Dependence of the intensity of electron spin resonance on the photon momentum

V. I. Sheka and L. S. Khazan
Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR

(Submitted 7 December 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 2, 61–63 (25 January 1985)

The interference of paramagnetic and combined resonances in crystals of the sphalerite type is analyzed. A relationship is established between the absorption intensity and the photon momentum which explains the experimental results of Dobrowolska *et al.* [Phys. Rev. Lett. **51**, 134 (1983)]. The parameter in the term $\sim k^3$ in the energy for a band electron in InSb is found for the first time.

Dobrowolska *et al.*[1] have recently observed a spatial dispersion of the intensity of a combined resonance in n-type InSb.

The combined resonance, predicted theoretically by Rashba,[2] can be summarized as follows: The electric vector of the electromagnetic wave excites electric dipole transitions between Landau levels accompanied by a change in the spin state of the carrier; the spin-orbit interaction is responsible. The combined resonance can occur both at ω_{pr}, the frequency of the paramagnetic resonance (which is excited, however, by the magnetic vector of the wave), and at the frequencies $l\omega^* \pm \omega_{pr}$ (ω^* is the cyclotron

 0021-3640/85/020072-04$01.00

frequency, and l is an integer). An anisotropic combined resonance with a spin-orbit interaction cubic in the quasimomentum was studied in Ref. 3 for the case of n-type InSb. Interest then focused on carrying out an experiment in the microwave range, where it would be possible to spatially separate the antinodes of the electric and magnetic fields of the electromagnetic wave: Near a resonator with a maximum of the electric field, it would be possible to observe the combined resonance in its pure form. Consequently, the intensities of the combined and paramagnetic resonances were calculated separately in Ref. 3. Under the light absorption conditions of Ref. 1, however, which were such that the electric and magnetic fields were not spatially separated, an interference of the two resonances occurs. Dobrowolska *et al.*[1] correctly suggested that this interference could explain the observed dependence of the absorption intensity on the direction of the photon momentum **Q** and, in particular, the change in the absorption upon a reversal of this momentum. The calculation below yields a quantitative relationship between the absorption intensity and **Q**, explains the experimental data of Ref. 1, and makes it possible to use these data to find (for the first time) the spin-orbit coupling constant δ_0, including its sign, for InSb.

The Hamiltonian of an electron in a crystal with the sphalerite lattice in a static magnetic field $\mathscr{H} = \text{curl}\mathbf{A}$ was derived in Ref. 3 for the case with a spin-orbit interaction:

$$H = \frac{\hbar}{2m^*}\hat{\mathbf{k}}^2 + \frac{g\beta_0}{2}(\vec{\sigma}\cdot\vec{\mathscr{H}}) + \delta_0(\vec{\sigma}\cdot\vec{\kappa}), \tag{1}$$

where

$$\hat{\mathbf{k}} = -i\nabla + \frac{e}{\cos\hbar}\mathbf{A}, \quad \kappa_\alpha(\mathbf{k}) = \hat{k}_{\alpha'}\hat{k}_\alpha\hat{k}_{\alpha'} - \hat{k}_{\alpha''}\hat{k}_\alpha\hat{k}_{\alpha''} \tag{2}$$

(α, α', and α'' form a cyclic permutation of x, y, and z); the operator representing the interaction with the light [the vector potential is $\mathscr{A}_\alpha = \mathscr{A}_0\tilde{e}_\alpha\cdot\cos(\mathbf{Qr} - \omega t + \varphi_\alpha)$, where the value of φ_α is determined by whether the wave is plane or circularly polarized] is

$$\widetilde{H} = \frac{e}{c}(\mathbf{v}\cdot\vec{\mathscr{A}}) + \frac{g\beta_0}{2}(\vec{\sigma}\cdot\text{curl}\,\vec{\mathscr{A}})$$

$$= \mathscr{A}_0\cdot\text{Re}\left\{\left[\frac{e}{c}(\mathbf{v}\cdot\mathbf{e}) - \frac{ig\beta_0}{2}(\mathbf{e}\times\mathbf{Q})\cdot\vec{\sigma}\right]\exp\left[i(\mathbf{Qr} - \omega t)\right]\right\}. \tag{3}$$

The first term in this expression is responsible for the combined resonance; the second is responsible for the paramagnetic resonance; and $\mathbf{v} = i[H, \mathbf{r}]/\hbar$.

Under conditions of a purely spin resonance, the absorption coefficient

$$\alpha_0 \sim \sum_{\sigma, j, k_z} |M_j|^2 (f_{-\sigma j} - f_{\sigma j})\delta(E_{\sigma j} - E_{-\sigma j} - \hbar\omega_{pr}) \tag{4}$$

would contain the transition matrix element $M_j = \langle j - |\widetilde{H}| j + \rangle \cdot c/e\mathscr{A}_0$ representing a transition between spin sublevels of the same Landau level [$E_{\sigma j}(k_z)$ and $f_{\sigma j}(k_z)$ are the corresponding energies and distribution functions]. For this matrix element, we find the following expression:

$$M_j = \sqrt{2}\left\{\frac{\delta_0}{\hbar}\,[(2j+1)K_{\mathcal{H}}^2 - 2k_{z'}^2]\sum_\alpha B_{(12\alpha)}\frac{\beta^*}{\beta^* - q_\alpha}e'_\alpha + \frac{g\beta_0}{2}\frac{c}{e}(e'_3 Q'_2 - e'_2 Q'_3)\right\}. \qquad (5)$$

Here $K_{\mathscr{H}}^2 = e\mathscr{H}/c\hbar$; $\mathbf{Q}' = B^{-1}\mathbf{Q}$; $\mathbf{e}' = B^{-1}\mathbf{e}[e'_{1,2} = (e'_x \mp e'_y)/\sqrt{2}, e'_3 = e_{z'}$, the z' axis of the primed coordinate system is directed parallel to $\vec{\mathscr{H}}$]; and β^*, q_α, and the matrices B (which determine the angular diagram of the absorption intensity) are given in Ref. 3, where the part of M_j independent of $\mathbf{Q}$ was calculated.

Since e'_1 does not appear in the last term in (5), there is no interference between the combined and paramagnetic resonances (there is no paramagnetic resonance) for a wave which is right-hand circularly polarized in the plane perpendicular to $\vec{\mathscr{H}}$ (i.e., in the case $e'_1 = 1$, $e'_2 = e'_3 = 0$). For a left-hand transverse polarization ($e'_2 = 1$, $e'_1 = e'_3 = 0$), there is again no interference, since $B_{(122)}$ is purely imaginary, and Q'_3 is real, according to Ref. 3.

The most interesting case is thus that of a wave polarized parallel to $\vec{\mathscr{H}}$ ($e_3 = 1$, $e'_1 = e'_2 = 0$), which was the case in the experiments of Ref. 1. For any other linear polarization, an interference will occur against the additional background of an isotropic combined resonance,[4] which arises from the "nonparabolicity" of the electron band and which was comparable to the intensity of the transitions of interest under the conditions of Ref. 1.

Estimates show that the electron gas in Ref. 1 was nondegenerate and that transitions occurred only within the lowest-lying Landau level. Since $\hbar\omega^* \gg KT$, only the term with $j = 0$ is retained in sum (4), and we can set $k_{z'} = 0$ in (5). In this situation, the angular patterns are determined by the anisotropic part of the square modulus of matrix element (5):

$$|M|^2_{\mathrm{an}} = \left(\frac{3}{2}\frac{\delta_0}{\hbar}K_{\mathcal{H}}^2\right)^2 \Omega - \frac{3}{4}\frac{\delta_0 g}{m_0}K_{\mathcal{H}}^2\,\Omega_Q \cdot Q, \qquad (6)$$

where $\Omega = \Sigma_\alpha \kappa_\alpha^2(h)$, $\Omega_Q = \Sigma_\alpha Q_\alpha \kappa_\alpha(h)/Q$, the $\kappa_\alpha(h)$ are defined in (2), and the h_α are the direction cosines of the magnetic field. A spatial dispersion arises because Q_α appears linearly in the second term.

In particular, if $\mathbf{Q}\|[001]$ and $\vec{\mathscr{H}} = (\mathscr{H}_x, \mathscr{H}_y, 0)$, we have $\Omega_Q = 0$, $\Omega = \frac{1}{4}\sin^2 2\Phi$, and there is no spatial dispersion. If $\mathbf{Q}\|[110]$ and $\vec{\mathscr{H}} = (\mathscr{H}_x, -\mathscr{H}_x, \mathscr{H}_z)$, we have $\Omega_Q = \sin\theta(1 - 3\cos^2\theta)$ and $\Omega = \Omega_Q^2$, in complete agreement with the behavior reported in Ref. 1. The spatial dispersion determines the value of the parameter δ_0:

$$\delta_0 = -75\frac{\hbar^4}{m_0^2 e^2} = -75 \text{ a.u.} \qquad (7)$$

This value agrees in order of magnitude with the estimate in Ref. 3.

The ratio of the maxima of the two terms in (6) is

$$\eta = \frac{|(\delta_0)_{\text{a.u.}}|}{g^2\sqrt{\epsilon}} \, 3\frac{\hbar c}{e^2} . \tag{8}$$

For InSb we have $\eta = 3$, and for GaAs and GaSb with the values of δ_0 given in Ref. 5 $[\delta_0 = \alpha/2\times(2m^{*3}E_g)^{-1/2}\cdot\hbar^3]$, we find $|\delta_{\text{a.u.}}| = 4$ and 25, from which we in turn find $\eta = 2\times10^3$ and 30, respectively. Consequently, the conditions for observing an interference of the combined and paramagnetic resonances would be more favorable in InSb.

We are deeply indebted to É. I. Rashba for several valuable discussions of this study.

[1]M. Dobrowolska, Y. Chen, J. K. Furdyna, and S. Rodriguez, Phys. Rev. Lett. **51**, 134 (1983).
[2]É. I. Rashba, Fiz. Tverd. Tela (Leningrad) **2**, 1224 (1960) [Sov. Phys. Solid State **2**, 1109 (1960)]; Usp. Fiz. Nauk **84** (1964) [Sov. Phys. Usp. **7**, 823 (1964)].
[3]É. I. Rashba and V. I. Sheka, Fiz. Tverd. Tela (Leningrad) **3**, 1735 (1961) [Sov. Phys. Solid State **3**, 1257 (1961)].
[4]V. I. Sheka, Fiz. Tverd. Tela (Leningrad) **6**, 3099 (1964) [Sov. Phys. Solid State **6**, 2470 (1964)].
[5]A. G. Aronov, G. E. Pikus, and A. N. Titkov, Zh. Eksp. Teor. Fiz. **84**, 1170 (1983) [Sov. Phys. JETP **57**, 680 (1983)].

Translated by Dave Parsons
Edited by S. J. Amoretty