Faraday effect at spin resonance in *n*-InSb

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A resonance increment in the Faraday effect due to optical spin–flip transitions has been observed for the first time. The magnetic field dependence of the magnitude and sign of the effect has been studied theoretically and experimentally for various orientations of the magnetic field in the crystal.

The Faraday effect (the rotation of the polarization plane of an electromagnetic wave as it passes through a crystal in a magnetic field) has been the subject of many theoretical and experimental studies (e.g., Refs. 1 and 2). In particular, this effect has been studied during interband transitions in semiconductors[3] and for free carriers in the cyclotron resonance region.[4] Agarwal *et al.*[5] have studied the increment in this effect which reflects the spin polarization of the electrons in a quantizing magnetic field. In the present letter we are reporting a study of the resonance component of the Faraday angle which stems from electron spin–flip transitions.

The Faraday angle per unit distance traversed by the wave is determined by the difference between the refractive indices for left- and right-hand-polarized waves. It can be expressed in terms of the real part of an off-diagonal component of the dynamic conductivity tensor:

$$\psi = \frac{2\pi}{cn_\omega}\mathrm{Re}\sigma_{yx}(\omega),$$

where n_ω is the refractive index in the absence of a magnetic field, c is the velocity of light in vacuum, ω is the frequency of the light, and the z axis runs along the magnetic field.

Two mechanisms are primarily responsible for optical transitions accompanied by the spin flip of an electron. One involves a crystal which does not have an inversion center,[6] and the other involves the quasimomentum dependence of the g-factor.[7] These mechanisms correspond to the incorporation of terms $\delta_0(\vec{\sigma}\cdot\vec{\chi})$ and $\tilde{g}\mu_B[(\vec{k}\cdot\vec{\sigma})(\vec{k}\cdot\vec{H}) + (\vec{k}\cdot\vec{H})(\vec{k}\cdot\vec{\sigma})]$ in the electron Hamiltonian, where $\vec{\sigma}$ are the Pauli matrices, μ_B is the Bohr magneton, and $\hbar\vec{k}$ is the momentum of the electron in the magnetic field $\vec{H}$. We have $\chi_x = k_y k_x k_y - k_z k_x k_z$ in the principle axes of the crystal (χ_y and χ_z can be found through a cyclic permutation). The parameters δ_0 and $\tilde{g}$ characterize these mechanisms.

For the first mechanism, in the case in which only the lower spin subband is filled (the superquantum limit) we find

$$\mathrm{Re}\sigma_{yx}^{(1)} = \frac{n_e e^2 \delta_0^2 \beta^2}{4\hbar^3 \omega_s a^4} - \frac{\Delta}{\Delta^2 + \Gamma^2}\left[\frac{1}{(1-\beta)^2}\left|B_{(233)}\right|^2 - \frac{1}{(1+\beta)^2}\left|B_{(133)}\right|^2\right], \quad (1)$$

where n_e is the electron density, $\Delta = \omega - \omega_s$ is the deviation from the resonant frequency, $\hbar\omega_s = |g|\mu_B H$, $\beta = (m/2m_0)g$, g is the g-factor, m is the effective mass, Γ is a resonance half-width, introduced in a phenomenological way, and a is the magnetic length. The coefficients B_{ijk} depend on the orientation of the magnetic field with respect to the crystallographic axes. Expressions for these coefficients are given in Ref. 6. For the directions of $\vec{H}$ of interest here we find the following from Ref. 6: $|B_{(133)}|^2 = 1$ and $|B_{(233)}|^2 = 0$ for $\vec{H} \| [001]$, $|B_{(233)}|^2 = 4/3$ and $B_{(133)} = 0$ for $\vec{H} \| [111]$, and $B_{(133)} = B_{(233)} = 0$ for $\vec{H} \| [011]$.

For the second mechanism we have

$$\mathrm{Re}\,\sigma_{yx}^{(2)} = \frac{2n_e e^2 \tilde{g} m \bar{\epsilon}}{\hbar\omega_s m_0^2 a^4} \frac{\Delta}{\Delta^2 + \Gamma^2}, \tag{2}$$

where $\bar{\epsilon}$ is the mean longitudinal energy. For nondegenerate statistics we would have $\bar{\epsilon} = T/2$, where T is the lattice temperature in energy units. This contribution differs from the first in that it is isotropic.

The following method was used to detect the small resonance component of the Faraday angle due to spin transitions. The magnetic field dependence of the transmission of linearly polarized light through a sample and through a polarizer behind the sample was measured near the spin resonance. The intensity of the light transmitted in this manner is proportional to

$$I(\varphi) \propto D^+ + D^- + 2\sqrt{D^+ D^-}\cos(2\varphi - 2\psi). \tag{3}$$

Here $D^{\pm} = \exp(-\alpha_{\pm} d)$, where $\alpha_{\pm}$ is the resultant absorption coefficient for right-hand (+) and left-hand (−) polarized light. This coefficient incorporates the cyclotron and spin transitions. In addition, φ is the angle between the axis of the polarizer and the polarization vector of the incident light, ψ is the Faraday angle, and d is the thickness of the sample. Relation (3) is valid under the condition $R_{\pm} D^{\pm} \ll 1$ ("simple" transmission; R is the reflection coefficient of the interface between the semi-infinite superconducting medium and vacuum), which corresponds to the experimental conditions. It can be seen from (3) that by measuring the intensity of the transmitted light at three fixed positions of the polarizer, e.g., at $\varphi = 0$, $\pi/4$, and $\pi/2$, one can reconstruct the dependence of the Faraday angle on the magnetic field with the help of

$$\tan 2\psi = 2\frac{I(\pi/4) - I(\pi/2)}{I(0) - I(\pi/4)} - 1.$$

After the monotonic component associated with the Faraday rotation on the wing of the cyclotron resonance is subtracted, we obtain the resonance part $\psi_s(H)$, which is a consequence of the spin transition.

The experiment was carried out at 4.2 K with a submillimeter laser with a wavelength $\lambda = 118.8$ μm on n-InSb samples with an electron density n_e of 3.6×10^{14} cm^{-3} in a magnetic field ~4.15 T. The thickness of the sample was 10 mm. The samples were oriented with [001], [011], and [111] axes along this direction. The points in Fig. 1 are experimental results on the spin component of the Faraday effect versus the magnetic field for three orientations of this field in the crystals. The shift of

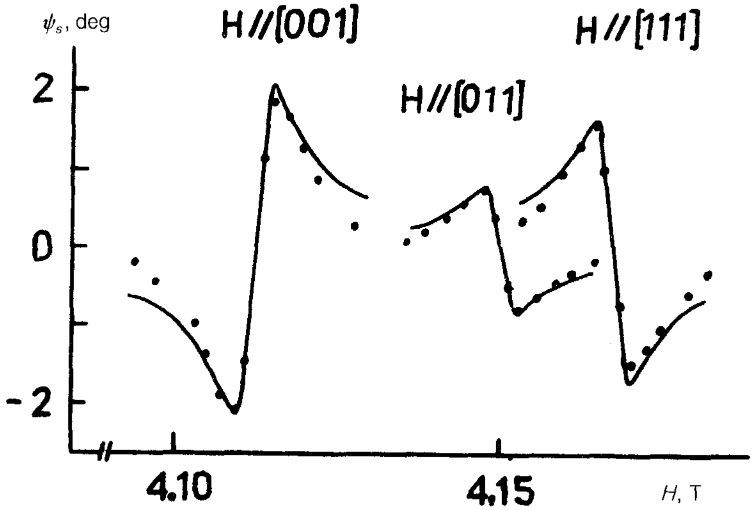

FIG. 1. Spin component of the Faraday angle versus the magnetic field for three field orientations.

the resonances in the magnetic field stems from the anisotropy of the g-factor.[8]

In the case $\vec{H} \parallel [011]$, only the mechanism involving the quasimomentum dependence of the g-factor [expression (2)] contributes to the effect. Substituting the measured width of the resonance line into this expression, we can adjust the parameter $\tilde{g}$ to bring the extrema on the theoretical and experimental curves of $\psi_s(H)$ into coincidence. The value found for the parameter $\tilde{g}$ in this manner is 0.6×10^{-12} cm^2.

In the cases $\vec{H} \parallel [001]$ and $\vec{H} \parallel [111]$, both contributions are present; the first is considerably larger. According to expression (1), the $\psi_s(H)$ curves have different signs and amplitudes in these orientations. With $\vec{H} \parallel [001]$, the magnitudes of the effect associated with the two mechanisms add together, while in the case $\vec{H} \parallel [001]$ they tend to cancel out. Using expressions (1) and (2), we can describe the experimental points in the orientations by assuming a parameter value $\delta_0 = 4.2 \times 10^{-34}$ erg·cm^3.

It can be seen from Fig. 1 that there is a substantial difference between the lineshapes on the theoretical and experimental curves. To obtain a better agreement of the curves in the derivation of the theoretical expression, it is necessary to take into account the circumstance that the lineshape of the spin resonance in n-InSb is determined not only by spin relaxation (the parameter Γ) but also by the deviation of the electron energy spectrum from a parabolic shape (a substantial deviation in this particular material).

The value found for the parameter δ_0 here agrees well with a value found in Ref. 9: $\delta_0 = 3.6 \times 10^{-34}$ erg·cm^3. With regard to the parameter $\tilde{g}$, we note that the value given above is lower than that found in Ref. 10, $\tilde{g} = 1.9 \times 10^{-12}$ cm^2.

[1]H. Piller, in *Semiconductor and Semimetals* (ed. R. K. Willardson and A. C. Beer), Vol. 8, 1972, p. 103.
[2]*Optical Properties of Solids* (ed. F. Abeles), Amsterdam, 1972, p. 366.
[3]I. M. Boswarva *et al.*, Proc. R. Soc. A **269**, 125 (1962).
[4]S. D. Smith, *et al.*, J. Phys. Chem. Solids **11**, 131 (1959).
[5]R. L. Agarwal *et al.*, Appl. Phys. Lett. **53**, 2656 (1988).
[6]É. I. Rashba and V. I. Sheka, Fiz. Tverd. Tela (Leningrad) **3**, 1735 (1961) [Sov. Phys. Solid state **3**, 1257 (1961)].
[7]V. I. Sheka, Fiz. Tverd. Tela (Leningrad) **6**, 3099 (1964) [Sov. Phys. Solid State **6**, 2470 (1964)].
[8]Z. Barticevic *et al.*, Phys. Rev. B **35**, 7464 (1987).
[9]Y.-F. Chen *et al.*, Phys. Rev. B **32**, 890 (1985).
[10]L. I. Magarill *et al.*, Zh. Eksp. Teor. Fiz. **96**, 950 (1990) [Sov. Phys. JETP (to be published)].

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