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# Splitting of the cyclotron resonance in two-dimensional electron systems

E.A. Henriksen[a,*], S. Syed[a,1], Y.J. Wang[b], M.J. Manfra[c], L.N. Pfeiffer[c], K.W. West[c], H.L. Stormer[a,c]

[a]Physics Department, Columbia University, New York, NY 10027, USA
[b]National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310, USA
[c]Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974, USA

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## Abstract

A large splitting of the cyclotron resonance line, observed in two different two-dimensional electron systems, remains unexplained. The splitting resembles an anti-level crossing with an unidentified mode of the semiconductor system. Here, we review our data on this splitting, and highlight some results of recent experiments.

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A large and prominent splitting of the cyclotron resonance (CR) line in two-dimensional electron systems (2DESs) is unexplained. First observed in 1984 by Schlesinger et al. [1] in AlGaAs/GaAs 2DESs, the generic 2D nature of this splitting was underlined by its recent observation in the AlGaN/GaN system [2]. Several attempts in the intervening years to explain the splitting have not resulted in a consensus on its origin [2].

The splitting resembles an anti-level crossing of the CR with another mode of the solid (see Fig. 1). The energy at which the splitting occurs, $E_{\text{crit}}$, is seen to vary with the 2D electron density, $n_{2\text{D}}$, as $E_{\text{crit}} = \sqrt{n_{2\text{D}}}e^2/\alpha\varepsilon = E_{\text{coul}}/\alpha$, implying that electron–electron interactions play a role. Here, $\varepsilon$ is the static dielectric constant and $E_{\text{coul}}$ is the Coulomb interaction energy. The coefficient $\alpha$ varies between material systems, with $\alpha \approx 1$ in AlGaAs/GaAs, and $\alpha \approx 2.5$ in AlGaN/GaN. In addition, in neither system does the splitting appear to have any dependence on the Landau level filling factor, $\nu$, which for AlGaAs/GaAs ranges over $\nu = 2.0-3.7$, and in AlGaN/GaN over $\nu = 4-7.5$.

In Ref. [1], it was noted that none of the usual excitations of the 2D system or bulk semiconductor host could explain the observed energies of the splitting. Thus, recourse was made to an ad hoc model, postulating an interaction with the *magnetoroton*, a minimum in the 2D magnetoplasmon dispersion located at $k \approx 2/l_B$, where $l_B = \sqrt{\hbar c/eB}$ is the magnetic length and $B$ is the applied magnetic field. Although the magnetoroton energy lies above the cyclotron energy $\hbar\omega_c$, where $\omega_c = eB/m^*c$ is the cyclotron frequency and $m^*$ is the effective mass, Schlesinger et al. assumed it to decrease with increasing magnetic field. A splitting will result when the magnetoroton becomes degenerate with the CR. Since then this assumption has been addressed in some detail [3–8], but its validity remains questionable.

In Fig. 1(a) and (c), we show typical splittings in AlGaAs/GaAs and AlGaN/GaN 2DESs, respectively. In both data sets, the usual single CR peak is observable at high and low values of $B$. However for $B = 5.5$ T in AlGaAs/GaAs, and $B = 10.8$ T in AlGaN/GaN, a clear splitting of the CR peak is observed. The position of the CR minima as a function of magnetic field is shown in Fig. 1(b) and (d) for these two systems. We characterize the

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*Corresponding author. Tel.: +1 212 854 8514.
*E-mail address:* erik@phys.columbia.edu (E.A. Henriksen).

[1] Present address: Department of Physics, University of Illinois, Urbana-Champaign, Urbana, IL 61801, USA.

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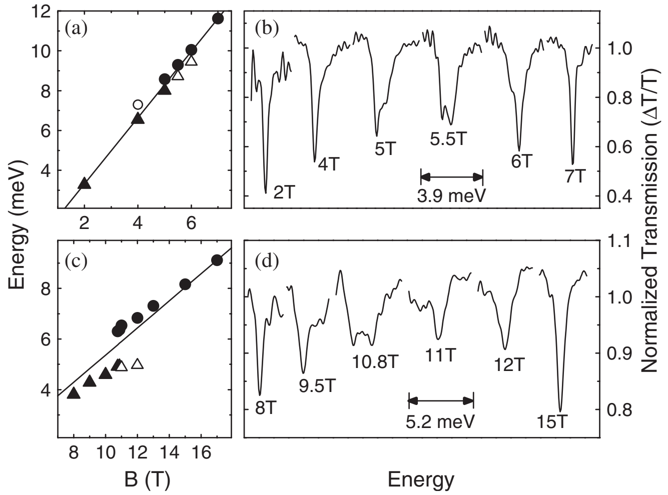

Fig. 1. Representative splittings. We show the normalized CR transmission ($\Delta T/T$) for a selection of $B$ fields in (a) AlGaAs/GaAs and (b) AlGaN/GaN (previously unpublished scans of Refs. [2,9], respectively). Traces are separated to avoid overlap. Panels (b) and (d) show energy position of $\Delta T/T$ minima vs. $B$ field; the solid line is the CR expected from the high- and low-field data. Circles (triangles) show higher (lower) energy minima, and closed (open) symbols indicate the stronger (weaker) minima.

splittings by $E_{\mathrm{crit}}$, the average energy of the two peaks when they are equal in intensity; and the splitting size, $\Delta E$, the distance between the two peaks. We note the splittings in both materials can be quite large, reaching $\Delta E/E_{\mathrm{crit}} \sim 20\%$.

In light of the fact that few experiments have directly addressed this splitting, Syed et al. performed CR on a collection of AlGaAs/GaAs 2DESs whose growth parameters, mobilities, and densities varied widely [9]. The authors observed a trend of decreasing $\Delta E$ with increasing transport lifetime, $\tau_\mu = (m^*/e)\mu$, where $\mu$ is the mobility, and with increasing quantum lifetime, $\tau_q$, derived from Shubnikov–de Haas data. They concluded that increased electron scattering was responsible for the increase in $\Delta E$. Since increased electron scattering samples a wider range of $k$-space away from $k = 0$, this suggests that the increase in $\Delta E$ is due to stronger coupling between resonances at different points in momentum space. In addition, a collective effect of impurities on the CR splitting was noted by Richter et al. in a study of AlGaAs/GaAs heterostructures having donor- (Si) or acceptor- (Be) δ-doping near the interface, with increasing impurity densities leading to larger splittings [10].

These are tantalizing clues to the nature of the splitting. However, due to the random nature of the samples used in Ref. [9], it is difficult to make a firm correlation of splitting size with the scattering times. Therefore, we were motivated to make a systematic study of the role of electron scattering in this CR splitting. We have performed CR on a sequence of AlGaAs/GaAs quantum wells, identical but for intentional doping of the wells with a varying density of carbon (C) acceptor impurities. All samples have 300 Å wide wells, with single-side doping at a setback of 800 Å. Samples without C doping exhibit mobilities in excess of $5 \times 10^6\,\mathrm{cm^2/V\,s}$. In the usual single particle picture, the C impurities are ionized and screened, and act primarily as short-range scatterers. In the inset to Fig. 2, we show the resultant mobility of our six samples as a function of the 2D C impurity density. With careful calibration of the flux of C atoms during molecular beam epitaxy growth, these samples provide an ideal system within which to study the splitting as a function of the electron scattering from impurities.

All CR experiments were performed at 4.2 K, using a Bruker IFS 113V Fourier transform spectrometer in combination with light pipe optics and a composite Si bolometer. All samples were wedged to ≈ 10° to suppress Fabry–Perot resonances. Data was taken after illumination with a red LED. Standard four-terminal transport was measured in situ, simultaneously with the CR.

In Fig. 2, we display a central finding of our experiments on the C-doped 2DESs. The CR splitting size, $\Delta E$, is seen to decrease dramatically with increasing sample mobility (or decreasing electron scattering). This result establishes conclusively a correlation between increasing $\Delta E$ and increasing electron scattering.

In Fig. 3, we summarize the available data on $\Delta E$ and $E_{\mathrm{crit}}$ as functions of $n_{2D}$ and $\nu$. Interesting to note is the apparent lack of any dependence on the filling factor, which is atypical of 2D phenomena at high magnetic fields. The increase of $E_{\mathrm{crit}}$ with sample density, roughly as $E_{\mathrm{crit}} \propto \sqrt{n_{2D}}$, is clear in both AlGaAs/GaAs and AlGaN/GaN. Taken together, all of the AlGaAs/GaAs data may display a trend of increasing $\Delta E$ with increasing $n_{2D}$. However, we note the C-doped samples (open circles in Fig. 3) alone exhibit no such trend.

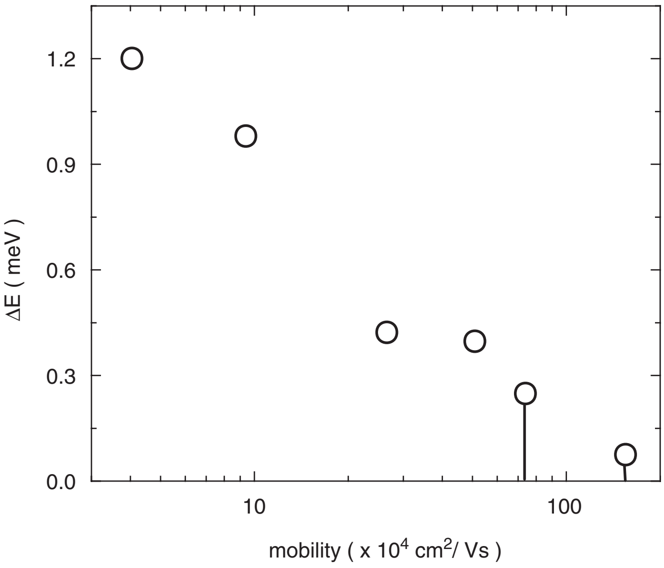

Fig. 2. CR splitting size, $\Delta E$, vs. sample mobility for AlGaAs/GaAs samples with C-doping in the quantum well. The two highest mobility samples show a broadening rather than a splitting, and so have error bars extending to zero.

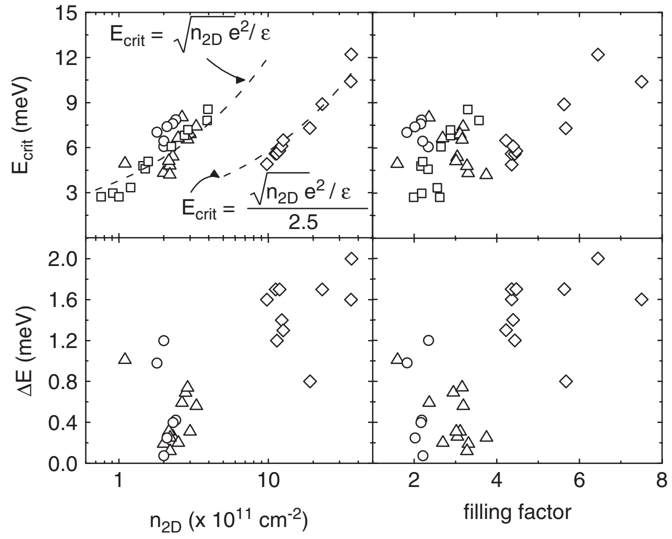

Fig. 3. Collected data on $E_{\text{crit}}$ and $\Delta E$ vs. 2D electron density and Landau level filling factor. ◇s are AlGaN/GaN 2DESs [2]; △s are an assortment of AlGaAs/GaAs 2DESs all grown under different conditions [9]; ○s are a sequence of AlGaAs/GaAs samples with intentional C-doping of the quantum well; □s are data of Schlesinger et al. [1].

In summary, the origin of the enigmatic large splitting of the CR line in 2DESs remains unexplained. The splitting has little dependence on the Landau level filling factor, but the critical energy at which the splitting occurs depends on the 2D electron density. The size of the splitting has been clearly linked to the sample mobility, confirming that electron scattering is essential for the splitting to occur.

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