Cyclotron resonance of interacting quantum Hall droplets

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Abstract

The line shape and position of cyclotron resonance in gated GaAs/GaAlAs heterojunctions with δ-doped layers of negatively charged beryllium acceptors, that provide strong potential fluctuations in the channels of the quasi-two-dimensional electron systems, are examined. Specifically, the magnetic quantum limit is considered when the electrons are localized in separate quantum Hall droplets in the valleys of the disorder potential. A model treating disorder and electron–electron interaction on an equal footing accounts for all of the principal experimental findings: blue shifts from the unperturbed cyclotron frequency that decrease when the electron density is reduced, surprisingly narrow lines in the magnetic quantum limit, and asymmetric lines due to additional oscillator strength on their high-frequency sides.

Cyclotron resonance (CR) of quasi-two-dimensional electron systems (2DES) has remained of interest since it was first observed 25 years ago [1]. Only recently, two long-standing mysteries of CR in high-mobility GaAs/GaAlAs heterojunctions with their unrivaled narrow line widths could be solved. These are the absence of splittings expected for the two spin orientations $s = \pm\frac{1}{2}$ due to the finite Landé factor [2] as well as for the distinct Landau transitions $n \to n+1$ due to subband nonparabolicity [3]. Both has been explained as a consequence of the electron–electron interaction that overcomes the splittings and couples individual transitions to a single hybridized resonance [3,4]. The role of disorder and associated electron localization is another issue. For translationally invariant systems, Kohn's theorem assures that CR is not affected by the electron–electron interaction. This is no longer true in disordered systems and numerous studies have addressed the interplay between disorder and interaction for CR [5,6]. The evidence in strong magnetic fields may be summarized as follows: in the magnetic quantum limit ($\nu < 1$) the CR is a sharp single line shifted upwards in frequency with respect to the cyclotron frequency. At higher filling factors, say in the regime

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$1 < \nu \gtrsim 3$, one observes a splitted CR. Here we report on experiments in the magnetic quantum limit which confirm the prediction that the disorder-induced shift does not only depend on the degree of disorder but on the electron density as well. The experiments also unveil asymmetric line shapes. All the essential features of the CR spectra, namely their narrowness, their asymmetries as well as their density-dependent shifts are consistently explained by a simple model [7] of interacting electrons localized in separate valleys of the disorder potential.

Standard modulation doped GaAs/GaAlAs heterojunctions have been grown by molecular-beam epitaxy. They include a δ-doped layer of negatively charged beryllium acceptors at a distance of 2.3 nm underneath the GaAs/GaAlAs interface. This layer acts as a source of potential fluctuations in the 2DES [8]. In the present sample we have a nominal beryllium concentration of $N_{\mathrm{Be}^-} = 2 \times 10^{10}\,\mathrm{cm}^{-2}$. In the spectroscopic experiments, the relative change of transmittance $\Delta T/T_{\mathrm{ref}} = (T - T_{\mathrm{ref}})/T_{\mathrm{ref}}$ with suitable reference spectra T_{ref} is recorded in a Fourier-transform spectrometer in Faraday geometry at liquid helium temperatures of 4 K.

Representative results are shown in Fig. 1. Above a filling factor of $\nu \simeq 1$ the resonance is split into two peaks, one being an essentially undisturbed CR at the cyclotron frequency $\omega_c = eB/m^*$, the second blue-shifted with respect to it. At filling factors $\nu < 1$ only the shifted resonance outlives as a single sharp line. Both, the splitting and the shift in strong magnetic fields have been observed previously in 2DES in metal-oxide-semiconductor structures on Si [9] as well as in GaAs/GaAlAs heterojunctions [8]. While the mechanism of the splitting is still unknown, there have been various attempts to explain the shift and the narrow lines in the magnetic quantum limit [5,6].

Recently, a simple model of interacting electrons localized in the valleys of the potential fluctuations has been suggested [7]. It has been argued there, that in the limit of strong interaction and high magnetic fields ($\omega_c \gg \omega_0$) the shift $\omega_s = \sqrt{2}\omega_0$ is determined by the average frequency $\omega_0 = (\sum \omega_i^2/N)^{1/2}$ when the N electrons experience local curvatures ω_i^2 in the bare disorder potential. For

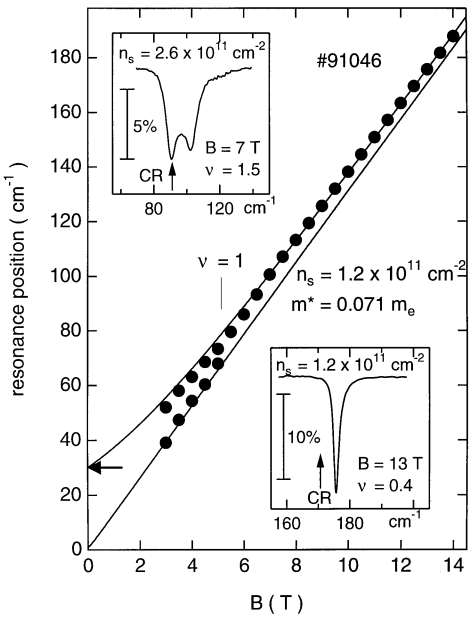

Fig. 1. Resonance positions for an electron density of $n_s = 1.2 \times 10^{11}\,\mathrm{cm}^{-2}$. The solid lines are best fits to the theoretical ω_+-mode and to the cyclotron frequency $\omega_c = eB/m^*$, respectively. The arrow indicates the frequency ω_0. The upper inset depicts a split resonance routinely observed for filling factors $\nu \gtrsim 1$, here for $\nu = 1.5$ at $n_s = 2.6 \times 10^{11}\,\mathrm{cm}^{-2}$. The lower inset shows a hybridized narrow line for $\nu = 0.4$.

complete hybridization, the eigenfrequency of the shifted mode $\omega_+ = [\omega_0^2 + (\omega_c/2)^2]^{1/2}$ is reminiscent of the higher dipole mode of a single quantum dot according to the generalized Kohn theorem [10]. The solid lines in Fig. 1 are best fits to the cyclotron frequency ω_c and to ω_+ allowing for the slight band nonparabolicity of GaAs by the detailed value of the effective electron mass m^*. It has also been predicted [7], that for repulsive scatterers the shift ω_s should decrease with electron density n_s. A decrease of the shift is in fact observed in the spectra of Fig. 2 and is summarized in Fig. 3. The spectra in Fig. 2 also reveal asymmetric line shapes. While there is additional oscillator strength on the low-frequency tails in the spectra for the higher densities due to the onset of the splitting at filling factors exceeding unity, a different type of asymmetry occurs in the spectra for the lower densities on their high-frequency sides. Relative to the total oscillator strength, this is most pronounced for the lowest

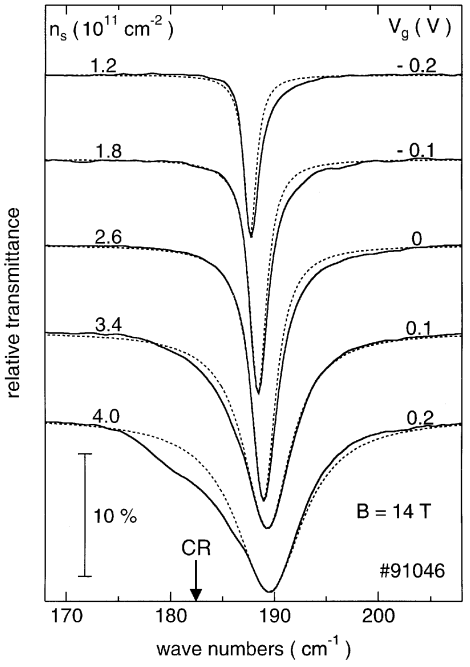

Fig. 2. Spectra for various electron densities in a fixed magnetic field of strength $B = 14$ T corresponding to filling factors $\nu = 0.35$–1.18. The dashed lines are Lorentzians that we include to demonstrate the asymmetry of the line shapes.

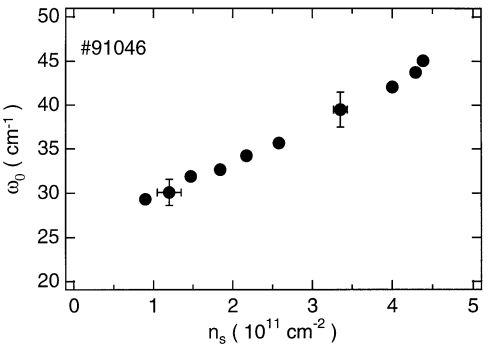

Fig. 3. Frequency ω_0 versus electron density.

density $n_s = 1.2 \times 10^{11}$ cm^{-2}. We regard the asymmetry on the high-frequency side as manifestation of the coupling of the far-infrared field to internal modes of the electron system.

In order to support this view, we have carried out model calculations. To simplify the numerical

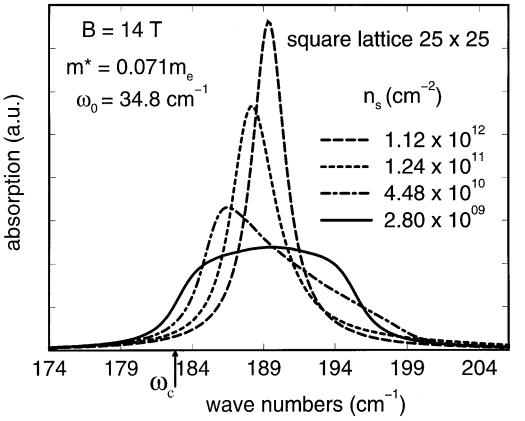

Fig. 4. Calculated absorption of interacting electrons in a potential landscape. Values $\sigma^2 = 2422$ cm^{-2} and $\omega_0^2 = 1211$ cm^{-2} are chosen for the width of the box distribution and its average, respectively. For the lowest density, the interaction can savely be ignored and the corresponding spectrum essentially reflects the disorder as it has been introduced in the model. The intergrated absorption is normalized.

calculations, we consider a 25×25 square lattice of electron sites with curvatures ω_i^2 and take into account nearest-neighbor interaction only. By this we mimic the localization of the electrons in the valleys of the fluctuating potential. However, we like to note that the results do not change qualitatively for random distributions of sites [11,12]. Also for simplicity reasons, we assume a box distribution $P(\omega_i^2)$ of width σ^2 around the average ω_0^2 though more realistic distributions can be deduced from the allied arrangement of the beryllium acceptors [11,13]. For the spectra of Fig. 4, we collected ten realizations of the distribution $P(\omega_i^2)$ and determined for each of them the possible excitation modes $\omega_{\lambda\pm}(\lambda = 1, \ldots, 625)$ of the system as well as the associated oscillator strengths $f_{\lambda\pm}$. The absorption is calculated for linearly polarized light [11] and averaged over the realizations to obtain the spectra of Fig. 4. A small momentum relaxation rate $\gamma \simeq \omega_0/10$ is introduced. As a consequence, for the absorption at the lowest electron density, i.e. negligible interaction, there is no one-to-one correspondence of the independent oscillators to the box distribution, but the line is smeared out at its edges. With increasing Coulomb interaction the line widths in Fig. 4 shrink until only the

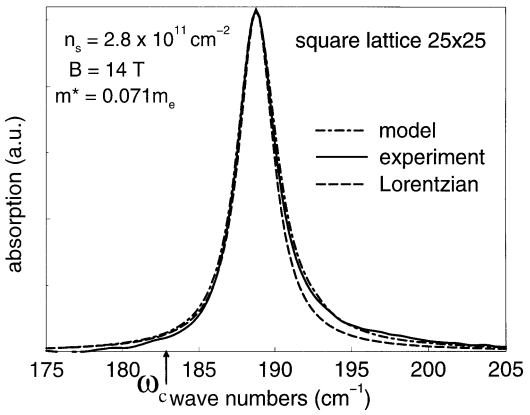

Fig. 5. Comparison of a typical experimental spectrum (solid line) to a Lorentzian (dashed line) and to our model (dash–dotted line). In the model we use values $\sigma^2 = 3028\ \mathrm{cm}^{-2}$ and $\omega_0^2 = 1211\ \mathrm{cm}^{-2}$.

center-of-mass excitation with a restoring force proportional to the average ω_0^2 remains. The curve for the highest density $n_s = 1.12 \times 10^{12}\ \mathrm{cm}^{-2}$ is only introduced to demonstrate the extreme limit of strong interaction.

Even more interesting, the shapes exhibit clear asymmetries on their high-frequency sides at intermediate values of the interaction strength. This indicates coupling to internal modes of the electron system as has previously been demonstrated for $N = 2$ electrons [7]. In an attempt for a more quantitative description of a measured line shape in Fig. 5, we use the cyclotron frequency $\omega_c = 182.8\ \mathrm{cm}^{-1}$ and the electron density $n_s = 2.8 \times 10^{11}\ \mathrm{cm}^{-2}$ which are known quite accurately from the experiments. The frequency $\omega_0 = 34.8\ \mathrm{cm}^{-1}$ results from an extrapolation of the experimental data to vanishing magnetic fields as depicted in Fig. 1. The only fit parameters then are the relaxation rate $\gamma = 2.8\ \mathrm{cm}^{-1}$ and the width $\sigma^2 = 3028\ \mathrm{cm}^{-2}$ of the box distribution $P(\omega_i^2)$. A satisfying agreement between our simple model and the experimental spectrum is obtained in Fig. 5, particularly concerning the asymmetry on the high-frequency tail.

Next, we like to discuss the experimentally observed increase of the frequency ω_0 with electron density n_s as shown in Fig. 3. By virtue of its determination, the increase of this frequency is equivalent to an increase of the blue shift of the CR. We think that there are two mechanisms that one can distinguish in explaining the size of the shift and its dependence on electron density. The first is directly related to the frequencies ω_i. For a statistically or moderately correlated arrangement [13] of negatively charged impurities, one expects that at low electron densities just the deep valleys between well separated impurities, which at the same time are flat, are occupied. Only for higher densities, valleys inside more dense clusters [12] of impurities, which lie higher in energy and concurrently possess stronger curvatures, become populated in this picture. This effect can explain the increase of the shift $\sqrt{2}\omega_0$ in case of strong interaction when it is solely determined by the average frequency ω_0. However, there is a second mechanism evidenced by the line shapes in Fig. 4. When the interaction is increased, the peak evolves from the low-frequency side of the inhomogeneously broadened line calculated for negligible interaction. It then shifts up to its final position valid for strong interaction. Since for all densities the box distribution of frequencies ω_i is kept constant in Fig. 4, the partition of oscillator strength and its redistribution for increasing interaction also play an important role for the density dependence of the shift at low and intermediate electron densities.

In conclusion, we have examined the blue shift observed for the CR of disordered 2DES in the magnetic quantum limit. The shift is caused by localization of the electrons in the valleys of the potential landscape. At common electron densities $n_s \simeq 10^{11}\ \mathrm{cm}^{-2}$, the shifted resonance is a sharp line due to hybridization of the individual transitions in the interacting 2DES. Only at lower electron densities, i.e. for weaker interaction, the excitation of internal modes becomes possible and causes asymmetric line shapes with additional oscillator strength on their high-frequency sides.

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