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OSCILLATIONS OF THE CYCLOTRON RESONANCE LINEWIDTH WITH LANDAU LEVEL FILLING FACTOR
IN GaAs/AlGaAs HETEROSTRUCTURES

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The linewidth of cyclotron resonance in a 2D electron gas in GaAs/AlGaAs heterojunctions shows oscillations between 0.070 T and 0.32 T as a function of the resonance magnetic field at 5 K. With increasing temperature the maximum linewidth decreases, whereas the minimum increases. This oscillatory behaviour is shown to be correlated with the filling factor of Landau levels.

In a two-dimensional (2D) electron gas confined in a potential well at the interface of a GaAs/AlGaAs heterostructure the electronic motion is restricted to a plane parallel to the interface. A strong magnetic field perpendicular to the interface quantizes the orbital motion in the plane leading to a complete quantization of the electronic system. Consequently the kinetic energy associated with the electron degeneracy is quenched, which favours the importance of Coulomb interaction between electrons and between electrons and impurities at low temperatures. Currently there is speculation about the existence of a highly correlated ground state of the charge-density-wave or Wigner lattice type at low carrier densities, especially in the extreme quantum limit [1-4]. It has also been predicted theoretically [5] that screening of impurities and consequently the width of Landau levels varies in the quantum limit with the filling factor of the last Landau level. Experimental evidence for the importance of correlation effects has been found recently in magnetotransport measurements on GaAs/AlGaAs heterojunctions in the extreme quantum limit [3]. The observation of a narrowing of the cyclotron resonance (CR) linewidth in Si inversion layers in the extreme quantum limit has also been attributed to such collective phenomena [4]. In this system, a maximum in the CR linewidth was observed, when the last spin and valley split level was completely filled, corresponding to a filling factor $\nu = 1$ (ν is the ratio of the total carrier density n_s to the degeneracy in one Landau level $e/h \cdot B$). No change was found, when the second or higher levels were completely occupied. Moreover, for $\nu < 1$, the resonance magnetic field was found to be higher than that expected for bulk Si. These results were explained qualitatively in terms of electron-electron correlation which leads to a phase transition to a charge-density-wave (CDW) ground state [1,2]. In order to account for the shift of the resonance position pinning of the CDW to impurities had to be invoked [4]. A narrowing of CR linewidth in the quantum limit has also been observed in GaAs/AlGaAs heterostructures [6].

In the present investigation we have studied the dependence of the resonance magnetic field and the linewidth of CR on the filling factor in modulation doped GaAs/Al_xGa_{1-x}As heterostructures, especially in the range of low carrier densities. In contrast to the experiment on Si inversion layers, where the filling factor was varied at constant magnetic field through a change in the gate voltage, in the present experiment the carrier concentration is fixed and the filling factor of a particular Landau level varies as a function of the magnetic field. Several samples were measured with electron densities between $n_s = 1.2 \times 10^{11} \text{ cm}^{-2}$ and $4.2 \times 10^{11} \text{ cm}^{-2}$ and with nominal mobilities of the order $100,000 \text{ cm}^2/\text{Vs}$. The Far Infrared (FIR) transmission was measured as a function of magnetic field and frequency. The FIR radiation was generated with an optically pumped molecular laser. Several different wavelengths between $41 \mu\text{m}$ and $1223 \mu\text{m}$ were used. The radiation intensity at the sample was estimated to be less than $100 \mu\text{W}/\text{cm}^2$. Care was taken to avoid spurious effects due to interference by using wedge shaped samples and a linear polarizer. In addition visible light was blocked off by means of a black polyethylen foil directly above the sample. The data shown in Figs. 1-3 were taken from the sample with the lowest carrier density.

Fig. 1 shows a plot of the relative change in transmission $\Delta T/T$, for 4 different FIR frequencies as a function of the magnetic field at $T = 5 \text{ K}$. A sharp resonance is observed as $\omega_C = \omega_0$, where $\omega_C = eB/m_C$ is the cyclotron frequency. The full width at half maximum (FWHM) can be as small as 0.07 T at $T = 5 \text{ K}$ corresponding to $\omega\tau \sim 100$ and $\hbar/\tau = 0.2 \text{ meV}$.

In Fig. 2 the resonance magnetic field is plotted for several radiation energies. At low magnetic fields (up to about 5 T) the data points lie on a straight line corresponding to a mass of $m_C/m_0 = 0.069 \pm 0.001$. At higher fields deviations from the straight line indicate a slight increase in the effective mass which can be understood in terms of non-parabolicity. The solid line in Fig. 2 represents the calculated resonance position including non-parabolicity [7]. The data point at 17.9 T ($41 \mu\text{m}$) deviates

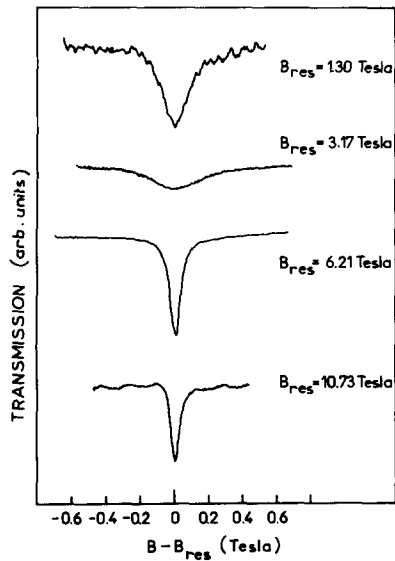


Figure 1: FIR Transmission vs. $B - B_{res}$, where B_{res} is the magnetic field at resonance, for four different laser frequencies.

slightly and corresponds to a lighter mass than expected from non-parabolicity. Within the experimental accuracy (1%) there is no evidence for a dependence of the resonance position on the filling factor. This behaviour is different from the results obtained from Si inversion layers [4].

As can already be seen in Fig. 1 the linewidth of CR varies considerably with resonance field. In Fig. 3 the linewidth (FWHM) is plotted as a function of B . It has two distinct maxima below 5 T, remains constant between 5 T and 10 T and increases slightly at higher fields.

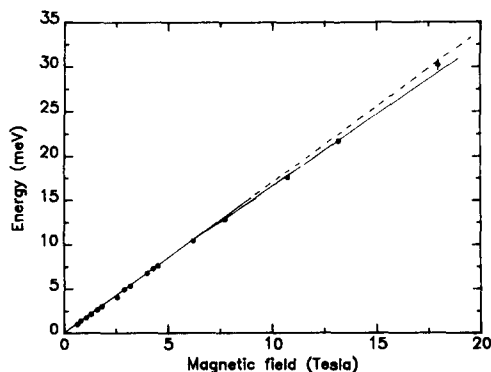


Figure 2: Laser energy vs. resonance magnetic field.

A comparison with measurements of the Shubnikov-de Haas (SdH) effect on the same sample shows unambiguously that the dominant maximum in the linewidth occurs when the last, spin degenerate Landau level, $N = 0$, is completely filled, corresponding to a filling factor $\nu = 2$. The next maximum at lower fields can be attributed to $\nu = 4$. The inset in Fig. 3 shows the temperature dependence of the linewidth at 2.56 T (maximum) and at 10.74 T (minimum). An unexpected temperature dependence is observed in the linewidth maximum: the CR sharpens a factor two when T is increased from 1.5 K to 40 K. The minimum has the opposite temperature dependence: the line broadens from 0.05 T to 0.17 T. In other words, the oscillations in the linewidth are smeared out at higher temperatures ($T \sim 40$ K) and approach roughly the mean value between the maxima and minima at low T . Similar oscillations of the linewidth were observed in two other samples (out of 5) with the next lower carrier concentration ($n_S = 2.0 - 2.5 \times 10^{11} \text{ cm}^{-2}$). The maxima occur at different magnetic fields for samples with different n_S , thus showing that the oscillations are not related to the magnetic field but to the filling factor ν . In all cases a maximum is observed for $\nu = 2$, the maximum at $\nu = 4$ is less well established. The spin splitting, although clearly observed in the SdH data, does not seem to have an influence on the oscillations of the linewidth. This is different from the results obtained on Si [4], where only one maximum was observed for $\nu = 1$, when the last spin and valley split Landau level was completely occupied.

In order to demonstrate the correlation between the filling factor and the linewidth we have made a semi-empirical model for the linewidth Γ assuming that it can be decomposed in an oscillatory and a nonoscillatory part:

$$\frac{1}{\Gamma} = \frac{1}{\Gamma_0} + \sum_N \frac{\nu_N \cdot (1 - \nu_N)}{\Gamma_1} \quad (1)$$

Γ_0 and Γ_1 are treated as fit parameters. Here it is assumed that only partly filled Landau

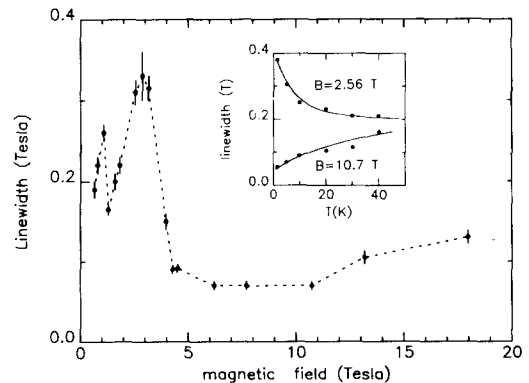


Figure 3: CR linewidth vs. resonance magnetic field at $T=5\text{K}$. The inset shows the temperature dependence of the linewidth for a maximum (2.56T) and a minimum (10.7T).

levels have to be considered and that nearly filled levels are equivalent to nearly empty ones. In the screening model [5,8] ansatz (1) means that screening is most efficient when a Landau level is half filled. In the other theoretical model [1,2], where electron-electron correlation plays the dominant role, the probability for the formation of a collective ground state is higher for a half filled level. The spin was not treated separately in eq. (1), because we have no experimental indication for the influence of the spin on the linewidth. The filling factor ν_N , which is here referred to the Landau level N and varies between 0 and 2, was calculated in the usual way by

$$\nu_N = 2 \cdot \int D_N(E) \cdot f(E-E_F) \cdot dE \quad (2)$$

where a Gaussian with width γ was assumed as density-of-state function. $f(E-E_F)$ is the Fermi function. Such assumptions were found to describe the magnetic field and temperature dependence of ShdH oscillations [9]. Fig. 4 shows a

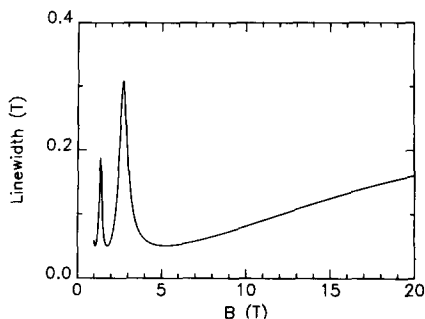


Figure 4: Model calculation of the CR linewidth

model calculation of the linewidth Γ for the sample of Fig. 3 using the experimental conditions ($T = 5$ K, $n_s = 1.23 \times 10^{11} \text{ cm}^{-2}$) with $\Gamma_0 = 0.31$ T, $\Gamma_1 = .092$ T and a Landau level width of $\gamma = 0.2$ meV. The agreement between the model and the experimental data is satisfactory, especially if one takes into account the simplifying assumptions made, that Γ_0 does not depend on the magnetic field and Γ_1 is independent of the Landau quantum number. We have also performed calculations of the temperature dependence of equation (1), which show, that the oscillations of the linewidth vanish with increasing T and disappear completely at above about $T = 30$ K due to the broadening of the Fermi function, which is also in agreement with the experimental findings (inset of Fig. 3). However, the absolute value of Γ at high T is smaller than experimentally observed.

In summary we have observed that at low T the CR linewidth oscillates as a function of the magnetic field in samples of low carrier densi-

ty. This behaviour is shown to be correlated with the filling factor of Landau levels. The width has a maximum, when a Landau level, including both spin states, is completely filled ($\nu = 2, 4$). The oscillations are smeared out at higher temperatures. We believe that these results are a direct demonstration of the influence of many-body effects (correlation and screening) on the CR linewidth in a 2D electronic system.

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