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OBSERVATION OF OSCILLATORY LINEWIDTH IN THE CYCLOTRON RESONANCE OF  
GaAs–Al<sub>x</sub>Ga<sub>1–x</sub>As HETEROSTRUCTURES

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The linewidth of the far infrared cyclotron resonance in the 2-D electron gas in GaAs–Al<sub>x</sub>Ga<sub>1–x</sub>As heterojunctions show oscillations between 0.070 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 behavior is shown to be correlated with the filling factor of the Landau levels.

WE WISH TO REPORT in this letter the first observation of an oscillatory behavior in the linewidth of the far infrared cyclotron resonance of two-dimensional (2-D) electrons. This new magneto-oscillatory effect was observed in the 2-D electrons in GaAs–Al<sub>x</sub>Ga<sub>1–x</sub>As heterostructures on samples with low electron densities. At 5 K the full width at half maximum (FWHM) of the cyclotron resonance, in a sample with a density  $n = 1.23 \times 10^{11} \text{ cm}^{-2}$  and a mobility  $\mu = 100,000 \text{ cm}^2/\text{Vsec}$ , oscillates between a minimum of 0.07 T and a maximum of 0.32 T. The oscillations decrease their amplitude as  $T$  increases and approaches the average width at  $\geq 40 \text{ K}$ . Results from the Shubnikov–de Haas (SdH) measurements made on the same sample show that this oscillatory behavior correlates with the filling of the Landau levels of the 2-D electrons and may be attributed to the dependence of impurity screening on the filling factor.

The cyclotron resonance (CR) was observed by measuring the transmission of the far infrared (FIR) radiation through the sample as a function of the magnetic field  $B$  applied perpendicular to the plane of the 2-D electrons [1]. The FIR radiation was generated with an optically pumped molecular laser. Several different wavelengths between 41 and 1223  $\mu\text{m}$  were used. The radiation intensity at the sample was estimated to be less than  $100 \mu\text{W cm}^{-2}$ . Care was taken to avoid spurious effects due to interference by using wedge shaped

samples and a linear polarizer. The visible light was blocked off by means of a black polyethylene foil directly above the sample.

The samples were selectively doped, single interface GaAs–Al<sub>x</sub>Ga<sub>1–x</sub>As ( $x = 0.3$ ) heterojunctions grown by MBE (molecular beam epitaxy) [2]. The structure consists of a 1  $\mu\text{m}$  thick undoped GaAs ( $p$ -type with  $p \sim 10^{14} \text{ cm}^{-2}$ ), an 800 Å thick Al<sub>0.3</sub>Ga<sub>0.7</sub>As selectively doped with Si donors, and a 200 Å cap layer of GaAs, sequentially grown on Cr-doped semi-insulating GaAs substrates. The top 200 Å GaAs layer as well as the Al<sub>0.3</sub>Ga<sub>0.7</sub>As layer are depleted of free carriers and the 2-D electrons, resulting from ionized donors in the Al<sub>0.3</sub>Ga<sub>0.7</sub>As are confined to the GaAs–Al<sub>x</sub>Ga<sub>1–x</sub>As interface in the undoped GaAs. Of the five samples, which we have studied, with  $n$  from  $1.2 \times 10^{11}$  to  $4.2 \times 10^{11} \text{ cm}^{-2}$  and  $\mu \sim 100,000 \text{ cm}^2/\text{Vsec}$ , the cyclotron resonance linewidth oscillations were observed in the three lower density samples, having  $n = 1.2 \times 10^{11}$ ,  $2.0 \times 10^{11}$  and  $2.5 \times 10^{11} \text{ cm}^{-2}$ . The data shown in Fig. 1 through to Fig. 3 were taken from the lowest density sample which shows most strikingly this oscillatory effect.

Figure 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 at  $\omega_c = 2\pi c/\lambda$  where  $\lambda$  is the wavelength of the laser and  $\omega_c = eB/m_c$  is the cyclotron frequency. The 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 Figure 2 the resonance magnetic field is plotted for several laser energies. At low magnetic fields (up to about 5 T) the data points lie on a straight line corre-

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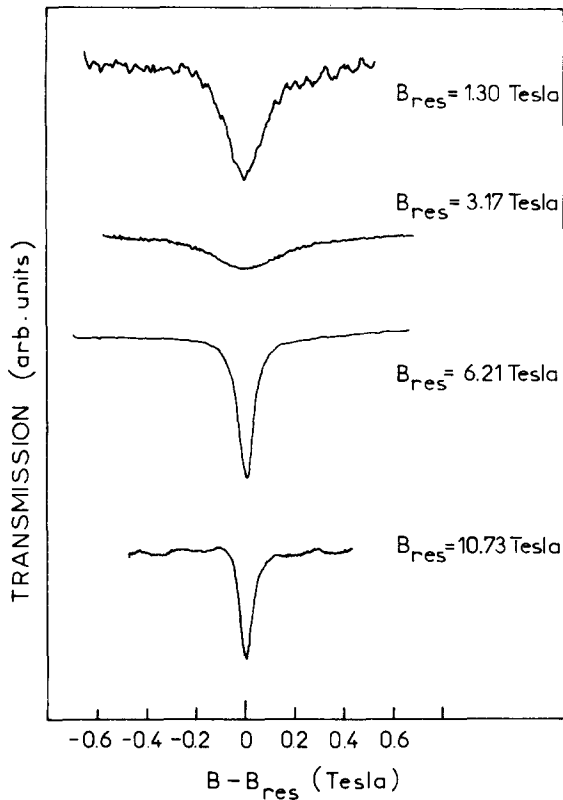


Fig. 1. FIR transmission vs  $B - B_{res}$ , where  $B_{res}$  is the magnetic field at resonance, for four different laser wavelengths. From top down:  $\lambda = 570.5, 232.9, 118.8$  and  $70.6 \mu\text{m}$ .

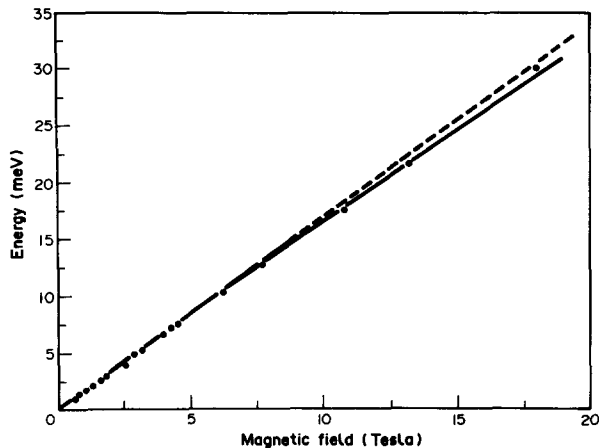


Fig. 2. Laser energy vs resonance magnetic field.

sponding to a cyclotron mass of  $m_c/m_0 = 0.069 \pm 0.001$ . At higher  $B$ , 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 [3]. The data point at 17.9 T ( $\lambda = 41 \mu\text{m}$ ) deviates slightly from the solid line and

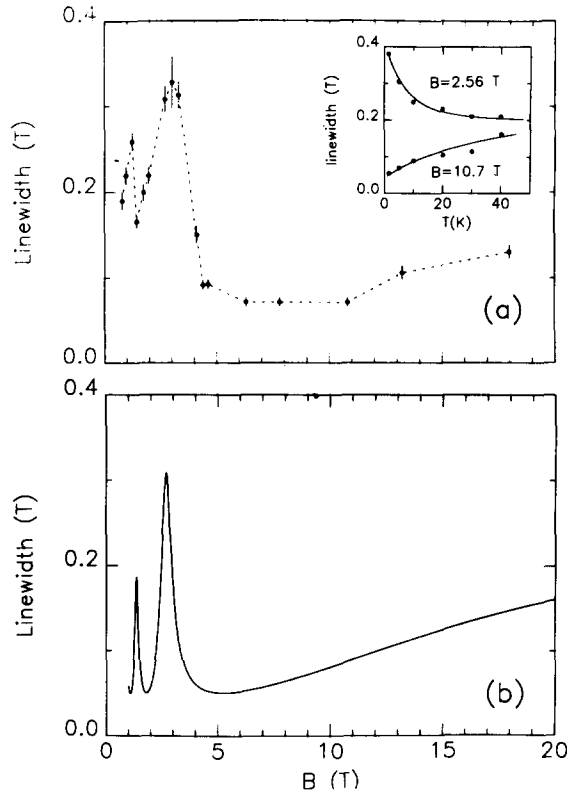


Fig. 3. (a) Linewidth vs resonance field at  $T = 5 \text{ K}$ . The inset shows the temperature dependence of the linewidth for a maximum at  $B = 2.56 \text{ T}$  and a minimum at  $B = 10.7 \text{ T}$ . (b) Model calculation of the CR linewidth.

this deviation corresponds to a lighter mass than expected from non-parabolicity.

As seen in Fig. 1, the linewidth of CR varies considerably with the resonance field. In Fig. 3 the linewidth (FWHM) is plotted as a function of  $B$ . It has two distinct maxima below 5 T, one at  $B \sim 3.0 \text{ T}$  and the other at  $B \sim 1 \text{ T}$ . A comparison with the results from SdH measurements on the same sample shows unambiguously that the dominant maximum at  $B \sim 3 \text{ T}$  occurs when the last, spin degenerate Landau level ( $N = 0$ ) is completely filled, corresponding to a Landau level filling factor  $\nu \equiv nh/eB = 2$ . The next maximum at a lower field can be attributed to  $\nu = 4$ . The inset in Fig. 3(a) shows the temperature dependence of the linewidth at  $B = 2.56 \text{ T}$  (maximum) at  $B = 10.74 \text{ T}$  (minimum). An unusual temperature dependence is observed in the linewidth maximum: the CR sharpens by a factor of two when  $T$  is increased from 1.5 to 40 K. The minimum shows the opposite temperature dependence: the line broadens from 0.5 to 0.17 T. In other words, the oscillations in the linewidth are smeared out at higher temperatures ( $T \sim 40 \text{ K}$ ) and approach roughly the mean value between the maxima and minima. Similar oscillations of the linewidth were

observed in the other two samples with the next lower carrier concentration,  $n = 2.0 \times 10^{11}$  and  $2.5 \times 10^{11}$  cm<sup>-2</sup>. The maxima occur at different magnetic fields for samples with different  $n$ , confirming that the oscillations are not related to the magnetic field, but to the Landau level filling factor  $\nu$ . In all cases a maximum is clearly observed at  $\nu = 2$ . The maximum at  $\nu = 4$  is not as well resolved in all three samples. The spin splitting, although clearly observed in the SdH data, has no observable influence on the oscillations of the linewidth.

A strong magnetic field perpendicular to the plane of the 2-D electrons quantizes their 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 and the importance of Coulomb interactions between electrons and between electrons and impurities is expected at low temperatures. It has long been anticipated that at low densities the ground state of the system may be a highly correlated charge density wave (CDW) state or a Wigner lattice [4, 5], especially in the extreme quantum limit. In Si inversion layers, a linewidth narrowing of the cyclotron resonance, concomitant with a shift in the resonance frequency, was observed in the extreme quantum limit, when  $\nu < 1$ , and a weak maximum in linewidth was observed at  $\nu = 1$  [6]. These results were explained phenomenologically by the existence of a CDW ground state. The shift in the resonance frequency, as well as the linewidth, were accounted for by invoking defect pinning of the CDW [4]. In GaAs–Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures, a narrowing of the CR linewidth has also been observed in the extreme quantum limit, but no shift of the resonance frequency was detected [7]. More recently, the quantized Hall effect was observed in the extreme quantum limit at  $\nu = 1/3$  and  $\nu = 2/3$  [8], an extraordinary phenomenon, which, though not yet understood at the present, is believed to be manifestation of a new electronic state. In this experiment, the extreme quantum limit is reached with  $B \geq 5.5$  T in our lowest density sample [Fig. 3(a)]. The CR linewidth, as seen in Fig. 3(a), reaches its minimum value at  $\nu \sim 1$  to 0.5, as previously observed, but increases slightly with further decrease of  $\nu$  at higher fields up to  $B = 18$  T, the highest field at which CR was observed. Except for the data taken with  $\lambda = 41$   $\mu$ m, the position of the resonance agrees well with that expected from the nonparabolic band model. With  $\lambda = 41$   $\mu$ m, the resonance occurs at  $\nu = 0.28$ , slightly less than  $\nu = 1/3$ , where the dominant quantized Hall anomalies were observed. At this frequency, the linewidth is narrowed to approximately half its average value, but the magnetic field position of the resonance is  $\sim 1\%$  lower than that expected from the nonparabolic band mass. It appears that these results from the GaAs–Al<sub>x</sub>Ga<sub>1-x</sub>As hetero-

structures differ qualitatively from those observed in Si inversion layers.

We attribute the oscillatory effect in the CR linewidth to the dependence of impurity screening on the occupation of Landau levels. As pointed out by Das Sarma [9], under complete quantization, screening is most efficient when a Landau level is half filled and least efficient when it is nearly filled or nearly empty. In order to demonstrate this correlation between the filling factor and the linewidth, we have made a semi-empirical model for the linewidth  $\Gamma$ , assuming that it can be decomposed in an oscillatory part and a nonoscillatory part:

$$\frac{1}{\Gamma} = \frac{1}{\Gamma_0} + \sum_N \frac{\nu_N(2 - \nu_N)}{\Gamma_1}, \quad (1)$$

where  $\Gamma_0$  and  $\Gamma_1$  are treated as fitting parameters. It is assumed that only partly filled Landau levels have to be considered and that nearly filled levels are equivalent to nearly empty ones. The spin was not treated separately in equation (1), because we have no experimental indication for the influence of the spin on the linewidth. The filling factor  $\nu_N$ , here, refers 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 function with width  $\gamma$  was assumed as the density-of-state function and  $f(E - E_F)$  is the Fermi function. Such assumptions were found to describe the magnetic field and temperature dependence of SdH oscillations [10]. Figure 3(b) shows a model calculation of the linewidth  $\Gamma$  for the sample of Fig. 3(a) using  $T = 5$  K and  $n = 1.23 \times 10^{11}$  cm<sup>-2</sup>, which yield  $\Gamma_0 = 0.31$  T,  $\Gamma_1 = 0.092$  T and a Landau level width of  $\gamma = 0.2$  meV. The agreement between the model calculation and the experimental data is satisfactory, especially if one takes into account the simplifying assumptions made that  $\Gamma_0$  does not depend on the magnetic field and  $\Gamma_1$  is independent of the Landau quantum number. We have also performed calculations of the temperature dependence of equation (1), which shows that the oscillations of the linewidth vanish with increasing  $T$  and disappear completely at  $T > 30$  K, due to the broadening of the Fermi function. This result is in reasonable agreement with the experiment (inset of Fig. 3). However, the absolute value of  $\Gamma$  at high  $T$  is smaller than experimentally observed.

In summary, we have observed that, at low  $T$ , the cyclotron resonance linewidth oscillates as a function of the magnetic field in samples of low carrier densities. This behavior is shown to be correlated with the filling factor of the Landau levels. The width has a maximum,

when a Landau level, including both spin states, is completely filled (i.e.  $\nu = 2$  and 4). The oscillations are smeared out at higher temperatures,  $\sim 40$  K. These results are attributed to the dependence of impurity screening on the filling of the Landau levels.

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