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Electron-active cyclotron resonance in p-doped InMnAs in high magnetic fields

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Abstract

We present a theoretical and experimental study of electron-active cyclotron resonance in p-doped InMnAs in high magnetic fields. Results are based on an 8-band Pidgeon–Brown model generalized to include finite k_z effects and s(p)–d exchange interaction between itinerant carriers and Mn d-electrons. The e-active transitions in the valence band in p-doped samples take place due to the nature of multiple valence bands (heavy and light holes). We have calculated the absorption spectra in high magnetic fields and identified optical transitions which contribute to the cyclotron resonance for both e-active and h-active polarizations. Calculations show agreement with experimental results.

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1. Introduction

III–V ferromagnetic diluted magnetic semiconductors (DMS) have attracted much attention because of their possible applications in spintronics [1–6]. InMnAs, the first III–V DMS in which ferromagnetism was observed, is a narrow gap semiconductor and a prototype for studying electronic, spin, and ferromagnetic properties. The ferromagnetic exchange interaction in III–V DMS such as $In_{1-x}Mn_xAs$ and $Ga_{1-x}Mn_xAs$ is believed to be hole-meditated [7,8]. Therefore, it is useful for both theory and application to obtain detailed information on the valence bands.

Cyclotron resonance (CR) is an extensively used and powerful diagnostic tool for studying the optical properties of semiconductors. Since the band structures of DMS are sensitive to magnetic fields, we can use CR to characterize these materials determining the carrier density, band parameters, and electron/hole-Mn ion sp–d exchange coupling. However, owing to the strong disorder and scattering, one needs to go to ultrahigh magnetic fields (50–100 T) in DMS systems to observe CR. Recent megagauss CR studies on n-type CdMnTe, and on n- and p-type

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InMnAs have revealed significant effects of the Mn ions on the electronic structure of the bands [9–13].

Selection rules for CR are a direct result of the conservation of energy and angular momentum. For a free gas of particles, CR can only be observed for a certain circular polarization of light. For instance, for an electron gas, CR transitions occur in σ^+ polarization while for a gas of positively charged particles, CR will occur only for σ^- polarization. As a result, CR in σ^+ polarization is often called electron-active (e-active) and σ^- polarization is referred to as hole-active (h-active).

The situation in real semiconductors, however, differs from that of a free gas of positive or negative charged particles. Recently, we have experimentally observed e-active CR in p-doped InAs and InMnAs. The temperature was quite low (12 K) and the hole concentration was high enough (10^{19} cm^{-3}) to safely eliminate the possibility that the e-active CR comes from the thermally excited electrons in the conduction band. We excluded the existence of electrons in the interface or surface inversion layers. Thus, the results suggest that e-active CR comes from the valence band holes, in contradiction with the simple picture of a free hole gas.

In this paper, we show that with a full treatment of the semiconductor energy band structure, that e-active CR in the valence band of cubic semiconductors is very natural and results from the degeneracy of the valence bands. Specifically, having multiple valence band states (heavy hole: $J=\frac{3}{2}, M_j=\pm\frac{3}{2}$; light hole: $J=\frac{3}{2}, M_j=\pm\frac{1}{2}$) allows one to satisfy conservation of angular momentum in cyclotron absorption for both σ^+ and σ^- polarizations. Note that this is not a consequence of valence band mixing between the heavy and light hole states (though mixing between the conduction and valence bands is needed to pick up oscillator strength for the transitions). It is simply required to have degenerate valence band states with differing M_j quantum numbers. Our calculations further show good agreement with the experimental results.

2. Qualitative picture

Within the effective mass theory, the electron wave functions can be expanded in the Luttinger–Kohn basis [14] and written as a product of the periodic part at the zone center u_α and an envelope function Φ_α

$$\Psi^i \equiv |i\rangle = \sum_\alpha \Phi^i_\alpha u_\alpha, \tag{1}$$

where the summation is performed over different energy bands. The optical matrix element of the momentum operator $\hat{\mathbf{P}}=\hat{\mathbf{p}}+e/c\mathbf{A}$ between initial $|i\rangle$ and final $|f\rangle$ states then reads

$$\langle f|\hat{\mathbf{P}}|i\rangle \approx \sum_{\alpha,\alpha'} \langle \Phi^f_{\alpha'}|\Phi^i_\alpha\rangle\langle u_{\alpha'}|\hat{\mathbf{p}}|u_\alpha\rangle + \langle u_{\alpha'}|u_\alpha\rangle\langle \Phi^f_{\alpha'}|\hat{\mathbf{P}}|\Phi^i_\alpha\rangle. \tag{2}$$

In contrast to the free electron gas case, two terms appear in Eq. (2). The second term, proportional to the momentum matrix element between the envelope functions describes optical transitions within the one-band model and corresponds to that in the free electron gas case. The first term, being proportional to the momentum matrix element between periodic parts of the Bloch functions, has interband nature and is present only if conduction–valence band mixing takes place. As shown in Ref. [15], the first term dominates in both narrow and wide gap semiconductors.

To obtain the optical selection rules, we consider an 8×8 $\mathbf{k}\cdot\mathbf{p}$ model in the spherical approximation. We assume for simplicity, that the k wave vector along the field is zero so that the 8×8 matrix factorizes into two 4×4 matrices. The general form of the wave function is then

$$\Psi_n = a^e_n\phi_n|e\uparrow\rangle + a^h_n\phi_{n-1}|hh\uparrow\rangle + a^l_n\phi_{n+1}|lh\downarrow\rangle + a^s_n\phi_{n+1}|so\downarrow\rangle, \tag{3}$$

where n is the manifold (Landau) quantum number, ϕ_n are harmonic oscillator wave functions and a_n are the complex constants. Note that our notation is such that for the heavy hole state, spin-up $|\uparrow\rangle$ is the $M_j=+\frac{3}{2}$ state while for the light and split-off holes spin-down $|\downarrow\rangle$ are the $M_j=-\frac{1}{2}$ states. For the Bloch part of the wave function, we use the Luttinger–Kohn representation [14]. Substituting Eq. (3) in Eq. (2), after simple algebra we find selection rules for optical transitions in σ^+ and σ^- polarizations

$$\langle \Psi_{n'}|\hat{P}_\pm|\Psi_n\rangle \propto \delta_{n',n\pm1}. \tag{4}$$

We stress that both terms in Eq. (2) result in the same selection rules. This means that the CR selection

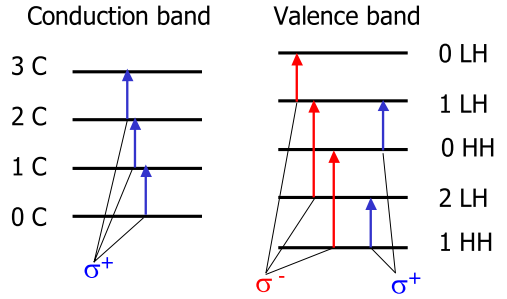

Fig. 1. Schematic diagram of Landau levels and CR transitions in conduction and valence bands. Both h-active and e-active transitions are allowed in the valence band because of the degenerate valence band structure. Only e-active transitions are allowed in the conduction band.

rules do not depend on the degree of conduction–valence band mixing. The same selection rules are obtained even if the k wave vector along the field is not zero. We also note that if the spherical approximation is not made, then there will be mixing of the states from different manifolds. In this case, it may even be possible to obtain h-active CR in the conduction bands, though this effect is very weak.

As a result of the selection rules, we see that σ^+ illumination leads to transitions which increase the manifold quantum number by one ($n \to n+1$) while σ^- leads to transitions which decrease the manifold quantum number and $n \to n-1$.

In the conduction band, increasing the manifold quantum number always increases the energy. As a result, only transitions with increasing n may take place in the absorption, that is, only e-active (σ^+) CR can be observed in the conduction band.

The valence band, however, consists of two types of carriers: heavy holes ($J=\frac{3}{2}, M_j=\pm\frac{3}{2}$) and light holes ($J=\frac{3}{2}, M_j=\pm\frac{1}{2}$). Each of them has their own Landau ladder in the magnetic field. An increase of n always means decrease of energy only within each ladder. Similar to the conduction band case, transitions within a ladder (hh $\to$ hh or lh $\to$ lh) can take place only in h-active (σ^-) polarization. However, the relative position of the two ladders can be such that interladder transitions (lh $\to$ hh) in e-active polarization are allowed.

This process is schematically shown in Fig. 1. Note that this figure is extremely simplified and should be used only as a qualitative explanation of the effect.

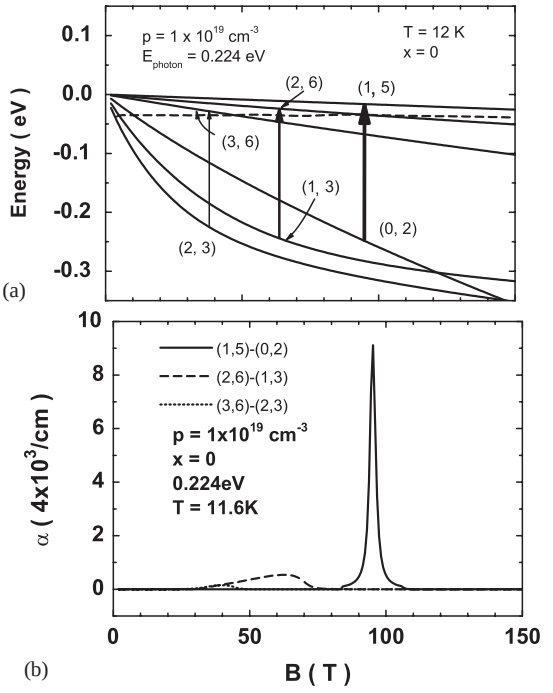

Fig. 2. The Landau levels and e-active CR. (a) The lowest three pairs of Landau levels in the e-active transition; (b) The separate CR absorption contributing to the e-active CR.

3. Theory and comparison with experiment

Our theory is based on the 8-band Pidgeon–Brown model and takes into account finite k effects along the field as well as the s–d and p–d exchange interactions between the electrons/holes and the localized Mn d-electrons. The exchange coupling was considered in a mean field approximation, and parameterized by two exchange integrals α and β defined in Ref. [16]. In the following we use (n, v) to label electronic states in the magnetic field. Here n is the Landau manifold quantum number and v labels the eigenstates within the manifold according to the eigenenergies in ascending order.

The valence band energy structure in a magnetic field, the e-active optical transitions and the corresponding CR absorption spectra are shown in Fig. 2. The most pronounced e-active transitions take place between the heavy hole state $(0,2)$ and light hole state $(1,5)$ and between the heavy hole $(1,3)$ and light hole $(2,6)$ states. There are some other less pronounced transitions, which contribute to absorption spectra at lower fields.

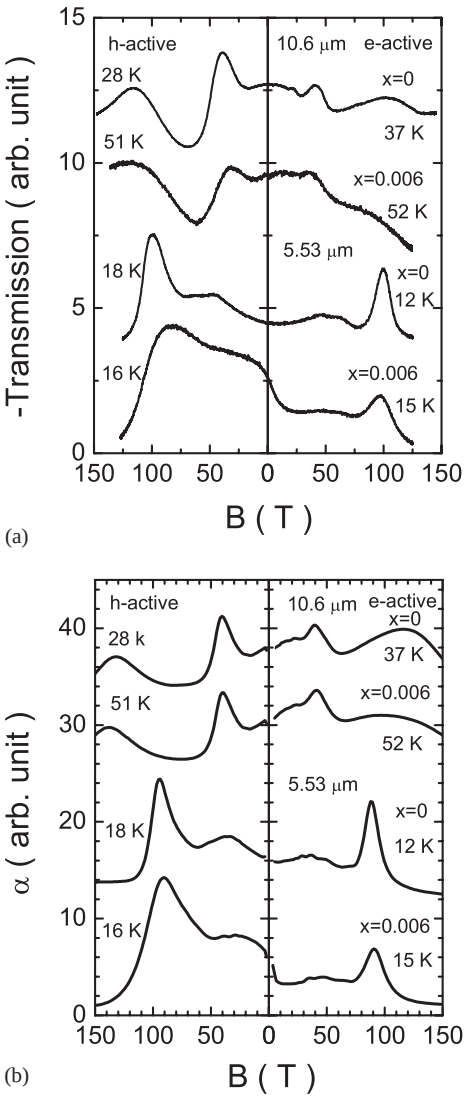

Fig. 3. Experimental and theoretical CR absorption. (a) Experimental CR spectra as a function of magnetic field for h-active and e-active polarizations. (b) Theoretical calculations corresponding to the experiments shown in (a).

Our calculations and the experimental CR are shown in Fig. 3 for both e-active and h-active polarizations. There is good agreement between theory and experiment. As discussed above, the electron active absorption is determined by the hh → lh transitions. The main contribution to the h-active absorption (left panel in Fig. 3) comes from the transitions within the heavy hole ladder. This is discussed in more detail in Ref. [13].

In conclusion, we have considered the origin of the e-active CR in p-doped InAs and InMnAs. We show that the e-active CR arises from the multiple valence bands. Our calculations based on the modified Pidgeon–Brown model show good agreement with the experimental results both in h-active and e-active cyclotron resonance in p-doped samples.

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