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Hydrostatic pressure dependence of negative-donor-ion singlet and singlet-like bound magnetoplasmon transitions in doped GaAs/AlGaAs quantum wells

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Abstract

Applied hydrostatic pressure modifies the Coulomb bound states of a quasi-two-dimensional electron gas in quantum wells by increasing the effective mass and by tuning the free electron density. Here, we explore these mechanisms by measuring the effects of pressure on the cyclotron resonance, the D^0 1s $\rightarrow$ $2p^+$ transition, and the D^--singlet and singlet-like transitions in low-and high-density, modulation-doped GaAs quantum wells. For low doping density, detailed calculations employing a pressure-dependent electron mass agree well with the observed magnetic field and pressure dependencies. For high doping density and low fields, the blue-shift of the D^--singlet-like transition at fields below 8 T decreases with applied pressure as anticipated, due to loss of free electrons via the Γ–X crossover. However, near $\sim$7.5 T, this singlet-like transition exhibits an anomalous branching for pressures above 4 kbar, which indicates the presence of a resonant level and obscures the blue-shift at high fields. © 2000 Elsevier Science B.V. All rights reserved.

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Electrons in low-dimensional semiconductor structures and high magnetic fields are strongly correlated, giving rise to a number of interesting phenomena such as the fractional quantum Hall effect, the Wigner solid, and Skyrmion excitations [1]. Previous work [2], in which *excess* electrons were introduced into a series of Si modulation-doped multiple quantum wells (MDQWs), demonstrated that for GaAs/AlGaAs structures with a controlled density of randomly distributed impurities in the wells, many-electron interactions of a quasi-two-dimensional electron gas (2DEG) are rendered visible in the far-infrared (FIR) magneto-optical spectrum. For example, with increasing excess electron density, the two-electron

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D^-singlet e.g., Refs. [3–7] transition evolves continuously into a blue-shifted many-electron D^--singlet-like bound magnetoplasmon excitation, which exhibits interesting behavior as a function of filling factor.

Earlier studies [8] showed that applied hydrostatic pressure modifies the Coulomb bound states of a 2DEG in MDQWs by increasing the electron effective mass and by tuning the free electron density. The former mechanism alters the single-particle wave functions and energies, and the latter mechanism affects the many-electron states and their interactions. In the present work, the influence of these mechanisms on neutral/negatively charged donors (D^0/D^-) and on the cyclotron resonance (CR) of free electrons is studied by high-pressure FIR magnetospectroscopy in GaAs/AlGaAs structures.

FIR magnetotransmission experiments were carried out under applied hydrostatic pressure with a diamond-anvil cell (DAC), in which pressure, magnetic field and temperature are varied independently (maximum operating ranges: 0–150 kbar, 0–9 T, and 2–300 K) [9]. Spectra were recorded up to 35 kbar at 4.2 K with a Fourier transform infrared spectrometer, in conjunction with a 9 T superconducting magnet. A Ge : Ga photoconductive detector measured the FIR signal in the range 80–240 cm^{-1} (see Ref. [9] for details). We studied a series of epitaxially grown $GaAs/Al_{0.3}Ga_{0.7}As$ QWs that were Si δ-doped [2,5] in both the 20 nm wells (at 2.0×10^{10} cm^{-2}) and in the 60 nm barriers (in the range $(3.5–28)\times10^{10}$ cm^{-2}). We present the data recorded in the Faraday geometry for the lowest concentration sample (3.5×10^{10} cm^{-2} – Sample 1) and the highest concentration sample (28×10^{10} cm^{-2} – Sample 2), which were cleaved into specimens of $\sim 150 \times 150 \times 30$ μm^3 size (substrate thinned) and suspended in a ^4He pressure medium [9]. Any pressure-induced DX centers were deactivated by intermittent exposure to visible (514 nm) laser light during ruby pressure calibration.

In Sample 1 (low doping) we observed the pressure and magnetic-field dependencies of the D^0 $1s \rightarrow 2p^+$, the D^-singlet, and the electron CR transitions. For this specimen the free electron concentration changes very little up to ~25 kbar, the onset of the Γ–X crossover between the well and barrier conduction band edges (see Ref. [8]). Hence, in Sample 1 we probe principally the effects of the pressure-induced increase in the effective mass. Fig. 1 shows the magnetic field dependencies observed for this sample, at 1 atm and at the highest pressure at which the different features could be observed – CR (22 kbar), D^--singlet transition (25 kbar), and D^0 $1s \rightarrow 2p^+$ transition (28 kbar). Above 30 kbar, no absorption features could be measured within our signal-to-noise level, due to the complete transfer of the QW electrons to the X-associated states in the barrier.

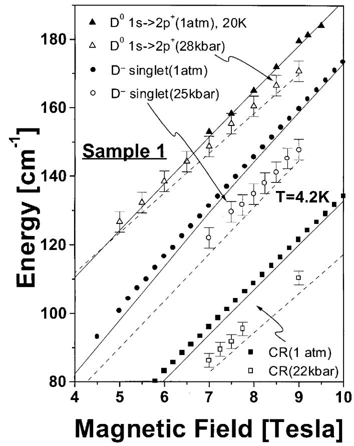

Fig. 1. Summary plot for Sample 1, showing the pressure and magnetic field dependencies of the CR, D^{-1}-singlet and D^0 $1s \rightarrow 2p^+$ transitions. The 1 atm points are from Ref. [6]. The solid (dashed) curves are calculated results for 1 atm (the same high pressures as the experimental data).

As expected, due to confinement the energy of the D^0 $1s–2p^+$ transition is higher at all pressures in Sample 1 than observed in prior experiments on Si-doped bulk GaAs [10]. A similar comparison is not possible for the D^--singlet transition, since this was not seen in the data of Ref. [10]. The field-slopes of the three observed features in Fig. 1 all decrease with applied pressure. The increase of the electron mass with pressure is the principal cause for this decrease in all cases. For the CR and the D^0 $1s–2p^+$ transitions, the rate of decrease in slope agrees, within experimental error, with the prior findings in bulk GaAs [10]. For these transitions, and for the D^- singlet QW feature, we explore the effects of changes in the electron mass in more detail by theoretical calculations.

In these calculations, the D^0 $1s \rightarrow 2p^+$, D^- singlet, and CR transitions are computed by numerical diagonalization (with a basis of 3000 Landau-oscillator and size-quantization wave functions) of the appropriate one- or two-electron Hamiltonians for a positive charge at the QW-center. Results were obtained for $B \geqslant 4T$ with pressure-dependent effective mass and dielectric constant [6,11,12] incorporating the effects of conduction band non-parabolicity, assumed to be pressure-independent and equivalent to that in GaAs at 1 atm. The dependence of the effective mass with applied pressure $m_{\text{eff}}(P)$ was taken from previous experiments [10], $m_{\text{eff}}(P) = m_{\text{eff}}(0) \times [1 + 6.08 \times 10^{-3}\ P - 1.3 \times 10^{-5}\ \text{P}^2]$, where P is the pressure in kbar and $m_{\text{eff}}(0)$ is the bottom-of-the-conduction-band effective mass at 1 atm ($0.067m_{\text{e}}$). The dielectric constant as a function of pressure $\varepsilon(P)$ was obtained by combining this result for $m_{\text{eff}}(P)$ with other measurements [13] of the pressure-dependent Rydberg constant, $\text{Ry}(P) = \text{Ry}(0) \times [1 + 9.61 \times 10^{-3}\ P + 1.51 \times 10^{-5}\ P^2 \equiv [m_{\text{eff}}(P)e^4]/c[2\varepsilon^2(P)^2]$. The solid (dashed) curve in Fig. 1 gives the calculated results for the CR, D^-singlet, and D^0 1s $\rightarrow$ 2p$^+$ transitions at 1 atm (22, 25 and 28 kbar, respectively). The qualitative behavior is well reproduced, although the calculated transition energies are in all cases somewhat smaller than the measured ones. This discrepancy could arise from an overestimate of the non-parabolicity in the calculation.

Note in Fig. 1 that the 1 atm *and* elevated-pressure curves cross at different B-fields for the D^0 1s $\rightarrow$ 2p$^+$ transition and the D^--singlet transition. Both the theoretical and the experimental results find that this crossing occurs at a higher field for the D^0 1s $\rightarrow$ 2p$^+$ case (at $\sim 5\,\text{T}$) than for the D^--singlet case (at a field below our measurement range). The overall agreement between theory and experiment is reasonable.

In Sample 2 (highly doped) we studied the D^--singlet-like transition and the CR over similar magnetic field and pressure ranges. Typical experimental spectra are shown for 27 kbar in Fig. 2. Within the experimental uncertainty, the CR energy position as functions of magnetic field and pressure is found to be the same as in Sample 1. However, the width of the CR evolves with applied pressure from a broad (overabsorbed) feature [2,5] to a much sharper peak. This behavior is a signature of the pressure-induced decrease in electron density caused by the Γ–X crossover.

The D^-singlet-like transition is blue-shifted relative to the isolated D^--singlet energy as expected, because of many electron effects [3–7]. This blue-shift is manifest in Fig. 3 by the energy difference between the data points (recorded for Sample 2) and the theoretical curves (calculated for Sample 1 as described). Although the anticipated trend is simply a decrease in the blue-shift due to the pressure-induced reduction

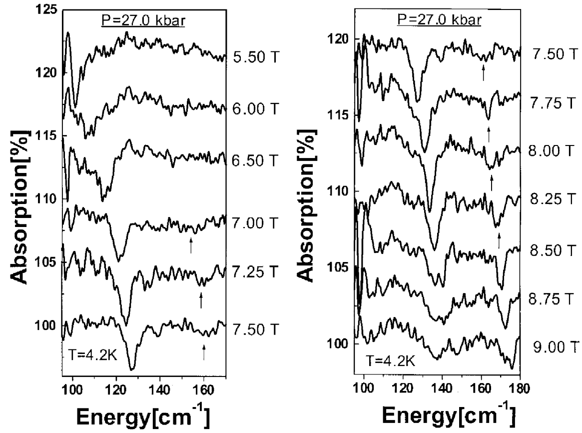

Fig. 2. FIR magneto-transmission spectra at 27 kbar for sample 2, showing the complicated branching of the D^{-1}-singlet-like transition.

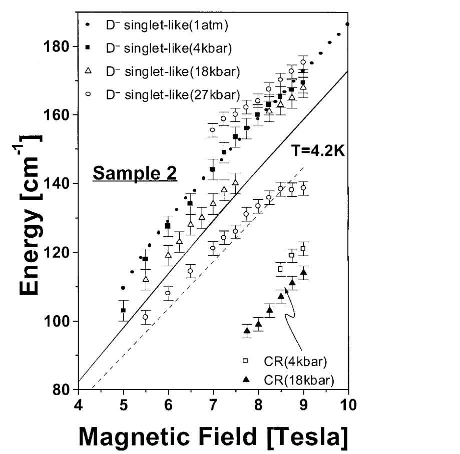

Fig. 3. Summary plot for Sample 2, showing the pressure and magnetic field dependencies of both D^--singlet-like branches, and the CR. The 1 atm data is from Ref. [6]. The solid and dashed curves show the theoretical *isolated* D^--singlet transition at 1 atm and 25 kbar, respectively (also in Fig. 1).

in QW electron density, we find much more complicated behavior. The 1 atm and 4 kbar data in Fig. 3 show essentially the same blue-shift relative to the calculated D^--singlet transition at 1 atm (solid curve). This is understandable, since a pressure of 4 kbar is too low to cause a decrease in the electron density via the Γ–X crossover [8]. However, at all pressures above 4 kbar, the D^--singlet-like data for Sample 2 show an anomalous (anti-crossing-like) branching around ∼7.5 T. With increasing pressure, the magnitude of the splitting between the two branches increases. The upper branch appears to evolve into the D^0 1s → $2p^+$ transition, while the lower branch approaches the isolated D^--singlet position (at the given pressure, dashed line). This behavior is most clear at 27 kbar in Fig. 2, where two absorption features are seen simultaneously between 7 and 9 T. We also find that the intensity of the higher energy peak increases with magnetic field, while the lower-energy peak decreases in strength and broadens. As in the low-density sample, no absorption features were observed in Sample 2 for pressures above the Γ–X crossover.

At fields below the onset of the anomalous D^- branching, the blue-shift of the singlet-like transition with respect to that of an isolated D^--singlet ion behaves as expected. At 18 kbar the blue-shift is still the same, within experimental error, as that observed at 1 atm (∼ 13 cm^{-1} relative to the calculated D^--singlet position). Over this pressure range the excess electron density remains essentially unchanged, and the shifts in energy and slope of the D^--singlet-like transition are related to the mass changes described above. For the highest pressure in Fig. 3 (27 kbar), at which the sample's excess QW electron density has now decreased substantially, the blue-shift in the low-field D^- branch is concomitantly smaller (∼5 cm^{-1} relative to the calculation).

In contrast, for higher fields (>7.5 T) the complicated branching of the D^--singlet-like transition in Sample 2 is currently not well understood. However, it is interesting to speculate on the origin of this branching. One possibility is misalignment of the sample's QW plane with respect to the magnetic field due to twisting of the specimen in the DAC. In this case, the magnetic field component in the QW plane couples free-carrier Landau states and impurity states associated with the first and second sub-bands. However, this possibility is ruled out because the large separation of these sub-bands (∼220 cm^{-1}, calculated via the pressure-dependent self-consistent model in Ref. [8]) should cause the branching to occur ∼75 cm^{-1} above the frequency where it is observed in Fig. 3. In addition, the branch splitting is unreasonably large for the estimated maximum tilt angle of the sample in the DAC.

A more realistic possibility is that the branching arises from the presence of a resonant level, which communicates with the free electrons in the quantum well for this field-pressure regime. If so, the experimental results suggest that the coupling of this level to the shallow donor and free carrier states in the well increases with applied pressure, and that for fields above ∼7.5 T, carriers are removed from the well into this level. This interesting, and previously unobserved phenomenon, merits further experimental and theoretical investigations.

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