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Cyclotron-resonance oscillations in a two-dimensional electron-hole system

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Pronounced oscillations have been observed in linewidth, amplitude, and mass of electron cyclotron resonance in InAs/$Al_xGa_{1-x}Sb$ quantum wells when holes coexist with electrons. The strength of the oscillations increases sensitively with electron-hole pair density; the oscillations are absent for semiconducting samples ($x>0.3$) in which there are no holes. Results are interpreted in terms of a filling-factor-dependent electron-hole interaction.

There has been considerable interest in electron-hole (e-h) systems in strong magnetic fields due to their fascinating array of possible physical states.[1] Although a great deal of effort has been made to observe the excitonic insulator phase in bulk semimetals at low temperatures and in high magnetic fields, no direct experimental evidence has been given to date. Since the pioneering work of Lozovik and co-workers,[2] attention has been paid to *spatially separated* two-dimensional (2D) electrons and holes in layered structures. The ground state of such systems in a strong perpendicular magnetic field has been theoretically studied and various possibilities have been predicted.[3] Several types of 2D e-h systems have been recently proposed and fabricated via modern crystal-growth technique,[4–6] making experimental studies possible.

Cyclotron resonance (CR) in quasi-2D systems has been studied extensively for the last two decades. However, many important aspects are still not well enough understood, and several sets of experimental data are apparently contradictory and sample dependent.[7] Workers have observed dramatic departures from classical behavior in Si inversion layers and GaAs/$Al_xGa_{1-x}As$ heterostructures, unrelated to single-particle band structures. One of the unresolved points, both theoretically and experimentally, is the origin of linewidth oscillations with filling factor $\nu=n_sh/eB$, where n_s is the 2D carrier density, observed by some workers. In studies to elucidate this point, it is important to distinguish universal properties of 2D CR from properties that depend on the particular system.

High-mobility 2D systems with InAs single quantum wells (QW's) have become available in recent years, and several groups have studied CR.[8–10] Heitman *et al.*[8] observed strong oscillations in CR linewidth and amplitude (but not mass) for electrons in InAs/GaSb QW's; linewidth maxima were observed at even ν's and minima at odd ν's. While the authors attributed the oscillations to ν-dependent screening of impurity scatterers by the 2D electron gas,[11] it is not clear why this particular 2D system shows such pronounced oscillations while other 2D systems do not. More recently, two groups[9,10] observed spin-resolved CR in InAs/AlSb QW's. Their data clearly revealed linewidth maxima (or larger splittings) at *odd* ν's, inconsistent with Ref. 8 but consistent with the idea[12] that nonparabolicity is the cause of CR oscillations. The primary difference between the earlier[8] and the later[9,10] experiments is the barrier material: GaSb or AlSb, respectively. Thus, InAs QW's with $Al_xGa_{1-x}Sb$ barriers with variable composition (x) comprise an interesting and important system to investigate these effects systematically.

The InAs/$Al_xGa_{1-x}Sb$ type-II QW has very interesting band lineups, its effective band gap varying over a wide range (-0.15 to $+0.3$ eV) with x. Since the conduction-band bottom of InAs is lower than the valence-band top of GaSb ($x=0$), there is a *negative* effective band gap, leading to a charge transfer between the layers, which results in the existence of spatially separated intrinsic electrons and holes (semimetallic). The band overlap decreases with increasing x, vanishing near $x=0.3$. When $x\geqslant0.3$, the effective band gap is positive; no intrinsic carriers exist at $T=0$ (semiconducting). However, in all samples grown to date there are extrinsic electrons in the InAs QW (10^{11}–10^{12} cm^{-2}), possibly because of pinning of the Fermi energy by surface donors,[13] Tamm-state-like interface states,[14] or metastable defects in the barrier.[15,16]

In this paper, we present results of far-infrared magnetospectroscopy on a series of InAs/$Al_xGa_{1-x}Sb$ single QW's ($0.1\leqslant x\leqslant1.0$). For "semimetallic" samples ($x<0.3$), strong ν-dependent oscillations have been observed in CR linewidth and amplitude, similar to the results of Ref. 8. However, in addition, we have observed a strong *CR mass oscillation*. Linewidth maxima, amplitude minima, and mass jumps occur at *even* ν's, so that nonparabolicity is *not* the cause of the oscillations.[12] The strength of the oscillations increases with e-h pair density; the oscillations are *not* observed for "semiconducting" samples ($x>0.3$). Also, the strength decreases drastically with increasing temperature and all oscillations disappear for $T>50$ K, where e-h interaction becomes rela-

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TABLE I. The electron densities and mobilities of the samples studied. The numbers in parentheses are the values after LED illumination. Densities were obtained at 4.2 K and mobilities at 77 K.

No.	x	Density (10^{11} cm^{-2})	Mobility (10^5 cm^2/V s)
1	0.1	6.2 (5.5)	1.1
2	0.2	6.4 (5.8)	1.7
3	0.4	6.4 (5.4)	0.9
4	0.5	8.5 (6.1)	2.2
5	0.8	8.2 (5.0)	0.5
6	1.0	9.5 (6.0)	0.3

tively unimportant. Results thus point to the coexistence of electrons and holes as an essential ingredient for the observation of the oscillations.

The six samples investigated were grown by molecular-beam epitaxy under the same conditions. They consisted of a 15-nm InAs QW sandwiched between two $Al_xGa_{1-x}Sb$ barrier layers grown on a semi-insulating GaAs substrate, with the thicknesses of the upper and lower barrier 15 nm and 3 μm, respectively. A 10-nm GaSb cap layer was grown on top of the whole structure. Samples were not intentionally doped, but a large density of free electrons exist in the InAs QW's; the carrier densities and mobilities deduced from magnetotransport measurements[17] are listed in Table I. All the samples showed the negative persistent photoeffect,[16,17] which was used to reduce electron densities in the well [and to increase hole densities in the barrier(s) for semimetallic samples]; to induce this effect a red light-emitting diode (LED) was mounted *in situ*. Fourier-transform spectrometers were used in conjunction with superconducting magnets and a Bitter-type magnet to carry out the magnetospectroscopy.

Typical spectra at 4.2 K for sample 1 are shown in Fig. 1 for the field range 3.75–7 T. Two absorption lines are seen, interchanging their relative intensities in an oscillatory manner. The low-energy line is due to CR of electrons in the InAs QW, having an average mass of $0.035m_0$. The high-energy line (X line) is clearly observable only at sufficiently low temperatures (<40 K) and high fields (>1 T), and is interpreted as an internal transition ($1s \rightarrow 2p_+$-like) of excitons composed of spatially separated electrons and holes.[18] In the low-field region $B<3.75$ T, which is not shown in the figure, CR is dominant. With increasing field, the X line increases in intensity very rapidly at the expense of CR, since the application of perpendicular fields stabilizes the quasi-2D excitonic state. In the field range 3.75–7 T, however, both lines oscillate with field; CR maxima coincide with minima of the X line. Both CR linewidth and amplitude oscillate strongly, linewidth maxima and amplitude minima occurring simultaneously at even ν's.

In Fig. 2 we plot CR mass $m^* = eB/\omega_c$, amplitude, and linewidth vs ν for sample 1 at 4.2 K after illumination. A strong CR mass variation is seen in (a), with abrupt mass changes at even ν's. A data point at 5.75 T ($\nu=3.95$) is not plotted because of the very large uncertainty in peak position due to line broadening and loss of intensity. It should be noted that *between* two adjacent even ν's (e.g., $\nu=6$ and 4) the CR mass *decreases* with decreasing ν (increasing B), opposite to what would be expected from nonparabolicity. The oscillations in amplitude and linewidth [(b) and (c)] are

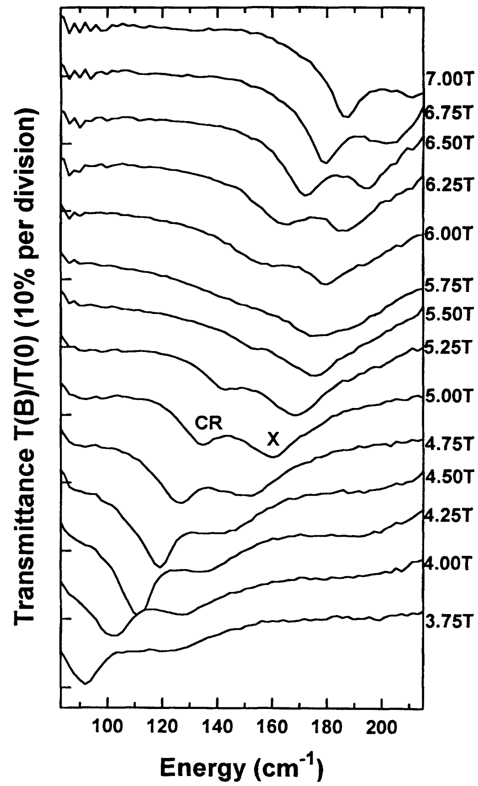

FIG. 1. Transmittance spectra for sample 1 at 4.2 K after LED illumination at several fields between 3.75 and 7 T. All traces are obtained by rationing to a zero-field spectrum.

similar to earlier results on InAs/GaSb QW's.[8] Clear oscillations are seen, linewidth maxima and amplitude minima occurring at *even* ν's; dramatic line broadening with concomitant amplitude reduction is observed at $\nu=4$. Thus the nonparabolicity interpretation[12] is obviously *not* appropriate to the present results. The small linewidth maximum near $\nu=5$ could be due to this effect.

We found that the strength of the oscillations increases with e-h pair density. Figure 3 displays CR mass vs B for four different e-h pair densities. Sample 2 shows semiconducting behavior before illumination and semimetallic behavior after illumination in magnetotransport properties in the field range of the present studies; this is because illumination lowers the Fermi energy E_F of the system, reducing the electron density and increasing the hole density.[16,17] Before illumination [3(a)] only CR, which does *not* exhibit oscillations, is observed, while after illumination [3(b)] both CR and the X line are observed *and* CR mass, amplitude, and linewidth oscillate. Sample 1 before illumination shows stronger oscillations [3(c)], since it has higher e-h pair density than sample 2; after illumination it shows even stronger oscillations [3(d)]. Before illumination [3(c)], the fields at which mass jumps occur for sample 1 do not agree with the even ν's calculated from the carrier density obtained by Shubnikov–de Haas (SdH) measurements on another piece of this sample (Table I), whereas after illumination [3(d)] they agree very well. The reason for this is that equilibrium in the system is achieved only after illumination, and E_F before illumination depends on the cooling history. The

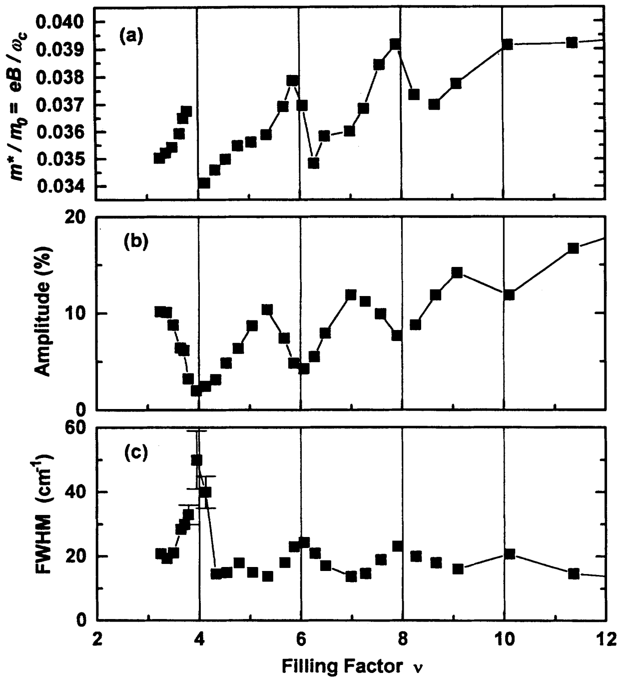

FIG. 2. CR oscillations vs filling factor for sample 1 after illumination at 4.2 K: (a) CR mass, (b) percent of absorption amplitude, and (c) full width at half maximum (FWHM). Values were obtained from fits of Lorentzians to the data.

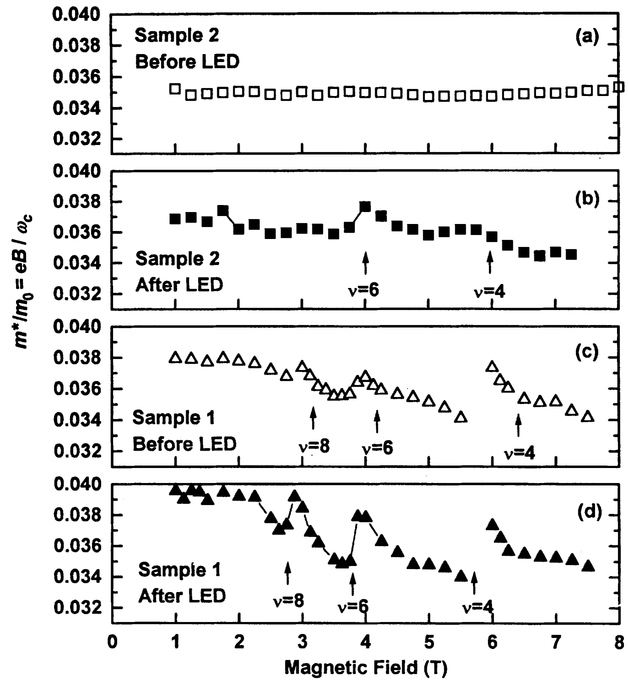

FIG. 3. Electron-hole pair density dependence of CR mass oscillation at 4.2 K. The lower panel for each sample [(b) and (d)] shows data for a higher pair density obtained by illumination with a red LED.

strength of amplitude and linewidth oscillations and the intensity of the X line also increase with e-h pair density, indicating that all the oscillations and the emergence of the X line are correlated.

For high-mobility semiconducting samples (samples 3 and 4), spin-resolved CR was observed, qualitatively the same as observed in InAs/AlSb QW's.[9,10] For relatively low-mobility semiconducting samples (samples 5 and 6), instead of splittings, weak linewidth oscillations were observed, with linewidth maxima at *odd* ν's: $\nu=9$, 7, and 5—consistent with the idea of Ref. 12. The strong even-ν oscillations observed for samples 1 and 2 were *absent* for these semiconducting samples, indicating that the existence of holes is essential for the oscillations.

Figure 4 shows CR mass vs T between 4.2 and 70 K at several magnetic fields. No data point at 5.75 T and 4.2 K is included because of the large uncertainty in peak position (see Fig. 1). The CR mass approaches the value $0.0352m_0$ at any ν as temperature is raised; if the mass at low temperature is lighter (heavier) than this value, it increases (decreases) with temperature. Similar tendencies are seen for amplitude and linewidth as well. Therefore, it can be concluded that all the oscillations become less pronounced with increasing temperature, disappearing at high enough temperatures ($T>50$ K), and the mass, amplitude, and linewidth of CR approach their mean values between maxima and minima. At high temperatures the X line also disappears,[18] consistent with the notion that the oscillations are intimately related to e-h correlations.

The screening properties of a 2D electron gas in a strong magnetic field and their effects on CR have been studied by several authors.[11] Since the screening of ionized impurities by free carriers is determined by the density of states at E_F, Landau-level widths vary with filling of the highest occupied Landau level. This has been invoked often to explain anomalies in CR line shape. In the present case, however, this is *not* the origin of the oscillations, since the observability of the oscillations is correlated *only* with the existence of holes, *not* of impurities; grown under the same conditions, all the samples should have similar residual impurity densities irrespective of being semiconducting or semimetallic. Furthermore, for samples 5 and 6, which have lower mobilities (more scatterers) than samples 1 and 2, we did not see the oscillations.

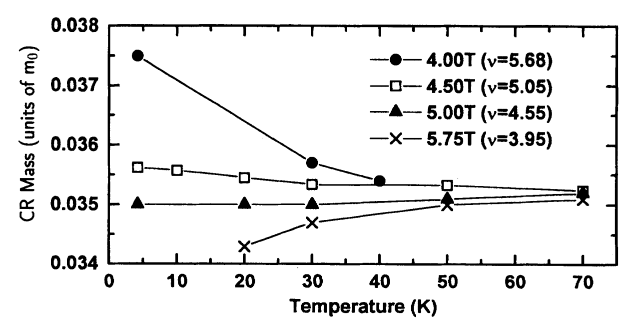

FIG. 4. Temperature dependence of CR mass for sample 1 after illumination at four different fields (filling factors). No data point at 5.75 T and 4.2 K is included because of the very large uncertainty in resonance position.

All the experimental facts lead us to conclude that the strong oscillations are due to ν-dependent e-h interaction. From the experimental results, particularly those on sample 2, it can be said that the existence of holes is indispensable for the oscillations. Electrons in the InAs QW and holes in the $Al_xGa_{1-x}Sb$ barrier(s) interact via their mutual Coulomb attraction, forming stable excitons at sufficiently low temperatures and high magnetic fields;[18] the X line has been assigned to an internal transition of the excitons. In the low-field regime $B<4$ T, the exciton binding energy increases strongly with field, stabilizing the excitonic state. In the high-field regime 4–7 T, where the quantization of the electron energy levels is significant as evidenced by SdH and quantum Hall effect measurements, the stability of the excitonic state must depend on ν.[19,20] This idea is strongly supported by the oscillatory ν dependence of the intensity of the X line, ν-dependent temperature dependence of the X-line intensity, and ν-dependent CR X separation. The overall tendency is that the X line is more stable at even ν than at odd ν, since at even ν screening is reduced. We attribute the dramatic mass variation to mass renormalization due to e-h interaction; Kohn's theorem breaks down because of the existence of holes (or excitons). It is important to note in Fig. 3 that the low-field CR mass after illumination is *larger* than before illumination for both samples 1 and 2, totally in disagreement with single-particle-band nonparabolicity effects since illumination *lowers* E_F, which should *reduce* the CR mass due to nonparabolicity. This observation thus strongly supports the idea that e-h interaction must be invoked in order to explain all the above phenomena consistently.

In conclusion, we have observed very strong filling-factor-dependent oscillations of CR linewidth, amplitude, and mass in semimetallic InAs/$Al_xGa_{1-x}Sb$ type-II QW's. Our results have made clear the fact that the oscillations are correlated with the existence of holes, *not* impurities. This finding resolves some of the discrepancies reported on CR in InAs type-II QW's. We believe that the Coulomb interaction between spatially separated electrons and holes plays a central role in the origin of the oscillations.

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