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PEAK SPLITTING OF THE CYCLOTRON RESONANCE SPECTRUM IN TWO DIMENSIONAL ELECTRON-PHONON-IMPURITY SYSTEMS

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We extend the generalized quantum Langevin equation approach to study the cyclotron resonance of the interacting two dimensional electron-phonon-impurity system. We find that the electron acoustic-phonon interaction and the fluctuation effect of the center of mass shift the RPA magneto-plasmon dispersion considerably, with the result that two resonance peaks may appear in the absorption spectrum. The positions, amplitudes, and the relative distance of these two peaks depend mainly on the magnetic field, the electron density, the sample mobility and the diffusion constant.

1. FORMULATION

The cyclotron resonance (CR) of a two dimensional electron gas (2DEG) provides one of the most interesting tests of many body theory[1]. Some problems, in particular the cyclotron effective mass, defined by the position of the main cyclotron resonance, is still very controversial[1]. Also, in recent years, more new phenomenon, such as the CR peak splitting and broadening in certain regions of magnetic field strength and electron density, have been discovered[2-5]. This peak splitting phenomenon, which has not been found in the former theories, is attributed to the possible softening of the 2D magneto-plasmon mode due to the many body effects[3].

Here we extend the generalized quantum Langevin equation (GLE) approach[5,6] to study 2D electron-phonon-impurity systems. In the quantum limit, ($E_F \gg T$, $\omega_c \gg T$), we obtain (using standard notation) the memory function $M(\omega) = M_1(\omega) + iM_2(\omega)$ - which is essentially the Fourier transform of the memory function appearing in the GLE - due to the electron-impurity and electron-phonon scattering, respectively,

$$M^{im}(\omega) = \frac{n_i g_v}{M\omega} \sum_{\vec{q}} q_x^2 |U(\vec{q})|^2 \{\chi(\vec{q},o) - \chi(\vec{q},\omega)\} , \quad (1)$$

$$M_1^{ph}(\omega) = \frac{g_v}{2M\omega} \sum_{\vec{q}} q_x^2 |M(\vec{q})| (\coth \tfrac{1}{2} \beta\Omega_{\vec{q}} - 1)[2\chi_1(\vec{q},\Omega_{\vec{q}}) - \chi_1(\vec{q},\omega+\Omega_{\vec{q}}) - \chi_1(q,\omega-\Omega_{\vec{q}})] . \quad (2)$$

$$M_2^{ph}(\omega) = -\frac{g_v}{M\omega} \sum_{\vec{q}} q_x^2 |M(\vec{q})|^2 \{[n(\Omega_{\vec{q}}) - n(\omega+\Omega_{\vec{q}})]\chi_2(\vec{q},\omega+\Omega_{\vec{q}})$$

$$+ [n(\Omega_{\vec{q}}) + n(\Omega_{\vec{q}} - \omega)]\chi_2(\vec{q},\omega-\Omega_{\vec{q}})\} . \quad (3)$$

Here $\chi(\vec{q},\omega) = \chi^o(\vec{q},\omega)/\varepsilon(\vec{q},\omega)$, and

$$\varepsilon(\vec{q},\omega) = 1 - V(\vec{q})\ \chi^o(\vec{q},\omega), \quad \chi^o(\vec{q},\omega) = \sum_{nn'} \frac{f(\varepsilon_n)-f(\varepsilon_{n'})}{\omega-\omega_{nn'}+iDq^2} C_{nn'}(\vec{q}) . \quad (4)$$

In Ref. 5, we neglected the electron-phonon interaction, and considered a short range impurity to perform numerical calculations, and we obtained a very good fit to some CR experiments on Si(001).

2. MANY BODY EFFECTS ON THE MAGNETO-PLASMON DISPERSION

The dispersion relation of a 2D magneto-plasmon, or the plasmon shifted cyclotron resonance, is determined by the zero of the dielectric function. In our formalism, three kinds of dielectric functions appear in (1)-(3), i.e. $\varepsilon(\vec{q},\omega)$, $\varepsilon(\vec{q},\omega+\Omega_{\vec{q}})$, $\varepsilon(\vec{q},\omega-\Omega_{\vec{q}})$, representing the dielectric property of the impurity, phonon-absorption and phonon emission respectively. These functions extend the conventional RPA dielectric result (with the iDq^2 term in (4) replacing the infinitisimal quantity $i\delta$) by two kinds of many body effects, namely, the self-diffusion effect of the center of mass, and the electron-acoustic phonon interaction. Using standard parameters for acoustic phonons, we find that at finite q in the phonon absorption (emission) case that the RPA dispersion is shifted downwards, (upwards). As a result of the shift, the value of the dielectric function after considering the acoustic phonon absorption or emission processes, changes dramatically in the vicinity of $\omega=\omega_c$, which will have a strong influence on the CR spectrum, in particular the temperature dependence. The inclusion of the fluctuation effect of the center of mass changes the dielectric property in two respects: the RPA dispersion is shifted at finite q and, more significantly, $\epsilon_2(\vec{q},\omega)$ is finite at any finite value of q. As a result of the non-vanishing of $\epsilon_2(\vec{q},\omega)$, the plasmon excitation is accompanied by damping and the absorption factor $\mathrm{Im}\{\epsilon(\vec{q},\omega)\}^{-1}$ will have non-plasmon contributions due to the fluctuation effect.

3. PEAK SPLITTING OF THE CR SPECTRUM

Using memory functions (1) - (3), we can calculate directly the CR absorption spectrum [5,6]. We found the CR spectrum in our theory has two resonances, one for the ordinary magnetoplasmon excitations at $\omega_c^* > \omega_c$; the other one is new, located at $\omega_c^* < \omega_c$ with an enhanced cyclotron effective mass. The overall shape of the CR spectrum depends on the magnitude of the sample mobility, electron density and the magnetic field. These two peaks will overlap at the lower magnetic field and high electron density side, resulting in a single peak located at ω_c^* slightly lower than ω_c. The result of this simple theoretical calculation is very consistent with the recent experimental observations [2,3].

As an example, we compare our theoretical calculations of the spectrum with the experimental data of Ref. 2 where direct absorption spectrum is available. The results are shown in Fig. 1, where we use impurity scattering only, $D^* = mD/\hbar = 0.526 \times 10^{11}\ \mathrm{cm}^{-2}/n_s$, and standard parameters for GaAs/AlGaAs heterojunction such as setback $\alpha = 50\text{Å}$, impurity density $n_i = 1.7\ n_s$, valley degeneracy $g_v = 1$. The figure illustrates one of the peak splitting features discussed before, i.e., the single absorption peak for the high n_s case will be broadened and eventually split when n_s is decreased. Also, very good agreement is obtained between our theory and the experiments.

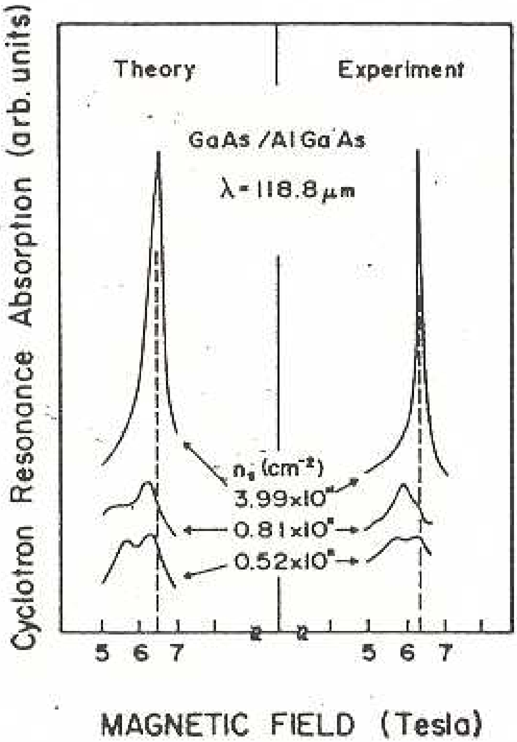

Fig. 1. Theoretical and experimental [2] CR spectrum versus the magnetic field at three different electron densities n_s for the GaAs/AlGaAs heterojunction.

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