Photomagnetic effect under cyclotron-resonance conditions

L. I. Magarill, A. M. Palkin, V. N. Sozinov, O. A. Shegaĭ, and M. V. Éntin
Institute of Semiconductor Physics, Siberian Branch, Academy of Sciences of the USSR

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An analog of a photoelectromagnetic effect has been discovered in optical transitions between Landau levels in *n*-type InSb. The effect is of odd parity in the magnetic field. The primary reason for the onset of a photo-emf is a spatial separation of nonuniformly excited carriers due to a difference between the diffusion for hot and cold electrons at the Landau ground level. The electron thermalization time has been determined.

Although the photomagnetic effect in quantizing magnetic fields has been under investigation for a long time now,[1] in no study has the condition of cyclotron resonance been met; i.e., in no study has the frequency of the light, ω, been found to equal the cyclotron frequency ω_c. It is generally believed that the photomagnetic effect has a photodiffusion or photothermomagnetic mechanism, but this interpretation breaks down under cyclotron-resonance conditions since at cyclotron resonance there is no change in the carrier density, and electron-electron collisions at the lower Landau level

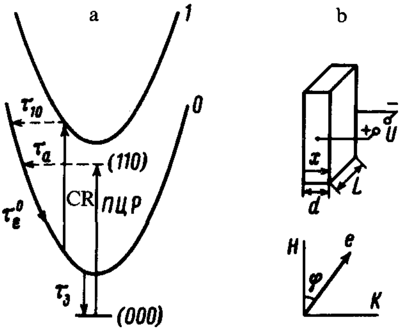

FIG. 1. a: Optical and relaxation transitions in a quantizing magnetic field. τ_a—Autoionization time; τ_c—capture time. b: Experimental geometry. k—Wave vector; e—polarization vector, e⊥k; ϕ—angle between **H** and e.

do not lead to a relaxation of momentum and energy.[2] The electron-temperature approximation[3] accordingly cannot be applied. The photomagnetic effect at cyclotron resonance is associated with the presence of highly nonequilibrium electrons.

The present experiments were carried out using n-type In-Sb samples with a density $n = 9\times 10^{13}$ cm^{-3} and a mobility $\mu = 6\times 10^5$ cm^2/(V · s) at 77 K. The source of electromagnetic radiation was a submillimeter laser with an output wavelength $\lambda = 119$ μm. A magnetic field was used to tune the energy spacing of the Landau levels to the fixed frequency of the laser beam. The emf was measured by an amplifier with a synchronous detector at a modulation frequency of 500 Hz. The experimental geometry is shown in Fig. 1b.

Figure 2 shows the observed photo-emf versus the magnetic field. There are two peaks in the resonant photo-emf; peak 1 corresponds to a transition between $n = 0$ and $n = 1$ Landau levels in the conduction band, while peak 2 corresponds (according to absorption data in the literature) to a transition of an electron from the ground state of a hydrogen-like impurity center with $n = 0$ and magnetic quantum number $m = 0$ to an excited state which is the lower of the group with $n = 1$, $m = 1$ (impurity cyclotron resonance). When the magnetic field is reversed, the photo-emf changes sign but retains the same magnitude. The photo-emf at the cyclotron-resonance and impurity-cyclotron-resonance peaks depends on the angle (ϕ) between the polarization vector **e** of the electromagnetic wave in a vacuum and the magnetic field; specifically, it varies in proportion to $\sin^2\phi$, which corresponds to a resonant cyclotron absorption.

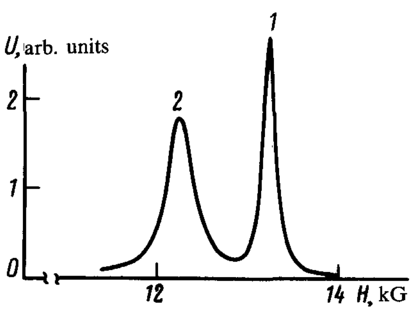

FIG. 2. Photo-emf versus the magnetic field at 4.2 K.

At cyclotron resonance, the mobile carriers appear just during the excitation process, whereas during the impurity cyclotron resonance they result from an autoionization of an excited level. In the present letter we discuss the theory for the cyclotron-resonance case alone; the photomagnetic effect at an impurity cyclotron resonance will be studied in a future detailed paper.

Two small parameters are important for the derivation of a theory: the ratio of the momentum relaxation time τ_p to the cooling time τ_ϵ and the ratio of the hot-electron diffusion length $l_D = \sqrt{D\tau_\epsilon}$ (D is the transverse diffusion coefficient) to the optical absorption depth α^{-1}. By virtue of the first small parameter and the standard assumption $\omega_c \tau_p \gg 1$ we can replace the nonequilibrium density matrix in the optical field by the distribution of electrons in Landau levels and energy ϵ (the energy is reckoned from the lower Landau level). Since the parameter αl_D is small, we can ignore the spatial gradients in the equation for $f_n(\epsilon)$ and use a local relationship between the current density, on the one hand, and the electric field **E** and the gradient of the function $f_n(\epsilon)$, on the other:

$$j_i = \sigma_{ij} E_j + e \sum_n D_{ij}^n(\epsilon) \frac{\partial f_n(\epsilon)}{\partial x_j} \nu_n(\epsilon) d\epsilon, \tag{1}$$

where $\nu_n(\epsilon)$ is the state density in the nth Landau subband.

Under experimental conditions the electron energy is lower than the frequency of optical phonons, so that the cooling results from acoustic phonons alone. Since the scale momentum of the phonons is $1/a$ (a is the magnetic length), and their energy is $S/a \ll \omega_c$ (the right side is the cyclotron frequency), the emission of the acoustic phonons is a quasielastic process. The distribution function $f_n(\epsilon)$ therefore satisfies a diffusion equation in energy space with a source $G_n(\epsilon)$:

$$-\frac{\partial}{\partial\epsilon}\left(\frac{\epsilon\nu_n(\epsilon)}{\tau_{n\epsilon}(\epsilon)}\left(1+T\frac{\partial}{\partial\epsilon}\right)f_n(\epsilon)\right)+\sum_{n'\neq n}\frac{f_n-f_{n'}}{\tau_{nn'}}=\nu_n(\epsilon)G_n(\epsilon), \tag{2}$$

where $\tau_{nn'}$ is the scale time for intersubband transitions, which are assumed to be elastic, and T is the temperature. In the nondegenerate ultraquantum limit, $\omega_c \gg T$, which corresponds to the experimental situation, the zeroth and first Landau subbands are in operation. An estimate yields $\tau_{10} \sim 5\times 10^{-11}$ s$\ll \tau_{1\epsilon}, \tau_{0\epsilon}$, so that electrons go from level 1 to the zeroth level without any loss of energy. The energy relaxation of these electrons at the zeroth level is determined by the time

$$\tau_{0\epsilon}(\epsilon) = \frac{\pi\rho\sqrt{2}}{(C\omega_c)^2}\left(\frac{\epsilon}{m}\right)^{5/2}\left(1+\frac{2\epsilon}{\omega_c}\right)^{-1},$$

where C is the strain-energy constant, ρ is the density of the crystal, and m is the effective mass. Using parameter values for InSb ($\rho = 5.76$ g/cm^3, $m = 0.014 m_0$, and $C = 30$ eV; Ref. 4), we find $\tau_{0\epsilon}(\omega_c) = 5.4\times 10^{-8}$ s at $H = 13.2$ kG.

The nonequilibrium increment in the distribution function $f_0(\epsilon)$ basically is given by

$$\frac{\epsilon\,\theta\,(\omega_c-\epsilon)}{1+2\epsilon/\omega_c}-\beta e^{-\epsilon/T},$$

where the two terms are the contributions of hot and thermal electrons, respectively. The coefficient β is determined by the normalization condition; in particular, for cyclotron resonance this condition is $\int f_0(\epsilon)\nu_0(\epsilon)d\epsilon = 0$. Current density (1) under open-circuit conditions satisfies the conditions $\int j_y dx = 0$, $j_x = 0$. Using the coefficient D_{ij} for scattering by charged centers in the expression for the current, we find the following expression for the emf in the cyclotron-resonance region:

$$U_{\text{phm}} = 12\pi\left(1-\frac{\arctan\sqrt{2}}{\sqrt{2}}\right)\tau_{0\epsilon}(\omega_c)\,e\,\frac{L}{d}\,\frac{\sigma_{xx}}{\sigma_{yx}}\,\frac{T}{\hbar\omega_c}\cdot\frac{\gamma}{(\omega-\omega_c)^2+\gamma^2}\,\frac{I\sin^2\phi}{mc\,(1+\sqrt{\chi})^2}\,(1-e^{-\alpha d}). \tag{3}$$

Here σ_{xx} and $\sigma_{yx} = nec/H$ are the transverse and Hall mobilities, n is the electron density, I is the light intensity at the illuminated surface, γ is the width of the cyclotron-resonance line in the model of Lorentz broadening, χ is the permittivity, and α is the absorption coefficient.

The current is dominated by the thermal part of the distribution function, because the transverse diffusion coefficient falls off with the energy in the case of scattering by charged impurities: The most mobile carriers are the cold carriers, which undergo frequent collisions. It can be shown that the hot electrons in the zeroth subband and the cold electrons in the first subband make small contributions $\sim\sqrt{T/\omega_c}$ in comparison with the basic contribution to the emf. This circumstance renders the model of Ref. 5—based on the approximation of two carrier species—inapplicable in our experimental situation.

The measured value of U_{phm} at the cyclotron-resonance peak in a sample with dimensions $L/d = 6$ at an intensity $I = 1$ mW/cm^2 was 4×10^{-5} V. Substituting the calculated ratio $\sigma_{xx}/\sigma_{yx} = 0.3$ and the experimental value $\gamma = 2\times10^{11}$ s into expression (3), and assuming $e^{-\alpha d} \ll 1$, we find $\tau_{0\epsilon}(\omega_c) = 7.5\times10^{-8}$ s, in satisfactory agreement with the value given above. It should be noted that the value found for $\tau_{0\epsilon}$ is only an estimate because of the difficulties in accurately measuring the absolute value of I.

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