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Cyclotron-resonance oscillations in InAs quantum wells

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The cyclotron resonance of a two-dimensional electron gas in an InAs quantum well sandwiched between two GaSb layers has been investigated experimentally for its dependence on the magnetic field. Both the amplitude and the half-width of the resonance show a strong oscillatory behavior, exhibiting a maximum amplitude and correspondingly a minimum half-width when the highest occupied Landau level is half filled. Oscillations for more than ten periods have been observed. From our experiments we can deduce that there is a considerable overlap of the Landau levels, which strongly increases with decreasing magnetic field.

The cyclotron resonance (CR) in a two-dimensional electron gas (2DEG) has been investigated extensively for different systems, e.g., Si metal-oxide-semiconductor structures,[1] InSb metal-insulator-semiconductor structures,[2] GaAs heterostructures,[3,4] and InAs quantum wells.[5] The dependence of the mass, amplitude, and linewidth of the CR on the magnetic field B shows a complex behavior. It differs for different systems and sample configurations due to different scattering and interaction mechanisms that are important for the particular situation (e.g., Refs. 6–9). For some $Al_xGa_{1-x}As$-GaAs heterostructure samples, in particular of not too high electron density N_S, an oscillation of the half-width related to an odd and an even filling factor $\nu = N_S h/eB$ has been observed[3,10] which has been explained by an oscillatory behavior of the screening properties for a 2DEG in a strong magnetic field B.[3,11,12]

We have investigated CR in a 2DEG of an InAs quantum well[13] sandwiched between two GaSb layers. This system has the advantage of a relatively low effective CR mass m_c with corresponding high cyclotron frequencies $\omega_c = eB/m_c$. This allows us to study CR down to low magnetic fields and high filling factors. Also of importance is that the charge density N_S and mobility are such that the effect of the optical signal saturation (see below) does not smear out oscillations and the internal CR scattering τ_c can be determined.

Since we can observe a large number of oscillation periods we are able to make detailed statements about the B dependence for the situations of both fully filled and half-filled highest Landau levels. In particular, we can conclude from our measurements that there is a significant overlap of the density of states between the different Landau levels, as has been discussed from magnetic susceptibility,[14] specific-heat,[15] and magnetocapacitance measurements.[16]

The experiments were performed on molecular-beam-epitaxially grown samples, similar to those described in Refs. 4 and 13. On a GaAs substrate, a buffer layer of GaAs and then a thick layer of GaSb were first grown. This was followed by the InAs well of 20 nm and completed with a GaSb cap of 20 nm. All layers are nominally undoped. This system represents a type-II heterostructure with the GaSb valence band about 150 meV above the InAs conduction band. In this system electrons are transferred from the GaSb into the InAs quantum well, creating, in an ideal case, an equal number of holes in GaSb and electrons in InAs. For the particular samples discussed here, due to extrinsic donors likely to be associated with the interfaces the number of electrons is $N_S = 8.8\times10^{11}$ cm^{-2}, whereas the number of holes is much smaller and cannot be detected in the experiment. The N_S and the width of the well are such that only the ground electron subband is occupied. The dc mobility (van der Pauw) of the electron at 4.2 K is 80000 cm^2/V s.

CR measurements were performed at 4.2 and 1.8 K in magnetic fields up to 12 T. The transmission of far-infrared (FIR) radiation through the sample was measured with a Fourier-transform spectrometer which was connected via a waveguide system to the cryostat. Spectra were taken in the frequency domain at fixed magnetic fields B. This means that for a given spectrum the filling factor ν is fixed which is important for the interpretation of the results.

Original experimental spectra for perpendicular magnetic fields are shown in Fig. 1. We find that both the amplitude of the absorption $A(B) = 1 - T(B)$ [$T(B)$ is the transmission at a field B] and the half-width $\Delta\omega$ of the resonances show a strong oscillatory behavior. The CR frequency ω_c varies linearly with B. The CR mass is extracted as $m_c = (0.0374 \pm 0.007)m_0$ and shows no oscillations to better than 1%. To discuss the oscillatory behavior of the amplitude and half-width in detail we have plotted in Figs. 2(a) and 2(b) the experimental (maximum) absorp-

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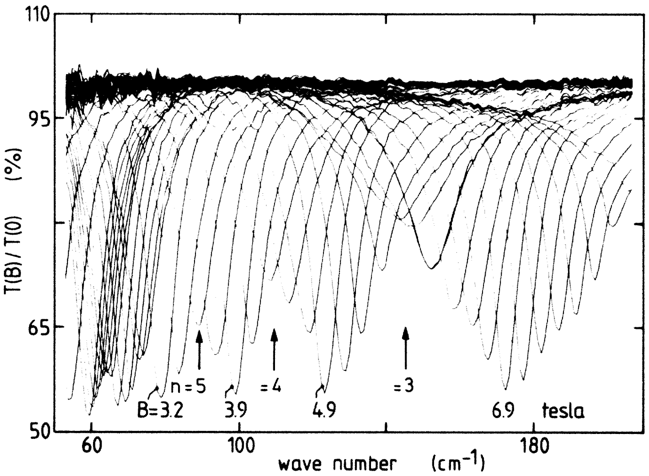

FIG. 1. Original experimental spectra of the transmission $T(B)$ at magnetic field B. Spectra are normalized to the transmission $T(O)$ at $B=0$. The figure shows 42 different spectra measured at different B which have been increased in small—sometimes different—increments from $B \approx 2.1$ T to $B \approx 8.2$ T. Some values of B are indicated. Also positions of the CR for n fully filled Landau levels are indicated. Temperature is 1.8 K, spectral resolution is 1 cm^{-1}.

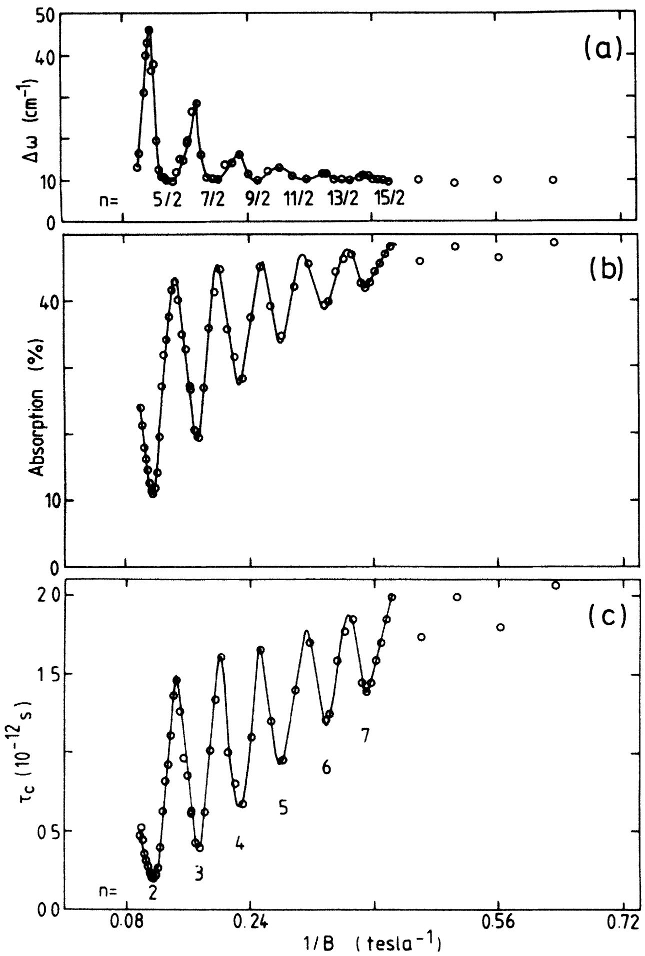

FIG. 2. (a) Resonance half-width $\Delta\omega$ (full width at half maximum), (b) experimental absorption amplitude, and (c) the "internal" cyclotron scattering time τ_c which has been extracted from fits of the complete Fresnel formulas to the transmission spectra (see text). The vertical axis is $1/B$, lines are guides for the eyes to connect experimental points.

tion A and the experimental half-width $\Delta\omega$ vs $1/B$. These figures show that the oscillations are, within the accuracy of knowing N_S ($\pm 3\%$), exactly related to the filling factor ν. Maximum absorption amplitudes and minimum half-widths occur under the condition that the highest Landau level n (spin not resolved) is half filled corresponding to odd filling factors ν as defined above.

To extract the CR scattering time τ_c from the experimental spectra we have to consider that for linearly polarized radiation the optical signal—the absorption amplitude—cannot exceed 50%. Thus in a system with fixed τ_c the amplitude of the absorption does not increase linearly with N_S but saturates and the half-width of the resonance broadens with respect to the half-width expected from $\Gamma_c = 1/2\pi c\tau_c$. We have fitted calculated transmission curves using the complete Fresnel formulas of the system. The dynamic conductivity of the 2DEG is described by $\sigma(\omega,B) = N_S e^2 \tau_c / m_c [1 - i(\omega-\omega_c)\tau_c]$. For the spectra shown in Fig. 1 we have used a grating coupler made of periodic metal stripes with the effect of enhancing the CR absorption (e.g., Ref. 17). From measurements on the same sample before the preparation of the grating coupler we know that the enhancement of the amplitude is 1.3 for the grating coupler here. Taking this into account we have evaluated from the experimental spectra for each B the value of $\tau_c = \tau_c(B)$, which includes consistently information from both the amplitude and the half-width. The oscillations of τ_c in Fig. 2(c) are even more pronounced than those appearing directly in the experimental amplitude and half-width.

Before we discuss the experimental results we would like to note some additional observations. The product $A\Delta\omega$ of the amplitude and the half-width is roughly constant for the entire B regime covered here. At $B > 5$ T, a simple evaluation of $A\Delta\omega$ gives a slight oscillation (15–20%); however, a fit including the optical saturation effect is not sensitive enough to reveal unambiguously an oscillation for the integrated oscillator strength also. Increasing the temperature from 1.8 to 4.2 K does not change the amplitude for $B < 3$ T. At $B > 3$ T, a slight decrease of the amplitude by 5–10% is observed only for odd filling factors. For measurements in magnetic fields tilted 45° with respect to the sample we find a similar oscillation if we plot the amplitude and half-width versus the reciprocal perpendicular field component $1/B_\perp$. Both the amplitude and reciprocal half-width decrease by a factor of about 0.7 for both even and odd filling factors (defined by $B_\perp$). A qualitatively similar behavior as described here has also been observed on different samples. In some cases additional complexity arises, e.g., coupling to intersubband resonances[18] and a small oscillation of the mass. At $B > 9$ T we also observe interaction of the CR with optical phonons in InAs and GaSb. These points will not be discussed here.

The oscillations of CR amplitude and half-width arise from the oscillatory behavior of the screening. The screening depends on the density of states (DOS) at the Fermi level E_F and is thus large if E_F lies at the center of the Landau level and is small if E_F is in the tail region. An oscillation of the CR half-width has first been observed and interpreted by screening effects in Ref. 3. The importance of filling-factor-dependent self-consistent effects on the CR linewidth has first been pointed out by Das Sarma.[19] Very recently, several self-consistent calculations of Landau-level broadening and screening have been performed using different approximations (e.g., Refs. 11 and 12). It is found that the self-consistent results depend strongly on the type of the scatterers and their separation from the 2DEG. Additional complexity arises from the fact that only for strictly short-range scatterers the Landau-level width Γ_N is directly related to the "internal" CR linewidth $\Gamma_c = 1/2\pi c \tau_c$. In particular, in the limit of long-range scatterers Γ_c is given by the difference of the widths of the Landau levels involved.[7]

To discuss our experimental results we plot in Fig. 3 $\Gamma_c = 1/2\pi c \tau_c$ [with τ_c from Fig. 2(c)] vs $\sqrt{B}$. The observation of a large number of oscillations in our sample enables us to evaluate the B dependence both for half-filled Landau levels (Γ_{hf}) and for the fully filled Landau levels (Γ_{ff}). Within the accuracy of determining Γ_{dc} from Shubnikov–de Haas measurements at small magnetic fields, Γ_{dc} coincides at low B with Γ_c. The theoretical B dependence $\Gamma_{\mathrm{sr}}^2 = 2\hbar^2\omega_c/\pi\tau_{\mathrm{dc}}$ for strictly short-range scatterers according to Ref. 7 lies at high B between our values of Γ_{ff} and Γ_{hf} indicating that strictly short-range scatterers cannot explain details of our experiment. We find that Γ_{hf} slowly increases with B. In Ref. 11 it has been calculated that for remote charged scatterers which are separated by a spacer layer, Γ_{hf} decreases with B. For distributed scatterers, e.g., ionized donors in the quantum well and in its vicinity, a nearly constant value of Γ_{hf} is calculated. The same effect has also been calculated for neutral scatterers.[11] That distributed scatterers are most likely the dominant scatterers in our samples is consistent with a nondecreasing Γ_{hf}. The observed slight increase of Γ_{hf} with B can perhaps be calculated within a more accurate model. Also, a frequency dependent coupling to plasmons[9,20] might explain this increase. At high magnetic fields we observe that Γ_{ff} is drastically larger than Γ_{hf}. The reason is that the long-range part of the scattering potential is not screened if E_F is in the tail region. One important observation of our experiment is that the envelope of Γ_{ff} strongly decreases with decreasing B and approaches Γ_{hf} for $\sqrt{B} \approx 1.5\ \mathrm{T}^{1/2}$. Note that at this small B we observe the absolutely smallest half-width and that in our frequency sweeps at fixed ν, oscillations are not smeared out due to varying ν values. In view of the complexity of self-consistent screening and broadening, we cannot give a quantitative explanation. Qualitatively, we relate the observation of the strong decrease of Γ_{ff} with decreasing B to two possible effects: the inefficient suppression of the screening at even filling factors for the higher Landau levels with their large cyclotron radii and the increase in overlap of the Landau levels with decreasing B. In particular, in Fig. 1 we find for $n \approx 3$ a broad resonance at 150 cm^{-1} with $\Delta\omega \approx 30$ cm^{-1}. We can expect that the Landau-level width is even broader, since for this situation Γ_c is given roughly by the difference of the Landau-level widths. If we assume for a moment a similar width for small B with corresponding small Landau-level separation (e.g., 60 cm^{-1} at 2 T) then the Landau levels should overlap. We can expect that in this case the DOS and thus the screening increases, resulting in a decrease of Γ_{ff}. Of course, the effect of overlapping has to be considered self-consistently in connection with the Landau levels and the screening. This complex behavior has so far not been included in the calculations,[11,12] which use the simple Born approximation.

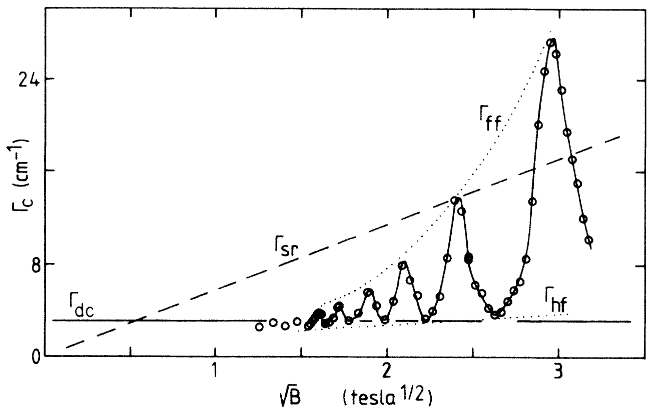

FIG. 3. $\Gamma_c = 1/2\pi c \tau_c$ from experiment vs $\sqrt{B}$. Γ_{ff} and Γ_{hf} are, respectively, the envelope curves for the condition of fully filled and half-filled highest Landau levels. Γ_{sr} is the CR linewidth for short-range scatterers according to Ref. 7. Γ_{dc} is the value from dc transport measurement at small magnetic fields $B \lesssim 2$ T.

In summary, we have observed very pronounced oscillations of CR amplitude and half-width for electrons in a quantum well of InAs. The oscillation is caused by a filling-factor-dependent screening of the 2DEG in the magnetic field. The oscillatory effect decreases significantly with decreasing B which is explained by an increasing overlap of the Landau levels.

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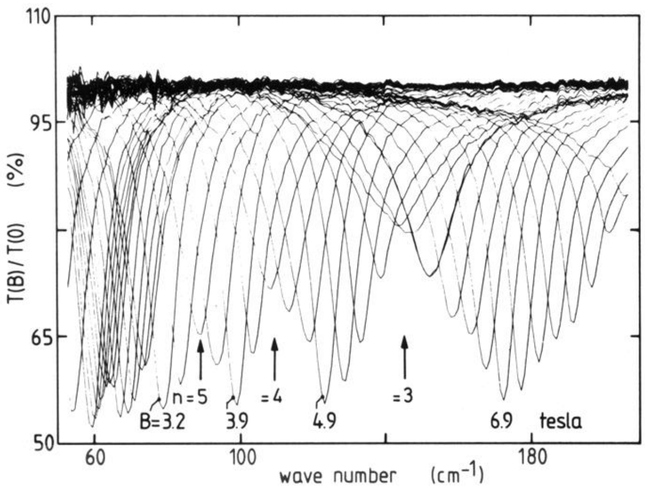
[20]A. Gold (private communication) finds, that the onset of the increase in Γ_{hf} that we observe at $B > 2.5$ T [corresponding to the decrease of τ_c for $1/B < 0.4\ \mathrm{T}^{-1}$ in Fig. 2(c)] agrees excellently with calculations using the memory function approach of Ref. 9.



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