Ground State of a Two-Dimensional Coupled Electron-Hole Gas in InAs/GaSb Narrow Gap Heterostructures

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The contributions of wave function hybridization and spontaneous exciton formation to the ground state of closely spaced electron and hole gases in InAs/GaSb heterostructures were investigated using cyclotron resonance (CR) spectroscopy. Strongly hybridized samples exhibit two electronlike CR absorptions at all perpendicular magnetic fields. The high frequency mode neither disappears at high temperatures ($\sim$100 K) nor is affected by changes in electron or hole density, but is eliminated by a high parallel magnetic field ($\sim$7 T). These effects can be understood as signatures of electron-hole wave function hybridization, and cannot be explained in terms of an excitonic gas. [S0031-9007(99)08733-5]

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The formation of a thermodynamically stable excitonic ground state in a narrow gap semiconductor is a possible precursor to Bose-Einstein condensation in such systems. In order to achieve this, the band gap energy E_g of the semiconductor must be smaller than the exciton binding energy E_b, making it energetically favorable to spontaneously form excitons. To achieve $E_g < E_b$, InAs/GaSb heterostructures have been proposed [1–3] because the gap between the InAs conduction band and the GaSb valence band can be tuned from ~ -150 meV to positive values [4]. Thus, the spontaneous formation of an excitonic gas might be realized using closely spaced InAs and GaSb quantum wells, containing two-dimensional electron and hole states, respectively. To achieve the large E_b needed for experimental observation of such excitons, the distance between the gases should be minimized, maximizing the Coulombic attraction between the electrons and holes. Whether such an excitonic gas forms the ground state of the system depends on other competing mechanisms. In particular, as the interwell separation decreases, conduction and valence band wave function overlap results in hybridized states characterized by a new band gap energy Δ [4]. Additional considerations such as high and unequal extrinsic populations of electrons and holes may also inhibit exciton formation. Recent far-infrared (FIR) cyclotron resonance (CR) studies [5,6] of adjacent electron-hole gases in InAs/Al_xGa_{1-x}Sb heterostructures revealed two absorption peaks near the electron CR energy at $x = 0.1$ and 0.2. These were not attributable to two occupied electron subbands as in early CR studies of InAs/GaSb multiheterojunctions [7]. Instead, the lower energy peak was assigned to electron CR, and the higher energy peak to a cyclotron-shifted internal transition of a ground excitonic state. However, subsequent reinterpretation of these experimental results by other investigators [8,9] has suggested hybridized electron and hole Landau levels as a possible description. FIR CR spectroscopy is ideally suited to elucidate the nature of this ground state because it is a sensitive probe of the internal modes (e.g., $1s$ to $2p$) of excitons [10] as well as wave function hybridization [11].

In the present study, FIR CR spectroscopy is used to investigate the ground state of both strongly ($\Delta = 1.75$ meV) and weakly hybridized ($\Delta < 0.3$ meV) electron-hole gases in InAs/GaSb quantum wells. The latter is realized by insertion of a 15 Å AlSb barrier between the InAs and GaSb wells. The samples here have the same InAs quantum well thickness as those in Refs. [5,6], but a more negative gap between the conduction and valence band edges at the electron-hole interface as GaSb rather than $Al_xGa_{1-x}Sb$ ($x = 0.1, 0.2$) is used. However, both sets of samples have a single interface (due to their asymmetric well profiles), where electron-hole wave function overlap and thus hybridization occurs. In addition to studying the effects of spatial separation of the gases, spectra were recorded at a variety of electron densities N_e and hole densities N_h, with a parallel magnetic field $B_\parallel$, and at different temperatures T. The ability here to study systems with different spatial separations at varying N_e, N_h, $B_\parallel$, and T allows the modes which appear in the FIR CR spectra of the ground state to be unambiguously identified with hybridization of the conduction and valence band wave functions, and demonstrates that no signature of an excitonic gas arises in the spectra.

The heterostructures studied here were grown by molecular beam epitaxy, with AlSb barriers surrounding the quantum wells. Two samples with different degrees of electron-hole hybridization were compared. Strong hybridization was realized in a 150 Å InAs/100 Å GaSb

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structure, where the hybridization gap $\Delta = 1.75$ meV was determined from the temperature dependence of the resistance versus N_e and N_h, using the method in Ref. [11]. By contrast, weak hybridization was achieved in a 150 Å InAs/15 Å AlSb/150 Å GaSb structure, where the AlSb barrier had the effect of significantly reducing the hybridization occurring between electron and hole states, yielding a calculated estimate of $\Delta < 0.3$ meV [13]. From magnetoresistance oscillations, electron densities and mobilities for the strong and weakly hybridized samples at $T = 3.5$ K were $N_e = 4.1 \times 10^{11}$ cm^{-2}, $\mu_e = 28\,000$ cm^2 V^{-1} s^{-1} and $N_e = 9.7 \times 10^{11}$ cm^{-2}, $\mu_e = 71\,500$ cm^2 V^{-1} s^{-1}, respectively. Hole densities N_h were estimated as $(1-2) \times 10^{11}$ cm^{-2} in both samples. A semitransparent NiCr front gate was evaporated on the more strongly hybridized sample, enabling the sample to be studied at N_e ranging from 7.1 to 4.1×10^{11} cm^{-2} by tuning the front gate voltage. Illuminating the sample reduced the electron density further and also enhanced the hole density, giving $N_e \approx N_h \sim 3 \times 10^{11}$ cm^{-2}. FIR CR measurements were performed using Fourier transform (FT) spectroscopy, where the transmission spectra T were normalized by dividing by a reference spectrum T_{ref} at zero magnetic field, and the relative transmission $-\Delta T/T_{\text{ref}} = (T_{\text{ref}} - T)/T_{\text{ref}}$ was recorded. In addition, FIR laser CR spectroscopy was performed on the strongly hybridized sample.

Important insight into the nature of the ground state of the InAs/GaSb system may be obtained by studying the CR spectrum as a function of electron density N_e. Figure 1(a) shows the effect of carrier concentration (and electron fill factor $\nu_e = hN_e/eB_\perp$) on $-\Delta T/T_{\text{ref}}$ for the strongly hybridized sample at $B_\perp = 5.5$ T. Lorentzian fits show two absorption peaks separated by ~ 12 cm^{-1} located at a resonant frequency ω_{res} where electron gas CR is expected. As N_e is reduced, the intensity of the lower energy peak decreases significantly, but the intensity of the higher energy peak remains approximately constant over all N_e *and* N_h. Note the data presented for $N_e = 3.0 \times 10^{11}$ cm^{-2} ($\nu_e = 2.2$) were obtained by illuminating the sample, and thus N_h is 3×10^{11} cm^{-2} rather than between (1 and 2) $\times 10^{11}$ cm^{-2} as in the other traces. This is particularly significant since the intensity of the higher energy peak changes little despite the increase in N_h. If excitonic effects [5] were responsible for this peak, increased absorption might be expected due to an increase in the density of electron-hole pairs. No such change is observed. In addition, significant changes in electron screening would be expected over the large variation in N_e (>50%) investigated. An increase in N_e would reduce the exciton binding energy and therefore be expected to change both the internal transition energies and absorption strength, but no such changes are observed. Both peaks in Fig. 1(a) shift down in energy as N_e increases, reflecting nonparabolicity in the conduction band, which gives a greater electron effective mass m^*_{CR} at higher energies [14]. Although this can cause a splitting in CR, this effect is not the cause of the main splitting observed in Fig. 1(a). If it were, then the nonparabolicity induced spin-resolved CR would have the greatest splitting at odd ν_e, where two peaks of equal intensity would be seen, such as in InAs/AlSb systems [14]. This is indeed observed in the weakly hybridized sample, but not in the more strongly hybridized system, where the peak separation is approximately constant at all $B_\perp$ between 2.5 and 8 T [summarized in Fig. 3(below)]. Also, fixing $B_\perp$ at other values in this range gives similar trends in amplitudes with N_e to those in Fig. 1.

The sensitivity of the lower energy peak to carrier density suggests its origin is due to a CR transition from a level close to the Fermi energy E_F, where the level occupancy changes with carrier density. In contrast, the insensitivity

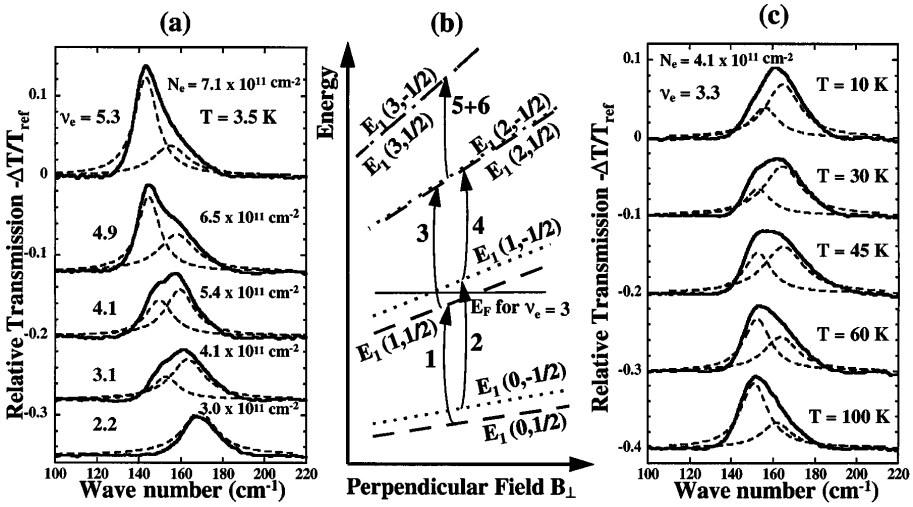

FIG. 1. Absorption spectra for 150 Å InAs/100 Å GaSb at $B_\perp = 5.5$ T vs (a) electron carrier density N_e and (c) temperature T. (b) shows schematic of electron levels $E_i(n, S_z)$ and CR transitions near $B_\perp = 5.5$ T predicted from the conduction/valence band hybridization model. In (a), the upper four curves correspond to changes in gate voltage, where $N_h = (1-2) \times 10^{11}$ cm^{-2}; the lower curve was achieved by illumination, where N_h increased to 3×10^{11} cm^{-2}.

of the high frequency peak to N_e suggests the likely cause for this peak is CR transitions with initial levels considerably below E_F, where changes in the carriers would have less effect on the spectrum. Thus, the carrier density dependent results of Fig. 1(a) can be explained by movement of E_F through levels involved in conduction and valence band hybridization. Tsay *et al.* have used $\mathbf{k} \cdot \mathbf{p}$ methods to calculate band structures for semimetallic $Al_xGa_{1-x}Sb/InAs$ quantum well structures with strong mixing between electron and hole Landau levels [9]. For a similar structure to the present strongly hybridized sample and close to $B_\perp = 5.5$ T, this model predicted enhanced spin splitting for Landau indices $n = 0, 1$, and virtually zero splitting for $n = 2$. Such behavior is illustrated schematically in Fig. 1(b) with the allowed CR transitions, using the notation $E_i(n, S_z)$, where i is the subband index, and S_z is the spin for the energy levels. In this figure, transitions 1 to 3, occurring at $\nu_e < 3$ have similar energy and appear as one unresolved peak in the FIR spectrum, as shown by the single peak observed under illumination. When $\nu_e > 3$, transition 4 becomes observable as a lower energy CR peak, with the frequency difference given by the spin splitting of the $n = 1$ levels. This is shown clearly in Fig. 1(a) by the increase in intensity of the lower frequency peak with N_e, and the splitting (12 cm^{-1}) is comparable to that predicted in the $\mathbf{k} \cdot \mathbf{p}$ model (15 cm^{-1}) [9]. For $\nu_e > 4$, the higher energy peak will decrease in amplitude reaching zero as the final state of transition 3 becomes occupied at $\nu_e = 6$; the start of this decrease is seen at the maximum N_e in Fig. 1(a). The lower energy peak will, however, maintain its amplitude since transitions 5 and 6 have similar energy to transition 4. Mixing of electron and hole Landau levels therefore explains the variation of amplitude of the two electronlike CR peaks. This $\mathbf{k} \cdot \mathbf{p}$ model also correctly predicts splitting for transitions between a spin-split and a spin-degenerate pair of electron levels at the other $B_\perp$ studied.

The effect of temperature T on the CR of this strongly hybridized sample also confirms that the spectral features are due to hybridization effects. This is shown in Fig. 1(c) for $N_e = 4.1 \times 10^{11}$ cm^2 at $B_\perp = 5.5$ T. As the temperature increases, there is an exchange in magnitude of the two peak amplitudes, with equal peak strengths occurring at $T \sim 50$ K. This result is explained by considering transitions 3 and 4 at $\nu_e = 3$. As the temperature rises, there will be an increase in electron occupation of the partially occupied level $E_1(1, -1/2)$ at E_F, at the expense of the filled level $E_1(1, 1/2)$ just below E_F. The intensities of CR transitions from initial states at E_F will therefore increase with temperature, while those from lower energy states will decrease. Although the higher energy CR peak decreases with temperature, it is notable that this peak is still present at $T = 100$ K. If this peak were associated with a bound excitonic state ~ 12 cm^{-1} above the electron CR peak, then its intensity would be expected to drop off more sharply, since the thermal energy kT would exceed this value by $T = 20$ K.

The effect of an in-plane magnetic field $B_\parallel$ on the transmission was also investigated in both samples. High $B_\parallel$ will significantly reduce the hybridization between the conduction and valence bands [15], thereby affecting the two CR peaks in Fig. 1 for the more strongly coupled sample. In particular, for $B_\parallel$-induced reduction of the hybridization, a single CR peak characteristic of an InAs quantum well should be recovered. By contrast, the effect of $B_\parallel$ on the binding energy of an exciton is much smaller. The magnetic length $l_B = (\hbar/eB)^{1/2}$ gives a value of ~ 90 Å at $B = 8$ T , so the diameter of the cyclotron orbit ($\geq 2l_B$) is always greater than the InAs well width. The additional confinement caused by $B_\parallel$ is about one tenth of the InAs well confinement energy and therefore has little effect on the spatial separation of the electrons and holes. Figure 2 compares (at fixed $B_\perp$) spectra at high $B_\parallel$ with those taken at $B_\parallel = 0$ T for the two structures; the parallel field is obtained by tilting the sample. In the strongly hybridized sample, the higher energy peak has disappeared at $B_\parallel \sim 7$ T, whereas the lower energy peak remains unchanged. Temperature-dependent magnetoresistance measurements on this sample confirm that all hybridization is destroyed at $B_\parallel \sim 7$ T. This differs from the weakly hybridized sample, where $B_\parallel$ has no effect on the spectra in Fig. 2. This contrasting behavior suggests that the higher energy peak in the more strongly hybridized sample at $B_\parallel = 0$ T is caused by conduction and valence band Landau level hybridization, rather than excitonic effects.

Further confirmation of wave function hybridization is provided in Fig. 3. This summarizes the peak positions obtained for the strongly hybridized sample over the entire $B_\perp$ range at $N_e = 4.1 \times 10^{11}$ cm^{-2}. The branches obtained by FT spectroscopy have a separation of ~ 12 cm^{-1}, and a cyclotron mass $m^*_{CR} \sim 0.0345$ calculated from the gradients. At even ν_e, the peak intensity of the lower

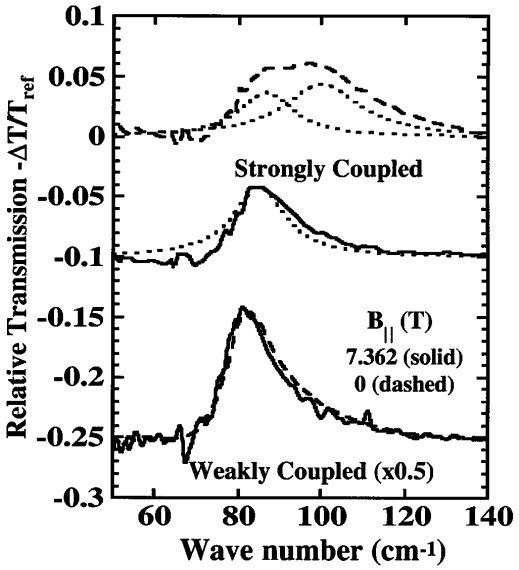

FIG. 2. Effect of high parallel field $B_\parallel$ on absorption spectra for the two samples at $B_\perp = 3.13$ T. The dotted lines show Lorentzian fits.

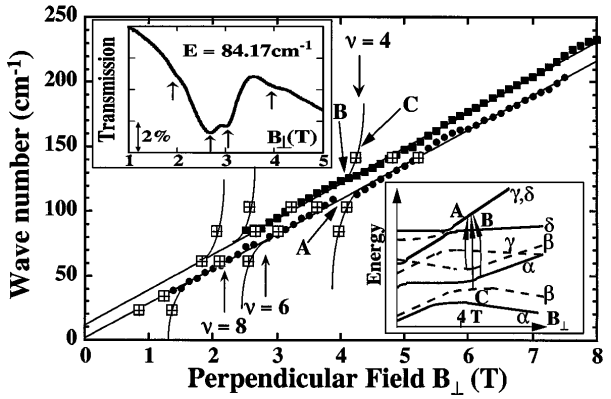

FIG. 3. Transition energy vs $B_\perp$ for 150 Å InAs/100 Å GaSb at 3.5 K from Fourier transform (solid squares and circles) and FIR laser (crossed squares) spectroscopy. Left inset shows four peaks in laser transmission spectrum at laser wavelength $\lambda = 118.8\ \mu$m ($E = 84.17\ \text{cm}^{-1}$). Right inset shows schematic of energy levels anticrossing at $B_\perp \sim 4$ T with transitions producing peaks labeled A, B, and C. Energy levels in the inset are mixtures of the following states: $\alpha = E_1(1, 1/2), H_1(3, -3/2)$; $\beta = E_1(1, -1/2), H_1(2, -3/2)$; $\gamma = E_1(2, 1/2), H_1(1, 3/2)$; $\delta = E_1(2, -1/2), H_1(0, 3/2)$.

branch falls off sharply, and measurements by FIR laser spectroscopy reveal additional peaks moving rapidly to lower energy near $\nu_e = 4$, 6, and 8. Similar curves and fluctuations in both ω_{res} and amplitude have been observed for a symmetric $AlAl_{0.1}Ga_{0.9}Sb/InAs/Al_{0.1}Ga_{0.9}Sb$ structure [6], also with a 150 Å InAs well thickness, where the splitting between branches reached 30 cm^{-1}. However, the FIR laser results in Fig. 3 show additional deviations from the *upper* dispersion branch, with ω_{res} rising rapidly with increasing $B_\perp$. The right inset of Fig. 3 shows schematically the origin of the three observed transitions at $\nu_e \sim 4$. Here, mixing and thus anticrossing occurs between the $E_1(1, 1/2)$ and $H_1(3, -3/2)$ levels, and also between the $E_1(1, -1/2)$ and the $H_1(2, 3/2)$ levels. The resulting curvature causes the observed deviations from the electronlike CR, and the mixing explains the decreasing amplitude. Therefore, FIR laser spectroscopy has successfully probed hybridized levels in this system, and can account for experimental observations such as the fluctuations in ω_{res} and amplitude as a function of $B_\perp$.

Several points relevant to the realization of a thermodynamically stable excitonic ground state in InAs/GaSb should be made with regard to the data and discussion above. First of all, no internal transitions of excitons were noted in the spectra of either the weakly hybridized sample or the strongly hybridized sample at high $B_\parallel$, where the energy gap Δ was suppressed. This was the case despite the small band gap energies ($\Delta < 0.3$ meV) and the fact that the electron and hole gases were separated by only ~145 Å on average, suggesting binding energies in the range $E_b \sim 3.3$ meV [1]. Theoretical treatments [2,3] also suggest that structures not dissimilar from those here might be suitable for excitonic formation. Moreover, no such transitions were observed at $N_e \approx N_h \sim 3 \times 10^{11}$ cm^{-2} when exciton formation might also be most favorable due to the equal carrier densities. The most likely reason for this absence of an excitonic signature in the CR spectra is that either the low mobility of the electron and/or hole layers proved detrimental to the observation of excitonic effects, or the carrier densities were too large for the formation of an excitonic gas.

In conclusion, ground states of both strongly ($\Delta \sim 1.75$ meV) and weakly ($\Delta < 0.3$ meV) hybridized electron-hole gases have been studied in InAs/GaSb heterostructures using FIR CR spectroscopy. Spectra for the weakly hybridized samples were dominated by well-known nonparabolicity effects [14]. In contrast, the strongly hybridized structure showed two distinct absorption modes over all $B_\perp$ investigated. The higher frequency mode persisted to $T \sim 100$ K and did not vary in absorption intensity over a range of N_e and N_h. Further, this mode was suppressed when $B_\parallel \sim 7$ T was applied. All of these characteristics are well explained by the presence of two CR transitions induced by hybridization of electron and hole Landau levels. They are inconsistent with an explanation of these modes in terms of effects arising from the presence of a spontaneously formed excitonic gas. Although spontaneous formation of an excitonic gas in narrow gap structures cannot be completely ruled out from these results, we believe that similar hybridization effects can explain the main features observed in previous work on these materials.

Note added.—Since submitting this Letter, Singh *et al.* [16] have presented further results and discussion concerning the two peaks revealed in Refs. [5] and [6].

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