Linewidth anomaly of two-dimensional-electron cyclotron resonance in the extreme quantum limit

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We report the observation of striking line narrowing with decreasing T in the cyclotron resonance (CR) of high-mobility two-dimensional electrons in $GaAs/Al_xGa_{1-x}As$ in the extreme quantum limit. From 4.2 to 1.2 K, where the dc mobility increases by less than 1%, the CR linewidth can decrease by as much as threefold, accompanied by a downward shift of $\sim 0.3\%$ in effective mass. Inhomogeneous broadening of Landau levels by long-range potential fluctuations can qualitatively account for the striking features of the data, though not their dependences on the filling factor ν.

We wish to report the observation of a striking line narrowing with decreasing temperature in the cyclotron resonance (CR) of the high-mobility two-dimensional electron gas (2D EG) in $GaAs/Al_xGa_{1-x}As$ heterostructures at extremely low densities. The experiment is in the low-temperature (T) and high-magnetic-field (B) limit when all electrons occupy the lowest Landau level with a filling factor $\nu < 1$. Among the large number of recent CR experiments[1–10] on this 2D EG system, Brummell *et al.*[5] reported a detailed study of CR from 4.2 to 280 K. They focused on the effect of T on the CR mass (m^*_{CR}) and found an anomalous increase with T to ~ 100 K. This mass increase is attributed to the strong screening of the electron–optic-phonon interaction which suppresses the polaron mass enhancement at low T. Chou *et al.*[8,9] systematically investigated at 4.2 K the effect of level filling in the extreme quantum limit and observed a strong dependence of the CR linewidth on ν, which at its narrowest corresponds to a scattering time τ_{CR} more than ten times longer than that from dc transport at $B = 0$. This marked reduction in the scattering rate is attributed to the strong screening at $\nu \sim \frac{1}{2}$ which greatly reduces scattering of the 2D EG by Coulomb centers in the sample. Schlesinger *et al.*[10] observed a dramatic resonance narrowing and shift as the 2D EG density was reduced below the point at which the lowest spin-split Landau level was filled. This result and the T dependence of their CR linewidth and resonance position were attributed to the electron screening of interactions between the finite-wavelength magnetoplasmon modes and the cyclotron mode. In their experiments, the CR linewidth is comparable with k_BT, and the T effect they observed is as expected from the calculations by Lassnig *et al.*[11] We have focused on the T dependence of CR of samples (filling factors close to $\frac{1}{2}$), from which extremely narrow CR linewidth (being much less than k_BT) are obtained and the T effect on CR from the electron screening is not expected.[11] We find that in the temperature range between 4.2 and 1.2 K, where the dc mobility increases by less than 1%, the CR linewidth can decrease by as much as threefold with decreasing T. This decrease is accompanied by a downward shift of $\sim 0.3\%$ in the resonance position, corresponding to a decrease in the effective cyclotron mass. The results are discussed with respect to lifetime broadening of Landau levels by scattering off phonons and screened ionized impurities and to inhomogeneous broadening by long-range potential fluctuations. The latter can qualitatively account for the observed striking features but not their dependences on ν.

The samples used in this work are from two wafers of selectively doped $GaAs/Al_{0.35}Ga_{0.65}As$ heterostructures grown by molecular-beam epitaxy with Si donors placed either 910 or 750 Å away from the $GaAs/Al_xGa_{1-x}As$ interface. A calculation following the approaches of Lin *et al.*[12] shows that the scattering rate due to the remote ionized impurities in the $Al_xGa_{1-x}As$ layer is strongly suppressed by this large setback and that the scattering is dominated by residual impurities in the structure. The 2D electron concentration (N_s) and dc mobility (μ_{dc}) were determined from magnetotransport measurements at the time when each sample was cooled down to take the CR curves. They are $N_s = 9.89\times10^{10}$, 6.6×10^{10}, and 5.3×10^{10} cm^{-2} and $\mu_{dc} = 398\,000$, 160 000, and 185 000 $cm^2/V\,sec$ for samples 32, 38E, and 38C, respectively, at 4.2 K. Swept-field CR experiments were performed under the Faraday configuration using the $\lambda = 119$ μm laser line from an optically pumped far-infrared laser. The filling factors ν at the observed resonance magnet field at 4.2 K are 0.66, 0.44, and 0.35, respectively. A cold filter and a linear polarizer were placed right above the sample and the transmitted radiation was detected by a Ga-doped Ge detector placed about 15 inches below the bottom of the magnet. The detector resistance at $T = 4.2$ K was systematically tested to insure no significant variations at different magnetic fields up to 8 T. During the measurement, the power of the FIR laser was monitored with a pyroelectric detector and the signal from it was used to normalize the CR spectrum using a two-channel boxcar averager.

While a full quantum theory for CR is not available, we use the Drude model to extract m^*_{CR} and τ_{CR} from the CR spectra.[13] The transmission coefficient $t_\pm$ (where the $\pm$ sign refers to the right- and left-hand circular polarizations, respectively) and the transmittance $T(B)$, obtained from the matrix method of Ref. 13 are given by

$$T(B)=\tfrac{1}{2}(|t_+|^2+|t_-|^2) \tag{1}$$

and

$$t_\pm=\frac{E_{\text{out},\pm}}{E_{\text{input},\pm}}=\frac{2}{m_{1,\pm}+m_{2,\pm}+m_{3,\pm}+m_{4,\pm}}\ , \tag{2}$$

where

$$\begin{bmatrix} E_{\text{input},\pm} \\ H_{\text{input},\pm} \end{bmatrix}=\begin{bmatrix} m_{1,\pm} & m_{2,\pm} \\ m_{3,\pm} & m_{4,\pm} \end{bmatrix}\begin{bmatrix} E_{\text{out},\pm} \\ H_{\text{out},\pm} \end{bmatrix} \tag{3}$$

and

$$\begin{bmatrix} m_{1,\pm} & m_{2,\pm} \\ m_{3,\pm} & m_{4,\pm} \end{bmatrix}=\begin{bmatrix} \cos(\phi_\pm) & i\sin(\phi_\pm)/n_\pm \\ in_\pm\sin(\phi_\pm) & \cos(\phi_\pm) \end{bmatrix} \times \begin{bmatrix} \cos(\theta) & i\sin(\theta)/n_{\text{GaAs}} \\ in_{\text{GaAs}}\sin(\theta) & \cos(\theta) \end{bmatrix} \tag{4}$$

is the characteristic matrix. Here,

$$\phi_\pm=k_\pm d_{2D}\ , \tag{5}$$

$$k_\pm=(\omega/c)n_\pm\ , \tag{6}$$

$$n_\pm=[\epsilon-i\sigma_\pm(B)/\omega\epsilon_0]^{1/2}\ , \tag{7}$$

$$\sigma_\pm(B)=\sigma_0[1+i\tau_{CR}(\omega\pm eB/m^*_{CR})]^{-1}\ , \tag{8}$$

and

$$\sigma_0=N_s e^2\tau_{CR}/m^*_{CR}\ . \tag{9}$$

In the above equations, d_{2D} is the effective thickness of the 2D EG,[14] ϵ is the dc dielectric constant, and $\sigma(B)$ is the Drude conductivity at ω in the presence of B. In addition, the second matrix on the right-hand side of Eq. (4) takes into account the interference effect in the GaAs substrate. The interference parameter θ is given by $\theta=2\pi n_{\text{GaAs}}d_{\text{substrate}}/\lambda$, where $d_{\text{substrate}}$ is the thickness of the GaAs substrate. In order to check if the interference effect is indeed properly taken into account, CR curves have been taken at different laser lines, different polarizations, different carrier concentrations, and different temperatures. The maximum discrepancy on the fitted interference parameter from our samples is less than 1°. One sample was subsequently wedged to 5° to eliminate interference and the results further confirm the corrections of our data fitting. It should be noted that when $\phi \ll 1$, small signal approximation is proper, and the half width at half maximum (HWHM) of the resonance lineshape is equal to $1/\tau$. However, it is well known that in a high-mobility 2D EG sample, saturation of the transmission signal close to the resonance occurs, and small signal approximation is no longer valid. In such cases, the linewidth of the CR spectra is not sensitive to $1/\tau$. Therefore, a direct estimation of the meaningful physical parameter $1/\tau$ from the experimental spectra is not possible and a model without using the small signal approximation is needed. Our model, which does not assume $\phi \ll 1$, is a such model. We have carefully studied the saturation effects using our model and have proven that a fitting to our data with the model is indeed necessary. Since the CR width loses its sensitivity to reflect a change of carrier mobility in the high-mobility regime, only the extracted $1/\tau$ can reflect the physical effects of the temperature on the CR linewidth.

Figure 1 shows the CR curves taken from sample 38E at several temperatures from 4.2 to 1.2 K. They are fitted with the Drude model to extract m^*_{CR} and τ_{CR}. The fit, as shown in the figure, is excellent in all cases and the extracted τ_{CR} and m^*_{CR} are shown in Fig. 2 as the HWHM of the CR $\Gamma_{CR}=\hbar/\tau_{CR}$ and the mass shift from its 4.2 K value $\Delta m^*_{CR}=m^*_{CR}-m^*_{CR}$ (4.2 K). It is clear from these two figures that as T decreases the CR linewidth decreases. In a relatively small temperature range of 3 K, the linewidth decreases by more than twofold from $\Gamma_{CR}\simeq 0.0247$ meV at 4.2 K to $\Gamma_{CR}\simeq 0.0104$ meV at 1.27 K. This striking line narrowing is accompanied by a small but unambiguous shift of the resonance position B_{CR} to a lower B, corresponding to a decrease in the effective cyclotron mass. Similar T dependences are observed in the data from samples 32 and 38C [shown as

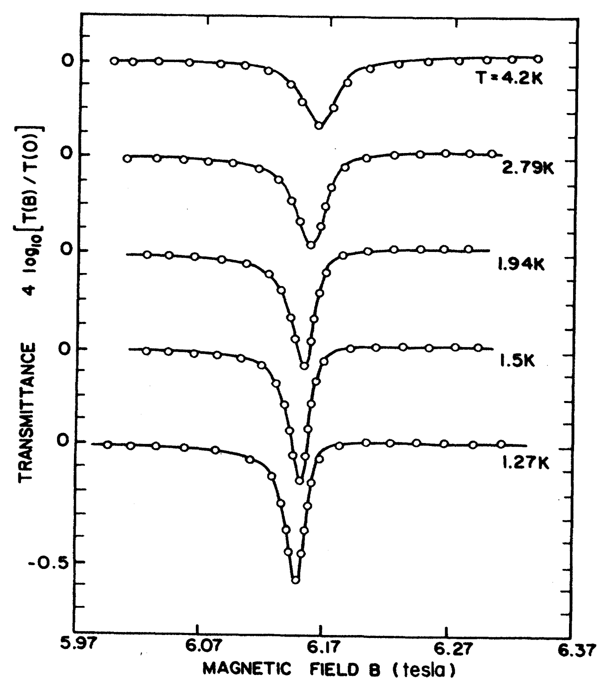

FIG. 1. Solid curves are CR traces at different temperatures taken from sample 38E with the $\lambda=119$ μm laser. Circles are fits to Eq. (1). Extracted τ_{CR} and m^*_{CR} are plotted in Fig. 2 and the interference parameter $\theta=91.0°\pm 0.1°$.

crosses (×) and solid circles (●) in Fig. 2], which have different densities and mobilities, and also in the data taken with the $\lambda=96$ μm laser line on sample 32 [which are the triangles (Δ) in Fig. 2]. However, there appears to be no obvious correlation between the observed line narrowing and the 2D electron density and mobility. On the other hand, in this limited temperature range of our experiment, the line narrowing observed in all our data can be described by a power-law dependence on T through $\Gamma_{CR}\sim T^{\alpha}$. The exponent $\alpha\simeq 1$ for CR at Landau-level filling factor $\nu\simeq 0.5$ ($\nu=0.44$ for sample 38E with $\lambda=119$ μm and $\nu=0.53$ for sample 32 with $\lambda=96$ μm) and $\alpha\simeq\frac{1}{2}$ for $\nu\simeq 0.5\pm 0.15$ ($\nu=0.35$ for sample 38C and $\nu=0.66$ for sample 32 with $\lambda=119$ μm).

In Fig. 3 we convert the $\lambda=119$ μm CR linewidth of all three samples into mobility using $\mu_{CR}=e\tau_{CR}/m^*_{CR}$ and plot it together with the dc mobility on a log-log scale as a function of T. The dc mobility is obtained from $\mu_{dc}=\sigma/eN_s$, where the zero-B-field conductivity σ and the 2D electron density N_s are determined from quantum-transport measurements on the same sample in the same run. This plot further demonstrates the two surprising aspects of the CR linewidth data. First, in the range of T the CR line narrowing is observed, μ_{dc} shows an extremely weak increase with decreasing T (by $\sim 1\%$ per degree K in comparison with $\sim 40\%$ per degree K for μ_{CR}). This increase in μ_{dc} is due to the decrease of scattering by acoustic phonons through deformation potential and piezoelectric coupling of the 2D electrons.[15,16] Since the increase of μ_{CR} is more than 40 times higher, it is unlikely that Landau-level broadening by the same phonon processes[17] can explain the observed line narrowing. Second, μ_{CR} is much higher than μ_{dc}, contrary to the expectation of a lower μ_{CR} based on the well-known semiclassical argument that dc transport probes only large angle scattering, while CR probes small angle scattering as well. This enhancement of μ_{CR} was previously observed[8,9] at 4.2 K and was attributed to the enhancement of screening.[18–21] When the Landau level is close to half-filling in the quantum limit, the density of states at E_F is high and the level broadening by scattering off ionized impurities is greatly reduced by screening. However, since $\Gamma_{CR}\ll k_BT$ in our experiments, this reduction of level broadening is not expected to be strongly T dependent,[11] and it too cannot be the origin of the strong T dependence observed in the CR line narrowing.

We believe that the observed line narrowing is a result of inhomogeneous broadening of the Landau levels. When the Landau levels are inhomogeneously broadened by long-range potential fluctuations, the CR linewidth is given approximately by the difference $\Delta\Gamma$ in the level width of the neighboring occupied and unoccupied Landau levels.[22] Since the perturbation by the electrostatic potential on both Landau levels is unlikely to be too different, extremely narrow linewidth can be expected at low T. The underlying physics is already apparent in the

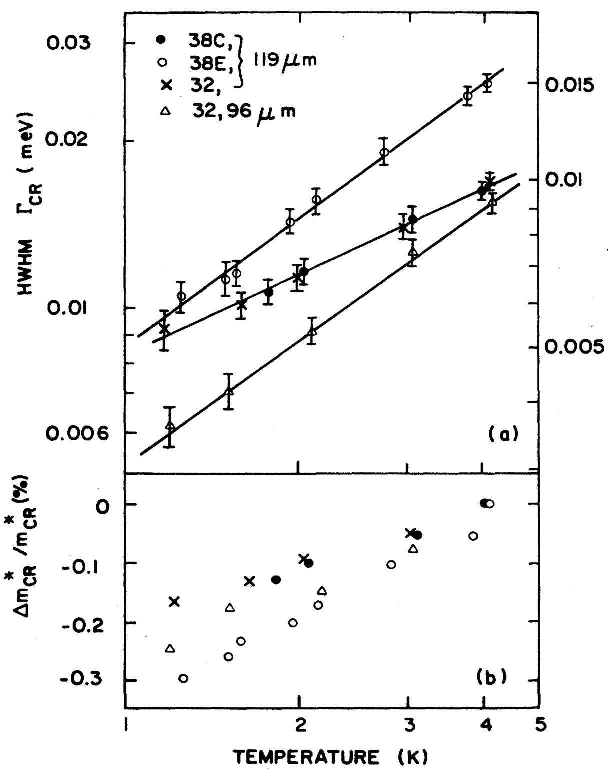

FIG. 2. (a) τ_{CR}^{-1} plotted as HWHM, $\Gamma_{CR}=\hbar/\tau_{CR}$. (b) Relative shift of the effective mass from its 4.2 K value $\Delta m^*_{CR}=m^*_{CR}(T)-m^*_{CR}$ (4.2 K). The Landau-level filling factor at CR is $\nu=0.35$ for sample 38C, (●); $\nu=0.44$ for 38E, (○); $\nu=0.66$ for 32, (×) all with $\lambda=119$ μm; and $\nu=0.53$ for 32, (Δ) with $\lambda=96$ μm.

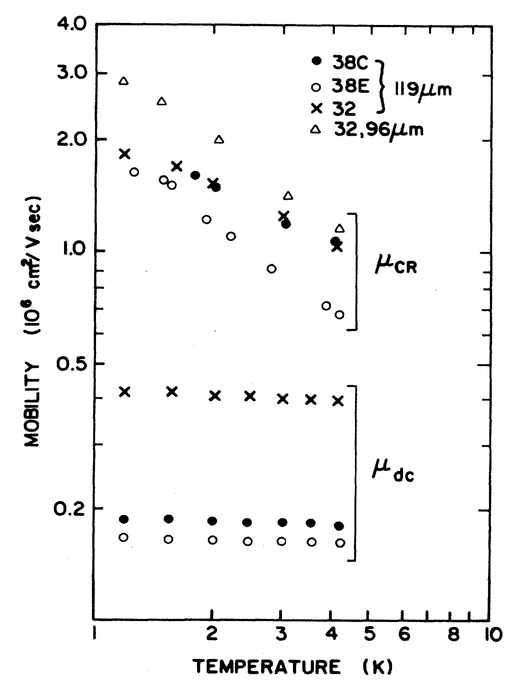

FIG. 3. Mobility vs temperature. The CR mobility is from $\mu_{CR}=e\tau_{CR}/m^*_{CR}$ and $\mu_{dc}=\sigma/eN_s$, where σ is conductivity at $B=0$ and N_s is determined from quantum oscillations.

simple potential fluctuation model, considered by Mikeska and Schmidt[23] and by Wilson, Allen, and Tsui,[24] where each local potential minimum is characterized by a harmonic potential with a characteristic frequency ω_0. In the high-magnetic field and low-temperature limit, the resonant absorption is shifted from the free-electron CR by an amount related to ω_0, and the transition is only possible between levels in the same local potential minimum. The difference in energy shift in different potential minima, which gives rise to the inhomogeneous broadening of the Landau levels, is unimportant to the absorption linewidth. Consequently, a CR experiment is expected to yield extremely narrow linewidth with a reduced effective $m^*_{\rm CR}$. Furthermore, as T increases, the effect of the confining potential becomes weak and the electrons can hop from potential minimum to potential minimum to increase the absorption linewidth. The calculations by Wilson *et al.*[24] have demonstrated that the model can account for these striking features of the experimental data, but it cannot explain their dependence on the filling factor. Indeed, it should be emphasized that the simple model of one-electron trapping in a random potential is not expected to describe all the physics. It completely neglects the Coulomb interaction between electrons, which is known to give rise to the fractional quantum Hall effect, for example, at $\nu=\frac{2}{3}$ and $\frac{1}{3}$ at lower T.[25] In this regard, we point out that experiments should be carried out at lower T and to more systematically investigate the role of the Landau-level filling factor and the role of impurities and that such experiments are currently in progress.

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