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High-field magneto-spectroscopy of quasi-2D electrons and holes in $InAs/Al_xGa_{1-x}Sb$ single quantum wells

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Abstract

Far-infrared magneto-transmission studies on two high mobility $InAs/Al_xGa_{1-x}Sb$ ($x = 0.1$ and 0.2) type-II single quantum wells in magnetic fields up to 30 T show that a magnetic-field-induced semimetal–semiconductor (SM–SC) transition occurs in the $x = 0.2$ sample between 8 and 12 T, and in the $x = 0.1$ sample in the vicinity of 28 T. The so-called X-lines vanish at high magnetic fields and temperatures, consistent with their assignment to internal transitions of stable, spatially separated excitons. A large splitting ($\sim 30\,cm^{-1}$) between cyclotron-resonance-like transitions for $13\,T \leqslant B \leqslant 23\,T$ for the $x = 0.1$ sample is attributed to enhanced spin splitting due to conduction–valence-band Landau-level mixing across the interface. © 1998 Elsevier Science B.V. All rights reserved.

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There has been considerable interest in the electronic properties of $InAs/Al_xGa_{1-x}Sb$ type-II heterostructures in the past two decades because of their unusual band-edge alignment, which results in spatially separated electrons and holes confined in adjacent layers. This has led to a variety of interesting experimental observations, such as a magnetic-field-induced semimetal–semiconductor (SM–SC) transition [1–3], strong cyclotron resonance (CR) oscillations [4,5], evidence for internal transitions of stable excitons [5] and effects of hybridization [6–8] of the in-plane dispersion of electrons (in InAs) and holes (in $Al_xGa_{1-x}Sb$) for $x < 0.3$. Calculations [6] for intrinsic InAs/GaSb superlattices and quantum wells that are usually termed semimetallic show a hybridization gap of a few meV owing to the coupling between electrons and holes across the interface. Yang et al. [7] have recently verified the existence of a small positive gap in a "semimetallic" InAs/GaSb quantum well when the electron density is made approximately

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equal to the hole density. Hence, extrinsic effects (such as surface states and deep levels) are believed to be responsible for the "semimetallic" behavior. For simplicity, we shall refer to semimetallic samples as those which have both electrons and holes, regardless of their origin.

Recently, Kono et al. [5] reported features in far-infrared (FIR) magneto-transmission experiments on $InAs/Al_xGa_{1-x}Sb$ single quantum wells at magnetic fields less than 7 T (e–X and h–X lines for $x = 0.1$, and an e–X line for $x = 0.2$) that were attributed to internal transitions of stable excitons. Electron and hole CR were also observed in the $x = 0.1$ sample, and electron CR in the $x = 0.2$ sample. The X-lines increased in intensity at the expense of CR with increasing electron–hole (e–h) pair density, decreasing temperature, or increasing magnetic field (B). The intensity of the e–X line (CR) also showed oscillations with B with maxima (minima) at approximately even filling factors.

We have extended the low field measurements [5] to 30 T to probe the magnetic-field-induced SM–SC transition and its influence on the X-lines, and to achieve a better understanding of the so-called conduction-valence Landau-level mixing (CVLLM) effect [6–8] on the hole (in barrier) and electron (in well) states. We find that the SM–SC transition occurs in the $x = 0.2$ sample between 8 and 12 T, in agreement with a previous report [2], while it occurs in the vicinity of 28 T in the $x = 0.1$ sample. The SM–SC transition in such structures, where the electrons are confined in the well (InAs) and the holes by their self-consistent potential [9] in the thick $Al_xGa_{1-x}Sb$ barrier, occurs when the lowest spin state of the $N = 0$ electron Landau-level $(0,\uparrow)$ crosses the highest spin state ($m_J = \frac{3}{2}$) of the $N = 0$ hole Landau level in the barrier. Simple calculations with band overlaps given by $(0.4x–0.15)$ eV show that the SM–SC transitions in the $x = 0.2$ and 0.1 samples occur at about 9 and 28 T, respectively. We have also observed a large separation ($\sim 30\ \mathrm{cm}^{-1}$), between two CR-like transitions for $13\ \mathrm{T} \leqslant B \leqslant 23\ \mathrm{T}$ in the $x = 0.1$ sample and attribute this enhanced splitting to the CVLLM effect, as described below.

Two samples were studied. Both have a single InAs (15 nm) quantum well located 25 nm below a 10 nm GaSb cap and a 15 nm $Al_xGa_{1-x}Sb$ barrier, all grown on a thick (3 μm) $Al_xGa_{1-x}Sb$ barrier on a GaAs substrate; the barrier compositions are $x = 0.1$ and 0.2. At low temperatures, after illumination with a red light-emitting diode (LED), the $x = 0.1$ and 0.2 samples have net electron densities of 5.5×10^{11} and $5.8 \times 10^{11}\ \mathrm{cm}^{-2}$, and mobilities of 1.1×10^5 and $1.7 \times 10^5\ \mathrm{cm}^2/\mathrm{V\,s}$, respectively. Fourier-transform spectrometers were used in conjunction with 9 and 17 T superconducting magnets at Buffalo and a 30 T resistive magnet at the NHMFL to carry out far-infrared magneto-spectroscopy experiments. Photoconductive Ge : Ga and Si : B detectors were used to cover the spectral region between 80 and $600\ \mathrm{cm}^{-1}$ at Buffalo and a 4.2 K Si composite bolometer was used to cover the spectral range $320–800\ \mathrm{cm}^{-1}$ at the NHMFL. Light pipes, mirror optics and condensing cones were used to guide far-infrared light from the spectrometer to the sample/detector arrangement.

Typical magneto-transmission spectra for the $x = 0.2$ sample at 15 T after red LED illumination are shown at several temperatures in Fig. 1. Two features are seen at all temperatures; these features were previously observed and attributed to spin-up and spin-down cyclotron resonance [5]. At low temperatures, the lower frequency line is weak and not completely resolved, but it gains strength as temperature is raised. At high temperatures, the lines narrow and are well resolved with a separation of about $17\ \mathrm{cm}^{-1}$. The similarity of the line shapes and the behavior of the line widths with temperature suggest a similar origin. The possibility that the higher-frequency line is the e–X line can be ruled out: the strength of this line does not decrease significantly with temperature up to 65 K, and hence it is not associated with a bound state [5]. These results are consistent with the assignment of the two lines to spin–split CR as indicated in the inset. The increasing strength of the lower-frequency line with increasing temperature is due to thermal population of the higher spin-down Landau states $(0,\downarrow)$ at high temperatures. Thus, the $(0,\downarrow) \rightarrow (1,\downarrow)$ transition gains strength with increasing temperature. The magnitude of the splitting (about $17\ \mathrm{cm}^{-1}$ at 15 T) is consistent with measurements in semiconducting InAs/AlSb quantum wells [10,11] and with semiconducting alloy samples [5]. The e–X line, which is observable below 7 T, is not

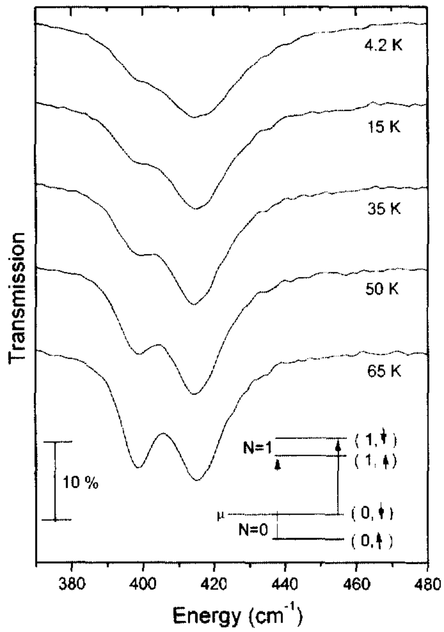

Fig. 1. Transmission spectra for the $x = 0.2$ sample at 15 T are shown for several temperatures after red LED illumination. The inset shows the level structure, the CR transitions, the position of the chemical potential, and the notation. N denotes the Landau quantum number, and ↑, ↓ the spin state.

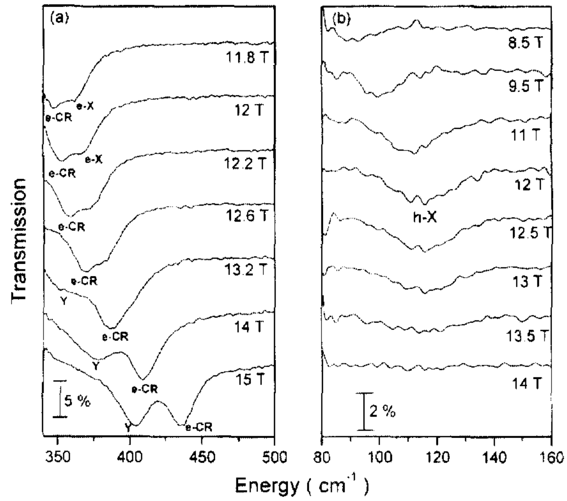

Fig. 2. Transmission spectra for the $x = 0.1$ sample at 4.2 K are shown for several magnetic fields after LED illumination in two different frequency regions: (a) high frequencies; (b) low frequencies. The various features are labeled as described in the text.

seen in this higher magnetic field range. The assignment of the e–X line to an internal transition of excitons and its disappearance between 8 and 12 T is consistent with the SM–SC transition occurring in this field range. Therefore, we conclude that the SM–SC transition takes place between 7 and 12 T (consistent with transport results [2] and the calculation) in this sample.

Magneto-transmission spectra in two different frequency regions are shown at several magnetic fields between 8.5 and 15 T at 4.2 K for the $x = 0.1$ sample in Fig. 2a and b. In Fig. 2a (frequencies above 340 cm^{-1}) two features separated by about 14 cm^{-1} are seen at 11.8 T. As the magnetic field is increased, the higher frequency line (labeled e–X) gains strength up to about 12.2 T and then gradually loses strength with a further increase in magnetic field. In Fig. 2b (frequencies between 80 and 160 cm^{-1}) a weak line (labeled h–X) that also gains strength with increasing magnetic field up to about 12 T is observed; it then decreases in strength at still higher fields. Near 12 T, the e–X and h–X lines both lose strength with increasing temperature, while the lower frequency line (labeled e–CR in Fig. 2a), gains strength slightly. In addition, as shown in Fig. 2a, a new feature, Y, appears about 30 cm^{-1} below e–CR at magnetic fields above 13 T. This line is initially broad with a low-frequency tail, narrows and gains strength with increasing magnetic field up to 16 T, loses intensity at still higher fields, and is not observable above 23 T. The separation between Y and e–CR increases with magnetic field above 16 T. The intensities of Y and e–CR show little dependence on temperature. Near 23 T (Landau-level filling-factor $\nu \sim 1$) another higher frequency line appears as shown in the summary plot of Fig. 3. Between 23 and 27 T ($\nu \leqslant 1$) these two lines are separated by 20 cm^{-1}. Above 27 T, only the higher frequency line survives.

The strengths of the lines labeled e–X and h–X in Fig. 2a and b show similar magnetic field and temperature dependences. The initial increase in strength of these lines up to 12.2 T ($\nu = 2$ at 11.5 T) is consistent with the even-filling-factor-dependent increase of the X lines observed previously [5] at lower magnetic fields ($B < 7$ T). If the e–X and h–X lines are different internal transitions of the same

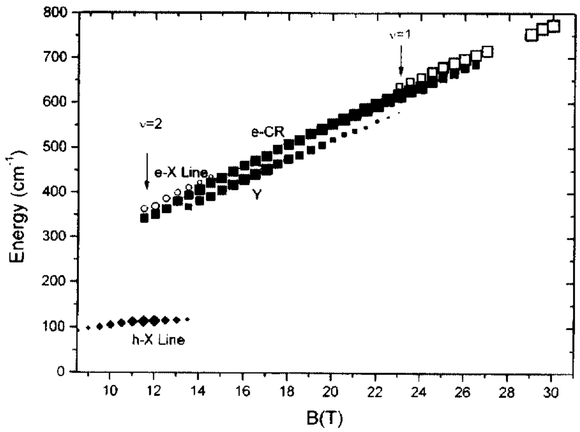

Fig. 3. Photon energies of the transmission minima for CR-like features (squares), e–X (open circles) and h–X (solid diamonds) are plotted versus magnetic field. The area of the symbols indicates the relative strength of the various features; the h–X line has been scaled up by a factor of 4. The field positions for filling-factors 2 and 1 are indicated by the arrows.

bound state, with increasing temperature their intensities should decrease in concert, as observed. The fact that the X-lines disappear at about 15 T indicates that the (0,↓) electron Landau level, which is partially occupied for $11.6\ T < B < 23\ T$, is already above the highest spin state ($m_J = \frac{3}{2}$) of the $N = 0$ hole Landau level in the barrier at this field.

The line labeled e–CR in Fig. 2a is identified as cyclotron resonance from the lowest spin-up Landau-level (0,↑) to (1,↑). This assignment is consistent with the experimental observations: (1) it is dominant for $11.8\ T \leqslant B \leqslant 25\ T$; (2) at the highest fields it is shifted up and becomes the only surviving feature beyond 27 T. The small separation ($\sim 14\ cm^{-1}$) between the e–CR and the e–X line at $B > 11.5$ T, compared to the $23\ cm^{-1}$ separation at 7 T, can be qualitatively understood from the following arguments. The e–X line is an internal transition (1s–2p$^+$ in the low-field, hydrogenic notation) of excitons formed from spatially separated electrons and holes. Increasing magnetic field compresses both the 1s and 2p$^+$ wave function in the plane perpendicular to the magnetic field. This will decrease the average distance between the electron and the hole in both states and increase the binding energy of both states. The fractional effect is larger for the more extended 2p$^+$ wave function. Therefore, the energy separation between the e–CR and the e–X line should decrease with increasing magnetic field as in the case of barrier impurities [12] and should approach e–CR in the high field limit. The measured separation between the CR and e–X lines decreases from $30\ cm^{-1}$ at 4 T to $14\ cm^{-1}$ at 12 T, consistent with the above explanation. All observations are consistent with the assignment of the e–X and h–X lines to internal transitions of spatially separated excitons.

The additional feature Y, which appears at about 13 T, and initially increases in strength, loses strength for $B > 16$ T and is not observable beyond 23 T ($\nu < 1$), as shown in Fig. 3. This indicates that it may be CR originating from the higher spin-down Landau states (0,↓). This assignment is compatible with the fact that increasing temperature has little effect on the strengths of Y and e–CR at 15 T, and the separation between these lines increases with increasing magnetic field for $B > 16$ T. The observed separation ($\sim 30\ cm^{-1}$) between these two CR-like transitions (Y and e–CR) for $B \geqslant 13$ T, is somewhat larger than expected for CR spin splitting due to the usual conduction band non-parabolicity ($\sim 17\ cm^{-1}$) [10,11]. Invoking the so-called Rashba effect [13], to explain this large spin splitting of CR in the $x = 0.1$ sample is not compatible with the entirely different measured spin splitting in the vicinity of 15 T (30 and $17\ cm^{-1}$) for the $x = 0.1$ and 0.2 samples, respectively. These samples have very similar electron densities and nominally identical structure, and thus should have very similar asymmetries. Recently, Chiang et al. [8] have performed calculations on similar structures and have demonstrated that the CVLLM effect can yield a large effective spin splitting of the lowest electron Landau-level in high fields. In this model, feature Y originates at intermediate magnetic fields from a mixed electron–hole Landau-level, while e–CR is due to the lowest unmixed (0,↑) electron Landau-level. Due to the resonant mixing, the oscillator strength of Y is initially small, but increases with magnetic field as the hole-like admixture decreases. This is qualitatively in agreement with the observed trends. Feature Y is not observed between 11.8 and 13 T; it appears as a broad line with a low-frequency tail at about 13 T, gains strength and narrows up to 16 T, and then decreases at still higher magnetic fields. The decreasing strength above 16 T results from decreasing occupancy of the (0,↓) Landau-level. Hence, the model calculations which incorporate the CVLLM effect [8] can explain the main qualitative behavior of Y and e–CR for $11.8 < B < 23$ T.

The existence of the two lines for $23 < B < 27$ T as shown in Fig. 3 is not well understood. At about 23 T ($\nu \sim 1$) the Fermi energy moves down (5–10 meV) from the (0,↓) electron Landau-level (in the well) to the highest spin state ($m_J = \frac{3}{2}$) of the $N = 0$ hole Landau-level (in the barrier). For $B > 23$ T electrons in the $(0, \frac{3}{2})$ hole Landau-level transfer to the lowest (0,↑) electron Landau-level, creating holes in the $(0, \frac{3}{2})$ level. This transfer must occur self-consistently while maintaining overall charge neutrality (*net* electron density = 5.5×10^{11} cm^{-2}) and satisfying the thermodynamic equilibrium requirement. Thus, both electron and hole densities initially increase with B and the hole Landau-level $(0, \frac{3}{2})$ is lowered due to increasing confinement from the self-consistent potential in the $Al_{0.1}Ga_{0.9}Sb$ barrier. This creates a complex situation in which there may be weak mixing of the predominantly $(0, \frac{3}{2})$ hole level with the (0,↑) electron level over a range of magnetic fields leading to two lines. Ultimately, the (0,↑) electron level crosses the self-consistently determined $(0, \frac{3}{2})$ hole level, and the SM–SC transition takes place with only a single line remaining at the highest field. This occurs at about 28 T, consistent with the estimate.

In conclusion, we have observed e–X and h–X lines in an $InAs/Al_xGa_{1-x}Sb$ ($x = 0.1$) single-quantum-well sample at high magnetic fields. Results, including the disappearance of the e–X and h–X lines, are consistent with magnetic-field-induced SM–SC transitions in both ($x = 0.1$ and 0.2) samples, and the assignment of these lines to internal transitions of stable, spatially separated excitons. The SM–SC transition occurs at a much higher magnetic field ($\sim$28 T) in the $x = 0.1$ sample. In the $x = 0.1$ sample, an enhanced spin splitting of electron CR is observed for $B \geqslant 13$ T, and two CR lines are seen for $23 \leqslant B < 27$ T. The enhanced spin splitting is attributed to the CVLLM effect. Detailed understanding of the two lines for $23 \leqslant B < 27$ T awaits self-consistent calculations.

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References

[1] T.P. Smith III, H. Munekata, L.L. Chang, F.F. Fang, L. Esaki, Surf. Sci. 196 (1988) 687.
[2] I. Lo, W.C. Mitchel, J.-P. Cheng, Phys. Rev. B 48 (1993) 9118; 50 (1994) 5316.
[3] D.J. Barnes et al., Phys. Rev. B 49 (1994) 10474.
[4] D. Heitmann et al., Phys. Rev. B 34 (1986) 7463.
[5] J. Kono et al., Phys. Rev. B 55 (1997) 1617; 50 (1994) 12242.
[6] A. Fasolino, M. Altarelli, Surf. Sci. 142 (1984) 322.
[7] M.J. Yang, C.H. Yang, B.R. Bennett, B.V. Shanabrook, Phys. Rev. Lett. 78 (1997) 4613.
[8] J.-C. Chiang, S.-F. Tsay, Z.M. Chau, I. Lo, Phys. Rev. Lett. 77 (1996) 2053.
[9] G. Bastard, E.E. Mendez, L.L. Chang, L. Esaki, J. Vac. Sci. Technol. 21 (1982) 531.
[10] J. Scriba et al., Semicond. Sci. Technol. 8 (1993) S133.
[11] M.J. Yang et al., Phys. Rev. B 47 (1993) 1691.
[12] A.A. Reeder, J.-M. Mercy, B.D. McCombe, IEEE J. Quantum Electron 24 (1988) 1690.
[13] E.I. Rashba, Sov. Phy. Stat. Sol. 2 (1960) 1109.