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Evidence for electron-hole hybridization in cyclotron-resonance spectra of InAs/GaSb heterostructures

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Cyclotron-resonance (CR) experiments have been performed on InAs/GaSb/AlSb double structures, in which electron and hole layers are separated by AlSb barriers. The strength of the electron-hole coupling is altered by varying the barrier width. Our data reveal that properties of InAs/GaSb systems with AlSb barriers thinner than 1.5 nm are entirely determined by interlayer tunneling and the CR features in such samples can be explained by hybridization between states in the InAs conduction band and in the GaSb valence band. [S0163-1829(99)14235-8]

Electron-hole coupling plays a decisive role in a variety of novel physical effects such as excitonic insulator phase, Bose-Einstein condensation, superconductivity, and others which were predicted for closely spaced parallel electron and hole layers. The validity of a given effect depends strongly on the character and the degree of the electron-hole coupling. Electron and hole states can be coupled through tunneling that results in overlap of their wave functions or can be bound by their Coulomb attraction.

Experimental realization of such a system can be easily done in an InAs/GaSb heterostructure. The bottom of the InAs conduction band lies about 150 meV below the top of the GaSb valence band that results in electron transfer from GaSb layers to InAs quantum wells and the formation of spatially separated electron and hole two-dimensional (2D) gas layers. Although intensive experimental studies were performed on these structures,[1–5] there is still controversy over the character of the electron-hole interaction, which is responsible for the experimentally observed features. In spite of that fact that theoretical studies stress the importance of electron-hole hybridization due to their wave-function overlap,[6,7] the most recent cyclotron-resonance (CR) experiments on such structures are treated on the basis of Coulomb interaction. The CR spectra in InAs/GaSb systems are characterized by the strong oscillations of the CR linewidth and amplitude with magnetic field. This effect was first observed by Heitmann *et al.*[1] and was attributed to filling-factor-dependent screening of the scattering potential. Detailed far-infrared magneto-optical studies of InAs/Al$_x$Ga$_{1-x}$Sb structures with different values of x were reported by Kono *et al.*[2] The authors have observed a clear difference between ''semiconducting'' ($x>0.3$) and ''semimetallic'' ($x<0.3$) samples, where only the ''semimetallic'' samples revealed oscillations. This difference was attributed to Coulomb interaction between the electrons and holes. Warburton *et al.*[3] reported studies of CR oscillations in InAs/GaSb with additional doping, and only p^+ samples revealed CR splitting and oscillations. The authors concluded that the presence of a sheet of mobile positively charged holes can somehow decouple CR transitions of electrons with different CR masses due to nonparabolicity of the InAs conduction band. Confirmation of electron-hole hybridization was recently obtained in electrical measurements[8,9] and only a few indications of such effects in CR experimental data have been reported.[2,10]

In order to clarify the nature of the electron-hole coupling, we have studied CR spectra for InAs/GaSb structures with an additional AlSb barrier layer grown at the GaSb/InAs interface. The strength of the coupling has been tuned by varying the barrier width. We have found that the CR features change when the barrier width is increased from 0.6 nm to 2 nm. Our data provide evidence that electron and hole 2D layers in InAs/GaSb structures are coupled through tunneling rather than through Coulomb interaction. We have revealed that strong CR linewidth and amplitude oscillations with magnetic field are the result of electron-hole hybridization. In addition, a weak CR splitting has been observed in the vicinity of electron and hole Landau-level anticrossing. This splitting decreases with increasing barrier width, suggesting hybridization as the origin of the minigap formation.

Our experiments were carried out on single InAs/GaSb quantum-well (QW) structures grown by molecular-beam epitaxy at 500 °C. The samples consist of a 20-nm InAs QW with InSb monolayers intentionally formed at both interfaces. The wells are separated from the GaSb environment by AlSb barriers of different thicknesses. The sample parameters are shown in Table I. The CR spectra were measured with a rapid-scan Fourier-transform spectrometer at $T=2.2$ K and at magnetic fields up to 13 T. The emission was detected by a Si-composite bolometer. The sample substrates were wedged to avoid interference distortions of CR spectra. The carrier concentration was changed by illuminating the samples with a red light emitting diode (LED).

Representative sets of CR traces for two samples with different barrier widths are shown in Fig. 1. All of the samples exhibit clear electron and hole (not shown) cyclotron resonances, which directly proves the coexistence of

TABLE I. Sample parameters. d is the AlSb barrier thickness, μ is the electron mobility at 77 K, and n_s is the electron density at 2.2 K.

No.	d (nm)	μ (10^5 cm^2/V s)	n_s (10^{12} cm^{-2})
1	0	0.61	1.1
2	0.6	0.65	1.34
3	2	1.37	0.9
4	10	1.65	1.0

electrons and holes in our samples. We observe strong differences in the electron CR line behavior for samples with different barrier thicknesses. The samples without a barrier or with a thin barrier (0.6 nm) reveal strong CR linewidth and amplitude oscillations, which resemble the CR data of Heitmann *et al.*[1] and Kono *et al.*[2] In Fig. 1(a) we show several CR traces at different magnetic fields for sample 2. A more complete understanding can be obtained from Fig. 2(a), which shows a contour plot of normalized transmission as a function of both energy and magnetic field. Presented in the form of a color scale plot, it demonstrates the dramatic change of CR linewidth and amplitude with magnetic field. Similar CR oscillations are observed for the sample without any AlSb barrier (sample 1), indicating that the properties of the interfaces are not essential for the onset of the CR oscillations in our samples. At the same time, the samples with thicker barriers (sample 3 and sample 4) show CR spectra with a pronounced splitting, qualitatively the same as reported in Refs. 4 and 5. Only weak variation of the CR linewidth and weak decrease of amplitude are observed in these samples [Fig. 1(b) and Fig. 2(b)].

It is especially worth noting that the CR oscillations disappear when the thickness of the barrier between the electron and hole layers is increased from 0.6 nm to 2 nm. The different behavior of these samples is obviously not related to the absence or presence of holes. This scale is also too small for the long-range Coulomb interaction. In our case the typical scale for remote charge scattering is about 10 nm,[11] which is considerably larger than the relevant barrier thickness. However, it is easy to show that the AlSb barrier with a width of 2 nm is enough to suppress the interlayer tunneling. The typical tunnel penetration length for an electron having energy near the Fermi energy E_F (about 80 meV) from InAs into the AlSb barrier is about 1 nm. This value for holes in GaSb is 0.8 nm, so a 2-nm AlSb barrier cuts off the wave-function overlap between states in the InAs conduction and the GaSb valence bands. Although the 0.6-nm barrier reduces tunneling, the wave-function overlap is still preserved to a smaller degree. These data prove the importance of tunneling between the conduction and valence bands in samples with thin (less than 1.5 nm) AlSb barriers and provide strong evidence that the wave-function overlap plays a crucial role in the onset of CR oscillations.

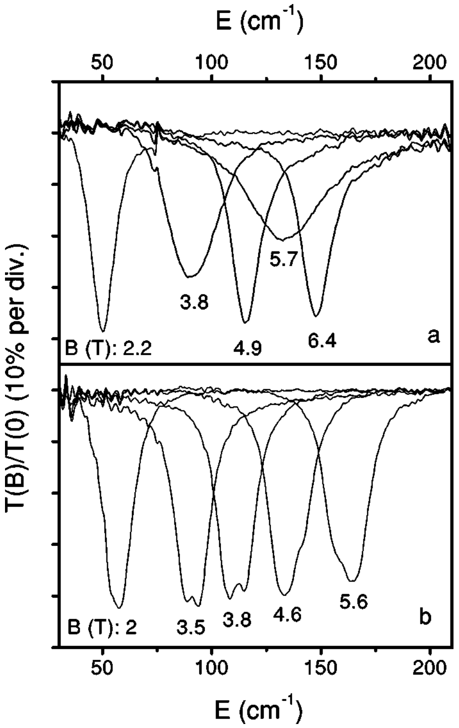

FIG. 1. Typical CR spectra (a) for sample 2 with 0.6-nm AlSb barrier at fields B (T)=2.2, 3.8, 4.9, 5.7, 6.4, and (b) for sample 3 with 2-nm AlSb barrier at fields B (T)=2, 3.5, 3.8, 4.6, 5.6. All traces are normalized with a zero-field spectrum.

In Fig. 3 we plot the magnetic-field (B) dependences of the CR linewidth for sample 2 before and after illumination. CR mass and amplitude oscillations (not shown) are correlated with the linewidth dependence so that amplitude and mass minima correspond to the linewidth maxima and vice versa. The most important observation is that, in contrast to the earlier reported results,[1,2] these oscillations are not correlated with the filling factor. We found that maxima and minima in the magnetic-field dependences are not shifted after illuminating the sample with a LED as seen from Fig. 3, although the electron density obtained from Shubnikov–de Haas (SdH) measurements varies from 1.39×10^{12} cm^{-2} to 1.28×10^{12} cm^{-2} upon illumination. Positions of integer filling factors are also shown in Fig. 3 for high magnetic fields. The carrier density change induced by the LED illumination does not influence the maximum positions in the magnetic-field dependences for this sample but changes the oscillation magnitude. Thus, both Coulomb interaction and screening effects are obviously not responsible for the CR oscillations. Below we argue that the observed CR oscillation features are directly related to hybridization between states in the InAs conduction band and the GaSb valence band.

Our results can be easily understood from the sketch of electron and hole Landau-level dispersion in an InAs/GaSb system based on two-band model calculations[6] (Fig. 3, inset). Resonant tunneling between conduction and valence bands is allowed for electron and hole Landau levels with numbers satisfying certain selection rules, which reflect the conservation of the total angular momentum parallel to the magnetic field.[12] Mixing between electron and hole Landau levels leads to the appearance of hybridized states and opens a hybridization gap in the vicinity of the Landau-level intersection. This coupling occurs near the magnetic-field values, which could be roughly estimated from the following equation:

$$\hbar \frac{eB}{m_e^* c}(N+1/2) \pm 0.5\mu_B B \frac{4m_0+m_h^*(3g_h-g_e)}{m_h^*+m_e^*} = \Delta \frac{m_h^*}{m_h^*+m_e^*}. \tag{1}$$

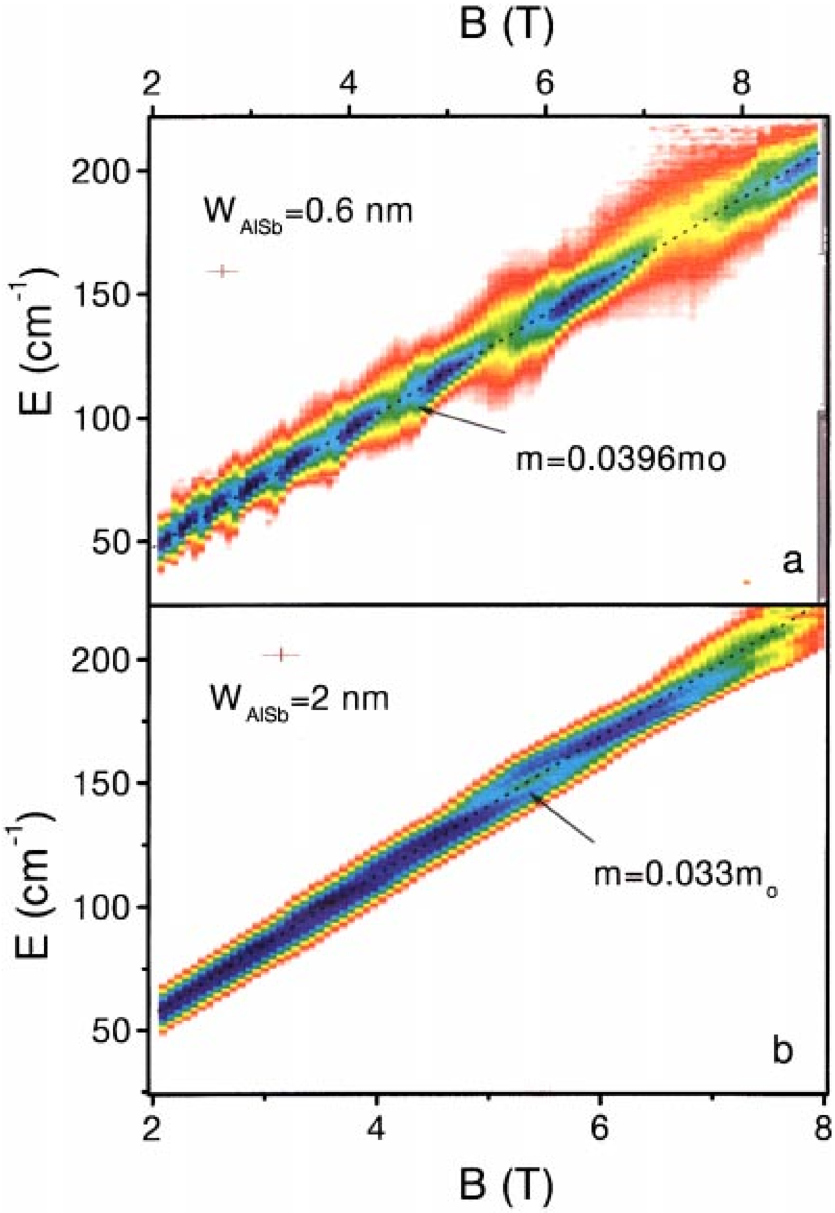

FIG. 2. (Color) Color-scale plot of transmission as a function of both energy and magnetic field (a) for sample 2 with 0.6-nm AlSb barrier and (b) for sample 3 with 2-nm AlSb barrier. Peak amplitude maxima are shown as dark areas.

Here μ_B is Bohr's magneton, g_e and g_h are electron and hole g factors, and Δ is the energy distance between electron and hole ground subbands.

As follows from this model, such features in CR spectra as linewidth maximum and/or CR splitting are expected to appear in the vicinity of the Landau-level anticrossing. The CR line broadens when the InAs conduction-band states, which participate in the absorption process, are coupled with the GaSb valence-band states. There are two possibilities for the CR line to become broader: first is an unresolved doublet including the transitions from split levels; the second, ''homogeneous'' broadening, may occur due to additional scattering processes arising from mixing of the hole states and the electron states. In our case the considerable enhancement of the CR linewidth is related to mixing between high-mobility ($\sim 10^5$ cm/V s) electrons and low-mobility ($\sim 10^4$ cm/V s) holes. Obviously, unresolved splitting cannot provide such a huge (more than five times) enhancement of the CR linewidth.

Another important point, which can be explained by this model, is the fact that the changes in carrier densities produced by external illumination of the sample do not affect the CR oscillation period (Fig. 3). The CR linewidth oscillations can be described within this simple model, in a manner similar to electron SdH oscillations with a 1/B period of

$$\delta_{1/B}=\frac{\hbar e}{m_e^* c E_{\text{eff}}}, \tag{2}$$

where $E_{\text{eff}}=\Delta m_h^*/(m_h^*+m_e^*)$. It is seen that the period of the CR linewidth oscillations does not depend on the Fermi-level position but is defined by the energy Δ separating the electron and hole ground levels. Thus, the anticrossing of the electron and hole levels, and not the position of the Fermi energy, determines the magnetic field of the CR linewidth maximum.[13]

In addition to the CR line broadening in samples with strong electron-hole hybridization, we observe a CR line splitting. Figure 4 shows several traces of the CR spectra for sample 2 at magnetic fields in the vicinity of the electron and hole Landau-level intersection. It is clearly seen that a second peak appears on the high-energy shoulder. Asymmetric

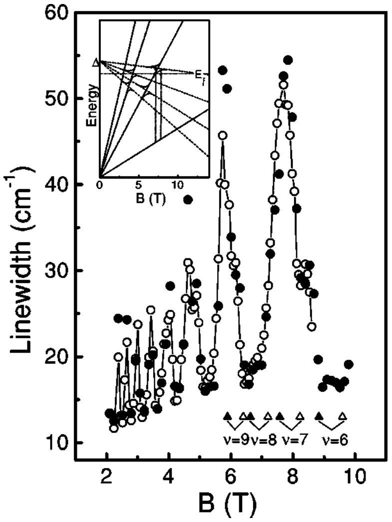

FIG. 3. Strong oscillations of linewidth before (open circles) and after (solid circles) illumination for sample 2. Several integer filling factors are shown for high magnetic fields before (open triangles) and after (solid triangles) illumination. Inset: qualitative representation of Landau-level structure for both electrons in the InAs conduction band (solid lines) and holes in the GaSb valence band (dotted lines). Hybridization gaps between respective Landau levels are also shown along with possible CR transitions.

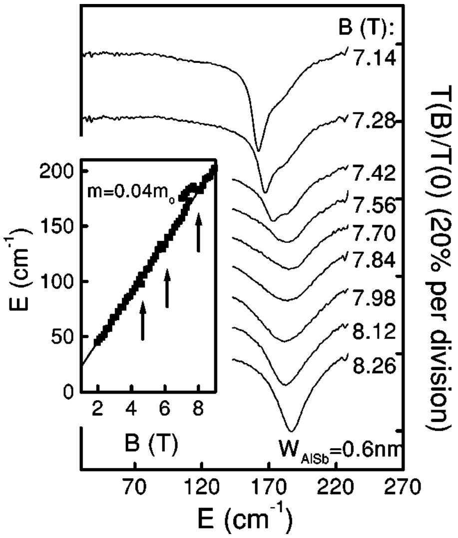

FIG. 4. CR spectra for sample 2 in the vicinity of the intersection between electron and hole Landau levels. Inset: Fan chart for sample 2; arrows indicate positions of splitting and asymmetric features of CR spectra.

broad features (Fig. 4, inset) appear also at smaller magnetic fields with a period different from the period of SdH oscillations, but consistent with the period given by Eq. (2). The CR splitting, which is resolved at high magnetic fields, can be attributed to split Landau-level transitions and gives the gap energy of about 1.3 meV. A similar CR splitting is also observed in sample 1 (without a barrier) and gives the splitting energy about 3.5 meV, which is in agreement with Ref. 8. We believe that the splitting energy corresponds to the value of the hybridization gap. All of the experimental observations support the assignment of the observed CR splitting to the hybridization gap. The strongest argument is the correlation between the splitting energy and the barrier thickness. The gap, which is determined by electron-hole coupling, clearly decreases with increasing barrier width.

In summary, we have shown that on the basis of the electron-hole hybridization model, a whole class of experimental results can be explained in a consistent way.

Note added in proof. Similar results have been obtained by Marlow *et al.*[14]

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