This result is quite interesting as a similar ratio calculated for the case of the QAME due to the Rayleigh sound wave was of that order [10]. In their case, $\Omega\tau \gg 1$ (quantized magnetic field) and the sample was a bulk material.

It is plausible that the mechanism responsible for the existence of the AME effect in a SL may be due to the finite band gap and the periodicity of the electron spectrum (dispersion law) along the x axis and not the dependence of τ on ϵ_p [7, 11]. The calculation was done on the basis of τ = constant and according to [6] the AME effect should be zero. However, for $\omega_q > \Delta$ and $\Delta \gg T$ when the SL behaves as a bulk monopolar semiconductor with parabolic law of dispersion, $j^{AME} \to 0$ as expected for τ = constant [6]. This is readily deduced from the conservation laws. The non-linear dependence of j^{AME} on the SL parameters Δ and d and the frequency ω_q and particularly the strong spatial dispersion of j^{AME} once again can only be attributed to the finite band gap and periodicity of the spectrum along the x axis.

For $\Delta = 0.1$ eV, $\tau = 10^{-12}$ s, $H = 2 \times 10^3$ A m^{-1}, $\omega_q = 10^{10}$ s^{-1}, $\phi = 10^4$ W m^{-2}, $s = 5 \times 10^3$ ms^{-1} and $d = 10^{-8}$ m, we have $j^{AME} \simeq 9.2$ mA, which should be possible to measure experimentally.

In conclusion, we have studied the AME effect in a semiconductor SL and noted that it exists at $\tau =$ constant and has a strong spatial dispersion.

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