Photomagnetic effect at a spin resonance

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An analog of the photoelectromagnetic effect has been observed under spin-resonance conditions in indium antimonide. The observed photovoltaic signals exhibit an anomalous dependence on the direction of the photon's momentum and the direction of the static magnetic field with respect to the crystallographic directions. Some possible mechanisms for the occurrence of this effect are discussed.

Rashba and Sheka[1] have shown that optical transitions accompanied by a spin flip can be excited in a narrow-gap semiconductor without an inversion center by the electric vector of electromagnetic radiation which is passing through the crystal. The intensity of the transitions depends on the angle between the crystallographic directions and the magnetic field.

It has recently been shown[2,3] experimentally and theoretically that the absorption coefficient at a spin resonance depends on the direction of the photon's momentum with respect to the axes of the crystal. It also changes when the magnetic field is reversed. The reason is an interference of the electric dipole and magnetic dipole transition matrix elements.

In this letter we are reporting experimental results which demonstrate a photomagnetic effect during the excitation of optical transitions accompanied by spin flip.

The experiments were carried out at liquid-helium temperature in the parallel Voigt geometry $\mathbf{E}\|\mathbf{H}\perp\mathbf{q}$, where $\mathbf{E}$ and $\mathbf{q}$ are the polarization and wave vector of the electromagnetic radiation, and $\mathbf{H}$ is the static magnetic field (Fig. 1a). The source of

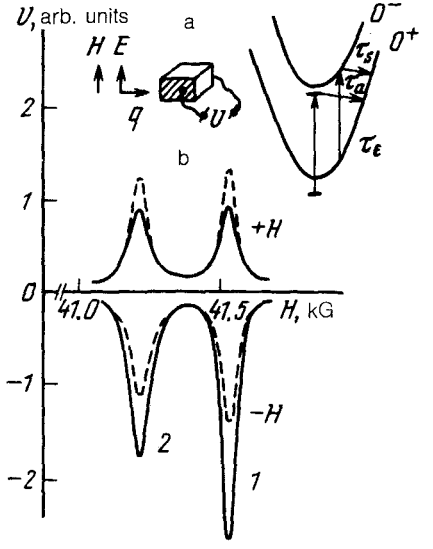

FIG. 1. a: Diagram of optical and relaxation transitions; experimental geometry. τ_s—Spin relaxation time; τ_a—autoionization time. b: Magnetic-field dependence of the photo-emf for sample 1. Solid line—$\mathbf{q}\|[110]$; dashed line—$\mathbf{q}\|[001]$.

the radiation was a submillimeter laser with a wavelength $\lambda = 118.8\ \mu$m. The energy gap between the spin sublevels of the ground Landau level was tuned to resonance by varying the magnetic field. We used indium antimonide samples with the following parameter values: for sample 1, a density $n_{77} = 1.3\times10^{14}$ cm^{-3} and mobility $\mu_{77} = 8\times10^5$ cm^2/(V·s); for sample 2, $n_{77} = 1\times10^{15}$ cm^{-3} and $\mu_{77} = 4\times10^5$ cm^2/(V·s). The samples were oriented in such a way that the $[\bar{1}10]$ direction was parallel to the magnetic field, while the radiation was incident along one of the directions [001], [110], [111]. The thicknesses of the samples were chosen to satisfy $\alpha_\pm d < 1$, where $\alpha_\pm$ is the absorption coefficient at resonance for the different directions of the magnetic field.

Figure 1 shows the magnetic-field dependence of the observed effect for sample 1 with $\mathbf{q}\|[110]$. Peak 1 corresponds to a spin resonance of conduction electrons, and peak 2 to an impurity transition. Changing the sign of the magnetic field or the direction of the incident radiation results in a change in the polarity of the photo-emf. It can be seen from Fig. 1b that for sample 1 the absolute magnitude of the photovoltaic peaks changes by a factor of 3.3. The absorption coefficient or photoconductivity signal measured under the same conditions varies by a factor of 1.9 as the direction of **H** or **q** is changed. Measurements of the photovoltaic signal (Fig. 2), the photoconductivity, and the absorption coefficient were also carried out for sample 2 in the orientation $\mathbf{q}\|[110]$. In this case, however, the absolute value of the photovoltaic signal changed by a factor of 1.8 when the direction of **H** or **q** was reversed; i.e., the behavior of the absorption coefficient was reproduced. At high impurity concentrations, we observe only the free-electron resonance. The impurity spin resonance disappears because of the coalescence of shallow impurity levels with the bottom of the conduction band. Similar measurements carried out for both samples in the orientation $\mathbf{q}\|[001]$ showed that when **H** or **q** is reversed the absolute values of the absorp-

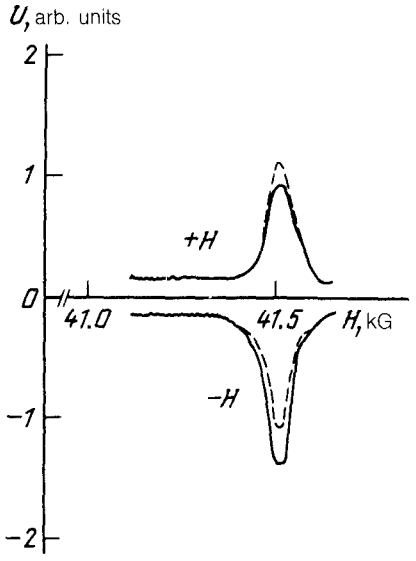

FIG. 2. Magnetic-field dependence of the photoemf for sample 2. Solid line—$\mathbf{q} \| [110]$; dashed line—$\mathbf{q} \| [001]$.

tion, photovoltaic, and photoconductivity signals remain the same. This behavior is a consequence of the absence of an interference between the electric dipole and magnetic dipole transition matrix elements in this geometry.

It can be seen from our experiments that for samples with a low concentration the absolute value of the observed effect is proportional to the square of the absorption coefficient. Such a behavior would be possible if the effect were caused by a nonuniform absorption of radiation in the interior of the semiconductor at $\alpha_{\pm} d \ll 1$.

As has been shown for a cyclotron resonance[4] resulting from an absorption gradients, the photomagnetic effect arises from a difference between the transverse diffusion coefficients for hot and cold electrons at the lower sublevel. Surface diamagnetic currents play a substantial role in the occurrence of the effect. The magnitude of this effect would be proportional to the energy relaxation time (τ_ϵ) at the lower sublevel. At low impurity concentrations, this time would be related to the cooling of electrons through the emission of acoustic phonons. A similar situation apparently arises at a spin resonance. After their excitation as a result of quasielastic scattering by ionized impurities or acoustic phonons accompanied by a spin flip,[5] hot carriers appear at the lower spin sublevel. In the case of an impurity spin resonance, the electrons in the lower sublevel appear as a result of an autoionization of the excited impurity level.

As the electron density increases, the relaxation time in terms of the energy at the lower spin sublevel decreases sharply as a result of electron-electron collisions in the presence of ionized impurities.[6] The photomagnetic effect, which is proportional to τ_ϵ, will be suppressed.

On the other hand, we may be seeing a manifestation of a drag exerted on electrons by photons in these experiments. This effect has previously been studied only in classical magnetic fields.[7] The phenomenological expression for the drag current for

the geometry of the present experiments can be written $J_{\text{phen}} = \text{const}\,\alpha[\mathbf{qh}]$, where $\hbar\mathbf{q}$ is the momentum of the photon, and $\mathbf{h}$ is a unit vector along the magnetic field. For thin samples the effect is proportional to the absorption coefficient. On the basis of our experimental data on samples with a high concentration we can assert that we are observing a photomagnetic drag effect in a quantizing magnetic field. Facts supporting this explanation are that the effect is of odd parity in the direction of the photon's momentum and that the polarization dependence of the effect is determined by the polarization dependence of the absorption coefficient, so that this effect can be distinguished experimentally from a possible photovoltaic effect in a semiconductor without an inversion center, e.g., InSb.

A more detailed analysis of the experimental results will require a theoretical analysis of the effects.

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