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High-field cyclotron resonance studies of InMnAs-based ferromagnetic semiconductor heterostructures

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Abstract

We report results of experimental and theoretical studies of hole cyclotron resonance (CR) in ferromagnetic InMnAs/GaSb heterostructures. We observe two clear resonances that exhibit strong temperature dependence in position, line width, and intensity, especially near and below the Curie temperature. We attribute the two resonances to the fundamental CR transitions expected for delocalized holes in the valence band in the magnetic quantum limit. Our theoretical calculations, based on an 8×8 $\mathbf{k} \cdot \mathbf{p}$ model with s(p)–d exchange interaction taken into account, reproduced temperature-dependent CR peak shifts with decreasing temperature, in qualitative agreement with experiment. We propose that the narrowing is due to the suppression of localized spin fluctuations at low temperature.

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1. Introduction

The recent discovery of carrier-induced ferromagnetism in magnetic III–V semiconductors such as InMnAs and GaMnAs [1–3] has not only opened up new device opportunities but also provided a novel material system in which one can study the physics of itinerant carriers interacting with localized spins. Various theoretical models have been proposed but the microscopic mechanism is still a matter of controversy. One of the open questions is the nature of the carriers mediating the exchange interaction between Mn ions, i.e., whether they reside in the impurity band (d-like), the delocalized valence bands (p-like), or some type of mixed states.

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Table 1
Characteristics of the $In_{1-x}Mn_xAs/GaSb$ samples

Sample no.	1	2	3
T_c (K)	55	30	40
Mn content x	0.09	0.12	0.09
Thickness (nm)	25	9	31
Density (cm^{-3})	1.1×10^{19}	4.8×10^{19}	1.1×10^{19}
Mobility ($cm^2/V\,s$)	323	371	317
m_A/m_0	0.0508	0.0525	0.0515
m_B/m_0	0.122	0.125	0.125

Densities and mobilities are room T values. m_A and m_B are the low-T cyclotron masses for the two lines (see Fig. 1).

Here, we report results of experimental and theoretical cyclotron resonance (CR) in ferromagnetic InMnAs/GaSb heterostructures. In all the samples studied, we observed two pronounced resonances. Both lines exhibited unusual temperature dependence in their position, intensity, and width. The lower-field resonance showed an abrupt reduction in line width with a concomitant decrease in resonance magnetic field slightly above the Curie temperature (T_c). The higher-field line, which was absent at room temperature, suddenly appeared above T_c, rapidly grew in intensity with decreasing temperature, and became comparable to the lower-field resonance at low temperatures. We performed calculations based on an 8×8 $\mathbf{k} \cdot \mathbf{p}$ model including the s(p)–d exchange interaction, reproducing temperature-dependent CR peak shifts, in qualitative agreement with experiment. We ascribe the narrowing to the suppression of localized spin fluctuations at low temperature.

2. Samples and experimental methods

The samples studied were InMnAs/GaSb single heterostructures containing high densities ($\sim 10^{19}$ cm^{-3}) of holes grown by low-temperature MBE. The growth conditions were described previously [4]. Unlike the paramagnetic n- and p-type InMnAs films we studied earlier [5,6], the samples in the present work showed ferromagnetism with T_c ranging from 30 to 55 K where their characteristics are summarized in Table 1. One of the samples was annealed at 250°C after growth, which increased the T_c by $\sim$ 10 K [7,8].

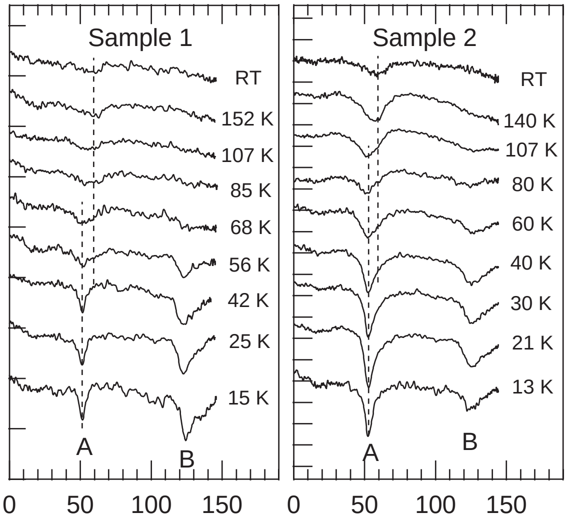

Fig. 1. Cyclotron resonance spectra for two ferromagnetic InMnAs/GaSb samples. The transmission of hole-active circular polarized 10.6 μm radiation is plotted vs. magnetic field at different temperatures.

3. Experimental techniques

We performed infrared (IR) CR measurements using ultrahigh magnetic fields ($\leqslant$ 150 T) generated by the single-turn coil technique [5,9]. We used IR laser beams with wavelengths of 10.6, 10.2, 9.25 μm (CO_2 laser), and 5.527 μm (CO laser). We circularly polarized the IR radiation using a CdS quarter-wave plate. The transmitted radiation through the sample was collected using a fast liquid-nitrogen-cooled HgCdTe photovoltaic detector.

Figs. 1(a) and (b) show the transmission of the 10.6 μm beam through two samples (T_c=55 and 30 K, respectively), at various temperatures as a function of magnetic field. The beam was hole-active circularly polarized. In Fig. 1(a), from room temperature down to slightly above T_c, a broad resonance feature (labeled ‘A’) is observed with almost no change in intensity, position, and width with decreasing temperature. However, at 68 K, which is still above T_c, we observe quite abrupt and dramatic changes in the spectra. First, a significant reduction in line width and a sudden shift to a lower magnetic field occur simultaneously. Also, it increases in intensity rapidly with decreasing temperature. In addition, a second feature

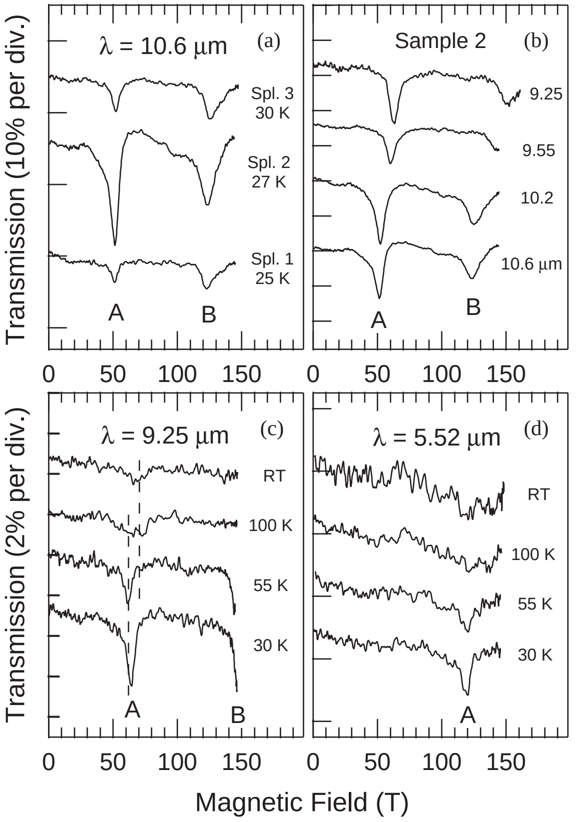

Fig. 2. Low-temperature CR spectra for the three samples at 10.6 µm. (b) Wavelength dependence of the CR spectra for sample 2 at 27 K. (c) CR spectra for sample 1 at different temperatures at 9.25 µm. (d) CR spectra for sample 1 at 5.52 µm.

(labeled ‘B’) suddenly appears around 125 T, which also rapidly grows in intensity with decreasing temperature and saturates, similar to feature A. At low temperatures, both features A and B do not show any shift in position. Essentially, the same behavior is seen in Fig. 1(b). We ascribe these lines to the two fundamental CR transitions expected for delocalized holes in the valence band of a zinc-blende semiconductor in the magnetic quantum limit.

The observed unusual temperature dependence is not specific to this particular wavelength used. Fig. 2(a) shows low-temperature CR traces for three samples (samples 1, 2, and 3) taken with 10.6 µm radiation. Both features A and B are clearly observed but their intensities and line widths vary from sample to sample. Figs. 2(b) displays the wavelength dependence of sample 2. We can see that both lines shift to higher fields with decreasing wavelength as expected. Figs. 2(c) and (d) show data at different temperatures for sample 1 measured with 9.25 and 5.52 µm radiation, respectively. The temperature dependence observed at these shorter wavelengths is similar to what was observed at 10.6 µm. All these data confirm the universality of the effects we observed.

4. Theoretical calculations

The CR peak A can be identified as a heavy hole to heavy hole (HH$(-1,1) \rightarrow$ HH$(0,2)$) [6,10] and the CR peak B as another hole transition. We attribute the temperature-dependent peak shift to the increase of carrier-Mn ion exchange interaction resulting from the increase of magnetic ordering at low temperatures. We observed this behavior in our theoretical calculations using an 8×8 $\mathbf{k} \cdot \mathbf{p}$ model with s(p)–d exchange interaction taken into account [5,11]. Results are shown in Fig. 3 for bulk In$_{0.91}$Mn$_{0.9}$As. The figure shows the shift of peak A with decreasing temperature. We used a broadening of 4 meV. Note that the peak in a bulk system occurs at room temperature at around 40 T as opposed to the heterostructures where the resonance occurs at $\sim$ 50 T.

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 one-dimensional, and $n=0$, which factors into two 2×2 matrices for $k_z=0$). Furthermore, to simplify the final expressions, we will 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

$$E_{\mathrm{CR}} = -\frac{E_{\mathrm{g}}}{2} + \frac{1}{4} x\langle S_z\rangle(\alpha-\beta) - \sqrt{\left[\frac{E_{\mathrm{g}}}{2} - \frac{1}{4} x\langle S_z\rangle(\alpha-\beta)\right]^2 + E_{\mathrm{p}}\mu_{\mathrm{B}}B}, \quad (1)$$

where E_{g} is the energy gap, E_{p} is related to the Kane momentum matrix element P as $E_{\mathrm{p}}=h^2P^2/2m_0$, α and β are s–d and p–d exchange constants, and $x\langle S_z\rangle$ is the magnetization per unit cell.

In the field range of our interest ($\sim$ 40 T), $\sqrt{E_{\mathrm{p}}\mu_{\mathrm{B}}B}$ is in the same order as $E_{\mathrm{g}}/2$, while the exchange

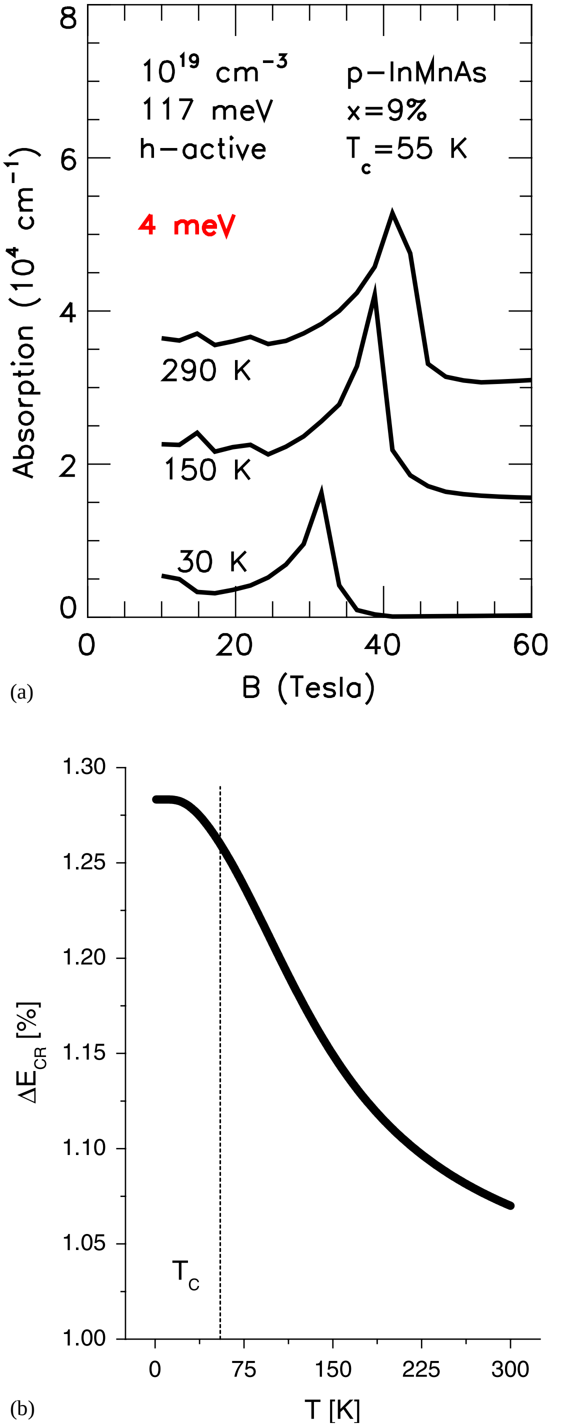

Fig. 3. (a) Theoretical CR spectra showing a shift of peak A with temperature. (b) Relative change of CR energy (with respect to that of high temperature limit) as a function of temperature. Vertical dashed line indicates T_c.

interaction is much smaller even in the saturation limit. Expanding the square root in (1), we obtain the final expression

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

where

$$\delta = \frac{E_g}{\sqrt{E_g^2+4E_p\mu_B B}}.$$

If we assume that the temperature dependence of E_g and E_p is small, it follows from Eq. (2) that the CR peak shift should follow the temperature dependence of the magnetization $\langle S_z\rangle$. We calculated the latter using standard mean-field theory [12], by solving the transcendental equation

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

where g is the free electron g-factor, B_S is the Brillouin function, $S=\frac{5}{2}$ is the spin of the magnetic ion, and $T_c = 55$ K for sample 1.

The relative change of the CR energy, calculated using Eqs. (2) and (3), as a function of temperature is presented in Fig. 3(b). It shows that from room temperature to 30 K the cyclotron energy *increases* about 20%, which corresponds to an approximately 20% *decrease* in the resonant magnetic field, approximately the result observed in the experiment. In addition, we found that the shift is nonlinear with temperature and the main shift occurs at temperatures well above T_c. These features are consistent with the experiment.

Along with the CR peak shift, experiment indicates a significant narrowing. We speculate that this effect may be associated with the suppression of localized spin fluctuations at low temperatures. A similar effect has been observed earlier in II–VI dilute magnetic semiconductors (see [13] and references therein). Spin fluctuations become important when a carrier in the band interacts simultaneously with a limited number of localized spins. This takes place, for example, for magnetic polarons and for electrons in dilute magnetic semiconductor quantum dots. The strong in-plane localization by the magnetic field may also result in a reduction of the number of spins which a carrier in the band feels, thus increasing the role of spin fluctuations.

In summary, we have carried out experimental and theoretical studies of hole cyclotron resonance in ferromagnetic InMnAs/GaSb heterostructures. We observed two pronounced resonances with unusual temperature dependence. Our calculations based on an 8 × 8 $\mathbf{k} \cdot \mathbf{p}$ model explain the main observed features qualitatively. These results provide important information on the carrier states and carrier-induced ferromagnetism in this family of magnetic semiconductors.

Acknowledgements

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