THEORY OF THE ACOUSTOELECTRIC CURRENT IN A QUANTUM WELL

LÝ THUYẾT DÒNG ÂM ĐIỆN TRONG HỐ LƯỢNG TỬ

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ABSTRACT

The acoustoelectric (AE) current in a quantum well (QW) is investigated for an acoustic wave whose wavelength $\lambda = 2\pi / q$ is smaller than the mean free path ℓ of the electrons and the hypersound in the region $q\ell >> 1$ (where q is the acoustic wave number). The nonlinear dependence of the AE current jac on the frequency of acoustic wave ω_q, and the temperature T of the system is obtained by using the Boltzmann kinetic equation. The analytical expression for the AE current jac is calculated in case the relaxation time of momentum τ is constant approximation. Numerical calculations are done, and the result is discussed for a typical AlAs/GaAs/AlAs QW. The result indicates that the existense peaks in QW may be due to the transition between mini-bands $n \to n'$. The dependence of the AE current on the temperature T and the Fermi energy ε_F with a maximum at T=50K, $\varepsilon_F = 0.03eV$ for $\omega_q = 3\times 10^{11}(s^{-1})$. These findings agree with the experimental results. All the results are compared with the normal bulk semiconductor and superlattice to highlight the difference.

Key words: acoustic wave; quantum well; acoustoelectric current; Boltzmann kinetic equation; Fermi energy

TÓM TẮT

Dòng âm điện trong hố lượng tử được khảo sát cho sóng âm với bước sóng $\lambda = 2\pi / q$ nhỏ hơn quãng đường trung bình tự do ℓ của điện tử và giả thiết nằm trong miền siêu âm $q\ell >> 1$ (ở đây q là số sóng). Sự phụ thuộc phi tuyến của dòng âm điện jac theo tần số sóng âm ω_q, nhiệt độ T của hệ đã đạt được bằng phương pháp phương trình động Boltzmann. Biểu thức giải tích của dòng âm điện jac đạt được trong trường hợp thời gian phục hồi xung lượng τ xấp xỉ là hằng số. Tính toán số được thực hiện và kết quả được được thảo luận cho loại hố lượng tử AlAs/GaAs/AlAs. Kết quả chỉ ra rằng sự xuất hiện các đỉnh trong trường hợp hố lượng tử là do sự dịch chuyển giữa các mini vùng $n \to n'$. Sự phụ thuộc của dòng âm điện theo nhiệt độ và năng lượng Fermi ε_F với giá trị cực đại tại T=50K, $\varepsilon_F = 0.03eV$ và $\omega_q = 3\times 10^{11}(s^{-1})$. Kết quả này phù hợp với kết quả thực nghiệm. Tất cả kết quả này được so sánh với kết quả trong bán dẫn khối để chỉ ra sự khác biệt.

Từ khóa: sóng âm; hố lượng tử; dòng âm điện; phương trình động Boltzmann; năng lượng Fermi

1. Introduction

When an acoustic wave is absorbed by a conductor, the transfer of the momentum from the acoustic wave to the conduction electron may give rise to a current usually called the AE current. The study of this effect is crucial, because of the complementary role it may play in the understanding of the properties of the QW, which we believe, should find an important place in the acoustoelectronic devices. The study of the AE effect in bulk materials has received a lot of attention [1-5].

It is well known that in low dimensional systems (QW, superlattices, quantum wires...), the motion of electrons is restricted in one dimension or two dimensions, so they can flow freely in two dimensions or one dimension. The confinement of electrons in low dimensional systems changes the electron mobility remarkably, which concerns a reduction of sample dimensions, and we think the electron confinement in the QW also has an influence on the AE current. Recently, the AE current was investigated theoretically in a one-dimensional channel [6], in a finite-length ballistic quantum channel [7-9], in superlattices [10-13]. In addition, the AE current was investigated experimentally in two dimensional systems (superlattice, QW) [14,15], in a quantum wire [16], and in a carbon nanotube [17]. However, the calculation of the AE current in the QW is still open for studying.

In this paper, we examine the calculated AE current in the QW in case the electron relaxation time is not dependent on the energy and we will show that the presence of mini-bands in the QW will result in a nonlinear dependence of the j^{ac} on the acoustic wave number q. The result shows that it exists even if the relaxation time τ of the carrier does not depend on the carrier energy; this result is different compared to those obtained in a bulk semiconductor and a superlattice. Especially, this result is compared with the experimental result [15]. This paper is organized as follows. In Section 2, we outline the theory and conditions necessary to solve the problem, in Section 3 we discuss the results, and in Section 4 we come to a conclusion.

2. Acoustoelectric Current

By using the Boltzmann kinetic equation method in [10-13], we calculated the AE current in the QW. The acoustic wave is considered a hypersound in the region $q\ell >> 1$. Under such circumstances, the acoustic wave can be interpreted as monochromatic phonons having the 3D phonon distribution function $N(\vec{k})$, and can be presented the acoustic flux by a δ function distribution in $\vec{k}$ -space [10]

$$N(\vec{k}) = \frac{(2\pi)^3}{\omega_{\vec{q}}\upsilon_s}\phi\delta(\vec{k}-\vec{q}) \qquad (1)$$

where Φ is the flux density of sound with frequency $\omega_{\vec{q}}$, υ_s is the speed of sound, and $\hbar = 1$.

It is assumed that the sound wave propagates perpendicularly the Oz axis of the QW (along the Oz direction the energy spectrum of electron is quantizied or the motive direction of electron is limited). After a new equilibrium has been established in the presence of the acoustic wave, the distribution function f of the electrons will obey the condition

$$\partial f / \partial t = (\partial f / \partial t)_{ac} + (\partial f / \partial t)_{th} = 0 \qquad (2)$$

$(\partial f / \partial t)_{ac}$ the rate of change caused by the interaction of the acoustic phonon with the electrons; $(\partial f / \partial t)_{th}$ the rate of change due to the interaction of the electrons with thermal phonons, the impurities, and with one another. Eq.(2) can be written as

$$\left(\frac{\partial f}{\partial t}\right)_{th} + \\ + \frac{\pi}{\sigma}\sum_{n,n'\vec{k}}\frac{\Lambda^2\vec{k}^2N(\vec{k})}{\omega_{\vec{q}}}\left\{\left[f(\varepsilon_{n,\vec{p}_\perp - \vec{k}}) - f(\varepsilon_{n',\vec{p}_\perp})\right]\times\delta(\varepsilon_{n,\vec{p}_\perp - \vec{k}} - \varepsilon_{n',\vec{p}_\perp} + \omega_{\vec{k}}) \right. \\ \left. + \left[f(\varepsilon_{n,\vec{p}_\perp + \vec{k}}) - f(\varepsilon_{n',\vec{p}_\perp})\right]\times\delta(\varepsilon_{n,\vec{p}_\perp + \vec{k}} - \varepsilon_{n',\vec{p}_\perp} - \omega_{\vec{k}})\right\} = 0 \qquad (3)$$

where Λ is the deformation potential constant, σ is th4e density of the QW, $f(\varepsilon_{n,\vec{p}_\perp})$ is the distribution function, $\varepsilon_{n,\vec{p}_\perp} = \frac{\vec{p}_\perp^2}{2m} + \frac{n^2\pi^2}{2mL^2}$ is the energy spectrum of electron in the QW, m is the effective mass of electron, L is the width of the QW, n denotes quantization of the energy spectrum and $\vec{p}_\perp = (\vec{p}_x, \vec{p}_y)$ is the transverse component of the quasi-momentum. We linearize Eq.(3) with respect to Φ, by replacing $f(\varepsilon_{n,\vec{p}_\perp})$ with $f_F(\varepsilon_{n,\vec{p}_\perp}) + f_1$, where $f_F(\varepsilon_{n,\vec{p}_\perp})$ is the equilibrium Fermi contribution function absence of the acoustic wave and f_1 is proportional to Φ, we verify that we can neglect in the collision integral $(\partial f / \partial t)_{th}$ the arrival terms, i.e., $(\partial f / \partial t)_{th} = f_1 / \tau_{\vec{p}}$; $\tau_{\vec{p}}$ is the momentum relaxation time. Thus,

$$f_1 = \frac{\pi\tau_{\vec{p}}\Lambda^2\Phi}{\sigma\upsilon_s^3}\times$$
$$\times\sum_{n,n'}\left\{\left[f_F(\varepsilon_{n,\vec{p}_\perp-\vec{k}}) - f_F(\varepsilon_{n',\vec{p}_\perp})\right]\times\delta(\varepsilon_{n,\vec{p}_\perp-\vec{k}} - \varepsilon_{n',\vec{p}_\perp} + \omega_{\vec{k}})\right. \quad (4)$$
$$\left.+\left[f_F(\varepsilon_{n,\vec{p}_\perp+\vec{k}}) - f_F(\varepsilon_{n',\vec{p}_\perp})\right]\times\delta(\varepsilon_{n,\vec{p}_\perp+\vec{k}} - \varepsilon_{n',\vec{p}_\perp} - \omega_{\vec{k}})\right\}$$

The density of the AE current j^{ac} in the direction of acoustic wave vector $\vec{q}$ is expressed by the formula [10]

$$j^{ac} = \frac{2e}{(2\pi)^2}\int\frac{\partial\varepsilon_{n,\vec{p}_\perp}}{\partial\vec{p}_\perp} f_1 d\vec{p}_\perp. \quad (5)$$

Substituting Eq.(4) into Eq.(5) and $\tau_{\vec{p}}$ is taken to be constant, we obtain for the AE current

$$j^{ac} = j_0^{ac}\sum_{n,n'}\exp\left(-\frac{\pi^2 n^2}{2mL^2 k_B T}\right)(B_+ - B_-), \quad (6)$$

Where

$$j_0^{ac} = \frac{(2\pi)^{3/2} e\Phi\Lambda^2\tau(mk_BT)^{1/2}}{(2\pi)^2\sigma\upsilon_s^3}\exp\left(\frac{\varepsilon_F}{k_BT}\right)$$

$$B_\pm = \left(1 + \frac{A_\pm^2}{mk_BT}\right)\exp\left(-\frac{A_\pm^2}{2mk_BT}\right),$$

ε_F is the Fermi energy, k_B is the Boltzmann constant, and $\Delta_{n,n'} = \frac{\pi^2}{2mL^2}(n^2 - n'^2)$,

$$A_\pm = \frac{q\hbar}{2} + \frac{m\Delta_{n,n'}}{\hbar q} \pm \frac{m\omega_{\vec{q}}}{q}.$$

Eq.(6) is the analytical expression of the AE current in the QW in case the momentum relaxation time is constant approximation.

3. Numerical results and discussion

To clarify the results that have been obtained, in this section, we examine the AE current. This quantity is considered as a function of the temperature T, the acoustic wave number q, the acoustic intensity Φ, and the parameters of the AlAs/GaAs/AlAs QW. The parameters used in the calculations are as follows: $\sigma = 5300\,kgm^3$, L=90 (nm), $\tau = 10^{-12}s$, m=0.067 m_0, m_0 being the mass of free electron, $\Phi = 10^4 Wm^{-2}$, $\upsilon_s = 5370\,m/s$, $e = 1.60219\times10^{-19}\,C$.

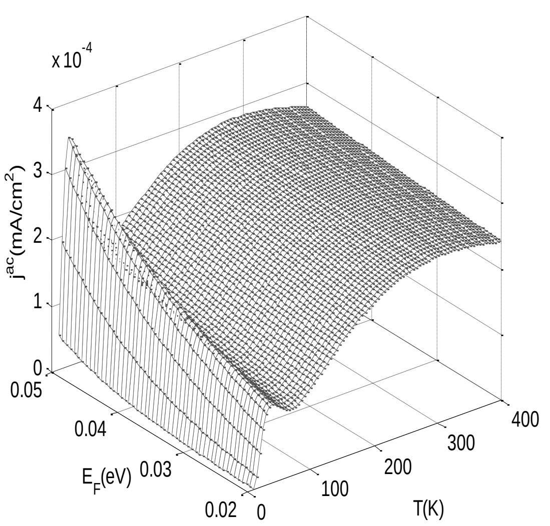

Figure 1. *The dependence of j^{ac} current on the T and Fermi energy for* $\omega_q = 3\times10^{11}(s^{-1})$.

Figure 1 shows the dependence of the AE current on the temperatures and the Fermi energy. The dependence of the AE current on the temperatures and the Fermi energy are not monotonous with a maximum at T=50K, for $\omega_q = 3\times10^{11}(s^{-1})$. This result agrees with the experimental result [15]. However, in [15] they had no explanation for this behaviour. We conclude that the dominant mechanism for such a behaviour is attributed to the electron confinement in the QW.

It can be seen from Figure 2 that AE current has peaks at $\omega_q = 2\times10^{11}(s^{-1})$ and $\omega_q = 1\times10^{12}(s^{-1})$ for T=300K, $\varepsilon_F = 0.045eV$, which corresponds to the maxima value of the AE current. This result is different from the AE current in the bulk semiconductor. Because in the bulk semiconductor, when the q rises up, the AE current increases linearly. The cause of the difference between the bulk semiconductor and the QW, because the 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 Figure 2, there are two peaks. This can be attribute to transitions between mini-bands ($n \to n'$) and there are two peaks corresponding to ($n = 1 \to n' = 2$) and ($n = 2 \to n' = 3$) transitions or intersubband transitions as main contribution to j^{ac}.

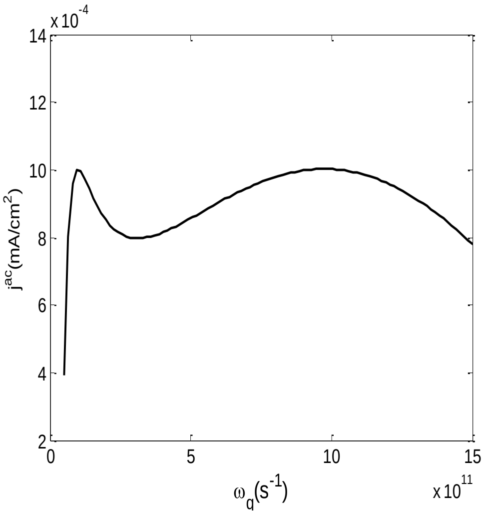

Figure 2. The dependence of j^{ac} current on the wave number for T=300K.

4. Conclusion

In this paper, we have obtained analytical expressions for the j^{ac} in a non-degenerate electron gas. We have shown the strong nonlinear dependence of j^{ac} on the temperature T, the wave number q and the width of the QW, which are complex and different compared to those obtained in the superlattice [10,13] and in bulk semiconductors [18,19]. The above results indicate that there exist some peaks which disappear in bulk semiconductors [18,19].

The numerical results obtained for the AlAs/GaAs/AlAs QW show that there exists a peak at T=50K, for $\omega_q = 3\times 10^{11}(s^{-1})$, which fits a the experimental result [15]. Our result indicates that the dominant mechanism for such a behaviour is attributed to the electron confinement in the QW and transition between miniband $n \to n'$. The j^{ac} exists even if the relaxation time τ of the carrier does not depend on the carrier energy, and the result is similar to those in the superlattice [11]. This is different from the bulk semiconductor, because in bulk semiconductor [18,19] the AE current vanished for a constant relaxation time.

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