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PHONON INDUCED DRAG OF CHARGE CARRIERS IN HETEROSTRUCTURES IN MAGNETIC FIELDS: LIMIT OF WEAK FIELDS

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The response of a 2D gas of charge carriers of mobility μ in magnetic field B to pulsed phonon beams is considered. Previously we derived a quantum Langevin equation for the centre-of-mass of the carrier gas, which allows us to calculate the time integrated drag current. This formula is studied in the weak magnetic field limit. When the ratio of the cyclotron frequency ω_c to the frequency ω of phonons is small and $\mu B \ll 1$, the general formula coincides with the corresponding expression obtained in the frame of the Boltzmann equation with the collision integral independent of B.

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1. Introduction

Let us consider a 2D gas of charge carriers lying in a plane perpendicular to a DC magnetic field $\boldsymbol{B}$ of the strength B. They are scattered by defects, the mean time elapsing between successive collisions is τ_e. The transport properties of this gas are characterized by the mobility $\mu = |e|\tau_e/m^*$, where m^* and e are respectively the effective mass and the charge of a carrier.

The field strength is characterized by comparing: (i) the cyclotron angular frequency $\omega_c = eB/m^*$ to the inverse of the mean time τ_e (or μB to the unity); (ii) for 2DG of electrons — $\hbar\omega_c$ to the spacing ΔE between the energy levels of carriers in a triangular well. Here we shall confine ourselves to the case of the fields which are not extremely strong, i.e. $\hbar\omega_c \ll \Delta E$.

In magnetic field the charge transport is related to the translational motion of the centre-of-mass (CM) of 2DCG. Recently we have derived the quantum Langevin equation for the CM valid for $0 < \mu B \ll \Delta E/(\hbar\tau_e^{-1})$ [1].

We also considered the non-stationary phonon drag effect and obtained the expression for the time integrated density of induced current (TICD for short). Besides being dependent on μB, TICD is also conditioned by the ratio of the frequency of absorbed phonon ω to ω_c. The purpose of this note is to study the dependence of TICD [1] on ω_c/ω. In particular, we shall show that for $\omega > \omega_c$, i.e. when the transfer of energy is greater than the spacing between the adjacent Landau levels, the quasiclassical approximation is valid. If additionally $\mu B \ll 1$, the transport of charge is due to the *translational motion* of carriers. In such fields the motion of carriers can be treated semiclassically on the basis of the Boltzmann equation with the collision integral calculated for $B = 0$. Such situation was considered in our previous paper [2].

2. Time integrated drag current induced by pulsed phonon beams in 2D gases of carriers in magnetic fields

We denote the deviation of the phonon distribution function from the Planck function by $\delta N(Q, r, t)$, where Q stands for a pair (q, j), q is the phonon wave vector, j enumerates the three polarizations and $\omega(Q)$ is the angular frequency of the phonon Q. The component of q lying in the gas plane is $q_\perp$, the component parallel to $\boldsymbol{B}$ is $q_\parallel$.

The carrier–phonon interaction is characterized by the matrix element $h(Q)$ containing contribution of the deformation potential and the piezoelectric coupling.

Using a procedure of Hu and O'Connel [3] we obtained the quantum Langevin equation for the CM of 2DCG [1]. We shall neglect the Coulomb interaction of carriers, many phonons absorption processes and mixed phonon-impurity processes. After taking the average over all impurities we obtain for the TICD in RPA

$$\int_{-\infty}^{\infty} \mathrm{d}t j(t) \equiv \bar{j}(0) = \frac{\tau_c}{\sqrt{1+(\mu B)^2}}[\boldsymbol{F}_{\mathrm{ph}}^{\mathrm{abs}}(0) + \mu B \boldsymbol{F}_{\mathrm{ph}}^{\mathrm{abs}}(0) \times \widehat{\boldsymbol{B}}], \qquad (1)$$

where $\bar{j}(\Omega)$ is the Fourier time transform of the current density, ω is the phonon frequency and

$$\boldsymbol{F}_{\mathrm{ph}}^{\mathrm{abs}}(\Omega) = \frac{\pi}{V}\sum_{q,j} q_\perp \mathcal{N}(\Omega)|h(Q)|^2 \sum_{m,m'} \mathcal{L}_{m,m'}(\omega, q_\perp, B)|G_{m,m'}(q_\parallel)|^2, \qquad (2)$$

where the function $\mathcal{L}_{m,m'}$ plays an important role in our discussion

$$\mathcal{L}_{m,m'}(\omega, q_\perp, B)$$

$$= \sum_{n,n'} C_{n,n'}(q_\perp l_B)[f(\varepsilon_{n',m'}) - f(\varepsilon_{n,m})]\delta[\varepsilon_{n',m'} - \varepsilon_{n,m} - \hbar\omega(Q)]. \qquad (3)$$

Above $\mathcal{N}(\Omega)$ is the Fourier transform of the phonon deviation function, $l_B = \sqrt{\hbar/eB}$ is the magnetic length and the function $C_{n,n'}$ is related to the associated Laguerre polynomials $L_n^{(n-n')}(y)$

$$C_{nn'}(x) = \frac{1}{2\pi l_B^2}\frac{n!}{n'!}\frac{x^{2(n-n')}}{2^{(n-n')}}\exp(-x^2/2)\left[L_n^{(n-n')}(x^2/2)\right]^2. \qquad (4)$$

The form factor $|G_{m,m'}(q_\parallel)|^2$ results from localization of carriers in the direction perpendicular to the surface of the (quasi-) 2DCG. The indices m, m' enumerate the subbands due to confinement perpendicular to the 2DCG plane and Landau levels due to magnetic quantization are labeled by the indices n, n'.

For weak magnetic fields ($\omega_c < \omega$) and for carriers occupying only the lowest subband ($m = m' = 0$) the formula (1) should coincide with the quasiclassical expression for TICD [2]. The comparison of these formulae gives

$$\lim_{B\to 0} \mathcal{L}_{0,0}(\omega, q_\perp, B) = -\frac{m^*}{2\pi^2\hbar^2 q_\perp}\mathcal{L}(\omega, q_\perp). \tag{5}$$

The function $\mathcal{L}(\omega, q_\perp)$ was introduced previously [2]

$$\mathcal{L}[\omega, q_\perp] = \mathrm{Re}\left(\sqrt{k_{\perp\mathrm{F}}^2 - L_-^2} - \sqrt{k_{\perp\mathrm{F}}^2 - L_+^2}\right),$$

and $L_\pm = q_\perp/2 \pm m^*\omega/(\hbar q_\perp)$.

Here $k_{\perp\mathrm{F}} = \sqrt{2\pi n_s}$ is the Fermi wave vector and n_s is the surface density of the gas.

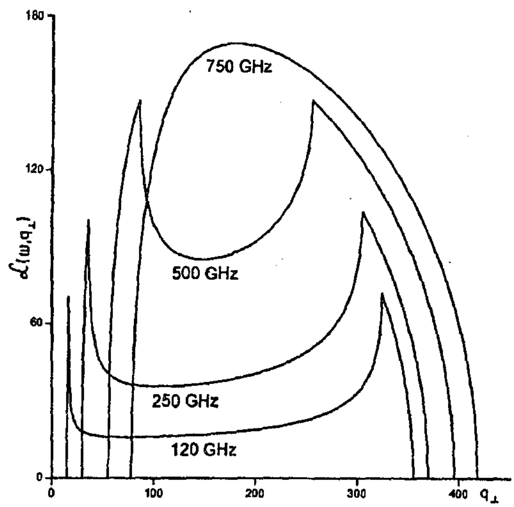

Fig. 1. Dependence of $\mathcal{L}(\omega, q_\perp)$ on $q_\perp$ for different values of $f = \omega/2\pi$. Axes units are $(\mu\mathrm{m})^{-1}$.

The calculations were performed for data corresponding to experiments on gas of holes in (001) plane of the GaAs/AlGaAs heterostructure [2]. The surface density of holes is $3300 \times 10^{12}\ \mathrm{m}^{-2}$, $m^* \approx 0.4m_e$. In Fig. 1 we show the dependence of $\mathcal{L}(\omega, q_\perp)$ on ω and on $q_\perp$. In Figs. 2a–d we depict the dependence of $q_\perp \mathcal{L}_{0,0}(\omega, q_\perp, B)$ on B for different values of $f = \omega/2\pi$. The oscillating lines with large amplitudes correspond to $\omega = \omega_c$, while the oscillating lines with smaller amplitudes correspond to $\omega = 5\omega_c$. The non-oscillating curves represent the function $q_\perp \mathcal{L}(\omega, q_\perp)$. Figures 2a–d show that when ω_c/ω diminishes, the amplitude of oscillations becomes smaller, so for $B \to 0$ ($\omega_c/\omega \to 0$) the function $\mathcal{L}_{0,0}(\omega, q_\perp, B)$ gradually goes to $(-m^*/2\pi^2\hbar^2 q_\perp)\mathcal{L}(\omega, q_\perp)$.

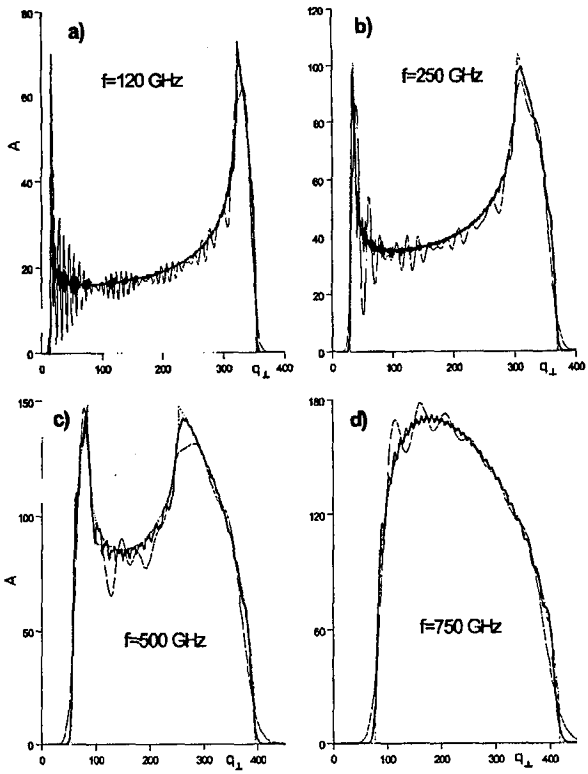

Fig. 2. Dependence of the function $A = (-m^*/2\pi^2\hbar^2 q_\perp)\mathcal{L}_{0,0}(\omega, q_\perp, B)$ on $q_\perp$ for different values of B and $f = \omega/2\pi$. Axes units are $(\mu\mathrm{m})^{-1}$.

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