Large Splitting of the Cyclotron-Resonance Line in AlGaN/GaN Heterostructures

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Ever since its first demonstration in 1953[1], cyclotron resonance (CR) has become the most widely used technique to determine effective masses of carriers in semiconductors and their heterojunctions. In the presence of an external magnetic field, an RF or far infra-red source is swept from 1 to 4 × 10^{12} cm^{-2} over wide ranges of magnetic field. The features resemble a level anti-crossing and imply a strong interaction with an unknown excitation of the solid. The critical energy of the splitting varies from 5 to 12 meV and as √n_{2D}. The phenomenon resembles data from AlGaAs/GaAs whose origin remains unresolved. It highlights a lack of basic understanding of a very elementary resonance in solids.

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For AlGaN/GaN heterostructures there exist only few CR data. Our study of CR in two-dimensional electron systems (2DESs) in a sequence of high-quality AlGaN/GaN structures with a wide range of carrier densities (1 - 4 × 10^{12} cm^{-2}) reveals splittings in the CR line reminiscent of level anti-crossings, reaching 20% of the resonance energy. While their origin is not established, they resemble splittings seen previously in the CR of AlGaAs/GaAs and Si systems. Our data do not support a universal ad-hoc model put forward in the AlGaAs/GaAs work and points to the lack of a theoretical understanding of this phenomenon, now seen in three different 2D systems.

Our AlGaN/GaN samples are grown by plasma-assisted MBE on thick GaN (∼15μm) templates prepared by hydride vapor phase epitaxy (HVPE) on the [0001] face of sapphire. The use of thick HVPE grown templates is essential for achieving low threading dislocation densities in the GaN buffer region. The reduction of the threading dislocation density has been shown to improve low temperature mobility at low electron densities. The typical MBE layer sequence consists of 400nm of GaN, followed by a layer of 25 to 50nm Al_{x}Ga_{1-x}N, which is capped by 3nm of GaN. In contrast to the AlGaAs/GaAs system, nitride heterostructures are not modulation doped. The creation of a 2DES rather originates from strong spontaneous and piezoelectric fields arising at the heterointerface. The Al mole fraction and the thickness of the barrier layer control the 2D electron density. In our samples the Al content varies from 3 to 10%, yielding the parameters listed in Table I. Samples with n_{2D} ∼ 1 - 3 × 10^{12} cm^{-2} show the integer and the fractional quantum Hall effects, further attesting to the high quality of the material.

All cyclotron resonance measurements were performed at 4.2 K. A Fourier transform spectrometer with light pipe optics was used in combination with a composite Si bolometer for the detection of the far-infrared (FIR) magneto-transmission. The backsides of samples 3,5,8, and 10 were wedged to reduce Fabry-Perot interferences. The B-field was applied normal to the 2D layer and the density of the 2DES was determined in situ via the Shubnikov-de Haas effect. The electron densities in samples 1-6 could be persistently increased (up to 30%) through illuminations with a blue LED for 20 - 60 seconds.

Fig. 1a shows a representative set of transmission spectra for sample 3 in different magnetic fields. All spectra are taken with 0.24 meV resolution and are normalized to the spectrum obtained at 0T. For clarity the data are vertically offset. For fields B > 15T and B < 8T singular
sharp resonance dips are observed in transmission. They represent the characteristic CR of the electrons. The 2D nature of the carrier motion is verified by observing the expected $1/\cos \theta$ shift of the resonances under tilted $B$ field. These high and low field resonance positions are linearly dependent on $B$, are consistent with each other, and yield an electron effective mass of $m^* = 0.22 m_e$. Around 11T an apparent level anti-crossing occurs with a critical energy $E_{\text{crit}} = 5.6$ meV.

Together with the appearance of a second resonance for each magnetic field. The two resonance branches are separated by a gap, $\Delta E$, of $\sim 1.2$ meV. The midpoint of this gap, $E_{\text{crit}}$, is $\sim 5.6$ meV. The splitting resembles a level anti-crossing between the CR of the system and some other resonance at $\sim 5.6$ meV. However, this “other resonance” is not observed outside of the crossing regime. In particular, it is not optically active at $B = 0$.

A clear splitting in the CR is observed in seven different samples and a distinct line broadening is observed in three others. Figure 2 shows the dependence of $E_{\text{crit}}$ and $\Delta E$ on the 2D density, $n_{2D}$, for all 10 samples. For specimens in which the splitting is not resolved, we take $E_{\text{crit}}$ as the energy of the maximally broadened line. The density dependence of the CR splitting, considering the scatter of the data, is approximately constant, $\Delta E \sim 1.5$ meV. Beyond our own data, Wang et al. [3] reported a broadening of the transmission dip near 8.6 meV. We obtained this specimen, determined its density and included these data in our graph. Their position indicates that the same phenomenon is at work. Other CR experiments on AlGaN/GaN heterostructures do not observe a splitting nor a broadening [4, 5, 6]. These experiments were performed on low mobility and very high-density specimens ($\sim 3.1 \times 10^{12} < n_{2D} < \sim 18 \times 10^{12}$ cm$^{-2}$). Judging from Fig. 2, the level anti-crossing position in most of these experiments exceeded the maximum field employed. In others the splitting may have been missed because of much wider CR line-widths and sparse data sets.

The splitting of the CR line in our samples appears to be the result of the coupling of the 2DES CR with another resonance of the system with an energy in the 5-12 meV range. Interaction between the 2D electrons and bulk or interface phonons cannot be the cause of the CR splitting since all optical phonon energies in AlGaN/GaN are above 65 meV [11, 12]. The common splitting due to a coincidence of the CR with the intersubband separation of the 2DES can also be ruled out: (a) the calculated subband separation is $\sim 23$ meV for $n_{2D} \sim 1 \times 10^{12}$ cm$^{-2}$ [13], which is much bigger than the observed $\sim 6$ meV; (b) such interaction occurs only at finite angles, whereas we observe the splitting for $\theta = 0^\circ$ and find no observable angular dependence. We can also safely rule out a coincidence of opposite spin states in neighboring Landau levels [13]. For our material system such a coincidence would occur for $\theta \sim 77^\circ$. The observed splitting cannot be due to a coupling of the 2DES with any 3D plasmon in any of the layers since there are very few carriers in the bulk. For example, for $n_{2D} \sim 1 \times 10^{12}$ cm$^{-2}$, the splitting occurs near 6 meV which requires a carrier density of $\sim 10^{17}$ cm$^{-3}$ in a 3D plasmon, whereas C-V measurements of the bulk set those densities to $< \sim 5 \times 10^{14}$ cm$^{-3}$ [3].

The closest resemblance to our observations is found in a previous report by Schlesinger et al. [12] who observed low-energy splittings in the CR of AlGaN/GaN heterostructures covering a density range of $1 - 4 \times 10^{11}$ cm$^{-2}$.  

![FIG. 1: (a) Far infrared transmission data on a 2DES of density $1.14 \times 10^{12}$ cm$^{-2}$ in AlGaN/GaN (sample 3) 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. A 10% transmission loss is indicated as a vertical bar. Sharp CR lines are observed for $B < 9$T and $B > 15$T. In the intermediate field regime large splittings occur. (b) Peak positions of transmission minima of (a) as a function of magnetic field. High and low field data follow the CR with an effective mass of $m^* = 0.22 m_e$. Around 11T an apparent level anti-crossing occurs with a critical energy $E_{\text{crit}} = 5.6$ meV.](image)
TABLE I: Parameters of all AlGaN/GaN 2DES samples used in our experiments. \( n_{2D} \) in units of \( 10^{11} \text{cm}^{-2} \) and the mobility, \( \mu \), in \( 10^3 \text{cm}^2/\text{Vs} \). \( E_{\text{crit}} \) and \( \Delta E \) are in meV. The values in parentheses are estimated from deconvolutions.

| # | \( n_{2D} \) | \( \mu \) | \( E_{\text{crit}} \) | \( \Delta E \) | # | \( n_{2D} \) | \( \mu \) | \( E_{\text{crit}} \) | \( \Delta E \) |
|---|------|------|--------|--------|---|------|------|--------|--------|
| 1 | 9.8  | 16   | 4.9    | 1.6    | 6  | 12.6 | 17   | 6.5    | 1.3    |
| 2 | 11.2 | 15   | 5.6    | 1.7    | 7  | 19.0 | 16   | 7.3    | (0.8)  |
| 3 | 11.4 | 16   | 5.6    | 1.2    | 8  | 23.0 | 18   | 8.9    | 1.7    |
| 4 | 11.9 | 20   | 5.8    | 1.7    | 9  | 35.8 | 8    | 10.4   | (1.6)  |
| 5 | 12.3 | 18   | 6.1    | 1.4    | 10 | 36.1 | 19   | 12.2   | (2.0)  |

Their data remain unexplained (e.g. Ref. [16]). Several observations of Ref. [16] are similar to ours: (a) the CR splitting is not affected by small tilt angles, (b) no absorption is seen in the \( B = 0 \text{T} \) spectrum at the critical energy, (c) at the critical \( B \)-field two resonances of roughly equal width and strength appear, and (d) the energy, \( E_{\text{crit}} \), at which a broadening/splitting is observed is proportional to \( \sqrt{n_{2D}} \) (see Fig. 2). While the similarities in these observations suggest a common origin of the CR splittings in AlGaAs/GaAs and our AlGaN/GaN interface, there are some differences. In AlGaAs/GaAs heterostructures the splitting appears “abruptly” whereas our AlGaN/GaN data show a gradual evolution of the splitting. Moreover, the separation between the split lines at the critical \( B \)-field is \( \sim 5\% \) of the CR energy in the AlGaAs/GaAs case, much smaller than the \( \sim 20\% \) seen in our AlGaN/GaN heterostructures.

The most important difference is a pronounced deviation of our data from a universality proposed by Ref. [18]. By including previous results of Wilson et al. [17] and Kennedy et al. [15] on CR line broadening in Si, Schlesinger et al. infer that the critical energy follows a universal relationship \( E_{\text{crit}} = \sqrt{n_{2D} e^2/\epsilon} \), where \( \epsilon \) is the dielectric constant. While our data also seem to follow a \( \sqrt{n_{2D}} \) dependence they deviate by a factor of \( \sim 2.5 \) from the AlGaAs/GaAs and Si case (see Fig. 2). Obvious differences in \( \epsilon \) and \( m^* \) between these materials cannot resolve the discrepancy. In fact, \( \epsilon \) and \( m^* \) of Si and GaN are within \( 15\% \) of each other and yet there exists a factor of 2.5 discrepancy in Fig. 2. A plot of \( E_{\text{crit}} \) vs. filling factor, \( \nu \), generates no apparent relationship. On the other hand, in a plot of \( B_{\text{crit}} \) vs. \( n_{2D} \) the AlGaAs/GaAs and AlGaN/GaN data fall onto the same line. However, now the Si data deviate by a factor of \( \sim 3 \).

As to the origin of the CR splitting, Schlesinger et al. propose an ad hoc model. The splitting is conjectured to result from a softening of the large \( q \sim 2/l_0 \) magnetoroton mode leading to a degeneracy with the CR at \( q = 0 \). The plasmon wave vector is denoted as \( q \) and \( l_0 = \sqrt{\hbar e/\epsilon B} \) is the magnetic length. Disorder breaks translation invariance, couples both modes, and causes the splitting. For this reason, the splitting is absent in very high-mobility specimens such as AlGaAs/GaAs with \( \mu > 10^6 \text{cm}^2/\text{Vsec} \). The origin of the softening of the magnetoroton and its \( B \)-dependence remain speculative in Ref. [18]. Kallin and Halperin [13] are among the first to address the field-dependence of the magnetoplasmon dispersion. Their analysis is limited to high magnetic fields where the cyclotron energy \( \hbar \omega_c \gg E_c \) of the Coulomb energy. Although in the experiments \( E_c \approx \hbar \omega_c \), the authors provide some general remarks about the CR splitting in AlGaAs/GaAs. According to their calculation the magnetoroton minimum never approaches the CR energy but always exceeds it. Even if the magnetoroton were to cross the CR due to some higher order interaction it would do so in the wrong direction. The roton minimum is expected to move downward in energy with decreasing field, in contrast to experiment, which requires the minimum to move upward in energy with decreasing field. A calculation by MacDonald [20], which includes higher order effects on the magnetoplasmon dispersion, also concludes that the corrections are too small to even bring the minimum into resonance with the CR. A recent calculation on interactions between magnetoplasmons by Cheng [21] asserts that the magnetoroton minimum actually can cross the CR energy. Cheng calculates dispersion relations only in the absence of disorder and does not derive actual splittings of the CR line. Furthermore, as previously argued by Kallin and Halperin, the direction of crossing of the magnetoroton minimum, calculated by

\[
E_{\text{crit}} = \sqrt{n_{2D} e^2/\epsilon}
\]

\[
E_{\text{crit}} = \frac{\sqrt{n_{2D} e^2/\epsilon}}{2.5}
\]

FIG. 2: Critical energy, \( E_{\text{crit}} \), (left scale) and splitting, \( \Delta E \), (right scale) versus electron density. All AlGaN/GaN samples of Table I are shown plus data from runs in which the density was increased (up to 30%) by light. Data from clearly resolved CR splittings are indicated by filled circles, broadenings are shown as filled triangles. The full squares are data from Ref. [16]. Open circles and open squares refer to AlGaAs/GaAs data (Ref. [17]) and Si data (Ref. [17, 18]) respectively. All data follow a \( \sqrt{n_{2D}} \) behavior, however with very different prefactors. The data set at the bottom (\( \Delta E \)) shows the magnitude of the CR splitting at \( B_{\text{crit}} \) as a function of density for all AlGaN/GaN samples. In the case of line broadening (triangles and square) the “splitting” was estimated from a deconvolution of the broadened CR line.
Cheng including these higher order effects, is again inconsistent with experiment (upward vs. downward in energy as a function of $B$). All previous references restrict their calculations to integral values of filling factor, $\nu$. Oji and MacDonald $^{22}$ consider the case of arbitrary filling factors but find no particularly strong dependence of the roton minimum energy on $\nu$. Instead, they propose that a combined action of spin density mode (largely below CR) and charge density mode (largely above CR) may be responsible for the CR line splitting. However, the coupling of spin and charge to the CR mode are very different in strength and runs counter to the observation of a simple level anti-crossing behavior. There are other attempts at interpreting the AlGaAs/GaAs CR data using a memory function approach. Gold’s calculations $^{23}$, performed in the small-$q$ limit can only account for a broadening but not for a splitting of the CR line. The calculations by Hu and O’Connell $^{24}$, also based on memory functions, remarkably, generate such a splitting. However, the center of gravity of the combined lines (see Fig. 3) always tend to reside above $\hbar\omega_c$ in conflict with experiment. Furthermore, extrapolating these results, equal amplitude of the peaks would occur at $B \approx 8T (E_{\text{crit}} \sim 5.3\text{meV})$ which deviates considerably from the $E_{\text{crit}} \sim 12\text{meV}$ of Ref. $^{15}$.

At this stage, we do not understand the splitting in the CR of 2D electrons in AlGaN/GaN heterostructures. The splitting is enormous, reaching up to $\sim 20\%$ of the CR energy. Its unambiguous observation in a second material system establishes the splitting as a general 2D phenomenon rather than being peculiar to just AlGaAs/GaAs.

Theoretical models that address the splitting in AlGaAs/GaAs appeal to a softening of the large wave vector magnetoplasmon mode, which mixes into the CR due to disorder. Yet the origin, $B$-field dependence, filling factor dependence, magnitude, and even the exact mode responsible for the mixing remain unresolved. At the present level of understanding of 2D electron dynamics it is remarkable that such a huge effect on one of the most fundamental excitations of a solid, the cyclotron resonance of electrons, remains obscure. Our data on the new AlGaN/GaN heterostructures clearly highlights the need for a detailed evaluation of the magnetoplasmon mode. Our observed density dependence, which differs significantly from an earlier conjecture, should provide a means to differentiate between various theoretical models.

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