Spin magnetoabsorption of electrons in semimagnetic semiconductors

G. I. Kropotov, Yu. G. Rubo, L. S. Khazan, and V. I. Sheka
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, 194021, Leningrad; Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR, 252650, Kiev

(Submitted 3 December 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 1, 34–37 (10 January 1991)

The magnetooptic spectra of $Hg_{1-x-y}Mn_xCd_yTe$ have been measured over a wide range of far-IR wavelengths, magnetic fields, and temperatures. An optical absorption due to an exchange scattering of free electrons by magnetic impurities with spin flip has been observed.

The carrier spectrum in a semimagnetic semiconductor is strongly modified by the exchange interaction of the carrier spins with the spins of magnetic impurities.[1] The parameters of the electron states in such semiconductors can easily be tuned by varying the concentration of magnetic impurities, the temperature, or an applied magnetic field. A powerful method for studying such states is to measure the resonant absorption of light in an external magnetic field or, especially, electric dipole resonances.[2-4]

In this letter we are reporting a study of semiconductor films (50–70 μm thick) of n-$Hg_{1-x-y}Mn_xCd_yTe$ [$0.11 \leqslant x \leqslant 0.12$; $0.08 \geqslant y \geqslant 0.03$; $n = N_D - N_A = (3\text{–}4) \times 10^{14}$ cm^{-3}], grown on CdTe substrates in the (111) orientation by liquid-phase epitaxy. The use of a quaternary solid solution provides additional flexibility for varying the band parameters (E_g, m^*, and the g-factor), by varying the Cd content. The magnetotransmission was measured for electromagnetic waves over the wavelength (λ) range 57–295 μm, over the magnetic field (B) range 0–6.5 T, and over the temperature (T) range 2–15 K. The measurements were carried out in the Voigt polarization, $\vec{E} \| \vec{B}$, and the Faraday polarization, $\vec{E} \perp \vec{B}$ (the direction of the light, $\vec{q}$, is perpendicular to the surface of the sample and to the magnetic field). As light sources we used CH_3OH and CH_3OD lasers, optically pumped by a CO_2 laser. The auxiliary interband illumination of the sample increased the density of electrons and neutral impurity particles and improved the signal-to-noise ratio. The light was detected by n-GaAs and n-Ge detectors cooled and shielded from the magnetic field.

Figure 1 shows a magnetotransmission spectrum of $Hg_{0.85}Mn_{0.12}Cd_{0.03}Te$ at the wavelength 294.8 μm. We see four absorption bands. Peak 1 corresponds to a cyclotron resonance of free electrons. This peak is observed only in the Faraday polarization, and its position is essentially independent of the temperature (Fig. 2). The effective mass ($m^* = 0.02m_0$) found from the transition energy $\hbar\omega_c = \hbar eB/(m^*c)$ agrees with the known value of the effective mass in this compound.

The most interesting feature of these spectra is the strong temperature dependence (Fig. 2) of the positions of the two high-field peaks, 3 and 4. This temperature dependence is unambiguous evidence that peaks 3 and 4 correspond to an absorption of light during spin–flip transitions of electrons. The energy of spin splitting in semi-

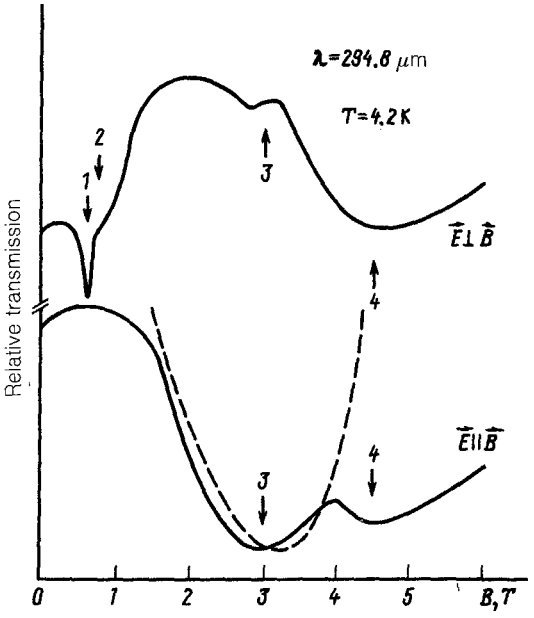

FIG. 1. Transmission spectra in a magnetic field for two polarizations of the light.

magnetic semiconductors is a strong function of the temperature:[1]

$$\hbar\omega_s = g^*\mu_B B, \quad g^* = g_0 + \frac{35}{12}\frac{J\bar{x}N_0}{k_B(T+T_0)}\, g_M \cdot \tag{1}$$

Here g_0 is the band (seed) g-factor, $g_M \simeq 2$ is the g-factor of Mn, N_0 is the number of cations per unit volume, J is the s–d exchange constant, and T_0 and $\bar{x} < x$ reflect the exchange interaction between Mn ions. In narrow-gap semiconductors, g_0 is negative and large in absolute value. As can be seen from the temperature dependence of the positions of peaks 3 and 4, the effective g-factor is positive, because of a huge contribution from the exchange interaction.

It is important to note that the ratio of magnetic fields corresponding to the minima of these peaks does not vary with the temperature. Peaks 3 and 4, however, differ substantially in the polarization dependence of their intensity. Peak 3 is intense only in the Voigt polarization, while peak 4 is seen in both polarizations.

These features of the spin absorption (the presence of two peaks and the polarization dependence) can be explained by invoking, in addition to the standard mechanisms,[5-7] an exchange mechanism for an electric-dipole spin resonance.[8,9] In contrast with Refs. 8 and 9, where electrons bound at donors were considered, that mechanism leads in the present case to a spin absorption by free carriers. This mechanism stems from a part of the Hamiltonian of the exchange interaction,

$$H_{ex} = -J\sum_j (\vec{s}\vec{s}_j)\delta(\vec{r} - \vec{R}_j) \tag{2}$$

[the diagonal part produces the second term in (1)], which is not diagonal in the

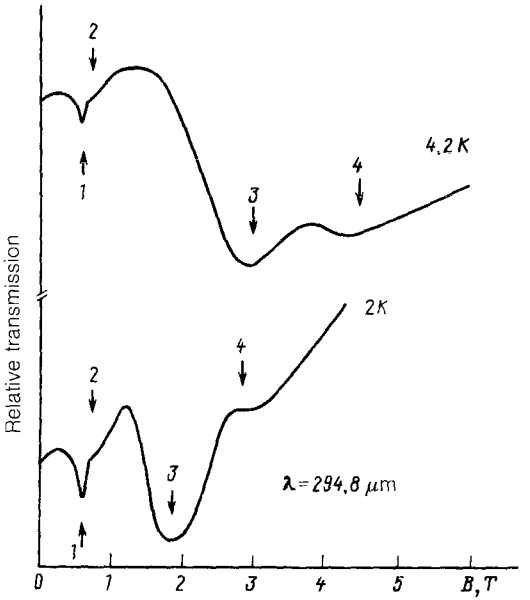

FIG. 2. Transmission spectra in a magnetic field at two temperatures (unpolarized light).

spins of the electron ($\vec{s}$) and of the magnetic impurity ($\vec{s}_j$). Here $\vec{r}$ is the coordinate of the electron, and $\vec{R}_j$ is the coordinate of magnetic impurity j. The off-diagonal part of (2) allows transitions accompanied by the absorption of light by virtue of a scattering of an electron by a magnetic impurity with changes in their spins. As was pointed out in Ref. 8, the free electron also undergoes a change in momentum, and the absorption is not resonant.

Calculations lead to different results for the Faraday and Voigt configurations. In the Faraday polarization, the transition matrix element is independent of the momentum transfer, while in the Voigt polarization the two are proportional. In the Faraday polarization, the absorption maximum thus corresponds to transitions between minima of Landau spin subbands ($\omega \simeq \omega_s$), while in the Voigt polarization it is shifted toward higher photon energies $\hbar\omega$. In magnetic fields such that $\omega < \omega_c$ (i.e., in the region of spin transitions), and also under the condition $\eta \equiv \hbar\omega_c/(2k_BT) \gg 1$, the absorption coefficient in the Voigt polarization is

$$\alpha(B) = \frac{35}{24\pi}\frac{\omega_p^2}{\omega c\sqrt{\kappa}}\left(\frac{Jn_M}{\hbar\omega}\right)^2 \frac{\sqrt{\eta/\pi}}{n_m l_B^3}\int \frac{x+\xi^2}{\sqrt{2x+\xi^2}} e^{-\eta\xi^2} d\xi,$$

$$\omega_p^2 = \frac{4\pi e^2 n}{m^*}, \quad l_B^2 = \frac{c\hbar}{eB}, \quad x = \frac{\omega - \omega_s'}{\omega_c}. \tag{3}$$

Here $n_M = \bar{x}N_0$, κ is the dielectric constant, and $\hbar\omega_s' = (g^* - g_M)\mu_B B \simeq \hbar\omega_s$. It follows from (3) that we have $\alpha(B) \propto B\sqrt{\hbar\omega - g^*\mu_B B}$ and that the absorption maximum corresponds to a magnetic field

$$B_{ex} \simeq \frac{2}{3}B_e, \quad B_e = \hbar\omega/g^*\mu_B. \tag{4}$$

In the Faraday polarization, in contrast, the maximum corresponds to B_s.

The magnetic fields corresponding to peaks 3 and 4 in Fig. 1 satisfy (4). We can thus associate peak 4 with transitions with a spin-splitting energy $\hbar\omega_s$, and peak 3 with transitions with an energy $3\hbar\omega_s/2$. In other words, peak 3 in the Voigt polarization and peak 4 in the Faraday polarization stem from the exchange mechanism for an electric-dipole spin resonance. The dashed line in Fig. 1 is a theoretical curve calculated from (3). The effective g-factor calculated from the second expression in (4) is 25 at $T = 4.2$ K and 16 at $T = 2$ K.

The exchange mechanism for an electric-dipole spin resonance also allows spin transitions at combinational frequencies (accompanied by a change in the index of the Landau level). Peak 2 in the Faraday polarization (Fig. 1), with an energy $\hbar\omega_c - \hbar\omega_s$, is a transition of this sort, from an upper spin sublevel of the lowest-lying Landau band to the lower spin sublevel of the following band.

We conclude with a look at the possible nature of the spin resonance at the frequency ω_s (peak 4) in the Voigt polarization. From x-ray spectral analysis and the observed shift of the magnetoabsorption lines during a layer-by-layer etching of the film we find evidence that the Cd concentration increases along the direction ($\vec{n}$) toward the substrate. This increase should lead to a term $[\vec{s}\times\vec{k}]\cdot\vec{n}$ which is linear in the momentum $\vec{k}$ in the Hamiltonian of a band electron. A term of this sort, in the case $\vec{B}\perp\vec{n}$, leads to an electric-dipole spin resonance in the Voigt polarization.[10]

An electric-dipole spin resonance in a magnetic material was also studied in Ref. 11. Transitions were initiated by a slight variation of the magnetic field, but the longitudinal momentum was conserved, in contrast with the present study.

We are deeply indebted to D. I. Tsypishka for assistance in the experiments and É. I. Rashba for a discussion of this study.

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Translated by D. Parsons