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LARGE CYCLOTRON-RESONANCE LINE SPLITTING OF TWO-DIMENSIONAL ELECTRONS IN AlGaN/GaN AND AlGaAs/GaAs HETEROSTRUCTURES

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Large cyclotron-resonance (CR) line splittings have been observed previously in two-dimensional (2D) electrons in AlGaN/GaN and in GaAs/AlGaAs heterojunctions. The features resemble a level anti-crossing and imply a strong interaction with an unknown excitation of the solid. The origin of this phenomenon remains unexplained. This paper reviews the existing data and presents some recently detected correlations of the splitting with other sample parameters.

Keywords: GaN; cyclotron resonance; two-dimensional electrons.

In 1984 Schlesinger *et al.* [1] made an astounding observation in the cyclotron resonance of high-mobility 2D electrons in AlGaAs/GaAs heterojunctions. These authors observed a well resolved splitting of the CR for samples covering a density range of n_{2D} ~1–4 x 10^{11}cm^{-2}. The line splitting had the appearance of a simple coupling to some other excitation of the solid but this was ruled out on the basis of several tests.

The critical energy, E_{crit} at which the splitting occurred in several samples showed a square-root dependence on 2D electron density, n_{2D}, suggesting an electron-electron interaction effect. Furthermore, line-broadening data on Si MOS-FETs [2] [3], when re-analyzed by Schlesinger *et al.* and plotted on the same graph showed very good overlap. While the silicon data never showed a splitting and were later reinterpreted as being due to electron localization [10], Schlesinger *et al.*'s observation in GaAs remain unexplained.

An *ad hoc* theoretical model by the authors provided a tentative interpretation of the data. According to this model the "other excitation" of the solid is – in some sense – the CR itself. Using a random-phase-approximation (RPA) the authors calculated the 2D magneto plasmon dispersion as function of in-plane wavevector, k. This dispersion starts with the CR at k=0, rises with increasing k, but returns towards the CR at a finite wavevector in the vicinity of $k \sim l_0$ (the magnetic length $l_0^2 = hc/eB$). (Today one would identify this feature as a magneto roton). If, as a function of B the energy of this feature in the magneto plasmon dispersion at finite k crosses the CR, then disorder could couple CR to this mode and produce the observed splitting. The universality of the data as well as the square-root of density dependence supported this model.

Since 1984, there had been no further reports on similar splittings in CR. However, theory progressed and today, we have a much better understanding of the magneto-plasmon dispersion. In particular, Kallin and Halperin [4] addressed its magnetic field-dependence. According to their calculation, performed in the limit of energy $\hbar\omega_c >> \mathrm{E}_c$, the magnetoroton minimum never approaches the CR energy but always exceeds it, see Fig. 1. Even if the magnetoroton were to cross the CR due to some higher order interaction it would do so "in the wrong direction": In theory, the roton minimum moves *down* in energy with decreasing B-field, in contrast to experiment, which requires the minimum to move *up*, as shown in Fig. 1.

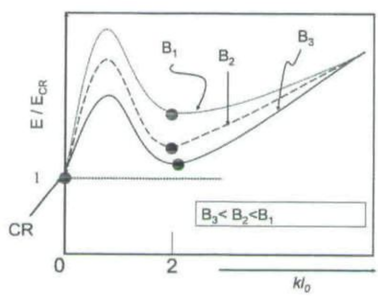

Fig. 1. Cartoon representing dispersions of a 2D magnetoplasmon at arbitrary B-fields. The vertical axis is energy normalized to the cyclotron resonance energy E_{CR}. The horizontal axis is a dimensionless wavevector kl_0, where k is the wavevector and l_0 is the magnetic length. The CR mode is at $k = 0$ and the minimum near $kl_0 \sim 2$ is the magnetoroton.

A calculation by MacDonald [5], which includes higher order effects arrives at similar conclusions. A recent calculation on interactions between magnetoplasmons by Cheng [6] asserts that the magnetoroton minimum actually *can* cross the CR energy. However, even if such crossing existed, its direction is again inconsistent with experiment. Oji and MacDonald [7] consider the case of arbitrary filling factors but find no particularly strong dependence of the roton minimum energy on ν. Gold's calculations [8], performed in the small-k limit can only account for a broadening but not for a splitting of the CR line. The calculations by Hu and O'Connell [9], also based on memory functions, remarkably, generate such a splitting. However, the center of gravity of the combined lines always resides above $\hbar\omega_c$ in conflict with experiment.

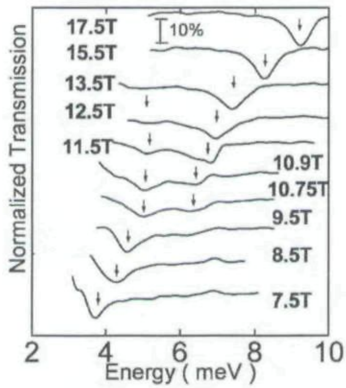

Fig. 2. Far infrared transmission data on a 2DES of density 1.14 x 10^{12} cm^{-2} in AlGaN/GaN for various magnetic fields, B, normal to the 2DES. All data are normalized to the transmission at B=0. Traces are offset vertically for clarity.

At this state of experiment and theory we discovered unexpectedly large splittings of the CR in the novel AlGaN/GaN system [11]. The splittings have all the characteristics of the earlier observation by Schlesinger et al. While many of the features are similar between the AlGaAs/GaAs and the AlGaN/GaN systems there are several decisive new findings that clearly demonstrate that we do not understand the origin of this unusual splitting. It is quite surprising that such a huge effect on one of the most fundamental excitations of a solid, the cyclotron resonance of electrons, remains so obscure.

All AlGaN/GaN samples were grown by plasma-assisted MBE on thick GaN ($\sim$15μm) templates prepared by hydride vapor phase epitaxy (HVPE) on the [0001] face of sapphire [12]. The typical MBE layer sequence consists of approximately 400nm of GaN, followed by a layer of 25 to 50nm thick $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$, which is then capped by a 3nm thick GaN layer.

All measurements were performed at 4.2 K. A Fourier transform spectrometer with standard light pipe optics was used in combination with a composite Si bolometer. Fig. 2 shows a representative set of transmission spectra in different magnetic fields. All spectra were normalized to the equivalent spectrum obtained at 0T.

For fields $B > 15$T and $B < 8$T singular sharp resonance dips are observed in transmission. They represent the characteristic CR of the electrons. These high and low field resonance positions are linearly dependent on B and are consistent with each other. They yield an effective mass of m^*=0.22m_e, very close to the literature value [15]. While the CR is well behaved in the high-field and low-field regimes it develops a clear splitting, at intermediate fields of 8T$< B <$ 15T.

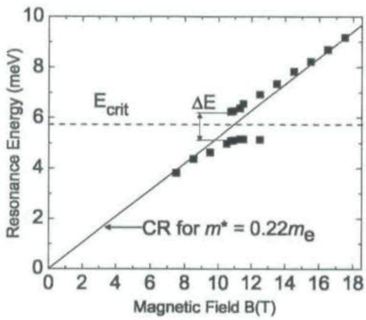

Fig. 3. Peak positions of transmission minima of Fig. 2 as a function of magnetic field. High and low field data follow the CR with an effective mass of m^*=0.22m_e. Around 11T an apparent level anti-crossing occurs with a critical energy E$_{crit}$=5.7meV, with the two branches separated by a gap of ΔE∼ 1.2 meV.

Fig. 3 shows the position of the resonance energies of Fig. 2 versus magnetic field. The solid line is a fit to the high and low field data. Between 10T and 14T the splitting of the CR is clearly visible. The two resonance branches are separated by a gap of ΔE∼ 1.2 meV. The midpoint of this gap resides at E$_{crit}$ ∼ 5.7 meV. The splitting resembles a level anti-crossing between the CR of the system and some other resonance at ∼ 5.7 meV. However, this "other resonance" is not observed outside of the crossing regime.

Similar strong splittings in the CR are observed in seven different samples and a distinct line broadening is observed in three other samples. Figure 4 shows the dependence of E$_{crit}$ on n_{2D}, for all 10 samples. A data point by Wang et. al. [16], who reported a broadening of the CR line is included. Its position indicates that the same phenomenon is at work. Other CR experiments on AlGaN/GaN heterostructures [15] [17] do not observe a broadening or splitting since they were performed on very high-density specimens in which the anticipated CR splitting exceeds the maximum field employed.

As in the work by Schlesinger et al. we can rule out several trivial crossings of the CR with other excitations of the system. Interaction with bulk or interface phonons cannot be the cause of the CR splitting, since the optical phonon energies are above 65 meV [18] [19]. A coincidence with the intersubband splitting can also be

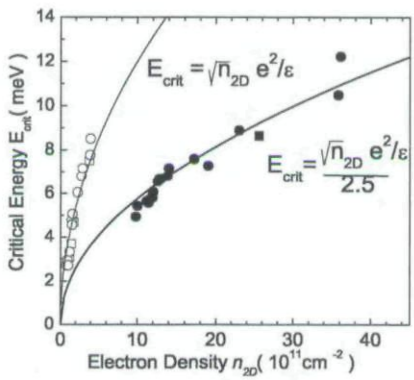

Fig. 4. Critical energy, E_{crit}, versus electron density. All AlGaN/GaN samples are shown plus data from runs in which the density had been increased (up to 30%) by light. The full square is an AlGaN/GaN specimen [16]. Open circles and open squares refer to AlGaAs/GaAs data [1] and Si data [2] [3] respectively. All follow a $\sqrt{n_{2D}}e^2/\varepsilon$ behavior, however with very different prefactors.

ruled out, since they exceed $\sim$ 23 meV [20] and since the splitting shows no angular dependence. Coincidence of opposite spin states in neighboring Landau levels [21], occur at $\theta \sim 77^0$. The observed splitting also cannot be due to a coupling to any 3D plasmon in any of the layers since there are much too few carriers in the bulk to reach energies of $\sim$6meV.

The critical energy in our CR data also seems to follow a $\sqrt{n_{2D}}$ dependence, similar to Schlesinger's work. From all these similarities we conclude that the splittings in AlGaN/GaN and in AlGaAs/GaAs have the same origin. However, our data refute the proposed simple relationship between n_{2D} and $E_{crit} = \sqrt{n_{2D}}e^2/\varepsilon$ for this phenomenon as well as universality across material systems. Fig. 4 includes the curve containing the MOSFET and AlGaAs/GaAs data from Ref. [1]. While these data follow a universal $\sqrt{n_{2D}}$ behavior, our data deviate from this relationship by a factor of $\sim$2.5. Obvious differences in ε and m^* between these materials cannot resolve the discrepancy.

Our data on large splittings in the CR of a 2DES in AlGaN/GaN have provided clear evidence for the existence of this unexplained phenomenon in a new material system. Its observation in an increasing group of 2DES strengthens the case for its universal existence and emphasizes the need to resolve the physical origin of such a large perturbation of the CR in 2D. At this stage we neither know the excitation that may be involved nor do we know the mechanism of coupling between CR and any such excitation. In an attempt to gain further experimental insight into this general phenomenon we returned to the AlGaAs/GaAs system, in which we had a set of samples with a large range of different parameters available to us.

We performed extensive CR measurements on a broad set of 2DES in modulation-doped AlGaAs/GaAs. The specimens consisted of quantum wells as well as single interfaces. Some wells were undoped others were doped with Si. Most specimens were grown on <100> surfaces, but one was grown on <110>. In most samples the electrons resided in GaAs but in one case 4% Al had been introduced. Set back of the modulation doping layer and thickness of the quantum wells varied as well. All samples were characterized in terms of electron density, n_{2D}, mobility, μ, SdH oscillations and CR.

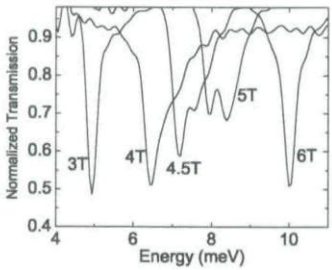

Fig. 5. Normalized transmission data of one of our AlGaAs/GaAs heterostructures. Resonance lines are single and sharp near 3 and 6T and a CR line splitting occurs near 5T.

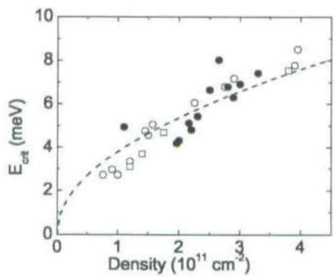

Fig. 6. Carrier density dependence of E_{crit} for all AlGaAs/GaAs samples studied (solid circles). Data from ref. 1,2,3 are plotted as open symbols for comparison. The dashed curve represents $E_{crit} = \sqrt{n_{2D}}e^2/\varepsilon$ with $\varepsilon = 12.9$.

Fig.5 shows typical CR data from one of the specimens. The expected splitting is well resolved and has the same characteristics as those observed previously in AlGaAs/GaAs and AlGaN/GaN. Extracting E_{crit} and combining all available data on AlGaAs/GaAs we arrive at Fig. 6. Generally, there is agreement between the data sets, although the scatter is appreciable.

Our aim was to extract some correlation between the CR splitting and any

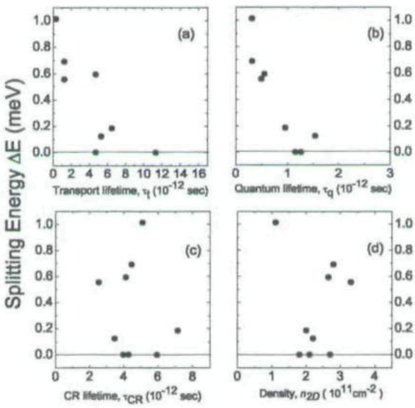

Fig. 7. (a) and (b) Magnitude of splitting ΔE of all samples plotted against transport and quantum lifetimes. Shorter lifetimes imply higher scattering rates. (c) and (d) Magnitude of splitting ΔE of all samples plotted against CR lifetime and carrier density.

other parameter of the samples in order to guide attempts to find an explanation for the origin of the splitting. Towards this end we show in Fig. 7 the magnitude of the splitting versus all other parameters that are known for all samples: transport lifetime τ_t, from mobility, quantum life, τ_q, from SdH, CR lifetime, τ_{CR}, from CR, and electron density, n_{2D}, from Hall measurements and SdH. The graphs contain considerable scatter, which may not be surprising to find in such a hodgepodge of 2DES specimens. There seems to be very little (if not no) correlation between ΔE and n_{2D} nor with CR lifetime. On the other hand, there seems to be a trend of decreasing ΔE with increasing transport lifetime, τ_t, and quantum lifetime, τ_q. In particular at low values of these parameters there is a stark increase in ΔE as either τ tends towards zero. If we accept this preliminary interpretation of Fig. 7 it would tell us that increased electron scattering increases the splitting, ΔE, of the CR line in the critical regime.

Increased electron scattering leads to a wider sampling of k-space away from k=0. A wider sampling leads to increased coupling between resonances at different points in k-space that otherwise would not couple at all. An increasing ΔE with increasing electron scattering indicates that increased coupling between resonances at different points in k-space is involved in the CR splitting.

If one accepts this interpretation of the data of Fig. 7 we would have learned an important fact about the unexplained splitting of the CR in 2DES. The excitation that couples to the CR resides at finite k, away from k=0. This observation supports an interpretation in terms of an extremum of the magneto plasmon dispersion, away from k=0, usually referred to as magneto roton. However, at this point there exists no convincing theory that results in a coincidence or can describe the correct motion of such a magnetoroton mode with B-field in order to explain the experimental data.

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References

1. Z. Schlesinger, S.J. Allen, Jr., J.C.M Hwang, P.M. Platzman, and N. Tzoar, *Phys. Rev. B* **30**, 435 (1984).
2. B.A. Wilson, S.J. Allen, Jr., and D.C. Tsui, *Phys. Rev. Lett.* **44**, 479 (1980);*Phys. Rev. B* **24**, 5887 (1981).
3. T.A. Kennedy, R.J. Wagner, B.D. McCombe, and D.C. Tsui, *Solid State Commun.* **21**, 459 (1977).
4. C. Kallin and B.I. Halperin, *Phys. Rev. B* **31**, 3635 (1985).
5. A.H. MacDonald,*J. Phys. C* **18**, 1003 (1985).
6. Szu-Cheng Cheng, *Phys. Rev. B* **49**, 4703 (1994).
7. H.C.A. Oji and A.H. MacDonald, *Phys. Rev. B* **33**, 3810 (1986).
8. A. Gold, *Phys. Rev. B* **41**, 3608 (1990).
9. G.Y. Hu and R.F. O'Connell, *Phys. Rev. B* **37**, 10391 (1988).
10. J.-P. Cheng and B.D. McCombe, *Phys. Rev. B* **44**, 3070 (1991).
11. S. Syed, M.J. Manfra, Y. J. Wang, H.L. Stormer, and R. J. Molnar, *Phys. Rev.* **B67**, 241304R (2003)
12. M.J. Manfra, L.N. Pfeiffer, K.W. West, H.L. Stormer, K.W. Baldwin, J.W.P. Hsu, D.V. Lang, and R.J. Molnar, *Appl. Phys. Lett.* **77**, 2888 (2000).
13. O. Ambacher, J. Smart, J.R. Shealy, N.G. Weimann, K. Chu, M.Murphy, W.J. Schaff, L.F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, *J. Appl. Phys.* **85**, 3222 (1999).
14. I. P. Smorchkova, C.R. Elsass, J.P. Ibbetson, R. Vetury, B. Heying, P.T, Fini, E. Haus, S.P. DenBaars, J.S. Speck, and U.K. Mishra, *J. Appl. Phys.* **86**, 4520 (1999).
15. W. Knap, H. Alause, J.M. Bluet, J. Camassel, J. Young, M. Asif Khan, Q. Chen, S. Huant, M. Shur, *Solid State Comm.* **99**, 195 (1996).
16. Y.J. Wang, R. Kaplan, H.K. Ng, K. Doverspike, D.K. Gaskill, T. Ikedo, I. Akasaki, H. Amono, *J. Appl. Phys.* **79**, 8007 (1996).
17. Z.-F. Li, W. Lu, S.C. Shen, S. Holland, C.M. Hu, D. Heitmann, B. Shen, and Y.D. Zheng, *Appl. Phys. Lett.* **80**, 431 (2002).
18. T. Azuhata, T. Sota, K. Suzuki, and S. Nakamura, *J. Phys.: Condens. Matter* **7**, L129 (1995).
19. J. Gleize, M. A. Renucci, J. Frandon, and F. Demangeot, *Phys. Rev. B* **60**, 15985 (1999).
20. L.Hsu and W.Walukiewicz,*Phys. Rev. B* **56**, 1520 (1997).
21. V.I. Fal'ko, *Phys. Rev. B* **46**, R4320 (1992).