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The effect of Landau quantization on cyclotron resonance in a non-parabolic quantum well

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Abstract. Electron cyclotron resonance is studied in very deep quantum wells consisting of InAs between AlSb barriers. High electron mobility and strong conduction band non-parabolicity together with the small effective mass and the large effective g factor of this material enable us to observe simultaneous cyclotron transitions between adjacent sets of spin–split Landau states. Our experiments resolve spin-conserving transitions involving two or three different Landau levels depending on the filling factor. The results are compatible with a single-particle model.

1. Introduction

Quantum wells consisting of epitaxial layers of AlSb and InAs are characterized by unusually high confinement energies (≈ 1.3 eV), high carrier densities (10^{12} cm^{-2}) and relatively high electron mobilities (600 000 cm^2 V^{-1} s^{-1}). The electronic properties make the system a promising candidate for transistor applications. Moreover, the small effective mass of the active layer InAs yields high quantization energies which make attractive electro-optical applications such as tunable detectors based on resonant quantum effects. To exploit such mechanisms it is necessary to take into account the effects of band non-parabolicity which has a much stronger influence in InAs quantum wells than in the widely used GaAs/GaAlAs systems.

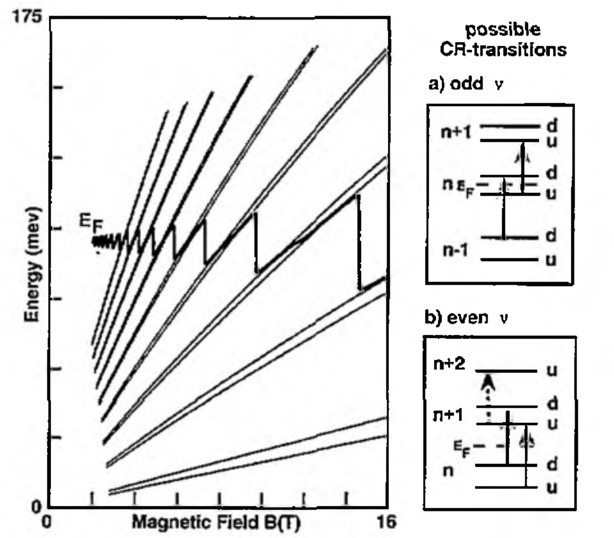

Figure 1. Nonlinear Landau fan chart obtained using our straightforward single-particle model including band non-parabolicity as described in the text. To calculate this fan chart and the corresponding Fermi level, we used a quantum well width $W = 12.5$ nm and a carrier density $n_s = 1.4 \times 10^{12}$ cm^{-2}. The energy of the lowest subband is $E_1 = 60$ meV. Non-parabolicity and nonlinear Zeeman splitting principally allow up to three energetically different simultaneous CR transitions, some of which are sketched in the boxes (a) and (b).

2. Cyclotron resonance

In a magnetic field perpendicular to the plane of a two-dimensional electron system (2DES) the electronic states in each subband are quantized in a ladder of Landau levels (LL). Figure 1 shows nine LLs of the lowest subband as a function of the magnetic field. The Fermi energy E_F determines which levels are populated at a given magnetic field. The two boxes depict the possible spin-conserving cyclotron resonance (CR) transitions at odd filling factors ν (a) and even ones (b). With a non-parabolic dispersion one type of CR splitting ('Δm^* splitting') is expected around odd-integer filling factors, as the energy dependence of the effective mass induced by conduction band non-parabolicity makes the energy separation of Landau levels $(n-1)$ and (n) larger than that of LL (n) and $(n+1)$. In the vicinity of even filling factors a somewhat smaller 'Δg splitting' of the CR is expected. This is caused by the energy dependence of the effective g factor making the Zeeman splitting of the nth LL larger than that of the $(n + 1)$th LL. Hence, the two spin-conserving transitions between adjacent pairs of Landau levels occur at different frequencies [1, 2]

In three-dimensional electron systems like, for example, bulk GaAs such splitting has, in fact, been observed [3, 4] and is well understood [5, 6]. In 2DES, however, such splittings have not been observed previously in spite of many different attempts [5 and references therein]. To prevent line broadening hiding the effect Watts and co-workers [7] narrowed the CR linewidth significantly by depositing gold layers on a GaAs/GaAlAs heterostructure to prevent saturation of the CR. Even though the spin splitting is expected to be much larger than the observed linewidth, no such structure was found.

3. Experiments

Here, we report on the unambiguous observation of both the Δm^* and the Δg splitting of the CR in a 2DES. Surprisingly, our results can be explained by a straightforward single-particle model. We investigate the 2DES in InAs quantum wells with AlSb barriers, forming a type-II staggered heterojunction. Due to the low effective mass of InAs ($m_\Gamma^* = 0.023m_0$) and the high bulk InAs effective g factor ($g \approx -15$) both the cyclotron energy $\hbar\omega_c$ and the Zeeman splitting $\Delta E = g\mu_B B$ are expected to be significantly higher than in GaAs. Also, the conduction band non-parabolicity is larger in InAs, increasing the separation of the expected transitions. The samples are grown on semi-insulating GaAs substrates by molecular beam epitaxy. The growth sequence is described in detail elsewhere [8]. The quantum well on which the data presented here have been measured is 12 nm wide, the 2D carrier density is $n_s = 1.41 \times 10^{12}\,\mathrm{cm}^{-2}$ as determined by Shubnikov–de Haas measurements.

The far-infrared spectra are measured with a rapid-scan Fourier transform spectrometer connected to a low-temperature cryostat containing a 15 T superconducting solenoid. We measure the relative change in transmission $-\Delta T/T = (T(0) - T(B))/T(0)$ where $T(0)$ denotes the transmission of the sample at zero magnetic field, $T(B)$ the one at finite B normal to the hetero-interface. Figure 2 shows typical spectra for different magnetic fields. Traces closest to an integer filling factor are marked by the inset boxes. The CR traces distinctly show a splitting around both integer filling factors in the depicted magnetic field range. As the magnetic field is varied, the two parts of the split resonance exchange oscillator strength. Around $B = 7.2$ T, just above $\nu = 8$ in this case, even three resonances can be detected. A qualitatively similar splitting occurs near all integer filling factors up to $\nu = 13$ and down to $\nu = 3$, the lowest one in the available magnetic field range. This splitting is larger close to an odd filling factor than to even filling factors.

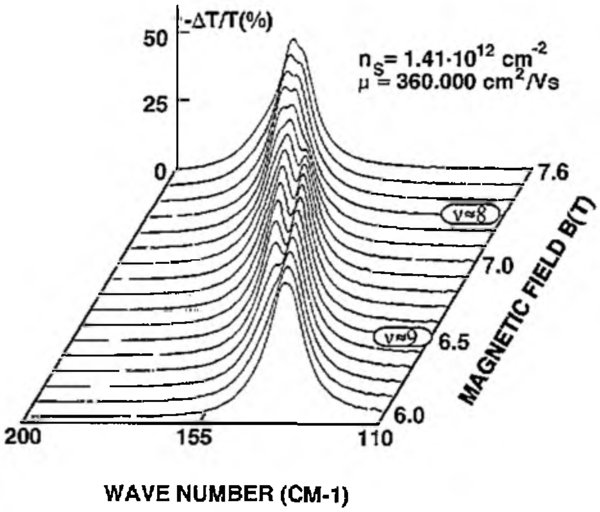

Figure 2. Typical CR spectra as functions of the magnetic field B. Traces closest to an integer filling factor ν are marked by the inset boxes. Two types of splitting are observed, one being larger close to odd filling factors ('Δm^* splitting'), and a smaller splitting ('Δg splitting') close to even filling factors. As the magnetic field is varied, the two parts of the split resonances exchange oscillator strength.

The sample presented here and other samples showing similar splittings have mobilities in the range of $\mu \leq 40\,\mathrm{m^2\,V^{-1}\,s^{-1}}$ at 4 K. On early samples with low electron mobilities ($\mu \leq 10\,\mathrm{m^2\,V^{-1}\,s^{-1}}$) instead of splittings we observe strong oscillations of the CR absorption depth, the CR linewidth, and the cyclotron mass as a function of the magnetic field similar to those reported in [9]. Such oscillations have often been explained in terms of filling-factor-dependent screening [10]. In a recent publication we, too, related these oscillations to screening effects [11]. Improvement of the sample quality, however, led us to discover the split CR. Therefore, we now believe that the oscillations of the CR amplitude and linewidth could show an onset of the splitting caused by non-parabolicity. Such an alternative explanation of the linewidth oscillation had been proposed earlier by Hansen and Hansen [12].

4. Model

To explain the observed splittings quantitatively, we employ a simple single-particle model, including the conduction band non-parabolicity in terms of the well known $\boldsymbol{k}\cdot\boldsymbol{p}$ formalism as introduced by Kane [13]. In a simplified form, this leads to an expression for the energy dependence of the effective mass

$$m^*(E) = m_\Gamma^*\left(1 + 2\frac{E}{E_G}\right). \qquad (1)$$

Here $m_\Gamma^* = 0.023m_0$ denotes the band-edge mass of InAs,

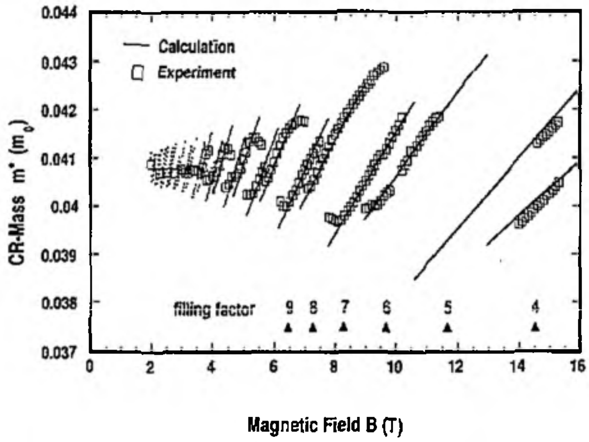

Figure 3. Cyclotron mass as a function of the magnetic field. The lines represent calculated transitions possible according to figure 1. The squares represent the experimental data.

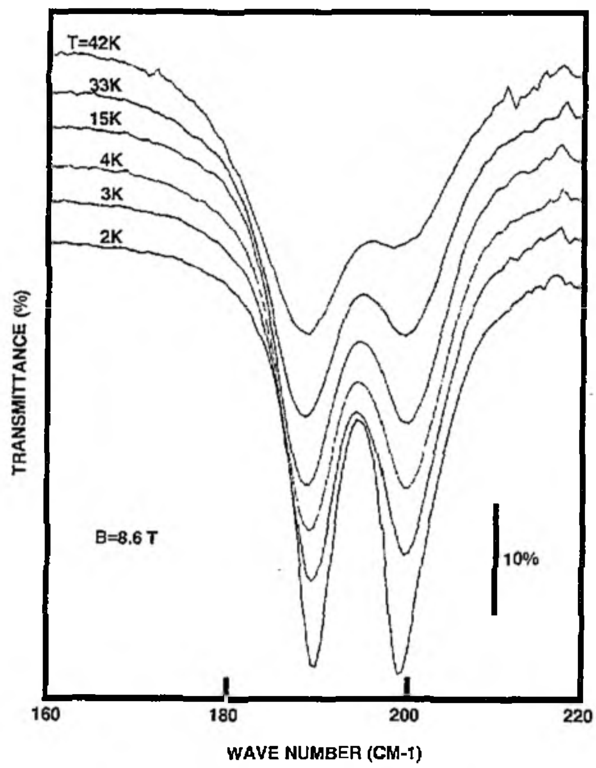

Figure 4. Split cyclotron resonance at a fixed magnetic field close to $\nu = 7$ at different temperatures. The temperature effect on the oscillator strength is more pronounced for the high-energy component of the split resonance as explained by a bleaching due to the modified Landau level population.

$E_G = 400$ meV the InAs bandgap energy and $E = E_1 + E_F$ the sum of the ground state energy E_1 of the quantum well and the Fermi level of the system. The quantum well is modelled by an infinitely deep rectangular confining potential with energy eigenvalues of the well known form $E_i = E_1 i^2$. With only the lowest subband occupied the Fermi level enters the calculation as $E_F = n_s \pi^2 \hbar^2 / 2m^*(E)$. Combining equation (1) and the expressions for E_1 and E_F then allows us to analytically calculate the n_s dependence of the effective mass, the subband energies and the Fermi level. Then it is quite straightforward to derive the eigenenergies $E = E_{1,n}$ (n being the Landau index) in the presence of a magnetic field [14]. The non-parabolicity of the Zeeman splitting $\Delta E = \pm\frac{1}{2}g\mu B$ is included via an energy-dependent effective g factor of the form $g = g_0(1 + \alpha E)$ where E denotes the energy of the nth Landau level above the conduction band edge [2–4, 15].

From the fan chart the expected CR transitions starting from a partially filled LL at the Fermi energy can be calculated. Instead of comparing these calculated CR positions with the experimental observations, it is more elucidating to plot the CR masses, defined by $m^* = e\hbar B/\Delta E_{CR}$ and $m^* = eB/\omega_c$, respectively. The result is shown in figure 3, where we display the CR masses versus magnetic field. The full lines represent the possible transitions according to our model. To keep the model simple we did not 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 our data is obtained using $g_0 = -15$, the InAs bulk value, and $\alpha = 2.25 \times 10^{-3}$ meV^{-1}. The amount of the Δg splitting depends quadratically on the magnetic field within the accuracy of our measurement.

5. Temperature dependence

To test our model we also performed temperature-dependent measurements as shown in figure 4. The magnetic field ($B = 8.6$ T) is chosen to observe a Δm^* split CR with approximately equal oscillator strengths close to filling factor 7. As the temperature is increased the lines broaden and the resonance depth decreases but the high-energy component of the split resonance loses oscillator strength much faster than the low-energy one. At the highest temperature available ($T = 42$ K) the high-energy resonance becomes a shoulder on the broadened CR. This behaviour is qualitatively compatible with our picture as shown in figure 1(a). Close to the odd filling factor, the Fermi energy is located between the levels 4_{up} and 4_{down}. The transition between Landau levels $3_{down} \rightarrow 4_{down}$ occurs at a higher energy than $4_{up} \rightarrow 5_{up}$. By increasing the temperature, the Fermi distribution is softened so the population of level 4_{down} is increased, weakening the oscillator strength of the corresponding transition. The effect on the population of level 5_{up} is much weaker since it is separated from the Fermi energy by a larger amount. A quantitative analysis, however, is not yet incorporated in our simple model.

6. Summary

We observe both spin and Landau splitting of the cyclotron resonance in a non-parabolic two-dimensional electron system on InAs/AlSb quantum wells. Although these splittings are expected in terms of Landau quantization and non-parabolicity and have been observed on many three-dimensional electron systems, previous investigations on 2DES did not show any sign of such a splitting of the cyclotron resonance. Obviously, the lack of splitting cannot be a consequence of the reduced dimensionality alone and the theoretical concepts are not complete to date. More detailed studies of the conditions under which splittings of the CR become visible promise clues for understanding the fundamental problem of the commonly observed mode hybridization.

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