Cyclotron-resonance linewidth oscillations in the integer and fractional quantum Hall regimes

W. Seidenbusch and E. Gornik
Institut für Experimentalphysik, Universität Innsbruck, A-6020 Innsbruck, Austria

G. Weimann
Forschungsinstitut der Deutschen Bundespost, D-6100 Darmstadt, Germany
(Received 9 July 1987)

The cyclotron-resonance linewidth was studied in GaAs/GaAlAs heterostructures as a function of filling factor, magnetic field, and frequency. Maxima in the cyclotron-resonance linewidth are found for integer and for fractional Landau-level fillings of $\frac{5}{3}$, $\frac{4}{3}$, and $\frac{2}{3}$, giving evidence for a reduced screening due to density-of-states gaps. For partly filled levels a strong reduction of the linewidth due to resonant screening is found. The oscillations in the linewidth are highest for high-mobility and low-density samples.

Transport studies of two-dimensional (2D) electrons in GaAs/GaAlAs heterostructures have led to the discovery of the quantum Hall and fractional quantum Hall effects.[1,2] In a transport measurement the observed physical quantity is averaged over the total sample; local effects cannot be distinguished from global ones. A complementary method is cyclotron resonance (CR), which samples locally the high-frequency conductivity in a magnetic field.

In a previous investigation of the CR linewidth, Störmer *et al.*[3] and Voisin *et al.*[4] found a $\sqrt{B}$ dependence in samples with rather low mobility, in agreement with theoretical predictions.[5,6] A quite complicated behavior of the linewidth was observed by Narita *et al.*[7] and Muro *et al.*;[8] it was explained by the presence of a pinned charge-density wave. Schlesinger *et al.*[9] observed a splitting and broadening of the linewidth which was not keyed to Landau-level (LL) filling (the LL filling factor $\nu=2n_s\pi l^2$ with n_s the 2D density and l the cyclotron radius). The observed behavior was explained by a softening of the two-dimensional magnetoplasma mode. Pronounced maxima in the observed linewidth were found by Englert *et al.*[10] at filling factors of 2 and 4, and minima in between. This behavior was found only in low-density samples ($n_s<1.5\times10^{11}$ cm^{-2}) and was absent for higher densities ($n_s>2.5\times10^{11}$ cm^{-2}). Weak oscillations in the linewidth were also found by Gornik *et al.*,[11] while rather large oscillations were observed by Rikken *et al.*,[12,13] who reported anomalous structure in the CR linewidth at or near the filling factors, where the fractional quantum Hall effect in these samples occurs ($\nu=\frac{4}{3},\frac{5}{3},\frac{7}{3}$). In a recent paper Heitmann *et al.*[14] have shown large oscillations of the linewidth with the filling factor up to $\nu=5$ for 2D electrons in InAs.

A detailed calculation of the LL width and CR linewidth was performed by Lassnig and Gornik[15] and Ando and Murayama[16] and suggested a filling-factor-dependent oscillation of the linewidth. The LL width has maxima for filled and minima for half-filled LL's, due to an oscillation of the static screening strength. The situation that only low-density samples show the theoretically predicted oscillation is still not explained in a satisfactory way in the literature.

It is the aim of this paper to present a detailed study of the cyclotron-resonance linewidth and to explain our observed data in a consistent way. It will be shown that linewidth maxima appear for filled levels and that the expected results are strongly influenced by saturation effects. In addition, we have observed evidence for an influence of the fractional quantum Hall effect on the CR linewidth.

Far-infrared (FIR) laser transmission spectra were measured as a function of magnetic field using several laser lines between 90 and 240 μm from an optically pumped FIR laser at temperatures between 1.6 and 2 K. The filling factor was varied by illuminating the sample with a light-emitting diode. Transmission spectra were also taken with a Fourier transform spectrometer for the same samples. The samples used were of Corbino geometry. The carrier density was determined by Shubnikov–de Haas (SdH) oscillations. The quality of sample 1 is demonstrated by a set of SdH measurements in Fig. 1.

Cyclotron-resonance spectra for sample 1 taken with the laser and the Fourier spectrometer are shown in Fig. 2. It is evident that the linewidth changes with filling factor for both experimental techniques. The spectra show clear evidence for a strong reduction in transmission of close to 50% at the resonance.

The measured spectra are analyzed by evaluating the full width at half maximum. Experimentally determined linewidths are plotted as a function of filling factor for several samples in Fig. 3. For comparison we have included the published data by Englert *et al.*[10] The properties of the samples are listed in Table I. The linewidth shows a clear maximum at $\nu=2$ for all samples. This value corresponds to a LL gap. For different laser wavelengths we always obtained the same linewidth for the

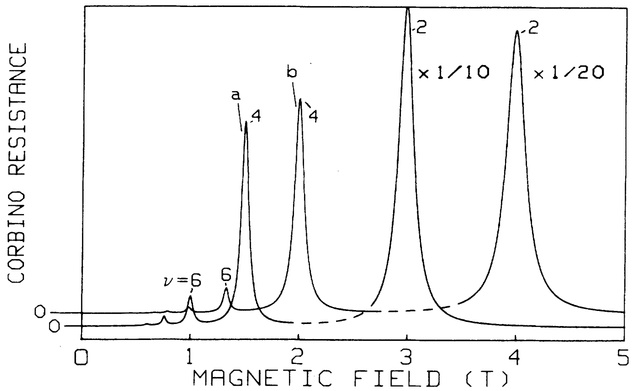

FIG. 1. One set of Shubnikov–de Haas oscillations for sample 1 for two different concentrations (before and after illumination). Curve a, carrier concentration $n_s=1.47\times10^{11}$ cm^{-2}; curve b, $n_s=1.94\times10^{11}$ cm^{-2}. The values of the filling factor (ν) are indicated.

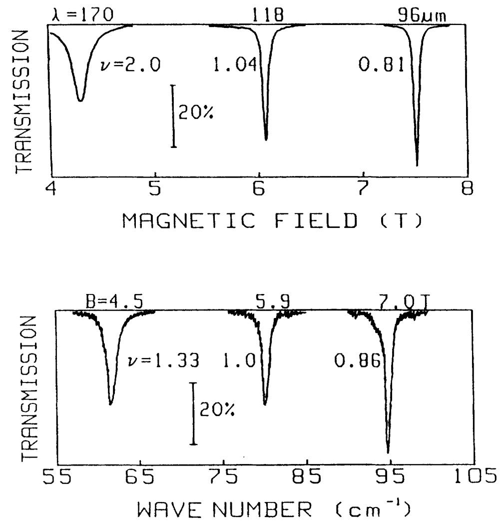

FIG. 2. Transmission spectra for sample 1, taken with the laser at the given wavelength (λ) (top) and with the Fourier spectrometer at the given magnetic field (B) (bottom) for different filling factors.

same ν. There is a systematic decrease in linewidth with decreasing ν to extremely low values. The decrease for $\nu>2$ is smaller. No significant structure in the linewidth is observed for $\nu=1$ and 3. These values correspond to the spin gaps, which are much smaller than the LL gaps (for even ν values).

It is quite remarkable that the sample with the lowest mobility [μ(4.2 K)$\sim10^5$ cm^2/V s] shows a considerably larger linewidth change between $\nu=2$ and $\nu=1$ than the sample with the highest mobility [μ(4.2 K)$\sim10^6$ cm^2/V s]. Some additional structure is found around the filling factors $\frac{4}{3}$ and $\frac{5}{3}$ for samples with mobilities larger than 4×10^5 cm^2/V s and densities below 2.5×10^{11} cm^{-2}.

A very detailed study of the linewidth was performed for sample 1, which shows the most pronounced structures. In Fig. 4 the laser data for this sample are shown together with results from Fourier spectrometer measurements. The Fourier data extend to lower filling factors and also show a small linewidth maximum at $\frac{2}{3}$. However, due to the limited resolution of the Fourier instrument and to problems with the determination of absolute transmission values, the Fourier data are not as accurate as the laser data. The accuracy of the analysis is shown by the error bars. Therefore the main conclusion will be drawn from the laser measurements. The Fourier data were taken to prove the consistency of the data. Since the reduction in transmission at the resonance is between 40% and 50%, an analysis of the spectra has to be performed before an interpretation can be made.

A Drude model was used to evaluate the transmission data.[17] We assume a single broadening parameter $\Gamma=\tau^{-1}$ in the expression for the conductivity,

$$\sigma_{\pm}(\omega)=(n_s e^2\tau/m^*)[1+i(\omega\pm\omega_c)\tau]^{-1} .$$

The ratio of the transmittance in a magnetic field $T(B)$ to the transmittance $T(0)$ without B for linear polarized light is calculated for the given electron densities, using τ as the only fitting parameter. For the transmitted intensity we use the expressions

$$\frac{T(B)}{T(0)}=\frac{T_+ + T_-}{2T(0)}$$

with

TABLE I. Properties of the investigated samples. The mobility and concentration were measured in the dark at 4.2 K.

Sample number	Spacer thickness (Å)	Mobility (cm^2/V s)	Carrier density (cm^{-2})
1	370	4.0×10^5	1.2×10^{11}
2	(Sample of Ref. 10)	1.2×10^5	1.2×10^{11}
3	360	1.0×10^6	2.0×10^{11}
4	220	6.1×10^5	2.3×10^{11}
5	240	6.0×10^5	2.4×10^{11}

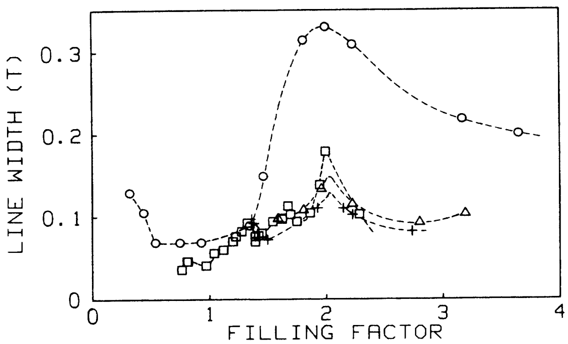

FIG. 3. Experimentally determined linewidth as a function of the filling factor for several samples: Sample 1 (□), sample 2 (○), sample 3 (+), and sample 4 (△).

$$T_{\pm}=\left[\frac{2}{1+(\epsilon_s)^{1/2}}\right]^2\frac{1+(\omega\pm\omega_c)^2\tau^2}{(1+\Gamma_s\tau)^2+(\omega\pm\omega_c)^2\tau^2}\ ,$$

$T(0)=T_{\pm}$ $(\omega_c=0)$, and $\omega_c=eB/m^*$. ϵ_s is the dielectric constant of the semiconductor and $\Gamma_s=\mu_0 c n_s e^2/m^*[1+(\epsilon_s)^{1/2}]$.

In this model an analytical expression can be given for the half-width Γ_H:

$$\Gamma_H=\frac{2}{\tau}\left[\frac{(1+\Gamma_s\tau)^2-(1+\Gamma_s\tau)^4}{1-(1+\Gamma_s\tau)^2}\right]^{1/2}.$$

In the limit $\tau\rightarrow\infty$, which is equivalent to $\mu\rightarrow\infty$, the half-width approaches a constant—saturated—value of $\Gamma_H=2\Gamma_s$. Thus the lowest observable value of the linewidth is a function of n_s. As a consequence the evaluation becomes difficult for spectra approaching the limiting linewidth $2\Gamma_s$. This is the case in our data for filling factors around 1 and below.

The obtained $1/\tau$ values are plotted in Fig. 4 as a function of the filling factor for sample 1. It is clearly seen that the oscillations in linewidth are strongly amplified by the analysis. The $\nu=2$ maximum becomes quite pronounced, and the change in $1/\tau$ between the lowest and highest value is as large as 15. A maximum at $\nu=1$ also becomes apparent, which is considerably smaller than the structure at $\nu=2$. The maxima at fractions of $\frac{5}{3}$ and $\frac{4}{3}$ become clearly distinguishable and the maximum at $\nu=\frac{2}{3}$ less pronounced. The error bars indicate the difficulty of the analysis for the narrowest lines. Our data are not obscured by subband resonances, since we have observed the linewidth maxima for fractional fillings for different laser frequencies. In addition, we do not see any discontinuities in the cyclotron mass between $\nu=1$ and $\nu=2$. The dependence of the CR mass determined from the position of the resonance peak and normalized with respect to the effective-mass value of $m_0^*=0.065m_0$ is shown as a function of the filling factor in Fig. 5. The laser data for two different lines show a similar behavior, which has been found in earlier work.[18] By illuminating the sample first, the depletion charge is compensated and the effective mass is decreased. If the carrier concentration increases further, the mass increases due to nonparabolicity; at $\nu=2$ especially a step increase is observed. In addition, the mass dependence of the Fourier data is shown in Fig. 5. The behavior is very different because of the different experimental situation. In this case the carrier density is constant and the filling factor is changed by the magnetic field. It can be clearly seen that at high magnetic fields and lower values of the filling factor the nonparabolicity plays an important role and therefore the CR mass is increasing.[19] Similar results have been found by Thiele *et al.*[20]

First we want to discuss the linewidth for integer filling: The linewidth values for $\nu=2$ (Landau gaps) are of special interest because only inter-LL (nonresonant) screening arises.[15,16] A plot of the experimentally observed linewidth and of the evaluated fitting parameter $1/\tau$ as a function of the zero-field mobility is shown in Fig. 6. Both plots clearly show a dependence on $\mu^{-1/2}$. Several samples with different mobilities and densities varying only between 1.2×10^{11} and 2.4×10^{11} cm^{-2} were used. The most conclusive results are from samples with the same density and considerably different mobilities. The interpretation of the data is straightfor-

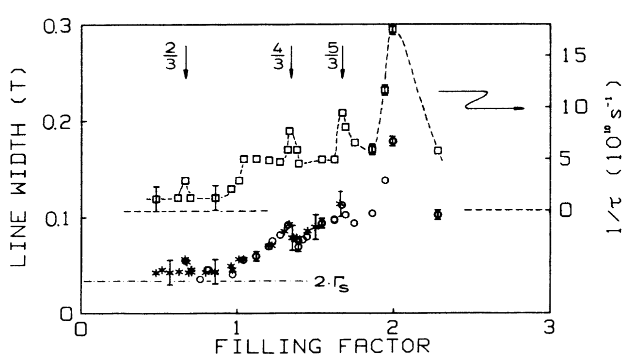

FIG. 4. CR linewidth vs filling factor for sample 1. The circles correspond to laser measurements, the asterisks to Fourier spectrometer data. The $1/\tau$ data, obtained by fitting the experimental curves (see text), are characterized by squares. The dashed curve is for guiding the eye. $2\Gamma_s$ indicates the saturation limited linewidth.

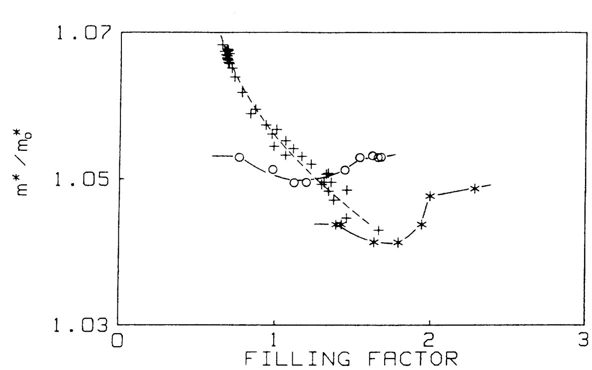

FIG. 5. The normalized CR mass ($m_0^*=0.065m_0$) as a function of the filling factor. The circles represent the data of the laser line with wavelength 118.8 μm, the asterisks correspond to the 170.6-μm line, and the crosses are the Fourier data.

ward. The zero-field mobility and thus the scattering time τ_{DC} is inversely proportional to the number of scatterers.[21,22] That means that a plot as a function of mobility is equivalent to a plot versus the reciprocal of the number of impurities N_i. On the other hand, the main process which determines the LL broadening and thus the CR linewidth is the virtual double scattering at the impurities. Thus in the above situation τ_H is proportional to $(N_i)^{1/2}$, as demonstrated in Fig. 6. The same behavior has been found in bulk GaAs previously.[23] The level width predicted by the theory for short-range scatterers (point scatterers),[6]

$$\Gamma_{SR} = [(2/\pi)(\hbar^2 e^2 B / m^{*2} \mu)]^{1/2} ,$$

is also plotted over μ in Fig. 6 for a magnetic field of 5 T. The obtained values lie systematically a factor of 2 above the experimental values. This reflects the long-range nature of the impurity potentials, which are less effective in the dynamic (local) CR process than in the dc response.

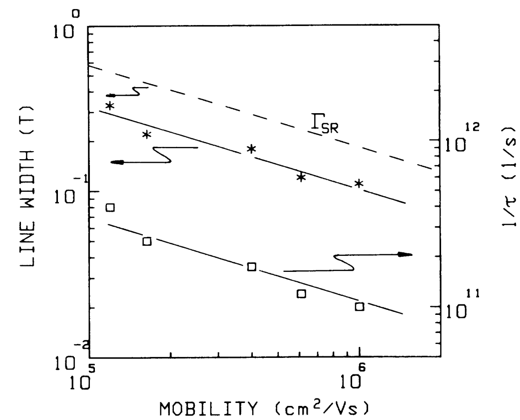

FIG. 6. CR linewidth values at $\nu=2$ and fitting parameter $1/\tau$ as a function of the zero-field mobility (samples 1–5). The slope of both lines is $-\frac{1}{2}$. Γ_{SR} is the CR linewidth for short-range scatterers predicted by the theory of Ref. 6.

For partly filled LL's, intra-LL screening strongly reduces the level width, which explains the drastic drop of the linewidth close to the integer values. For $\nu < 1$ extremely narrow lines are observed, approaching the limiting values due to saturation effects. The saturation effects are also the reason that the main features in the linewidth are masked for samples with densities higher than 2.5×10^{11} cm^{-2} and mobilities higher than 500 000 cm^2/V s. Furthermore, the superposition of individual CR transitions, which differ due to nonparabolicity, can alter the behavior. It could even lead to maxima in linewidth at half fillings.

In addition to the well-understood linewidth maxima at filled LL's, easily distinguishable maxima are observed at fractional fillings of $\frac{5}{3}$, $\frac{4}{3}$, and not so pronounced at $\frac{2}{3}$. We want to discuss two explanations for the appearance of this effect. (a) Through localization and condensation into the fractional state, resonant screening is reduced, which leads to an increase of the CR linewidth. This is equivalent to the formation of a density-of-states gap. (b) The CR-excitation process leads to an inelastic breaking of fractional states. Inelastic processes have been used to explain line shifts in the photoluminescence from fractional states in n-channel Si metal-oxide-semiconductor field-effect-transistors (MOSFET's).[24] Since we do not observe significant shifts in the line position together with the broadening we favor the first explanation.

The observation of an influence of the fractional state on a local property such as CR is not contradictory to the fact that the dc conductivity does not show a structure at these fractions at the temperatures used (they are observed below 1 K). Since the fractional gap is on the order of the experimental temperature,[25] a certain fraction of the electrons will be condensed. Therefore we expect to be able to observe these locally condensed areas with a change in CR linewidth. For an observation in dc transport the states have to extend from contact to contact. In addition, we can argue that localization which is needed to observe plateaus is reduced by the "high" temperature used (2 K), while CR will not be influenced by disorder in the same way as dc transport. The properties of sample 1 which show the most pronounced effects are consistent with the above arguments: sample 1 shows extremely narrow plateaus for integer filling, indicating rather weak localization.

In a recent paper Schlesinger *et al.*[26] report an analysis of the dynamical conductivity for $\nu=1$ and below. They observed a systematic linewidth narrowing and resonant field shift below $\nu=1$, which are also observed in our data. However, the observation of a linewidth change at fractional filling seems to be keyed to samples which show very strong linewidth oscillations between $\nu=2$ and $\nu=1$ and still have a high mobility.

This work is supported by the Stiftung Volkswagenwerk, Project No. I 61 840, and by the Jubiläumsfonds der Österreichischen Nationalbank, Project No. 2907. We gratefully acknowledge the Fourier spectrometer measurements performed by Dr. Merkt and Dr. F. Thiele (University of Hamburg) and Professor Kuchar (University of Vienna). We thank Dr. R. Lassnig for valuable discussions.

[1]K. v. Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
[2]D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[3]H. L. Störmer, R. Dingle, A. C. Gossard, W. Wiegmann, and M. D. Sturge, Solid State Commun. **29**, 703 (1979).
[4]P. Voisin, Y. Guldner, and J. P. Vieren, Appl. Phys. Lett. **39**, 982 (1981).
[5]C. K. Sarkar and R. J. Nicholas, Surf. Sci. **113**, 326 (1982).
[6]T. Ando, J. Phys. Soc. Jpn. **38**, 989 (1975).

[7]S. Narita, K. Muro, S. Mori, S. Hiyamizu, and K. Nanbu, in *Proceedings of the International Conference on the Application of High Magnetic Fields to Semiconductor Physics,* Vol. 177 of *Lecture Notes in Physics,* edited by G. Landwehr (Springer-Verlag, Berlin, 1983), p. 194.

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

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

[10]T. Englert, J. C. Maan, Ch. Uihlein, D. C. Tsui, and A. C. Gossard, Physica **117&118B**, 631 (1983).

[11]E. Gornik, W. Seidenbusch, R. Lassnig, H. L. Störmer, A. C. Gossard, and W. Wiegmann, in *Two Dimensional Systems, Heterostructures, and Superlattices,* Vol. 53 of *Springer Series in Solid-State Sciences,* edited by G. Bauer, F. Kuchar, and H. Heinrich (Springer-Verlag, Berlin, 1984), p. 60.

[12]G. L. J. A. Rikken, H. W. Myron, P. Wyder, G. Weimann, W. Schlapp, R. E. Horstman, and J. Wolter, J. Phys. C **18**, L175 (1985).

[13]G. L. I. A. Rikken, H. W. Myron, G. J. G. M. Langerak, and H. Sigg, Surf. Sci. **170**, 160 (1986).

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

[15]R. Lassnig and E. Gornik, Solid State Commun. **47**, 959 (1983).

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

[17]K. W. Chiu, T. K. Lee, and J. J. Quinn, Surf. Sci. **58**, 182 (1976).

[18]W. Seidenbusch, G. Lindemann, R. Lassnig, J. Edlinger, and E. Gornik, Surf. Sci. **142**, 375 (1984).

[19]W. Seidenbusch, Phys. Rev. B **36**, 1877 (1987).

[20]F. Thiele, W. Hansen, M. Horst, J. P. Kotthaus, J. C. Maan, U. Merkt, K. Ploog, G. Weimann, and A. D. Wieck, in *High Magnetic Fields in Semiconductor Physics,* Vol. 71 of *Springer Series in Solid-State Sciences,* edited by G. Landwehr (Springer-Verlag, Berlin, 1987), p. 252.

[21]F. Stern and W. Howard, Phys. Rev. **163**, 816 (1967).

[22]W. Walukiewicz, H. E. Ruda, J. Zagowski, and H. C. Gatos, Phys. Rev. B **30**, 4571 (1984).

[23]E. Gornik, Physica **127B**, 95 (1984).

[24]I. V. Kukushkin and M. P. Timofeev, *High Magnetic Fields in Semiconductor Physics,* Vol. 71 of *Springer Series in Solid-State Sciences,* edited by G. Landwehr (Springer-Verlag, Berlin, 1987), p. 282.

[25]G. S. Boebinger, A. M. Chang, H. L. Störmer, and D. C. Tsui, Phys. Rev. Lett. **55**, 1606 (1985).

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