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1961

SovietRxiv

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Abstract

Full Text

PHYSICS

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A NEW EFFECT OF NEGATIVE PHOTO-CONDUCTIVITY IN A MAGNETIC FIELD

(Presented by Academician A. F. Ioffe, 1 VIII 1960)

The phenomenon of negative photoconductivity has been experimentally discovered in a number of semiconductors quite long ago. However, up to the present time it has not yet found a sufficiently convincing interpretation, although there do exist quite plausible points of view concerning its nature. In contrast to this, the new effect of negative photoconductivity in a magnetic field investigated in the present work finds a natural and sufficiently convincing explanation.

Fig. 1. Scheme for observing negative photoconductivity in a magnetic field. 1 –specimen, 2 –light source, 3 –objective, 4 –light modulator

The scheme for observing the effect is shown in Fig. 1. The specimen is connected in an ordinary circuit for measuring photoconductivity. For convenience of measurement it is illuminated by short light pulses separated by long intervals of darkness. To eliminate the photomagnetic emf, the specimen was illuminated "along" the magnetic field. The signal taken from the load resistance R is analyzed by means of an oscilloscope. Typical oscillograms are shown in Figs. 2a and 2b.

Oscillogram *a* was obtained in the absence of a magnetic field and corresponds to ordinary "positive" photoconductivity ("upward pulses"). When the magnetic field is switched on (oscillogram "b"), the photoconductivity changes sign ("downward pulses"), i.e., becomes negative*.

A qualitative explanation of the effect is as follows. When current carriers drift in a transverse magnetic field, their trajectories (over the mean free path) are curved. Connected with this, as is known, is a decrease in mobility (an increase in resistance) in a magnetic field. However, the arising Hall field partially "straightens" the trajectories of the particles and thereby reduces the effect of the increase in resistance in the magnetic field**.

Fig. 2

Figure 2: Fig. 2

* When the specimen is illuminated "across" the magnetic field, an inequality of the pulses of "negative" photoconductivity is observed for different directions of the magnetic field. This effect proves to be connected not only with the presence of a photomagnetic emf on the specimen under this method of illumination, but also with phenomena occurring at the contacts.

** As a result, in semiconductors with a relaxation time independent of energy, the effect of a change in resistance in a transverse magnetic field is zero in the monopolar case. In other cases it at least decreases.

Consequently, if the Hall field is reduced in some way, the curvature of the carrier trajectories can thereby be increased and, consequently, the resistance of the semiconductor.

A reduction of the Hall field can be achieved:

a) by "short-circuiting" the Hall emf by means of a small external resistance;

b) by using samples in the form of so-called Corbino disks, where (as follows from the nature of the symmetry) no Hall field arises.

It is possible, however, to propose another method as well, suitable for the case of impurity conduction, when the concentration of carriers of one sign (for example, holes p_0) considerably exceeds the concentration of carriers of the other sign (electrons n_0) and, consequently, the Hall constant in equilibrium is determined by the magnitude p_0.

Fig. 2. Oscillograms of photoconductivity. *a*—photoconductivity pulses in the absence of a magnetic field; *b*—photoconductivity pulses in a magnetic field

If such a semiconductor is illuminated with light from its own absorption band, electron-hole pairs are produced. The associated increase in the electron concentration reduces the Hall field, which leads, as emphasized above, to an increase in resistance, i.e., it appears as negative photoconductivity.

Thus, on the one hand, under illumination the conductivity increases owing to the appearance of nonequilibrium carriers; on the other hand, it decreases owing to a reduction of the Hall field and, consequently, of the mobility of the equilibrium carriers. If the second effect predominates, negative photoconductivity will occur.

In experimentally checking the considerations set forth above, it is important to keep the following circumstance in mind. In almost all semiconductors, and even in such materials as germanium and silicon, trapping levels are retained despite careful purification. It is not difficult to show that if the minority carriers are trapped, the negative photoeffect is weakened, and if the trapping is large, it

Fig. 3

Figure 3: Fig. 3

"passes over" into a positive one. The reason for this is easy to understand if one notes that the Hall field in a semiconductor with monopolar conduction at $E_1 = \text{const}$ does not depend on the concentration of current carriers.

Fig. 3. Dependence of $\Delta\sigma_H/\sigma_H$ on the excitation level $\Delta p/n_0$ for $n = \text{Ge}$ at $T = 77^\circ\text{K}$, $H = 10000$ oersteds, and different values of the coefficient β: 1—$\beta = 1$; 2—$\beta = 1.5$; 3—$\beta = 2.3$; 4—$\beta = 1$ at $H = 0$

It can be shown that if an additional concentration of holes Δp and electrons Δn is introduced into an n-type sample (uniformly throughout the entire volume) (because of trapping levels $\Delta n = \beta\Delta p$ with $\beta \neq 1$), then the relative change in the material conductivity upon injection is determined by the formula

$$\frac{\Delta\sigma_H}{\sigma_H} = \frac{\left(\beta + \frac{\mu_p\varphi_p}{\mu_n\varphi_n}\right)\frac{\Delta p}{n_0}}{1 + \operatorname{tg}^2\theta_n} + \frac{\left\{\operatorname{tg}\theta_n + \left(\frac{\mu_p\varphi_p}{\mu_n\varphi_n}\operatorname{tg}\theta_p + \beta\operatorname{tg}\theta_n\right)\frac{\Delta p}{n_0}\right\}^2}{\left[1 + \left(\beta + \frac{\mu_p\varphi_p}{\mu_n\varphi_n}\right)\frac{\Delta p}{n_0}\right]\left(1 + \operatorname{tg}^2\theta_n\right)} - \frac{\operatorname{tg}^2\theta_n}{1 + \operatorname{tg}^2\theta_n}, \tag{1}$$

where

$$\varphi_n = \frac{4}{3\sqrt{\pi}}\frac{q}{m_n^*\mu_n}\int_0^\infty \frac{\tau e^{-\varepsilon/kT}}{1 + \left(\frac{q\tau}{m_n^* c}H\right)^2}\left(\frac{\varepsilon}{kT}\right)^{3/2} d\left(\frac{\varepsilon}{kT}\right);$$

$\theta_n,\ \theta_p$ are the Hall angles of electrons and holes, respectively ($\theta_n < 0$); $\mu_n,\ \mu_p$ are the mobilities; m^* is the effective mass; τ is the lifetime; q is the electron charge; ε is the energy.

For illustration, Fig. 3 gives the relative change in the photoconductivity of n-germanium, calculated by formula (1). The temperature is taken to be 100°K, so that the electron and hole mobilities are approximately equal to $24\,000\ \text{V}\cdot\text{sec/cm}$. The magnetic-field strength is 10^4 oersted. The curve with $\beta = 1$ (absence of trapping levels) shows that $\Delta\sigma_H$ remains negative up to an injection level $\Delta p/n_0$ equal to 0.46. The curves with $\beta = 1.5$ and $\beta = 2.3$ illustrate the influence of trapping levels on the effect under study.

It can be shown that the negative photoeffect will not be observed if the following inequalities hold:

a) for an n-material

$$\beta > -\frac{\mu_p\varphi_p}{\mu_n\varphi_n}\frac{1 - \operatorname{tg}^2\theta_n - 2|\operatorname{tg}\theta_n|\operatorname{tg}\theta_p}{1 + \operatorname{tg}^2\theta_n}; \tag{2}$$

b) for a p-material

$$\beta < -\frac{\mu_p\varphi_p}{\mu_n\varphi_n}\,\frac{1+\operatorname{tg}^2\theta_p}{1-\operatorname{tg}^2\theta_p-2|\operatorname{tg}\theta_n|\operatorname{tg}\theta_p}. \tag{3}$$

These conditions prove to be very stringent even for such a semiconductor as n-Ge, since at present it is not possible to purify it sufficiently of trapping levels. The situation is more favorable with hole germanium, in which the trapping of minority carriers is much less pronounced than in n-germanium.

The results shown in the oscillogram were obtained on samples of p-germanium with $\rho = 12\ \Omega \cdot \text{cm}$ at $T = 77^\circ\text{K}$, $H = 20\,000$ oersted; the excitation level $\Delta n/p_0$ was ~ 0.005.

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Received
28 VII 1960

Note: Figure translations are in progress. See original paper for figures.