Spin- and Landau-splitting of the cyclotron resonance in a nonparabolic two-dimensional electron system

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We study cyclotron resonance (CR) in a two-dimensional electron system on InAs/AlSb-quantum wells observing discrete transitions between adjacent sets of spin-split Landau states. While in three-dimensional electron systems such splittings are well established, no spin-split CR has been observed in a two-dimensional electron system, to date. Theoretical attempts link this fact to the reduced dimensionality and strong electron-electron coupling. Our results, however, can be interpreted quantitatively in a straightforward single-particle model offering new clues to this major puzzle.

Cyclotron resonance (CR) has proven to be a powerful tool for studying the properties of a two-dimensional electron system (2DES) as realized in many different semiconductor structures. Especially for n-GaAs/$Al_xGa_{1-x}As$ heterostructures, CR has been studied in a large number of investigations both experimentally and theoretically. Many aspects such as the effect of screening on the CR linewidth in partially or completely filled Landau levels (LL)[1,2], polaron effects [3], and effects arising from the nonparabolicity of the conduction band [4,5] have been investigated. In different experiments strong oscillations of the CR absorption depth, the CR linewidth, and the cyclotron mass as a function of the magnetic field have been reported [6-9]. These oscillations have mostly been described in terms of a filling factor dependent screening.

Up to now, however, no splitting of the CR due to transitions originating from different Landau levels or the different spin states of a given LL has been observed unambigously in a 2DES at low temperatures, even in highest purity samples. One type of such splitting ("Δm-splitting") should be detected, whenever the energy dependence of the effective mass induced by conduction band nonparabolicity leads to a sufficiently large energy separation of adjacent pairs of LLs, namely {(n-1),n}, and {n,(n+1)} where the n^{th} level is partially occupied. Of particular interest is the nonparabolicity induced "Δg - splitting", i.e. the fact that the energy dependence of the Landé g-factor causes the Zeeman splitting of the n^{th} LL to be larger than that of the $(n+1)^{st}$ LL. With a nonparabolic dispersion, as exists in most semiconductors, spin-orbit coupling in fact makes the g-factors of different LL different, causing thereby the transition energies of electrons with opposite spin projections to be likewise different. Therefore, the spin conserving CR-transition between spin-up LLs should occur at a higher energy than that between spin-down LLs [10, 11]. In three dimensional crystals as, e.g., bulk GaAs, in fact, such splitting has been observed [12,13] and the underlying mechanism is well understood. In a 2DES, however, such splittings have not been observed previously in spite of many different attempts [4]. Most recently, Watts and coworkers used an elegant impedance matching technique on GaAs/AlGaAs heterostructures [14] to reduce the linewidth of the CR well below the expected splitting but did not detect any signature of a split CR. To our knowledge, there is only little understanding of the mechanisms responsible for this apparently fundamental difference of the CR in three and two dimensions.

Here, we report the observation of both the Δm- and the Δg-splittings of the CR in a 2DES, demonstrating that the missing splitting of the CR in other studies is not an effect of the reduced dimensionality alone. In view of the many previous attempts to identify quantization related splittings of the CR in a 2DES our present unambigous observation, as well as the excellent agreement with a straightforward single-particle model, certainly comes as a surprise. We investigate the 2DES in very deep ($\approx$1.3eV) InAs quantum wells with AlSb-barriers grown by molecular beam epitaxy. Due to the low effective mass of InAs ($m_\Gamma^* = 0.023m_0$) and the high bulk-InAs Landé g-factor ($g \approx -15$) both the cyclotron energy $\hbar\omega_c$ as well as the Zeeman splitting $\Delta E = g\mu_B B$ are significantly larger than in GaAs. Also, the conduction band nonparabolicity is larger in InAs, leading to a larger separation of the expected transitions.

Here we only give the growth data for a representative sample named (A). The complex smoothing layers required by the large lattice misfits are described in detail elsewhere [15]. The InAs quantum well is 12 nm wide, sandwiched between a 20 nm thick, undoped lower AlSb barrier and a 60

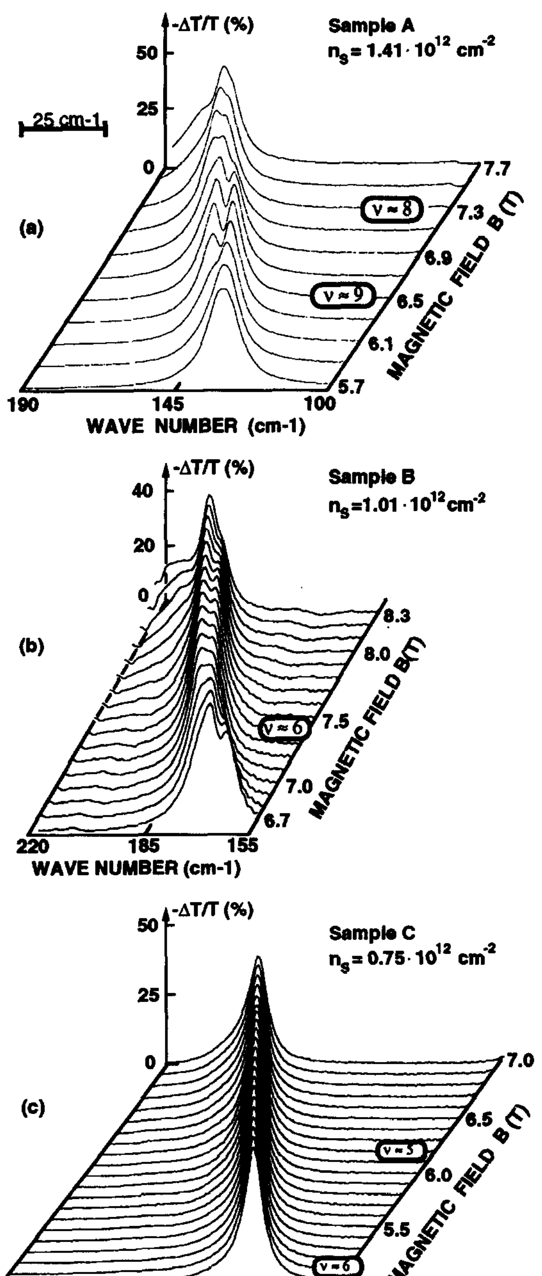

Fig. 1.: (a), (b) Typical spectra showing the splitting of the CR for two different samples as a function of the magnetic field B. Two types of splittings are observed, one being larger close to odd filling factors ("Δm-splitting"), and a smaller splitting ("Δg-splitting") close to even filling factors. As the magnetic field is varied, both parts of the split resonances exchange oscillator strength. Traces closest to an integer filling factor ν are marked by the inset boxes. In (c) we show spectra of a third sample as described in the text with narrow CR linewidth, but surprisingly no splitting at all. All figures are drawn with identical x-scaling to simplify comparison of the lineshapes.

nm thick AlSb top barrier which is Te:δ-doped 50 nm above the heterointerface ($1.5 \cdot 10^{12}$ cm^{-2}). The sample surface is covered with a 140 nm thick $Al_{0.8}Ga_{0.2}Sb$ cap layer. The resulting 2D carrier density is $n_s = 1.41 \cdot 10^{12}$ cm^{-2} if cooled down in the dark. The mobility at T=2 K is of the order of $\mu = 36$ $m^2V^{-1}sec^{-1}$. The far infrared spectra have been taken using a rapid scan Fourier transform spectrometer connected to a low temperature cryostat containing a 15 T superconducting solenoid. We determine the relative change in transmission $-\Delta T/T = (T(0)-T(B))/T(0)$ being proportional to the real part of the dynamical conductivity $\sigma(\omega,B)$. T(0) is the transmission of the sample at zero magnetic field, T(B) the one at finite B normal to the heterointerface.

Fig. 1 displays typical spectra for different magnetic fields. In (a) the result of sample A is shown, whereas in (b) spectra of a second sample (B) are given for comparison. Similar results have been obtained on a variety of samples. However, (c) depicts the spectra of a third high mobility sample (C) where surprisingly no splitting is detected at all. Traces closest to an integer filling factor are marked by the inset boxes. For samples (A) and (B) a splitting of the CR for specific magnetic field regions is clearly observed. This splitting is larger close to an odd filling factor than for even filling factors. The filling factors ν are determined from Shubnikov-de Haas oscillations of the magneto resistance either in situ or on a reference sample from the same wafer. As the magnetic field is varied, both parts of the split resonance exchange oscillator strength. In (a) even three lines can be seen around B=7.2 T, just above ν=8 in this case. A qualitative similar splitting occurs near all integer filling factors up to ν=13 and down to ν=3, which is typically the lowest one that we can reach with the magnetic field available.

We wish to stress, again, that the splitting of the CR as described above is not observed on all samples. For samples with low electron mobilities ($\mu \leq 10$ $m^2V^{-1}sec^{-1}$) we instead observe strong oscillations of the CR absorption depth, the CR linewidth, and the cyclotron mass similar to those reported in ref. [8]. In a recent publication [16] we related these oscillations to filling factor dependent screening. Improvement of the sample quality led us to discover the split CR. Therefore we now believe that the oscillations of the CR amplitude and linewidth could mark an onset of the splitting which is hidden by broad CR line widths; this view has earlier been proposed by Hansen [17]. Sample (C), however, shows neither a splitting nor strong oscillations although it exhibits the smallest CR line width and has the highest electron mobility ($\mu \geq 65$ $m^2V^{-1}sec^{-1}$). The growth parameters differ slightly from those of samples A and B: Sample C contains two additional thin (2.5 nm) GaSb layers at the InAs interfaces and a 2.5nm/2.5nm GaSb/AlSb smoothing superlattice in lieu of the lower AlSb-barrier. This modification is used to reduce interface roughness limiting electron mobility.

We explain the observed splittings quantitatively using a simple single particle model, including conduction band nonparabolicity in terms of the well known **k·p** formalism as introduced by Kane [18]. In a simplified form, this leads to an expression for the energy dependence of the effective mass:

$$m^*(E) = m^*_\Gamma \cdot (1 + 2\frac{E}{E_G})$$

Here m_Γ* denotes the band edge mass of InAs, E_G = 400 meV the InAs band gap energy, and E = E_1+E_F the sum of the groundstate energy E_1 of the quantum well and the Fermi level. The quantum well is modeled by an infinitly deep rectangular confining potential with only the lowest subband being occupied. Then it is quite straightforward to derive the eigenenergies E=$E_{n,1}$ (n : Landau index) in the presence of a magnetic field [19,20]. The influence of nonparabolicity on Landauenergies E_n and subband energy E_1 is described by:

$$\left(n+\tfrac{1}{2}\right)\hbar\omega_C^0 = E_n\left(1+\frac{E_n}{E_G}\right) - E_1\left(1+\frac{E_1}{E_G}\right)$$

where $\hbar\omega_C^o$ is the cyclotron energy containing the band edge mass of InAs. The result of this calculation as a function of the magnetic field is given in Fig. 2 together with the oscillating Fermi level. The nonparabolicity of the Zeeman splitting $\Delta E = \pm(1/2)\cdot g\mu B$ is included via an energy dependent g-factor, $g=g_0\cdot(1 - \alpha E)$, as known for the three-dimensional case [10,11]. The insets in Fig. 2 depict the possible spin-conserving transitions that result from this Landau-fanchart. Close to an even integer filling factor the dominating transitions start from the same Landau level (Δg - splitting), whereas for odd ν the levels n-1, n, and n+1 are involved (Δm-splitting). For intermediate filling factors even three transitions are possible, depending on the actual level occupancy.

To obtain a clearer picture, instead of plotting the observed resonance positions we convert them into cyclotron masses and compare those to the ones obtained from our calculation, as $m^*=e\hbar B/\Delta E_{CR}$. The result is shown in Fig. 3, where we display the CR masses vs. magnetic field. The solid lines represent the possible transitions according to our model. To keep the model simple we chose

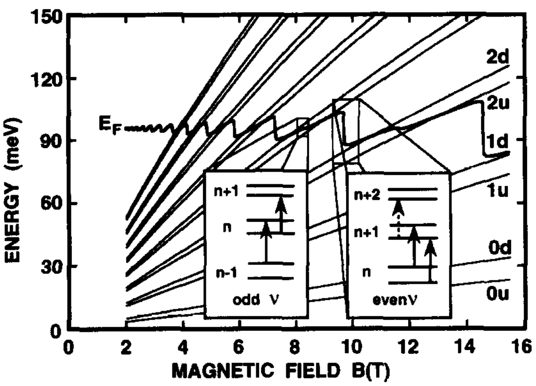

Fig. 2.: Nonlinear Landau fanchart obtained using our straightforward single particle model including band-nonparabolicity as described in the text. To calculate this fanchart and the corresponding Fermi level, we used a quantum well width of W=12.5nm and a carrier density of n_s= $1.41\cdot10^{12}cm^{-2}$ (sample A). The energy of the lowest subband is E_1=60meV. Nonparabolicity and nonlinear Zeeman splitting principally allow up to three energetically different CR transitions simultaneously, some of which are sketched in the insets.

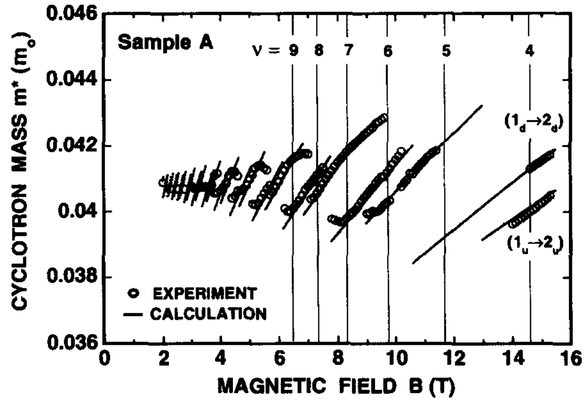

Fig. 3.: Cyclotron masses for sample A as a function of the magnetic field. The lines represent calculated transitions possible according to Fig. 2. The symbols represent the experimental data.

not to include the effects of temperature dependent Landau level population. Therefore the calculated masses jump abruptly when levels are completely filled whereas the experimental values cross over smoothly. The agreement of both the resonance positions as well as the size of the splittings is very good over a large range of magnetic fields.

The best fit to all our data is obtained using g_0=-15 as the InAs bulk value and α = 0.0025 meV^{-1}. The amount of the Δg-splitting depends quadratically on the magnetic field within the accuracy of our measurement. Such a quadratic dependence is predicted and has been observed in different experiments [12,13] on bulk material. The calculation of the proportionality factor, however, involves the dipole matrix elements relating the states of the valence- and conduction bands. Those matrix elements are not yet well known for the InAs-system, so we restrict ourselves to giving the experimental result. In our experiments, the factor is of the order of 6 μeV T^{-2} which has to be compared with a future theoretical calculation.

In spite of different attempts, no complete theoretical description of the mechanisms that suppress CR splittings on previously studied 2DES could be developed to date. MacDonald and Kallin recently used a generalized single-mode approximation [21] to investigate the CR of a 2DES. In their model two of three possible resonances hybridize if the electron-electron interaction is sufficiently large. Even then, the spin-splittting should remain observable. A different kind of hybridization of distinct CR transitions in a 2DES has been found by Stallhofer and coworkers [22] in studies of (100)-Si with two different valleys occupied by the application of stress. To explain these findings, Appel and Overhauser [23] studied the electron-electron interaction in a two-component plasma. Basically, they expect hybridization of the two CR transitions when $\tau_e \ll \tau$, where τ_e denotes the electron-electron scattering time and τ is the Drude relaxation time. Alternatively, Takada and Ando [24] used Landau´s Fermi-liquid theory to demonstrate hybridizytion of distinct CR-peaks in the limit of strong electron-electron interaction.

All the CR-splittings we observe can be described in the straightforward single-particle picture laid out above. However certain types of samples, like the high-mobility one (C), show a single CR-line. This is surprising since this sample has the smallest CR-linewidth. This situation resembles the hybridization observed on high mobility GaAs/AlGaAs-heterostructures. Obviously, there are two regimes: one where the CR-spectrum of the 2DES is single particle-like as already observed on 3D-systems and another where CR-modes hybridize by some interaction which cannot be described theoretically to date. It is still unclear what parameters of a 2DES constitute the hidden critera that separate the two regimes. One might speculate that the electron mobility is just a signature of the underlying fundamental mechanism.

Recently, two groups have reported splittings of the CR in a 2DES on GaAs in the extreme quantum limit that are surprisingly close to the one expected for spin-splitting [25,26] though interpreted in terms of Wigner crystallization. Warburton [27] has reported spin splitting on high mobility GaAs/AlGaAs-heterostructures at filling factors smaller than 1/6. The fundamental problem of CR-hybridization in two-dimensional systems is of great current interest. Both, further theoretical and experimental work is highly desirable to solve this puzle.

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