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Cyclotron resonance in $Al_xGa_{1-x}As$-GaAs heterostructures with tunable charge density via front gates

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$Al_xGa_{1-x}As$-GaAs heterostructures have been prepared in which the charge density N_S can be varied over a wide regime: $N_S=1\times10^{10}$ cm^{-2} to 5×10^{11} cm^{-2}. This gave us the possibility to study in detail filling-factor- (ν) dependent effects on the cyclotron-resonance mass m^*, linewidth, and amplitude. We found abrupt jumps for m^* near $\nu=1$ and 2 which are explained by energy renormalization effects and combined interacting cyclotron resonances from different Landau or spin levels.

Fundamental investigations in $Al_xGa_{1-x}As$-GaAs heterostructures have so far been performed mostly in systems where the two-dimensional (2D) charge density N_S is determined by the doping and geometry of the $Al_xGa_{1-x}As$ layer. For many investigations it is highly desirable to control N_S via a front gate in a reversible way over a wide regime, including fully depleting the channel. For the Si-SiO_2 system this made possible the study of many fundamental properties of the 2D system.[1] Gated $Al_xGa_{1-x}As$-GaAs structures with small gates are used in dc devices.[2] Fundamental investigations of cyclotron resonances (CR) also have been reported.[3]

We have prepared $Al_xGa_{1-x}As$-GaAs heterostructures with large-area from gates in which N_S could be varied from $N_S=1\times10^{10}$ cm^{-2} to $N_S=5\times10^{11}$ cm^{-2}. We have used this system to study in detail CR in $Al_xGa_{1-x}As$-GaAs, in particular its dependence on the filling factor $\nu=N_Sh/eB$ (B denotes magnetic field). In the following we will distinguish the filling factor ν and the Landau levels $n^{\pm}$ with upper and lower spin state ($n=2\nu$).

There is a great number of publications on the CR in $Al_xGa_{1-x}As$-GaAs and related systems (e.g., Refs. 4-12). In general it was found that the CR mass m^*increases with N_S and B due to band structure and polaron-induced nonparabolicity. In addition, maxima in the linewidth were found which sometimes were related to integer ν (Refs. 4, 9, and 10) and have been explained by self-consistent ν-dependent screening effects. Sometimes no correlation with ν was deduced.[8] Evidence for structures in the linewidth at fractional ν was also reported.[13,14] On other samples discontinuities in m_c near $\nu=2$ and $\nu=4$ were reported which were related to the different masses for different Landau-level transitions ($n=0\rightarrow1$ and $n=1\rightarrow2$, respectively).[7] These discontinuities however could not be explained in detail. Thus so far there are still open questions concerning the CR in $Al_xGa_{1-x}As$-GaAs. With our samples, where we can vary N_S over a wide regime, we can realize in the same sample a certain value of ν at widely different B and can thus clarify some of the controversial observations made so far.

The samples were grown by molecular beam epitaxy and have the following structure: semi-insulating substrate, 1.5-μm buffer layer, and active GaAs ($N_{depl}\approx5\times10^{10}$ cm^{-2}), 18-nm spacer of $Al_xGa_{1-x}As$, 50-nm Si-doped $Al_xGa_{1-x}As$ ($x=0.36$, $N_d\approx5\times10^{17}$ cm^{-3}), and a 5-nm GaAs cap layer. Gates of 5-nm Ni-Cr with 3-mm diameter were evaporated onto the sample. Outside the gate area contracts were made to the 2D channel. CR was measured with a Fourier transform spectrometer which was connected via a waveguide system to a 14.5-T superconducting magnet. Spectra were measured at fixed N_S and B (B was perpendicular to the sample plane). The temperature was normally 2.2 K and the resolution of the spectrometer was set to 0.03 or to 0.06 cm^{-1}. N_S was determined *in situ* under the conditions of the experiment from magnetocapacitance measurements. A gate voltage V_g was applied between the gate and the channel contracts. The onset of the channel conductance (threshold voltage) occurs at $V_g=-0.38$ V. Dips in the magnetocapacitance are observed at small B for even $\nu=2,4,6,\ldots$ caused by the variation of the density of states at the Fermi energy $D(E_F)$. For $B\gtrsim5$ T, due to the enhanced g factor, spin splitting is resolved and dips at $\nu=1$ and 3 can be observed. N_S is calculated from the position of the dips. We find that for all B and for $V_g=-0.4$ V to $+0.3$ V (corresponding to $N_S=3\times10^{10}$ cm^{-2} to 5×10^{11} cm^{-2}), N_S depends linearly on V_g with better than 2% accuracy.

Figure 1 shows experimental spectra measured at fixed $B=8.24$ T for different N_S. With decreasing N_S the amplitude of the CR decreases and the position of the CR generally shifts to higher frequencies. We have fitted the CR spectra with a Drude-type conductivity

$$\sigma^{\pm}(\omega)=N_Se^2\tau/m^*[1+(\omega\mp\omega_c)^2\tau^2]$$

(τ denotes scattering time, m^* denotes effective mass, $\omega_c=eB/M$ denotes cyclotron frequency) using the full Fresnel equations including signal saturation (see e.g., Refs. 9 or 10). We find that the density N_S that we evaluate from these fits agrees for the whole density regime where we determine N_S from magnetocapacitance within the experimental accuracy of about 5% with the latter values. In particular this is also found in the density regime near integer ν where we observe, as will be discussed below, large variations in linewidths, amplitudes, and resonance positions. This indicates that all carriers as deter-

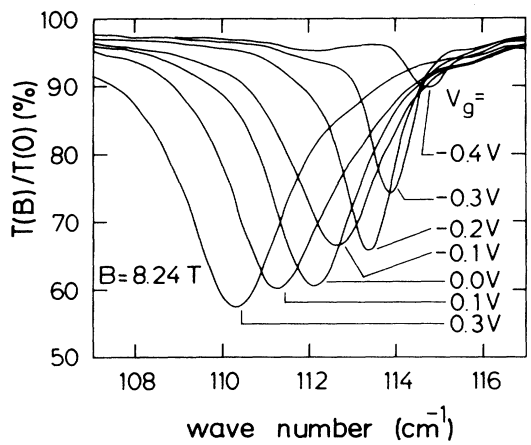

FIG. 1. Experimental CR excitation in front-gated $Al_xGa_{1-x}As$-GaAs heterostructures. The transmission $T(B)$ is measured at fixed $B=8.24$ T and is normalized to the transmission $T(0)$ at $B=0$. From mangetocapacitance we find that the gate voltages $V_g(\mathrm{V})=0.3$, 0.1, 0.0, -0.1, -0.2, -0.3 correspond to densities $N_S(10^{11}\ \mathrm{cm}^{-2})=5.35$, 3.94, 3.16, 2.37, 1.74, and 0.80, respectively.

mined from the magnetocapacitance are also active for the CR. The smallest resonance in Fig. 1 is a CR at $V_g=-0.4$ V which lies in the threshold region. In this regime ($N_S \lesssim 3\times10^{10}\ \mathrm{cm}^{-2}$) where N_S cannot directly be derived from magnetocapacitance, the amplitude still decreases and the resonance position shifts with V_g. From the latter we deduce that we observe CR at a macroscopically well-defined density $N_S=1.7\times10^{10}\ \mathrm{cm}^{-2}$ (determined from a Drude fit, see above) with a surprisingly small half-width $\Delta\omega=1\ \mathrm{cm}^{-1}$ (full width at half maximum).

We will first give a summary of experimental results on CR linewidth, amplitude, and resonance frequency and discuss all these results in the last part of the paper. In the following we will express the experimental resonance position ω_r in terms of an effective CR mass $m^*=eB/\omega_r$.

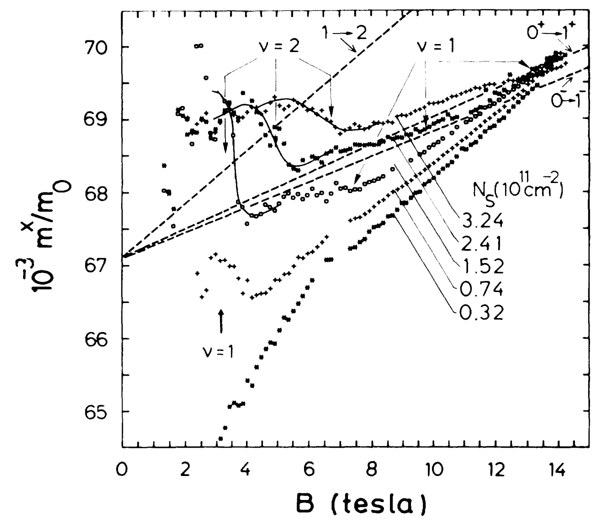

FIG. 2. Experimental CR positions expressed in terms of an effective mass $m^*=eB/\omega_r$ vs B for five different N_S. For some densities experimental data have been connected by full lines for clarity. Broken lines represent calculated m^* for $0^+\rightarrow1^+$, $0^-\rightarrow1^-$, and $1\rightarrow2$ transitions at $N_S=1.1\times10^{11}\ \mathrm{cm}^{-2}$ and $N_{\mathrm{depl}}=5\times10^{10}\ \mathrm{cm}^{-2}$ from Ref. 7. Positions of full filling factors ν are indicated.

In Fig. 2, m^* generally decreases with decreasing B, roughly as expected from nonparabolicity. A characteristic feature is that near $\nu=1$ and $\nu=2$ sudden jumps in m^* occur. The heights of these jumps increase significantly with decreasing N_S and, at fixed ν, with the corresponding B and ω_r. In Fig. 3 we show data which were measured at three different values of B where N_S was varied in small increments. For $B=3.63$ T in Fig. 3(a), a drastic jump in m^* is observed. The onset occurs for ν slightly smaller than 2 and we find that this onset coincides with the decrease that we observe for the magnetocapacitance in the regime close to $\nu=2$. The experimental linewidth $\Delta\omega$ is smallest for ν below 1. It has a

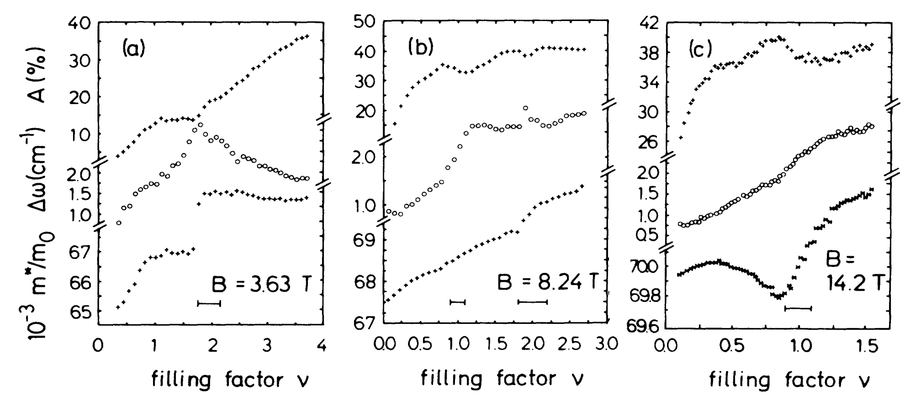

FIG. 3. Effective mass m^*, linewidth $\Delta\omega$ (FWHM), and amplitude A of CR for three fixed values of B vs filling factor $\nu=hN_S/eB$ which has been varied via N_S. The bars mark the regime near integer ν where the magnetocapacitance has dropped to less than 50%.

maximum close to $\nu=2$, more exactly, just in the position of the abrupt jump of m^*, and decreases for $\nu>2$ to a level of about 2–3 times larger than for $\nu<0.5$. The amplitude $A=1-T_{\min}$ has a relative minimum near $\nu=2$. For $B=8.24$ T in Fig. 3(b), the discontinuity in m^* near $\nu=2$ is smaller as compared with $B=3.63$ T. However, also at $\nu=1$ a jump in m^* can be observed. This is related to the fact that for this B the enhancement of the effective g factor is large enough to split the spin states of the lowest Landau level, as is directly observed in the magnetocapacitance. For the linewidth of the CR we observe that for both $\nu=1$ and 2 no maximum exists (as was found for $B=3.63$ T). Rather, just below $\nu=1$ and 2, the linewidth begins to increase with a steeper ascent. For even higher $B=14.2$ T in Fig. 3, the discontinuity in m^* appears as a dip with a minimum at $\nu=0.9$. [Note the scale in Fig. 3(c) compared with Fig. 3(a). The absolute variation in m^* with N_S is very small, as can be seen also in Fig. 2 at high B]. At this high B the linewidth at low N_S is very small (0.5 cm^{-1}). This means, that with increasing N_S the amplitude approaches 50%. In this case the effect of signal saturation occurs and the observed increase of the linewidth is more related to N_S than determined by scattering processes or Landau-level widths.

In Fig. 2 the experimentally observed CR masses are compared with masses derived from band structure calculations of Ref. 7. For high N_S (2.41 and 3.24×10^{11} cm^{-2}) the slope of the increase of m^* with B, which is according to Ref. 7 nearly independent of N_S, agrees roughly with the calculated value. For very high B, a steeper increase of m^*, possibly due to the resonant polaron effect,[5,6] is observed, which is not included in the calculations.[7] However, the structures and abrupt jumps for m^* and $\Delta\omega$ near $\nu=1$ and $\nu=2$ and in particular the behavior that we observe at high B [Fig. 3(c)] and which changes gradually to a very different behavior at low B [Fig. 3(a)] cannot be fully explained by any existing theory on CR.

We believe that several of the filling-factor-dependent effects that have been discussed so far (e.g., ν-dependent dynamic screening,[4,10,15] nonparabolicity-induced band-structure effects,[7] polaron effects[16,17]) and additional effects (energy renormalization, combined interacting CR) are present here and are differently pronounced in different B regimes. In the following we will give a tentative explanation. If we look closer to the N_S dependence of m^* at high B in Figs. 3(b) and 3(c) we find that the drop in m^* occurs in the ν regime where, at the same B, we observe the decrease of the magnetocapacitance. We conclude that in particular at high B the drop in m^* is caused by energy renormalization in the following sense. Near even ν and, if the enhancement of the g factor is large enough, also at odd ν, the density of state at the Fermi energy $D(E_F)$ decreases leading in a self-consistent way to a reduced static screening.[18] Thus more and more carriers become localized in shallow potential fluctuations.

The energy spectrum, in particular of the excited states for these localized electrons, is not exactly known. We expect that the localization causes an increased CR frequency (and corresponding reduced m^*) similar to that known for isolated discrete impurity resonances or as can be calculated for the simple model of electrons which are bound in a harmonic oscillator potential. In the latter case the CR frequency shifts from the nonbound frequency ω_c to $\omega_r=(\omega_0^2+\omega_c^2)^{1/2}$ (ω_0 denotes oscillator frequency). However, energy renormalization is not all. With decreasing B and increasing ν more complexity arises. In a simple one-particle model of CR we would expect for $\nu<2$, $0\rightarrow1$ CR transitions. For $\nu>2$ with decreasing B at fixed N_S, the $n=1$ level becomes occupied and one would expect a second $1\rightarrow2$ CR, with, caused by the nonparabolicity, higher m^* as has been observed in bulk GaAs where higher Landau levels have been occupied by electron heating.[19] Surprisingly for the 2D system here we do not observe two resonances. Rather, near $\nu=2$ the CR broadens and only one resonance is observed which does not have the average position of both the expected CR. Even if for some reason the $0\rightarrow1$ and $1\rightarrow2$ CR could not separately be resolved, one would expect in a one-particle picture, assuming equal transition probabilities, that the averaged m^* should stay constant for $\nu>2$. Here, a distinct jump in m^* is observed which is significantly larger than the difference of m^* calculated from the band structure for the $0\rightarrow1$ and $1\rightarrow2$ CR. This all leads to the conclusion that the CR in this 2D nonparabolic system is a combined interacting CR of both Landau-level transitions.

Interacting CR's in a two-carrier system with different masses [the E_0 and E_0' valley of Si(100)] have been calculated in Ref. 20. It was found that the intrinsic Coulomb interaction in this system couples both CR's leading to a shift of the resonance position and transfer of transition probability. If the interaction is strong enough, only one combined CR is observed.

For our system here, due to the small nonparabolicity induced mass difference, we expect that the effect of direct Coulomb interaction will be small. So far we do not know the exact origin of the interaction. Interacting CR means that the resonance position is not directly determined by the band structure or the renormalized energy spectrum of the localized carriers near integer ν. Rather, the position is governed in addition by the strength of the interaction. This is in particular the case near $\nu=1$ [Figs. 3(b) and 3(c)]. Here m^* reflects the interaction of CR from the different spin states ($0^+\rightarrow1^+$, $0^-\rightarrow1^-$). Near $\nu=1$ the spin states 0^+ and 0^- are separated due to the enhanced g factor. We wish to note here, that near $\nu=1$, the enhanced exchange interaction should lead to an intrinsic coupling process of the $0^+\rightarrow1^+$ and $0^-\rightarrow1^-$ CR transition and may be the origin of the interacting CR. We do not know whether it is by accident or not that the smallest mass in Figs. 3(b) and 3(c) and the increase in m^* in Fig. 3(a) occur at ν values slightly smaller than integer ($\nu=0.9$ and $\nu=1.8$) which coincides exactly with those values of ν where in the magnetocapacitance we see the onset of the drop near integer ν.

We would also like to note the following finding. We have used the ansatz

$$\sigma(\omega)=iN_Se^2/m_c(\omega-\omega_c+M(\omega))$$

for the 2D magnetoconductivity.[1,21] Here $M(\omega)$ is the memory function with the real part $M'(\omega)=\omega_c-\omega_r(\omega)$

and imaginary part $M''(\omega)=\Gamma_r(\omega)$ (ω_r denotes resonance position, ω_c denotes noninteracting CR frequency, Γ_r denotes linewidth). It is clear, that at *fixed B* $\sigma(\omega)$, $M'(\omega)$, and $M''(\omega)$ have to satisfy the Kramer-Kronig (KK) relation. We have preformed a KK transform on the experimental values of the halfwidth $\Gamma_r(B)=\Delta\omega(B)/2$ which was measured at *different B* by identifying $M''(\omega)=\Gamma_r(\omega=eB/m_c)$. We find that the KK transform gives surprisingly well the experimentally observed behavior of the resonance position $\omega_r(B)-\omega_c$. This indicates that the magnetic field dependence of the resonance position and half-width are not independent but coupled to each other in a self-consistent way. From this we also conclude that there is an interaction mechanism present which produces this coupling. This also means that ν-dependent oscillations of the halfwidth that have been observed in Refs. 4 and 10 may not only be caused by oscillatory dynamic screening,[15] but are in addition also determined in an interacting way by the anomalies in the energy spectrum at integer ν.

We do not believe that the filling-factor-dependent resonant polaron effects[16] are very important for the anomalies of m^* in our experiments because (a) the discontinuities at integer ν increase with decreasing B and ω_r, and (b) according to recent calculations[17] the effect on m^* is significantly smaller than observed here. Coupling to magnetoplasmons[9] is also unlikely to be an overwhelming effect, since in our experiments m^* becomes, approaching integer ν from low values, far smaller than the undressed mass (i.e., the band-structure mass). This is in contrast to the calculation in Fig. 2 of Ref. 9.

In summary, front-gated $Al_xGa_{1-x}As$-GaAs heterostructures have been prepared, where N_S could be varied over wide density regimes. This allowed us to study CR in detail in its dependence on N_S, B, and the related filling factor. Abrupt and large jumps in the CR mass show that the CR does not directly reflect the band structure but is governed by energy renormalization and interaction effects.

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[1]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[2]See e.g., contributions in *Proceedings of the Conference on Modulated Semiconductor Structures, Kyoto, Japan, 1985* [Surf. Sci. **174** (1986)].

[3]K. Muro, S. Mori, S. Narita, S. Hiyamizu, and K. Nanbu, Surf. Sci. **142**, 394 (1984).

[4]Th. Englert, J. C. Maan, Ch. Uihlein, D. C. Tsui, and A. C. Gossard, Solid State Commun. **46**, 545 (1983).

[5]M. Horst, U. Merkt, W. Zawadzki, J. C. Maan, and K. Ploog, Solid State Commun. **53**, 403 (1985).

[6]H. Sigg, P. Wyder, and J. A. A. J. Perenboom, Phys. Rev. B **31**, 5253 (1985).

[7]F. Thiele, U. Merkt, J. P. Kotthaus, G. Lommer, F. Malcher, U. Rössler, and G. Weimann, Solid State Commun. **62**, 841 (1987).

[8]Z. Schlesinger, S. J. Allen, J. C. M. Huang, P. M. Platzman, and N. Tzoar, Phys. Rev. B **30**, 435 (1984).

[9]Z. Schlesinger, W. I. Wang, and A. H. MacDonald, Phys. Rev. Lett. **58**, 73 (1987).

[10]D. Heitmann, M. Ziesmann, and L. L. Chang, Phys. Rev. B **34**, 7463 (1986).

[11]E. Batke, H. L. Störmer, A. C. Gossard, and J. H. English (unpublished).

[12]R. J. Nicholas, M. A. Hopkins, M. A. Brummell, D. Barnes, H. Sigg, D. Heitmann, K. Ensslin, J. J. Harris, C. T. Foxon, and G. Weimann (unpublished).

[13]G. L. J. A. Rikken, H. W. Myron, P. Wyder, G. Weimann, W. Schlapp, R. E. Horstmann, and J. Wolters, J. Phys. C **18**, 1175 (1985).

[14]W. Seidenbusch, E. Gornik, and G. Weimann (unpublished).

[15]S. Das Sarma, Solid State Commun. **36**, 357 (1980).

[16]D. M. Larsen, Phys. Rev. B **30**, 4595 (1984).

[17]W. Xiaoguang, F. M. Peeters, and J. T. Devreese, in *Proceedings of the 18th International Conference on the Physics of Semiconductors, Stockholm, Sweden, 1986*, edited by O. Engström (World Scientific, Singapore, 1987), p. 589; and (unpublished).

[18]T. Ando and Y. Murayama, J. Phys. Soc. Jpn. **54**, 1519 (1985).

[19]G. Lindemann, R. Lassnig, W. Seidenbusch, E. Gornik, Phys. Rev. B **28**, 4693 (1983).

[20]Y. Takado and T. Ando, J. Phys. Soc. Jpn. **54**, 905 (1978).

[21]A. Gold, Z. Phys. B **63**, 1 (1986).