Photoelectromagnetic effect

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A review is given of the current status of research on photoelectromagnetic effects. A detailed analysis is made of the results of the more recent experimental studies of the anisotropy of the even and odd photoelectromagnetic effects, the effect across *p–n* junctions, the effect at low temperatures (when the electron system is heated by the incident radiation and the electron temperature is higher than the lattice temperature), and the radiation electromagnetic effect (when a sample in a magnetic field is not illuminated but irradiated with a flux of ionizing particles). The experimental data are compared with the theory. Directions of future studies of the photoelectromagnetic effect are suggested.

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1. INTRODUCTION

Classical galvanomagnetic and thermomagnetic effects in metals and semiconductors are very similar in the qualitative sense. The special nature of semiconductors is usually manifested by a quantitative difference between the transport coefficients and those of a metal, but in some cases these differences can be of many orders of magnitude. However, in contrast to a metal, the motion of carriers in a homogeneous semiconductor may occur not only due to an externally applied electric field but also as a result of diffusion. Such diffusion of mobile charges is associated with the likelihood of inhomogeneous carrier density or energy distributions in semiconductors. (This is practically impossible in metals because the carrier densities and energies are high and both these quantities relax very rapidly to the thermodynamic equilibrium values.) Interaction between the diffusion fluxes of carriers with an external magnetic field (Hall effect due to a diffusion current) gives rise to a number of special phenomena which can be classified in accordance with the origin of the diffusion current:

a) the diffusion of charge carriers because of a gradient of their density created by illumination of a semiconductor, which gives rise to the photoelectromagnetic (PEM) effect;

b) the diffusion of carriers due to their energy gradient (in the case of a homogeneous distribution of the lattice temperature) resulting from illumination of a semiconductor and giving rise to the photothermoelectromagnetic (PTEM) effect.

c) the diffusion of carriers due to their density gradient (?) resulting from irradiation of a semiconductor with high-energy particles (for example, α rays), which is the origin of the radiation electromagnetic (REM) effect.

All these diffusion effects depend on the characteristics of the energy spectrum of carriers and on their kinetic properties. Therefore, even in the case of isotropic crystals we may expect an anisotropy of the diffusion phenomena and also some features associated with the distortion of the electron spectrum by an external agency, such as pressure, quantizing magnetic field, etc.

It follows from the above short discussion that the PEM, PTEM, and REM diffusion effects can serve as convenient means for investigating a great variety of characteristics of semiconductor crystals under the action of various agencies.

2. PHOTOELECTROMAGNETIC EFFECT

a. Discovery and qualitative explanation of photoelectromagnetic effect

The photoelectromagnetic effect (PEM effect), also known as the photomagnetic effect, was first discovered in 1934 in cuprous oxide crystals.[1] It was manifested by the appearance of an emf in a semiconductor plate subjected to a magnetic field and illumination. This PEM emf appeared at right-angles to the light beam and magnetic field (Fig. 1). In weak magnetic fields the PEM emf was found to be proportional to the magnetic field and reversed its sign when the direction of

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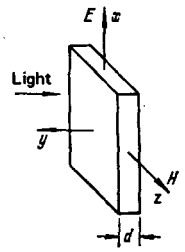

FIG. 1. Schematic representation of the origin of the odd PEM effect. The electric field E due to this effect appears along the z axis.

the magnetic field was reversed (odd PEM emf). A qualitative explanation of the PEM effect is as follows.

Illumination of a sample with strongly absorbed light creates a thin surface layer with a higher concentration of electron–hole pairs, which diffuse into the sample. The diffusing carriers are deflected in a magnetic field in opposite directions producing a photomagnetic current whose density decreases with depth of penetration into the sample because of the recombination of the excess carriers. If the contacts of the sample are short-circuited, then a PEM short-circuit current flows through the external circuit. If this external circuit is open, an electric field (emf) appears and it is directed along the sample. This field creates a conduction current which, on the average, compensates the magnetodiffusion current so that under steady-state conditions a PEM emf is observed in the open-circuit condition.

The inhomogeneity of the density of the magnetodiffusion current causes a circulation of the current in the sample. Indeed the processes of diffusion and recombination of photocarriers occur in a layer whose thickness is of the order of the diffusion length. The rest of the sample plays a passive role and acts as a conductor which short-circuits the PEM emf and this gives rise to a closed circulating current in the sample. Clearly, under steady-state conditions the total current through the whole cross section of the sample in the (y, z) plane is zero (Fig. 2). The presence of a closed circulating current in a sample can be demonstrated directly by the following simple experiment.[3] A cylindrical semiconductor is supported by the point of a needle and subjected to a magnetic field (Fig. 3). If this sample is illuminated in such a way that the angle θ between the directions of the light beam and magnetic field is $0° < \theta < 90°$ (θ is the angle between the diffusion flux of carriers and the magnetic field), the sample begins to rotate continuously about its axis (this is a manifestation of the direct conversion of light into mechanical energy!). In this experiment the photomagnetic current is proportional to $B\cos\theta$ and it interacts with the component of the magnetic field equal to $B\sin\theta$.

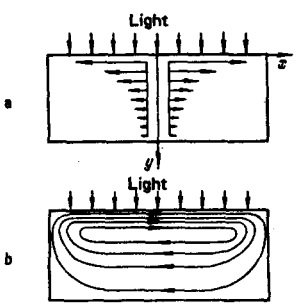

FIG. 2. Closed circulating current in a sample: a) change in the density of the magnetodiffusion current along the direction of a light beam directed parallel to the y axis (the magnetic field is applied along the x axis); b) circulating current.

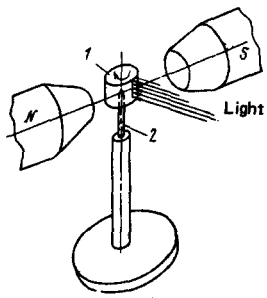

FIG. 3. Photomagnetomechanical effect: 1) cylindrical sample; 2) supporting needle.

The torque acting on the current-carrying frame is proportional to $B\cos\theta \cdot B\sin\theta = (1/2)B^2\sin 2\theta$. This torque remains constant when the magnetic field direction is reversed and it reaches its maximum value for $\theta = 45°$ and 135°.

This phenomenon, which can be called the photomagnetomechanical effect, is easy to study because no electrical contacts are needed.

The discovery of the odd PEM effect was soon followed by the discovery of an even photoelectromagnetic potential (whose sign does not change when the direction of the magnetic field is reversed),[2] which varies along the projection of the magnetic field onto the plane of the sample (along bb' in Fig. 4) when the magnetic field makes an angle of $\theta \neq 90°$ with the normal to the plane of the sample (Fig. 4).

This even PEM effect appears as a result of the action of the external magnetic field on the closed circulating current.[30,31]

The PEM effect has now been investigated in almost all the known semiconductors.[4-21] It has become a simple and reliable method for the determination of very important parameters of semiconducting materials, such as the lifetime, surface recombination velocity, diffusion length, and carrier mobility. There are many papers and monographs on the methodology of determination of these parameters.[24-29]

Since the photomagnetic current is proportional to the intensity of the incident light and the magnetic field, the PEM effect has been utilized in photodetectors and magnetometers which have a number of valuable advantages. Photodetectors based on the PEM effect differ from photodiodes by a very wide range of linear dependence of the signal on the illumination intensity. Moreover, such detectors are characterized by a short response time and can be used in studies of fast processes.

A photomagnetic magnetometer (see Sec. 2), like a

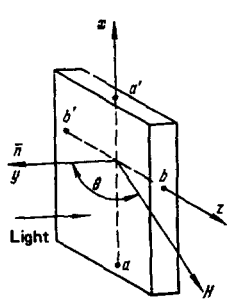

FIG. 4. Even PEM effect. The electric field due to this effect appears along the $b'b$ direction and the field due to the odd effect along $a'a$.

PEM photodetector, does not require an external electric field and has a short response time.

b. Theory of photoelectromagnetic effect

The first explanation of the PEM effect was given by Frenkel',[22] who pointed out that, in principle, it is necessary to take into account the presence of carriers of charges of opposite sign. However, Frenkel' assumed that under open-circuit conditions the current density at each point in the sample is zero. Van Roosbroeck[23] showed that this condition is far too stringent: it is simply necessary that the total current through the cross section of the sample is zero.

We shall calculate the electric field created by the PEM effect in a crystal with isotropic laws of dispersion of electrons and holes in the simple geometry shown in Fig. 1. In this case the expressions for the currents along the two directions at right-angles to the magnetic field can be written in the form

$$j_x=\sigma_{xx}^{(n)}E_x+\sigma_{xy}^{(n)}\left(E_y+\frac{1}{e}\frac{\partial\zeta_n}{\partial y}\right)+\sigma_{xx}^{(p)}E_x+\sigma_{xy}^{(p)}\left(E_y-\frac{1}{e}\frac{\partial\zeta_p}{\partial y}\right), \quad (1)$$

$$j_y=\sigma_{yx}^{(n)}E_x+\sigma_{yy}^{(n)}\left(E_y+\frac{1}{e}\frac{\partial\zeta_n}{\partial y}\right)+\sigma_{yx}^{(p)}E_x+\sigma_{yy}^{(p)}\left(E_y-\frac{1}{e}\frac{\partial\zeta_p}{\partial y}\right), \quad (2)$$

where $\sigma_{ik}^{(n)}$ and $\sigma_{ik}^{(p)}$ are the components of the electron and hole conductivity tensors ($\sigma_{xz}=\sigma_{zx}=\sigma_{zy}=0$); ζ_n and ζ_p are the chemical potentials of electrons and holes. The expressions (1) and (2) should be supplemented by the condition that the current density in the direction of incidence of light is zero

$$j_y=0 \quad (3)$$

and that the total current through the (y, z) cross section is also zero:

$$\int_0^d j_x\,dy=0. \quad (4)$$

If we assume that the components of the conductivity tensors do not vary across the thickness of the sample, which is true under weak excitation conditions ($\Delta n, \Delta p \ll n_0, p_0$), we find from Eqs. (1)–(4) that the electric field due to the PEM effect is

$$E_x=\frac{(\sigma_{xy}^{(p)}\sigma_{yy}^{(n)}-\sigma_{xy}^{(n)}\sigma_{yy}^{(p)})\,\Delta\zeta_n-(\sigma_{xy}^{(n)}\sigma_{iy}^{(p)}-\sigma_{xy}^{(p)}\sigma_{yy}^{(n)})\,\Delta\zeta_p}{ed\,[(\sigma_{xx}^{(n)}+\sigma_{xx}^{(p)})\,(\sigma_{yy}^{(n)}+\sigma_{yy}^{(p)})-(\sigma_{xy}^{(n)}+\sigma_{xy}^{(p)})\,(\sigma_{yx}^{(n)}+\sigma_{yx}^{(p)})]}, \quad (5)$$

which is expressed in terms of the quantities $\Delta\zeta_n=\zeta_n(0)-\zeta_n(d)$, $\Delta\zeta_p=\zeta_p(0)-\zeta_p(d)$, governed by an inhomogeneous distribution of carriers in the illuminated sample.

If carriers are not degenerate, then $n\propto\exp(\zeta_n/kT)$, $p\propto\exp(-\zeta_p/kT)$, and we have

$$\Delta\zeta_n=kT\ln\frac{n(0)}{n(d)}, \quad \Delta\zeta_p=-kT\ln\frac{p(0)}{p(d)}, \quad (6)$$

where $n(0)$, $n(d)$ and $p(0)$, $p(d)$ are, respectively, the electron and hole densities on the illuminated and dark sides of the sample. In the case of weak excitation of an n-type sample ($\Delta n=\Delta p\ll p_0\ll n_0$), we have

$$-\Delta\zeta_p\approx kT\frac{\Delta p}{p_0}\gg\Delta\zeta_n=kT\frac{\Delta p}{n_0}.$$

It then follows from Eq. (5) that

$$E_x=\frac{kT}{ed}\frac{\Delta p}{p_0}\frac{\sigma_{xy}^{(n)}\sigma_{yy}^{(p)}-\sigma_{xy}^{(p)}\sigma_{yy}^{(n)}}{\sigma_{xx}^{(n)}\sigma_{yy}^{(n)}-\sigma_{xy}^{(n)}\sigma_{yx}^{(n)}}, \quad (7)$$

or, in the more symmetric form,

$$E_x=-\frac{kT}{ed}\frac{\Delta p}{p_0}(\rho_{xx}^{(n)}\sigma_{xy}^{(p)}+\rho_{yx}^{(n)}\sigma_{yy}^{(p)}), \quad (8)$$

where $\rho_{ik}=\sigma_{ik}^{-1}$ is the resistivity tensor.

Thus, the problem of determination of the electric field due to the PEM effect in a specific semiconductor (whose properties are governed by the tensors $\sigma_{ik}^{(n)}$ and $\sigma_{ik}^{(p)}$) reduces to the determination of the distribution of the excess carrier density across the thickness of the illuminated sample. This distribution can be found by solving the relevant diffusion equation allowing for the characteristics of the incident light, and also for the recombination of nonequilibrium carriers in the bulk and on the surface.

In the more general case of an arbitrary orientation of a magnetic field when the direction of diffusion of photocarriers (unit vector **q**) is perpendicular to the direction of the PEM electric field (unit vector **e**), Eq. (8) can be generalized in a natural manner to[39]

$$\mathbf{E}\cdot\mathbf{e}=-\frac{kT}{ed}\frac{\Delta p}{p_0}(e_i\rho_{ik}^{(n)}\sigma_{ij}^{(p)}q_j). \quad (9)$$

In a weak magnetic field the tensors ρ_{ik} and σ_{ij} can be expanded as series of powers of H. Consequently, in the case of a cubic crystal we obtain [the last term in Eq. (10) was derived by V. N. Sobakin; see also Kagan and Smorodinskii[33]]

$$E_i=L_1e_{ikl}q_kH_l+L_2H_iq_kH_k+L_3q_iH_i^2+e_{ikl}\,[L_4q_kH_l^2+L_5H_k\,(q_lH_l^2)], \quad (10)$$

where L_1, L_2, L_3, L_4, and L_5 are the constants of the semiconductor; e_{ikl} is a completely antisymmetric unit third-rank tensor (no summation is carried out with respect to the italic indices).

In the above expression the first two terms correspond to the isotropic odd (E_-) and even (E_+) PEM effects, whereas the last two describe respectively the anisotropy of the even and odd PEM effects. An analysis shows that, irrespective of the orientation of a crystal, the odd PEM effect is purely anisotropic (it disappears in the isotropic case) if the vectors **e**, **q**, and H are in the same plane, whereas the even PEM effect is purely anisotropic if the vector **e** is perpendicular to the plane defined by the vectors **q** and H.

A complete analysis of the photomagnetic (particularly anisotropic) effects requires the knowledge of the tensors $\sigma_{ik}^{(n)}$ and $\sigma_{ik}^{(p)}$ for arbitrary values of the magnetic field and arbitrary orientation of a crystal. In the case of Ge and Si the hole band anisotropy can be ignored compared with the very strong anisotropy of the electron constant-energy surface. Investigations of the dependences of the various components of the PEM effect on the magnetic field and orientation of a crystal can be found for this case in the papers of Kagan and Sobakin.[39,42] By way of example, we shall give an expression for the electric field of the even PEM effect when the illuminated surface of a sample coincides with the (111) crystallographic plane. In the limit of a weak magnetic field, we then have

$$E_+=L_2H^2\sin2\theta\cos\varphi_0+L_3H^2\left[\frac{1}{3}\sin2\theta\cos\varphi_0+\frac{1}{3\sqrt{2}}\sin^2\theta\cos(3\varphi-2\varphi_0)\right], \quad (11)$$

where θ is the angle between the direction of the magnetic field and the normal to the plane of the sample (Fig. 4), φ is the angle between the [110] direction and the electric field E_+, and φ_0 is the angle between the projection of the magnetic field onto the plane of the sample and the direction of E_+. Most of the experiments

on the anisotropy of the even PEM effect have been carried out using the geometry corresponding to $\varphi_0 = \pi/2$, when E_+ is measured only along the same direction (shown as bb' in Fig. 4) as the odd photomagnetic emf. In this case, Eq. (11) simplifies to

$$E_+ = -\frac{1}{3\sqrt{2}} L_3 H^2 \sin^2\theta \cos 3\varphi. \qquad (11')$$

It follows from general considerations[39,42] that in the case of cubic crystals the anisotropic part of the emf due to the even PEM effect saturates in a classically strong magnetic field and the anisotropic part of the odd PEM emf has an extremum in moderate magnetic fields but disappears in strong magnetic fields.

In general, the angular and field dependences of the measured electric field, which is the sum of the isotropic and anisotropic components of the even and odd PEM effects, are very complex (this is discussed below). Nevertheless, the agreement between the theory and experiments carried out on the PEM effect in cubic crystals can be regarded as good.

The possibility of appearance of the PEM effect in unipolar semiconductors was discussed by Grinberg and Ryvkin.[74] In this case we may expect only a transient PEM effect associated with the establishment of a diffusion-drift equilibrium in the direction of the photocarrier gradient. The time taken to establish such an equilibrium (known as the Maxwellian time $\tau_M \sim \varepsilon/\sigma$) is usually very short and, therefore, the magnitude of the transient effect must also be very small.

c. Experimental investigations of photoelectromagnetic effect

We shall not describe the numerous experimental investigations of the isotropic odd and even PEM effects[1,2,4-29] in which dependences have been obtained of the relevant photomagnetic emf on the magnetic field, illumination intensity, velocities of bulk and surface carrier recombination, etc. (for the review see Ravich's monograph[24]). We shall discuss only the finer experiments concerned with the anisotropy of the PEM effects, whose existence was first discovered in n-type Ge[32] in a study of the even PEM effect in a weak magnetic field.

Figure 5 shows the asymmetry of the angular dependence of $E_+(0)$ associated with the anisotropic component of E_+. Later, a special method[3] was developed for investigating the anisotropy of the photomagnetic effects. In the traditional method (used to investigate the anisotropy of the galvanomagnetic effects) the measurements have been carried out on different samples with different orientations of the crystallographic axes and an analysis of the results obtained has yielded the anisotropy pattern. However, the PEM emf is very sensitive to the parameter representing the quality of the sample surface (surface recombination velocity). Consequently, it is very difficult to prepare a batch of identical samples with the same photomagnetic emf (because of different values of the surface recombination velocity). Therefore, the anisotropy of the PEM effect is studied by recording the anisotropy curves for the same sample. The sample is in the form of a flat disk, whose periphery is cut to form gear-like teeth (Fig. 6). This is done in such a way that the plane of the disk coincides with one of the crystallographic planes (111), (110), or (100). Rotation of a sample in a magnetic field about an axis perpendicular to the disk plane (through an angle φ) and measurements of the photomagnetic emf between the diametrically opposite contacts give an anisotropic curve for the sample in question. At the same time the PEM emf is determined as a function of the angle θ (which is the angle between the magnetic field and the normal to the plane of the sample). In studies of the anisotropic photomagnetic effect some of the experiments have been carried out in such a way that the incident light beam (and the direction of the diffusion flux of carriers) has been the same as the direction of the magnetic field. In this case there are no isotropic photomagnetic effects. Cylindrical samples are most convenient for such measurements. A sample of this kind is subjected to a magnetic field in such a way that the cylinder axis is perpendicular to the magnetic field, which is parallel to the z axis (Fig. 7). This sample is illuminated so that the light beam is parallel to the magnetic field and the illuminated area is a narrow strip on the lateral surface of the cylinder, parallel to its axis. Rotation of the sample about its axis alters the relative orientations of the crystallographic axes of the sample and the magnetic field. Such experiments have been carried

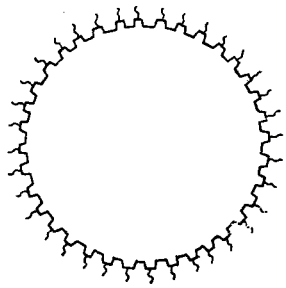

FIG. 6. Shape of a sample used in investigations of the anisotropy of the PEM effects. Conductors establishing good ohmic connections are soldered to each tooth of the disk.

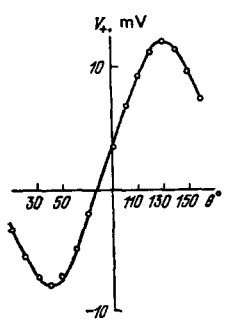

FIG. 5. Discovery of the anisotropy of the even PEM effect. The curve shows the asymmetry of the angular dependence of the even PEM emf developed in a germanium single crystal: $V_+(\theta = 90°) \neq 0$, $H = 1.5$ T, $T = 300$°K.

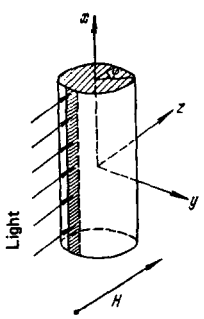

FIG. 7. Cylindrical sample for investigating the anisotropy of the PEM effects in a sample illuminated along the magnetic field. The even and odd PEM emf's are measured along the x axis.

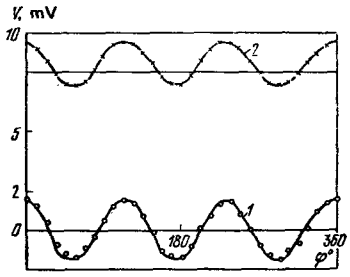

FIG. 8. Anisotropy curves of the even PEM effect in germanium. The [111] axis was perpendicular to the sample surface. $H = 1.5$ T; $T = 300$°K.

out on Ge and Si samples oriented in such a way that the cylinder axis coincides with the [111] crystallographic axis.

This method for measuring the anisotropic photomagnetic effects in the case of illumination along the magnetic field is convenient because it provides an opportunity for continuous variation of the angle of rotation of the sample (φ) in the magnetic field. There is some difficulty because the homogeneity of the surface of the sample has to be high since rotation causes light to fall on different parts of the lateral surface of the cylinder. If the surface homogeneity is insufficient, this may distort the anisotropy curve. We shall begin by considering the experimental data on the even PEM effect.

Curve 2 in Fig. 8 shows the dependence of the even PEM emf on the angle of rotation φ for $\theta = 45°$. It represents measurements carried out on a disk in the direction of the projection of the magnetic field on the disk surface, which coincides with the (111) plane. We can see that the even PEM effect is strongly anisotropic. The period of the anisotropy curve is $2\pi/3$ since the normal to the surface of the sample coincides with the crystallographic axis of threefold symmetry. If the anisotropy curve is recorded for $\theta = 90°$ (in this case the plane of the sample is parallel to the magnetic field), there is no isotropic component of the even PEM effect (curve 1 in Fig. 8) and the measured PEM emf is due to the anisotropy. In fact, curve 1 in Fig. 8 is completely symmetric relative to the φ axis. Curve 2 in Fig. 8 is the sum of the isotropic and anisotropic components of the even PEM effect. The purely anisotropic component of the PEM effect is obtained also when a sample is illuminated along the magnetic field. The dependence of the even PEM (photomagnetic) emf on the angle of rotation of a cylindrical sample (whose axis coincides with a crystallographic axis and is perpendicular to the magnetic field) is identical with curve 1 in Fig. 8. Moreover, it is found that the angular dependences describing the relevant ratios [Eq. (10)] remain valid also in magnetic fields such that the

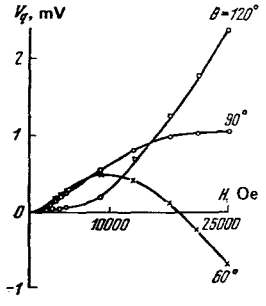

FIG. 9. Change of the sign of the even PEM emf with increasing magnetic field ($T = 300$°K, p-type Ge). In the $\theta = 90°$ case measurements were made of the anisotropic component of the even PEM effect; for $\theta = 120°$ and 60° the sum of the isotropic and anisotropic components of the effect were obtained.

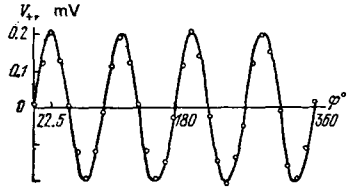

FIG. 10. Anisotropy curve of the even PEM emf in germanium. The [100] axis was perpendicular to the sample surface: $T = 300$°K, $H = 1.6$ T, $\varphi_0 = \pi/2$, $\theta = 60°$.

even PEM effect no longer varies quadratically with the magnetic field (this applied to fields of ~ 0.5 – 3 T at $T = 300$°K). In this range of magnetic fields the anisotropic and isotropic components of the even PEM effect depend in different ways on the magnetic field (Fig. 9). This is responsible for the reversal of the sign as the magnetic field is increased, exhibited by the experimentally determined even PEM emf of germanium crystals, which occurs for certain values of the angles θ and φ. (The measured emf is the sum of the isotropic and anisotropic components of the even PEM effect. The signs of these components and their dependences on the magnetic field vary with the selected angle.)[34,35] The anisotropy curve for a sample whose surface coincides with the (100) crystallographic plane is shown in Fig. 10 ($\theta = 60°$, $H = 1.6$ T).

This anisotropy of the PEM effect is associated with the characteristic shapes of the constant-energy surfaces of carriers in germanium and silicon. Although the surfaces of n-type germanium differ very greatly from those of p-type germanium, the nature of the anisotropy curves obtained at $T = 300$°K in magnetic fields up to 3 T is practically the same for n- and p-type germanium. This insensitivity of the anisotropy to the shape of the constant-energy surfaces is due to the fact that the above experiments have been carried out in relatively weak effective magnetic fields (defined in terms of the parameter $\mu H/c$, where μ is the carrier mobility).

Experiments carried out in magnetic fields of 3 T at $T = 77$°K[36,37] (in this case the parameter $\mu H/c$ rises strongly because of an increase in the carrier mobility μ as a result of cooling) and also the experiments carried out at $T = 3000$°K in a field $H \sim 15$ T[38] have demonstrated a considerable difference between the anisotropy curves of n-type and p-type germanium.

Figure 11a shows the dependence of the anisotropic even photomagnetic emf on the angle of rotation θ obtained for a sample of n-type germanium oriented in such a way that the [111] crystallographic axis coincides with the normal to the illuminated surface. The results in Fig. 11a represent the case when $\varphi_0 = \pi/2$ and $T = 77$°K. The individual curves correspond to different values of the magnetic field, given in the figure itself. The dependences of the anisotropic even PEM emf on the magnetic field vary with the angle θ (Fig. 11b). Similar curves for a p-type germanium single crystal are quite different (Fig. 12).

A theoretical analysis of the anisotropy in high effective magnetic fields was carried out by Kagan and Sobakin.[39] Their theory was found to be in excellent agreement with the experimental data.

We shall now consider the experimental results on the

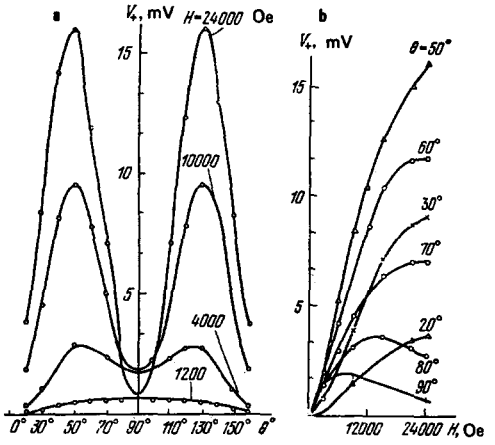

FIG. 11. a) Anisotropy of the even PEM emf in high effective magnetic fields (dependence of the even anisotropic PEM emf for n-type Ge on the angle θ at $T=78°K$; the [111] axis is perpendicular to the sample surface); b) dependence of the even anisotropic PEM emf of n-type Ge on the magnetic field at $T=78°K$ ([111] axis is perpendicular to the sample surface).

odd PEM effect.

It follows from general considerations that in cubic crystals (germanium, silicon) any effect which is strictly speaking linear in respect of the magnetic field should be isotropic. The anisotropy of such effects may appear only when the field dependence is no longer linear.[40] In the case of germanium single crystals the deviation of the dependence of the odd PEM emf from linearity occurs in fields of ~0.5 T ($T=333°K$). These experiments have been carried out on disk-shaped germanium and silicon samples in accordance with the method described above.[40] The anisotropy curve of the odd PEM effect of a germanium sample, oriented so that the normal to its surface coincides with the [111] crystallographic axis, is represented by curve 1 in Fig. 13; in this case $H=2.4$ T, $\theta=\pi/2$, $\varphi_0=\pi/2$.

The anisotropic component of the odd PEM effect has been measured along the direction of the magnetic field or along the projection of this field on the plane of the sample, i.e., for $\varphi_0=0°$. Measurements of the anisotropic component of the odd effect along the mag-

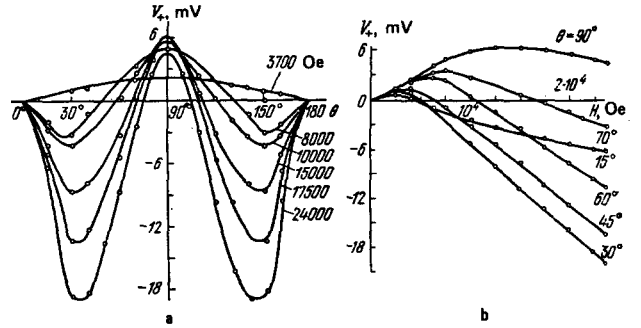

FIG. 12. a) Anisotropy of the even PEM emf in high effective magnetic fields applied to p-type Ge (dependence of the even anisotropic PEM emf of p-type Ge on the angle θ at $T=78°K$; the [111] axis is perpendicular to the sample surface); b) dependence of the even anisotropic PEM emf of p-type Ge on the magnetic field at $T=78°K$ (the [111] axis is perpendicular to the sample surface).

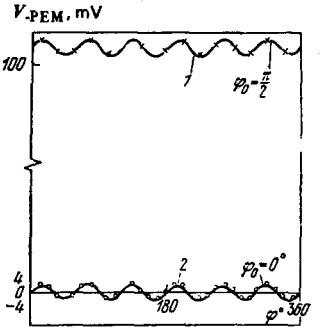

FIG. 13. Anisotropy of the odd PEM effect in germanium single crystals: 1) measurements for $\theta=\pi/2$, $\varphi_0=\pi/2$; 2) measurements along the magnetic field.

netic field require high precision in the determination of the angle of rotation φ in a magnetic field.

Curve 1 in Fig. 13 shows that the amplitude of the "modulation" representing the magnitude of the anisotropic component is about 2% of the isotropic component. Therefore, if the angle $\varphi_0\neq0$ is set inaccurately, then the anisotropic component of the odd PEM effect includes a contribution from the isotropic component equal to $V_{is}\sin\varphi_0$. This may distort the anisotropy curve. Therefore, the instrument used to study the anisotropy of the PEM effect has to be highly accurate (it should be possible to set the angle to within 30"). The dependence of the anisotropic component of the odd PEM effect on the angle of rotation φ in measurements along the magnetic field is given in Fig. 13 (curve 2).

The latter curve corresponds to sixfold symmetry and is described by $V_-\propto\sin 6\varphi$. The dependence of the anisotropic component of the odd PEM effect on the magnetic field is close to $V_-\propto H^3$. The anisotropy of the odd PEM effect has also been studied for silicon single crystals. In high effective magnetic fields[41] the anisotropy curves of n- and p-type germanium single crystals are very different. A theoretical analysis of these questions can be found in the paper by Kagan and Sobakin[42] whose results are in good agreement with the experimental data.

d. Photoelectromagnetic effect across p-n junctions

The photoelectromagnetic (photomagnetic) effect across a $p-n$ junction was discovered in 1961 by Kikoin and Nikolaev.[63] The effect was observed in a germanium sample one part of which had p-type conduction and the other n-type conduction; illumination of the $p-n$ junction subjected to a magnetic field produced a photomagnetic current across the $p-n$ junction plane.

The odd PEM effect across a $p-n$ junction can be explained as follows (Fig. 14). The minority carriers created by illumination diffuse into the sample and

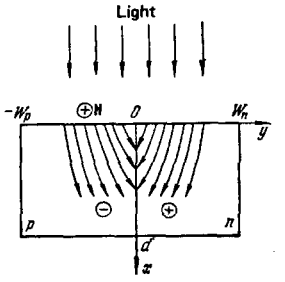

FIG. 14. Conditions for the observation of the PEM effect across a $p-n$ junction.

toward the $p-n$ junction. The photocarriers reaching the junction cross it and create a photo-emf across the junction. A magnetic field, indicated in Fig. 14, deflects the electron and hole fluxes toward the $p-n$ junction. The components of the minority carriers traveling in the p- and n-type regions toward the junction are greater than the fluxes in the absence of a magnetic field. This enhances the photocurrent and the photo-emf across the $p-n$ junction in such a field. When the direction of the magnetic field is reversed, the photocarriers are deflected in opposite directions and the photoeffect decreases. The effect is proportional to the magnetic field and its sign is reversed on reversal of the magnetic field direction.

A theory of the PEM effect across a $p-n$ junction[64,65] is in good agreement with the experimental results.[63,66] In the case of a symmetric $p-n$ junction (with the same carrier mobilities $\mu_n = \mu_p = \mu$) illuminated sufficiently strongly, we find that the PEM emf obtained under conditions of saturation of the photomagnetic effect on increase of the illumination intensity is given by[24]

$$U_- = \frac{kT}{e} \cdot \frac{2}{\pi} \frac{\mu H}{c}. \qquad (12)$$

This effect may be used to measure the intensity of a magnetic field. An increase in the sensitivity of a magnetometer of this kind is obtained by producing a large number of $p-n$ junctions arranged in series in a semiconductor plate. Illumination of such a plate results in mutual balancing out of the secondary photovoltaic effects at neighboring $p-n$ junctions (because the photo-emf's of the neighboring $p-n$ and $n-p$ junctions have opposite signs) but the photomagnetic emf's are added up (the signs of the PEM emf's of the neighboring $p-n$ and $n-p$ junctions are the same). The PEM effect can then be observed in its pure form and not against the background of the primary photo-emf. Experiments implementing this idea were carried out on an n-type germanium single crystal ($\rho = 30\ \Omega \cdot$cm). A set of $p-n$ junctions was produced by irradiation with α rays, passed through a special mask with cuts, which was placed above the sample. The α-ray source was a cyclotron. Irradiation of n-type germanium single crystals with α particles was known to cause inversion of the type of conduction[67] so that n-type germanium acquired p-type conduction. This was used to produce a set of $p-n$ junctions. In this way twelve such $p-n$ junctions were produced in a plate of $16 \times 5 \times 0.3$ mm dimensions (Fig. 15). The experiments were carried out in a magnetic field of 0.6 T using illumination of 3×10^{14} photons $\cdot$ cm$^{-2} \cdot$ sec^{-1} intensity. The PEM emf obtained on illumination of a single junction reached 1 mV (against the background of the photo-emf of 8 mV), whereas illumination of the whole sample produced 12 mV (in this case there was no photo-emf). The same idea was implemented in a very interesting manner in a study of the PEM effect in cadmium telluride films with a special structure (known as anomalous photovoltage or APV films).[68-70] The effect of anomalously high photovoltages (APV effect) has been discovered earlier in some semiconductor films formed by "oblique" evaporation on a substrate. Such films illuminated with relatively weak light generate

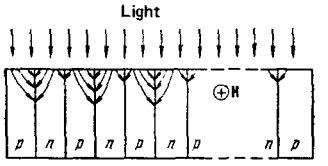

FIG. 15. Multilayer $p-n-p\ldots-n$ system for the observation of the PEM effect.

photovoltages of the order of hundreds or even thousands of volts per 1 cm of their length. According to the theoretical model,[68-70] such a film is a multilayer structure containing tens and hundreds of microscopic $p-n$ junctions shunted by the photovoltaically passive but photoconducting "bulk" of the film (Fig. 16). Because of the characteristic structure of such a film, only half the junctions are illuminated by a normally incident beam. As shown in Fig. 16, only the $p-n$ junctions are illuminated and all the neighboring $n-p$ junctions are in darkness. Consequently, the photovoltaic effects produced by the junctions are additive and the APV effect is produced. The PEM effect was measured in such a structure.[71] The strong background of the APV effect was eliminated by ensuring normal rather than oblique incidence of CdTe on the substrate during evaporation. Such films showed no APV effect and the PEM effect was measured practically against zero background. When the illumination intensity was 2.8×10^5 lx per 1 cm of the length of the CdTe film, the PEM emf reached a value exceeding 100 V in a magnetic field of 8 T. The emf was a linear function of the magnetic field. The optical-frequency resistance was $\sim 10^{10}\ \Omega$ and the film thickness was $\sim 1\ \mu$. The theoretical model made it possible to estimate the number N of $p-n$ junctions per 1 cm, as well as the photocarrier mobility μ.

It was found that $N \approx 5 \times 10^4$ and $\mu = 300$ cm$^2 \cdot$V$^{-1} \cdot$sec^{-1}. The sensitivity of such a film magnetometer amounted to a few millivolts per oersted, which was not inferior to the sensitivity of the traditionally used Hall magnetometers.

3. PHOTOTHERMOELECTRIC EFFECT

a. Optical heating of electron

We have mentioned above that the photoelectromagnetic (photomagnetic) effect is essentially the Hall effect due to the diffusion-drift flux of thermalized (i.e., having the lattice temperature) electrons and holes associated with the establishment of a carrier density gradient in a semiconductor as a result of its illumination. Clearly, the PEM emf should exist also for other mechanisms creating a carrier flux. If such a flux is associated with a temperature gradient in a crystal, then the Nernst–Ettingshausen effects appears and in many cases this may be much greater than the "pure" PEM effect. The Nernst–Ettingshausen effect obvi-

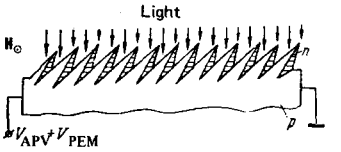

FIG. 16. Physical model of an APV film in the form of a multilayer structure of $p-n$ junctions shunted by the photovoltaically passive "bulk" of the film.

ously explains the observations of the "photomagnetic" emf in bismuth.[43-45]

Another possible reason for the appearance of a carrier flux is, for example, inhomogeneous heating by the incident light (visible or of longer wavelengths). This may occur when the excess energy of the photoelectrons is transferred rapidly (compared with their lifetime) to the equilibrium electron system by the electron–electron interaction. However, if the transfer of energy from the equilibrium electrons to the lattice is slow, the former may be heated and their effective temperature T_e may exceed the lattice temperature T_0. Illumination of a semiconductor under these conditions produces not only a carrier density gradient but also an effective temperature gradient, which the case of weak excitation and low lattice temperatures may govern all the features of the photomagnetic phenomena[58-60] associated in this case with the photothermoelectromagnetic (PTEM) effect.

Once again Eq. (5) describes the electric field of the photomagnetic effect (it is assumed that $T_e - T_0 \ll T_0$). For simplicity, we shall consider an n-type semiconductor with nondegenerate electrons. In this case we have $n = N_c \exp(\zeta_n / kT_e)$ and for $n = \text{const}$, we obtain $\Delta\zeta_n \approx -k\Delta T_e \ln(N_c/n)$, where $\Delta T_e = T_e(0) - T_e(d)$ and $T_e(0)$ and $T_e(d)$ are the effective temperatures of electrons on the illuminated and dark surfaces of a sample. Substituting the obtained expression for $\Delta\zeta_n$ in Eq. (5), we find (assuming the holes are not heated and $\Delta\zeta_p = 0$)

$$E_x = -\frac{kT_0}{ed}\frac{\Delta T_e}{T_0}(\rho_{xx}^{(n)}\sigma_{xy}^{(p)} + \rho_{yx}^{(n)}\sigma_{yy}^{(p)}). \quad (13)$$

We can see that the problem reduces to the determination of the electron temperature and its distribution across the thickness of a sample. In contrast to the classical PEM effect, governed by the change in the minority carrier density [see Eq. (8)], the magnitude of the PTEM effect considered here depends on the majority-carrier heating.

The distribution $T_e(y)$ is governed by the effective energy ε_{eff} transferred by one photoelectron to the equilibrium electron system and by the relaxation time τ_ε of the energy of the equilibrium electrons[58-60]

$$\Delta T_e \propto \varepsilon_{\text{eff}}\tau_\varepsilon. \quad (14)$$

The value of ε_{eff} depends strongly on the electron density: at high values of n all the photoelectron energy (equal to $h\nu - \varepsilon_g$, where ν is the frequency of light and ε_g is the band gap) is transferred to the equilibrium electron system, whereas for low values of n the photoelectrons lose their energy mainly by emission of optical phonons and only the residue is given up to the equilibrium electron system. In the latter case the spectral dependences of ε_{eff} and T_e oscillate with a period equal to the optical phonon frequency. There should be similar oscillations in the value of E_x.

In a quantizing magnetic field the probability of emission of an optical phonon by a photoelectron has its highest value (i.e., the value of ε_{eff} is minimal) when $N\Omega = \omega_0$, where Ω is the cyclotron frequency and N is an integer. This should give rise to magnetophonon oscillations of the PEM effect. Moreover, there should be the usual Shubnikov oscillations of E_x associated with quantum oscillations of the conductivity.

The energy relaxation time τ_ε depends on the lattice temperature. For example, in the case of InSb at $T_0 > 20\,^\circ\text{K}$ the main contribution to the energy losses is made by optical phonons. In this case we have $\tau_\varepsilon \propto \exp \times(\hbar\omega_0/T_0)$, where ω_0 is the limiting frequency of the optical phonons. The rapidly varying exponential function governs the temperature dependence of the heating photomagnetic effect in the temperature range 20–100 °K. At lower temperatures the value of τ_ε is governed by the interaction of electrons with the acoustic phonons.

In the case of semiconductors with a low carrier density and a short photoelectron lifetime the time is insufficient for the loss of excess energy by photoelectrons (we are speaking here of the residue left after the fast emission of the optical phonons). Heating of the majority carriers does not occur and all the features of the photoelectric and photomagnetic phenomena are now associated with a small group of high-energy photoelectrons.[57] Such a model applies to pure semiconductors ($n \lesssim 10^{12}$ cm^{-3}) in weak magnetic fields ($H \lesssim 0.01$ T).

b. Experimental investigations of the photothermoelectromagnetic effect

Investigations of the PEM effect at helium temperatures started in the sixties. The very first experiments revealed a number of features of the photomagnetic effect which did not fit the usual diffusion model. Oscillations of the odd and even PEM effects with the magnetic field were discovered in 1966.[46] The experiments were carried out on n-type InSb single crystals with carrier densities of 10^{15} cm^{-3} at $T = 4.2\,^\circ$K (Fig. 17). Oscillations of the PEM effect, resulting in a periodic variation of the sign of the photomagnetic emf with the magnetic field, were discovered in 1967 in n-type InAs single crystals (Fig. 18). The experiments were carried out in the temperature range 1.7–4.2 °K in magnetic fields up to 6.5 T.[47]

An attempt to explain oscillations of the photomagnetic current by quantum (Shubnikov) oscillations of the resistivity of a sample in a magnetic field was unsuccessful. The photomagnetic current oscillated much more strongly than did the magnetoresistance. Oscillations of the PEM effect in some InSb and InAs samples exhibited a change of sign, which in no way could be explained by the oscillatory dependence of the magnetoresistance. One should also point out another feature of the oscillations of the photomagnetic current.

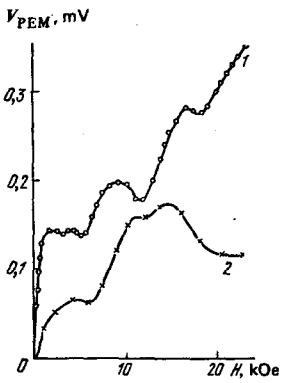

FIG. 17. Oscillations of the odd (curve 1) and even (curve 2) PEM emf's as the magnetic field is increased. $T = 4.2\,^\circ$K, n-type InSb, $n = 10^{15}$cm^{-3}.

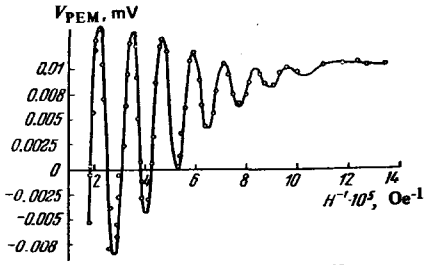

FIG. 18. Giant alternating oscillations of the PEM effect in a magnetic field. $T = 4.2$°K, n-type InAs, $n = 9.2 \times 10^{16}$ cm^{-3}.

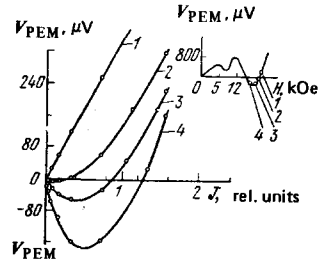

FIG. 19. Anomalous dependence of the PEM emf on the intensity of the light incident on a sample of n-type InSb with $n = 5.5 \times 10^{15}$ cm^{-3} at $T = 4.2$ °K. Curves 1–4 were obtained in different magnetic fields, whose values can be deduced from the inset.

The range of existence of the oscillations (n-type InSb, $n = 10^{15}$ cm^{-3}, Fig. 17) extended up to magnetic fields of 1.7 T. This magnetic field was beyond the quantum limit for a sample with this carrier density (i.e., $\hbar\Omega > \varepsilon_F$ and, consequently, the quantization conditions were not satisfied). Further investigations[48] showed that in addition to the Shubnikov–de Haas oscillations of the PEM effect there were also magnetophonon oscillations,[49] which appeared because of the resonance nature of the inelastic scattering of electrons by the optical vibrations of a crystal. Interaction of electrons with the optical phonons was amplified every time the energy of a longitudinal optical phonon $\hbar\omega_0$ became equal to the gap between the Landau levels $\hbar\Omega$. The period of the magnetophonon oscillations was independent of the carrier density (in contrast to the Shubnikov–de Haas oscillations) and was governed by the effective electron mass and the limiting phonon frequency. Such oscillations could be observed in the quantum limit, when the Shubnikov–de Haas oscillations were impossible. In the case of the magnetophonon oscillations the necessary condition was the excitation of the optical vibrations and, therefore, these oscillations were usually observed at much higher temperatures than the Shubnikov–de Haas oscillations. However, the oscillations of the PEM effect were found at $T \approx 4$ °K, when the optical vibrations were not normally excited and when other transport effects showed no such oscillations.

One should mention also a number of other investigations reporting results which did not fit the diffusion representation. Oscillations of the PEM effect due to variation of the incident-light frequency were observed at helium temperature.[50,51] The period of these oscillations was equal to the longitudinal optical phonon frequency ω_0. These measurements were carried out on n- and p- type InSb samples. The temperature dependences of the short-circuit photomagnetic current in n-type InSb indicated that the current increased (by a factor of 30–40) when the temperature was lowered from 50 to 15 °K. Further cooling caused the current to reach a saturation value. At the same time the electron and hole lifetimes changed only slightly.[52,53]

Under weak illumination conditions ($\Delta n \ll n_0$) it was found that samples of InSb and InAs exhibited a deviation from the linear dependence of the photomagnetic emf on the light flux.[54] In certain magnetic fields the PEM emf changed sign when the illumination intensity was increased (Fig. 19). These measurements were carried out on a sample illuminated with white light and also with monochromatic light over a fairly wide spectral range.

In addition to the PEM effect, other photoeffects were studied at low temperatures: these included photoconducitivty,[55] Hall photoelectric effect,[56] etc. Several interesting phenomena were observed. The most striking among them were the oscillations of the photoconductivity with the magnetic field which showed reversal of the sign (sample of n-type InAs, $T = 4.2$ °K). In certain magnetic fields the resistance of a sample increased on illumination (Fig. 20).

Experimental investigations of the photoelectromagnetic phenomena at low temperatures led to some modification of the theory of photoelectric effects.

All the features of the photomagnetic and photoelectric effects in quantizing magnetic fields observed in degenerate semiconductors (with carrier densities in the range $n \gtrsim 10^{13}$ cm^{-3}) could be explained satisfactorily by the model of heating of electrons by the incident light. The decisive argument in support of this model was provided by a comparative investigation of the photomagnetic and photothermomagnetic effects, which appeared when electrons were heated by microwave radiation.[61]

Dependences of the PEM emf and of the PTEM effect (Fig. 21) on the magnetic field were found to be completely identical. In particular, both effects exhibited a change of sign in the same magnetic field. Hence, the observed emf was essentially the manifestation of the Nernst effect due to hot electrons, which—in principle—could change its sign in a magnetic field. The contribution of the diffusion term was negligible. This accounted for the magnetophonon oscillations of the PEM effect at helium temperatures, which were thus due to oscillations of the energy lost by hot photoelectrons due to interaction with the optical phonons. It should be pointed out that the magnetophonon oscillations were not observed in measurements of the PTEM

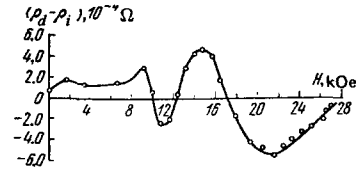

FIG. 20. Dependence of the photoconductivity of n-type InAs ($n = 1.8 \times 10^{16}$ cm^{-3} and $T = 4.2$ °K) on a transverse magnetic field. The ordinate gives the difference between the dark resistivity $\rho_d(H)$ and the resistivity of an illuminated sample in a transverse magnetic field $\rho_i(H)$.

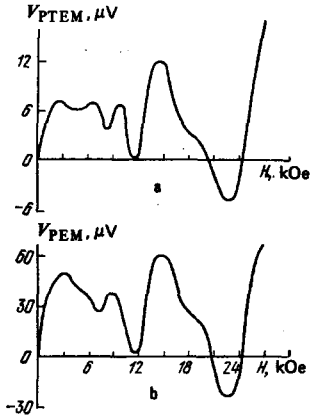

FIG. 21. Photoelectromagnetic effect (a) and photothermoelectromagnetic effect (b) in n-type InSb ($n = 3.7 \times 10^{16}$ cm^{-3}, $T = 4.2$°K). The microwave wavelength was $\lambda = 15$ mm.

effect because there were no photoelectrons. Measurements of the PEM and PTEM effects in the same sample provided a convenient method for detecting the magnetophonon oscillations.

The above model explains practically all the "anomalies" observed in studies of the PEM effect at low temperatures. The spectral oscillations of the PEM effect are due to oscillations of the energy ε_{eff} given up by photoelectrons to the equilibrium electron system. In the diffusion theory the PEM effect is independent of the frequency of the incident light. The exponential rise of the photomagnetic current as a result of cooling is due to an increase of the contribution made by the heated electrons. At low temperatures the conditions are favorable for the effective heating of carriers by the incident radiation and the phenomena associated with the excess electron temperature predominate over the carrier-density effects. The photoconductivity is due to the heating of the equilibrium electrons by electron–electron interaction with the relaxing photoelectrons, which alters the mobility of the equilibrium electrons and the dark conductivity. According to the diffusion theory, the photoconductivity cannot change its sign when the magnetic field H is varied, but in the case of electron heating by the incident radiation in quantizing magnetic fields the photoconductivity becomes negative in fields corresponding to the magnetoresistance minimum.[62] This result is in agreement with the experimental data.

4. RADIATION ELECTROMAGNETIC EFFECT

Recent experiments[72] involved irradiation of a homogeneous germanium single crystal, subjected to a magnetic field, with a flux of ionizing particles (α rays, protons). This gave rise to the radiation electromagnetic (REM) effect in a direction perpendicular to the

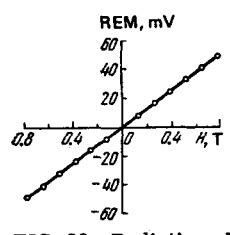

FIG. 22. Radiation electromagnetic effect in a germanium single crystal presented as the dependence of the emf on the magnetic field. The α-ray dose rate was $N = 8 \times 10^{11}$ cm$^{-2} \cdot$ sec^{-1} and the α-ray energy was 40 MeV.

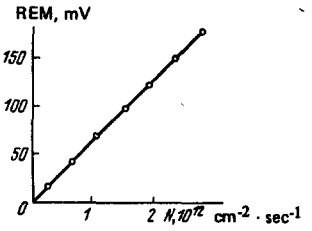

FIG. 23. Dependence of the radiation electromagnetic effect in n-type Ge on the α-ray dose rate ($H = 0.8$ T).

magnetic field and to the particle beam; the resultant emf changed its sign when the magnetic field was reversed. A cyclotron was used as the α-ray source. The experiments were carried out on n- and p-type germanium single crystals (resistivity 30–60 Ω·cm) which were irradiated with single pulses of 100–400 μsec duration (to avoid heating the samples). Contacts were deposited on the unirradiated part of the surface and were protected from the direct incidence of the α-ray beam.

Figures 22 and 23 show the linear dependences of the REM emf on the magnetic field and on the α-ray flux for a sample of n-type germanium (the α-ray energy was 40 MeV). The magnitude of the effect depended weakly on the α-ray energy (this energy was in the range 5–40 MeV).

Measurements of the photomagnetic and Hall effects on α-particle-irradiated samples demonstrated a strong reduction (by a factor exceeding 10) of the photomagnetic emf (compared with the effect observed for an unirradiated sample) and an inversion of the sign of the Hall emf in n-type germanium. An irradiated sample became strongly inhomogeneous along the direction of irradiation. A surface p–n junction was formed in the sample. The current-voltage characteristic of the irradiated sample (the electrodes were located on the front, i.e., irradiated, and the opposite faces of the sample) was of the shape typical of p–n junctions. The REM effect was clearly associated with the p–n junction created by irradiation. To form an abrupt p–n junction a highly monochromatic α-ray beam is required (in the cyclotron experiments the scatter of the α-ray energies did not exceed 1–2%). When the energy spectrum of the α rays was spread out over a wide range (i.e., when the same sample was irradiated successively by α rays of different energies), the measured REM emf decreased practically to zero. When the REM effect was investigated using a radioactive ^{238}Pu α-ray source[73] the α particles had a considerable scatter of energies because of the absorption in the substrate material. The REM effect measured under these conditions diminished strongly on increase of the duration of irradiation. When the REM effect was measured in n-type Ge ($\rho = 30\,\Omega \cdot$ cm) using cyclotron-accelerated α rays, the REM emf increased with time from one irradiation pulse to another and after 40–50 pulses (the α-ray dose rate was 10^{12} cm$^{-2} \cdot$ sec^{-1} and the pulse duration was 200 μsec) there was no further change in the emf. Clearly, 40–50 pulses at this α-ray dose rate were sufficient to complete the formation of a p–n junction. These experiments suggested that the resultant emf could be due to some phenomenon associated with electron emission resulting from the bombardment of the sample with α rays. Clearly, this electron

emission could not depend on the spreading of the energy spectrum of the α rays or on the number of the α-ray pulses. A study was also made of the even REM effect. The magnitude of the even REM emf was about ~10 times smaller than the corresponding odd emf. A quantitative theory of the REM effect is not yet available.

5. CONCLUSIONS

The main mechanisms and laws governing the photoelectromagnetic (photomagnetic) effects in semiconductors can now be regarded as fully established. However, as in any other "live" research topic, there are a number of physical problems which have yet to be explained theoretically or solved experimentally.

Experience shows that the "center of gravity" of the topics discussed above is shifting. It seems that in the near future the most important task will be to investigate the physics of the REM effect, the anisotropy of the heating PTEM effect, and the PEM effect in quantizing magnetic fields. Undoubtedly, such investigations will extend our ideas on these phenomena.

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