Magnetic-field-induced circular photovoltaic effect in semiconductors

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(Submitted 18 June 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 4, 131–133 (25 August 1984)

The first experimental observation of a magnetic-field-induced circular photovoltaic effect in nongyrotropic crystals is reported. The experiments were performed in magnetic fields of 1–8 kOe in *p*-GaAs(Zn) with excitation by CO_2 laser light.

The circular photovoltaic effect (CPVE) is a manifestation of a stationary photocurrent in gyrotropic crystals. This photocurrent, which is proportional to the degree of circular polarization of the exciting light, arises as a result of optical orientation of charge carriers.

In this letter we report the experimental observation of a new phenomenon: the magnetic-field-induced circular photovoltaic effect in nongyrotropic piezoelectric crystals. The possibility of the existence of this effect is pointed out in Ref. 2. The magnetic-field-induced CPVE is described by the following phenomenological relation:

$$j_\alpha = I\Gamma_{\alpha\beta\gamma} H_\beta \kappa_\gamma , \tag{1}$$

where I is the intensity of the light, **H** is the magnetic field, $\vec{\kappa} = i[\mathbf{e}\times\mathbf{e}^*]$, **e** is the polarization vector, $\Gamma_{\alpha\beta\gamma}$ is a tensor of rank three, which, according to its transformation properties, is completely analogous to the piezoelectric tensor.

The experiments were performed on crystals of *p*-GaAs(Zn), which at $T = 300$ K had a hole density of 2.3×10^{16} cm^{-3} and a mobility of 250 cm^2/V s. A *q*-switched CO_2 laser with a pulse power of $\simeq 5$ kW and pulse duration $\simeq 150$ ns was used as the source of excitation. The experiments were performed in magnetic fields of 1–8 kOe in the temperature range 78–300 K. The samples had the shape of rectangular parallelepipeds with dimensions $7\times4\times1.5$ mm, oriented as shown in Fig. 1. As can be seen

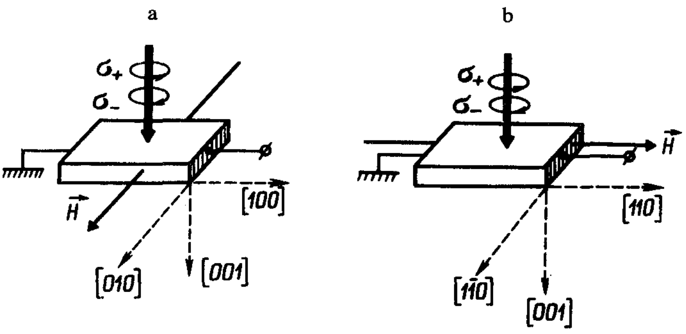

FIG. 1. Geometry of the experiment. (a) $\mathbf{H}\perp\mathbf{j}\perp\mathbf{q}$ and (b) $\mathbf{H}\parallel\mathbf{j}\perp\mathbf{q}$.

from (1), in the case of the geometry of the experiment corresponding to Figs. 1a and 1b, the circular photovoltaic current being measured must have the following form:

$$j = IH\Gamma\eta\,, \tag{2}$$

where Γ is the only linearly independent component of the tensor $\Gamma_{\alpha\beta\gamma}$ in the GaAs crystal. The linearly polarized CO_2 laser beam was passed through the quarter-wave plate, which transformed the initial beam into a circularly polarized beam with a degree of circular polarization $\eta = \sin 2\phi$, where ϕ is the angle between the optical axis of the quarter-wave plate and the polarization vector of the CO_2 laser beam. The beam was then focused on the sample under study. In the absence of a magnetic field, virtually no signals were observed. With the magnetic field switched on, a fast photo-emf, which completely duplicated the shape of the laser pulse, was generated on the contacts. The observed photo-emf depended on the position of the optical axis of the quarter-wave plate as $\sin 2\phi$ and its sign changed with a change in the sign of the circular polarization of the exciting light. The sign of the photo-emf changed when the orientation of the magnetic field changed (Fig. 2). The properties of the photo-emf, which were observed in the geometries of the experiment corresponding to Figs. 1a and 1b, were virtually identical. These facts lead to the conclusion that the observed rapid photo-emf is due to CPVE induced by the magnetic field.

The effect mentioned above is not observed in *n*-GaAS crystals, which apparently indicates that there is a relation between the magnetic-field-induced CPVE and the orbital rotation of the charge carriers caused by the optical transitions between subbands of the valence band due to the absorption of circularly polarized light.

The magnetic-field-induced CPVE is quite strong, and at $H = 7$ kOe it is only 3.7 times weaker than the linear photovoltaic effect (LPVE).[3] The constants Γ and $D = \Gamma/\sigma$, where σ is the electrical conductivity of the crystal characterizing the current and voltage of this phenomenon, were determined; at $T = 300$ K and $\lambda = 10.6\ \mu$m, they are equal to 8.4×10^{-12} A/W Oe and 9×10^{-12} [V/(W Oe)] cm, respectively.

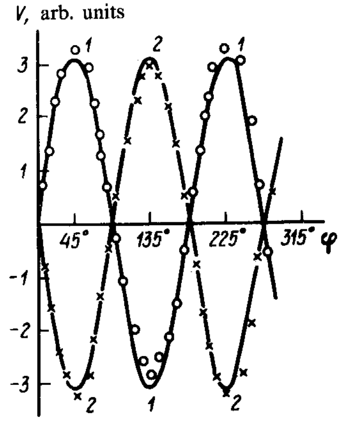

FIG. 2. Dependence of the magnitude of the rapid photo-emf on the position of the optical axis of the quarter-wave plate. $T = 300$ K, $\lambda = 10.6\ \mu$m the geometry of the experiment is illustrated in Fig. 1a; 1—$H = 6.9$ kOe; 2—$H = -6.9$ kOe; O, ×—experiment;— — sin 2ϕ;— - $(-1)\sin 2\phi$.

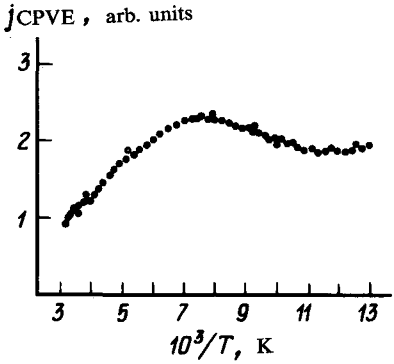

FIG. 3. Temperature dependence of the magnetic-field-induced circular photocurrent. $\lambda = 10.6$ μm, $H = 4.8$ kOe.

The temperature dependence of the magnetic-field-induced circular photocurrent is shown in Fig. 3. This dependence is apparently related to the redistribution of holes between the valence band and the impurity level of Zn and the different nature of the optical orientations in the impurity and intraband transitions, as well as to the temperature dependence of the corresponding characteristic times (spin relaxation, asymmetric scattering, etc.).

From the considerations of time-reversal symmetry of expression (1) it follows that the magnetic-field-induced CPVE observed by us, just as the LPVE,[3] is fundamentally related to dissipation processes and it appears as a result of optical transitions with scattering of charge carriers. This phenomenon is attributable to the asymmetrical scattering of optically oriented charge carriers in a magnetic field. Asymmetric scattering centers, such as phonons, impurities, and lattice defects, can cause a breakdown of the periodicity of a crystal lacking an inversion center. It should be noted that the magnetic-field-induced CPVE, just as LPVE, can have both a ballistic component, which is attributable to the optical transitions with scattering of charge carriers, and a displacement component,[4] which is linked with the quantum-transition-induced displacement of charge carriers in **r** space.

The authors thank E. L. Ivchenko for a discussion and O. V. Sulim for his assistance in preparing the samples.

[1] V. M. Asnin, A. A. Bakun, A. M. Danishevski, E. L. Ivchenko, G. E. Pikus, and A. A. Rogachev, Solid State Commun. **30**, 565 (1979).

[2] E. L. Ivchenko and G. E. Pikus, Problemy sovremenoĭ fiziki (*K* 100-letiyu so dnya rozhdeniay A. F. Ioffe) (Problems in Modern Physics (In Honor of the 100th Anniversary of the Birth of A. F. Ioffe), Nauka, Leningrad, 1980, p. 275.

[3] A. V. Andrianov, E. L. Ivchenko, G. E. Pikus, R. Ya. Rasulov, and I. D. Yaroshetskiĭ, Zh. Eksp. Teor. Fiz. **81**, 2080 (1981) [Sov. Phys. JETP **54**, 1105 (1981)].

[4] V. I. Belinicher, E. L. Ivchenko, and B. I. Sturman, Zh. Eksp. Teor. Fiz. **83**, 649 (1982) [Sov. Phys. JETP **56**, 359 (1982)].

Translated by M. E. Alferieff
Edited by S. J. Amoretty