Probing two-subband systems in a quantizing magnetic field with non-equilibrium phonons

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Abstract. We propose to use phonon absorption spectroscopy to study many-body gaps and phases of two-subband heterostructures in the quantum Hall regime. Implications of the spin-orbit interaction for phonon absorption in this system are considered.

Phonon spectroscopy is a powerful experimental technique that has been successfully used in the study of the properties of a two-dimensional (2D) electron gas in the quantum Hall regime [1]. It allows probing of the states with non-zero momentum, which are not accessible by either cyclotron resonance or photoluminescence methods. We propose to use acoustic-phonon spectroscopy to study many-body effects in a two-subband quasi-2D system, formed at a single semiconductor heterojunction and subjected to a quantizing magnetic field. We show that the formation of many-body gaps and the existence of different spin phases in this system result in a striking difference in the magnetic field dependence of the phonon absorption rate at different filling factors.

Acoustic-phonon scattering of 2D electrons in a quantizing magnetic field is strongly suppressed due to the dispersionless structure of the Landau levels (LLs). In a two-subband system, however, a sharp enhancement of the electron-phonon interaction occurs when the two LLs corresponding to different size-quantization subbands (we consider the second LL of the first subband and the first LL of the second subband only) approach one another, and the separation between these energy levels, $\Delta = \Delta_{12} - \hbar\omega_c$, becomes close to $\hbar s/l$. Here $\hbar\omega_c$ is the cyclotron energy, Δ_{12} is the intersubband splitting, s is the velocity of sound and l is the magnetic length. This electron-phonon interaction enhancement should manifest itself in the magnetic field dependence of the phonon absorption rate and dissipative conductivity. At filling factor slightly greater than two, when the electron-electron interaction between the particles belonging to either of the intersecting LLs can be neglected, a double-peak structure in the magnetic field dependence of the phonon-mediated transport properties of the two-subband system has been predicted [2]. With increasing electron density, the repulsion between the levels due to electron-electron exchange interactions opens a gap in the interlevel excitation spectra. At filling factor $\nu = 3$ this gap exists at all values of the bare level splitting Δ and can well exceed $\hbar s/l$. As a result, the double-peak structure transforms into a single-peak one (see Figure 1). By far the most interesting case is when the electron filling factor $\nu = 4$. When the cyclotron energy is close to the intersubband splitting the system can be mapped onto a four-level electron system with an effective filling factor $\nu^* = 2$. The ground state is either a ferromagnetic state or a spin-singlet state, depending on the values of the interlevel splitting and Zeeman energy Δ_Z. The electron-electron interaction renormalizes the phase boundaries, which results in the existence of a ferromagnetic phase even for $\Delta_Z = 0$. The excitation spectrum has a gap for any value of the interlevel splitting Δ and Zeeman

splitting Δ_Z. This results in strong suppression of the electron-phonon interaction. The rate of phonon absorption by the considered quasi-2D electron system at $\nu = 4$ again has a double-peak structure as a function of level splitting and a steplike structure as a function of Zeeman splitting (see Figure 2).

In the absence of the spin-orbit interaction, the transitions between levels with different spin indices are forbidden because the electron-phonon interaction conserves the electron spin. The spin-orbit interaction allows such transitions. Matrix elements of the spin-orbit interaction Hamiltonian H_{SO} between levels differing by subband number, LL number, and spin projection on the normal to the structure plane, are given by following expressions [3]:

$$\begin{aligned}
\langle \eta, n, k_x, -1/2 \,|H_{SO}|\, \mu, n-1, k_x, +1/2 \rangle &= iC\frac{1}{l_H}\sqrt{2n}, \\
\langle \eta, n, k_x, +1/2 \,|H_{SO}|\, \mu, n-1, k_x, -1/2 \rangle &= A\frac{1}{l_H}\sqrt{2n}, \\
\langle \eta, n-1, k_x, -1/2 \,|H_{SO}|\, \mu, n, k_x, +1/2 \rangle &= A\frac{1}{l_H}\sqrt{2n}, \\
\langle \eta, n-1, k_x, +1/2 \,|H_{SO}|\, \mu, n, k_x, -1/2 \rangle &= -iC\frac{1}{l_H}\sqrt{2n}, \qquad (1)
\end{aligned}$$

where $H_{SO} = \left(\alpha\hbar^3\left(2m^3E_g\right)^{-1/2}\mathbf{K} + \beta\left[\mathbf{k}\times\nabla V\right]\right)\cdot\mathbf{S}$, $\mathbf{K} = \left[k_x(k_y^2-k_z^2), k_y(k_z^2-k_x^2), k_z(k_x^2-k_y^2)\right]$, η and μ numerate subbands, n is the LL number, and α and β are phenomenological spin-orbit constants of the semiconductor [4]. The expressions for A and C are given by

$$\begin{aligned}
A &= \alpha\hbar^3\left(2m^3E_g\right)^{-1/2}\int_{-\infty}^{+\infty}\Psi_\mu(z)\frac{d^2\Psi_\eta(z)}{dz^2}dz, \\
C &= \beta\int_{-\infty}^{+\infty}\Psi_\mu(z)\Psi_\eta(z)\frac{dV_{QW}}{dz}dz, \qquad (2)
\end{aligned}$$

where V_{QW} is the quantum-well confinement potential. These matrix elements cause an admixture of states with opposite spin direction to both the initial and final states for the phonon absorption. As a result, the phonon absorption rate at $\nu = 4$ never becomes zero; in the region between peaks, it is of the order of $(M/\Delta_g)^2$ times its value at the peak of absorption, where M is the corresponding matrix element of the spin-orbit interaction (Eq.(1)), and Δ_g is the many-body energy gap.

In the absence of many-body effects, the inter-subband spin-orbit coupling results in anticrossing of levels with different spin, subband and LL indices. The resulting energy gaps can be measured by high-resolution spectroscopic techniques (optical or spin/cyclotron resonance spectroscopy), as has been suggested for one-subband systems in tilted magnetic fields [5].

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References

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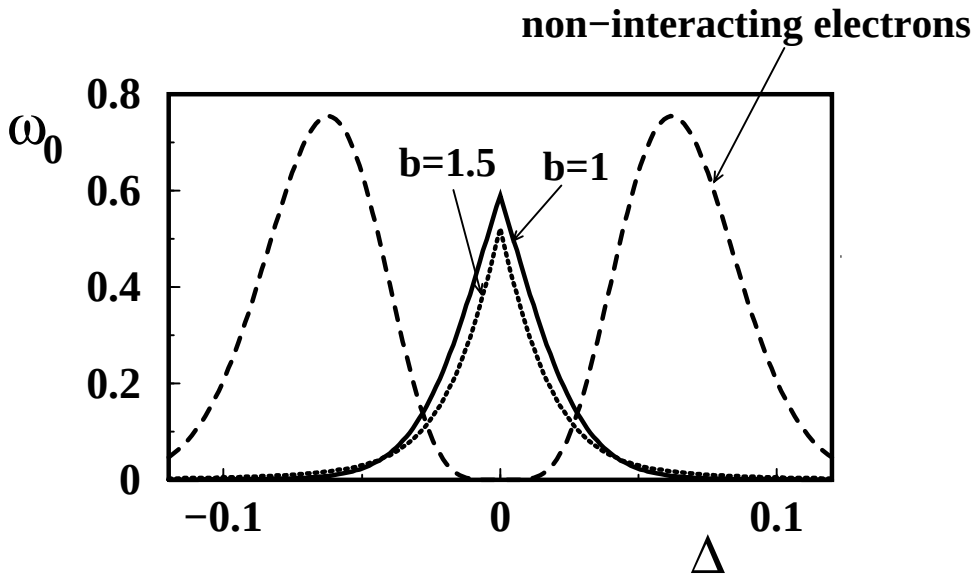

Figure 1. The phonon absorption rate per phonon, $\omega_0 = \omega_{abs}/n(q_0)$, as a function of bare level separation, $\Delta = \Delta_{12} - \hbar\omega_c$, at filling factor $\nu = 3$ (solid and dotted lines) and for the case of non-interacting electrons (dashed line). The results for $\nu = 3$ are shown for two different values of the Fang-Howard parameter (inverse quantum well width) $b = 1$ and $b = 1.5$ in units of inverse magnetic length l^{-1}. The absorption rate ω_0 is in units of 10^{10} s^{-1}; Δ is in Coulomb units ($\varepsilon_C = e^2/\kappa l$).

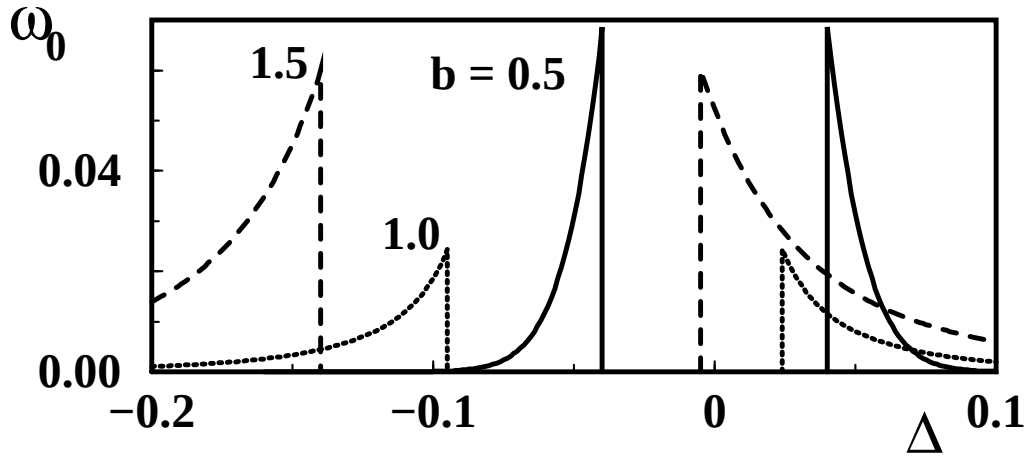

Figure 2. The phonon absorption rate ω_0 at filling factor $\nu = 4$ as a function of interlevel separation Δ for the case of zero Zeeman splitting, $\Delta_Z = 0$, for three values of parameter b. The data for $b = 1.0$ and 1.5 are multiplied by 10. The absorption rate ω_0 is in units of 10^{10} s^{-1}; Δ is in units of ε_C.