Theory of cyclotron resonance of correlated electron systems

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Abstract

The cyclotron resonance (CR) absorption of 2D electrons in semiconductor heterostructures GaAs/AlGaAs in high magnetic fields is investigated. The theory explicitly takes the Coulomb correlation into account through the Wigner phonons. The CR linewidth is in quantitative agreement with the experiment in the Wigner crystal regime at $T = 4.2$K. The diagonal conductivity has the two-peak structure as predicted by Fukuyama and Lee.

Key words: Cyclotron resonance; Semiconductor heterostructure; Quantum transport; Wigner crystal.

1. Introduction

Two-dimensional electron system in strong magnetic fields has been studied intensively for many years. Until recently, most of the work has concentrated on the dc magnetotransport, photoluminescence [1,2]. Important information about the 2D electron system can be obtained also from the cyclotron resonance. There are numerous experimetal and theoretical investigations which concentrate on the low density electron system in high magnetic fields when the electron correlation will dominate and the crystalization of electrons into a Wigner lattice is expected [3,4].

In this work, we present the theoretical analysis of the linewidth of the CR due to impurity scattering of the 2D electron systems in high magnetic fields applied which is normal to the electron plane. Electrons are assumed to form a Wigner crystal in which the electrons are localized and oscilate around their equilibrium positions, and the electron correlation is taken into account through the Wigner phonons. The numerical results of the CR linewidth are compared with the experiment in the electron systems in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructures in a high magnetic field.

2. Theory and numerical results

The absorption lineshape of the 2D electron system in a magnetic field is characterized by the conductivity $\sigma_{\pm}(\omega)$ which may be expressed through the memory function $M(\omega)$ by:

$$\sigma_{\pm}(\omega) = \frac{in_e e^2}{m} \frac{1}{\omega \mp \omega_c + M(\omega)}, \tag{1}$$

where ω_c is the cyclotron frequency, $-e, m$, and n_e are the charge, effective mass and 2D density of the electron, respectively.

The width function $\gamma(\omega)$ of the absorption lineshape of the CR is governed by the imaginary part of the memory function $M(\omega)$ and is expressed by the dynamic structure factor (DSF) or the Fourier transform of the density-density correlation function:

$$\gamma(\omega) = \frac{1 - e^{-\hbar\omega\beta}}{m\omega} \frac{1}{A} \sum_{\mathbf{q}} \hbar W_{\mathbf{q}} \mathbf{q}^2 S(\mathbf{q}, \omega), \tag{2}$$

where β is the inverse temperature, A the area of the electron system, and W_q the Fourier transform of the

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random averaged correlation function of impurity potentials $< U(\mathbf{r})U(0) >_r$ [5].

Assuming $\beta\hbar\omega_c \gg 1$, we can express DSF as a summation over the contributions of all Landau levels:

$$S(\mathbf{q},\omega) = \frac{2\sqrt{\pi}\hbar}{\Gamma_c}\sum_{n=0}^{\infty}\frac{x^{n-\frac{1}{2}}}{n!}e^{\beta\hbar(\omega-n\omega_c)/2} \times \exp\left[-x\left(1+\left(\frac{\Gamma_c\beta}{4}\right)^2\right)-\frac{\hbar^2(\omega-n\omega_c)^2}{x\Gamma_c^2}\right] \quad (3)$$

where $x = \hbar q^2/2m\omega_c$, and $\Gamma_c = \sqrt{\Gamma_{e-i}^2+\Gamma_{e-e}^2}$ is the Coulomb broadening parameter. Here

$$\Gamma_{e-i}^2 = \frac{2}{\pi}q^2 W_q = \frac{8\hbar^3 n_e}{m\tau}, \quad (4)$$

$$\Gamma_{e-e}^2 = \frac{(0.85\hbar\omega_0)^2}{\beta\hbar\omega_c}, \quad (5)$$

where $\omega_0 = 2(\pi n_e)^{3/4}(e^2/\kappa m)^{1/2}$ is the 2D plasma frequency and κ the dielectric constant of the matter. Γ_{e-i} describes the single-electron effect which is related to the collision time τ due to the electron-impurity scattering, and Γ_{e-e} to the many-electron effect.

The expression (3) is similar to Monarkha and coworkers' results [3], but their expression of Γ_c^{M} corresponds to our expressions by $\Gamma_c^{\mathrm{M}} = \sqrt{\Gamma_{e-i}^2 + x\Gamma_{e-e}^2}/x$, and the factor $\exp\left[\beta\hbar(\omega-n\omega_c)/2 - x(\Gamma_c\beta/4)^2\right]$ is missing.

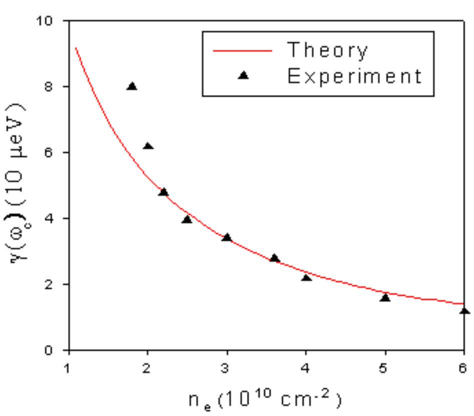

Fig. 1. $\gamma(\omega_c)$ vs n_e for the 2D electrons in heterostructure GaAs/AlGaAs doped with Si impurities at $T = 4.2$ K, and $B = 7.4$ T. The triangles are taken from the experimental result of Chou et al. [4].

The electron density dependence of the CR linewidth is shown in Fig. 1. Our theoretical result is in quantitative agreement with the experiment in the region of the electron density 2.10^{10} cm$^{-2} \le n_e \le 6.10^{10}$ cm^{-2} (the filling factor varies from 0.08 to 0.34), where the electron system is expected to crystalize into a Wigner crystal.

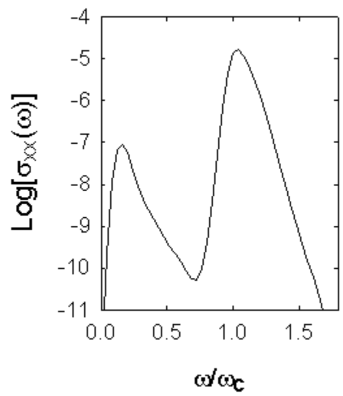

Fig. 2. Frequency dependence of the diagonal conductivity

Fig. 2 shows the diagonal conductivity $\sigma_{xx}(\omega)$ as a function of ω/ω_c. Two peaks are visible in the conductivity. It is well-known that Wigner phonon spectra in the magnetic field split into two modified modes $\omega_\pm$. In a high magnetic field $\omega_+ \approx \omega_c$ and $\omega_- \approx \hbar^2 n_e\beta/m\tau = \Gamma_{e-i}^2\beta/8\hbar$. The peak at $\omega = \omega_c$ corresponds to the ordinary CR, and one at lower frequency $\omega = \omega_-$ is related to the pinning mode due to impurities. This behavour was also predicted by Fukuyama and Lee [6], though their expression of the pinning mode is different from our ω_-.

3. Conclusion

The cyclotron resonance of the 2D electron system in heterostructures in high magnetic fields is investigated with the electron correlation is taken into account through Wigner phonons. The single-electron and many-electron effects are considered simultaneously. The result obtained is in quantitative agreement with experiment in the Wigner crystal regime. Similar to Fukuyama and Lee, our results also show the doubling of the resonance peaks.

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