IMPURITY STATIONARY PHOTOMAGNETIC EFFECT

V. N. ABAKUMOV, É. K. GUSEĬNOV, D. N. NASLEDOV, Yu. G. POPOV, and I. N. YASSIEVICH

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

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A theory of the stationary photomagnetic effect in the region of impurity absorption, when the electrons are heated by light, is developed. The effect is due to the existence of an electron temperature gradient. The analysis is carried out for the case when $\alpha d \ll 1$ (α is the absorption coefficient, d the sample thickness), surface recombination being taken into account. A monopolar stationary photomagnetic effect in n-InSb samples has been observed for the first time at helium temperatures. The experimental results are in agreement with the theory.

IN the approximation of the usual diffusion theory, no stationary photomagnetic effect (PME) occurs in the impurity-absorption region (monopolar case). At helium temperatures, when the heating of the electrons by the light is important[1,2], the photomagnetic effect should be observed also in the region of impurity absorption, which now is simply the Nernst effect resulting from the gradient of the electron temperature[3]. In[3] we obtained an expression for the impurity photomagnetic short-circuit current for n-semiconductors under the condition $\alpha d \gg 1$ (α—light absorption coefficient, d—sample thickness) and without allowance for surface recombination. However, in the region of impurity absorption α^{imp} is small, so that most frequently the opposite case, $\alpha^{imp} d \ll 1$, is realized (for example, $\alpha^{imp} = 1\ cm^{-1}$ in typical n-InSb samples). It is clear that in this case it is important to take the surface recombination into account.

In Sec. 1 of this paper we construct the theory of the stationary monopolar PME with allowance for surface recombination. In Sec. 2 we present the experimental results obtained with n-InSb samples, as well as a comparison with theory.

1. THEORY

Let us consider first a degenerate n-semiconductor of the n-InSb type with one deep impurity level, from which excitation of photoelectrons takes place and which is simultaneously a recombination level. The influence of shallow donor levels is neglected, it being assumed that they merge with the bottom of the conduction band. In such semiconductors, the density n_0 of the equilibrium electrons is so large, that the conditions $\tau_{ee} \ll \tau_n$ and $\tau_{ee} \ll \tau_{lat}$ are satisfied, where τ_{ee} is photoelectron relaxation time in interelectron interaction, τ_n is their lifetime, and τ_{lat} is the time of energy relaxation due to scattering by the piezoelectric and deformation potentials of the acoustic oscillations. Under such conditions it can be assumed that almost all the electrons have a Fermi distribution with a temperature $T_e(x) = T_0 + T_1(x)$ and with a chemical potential $\zeta(x) = \zeta_0 + \zeta_1(x)$ (T_0 and ζ_0 are the equilibrium values). This model is discussed in detail in[1,2].

Let the light be incident along the x axis, and let the magnetic field be directed along the z axis. Then, in the case of a weak light signal, the small corrections $T_1(x)$ and $\zeta_1(x)$ can be obtained from the balance equations for the flux of the particles q_n and their energies Q_n:

$$q_n{}^x = 0, \quad \left(\frac{\delta n}{\delta t}\right)_{ri} = \alpha I e^{-\alpha x},$$
$$\frac{\partial Q_n{}^x}{\partial x} = \alpha I e^{-\alpha x} \varepsilon_{eff} - \left(\frac{\delta \varepsilon}{\delta t}\right)_{ri} - P_{lat}. \tag{1}$$

Here I is the density of the photon flux entering the sample, ϵ_{eff} is the effective energy given up by the photoelectron to the electron system (an expression for ϵ_{eff} at an arbitrary relation between τ_{ee} and τ_{opt}—the time of emission of the optical phonon—is given in[2,5]). In the Shockley-Read model we have for the semiconductor under consideration[2]

$$\left(\frac{\delta \varepsilon}{\delta t}\right)_{ri} = \frac{\gamma_{n1}}{\gamma_n}\frac{n_1 \zeta_0}{\tau_n}, \quad \left(\frac{\delta n}{\delta t}\right)_{ri} = \frac{n_1}{\tau_n};$$

$P_{lat} = n_0 T_1/\tau_{lat}$ is the power given up by the electrons to the lattice upon scattering by the piezoelectric and deformation potentials (an expression for τ_{lat} can be found, for example, in[2,4]). The fluxes of the electrons and of their thermal energy in a magnetic field, introducing tensor kinetic coefficients, will be written in the form

$$\mathbf{q}_n = -\frac{\hat{\sigma}}{e}\left(\frac{\nabla \zeta_1}{e} + \mathbf{E}\right) - \frac{\hat{\beta}}{e}\nabla T_1,$$
$$\mathbf{Q}_n = -\hat{\chi}\left(\frac{\nabla \zeta_1}{e} + \mathbf{E}\right) - \hat{\varkappa}\nabla T_1. \tag{2}$$

The boundary conditions with allowance for the surface recombination are[5]

$$Q_n{}^x(x) + s_{1T} n_0 T_1(x)\,|_{x=0} = 0,$$
$$Q_n{}^x(x) - s_{2T} n_0 T_1(x)\,|_{x=d} = 0, \tag{3}$$

s_1T and s_2T are the rates of surface energy loss on the front and rear walls of the sample. It is more convenient to carry out the calculations in terms of the variables $T_1(x)$ and $n_1(x)$ ($n_1(x)$ is the excess electron density).

For an open-circuited sample, the photomagnetic emf V_{pm} and the Dember emf V_D, in the case of arbitrary magnetic fields, can be obtained by a method described in detail in[6]:

$$V_{pm} = -QH\frac{l}{d}[T_1(0) - T_1(d)], \quad Q = \frac{\beta_{yx}\sigma_{xx} - \beta_{xx}\sigma_{yx}}{H(\sigma_{xx}{}^2 + \sigma_{yx}{}^2)},$$

$$V_D = V_D' + V_D'' = \left[\frac{\beta_{xx}\sigma_{xx} + \sigma_{yx}\beta_{yx}}{\sigma_{xx}^2 + \sigma_{xy}^2} - \frac{\pi^2}{6}\frac{T_0}{e\zeta_0}\right]\left[T_1(0) - T_1(d)\right] + \frac{2}{3}\frac{\zeta_0}{en_0}[n_1(0) - n_1(d)]. \quad (5)$$

Here Q is the Nernst coefficient. It is seen from (4) that V_{pm} is the Nernst effect on the electron-temperature gradient, and V_D consists of two terms: V_D'—the thermal emf on the electron-temperature gradient, and V_D'' is the Dember field proper for the monopolar case. We note that in all formulas T is the temperature in the energy scale.

For the differences of the concentrations and of the temperatures, the solution of the system (1) with boundary conditions (3) in the approximation $(\alpha^{imp})^{-1} \gg d \gg L$ (L—length over which the electron temperature changes, $L^2 = (\kappa_{xx}\sigma_{xx} - \beta_{xx}\chi_{xx})\tau_{lat}/n_0$) yields $n_1(0) - n_1(d) = (\alpha^{imp})^2 I\tau_n d$,

$$T_1(0) - T_1(d) = \frac{\alpha^{imp} I\tau_{lat}}{n_0}\left(\varepsilon_{eff} - \frac{\gamma_{n1}}{\gamma_n}\zeta_0\right)\frac{(1+s_2) - (1+s_1)(1-\alpha^{imp}d)}{(1+s_1)(1+s_2)}$$

$$s_1 = \frac{s_{1T}\tau_{lat}}{L}, \quad s_2 = \frac{s_{2T}\tau_{lat}}{L}.$$

If the conditions on both walls are the same, so that $s_1 = s_2$, then the temperature difference arises only as the result of the non-uniform absorption of the light, and the PME is proportional to the small quantity αd:

$$T_1(0) - T_1(d) = \frac{^{imp}I\tau_{lat}}{n_0}\left(\varepsilon_{eff} - \frac{\gamma_{n1}}{\gamma_n}\zeta_0\right)\frac{\alpha d}{1+s_1}. \quad (7)$$

On the other hand, if $s_1 \neq s_2$, i.e., the condition on the walls are different and $|s_1 - s_2| \gg \alpha^{imp}d(1 + s_1)$, then we have

$$T_1(0) - T_1(d) = \frac{\alpha^{imp} I_{lat}}{n_0}\left(\varepsilon_{eff} - \frac{\gamma_{n1}}{\gamma_n}\zeta_0\right)\frac{s_2 - s_1}{(1+s_1)(1+s_2)}. \quad (8)$$

Thus, by producing different conditions on the walls, it is possible to increase the effect appreciably.

In the case of nondegenerate semiconductors with sufficiently large conduction-electron density n_0, making it possible to introduce an electron temperature, the analysis is similar. We present only the final results. The PME is again determined by formula (4), and the expression for V_D changes somewhat, because the electrons are not degenerate:

$$V_D = \frac{(\beta_{xx}\sigma_{xx} + \sigma_{yx}\beta_{yx})}{(\sigma_{xx}^2 + \sigma_{yx}^2)}[T_1(0) - T_1(d)] + \frac{T_0}{en_0}[n_1(0) - n_1(d)]. \quad (9)$$

The differences between the concentrations and the temperatures, in the approximation $(\alpha^{imp})^{-1} \gg d \gg L$, are determined by the formulas

$$n_1(0) - n_1(d) = (\alpha^{imp})^2 I\tau_n d - n_0\frac{\tau_n}{\tau_n'}\frac{[T_1(0) - T_1(d)]}{T_0},$$

$$T_1(0) - T_1(d) = -\frac{\alpha^{imp} I\tau_T}{n_0}\left(\varepsilon_{eff} - \frac{\gamma_{n1}}{\gamma_n}T_0\right)$$

$$\times \begin{cases} \dfrac{\alpha^{imp} d}{1+s_1} & \text{when } s_1 = s_2 \\ \dfrac{s_2 - s_1}{(1+s_1)(1+s_2)} & \text{when } |s_1 - s_2| \gg \alpha d \end{cases}, \quad (10)$$

$$s_1 = \frac{s_{1T}\tau_T}{L}, \quad s_2 = \frac{s_{2T}\tau_T}{L}, \quad L^2 = \frac{\varkappa_{xx}\sigma_{xx} - \chi_{xx}\beta_{xx}}{n_0\sigma_{xx}}\tau_T,$$

$$\frac{1}{\tau_T} = \frac{1}{\tau_{lat}} + \frac{1}{\tau_n''} - \frac{\gamma_{n1}}{\gamma_n}\frac{1}{\tau_n'}.$$

Concerning the times τ_n', τ_n'', and τ_{lat} and the electron capture coefficients γ_n and γ_{n1}, see [1,5].

The impurity photoconductivity can be readily calculated by the method described in [5], and the principal role is played in it likewise by the temperature term. It should be noted that a study of the stationary impurity PME together with the impurity conductivity yields information on the surface energy loss of the electrons.

2. EXPERIMENTAL RESULTS

An experimental verification of the foregoing theory was carried out on a number of nondegenerate n-InSb samples at a temperature close to that of liquid helium. The investigations were performed with radiation modulated at 800 Hz. The photomagnetic-effect signal was amplified by a system consisting of a narrow-band amplifier and a phase detector, after which it was registered with an automatic recorder. The measurements were performed under conditions when the photomagnetic emf was registered. The effect turned out to be small for samples with low electron density, $n_0 = 10^{12}$—10^{13} cm^{-3}, i.e., for strongly compensated samples; a large signal was produced by the impurity photo emf, which changed with the magnetic field as the result of the magnetoresistance effect. The signal turned out to be even in the magnetic field. A monopolar odd photomagnetic effect could be reliably detected only for samples of thickness d = 0.2 cm with density $n_0 = 10^{14}$ cm^{-3} and higher. The fact that the measured signal has no time lag, has a strong spectral dependence, and increases with increasing n_0, indicates that this is not the Nernst effect resulting from the heating of the crystal by the light on the forward side.

The increase of the effect with increasing equilibrium-electron (impurity) concentration is connected with the growth of α and with the increase of ϵ_{eff}, since an increase of n_0 is accompanied by an increase of the fraction of the energy transferred by the photoelectron to the system of electrons as the result of the interelectron interaction.

The impurity photomagnetic effect is small, since the absorption coefficient in the impurity region is small ($\alpha^{imp} < 1$ cm^{-1}). Under the conditions of our experiment $\alpha^{imp}d \ll 1$. In accordance with the theory (formulas (4) and (10) of Sec. 1), the effect is greatly increased when the rear surface was damaged and the condition $s_2 \gg s_1$ was satisfied.

An estimate of the absolute value of the effect from Eqs. (4) and (10), for the purpose of comparison with the experimental results, is difficult, since we do not know a number of parameters. However, it is easy to obtain an estimate of the ratio $V_{pm}^{imp}/V_{pm}^{intr}$ of the values of the PME emf's in the regions of the impurity and intrinsic absorption.

When $s_2 \gg s_1$ the value of V_{pm}^{imp} for nondegenerate semiconductors is determined by formulas (4) and (10), and for V_{pm}^{intr} we have from [5,6], in the case when the contribution from $\partial T_1/\partial x$ predominates

$$V_{pm}^{intr} = \frac{l}{d}QH\frac{\alpha^{intr} I\tau_T}{(1+\alpha^{intr}L)n_0}\left(\varepsilon_{eff} - \frac{\gamma_{n1}}{\gamma_n}T_0\right); \quad (11)$$

under our conditions $\alpha^{intr} = 5 \times 10^3$ cm^{-1} and L $\approx 10^{-3}$ cm, and then

$$\frac{V_{pm}^{imp}}{V_{pm}^{intr}} = \frac{\alpha^{imp}}{\alpha^{intr}(1+\alpha^{intr}L)} \approx 10^{-3}. \quad (12)$$

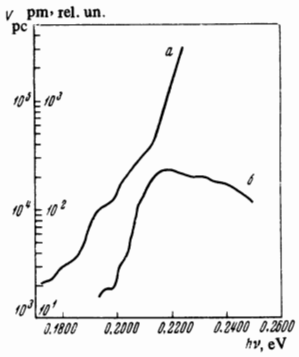

FIG. 1. Spectral dependences of the impurity photoconductivity (a) and of the photomagnetic effect (b) at 8°K.

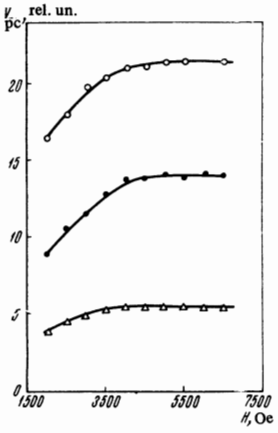

FIG. 2. Dependence of monopolar photomagnetic voltage V_{pm} on the magnetic field H at 8 (○), 21 (●), and 41°K (△).

This estimate agrees well with the experimental results.

To decrease the scattered light due to radiation in the intrinsic band of sensitivity, a filter of pure n-InSb, of thickness ≈40 μ, was placed ahead of the sample.

Figure 1 shows the spectral dependence of V_{pm} at H = 3 kOe and the quantum energy interval from 0.193 to 0.25 eV. The same figure shows the impurity photoconductivity in the case of the small electric field, when the effects of ionization and heating due to the electric field can be neglected. The photoconductivity signal is much larger than the photomagnetic-effect signal, but their relative variations below 0.22 eV are the same. Owing to the action of the filter, there is a broad maximum on the photomagnetic-effect curve in the region of 0.23 V. On the photoconductivity curve, in the region of lower quantum energies there appear a number of peaks resulting from the ionization of the impurity levels. Two of these shallow peaks can be seen, but less distinctly, also on the photomagnetic-effect curve. No oscillations are seen on the spectral curve of the photomagnetic effect. When the temperature is increased, the impurity photomagnetic effect decreases and this appears completely at temperatures above 50°K.

Figure 2 shows plots of V_{pm} against H for the same sample at $h\nu = 0.218$ eV for three temperatures: 8, 21, and 41°K. From the value of the magnetic field at which saturation is reached, we have estimated the mobility of the electrons and obtained at T = 7°K, $\mu_n \approx 3 \times 10^{14}$ cm^2/V-sec. With increasing temperature, the region of saturation shifts toward weaker magnetic fields, corresponding to an increase of μ_n. The effect itself decreases in this case, owing to the decrease of τ_{lat}. With increasing light-quantum energy in the impurity region, the saturation of the field dependences also shifts towards weaker fields. This is apparently connected with the contribution made to the photomagnetic effect by the non-thermalized photoelectrons[7].

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