P kg/cm^2	$(1/H) \times 10^{-5}$ Oe^{-1}	Amplitude, in per-cent of total signal (for largest peak)	$S_{m\ exp}$ Å^{-2}	$S_{m\ calc}$ Å^{-2}
0	6.33 ± 0.06	10.8	0.00015	0.00037
11,100 ± 500	1.284 ± 0.012	3.5	0.00074	0.0011
15,900 ± 700	0.898 ± 0.007	1.5	0.00105	0.0015

the calculated and experimental data is satisfactory.

Thus, the Harrison model can explain the obtained results and can be used for an estimate of the expected pressure effect in hexagonal metals. In particular, an estimate made for cadmium, using data on the compressibility [9], shows that the critical ratio c/a at which the needle-like surface is produced is attained at a pressure close to 1000 kg/cm^2, and that at 15,000 kg/cm^2 we have c/a = 1.8200, which leads to $S_{m\ calc} = 6.3 \times 10^{-4}$ Å^{-2}. Even if we assume that these values are too high, as is also the case for zinc, observation of the needle-shaped surface of cadmium and of its growth can still be attempted in the pressure range at our disposal.

In conclusion, the authors take the opportunity of thanking Professor L. F. Vereshchagin for continuous interest in the work.

[1] Yu. P. Gaidukov and E. S. Itskevich, JETP 45, 71 (1963), Soviet Phys. JETP 18, 51 (1964).

[2] E. S. Itskevich, PTE No. 4, 148 (1963).

[3] R. W. Stark, Phys. Rev. Lett. 9, 482 (1962).

[4] Yu. P. Gaidukov and I. P. Krechetova, JETP Letters 1, No. 3, 25 (1965), translation 1, 88 (1965).

[5] A. S. Joseph and W. L. Gordon, Phys. Rev. 126, 489 (1962).

[6] W. A. Harrison, Phys. Rev. 118, 1190 (1960).

[7] P. W. Bridgman, Proc. Amer. Acad. Sci. 77, 187 (1949).

[8] G. A. Alers and J. R. Neighbours, J. Phys. Chem. Solids 7, 58 (1958).

[9] P. W. Bridgman, Proc. Amer. Acad. Sci. 62, 207 (1927).

ANISOTROPY OF ODD PHOTOMAGNETIC EFFECT IN SEMICONDUCTORS OF CUBIC SYMMETRY

Yu. Kagan and V. Sobakin

Submitted 25 May 1965

Until recently, experimental studies were devoted mainly to the anisotropy of the even photomagnetic effects in Ge crystals [1-3]. In strong magnetic fields, however, it is possible to obtain data on the behavior of purely anisotropic odd photomagnetic effects, depending on the magnitude and orientation of the magnetic field. These effects, like the purely anisotropic even ones, are determined by the carrier spectrum and by the carrier relaxation times.

It can be shown from general considerations that the expression for the emf of odd photomagnetic effects (E_-) in a semiconductor of cubic symmetry begins with the term proportional to H^3 in a sufficiently weak magnetic field and drops to zero like $1/H$ at very large magnetic-field intensities. It is thus obvious that in intermediate fields E_- should go through a maximum (or minimum, depending on the relative orientation of the magnetic field and the crystal axes). In a more detailed analysis it becomes necessary to use data on the structure of the carrier energy spectrum in the semiconductor. We have developed in [4] a theory of photomagnetic effects for a semiconductor of cubic symmetry with doubly degenerate valence band (isotropic effective masses m_{p_1} and m_{p_2}; relaxation times $\langle\tau_{p_1}\rangle$ and $\langle\tau_{p_1}\rangle$) and with several equivalent minima in the conduction band (the equal-energy surfaces are ellipsoids of revolutions with effective masses m_ℓ and m_t along the principal axes; relaxation times $\langle\tau_n\rangle$) for an arbitrary orientation of the magnetic-field vector $\underset{\sim}{H}$ and direction of photoproduced-carrier diffusion (unit vector g). The chosen model is close to the true picture which takes place in semiconductors like Ge and Si, although this does not take into account the real anisotropy of the valence bands. Such a model can be perfectly suitable for a description of the photomagnetic effect, if account is taken of the fact that for any type of equilibrium conductivity this effect is due to the diffusion of the carriers of both types. Indeed, in vie- of the strong anisotropy of the common equal-energy surface for the electron band ($m_\ell >> m_t$) and the effectively weak anisotropy of the valence bands, connected with the corrugation of the spherical equal-energy surfaces, the anisotropy of the electron dispersion law will exert the decisive influence on the photomagnetic effect.

For a detailed analysis we present here results pertaining particularly to Ge. We assume here that the vector g coincides with the [111] axis. Then, in the approximation linear in the density of the photoproduced carriers (Δn, $\Delta p << n_0$, p_0) we have the following expression for the emf of the even photomagnetic effect in n-type Ge ($n_0 >> p_0$):

$$E_- = \frac{kT}{\ell d}\,\frac{\Delta p_1(0) - \Delta p_1(d)}{n_0}\,\frac{m_t}{m_{p_1}}\,\frac{\langle\tau_{p_1}\rangle}{\langle\tau_n\rangle}\,\frac{x^3\sin^2\theta\sin 3\Phi}{54\sqrt{2}}\times$$

$$\times\frac{[x_0^p + x^2\cos^2\theta(\lambda_1^p + \lambda_2^p)][3\Phi_2 + \cos\theta(2\Phi_0 - \Phi_1)] - \lambda_0^p[(3\Phi_2 - \cos\theta\cdot\Phi_1)(4\Phi_0 - 1) - (2/3)\cos\theta\cdot\Phi_0(2x^2 - 1)]}{-[(1 + x^2)/27](\Phi_0 + \Psi_1) + (2/9)(\Phi_0\Psi_1 + \Psi_2) + \gamma\{\Phi_0\Psi_2 + [1 + \gamma(1 + x^2)]\Phi_1^2 + x^2\Phi_1^2\}}, \qquad (1)$$

$$\Phi_0 = 1 + \gamma(1 + x^2) + x^2\cos^2\theta, \quad \Phi_1 = 1 + \gamma(1 + x^2) + x^2[(2 - 3\cos^2\theta)/3],$$

$$\Phi_2 = \cos\theta\{1 + \gamma(1 + x^2) + x^2[(6 - 7\cos^2\theta)/27]\} - x^2(4\sqrt{2}/27)\sin^3\theta\cos 3\Phi,$$

$$\Psi_1 = \Phi_1 + 2[1 + \gamma(1 + x^2) + (x^2/3)], \quad \Psi_2 = \Phi_1^2 + 2\Phi_1[1 + \gamma(1 + x^2)] + 2x^2\cos\theta\cdot\Phi_2$$

Here

$$\cos\theta = (\underset{\sim}{H}, \underset{\sim}{g})/\underset{\sim}{H}, \quad \underset{\sim}{x} + [(\ell\langle\tau_n\rangle)/cm_t]\underset{\sim}{H}, \quad \gamma = m_t/(m_\ell - m_t),$$

$$\lambda_j^p = \frac{(\Delta p_1)^j}{1 + x^2(\Delta p_1)^2} + g_p \frac{(\Delta p_2)^j}{1 + x^2(\Delta p_2)^2} \; (j = 0, 1, 2), \quad \Delta p_i = \frac{m_t}{m_{p_i}} \frac{\langle \tau_{p_i} \rangle}{\langle \tau_n \rangle} \; (i = 1, 2)$$

and

$$g_p = \kappa[(m_{p_1}/m_{p_2})(\langle \tau_{p_2} \rangle / \langle \tau_{p_1} \rangle)], \quad \kappa = p_{20}/p_{10}$$

is the concentration of the light holes, equal to ~ 0.02 for Ge. ϕ is the angle between $\underset{\sim}{E}_-$ (which is perpendicular to $\underset{\sim}{q}$ and lies in the plane of the vectors $\underset{\sim}{H}$ and $\underset{\sim}{q}$) and the projection of one of the crystal axes on the plane perpendicular to the vector $\underset{\sim}{q}$.

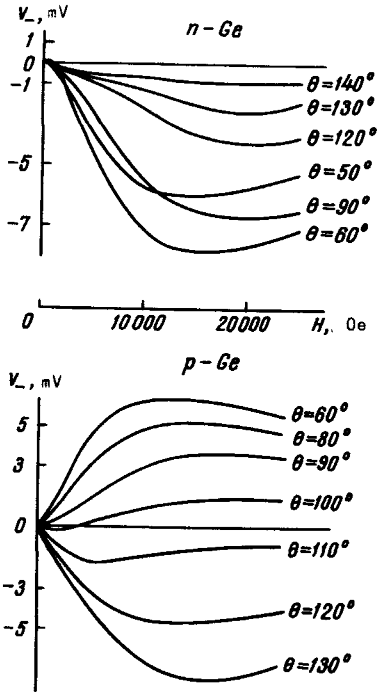

Fig. 1. Plot of the emf of the even photomagnetic effect in Ge (in arbitrary units) against x for fixed magnetic field directions ($\phi = \pi/4$).

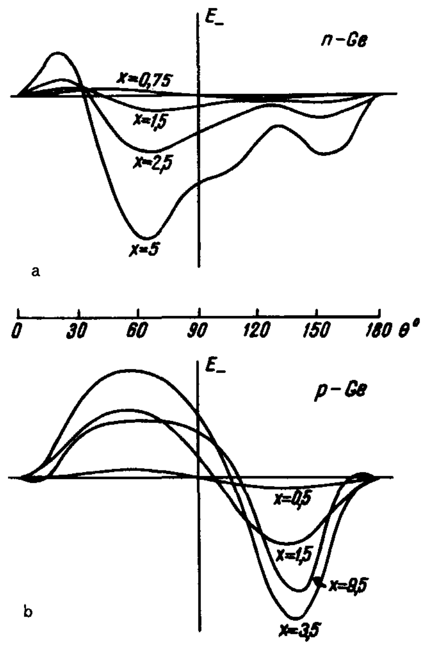

Fig. 2. Plot of E_- against the angle θ of the magnetic field for Ge at fixed values of x.

An analysis of (1) shows that along with the already noted singularities of E_- as a function of x, the dependence on the angle ϕ contains terms with sin 3ϕ and sin 6ϕ. If the position of the zeroes of E_- as a function of ϕ is independent of the temperature (the zeroes are determined by the function sin 3ϕ which precedes the entire expression), then the maxima and the minima will be displaced as a result of the appreciable temperature dependence of $\langle \tau \rangle$. If x and ϕ are specified, on the other hand, then E_- depends in a very complicated manner on the angle θ of the magnetic field. In the general case this dependence has nothing in common with that observed at low magnetic field intensities. All these laws are clearly illustrated by the curves of Figs. 1a and 2a, calculated from the known values of the effective masses [5] and the ratios of the relaxation times at T = 77°K [6].

The form of E_- is much simpler for p-type germanium ($p_0 \gg n_0$):

$$E_- = \frac{kT}{ed} \frac{\Delta n(0) - \Delta n(d)}{p_{10}} \frac{\langle\tau_p\rangle}{\langle\tau_{p_1}\rangle} \frac{m_{p_1}}{m_t} \frac{x^3 \sin^2\theta \sin 3\Phi}{(\lambda_0^p)^2 + x^2(\lambda_1^p)^2} \frac{3\lambda_0^p\Phi_2 + \cos\theta\cdot\lambda_1^p\cdot\Phi_1}{[1 + \gamma(1 + x^2)]\Phi_1^2 + x^2\Phi_1^2} \qquad (2)$$

The results of the calculations by means of (2) are plotted in Figs. 1b and 2b.

An experimental verification of these results, undertaken by I. K. Kikoin and S. D. Lazarev [7], gave good agreement with the theoretical data.

The authors are grateful to Academician I. K. Kikoin and to S. D. Lazarev for supplying their experimental data prior to publication.

[1] I. K. Kikoin and S. D. Lazarev, JETP 39, 1471 (1960), Soviet Phys. JETP 12, 1022 (1961).

[2] I. K. Kikoin and S. D. Lazarev, J. Phys. Chem. Solids 26, 1965 (in press).

[3] I. K. Kikoin and S. D. Lazarev, FTT 7, No. 8 (1965), Soviet Phys. Solid State 7, in press (1966)

[4] Yu. Kagan and V. Sobakin, J. Phys. Chem. Solids 26, 1965 (in press).

[5] B. Lax, Revs. Mod. Phys. 30, 122 (1958).

[6] Bagguley, Stradling, and Whiting, Proc. Roy. Soc. A262, 340 (1961).

[7] I. K. Kikoin and S. D. Lazarev, this issue p. 47 (Russ. p. 75).

ERRATUM

Figure 1 of the article by Yu. Kagan and V. Sobakin, "Anisotropy of Odd Photomagnetic effect in Semiconductors of Cubic Symmetry," in JETP Letters 2, 46 (1965), was erroneously identified in the caption as pertaining to the even photomagnetic effect, in place of the odd effect.