Cyclotron resonance of electron-hole systems in InAs/GaSb/AlSb

R.J Warburton, B Brar, C Gauer, Achim Wixforth, Jörg P. Kotthaus, H Kroemer

Angaben zur Veröffentlichung / Publication details:

Warburton, R.J, B Brar, C Gauer, Achim Wixforth, Jörg P. Kotthaus, and H Kroemer. 1996. "Cyclotron resonance of electron-hole systems in InAs/GaSb/AlSb." *Solid-State Electronics* 40 (1-8): 679–82. https://doi.org/10.1016/0038-1101(95)00385-1.

CYCLOTRON RESONANCE OF ELECTRON–HOLE SYSTEMS IN InAs/GaSb/AlSb

R. J. WARBURTON[1], B. BRAR[2], C. GAUER[1], A. WIXFORTH[1], J. P. KOTTHAUS[1] and H. KROEMER[2]

[1]Sektion Physik der Ludwig-Maximilians-Universität München, Geschwister-Scholl-Platz 1, 80539 München, Germany

[2]Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, U.S.A.

Abstract—We present cyclotron resonance measurements on electron–hole systems in the crossed gap system InAs/GaSb with additional confinement from AlSb barriers. A large, ~ 2.5 meV, splitting has been observed in the electron cyclotron resonance when holes are also present. We focus on the pronounced filling factor dependence of the effect to argue that we have a nonparabolicity-induced splitting, enhanced through an additional energy dependence of the g factor. This enhancement could be caused by a spin-orbit effect, with the holes apparently allowing the two transitions to be observed through a decoupling of the two cyclotron resonance transitions.

The InAs/GaSb system has a remarkable crossed band-lineup[1] which allows the generation of both electron and hole gases confined on the InAs- and GaSb-side of the interface, respectively. One has therefore a semi-metal with a large degree of tunability for studies of carrier–carrier interactions in two-dimensions. Notable are experiments[2] aimed at resolving a very long standing controversy concerning the possibility of an excitonic groundstate at low density[3]. In this paper, we report cyclotron resonance (CR) measurements on an InAs/GaSb system with additional confinement from AlSb barriers. The main effect is the appearance of an unexpectedly large splitting in the electron cyclotron resonance when holes are present. We do not find any compelling evidence for an excitonic groundstate; instead we focus on the filling factor dependence to argue for an explanation in terms of the single particle band structure. We comment on the role of the holes. As such, the results offer some insights into as yet unresolved issues in the CR of two-dimensional systems.

The samples, grown by MBE on GaAs substrates, consist of an AlSb buffer, 150 Å GaSb and 150 Å InAs active layers, a 300 Å AlSb barrier, and 50 Å GaSb and 30 Å InAs cap layers. We present data here from two samples, which we label p^+ and n^+. The p^+ (n^+) is modulation doped p- (n-) type in the AlSb barrier on the GaSb (InAs) side of the device. We have determined the carrier concentrations and mobilities at low magnetic field B from the classical Hall effect (Fig. 1), yielding the values as listed in Table 1. For the p^+ sample we have the unusual case that the hole density, p, is considerably higher than the electron density, n. Hole CR confirmed the transport density and mobility, and gave also the rather large effective mass, $0.48m_0$, a consequence of the large hole concentration in this sample. The heavy doping in the n^+ sample precludes the confinement of any holes. We can reproduce the carrier concentrations reasonably well from self-consistent calculations by incorporating the surface pinning of the Fermi energy ~ 80 meV above the InAs conduction band edge.

Electron CR on the n^+ sample gives a single line with a width and absorption which correspond well to the sample mobility and density. The effective mass, m^*, of $0.0476m_0$ is somewhat higher than that of an InAs/AlSb quantum well[4] with equal density ($0.0444m_0$), but otherwise there are no anomalies. Notably, in contrast to Ref.[5], there are no oscillations in the linewidth as a function of magnetic field. These results correspond in essence to the standard for two-dimensional systems in the integral quantum Hall regime[6]. At each filling factor ν there are three single particle CR transitions, but they are coupled by electron–electron interactions into a single line[7–9]. Conversely, the p^+ sample exhibits a radically different behaviour (Fig. 2): we do observe a splitting, with an exchange of oscillator strength, up to a magnetic field of ~ 7 T. Figure 3 shows how all the CR parameters (effective mass, linewidth and absorption) correlate with the *electronic* filling factor which can be deduced either from the n of the low-B Hall measurements or from weak electron Shubnikov-de Haas oscillations in the resistance. Note particularly the oscillations in the effective mass which persist to $\nu \sim 14$. Above 7 T, we have just a single line. At these high magnetic fields we can also observe the hole Shubnikov-de Haas oscillations (Fig. 1) which give a hole concentration reduced from the low field value. Assuming then that $p - n$ remains constant, this implies that n has also reduced, so that

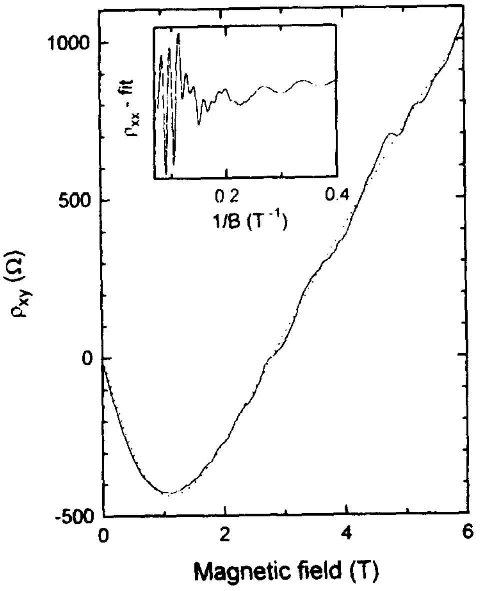

Fig. 1. The Hall resistance, ρ_{xy}, is plotted for the p^+ sample, along with the two-carrier fit (dotted). The inset shows the diagonal resistance, ρ_{xx}, with the sharp rise at low field subtracted, showing two Shubnikov-de Haas periods, one from the holes and one from the electrons.

7 T is probably closer to $\nu = 2$ than $\nu = 4$. Experiments on other samples, and also on the p^+ with altered densities (achieved by etching away the InAs cap), confirm these results: we have a large splitting in the electron CR, correlating with the electronic filling factor, only when holes are present and when the electronic filling factor is larger than ~ 2.

Similar results have recently been published on InAs/AlGaSb heterostructures[2], with the claim that the upper resonance corresponds to the $1s - 2p_+$ transition of a magnetic-field stabilized exciton, and

Table 1. The sample parameters. The electron and hole carrier concentrations n and p are in units of 10^{11} cm^{-2}, and the corresponding mobilities μ_e and μ_h are in cm^2 V^{-1}s^{-1}

	n	p	μ_e	μ_p
n^+	21.5	0	70,000	—
p^+	6.6	33	51,000	1800

that the lower resonance is conventional CR. This picture offers an explanation of the splitting, and also in our case of the disappearance of "CR" at $B > 7$ T when, supposedly, all the free electrons bind into excitons. However, we cannot support this hypothesis. In fact, the change of the carrier concentrations is more simply interpreted in terms of Landau level crossings between the electron and hole Landau levels[10]. Furthermore, on increasing the temperature we do not see an activated behaviour (in contrast to Ref.[2]) which would correspond to the thermal dissociation of excitons; instead, we observe simply a thermal broadening. Also, the overwhelming excess of holes over electrons must lead to a drastic reduction in exciton binding energy, as can be judged from the disappearance of excitonic effects in the optical spectra of doped quantum wells[11]. We cannot therefore accommodate a binding energy of 4–5 meV as our low temperature optical data would predict.

Instead, we focus on the pronounced filling factor dependence of Fig. 3. This is entirely reminiscent of the CR data of Scriba *et al.*[9] on InAs/AlSb quantum wells where, for reasons that have never been clarified, the hybridization was lifted in a few samples so that the single particle transitions were observed. The filling factor dependence is then a natural consequence of the changing level occupancies. At odd (even) ν one has the so-called Δm (Δg) splitting,

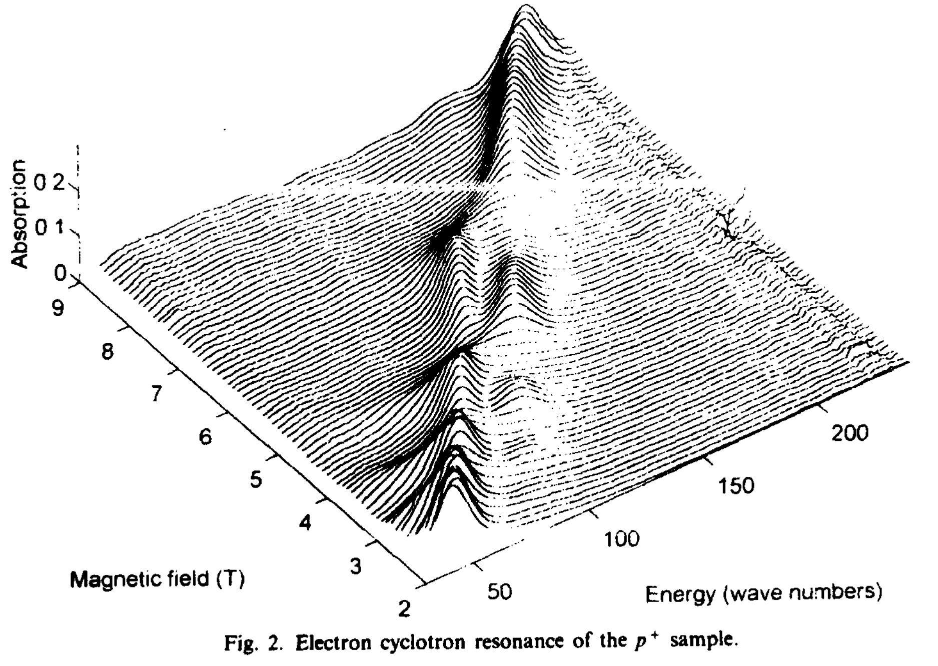

Fig. 2. Electron cyclotron resonance of the p^+ sample.

arising from the energy dependence of the effective mass (g factor). We propose that the origin of the splitting in the p^+ CR lies in a resolution of the single particle Δm splitting. This assertion is further supported by measurements in a tilted magnetic field where we can also observe the Δg splitting (which, incidentally, is very hard to accommodate into the exciton picture). However, two questions pose themselves immediately. Why is the splitting so large, some 2.5 meV? (Scriba has $\sim$0.9 meV for the same n at $\nu = 5$). And, what roles do the holes play? We make the following observations.

The Δm splitting corresponds to two CR transitions with opposite spin and so can be enhanced by an energy dependence of the g factor additional to that arising from ordinary band nonparabolicity. It is not impossible that a many body effect is at work, but we propose here a simpler alternative, namely, a spin-orbit effect through an electric field in the growth direction. This gives the so-called Rashba term[12] in the Hamiltonian, $a\sigma \cdot (K_{\parallel} \wedge E)$, and affects different Landau levels differently, as we require, because $k_{\parallel} \propto \sqrt{n}$, where n is the Landau level index. We have solved the Hamiltonian for an electron confined in a deep potential well including nonparabolicity and the Rashba term; the cyclotron resonance splittings are plotted in Fig. 4. It can be seen that $\alpha = aE_z \sim 3.0 \times 10^{-9}$ eV cm gives a tolerable description of the data, namely a splitting at odd ν close to $\sim$2.5 meV, not strongly dependent on ν, and a smaller splitting for even ν. This α is similar to the only existing measurement of 1×10^{-9} eVcm for InAs/GaSb structures[13], estimated from a beating in Shubnikov-de Haas experiments. Unfortunately, the matrix element a itself is not known, and it is also not clear how to calculate the electric field E_z.

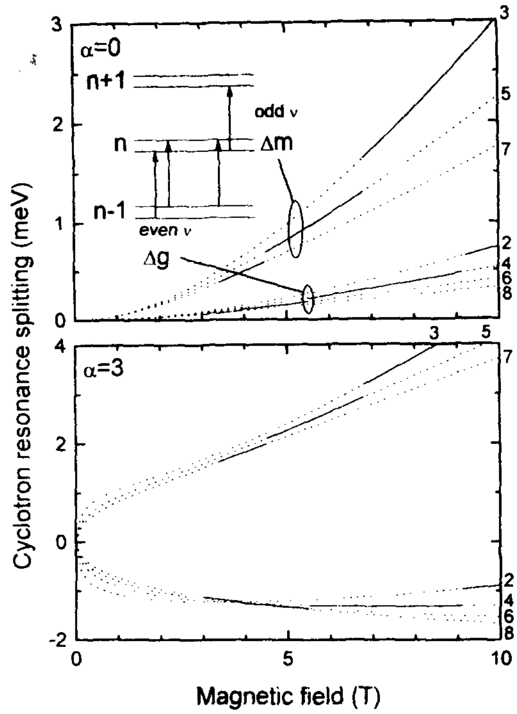

Fig. 4. The calculated cyclotron resonance splitting without the Rashba term (upper plot), and with the Rashba term (lower plot). The solid lines show the magnetic field range in which a particular resonance is observable (at zero temperature) according to the statistics for $n = 6.6 \times 10^{11}$ cm^{-2}, and each line is labelled with the filling factor at which the resonance is centred. α is a matrix element times an electric field in units of 10^{-9} eVcm.

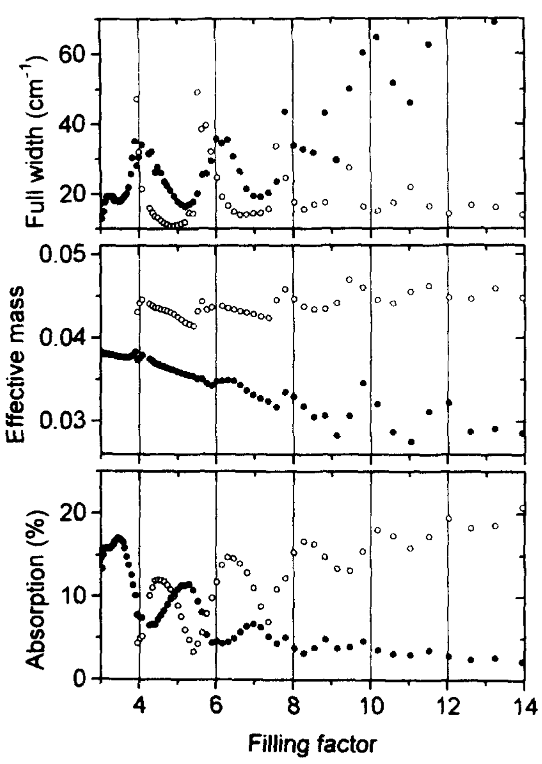

Fig. 3. Properties of the electron cyclotron resonance from the p^+ sample, as obtained by fitting the traces of Fig. 2 to two Lorentzians, plotted against the electronic filling factor (calculated from $n = 6.6 \times 10^{11}$ cm^{-2}). The filled (hollow) symbols refer to the higher (lower) energy mode.

Naturally, single particle splittings will exist also for the n^+ sample. It can be expected that the n^+ sample also has a non-zero net electric field in the growth direction, leading to an enhanced Δm splitting. However, we observe only a single line. This does not necessarily mean that the single particle splittings are small; rather, it implies that the various transitions are coupled. The puzzle is to explain why the single particle splittings are resolved for the p^+ sample. The experiments themselves point to the holes, suggesting that this adjacent sheet of mobile positive charge somehow lifts the coupling. Further experiments and theoretical analysis are required to resolve this crucial point.

To conclude, we have observed an unexpectedly large splitting in the cyclotron resonance of electrons in InAs/GaSb/AlSb structures when holes are also present. We argue against the formation of an exciton complex, and propose instead that we have a nonparabolicity-induced splitting enhanced by a strongly energy dependent g factor. It is shown how the

Rashba effect can lead to such a change in the g factor. The structures with holes allow the resolution of something akin to the single particle spectrum; without holes the single particle spectrum is obscured presumably by electron–electron interactions.

REFERENCES

1. see for e.g. L. L. Chang *et al.*, *J. Phys. Soc. Jap.* **49,** 997 (1980).
2. J.-P. Cheng *et al.*, *Phys. Rev. Lett.* **74,** 450 (1995).
3. B. I. Halperin and T. M. Rice, *Rev. Mod. Phys.* **40,** 755 (1968).
4. C. Gauer *et al.*, *Semicond. Sci. Technol.* **9,** 1580 (1994).
5. D. Heitmann *et al.*, *Phys. Rev. B* **34,** 7463 (1986).
6. M. Watts *et al.*, in *Proc. 20th ICPS*, Vol. 2, p. 1465 (1990).
7. A. H. MacDonald and C. Kallin, *Phys. Rev. B* **40,** 5795 (1989).
8. N. R. Cooper and J. T. Chalker, *Phys. Rev. Lett.* **72,** 2057 (1994).
9. J. Scriba *et al.*, *Solid St. Commun.* **86,** 633 (1993).
10. R. J. Nicholas *et al.*, *Physica B* **184,** 268 (1993).
11. see for e.g. S. Schmitt-Rink *et al.*, *Adv. Phys.* **39,** 89 (1989).
12. E. I. Rashba, *Sov. Physics-Solid St.* **2,** 1109 (1960).
13. J. Luo *et al.*, *Phys. Rev. B* **41,** 7685 (1990).