Cyclotron resonance in InMnAs and InMnSb ferromagnetic films

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Abstract.
We report cyclotron resonance measurements on ferromagnetic InMnAs and InMnSb films at high magnetic fields in the megagauss range (B > 100 T). The cyclotron resonance transitions between the Landau levels with small indices (N = 0, 1, 2, …) are clearly observed. The effective masses deduced from the resonance fields at 117 meV are 0.037 m₀ and 0.051 m₀ in InMnAs and InMnSb, respectively. They are considerably smaller than the classical band edge effective masses of heavy holes in the host semiconductors (0.35 m₀ in InAs and 0.32 m₀ in InSb) due to the quantum effect in high-magnetic fields. The Landau levels calculated by the 8-band model, semi-quantitatively can explain the cyclotron resonance positions, indicating the itinerant holes in InMnAs and InMnSb are p-like holes in the valence band of the host semiconductors.

1. Introduction
Ferromagnetic semiconductors are important materials for development of spintronic devices. While effort in this area was made primarily on GaMnAs [1], other ferromagnetic III-Mn-V alloys have also been developed, including the narrow gap ferromagnetic alloys InMnAs [2] and InMnSb [3]. For example, important advances have now been made in the MOVPE growth of these latter systems [4, 5]. Investigation of the electronic structure of III-Mn-V alloys by techniques such as the cyclotron resonance (CR) can shed important light on the origin of ferromagnetism and the p – d exchange interaction in III-Mn-V systems. In this work we report on CR experiments carried out on the ferromagnetic InMnAs and InMnSb films, on which clear resonance signals have been successfully observed in high magnetic fields.

2. Experiment
In₁₋ₓMnₓAs films were grown by MOVPE at the Northwestern University and In₁₋ₓMnₓSb films at the University of Notre Dame by low temperature MBE [3, 6, 7]. The Mn content (x), thickness (d), and hole concentration (nₚ) are x ~ 0.02, d = 200 nm, nₚ ~ 2 × 10¹⁸ cm⁻³ for In₁₋ₓMnₓAs, and x ~ 0.02, d=230 nm, nₚ ~ 1 × 10²⁰ cm⁻³ for In₁₋ₓMnₓSb. The Tc’s are about 320 K and 10 K in In₁₋ₓMnₓAs (x=0.02) and In₁₋ₓMnₓSb (x=0.02), respectively. (We use simpler descriptions, InMnAs and InMnSb, to denote the samples in the following sections).
CR measurements were performed using CO₂ and H₂O lasers, providing laser radiation at 10.6,
10.7, and 16.9 µm wavelengths. Magnetic fields exceeding 100 T were generated by a single turn coil technique [8].

3. Experimental Results

Figure 1 shows the CR spectra in InMnAs and InMnSb for the excitation wavelength of ∼10 µm. The resonance fields for InMnAs are 36.0 T at room temperature (RT) and 37.5 T at 121 K. The effective masses calculated from the resonance fields are 0.036$m_0$ and 0.037$m_0$ at RT and 121 K, respectively. ($m_0$ is the mass of a free electron.) Our earlier studies on ferromagnetic InMnAs films with $T_c$’s of ∼10 K [8], demonstrated the heavy hole (HH) effective mass ranging from 0.033$m_0$ to ∼0.040$m_0$. These significant deviations compared to the band edge HH mass of InAs (0.35$m_0$) is due to the quantum effect of the complex valence band structure [9]. The results presented here are indicating similarities in the electronic band structure of MOVPE grown InMnAs with the high $T_c$=320 K and the MBE grown InMnAs with the low $T_c$ of ∼10 K.

The cyclotron mobility, $\mu_{CR}$, was extracted from the width of the resonance peaks. We have $\mu_{CR}$=4.8 × 10² cm²/(Vs) at a room temperature and $\mu_{CR}$=6.0 × 10² cm²/(Vs) at 121 K. These values are higher than the cyclotron mobilities of the MBE grown InMnAs films reported previously [8]. Moreover, in contrast to the previous results [8], the mobility increases with decreasing temperature. Similar temperature dependence of the mobility has been reported in InAs [8]. It is likely that the impurity scattering is not a significant scattering mechanism in the MOVPE grown InMnAs, suggesting the high quality of the material.

The CR of holes in InMnSb has been observed for the first time. The measured cyclotron masses are 0.057$m_0$ at RT and 0.051$m_0$ at 121 K. These are much smaller than the band edge HH mass in InSb (0.32$m_0$) and similar to the observations in the InMnAs, can be explained by the quantum effects in the valence band. In addition, the observed cyclotron mass in the InMnSb is larger than that in InAs. The small Mn concentration (\(x \sim 0.02\)) can not modify the bandgap of the InMnSb significantly; whereas, the larger hole density in the InMnSb compared to the InMnAs, can shift the Fermi energy to a much higher level. The cyclotron mass can be enhanced when the resonance transition takes place between the Landau levels with higher indices. When we simply estimate the Fermi energy ($E_f$) at zero magnetic fields and 0 K using the classical band edge masses, we have $E_f$ =16 meV for the InMnAs film and $E_f$ =244 meV for the InMnSb film. The cyclotron resonance spectra in InMnAs and InMnSb at 16.9 µm are

![Figure 1. CR spectra for InMnAs and InMnSb films. The CR of InMnSb at 295 K, was measured at 10.6 µm; whereas, the other three resonances were measured at 10.7 µm.](image-url)
shown in Fig. 2. The resonance feature of InMnAs is less clear than that found at 10.6 and 10.7 µm. This fact can be due to the low mobility of the sample and the plasma absorption effect. For InMnSb, the resonance pattern is different compared to a typical single resonance peak. According to our Landau level calculations, the overlap of the light hole and heavy hole resonances can result in the unusual CR pattern.

![Figure 2. Cyclotron resonance spectra of InMnAs and InMnSb at 16.9 µm.](image)

4. The Landau Level Calculations
We calculated the Landau levels for InMnAs and InMnSb and demonstrated the inter Landau level transition energies as a function of the applied magnetic field. In modeling the transitions, the modified 8-band Pidgen-Brown model [9, 10] was used, where the $p - d$ exchange interaction between the valence band holes and the Mn spins can be included in the Hamiltonian. At this stage, the number of the experimental data points is not enough to determine the exchange interaction constant. Therefore, we simply calculated the Landau levels without the $p - d$ exchange interaction; namely, calculated the Landau levels for InAs and InSb and compare the results with the experimental data.

Figure 3(a) and (b) demonstrate the calculated inter-Landau level transition energies for InAs and InSb, and the experimental data, extracted from the CR peak positions. The solid curves are the calculated transitions from N=0 to N=1 Landau levels and the dashed curves are those from N=1 to N=2 Landau levels. In Fig. 3 (a), the experimental data for InMnAs can fit within the solid curves labeled as $b_4$, corresponding to the HH (heavy hole) CR transition (N=0 to N=1). This fact is suggesting that the observed hole CR in the MOVPE grown InMnAs is due to the HH transition in the quantum limit (N=0).

In contrast to the InMnAs case, the experimental observations in the MBE grown InMnSb can not be explained by any inter-Landau level transitions from N=0 to N=1, as shown in Fig. 3 (b). The CR positions are in a better agreement with the theoretical calculations labeled as $a_5'$ or $b_4'$. Both curves describe the transition from N=1 to N=2 Landau levels. The $b_4'$ transition mainly originates from the HH band, with small contributions from the light hole (LH), due to the Landau level mixing. The nature of the $a_5'$ transition originates mainly from the LH band. Since the $b_4'$ and $a_5'$ levels are rather close to each other, the two resonances can overlap as a single peak. As shown in Fig. 2 for 16.9 µm excitation wavelength, the observed flat resonance in InMnSb can be due to the overlap of the two CR peaks originated from both the HH and LH bands.
Figure 3. The calculated inter Landau level transition energies as a function of magnetic fields, for InAs and InSb, are plotted in (a) and (b), respectively. The labels such as $b_4$ denote the possible Landau level transitions. The solid curves are the calculated transitions from $N=0$ to $N=1$ Landau levels and the dashed curves are those from $N=1$ to $N=2$ Landau levels.

5. Summary
The hole cyclotron resonances are clearly observed in ferromagnetic semiconductors In$_{1-x}$Mn$_x$As ($x=0.02$) and In$_{1-x}$Mn$_x$Sb ($x=0.02$) thin films. Both resonance are semi-quantitatively explained by the inter Landau level transitions of the host semiconductors, i.e., InAs and InSb. Therefore, the electronic structures of In$_{1-x}$Mn$_x$As ($x=0.02$) and In$_{1-x}$Mn$_x$Sb ($x=0.02$) are not significantly modified from that of the host materials. More detailed comparison of the cyclotron resonance of the samples with different $T_c$’s or different Mn concentrations can provide important information on the origin of the high $T_c$ in the MOVPE grown narrow gap III-Mn-V ferromagnetic semiconductors.

6. Acknowledgment
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