Cyclotron Resonance in Ferromagnetic InMnAs/(Al,Ga)Sb Heterostructures

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We report the observation of hole cyclotron resonance (CR) in InMnAs/(Al,Ga)Sb heterostructures in a wide temperature range covering both the paramagnetic and ferromagnetic phases. We observed two pronounced resonances that exhibit drastic changes in position, linewidth, and intensity at a temperature higher than the Curie temperature, indicating possible local magnetic ordering or clustering. We attribute the two resonances to the fundamental CR transitions expected for delocalized valence-band holes in the quantum limit. Using an 8-band $k\cdot p$ model, which incorporates ferromagnetism within a mean-field approximation, we show that the temperature-dependent CR peak shift is a direct measure of the carrier-Mn exchange interaction. Significant line narrowing was observed at low temperatures, which we interpret as the suppression of localized spin fluctuations.

| Sample No. | 1 | 2 | 3 | 4 |
|------------|---|---|---|---|
| $T_c$ (K)   | 55 | 30 | 40 | 35 |
| Mn content $x$ | 0.09 | 0.12 | 0.09 | 0.12 |
| Al content $y$ | 0 | 0 | 0 | 1 |
| Thickness (nm) | 25 | 9 | 31 | 9 |
| Density ($\text{cm}^{-3}$) | $1.1\times10^{19}$ | $4.8\times10^{19}$ | $1.1\times10^{19}$ | $4.8\times10^{19}$ |
| Mobility ($\text{cm}^2/\text{Vs}$) | 323 | 371 | 317 | 384 |
| $m_A/m_0$ | 0.0508 | 0.0525 | 0.0515 | 0.0520 |
| $m_B/m_0$ | 0.122 | 0.125 | 0.125 | 0.127 |

The samples were $\text{In}_{1-x}\text{Mn}_x\text{As}/\text{Al}_y\text{Ga}_{1-y}\text{Sb}$ single...
K, which is still above labeled ‘A’) is observed with almost no change in intensity, room reduction in linewidth and a sudden shift to a lower dramatic changes in the spectra. First, a significant re-
cur simultaneously. Also, it increases in intensity rapidly signals from the pick-up coil and the detector.

\[ T \]

through sample 1 at various \( \lambda \)-polarized radiation with wavelengths of 10.6 \( \mu \)m, 9.25 \( \mu \)m, 10.2 \( \mu \)m, 9.25 \( \mu \)m (CO2 laser), and 5.527 \( \mu \)m (CO laser), and the transmitted radiation was detected using a fast HgCdTe detector. A multi-channel digitizer recorded the signals from the pick-up coil and the detector.

Figure 1 shows the transmission of the 10.6 \( \mu \)m beam through sample 1 at various \( T \)’s as a function of \( B \). From room \( T \) down to slightly above \( T_c \), a broad feature (la-
beled ‘A’) is observed with almost no change in intensity, position, and width with decreasing \( T \). However, at \( \sim 68 \) K, which is still above \( T_c \), we observe quite abrupt and dramatic changes in the spectra. First, a significant re-
duction in linewidth and a sudden shift to a lower \( B \) oc-
cur simultaneously. Also, it increases in intensity rapidly with decreasing \( T \). In addition, a second feature (labeled ‘B’) suddenly appears \( \sim 125 \) T, which also rapidly grows in intensity with decreasing \( T \) and saturates, similar to feature A. Note that the temperature at which these unusual sudden CR changes occur \( (T^*_c) \) is higher than \( T_c \).

The observed unusual \( T \)-dependence is neither spe-
cific to this particular wavelength (\( \lambda \)) used nor to the sample measured. We observed essentially the same \( T \)-dependent behavior in all the samples studied. Figure 2(a) shows low-\( T \) CR traces for three samples at 10.6 \( \mu \)m. Both features A and B are clearly observed but their intensities and linewidths vary from sample to sample. Figure 2(b) displays the \( \lambda \)-dependence of the CR spectra for sample 2. We can see that both lines shift to higher \( \lambda \)’s with decreasing \( \lambda \) (i.e., increasing photon energy), as expected. Figures 2(c) and 2(d) show data at different \( T \)’s for sample 1 measured at 9.25 \( \mu \)m and 5.52 \( \mu \)m, respectively. The \( T \)-dependence observed at these shorter \( \lambda \)’s is similar to what was observed at 10.6 \( \mu \)m. The observations of CR with essentially the same masses in samples with different buffer layers (GaSb or AlSb) exclude the possibility of hole CR in the buffer. We also confirmed the absence of CR in a control sample which consisted of only a GaSb layer grown on GaAs. All these facts confirm the universality of the effects we observed and their relevance to ferromagnetic order.

The clear observation of CR indicates that at least a fraction of the holes are delocalized. This is in agreement with our measurements on low-\( T \) films [10, 11], which showed similar two resonance spectra although the resonances were much broader and \( T \)-dependence was much weaker. However, extensive earlier attempts to observe CR in GaMnAs [14] did not detect any sign of resonant absorption within the \( B \) and \( \lambda \) ranges in which both light hole (LH) and heavy hole (HH) CR in GaAs were expected. This fact indicates that the holes in GaMnAs are strongly localized, that the mixing of p- and d-like states makes the effective masses of holes extremely large, or that scattering is too strong to satisfy \( \omega _{c}\tau > 1 \). In any case, it appears that the carriers mediating the Mn-Mn exchange interaction are considerably more localized in GmMnAs than in InMnAs, consistent with recent optical conductivity [15] and photoemission experiments [16].

Feature A becomes strikingly narrow at low \( T \)’s. The estimated CR mobility is \( 4 \times 10^{4} \) cm²/Vs, which is one order of magnitude larger than the low-\( T \) mobilities measured by the Hall effect (see Table I). We speculate that this is associated with the suppression of localized spin fluctuations at low \( T \)’s. A similar effect has been observed in (II,Mn)VI systems [17]. Spin fluctuations become important when a band carrier simultaneously interacts with a limited number of localized spins. This occurs, for example, for magnetic polarons and for electrons in (II,Mn)IV quantum dots. The strong in-plane localization by the magnetic field may also result in a re-
duction of the number of spins which a band carrier feels, thus increasing the role of spin fluctuations.

It is important to emphasize that the \( T \) at which the significant spectral changes start to appear \( (T^*_c) \) is con-

FIG. 1: CR spectra for sample 1. The transmission of hole-active circular polarized 10.6 \( \mu \)m radiation is plotted vs. magnetic field at different temperatures.

\[ \text{Sample 1, } h \nu = 117 \text{ meV} \]

\[ \text{RT} \quad 15K \quad 25K \quad 42K \quad 56K \quad 68K \quad 85K \quad 107K \quad 125K \]

Transmission (10% per div.)

Magnetic Field (T)

Transmission (10% per div.)
Our calculated CR spectra are shown in Fig. 3(a) for increasing from the increase of magnetic ordering at low temperature. Note that the peak in a bulk system occurs at room $T$ at $\approx 40$ T as opposed to the heterostructures where the resonance occurs at $\approx 50$ T due to quantum confinement/strain.

It is easy to obtain an exact analytical expression for this shift since it involves only the lowest two manifolds in our model ($n = -1$, which is 1 dimensional, and $n = 0$, which factors into two $2 \times 2$ matrices for $k_z = 0$). Furthermore, to simplify the final expressions, we neglect the small terms arising from the interaction with remote bands. With these simplifications, the cyclotron energy (at the center of the Landau subbands) has the form:

$$E_{CR} = -\frac{E_g}{2} + \frac{1}{4} x(S_z)(\alpha - \beta) + \sqrt{\left[\frac{E_g}{2} - \frac{1}{4} x(S_z)(\alpha - \beta)\right]^2 + E_p \mu_B B},$$

where $E_g$ is the energy gap, $E_p$ is related to the Kane momentum matrix element $P$ as $E_p = \frac{k^2 P^2}{2m_0}$, $\alpha$ and $\beta$ are $s$-$d$ and $p$-$d$ exchange constants, and $x(S_z)$ is the magnetization per unit cell.

In the field range of our interest ($\approx 40$ T), $\sqrt{E_p \mu_B B}$ is in the same order as $\frac{E_g}{2}$, while the exchange interaction is much smaller even in the saturation limit. Expanding the square root in (1), we obtain the final expression

$$E_{CR} \approx -\frac{E_g}{2} \left(1 - 1\right) + \frac{1}{4} x(S_z)(\alpha - \beta)(1 - \delta),$$

where $\delta = E_g/(E_g^2 + 4E_p \mu_B B)^{1/2}$.

In order to further understand the effects of ferromagnetism on band structure, we used an $8 \times 8 \mathbf{k} \cdot \mathbf{p}$ model with $s(p)$-$d$ exchange interaction taken into account [9, 20]. Each state is specified by two indices, $\langle n, \nu \rangle$, where $n$ is the Landau quantum number and $\nu$ labels the eigenvectors within each Landau manifold. Peak A can be identified as the HH(−1, 1) $→$ HH(0, 2) transition [11, 22]. We attribute the $T$-dependent peak shift to the increase of carrier-Mn exchange interaction resulting from the increase of magnetic ordering at low $T$. Our calculated CR spectra are shown in Fig. 3(a) for bulk $\text{In}_{0.93}\text{Mn}_{0.9}\text{As}$ with only a minimal broadening of 4 meV. The figure shows the shift of peak A with decreasing $T$.

FIG. 2: (a) Low temperature CR spectra for three samples at 10.6 $\mu$m. (b) Wavelength dependence of the CR spectra for sample 2 at 27 K. CR spectra for sample 1 at different temperatures at (c) 9.25 $\mu$m and (d) 5.52 $\mu$m.

FIG. 3: (a) Theoretical CR spectra for sample 1 showing a shift of peak A with temperature. (b) Calculated temperature-dependence of the resonance field for peak A in sample 1.
If we assume that the $T$-dependence of $E_g$ and $E_p$ is small, it follows from Eq. 2 that the peak shift should follow the $T$-dependence of $\langle S_z \rangle$. This shift directly measures the carrier-Mn exchange interaction. To obtain quantitative agreement with the experiment, one should calculate $\langle S_z \rangle$ by taking into account the possibility of short-range ordering, as discussed above. This effect could substantially modify the band structure at low $B$. At high $B$, however, this effect should be smoothed out by the field-induced magnetic ordering. In the following we neglect this effect and calculate $\langle S_z \rangle$ via standard mean-field theory [22], solving the transcendental equation

$$\langle S_z \rangle = S B_S \left( \frac{g S}{kT} \left[ \mu_B B - \frac{3kT_c \langle S_z \rangle}{gS(S+1)} \right] \right),$$

where $g$ is the free electron $g$ factor, $B_S$ is the Brillouin function, and $S = \frac{5}{2}$ is the spin of the magnetic ion.

The $T$-dependence of the resonance field, calculated using Eqs. 2-3, is presented in Fig. 3(b). Parameters used in the calculation are $x = 0.09$, $T_c = 55$ K, $E_g = 0.4$ eV, $E_p = 21$ eV, and $\alpha - \beta = 1.5$ eV. It shows that from room temperature to 30 K the resonance $B$ decreases by $\sim 20\%$, approximately the result observed in the experiment. In addition, we find that the shift is nonlinear with $T$ and the main shift occurs at $T_c$’s well above $T_c$, which is also consistent with the experiment.

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