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Inelastic light-scattering study of magnetoplasma modes in a wide parabolic quantum well

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Inelastic light scattering was used to study the dispersion and magnetic-field dependence of both inter-Landau and intersubband magnetoplasma modes in a wide parabolic quantum well. The intersubband magnetoplasmon energy (~11 meV) was found to be much greater than expected from a simple self-consistent Hartree calculation (~2 meV). The value is in fact very close to the bare harmonic energy of the well. This striking example of the absence of corrections to the single-particle energy from electron-electron interactions is the result of Kohn's theorem. In a magnetic field, the intersubband magnetoplasmon energy is constant except at the field where the inter-Landau energy crosses the intersubband energy. After the crossover, the intersubband energy shifts to a lower value. This is interpreted as a shift in oscillator strength from a bulklike to a surfacelike magnetoplasma mode.

Electrons confined in a wide, remotely doped parabolic quantum well have attracted recent theoretical[1–5] and experimental work.[6–13] The reason for much of the effort is that parabolic wells are structures that realize uniform density electron slabs. Due to the electrostatic potential between the electrons and between the electrons and ionized donors, remotely doped electrons in a wide square quantum well tend to separate into two narrow slabs localized near the well edges. To overcome this, a parabolic potential can be imposed on the conduction band which cancels the Hartree potential. The electrons in the well then minimize their energy by spreading into a uniform slab. Transport measurements have revealed close subband spacings resulting from the large width of the electron slab.[9,11] Although the Hartree part of the electron-electron interaction significantly reduces the subband spacings to only a few meV, we find that the intersubband (IS) energies from inelastic light scattering are much greater, representing values near the bare harmonic energy determined by the design curvature of the well. This is due to the cancellation of the Hartree term with the time-dependent Hartree (or random-phase-approximation) term. It is a striking manifestation of Kohn's theorem, demonstrating that the transition energy is unaffected by many-body electron-electron interactions.

In a perpendicular magnetic field there should be two primary peaks in the optical spectrum: one at the cyclotron energy [inter-Landau (IL) transition] and another at the bare IS energy. It is interesting to note that no many-body correction to the single-particle energy can be detected in either the IS or the IL transition as the in-plane wave vector q goes to zero — both satisfy Kohn's theorem. As a result, simple infrared optical absorption experiments can tell nothing about the electron-electron interaction in a perfect parabolic well. This is not the case for excitations at finite wave vectors or in imperfect parabolic wells. An advantage of using inelastic light scattering[14] over optical absorption is that we can select the excitation wave vector by the geometry of our light-scattering experiment. The technique of optical absorption would require samples with different gratings for each desired wave vector. In the present work, we use resonant inelastic light scattering to study the magnetoplasma modes in a wide parabolic quantum well as a function of perpendicular magnetic field B and in-plane wave vector q. We have observed two spectral peaks at most magnetic fields greater than 4 tesla (T). One of the peaks is near the cyclotron energy, scales linearly with magnetic field, and has a narrow linewidth of 0.3 meV. We identify this as the IL peak. The other peak is nearly independent of the magnetic field, has an energy near the bare harmonic energy of the well, and is broad (1.0 meV). We identify this as the IS peak. The IS peak shifts abruptly to a lower energy value after the cyclotron energy crosses the bare harmonic energy of the well. Upon closer examination of the spectra near the crossing at 7 T, we can resolve three peaks, two IS peaks and one IL peak. By studying their dispersion and behavior in magnetic fields applied perpendicular to the electron slab, we are able to identify the peaks with the magnetoplasma modes[15] obtained from simple hydrodynamic calculations as described below.

The sample used in this work has a width of 760 Å, mobility of 0.72×10^5 cm^2/V s, and electron density of 8×10^{11} cm^{-2} (4.8×10^{11} cm^{-2} without illumination). We note that the well is overfilled because the electron density is greater than the design three-dimensional (3D) density multiplied by the well width (5.6×10^{11} cm^{-2}). The composition inside the well alternates between GaAs and $Al_{0.3}Ga_{0.7}As$ in a 20-Å superlattice. The average Al mole fraction is smoothly varied such that the conduction-band edge has the desired parabolic profile with the bare harmonic energy of 10.6 meV.

To calculate the magnetoplasma mode dispersion for our sample, we use a hydrodynamic model similar to that of Dempsey and Halperin.[1] In the hydrodynamic limit, the electron collision rate is high enough to establish local equilibrium so that the properties of the system can be calculated using macroscopic arguments without the use of the Boltzmann transport equation for the distribution function.[16] We solve the force equation and Maxwell's equations subject to the appropriate boundary conditions:

$$m^* n \left[\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v}\right] = -en\vec{E} - en\frac{\vec{v}}{c}\times\vec{B} - n\nabla V - \nabla p, \tag{1a}$$

$$\vec{E} = -\nabla\phi, \tag{1b}$$

$$\nabla^2\phi = \frac{4\pi n e}{\epsilon}, \tag{1c}$$

$$\frac{\partial n}{\partial t} + \nabla\cdot(n\vec{v}) = 0. \tag{1d}$$

It is assumed that the plasma modes of the well can be described by fluctuations about the equilibrium values of density (n), velocity ($\vec{v}$), fields ($\vec{E},\vec{B}$), and potential (ϕ). We proceed to linearize Eq. (1) by using $n = n_0 + n_1$, $\vec{E} = \vec{E_0} + \vec{E_1}$, $\vec{B} = \vec{B_0} + \vec{B_1}$, $\vec{v} = \vec{v_0} + \vec{v_1}$, and $\phi = \phi_0 + \phi_1$. In Eq. (1a), V is the externally imposed potential and p is the pressure of the electron gas. V is the quadratic potential profile of the conduction band and p will also be assumed to be linear in density: $p = m^* s^2[n(z) - n_c]$. The quantity of s is chosen to be $\sqrt{\frac{3}{5}}v_f$, where v_f is the Fermi velocity.[1] One complication in finding the solution of Eq. (1) is that we have to solve for the equilibrium values self-consistently before we can solve the linearized problem. We can simplify the problem by assuming that n_c has the value of the design 3D density. For this value of n_c, the self-consistent equilibrium density $n_0(z)$ inside the well is constant, with the value n_c, while outside the well it is zero. This simplification appears to be quite drastic. The equilibrium density in our overfilled well is not constant because of an excess charge density which accumulates around the edges. However, we can take this simple model as a reasonable approximation for small deviations from the ideal system. Due to the overfilling of the well when illuminated, the appropriate boundary conditions are the so-called hard-wall boundary conditions: continuity of E_z and ϕ at $z = \pm a$, and $v_z(\pm a) = 0$.

According to the hydrodynamic model, there are two sets of magnetoplasma modes in a wide parabolic well. The distinction between the two sets of modes is clear when the cyclotron energy is less than the bare harmonic energy of the well. One set of modes is associated with the IS transition and is independent of the magnetic field, while the other set is associated with the IL transition and scales linearly with the magnetic field. Figure 1 shows representative experimental spectra for a range of magnetic fields at $qa = 0.05$, while Fig. 2 shows representative spectra for $qa = 0.21$. Both sets of spectra show similar behavior. For most fields, we find two features in the spectrum: one IL peak and one IS peak. Figure 1 shows that at low magnetic field there is one IL peak at the cyclotron energy and one IS peak near the bare harmonic energy of the well. The most interesting behavior occurs near the crossover region of the IL and IS peaks. At 6.5 T, we see only one unresolved broad feature. At

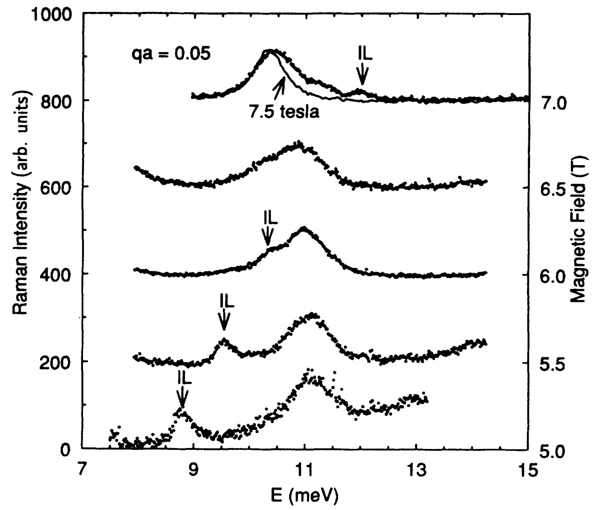

FIG. 1. Inelastic-light-scattering spectra from a wide $GaAs/Al_xGa_{1-x}As$ parabolic quantum well. Representative spectra (normalized) for $qa = 0.05$ at various perpendicular magnetic fields, where $a = 380$ Å is half the well width and q is the in-plane wave vector. The spectra were taken with laser energy near 1550 meV and temperature of 1.6 K. The laser energy was varied slightly at the different magnetic fields.

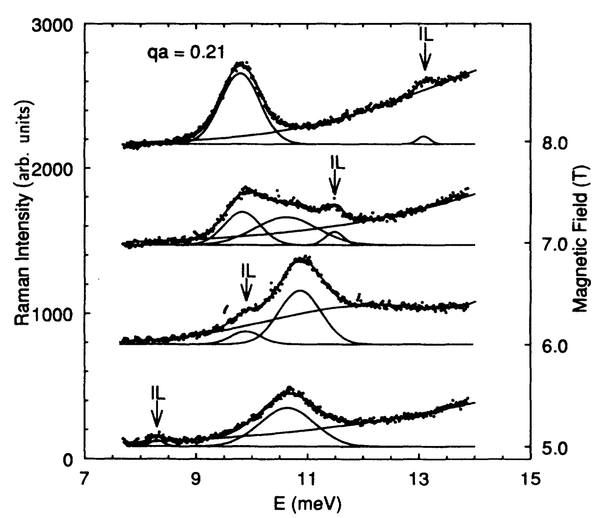

FIG. 2. Inelastic-light-scattering spectra from a wide $GaAs/Al_xGa_{1-x}As$ parabolic quantum well. Representative unnormalized spectra for $qa = 0.21$ at various magnetic fields. The laser is set at 1550 meV. The solid curves are Gaussian line-shape fits to the experimental spectra, including a substantial background due to photoluminescence.

$B = 7$ T the IL peak has crossed the IS peak, but the IS peak has shifted to a lower energy by 0.6 meV. Figure 2 shows a qualitatively similar but larger shift of the IS peak to lower energy after the crossover region. The shift for $qa = 0.21$ is roughly 1.0 meV. At 7 T we can observe three plasmon modes: two IS modes near the bare harmonic energy of the well and one IL mode near the cyclotron energy. (Similar, but less clear behavior is observed for $qa = 0.05$, where the presence of two IS modes is deduced from the fact that the 7-T spectrum in Fig. 1 has a higher energy shoulder which is not present at 7.5 T.) The spectral positions of the two IS modes suggest that they are the two lowest odd-symmetry plasma modes associated with IS transitions. This assignment is also supported by the observed wave-vector dependence of the magnitude of the IS energy shift, as is evident by comparing the two panels of Fig. 3. After the crossover of the IS and IL modes, the IS peak energy agrees with the calculated energy for the lowest density oscillation mode associated with the bare harmonic energy.

By comparing the measured and calculated spectral positions of the various peaks versus magnetic field, we interpret the shift in energy of the IS peak near the crossover of the IS and IL peaks as a shift in the oscillator strength between the modes. This can be seen in Fig. 3 where the solid lines are the excitation energies obtained from our hydrodynamic calculation of odd density fluctuation modes. Before the crossover, only the bulklike IS mode is observed, while the surfacelike IS mode is observed only after the crossover of the IS and IL modes. Both modes are present near the crossover region at 7 T. In the lower panel of Fig. 3, the normalized density fluctuations associated with the two modes are shown in the insets. Before the crossover, the inset shows the density fluctuation at 5.5 T associated with the mode having an energy nearest the experimental points: the lowest bulklike odd-symmetry density oscillation near the bare harmonic energy. After the crossover, the inset shows the lowest energy mode of the system at 7.5 T: an odd-symmetry surfacelike mode. Here, the vertical edges of the insets are the quantum well edges and the density oscillation is normalized to 1 at the maximum value obtained at 7.5 T. It is important to note that the center-of-mass mode is absent for the hard-wall boundary conditions. Only bulk density-oscillation modes with energies greater than the bare harmonic energy of the well are allowed at $q = 0$. A heuristic picture of the situation can be achieved by considering the 3D jellium model. In our quasi-3D system, when $q = 0$, we must satisfy the boundary conditions by requiring that the z-component wave vector (q_z) takes on the values $\frac{k\pi}{2a}$, where k is any non-negative integer. The mode with $k = 0$ is a special case. This is the so-called center-of-mass mode which is the only mode that satisfies Kohn's theorem exactly.[1] This mode involves only a delta-function surface density oscillation. It is not allowed under hard-wall boundary conditions because it is impossible to displace the electron slab as a whole in the z direction to create the delta-function surface density in the presence of hard-wall boundaries. For $k \neq 0$, we can think of each mode as having an effective finite wave vector q_z. All modes should have energies greater than the bare harmonic energy because the energy dispersion of the 3D plasmon increases quadratically with wave vector for small wave vector. As the in-plane wave vector q increases from zero, the lowest energy IS mode acquires surface characteristics as the density fluctuation becomes localized near the edges of the well. All the other excited modes remain bulk in character. In Fig. 4, we have plotted the measured and calculated wave-vector dispersion of the lowest

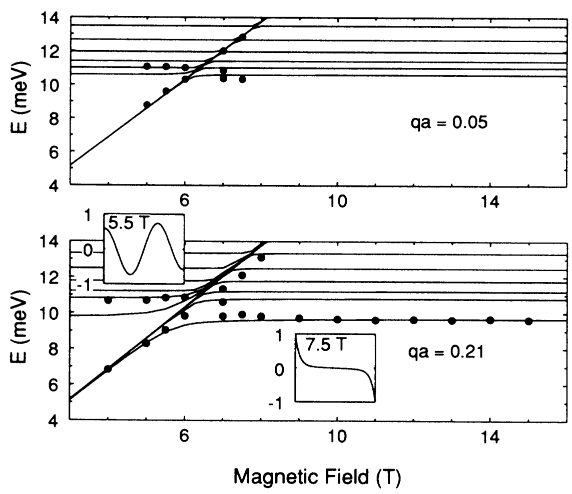

FIG. 3. The solid curves represent the calculated odd-symmetry density oscillation modes of a wide parabolic quantum well in the hydrodynamic model with hard-wall boundary conditions. For the upper panel with $qa = 0.05$, we used 10.8 meV as the value of the bare harmonic energy, while for the lower panel with $qa = 0.21$ we used the value of 10.6 meV. These values were chosen to best fit the experimental points. The insets are the normalized density fluctuations inside the well for the odd-symmetry modes at low fields (left-hand side) and high fields (right-hand side).

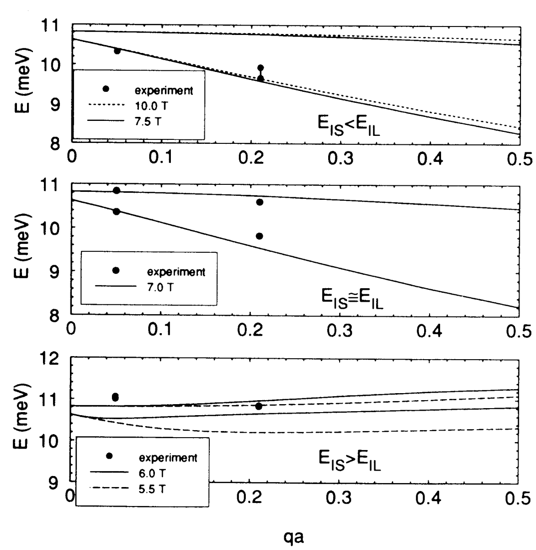

FIG. 4. Theoretical wave-vector dispersion curves and experimental points for the lowest two odd-symmetry intersubband plasma modes at various magnetic fields.

two odd-symmetry IS plasma modes at various magnetic fields. Before the crossover of the IS and IL modes (bottom), only the higher energy IS mode is observed, while after the crossover (top) only the lowest energy IS mode is observed. At $B = 7$ T, both modes are present and the separation between the two IS modes increases with the in-plane wave vector. Thus far, we have been unable to explain why both plasma modes are not observed at all fields.

In addition to the IS modes, we have also observed one IL mode. The IL mode we have observed is not the usual intrasubband surface magnetoplasmon which has an even-symmetry density fluctuation and a sharp, positive energy dispersion near $q = 0$.[13] The mode which we have observed shows slight negative dispersion before the crossover with the IS mode. It exhibits anticrossing behavior with increasing magnetic field. The dispersion and magnetic field dependence of this mode strongly suggest that it is one of the bulklike IL modes. These IL modes have negative dispersion and collapse to the cyclotron energy as $q \to 0$. We see from Fig. 3 that while the IL peak follows the cyclotron energy closely for $qa = 0.05$, it falls below the cyclotron energy for $qa = 0.21$ after the crossover region. Since the IL transition is usually not an allowed Raman transition, we speculate that it can be observed only when it acquires enough hybrid subband character. This occurs in the resonant crossover region where IL and IS transitions exhibit anticrossing behavior. Thus, the IL peak position deviates more from the cyclotron energy at the larger in-plane wave vector where the anticrossing behavior is stronger.

We have observed several magnetoplasma modes of a wide parabolic quantum well by inelastic light scattering. There are two sets of modes, associated with IS and IL transitions. At low fields before the crossover, the IL peak follows the cyclotron energy closely and has a slight negative dispersion. At high fields, the IL peak tends to fall below the cyclotron energy when the in-plane wave vector is large. The other modes are observed to have energy shifts near the bare harmonic energy of the well and arise from the IS transition. The IS peak spectral position is independent of magnetic field except near the crossover of IS and IL modes — on the higher field side the IS peak shifted to a lower energy. This is interpreted as a shifting of oscillator strength from an odd-symmetry bulklike magnetoplasma mode to a surfacelike mode at higher fields.

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