Interaction Coupled Cyclotron Transitions of Two-Dimensional Electron Systems in GaAs at High Temperatures

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We report here the first observation of the cyclotron resonance Landau splitting for low density electron inversion layers in $Al_xGa_{1-x}As$-GaAs heterojunctions. Even at temperatures close to 100 K electron-electron interactions couple the electrical dipole transitions from the ground and first excited Landau levels, with a coupling strength comparable to the one found at liquid helium temperatures. The experiment can be explained only in a single-particle approximation at sufficiently low densities and/or magnetic field strengths where the resonant polaron effect is important.

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Cyclotron resonance (CR) in a translational invariant system is a center-of-mass motion and independent of the electron-electron interaction. This famous result, known as Kohn's theorem [1], has been an important guideline for the interpretation of cyclotron resonance experiments. A reintroduction of electron-electron influences can be expected if the translational symmetry is broken, e.g., due to the energy dependence of the effective mass and/or the presence of disorder. First evidence for influences of electron-electron interactions were reported in cyclotron excitation of degenerate quasi-two-dimensional (2D) electron inversion layers in Si [2]. This subject has attracted considerable theoretical interest [2–4]. Today there is no doubt that also various CR anomalies observed for electron inversion layers in GaAs [5–8] and InAs [9,10] can be attributed to influences of electron-electron interactions.

There are two long-standing mysteries that concern the interpretation of CR for high-mobility electron inversion layers in $Al_xGa_{1-x}As$-GaAs heterojunctions. As is well known from experiments on nondegenerate electrons in the bulk [11], electrical dipole transitions $N \rightarrow N + 1$ from different Landau levels N have different frequencies due to the energy dependence of the electron effective mass. In addition to this Landau splitting, at sufficiently high magnetic field strengths the spin splitting of the $0 \rightarrow 1$ transition was also observed. However, no clear evidence for either Landau or spin splitting was found for samples with surface electron densities N_s of the order of 10^{11} cm^{-2} [5–8]. The spin splitting of the $0 \rightarrow 1$ transition was observed only recently at liquid helium temperatures on low density samples, providing evidence that the single-particle approximation fails to explain resonance positions and oscillator strengths [12,13]. The unexpected striking variation of the frequencies and intensities was explained by Cooper and Chalker [14] who demonstrated that electron-electron interactions couple the electrical dipole transitions with different spin orientation, and the interaction strength was predicted to follow a $N_s^{3/2}$ relation for ideally 2D electron systems [14]. We recently performed a detailed study of the influences that rule the interaction coupling of the spin transitions for inversion layer electrons in GaAs heterojunctions and found a strong dependence on the details of the electron distribution in space [15]. Whereas the problem of the spin splitting has been resolved successfully for electron inversion layers in GaAs at liquid helium temperatures, we still lack an understanding of the Landau splitting. It is also not clear yet what consequences result for the interaction coupling if we go to high temperatures.

We report here the first observation of the Landau-level transitions $0 \rightarrow 1$ and $1 \rightarrow 2$ in electron inversion layers that differ in position due to band coupling phenomena and the resonant polaron effect. The experiment was performed with far-infrared spectroscopy on a gated $Al_xGa_{1-x}As$-GaAs single heterostructure at densities on the order of 10^{10} cm^{-2}. The magnetic field strength B was kept sufficiently low such that the influence of the electron spin could be neglected. However, the magnetic fields employed were still higher than that required for establishing the magnetic quantum limit at liquid helium temperatures. By raising the temperature up to 100 K we achieved the necessary population of the $N = 1$ Landau level. The experiment can be explained in the single-particle approximation only at extremely low N_s or when the resonant polaron effect strongly enhances the single-particle resonance splitting. Electron-electron interactions couple the two Landau transitions also at these high temperatures with a strength comparable to the one observed for the $0 \rightarrow 1$ spin transitions at liquid helium temperatures.

Electron cyclotron resonances were studied in the Faraday geometry in transmission with unpolarized far-infrared radiation at temperatures and magnetic field strengths up to 100 K and 12 T, respectively. Details of the experimental setup are presented elsewhere [16]. Our sample is a modulation doped $Al_{0.3}Ga_{0.7}As$-GaAs single

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heterostructure with a layer sequence 1 μm buffer, 60 nm spacer, 80 nm $Al_{0.3}Ga_{0.7}As$ layer doped with Si to 1×10^{18} cm^{-3}, and 20 nm GaAs cap. A semitransparent NiCr top gate with conductivity $\sigma_g \approx 10^{-3}\ \Omega^{-1}$ allows us to vary the density via the field effect. At 4.2 K and zero gate voltage V_g the sample has an average mobility of 3.5×10^5 cm^2/V s at $N_s \approx 8 \times 10^{10}$ cm^{-2}. In the corresponding figures CR is shown by plotting the normalized transmission $T(V_g)/T(V_{\text{th}})$ for fixed B, where a threshold voltage of $V_{\text{th}} = -5$ V has been applied to ensure complete depletion of the electron inversion channel.

In Fig. 1 the gate voltage dependence of the normalized transmission for the temperature of $T = 90$ K and magnetic fields between 8 and 10 T are shown. At $B = 10$ T we observe two well-resolved resonances which are separated by ~ 10 cm^{-1} in frequency space. We attribute these resonances to the $0 \rightarrow 1$ and $1 \rightarrow 2$ Landau transitions, which differ in energy due to influences of the nonparabolicity of the GaAs conduction band and the polaron effect. In Figs. 1(b) and 1(c) the intensities of the $0 \rightarrow 1$ and $1 \rightarrow 2$ transitions at $B = 9$ and 10 T are in good agreement with the predictions of a single-particle approximation, i.e., the thermal populations of the $N = 0$ and $N = 1$ Landau levels. Since the cyclotron resonance amplitudes are only of the order of a few percent, one can calculate the intensities in the small signal approximation [16], $T(V_g)/T(V_{\text{th}}) = 1 - \text{Re}\sigma_+(\omega)/\{[1 + (\varepsilon)^{1/2}]\varepsilon_0 c + \sigma_g\}$, where ε is the dielectric constant of GaAs. The normalized transmission is related to the real

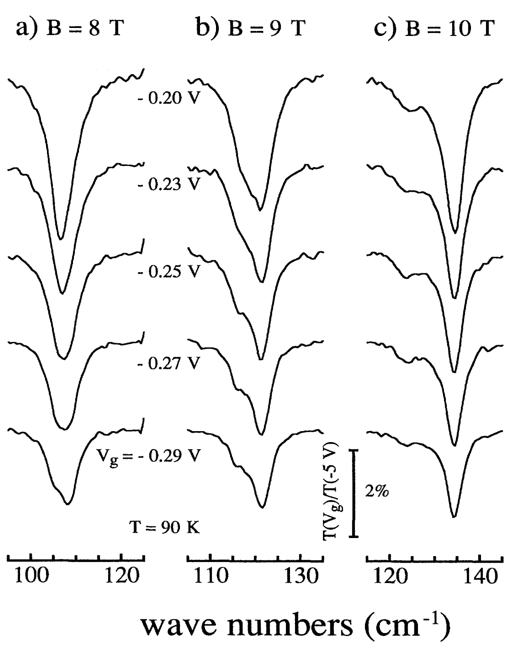

FIG. 1. Gate voltage dependence of the electron CR in $Al_xGa_{1-x}As$-GaAs single heterojunctions at a temperature of $T = 90$ K and magnetic fields of (a) $B = 8$ T, (b) 9 T, and (c) 10 T.

part of the high frequency conductivity $\sigma_+(\omega)$ for the cyclotron active mode for circular polarization, which in the single-particle approximation [11] can be expressed as

$$\sigma_+(\omega) = (e\tau/B) \sum_{N=0} \frac{(n_{sN} - n_{sN+1})(N + 1)\,\omega_{cN}}{1 + i(\omega - \omega_{cN})\tau},$$

where n_{sN}, ω_{cN}, and τ are the Landau-level populations, the $N \rightarrow N + 1$ transition frequencies, and a phenomenological relaxation time, respectively.

The $0 \rightarrow 1$ transition in Figs. 1(b) and 1(c) has a larger strength compared to the $1 \rightarrow 2$ transition, since the ground Landau level is more heavily populated. In order to estimate their relative strengths the use of Boltzmann statistics is justifiable at these low densities and high temperatures. Assuming equal broad peaks the transition amplitudes A_N for $N \rightarrow N + 1$ are proportional to $n_N = (n_{sN} - n_{sN+1})(N + 1)$. This results in $A_1/A_0 \approx 2\exp(-\hbar\omega_c/kT)/[1 - \exp(-\hbar\omega_c/kT)]$. Since band coupling and polaron effects are small for the $N = 0$ and $N = 1$ Landau levels at these magnetic field strengths, one can replace the cyclotron mass in $\omega_c = eB/m_c$ by the conduction band edge mass $m_0^* \approx 0.0663 m_e$ of the bulk, including the nonresonant polaron correction. This estimate results in $A_1/A_0 \approx 0.2$ and 0.3 for $B = 10$ and 9 T, respectively, which is in reasonable agreement with a numerical calculation of the normalized transmission which takes Fermi-Dirac statistics into account. For the gate voltages from -0.29 to -0.20 V we get electron densities varying from $\sim 2 \times 10^{10}$–6.5×10^{10} cm^{-2}.

For the measurement shown in Fig. 1(a) the situation is not this simple. Here the resonance positions depend on V_g, i.e., N_s. This is in contrast to Figs. 1(b) and 1(c) where all positions are nearly independent of electron density. The dependence of the line shape on N_s cannot be explained in the single-particle approximation. This is even more apparent for a measurement at $T = 80$ K, shown in Fig. 2(a). At $V_g = -0.29$ V two resonances are observed where the resonance with the higher strength is located on the high energy side of the asymmetric line, as can qualitatively be expected in the single-particle approximation. With increasing V_g, i.e., increasing N_s, both resonances form a single line at $V_g = -0.25$ V. Upon further increasing N_s, a shoulder develops on the high energy side, and at even higher N_s we again find a single line, which, however, exhibits an asymmetric shape with a high energy tail. The position at $V_g = -0.20$ V is roughly midway between the two resonance positions observed at $V_g = -0.29$ V.

Since qualitatively similar variations of the positions and intensities were observed for the spin transitions from the ground Landau level at liquid helium temperatures [12–15], we attempt an explanation in the framework of interaction coupled cyclotron transitions. We analytically derive the high-frequency conductivity for inversion layer electrons, describing the interaction coupling of the dipole transitions between different Landau levels. We start

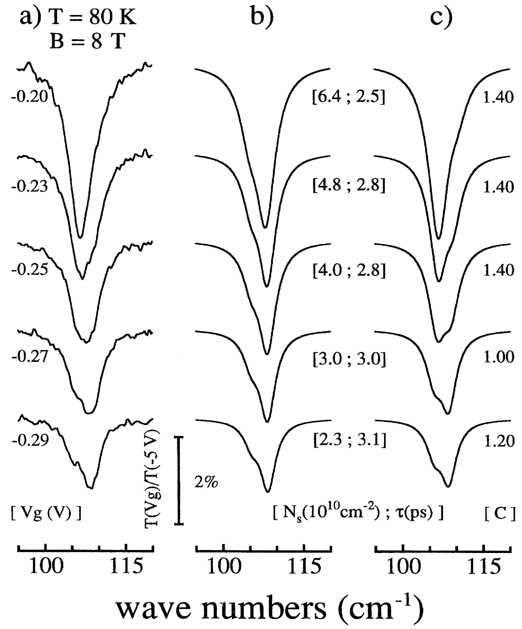

FIG. 2. Gate voltage dependence of the CR Landau splitting for 2D electron systems in GaAs observed at $T = 80$ K and $B = 8$ T. (b) The best fit to (a) in the single-particle approximation. (c) The prediction of the interaction model. Parameters N_s and τ for (b) and (c) are given in brackets. C is the configuration constant determined from the fit.

from the Hamiltonian of a strictly 2D electron gas

$$H = \sum_{i=1}^{\tilde{n}_0} \hbar\omega_{c0}(a_i^\dagger a_i + \tfrac{1}{2}) + \sum_{j=1}^{\tilde{n}_1} \hbar\omega_{c1}(a_{\tilde{n}_0+j}^\dagger a_{\tilde{n}_0+j} + \tfrac{1}{2}) + \frac{(e\ell)^2}{8\pi\varepsilon\varepsilon_0} \sum_{\substack{i=1 \\ i\neq j}}^{\tilde{N}_s} \sum_{j=1}^{\tilde{N}_s} \frac{(a_i^\dagger - a_j^\dagger)(a_i - a_j)}{|\mathbf{R}_i - \mathbf{R}_j|^3}, \tag{1}$$

where we defined operators $a_i = (\rho_i^x - \iota\rho_i^y)/\sqrt{2}\,\ell$ and $a_i^\dagger = (\rho_i^x + \iota\rho_i^y)/\sqrt{2}\,\ell$, which relate to the orbital coordinates ρ of the electrons, whereas the $\mathbf{R} = \mathbf{r} - \rho$ are their guiding center coordinates. Equation (1) describes two one-dimensional oscillators with frequencies ω_{c0} and ω_{c1} that are coupled by a harmonic electron-electron interaction potential [14,15]. This approximation of the Coulomb potential can be justified for a sufficiently dilute electron gas for which the mean interparticle distance $r_0 = (\pi N_s)^{-1/2}$ is large compared to the size of the Landau orbit $\ell = (\hbar/eB)^{1/2}$ and the extent of the inversion layer in the growth direction. To describe the relative strengths of the different Landau-level transitions correctly, the upper limit for the summation of the uncoupled oscillators is $\tilde{n}_N = n_N L^2$, where L^2 is the sample area, whereas the interaction depends on the total number of electrons $\tilde{N}_s = N_s L^2$. In Eq. (1) we have neglected the contributions from higher Landau-level transitions, since the populations of their initial levels are small and these transitions were not observed here.

By transforming the Hamiltonian Eq. (1) to harmonic coordinates, i.e., $H^* = \sum \hbar\omega_i(\alpha_i^\dagger\alpha_i + \frac{1}{2})$ such that $[\alpha_i, H^*] = \hbar\omega_i\alpha_i$, we obtain resonance positions and intensities by solving the 2×2 eigenvalue problem

$$\begin{pmatrix} \omega_{c0} + \rho_1\omega_I - \omega & -\sqrt{\rho_0\rho_1}\,\omega_I \\ -\sqrt{\rho_0\rho_1}\,\omega_I & \omega_{c1} + \rho_0\omega_I - \omega \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = 0, \tag{2}$$

where $\rho_0 = -n_{s0}/N_s$ and $\rho_1 = n_{s1}/N_s$. The Coulomb interaction governs Eq. (2) via the interaction energy $\hbar\omega_I = C(\pi N_s)^{3/2}(e\ell)^2/8\pi\varepsilon\varepsilon_0$, which depends on a dimensionless configuration constant C, reflecting the electron distribution in space. Solving Eq. (2) for the eigenfrequencies and projecting the eigenvectors $\mathbf{f}^{(i)} = (f_1^{(i)}, f_2^{(i)})$ $(i = 1,2)$ onto the perturbation Hamiltonian for right circular polarized light, we get for the high-frequency conductivity of interacting electrons $\sigma_+(\omega) = \{N_s e\tau/B\}\{F_1\omega_1/[1 + i(\omega - \omega_1)\tau] + F_2\omega_2/[1 + i(\omega - \omega_2)\tau]\}$. With the $\Theta = \{[1 - (\rho_0 + \rho_1)\Phi]^2 + 4\rho_1\Phi]\}^{1/2}$ abbreviation and the ratio $\Phi = \omega_I/\Delta\omega$ of the interaction energy and the single-particle resonance splitting $\Delta\omega = \omega_{c0} - \omega_{c1}$, one gets for the transition energies ω_k and intensities F_k $(k = 1,2)$

$$\omega_k = \omega_{c0} + \frac{(\rho_0 + \rho_1)\Phi - 1 - (-1)^k\Theta}{2}\Delta\omega,$$
$$F_k = \frac{[(\rho_0 + \rho_1)\Phi - 1 + (-1)^k\Theta]^2}{2\Theta\{\Theta - (-1)^k[1 - (\rho_0 + \rho_1)\Phi]\}}\rho_0. \tag{3}$$

For a quantitative analysis of the experiment it is essential to know $\Delta\omega$. A complete description would require the inclusion of the conduction band nonparabolicity due to band coupling phenomena and the polaron effect. In particular, the inclusion of the resonant polaron effect is cumbersome. For the sake of simplicity we shall treat here only the band coupling which can be done analytically in the two band approximation. In the framework of the ansatz of Ref. [17] we obtain the transition energies for sufficiently small B and N according to $\omega_{cN} \approx \omega_c[1 - 2E_0/3E_g^* - 2\hbar\omega_c(N+1)/E_g^*]$. E_0 is the confinement energy of the ground 2D subband and E_g^* is an effective gap between the conduction and valence bands. Thus, we obtain $\Delta\omega \approx 2\hbar(eB)^2/(m_0^{*2}E_g^*)$ proportional to the square of the magnetic field strength. Although m_0^*, E_0, and E_g^* depend in principle on temperature, in the regime up to 100 K, their variation can be expected to be small, and it is justified to employ the values determined at liquid helium temperature [11]. We have calculated E_0 self-consistently and find energies ranging from 18 to 21.5 meV in the density regime from 2×10^{10} to 6.5×10^{10} cm^{-2} [2]. From other samples grown under similar conditions, we have roughly estimated a background doping of $N_A = 3 \times 10^{14}$ cm^{-3} which corresponds to a depletion charge of 8×10^{10} cm^{-2}. The effective gap is treated as a parameter which is fixed by the experimental resonance position ω_{c0} at $B = 10$ T, where the single-particle approximation is valid. From this procedure we obtained a value of 1 eV, which is close to the effective gap obtained in the bulk [11].

In Figs. 2(b) and 2(c), the predicted cyclotron resonance line shapes from the single-particle and the interaction model are shown. The populations n_{sN} were calculated numerically from Fermi-Dirac statistics by considering up to ten Landau levels. It is apparent that only the interaction model explains the line shapes and the N_s dependence satisfactorily. The experimental configuration constants obtained from the fits range from 1.2 to 1.4. These values are close to the configuration constants determined previously at liquid helium temperatures. The slightly smaller experimental values compared to $C_{2D} \approx 1.6$ for ideally 2D electron systems at liquid helium temperatures can be well attributed to influences of the finite thickness effect and screening by the gate [15]. This provides strong evidence that there is essentially no effect of the temperature on the mechanism ruling the interaction coupling of the Landau transitions.

In Fig. 3 we show the resonance positions interpreted in terms of a cyclotron mass for different N_s at a temperature of $T = 80$ K. The experimental positions were deduced by fitting the resonances by two Lorentzian lines. The thin and bold lines are the predicted mass variations in the single-particle and the interaction model assuming $C = 1.2$, respectively. The single-particle cyclotron masses follow the relationship $m_{cN} \approx m_0^*(1 + 2E_0/3E_g^*) + 2\hbar eB(N + 1)/E_g^*$. Neglecting the $2E_0/3E_g^*$ correction we end up with the cyclotron mass at the Landau band edges in the bulk.

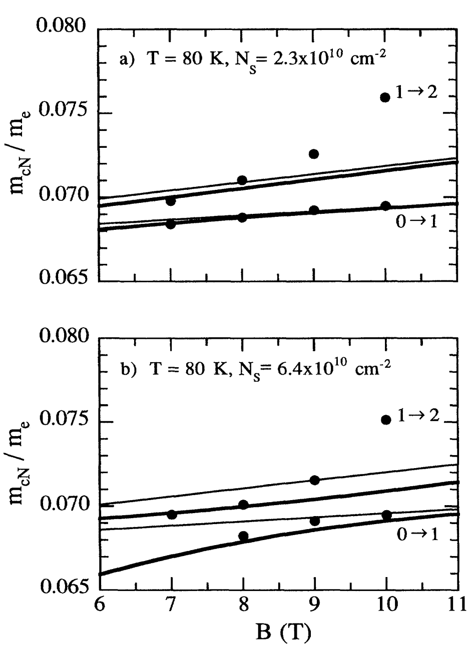

FIG. 3. Experimental cyclotron masses vs magnetic field strength at a temperature of $T = 80$ K and electron densities of (a) 2.3×10^{10} cm^{-2} and (b) 6.4×10^{10} cm^{-2}. The thin and bold lines indicate the predicted mass variations due to the nonparabolicity of the conduction band in the single-particle and the interaction model, respectively.

Thus, the confinement simply increases the mass at the subband edge. As shown in Figs. 3(a) and 3(b) mass values for the $1 \rightarrow 2$ transition for magnetic field strengths above 9 T cannot be explained here, since the resonant polaron contribution to the $N = 2$ Landau level is not included. However, at the higher density shown in Fig. 3(b) only the interaction model provides a good description of the masses. Upon reducing N_s, the interaction model prediction approaches that of the single-particle approximation as is apparent in Fig. 3(a).

In conclusion, we studied the interaction coupling of the $0 \rightarrow 1$ and $1 \rightarrow 2$ cyclotron transitions for electron inversion layers in GaAs heterojunctions with densities of the order of 10^{10} cm^{-2}. An interpretation of the experiment in terms of the single-particle approximation is possible only when the interaction energy is small compared to the difference in the Landau-level separations. Our experiment does not strongly depend on temperature. Previous interpretations of CR investigations at densities above 10^{11} cm^{-2}, which rely on the single-particle picture, will possibly have to be revised.

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