Heating of electron subsystem by the Dember field in ambipolar diffusion in germanium

V. F. Gantmakher and V. N. Zverev

Institute of Solid State Physics, USSR Academy of Sciences
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When the distribution function of the photoelectrons near the bottom of the lower Landau subband is distorted as a result of heating of the cold electrons by the Dember field, negative conductivity arises in the electron subsystem [V. F. Elesin, Zh. Eksp. Teor. Fiz. **28**, 410 (1969)]. It is responsible for the inversion of the magnetic-impurity oscillations of the photomagnetic effect in germanium.

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When a semiconductor is illuminated, a diffusion flux of electrons and holes is produced at the surface by interband transitions and flows into the interior along the direction of the normal **G** to the surface. The very presence of this flux produces in the sample the following electric fields: a field E_G along **G**, proportional to the difference between the diffusion coefficient of the electrons and holes (D_e and D_p), and equalizing the fluxes of particles with opposite signs (the Dember effect in ambipolar diffusion). In the presence of a magnetic field $\mathbf{H} \perp \mathbf{G}$, a photomagnetic-effect field E_{GH} is produced as a result of the deflection of the diffusion fluxes in the magnetic field; this field is directed perpendicular to the vectors **G** and **H** (the Kikoin-Noskov effect). If the lines of these fields are not closed in external circuits, then the total energy transferred from them to the carriers is zero. It can, however, be different from zero for individual carrier groups. For example, at $D_p > D_e$ the hole flux is decelerated by the field E_G, so that the holes are cooled by the field, whereas the electrons are heated. In the presence of several carrier groups of the same sign with different average energies $\tilde{\epsilon}$, i.e., with different ratios of the diffusion coefficient to the mobility $D_i/\mu_i \approx \tilde{\epsilon}/e$, the picture becomes more complicated. Whether a given carrier group is heated or cooled in the field depends not only on the gradient ∇n_i, but also on the ratio of the diffusion $eD_i \nabla n_i$ and field $n_i e \mu_i E_G$ currents produced by this group. If the energy exchange between the carriers of the different groups is small, then the work produced by the field forces may be appreciable and may influence the distribution function $f(\epsilon)$ of the corresponding carrier group.

We have succeeded in establishing the presence of a similar effect—electron heating by the Dember field E_G—in germanium illuminated at helium temperature by light from an He-Ne laser and situated at the same time in a strong magnetic field $\mathbf{H} \perp \mathbf{G}$. The samples were p-germanium plates measuring $4\times4\times0.3$ mm, with approximate acceptor (Ga) concentration 2×10^{14} cm^{-3}. Four linear electrodes, gold wires of $\sim 50\ \mu$ diameter, were welded to the samples (see the diagram in Fig. 1). As established in[2], a characteristic feature of the photoelectric properties of p-germanium under these conditions is the presence of magnetic-impurity oscillations due to the resonances produced when the electrons located near the bottom of the lower Landau subband are scattered by the neutral excited acceptors. The resonance condition takes the form $N\hbar\Omega = \mathcal{E}$ $(N = 1, 2, 3\cdots)$, where Ω is the cyclotron frequency of the electrons and $\mathcal{E}$ is the acceptor excitation energy. By measuring the potential difference u_{12} between electrodes 1 and 2 we observed oscillations of the field E_{GH}; the input resistance of the measurement circuit exceeded the sample resistance by several orders of magnitude.

One of the most curious features of the magnetic-impurity oscillations in germanium is their inversion—the minima are replaced by maxima when the temperature T or the intensity of the photoexcitation I is changed. Inversions of the oscillations of the transverse photoconductivity $\sigma_\perp$ were investigated in detail in[3] for a uniform distribution of the carriers over the sample thickness. It was shown that all the experimental facts can be explained by assuming that the inversion of the oscillations is a manifestation of absolute negative conductivity,[1] i.e., the appearance of minima in $\sigma_\perp$ following resonant increase of the scattering is evidence of the appearance of a maximum in the distribution function $f(\epsilon)$ of the electrons in the lower Landau subband. This maximum can be caused either by high excitation intensity (curve G_1 in Fig. 2 of[3]) or else, at low intensity I, by heating of the electron system by an external electric field (curve G_2 in the same figure).

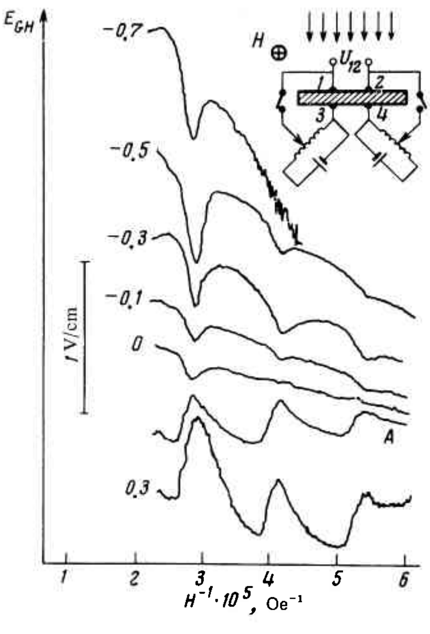

FIG. 1. Oscillations of the field E_{GH} at different values of the voltage $u_{13} = u_{24}$ marked on the left sides of the curves. Curve A was plotted with the contacts open. $I = 2\times10^{14}$ cm^{-2} sec^{-1}; $T = 1.65$ °K.

It is natural to attempt to explain the inversion of the oscillations of the field E_{GH} within the framework of the same model. It must be borne in mind here that the maxima of the function $\sigma_\perp(H)$ correspond to minima of $E_{GH}(H)$, inasmuch as in first-order approximation the product $\sigma_\perp E_{GH} = j_{GH}^{(\mathrm{dif})}$ is a monotonic function of H.[2] Thus, the minima of the field E_{GH} should indicate in the case of scattering resonances that $f(\epsilon)$ is a Boltzmann function, while maxima should indicate distortion of the function. Comparison with[3] shows that the E_{GH} oscillation inversion observed in[2] corresponds to inversion G_2 of the quantity $\sigma_\perp$ and should be attributed to heating of the electrons in an electric field.

When speaking of heating, we have in mind the cold part of the electron subsystem in the energy region $0 < \epsilon < kT$. The function $f(\epsilon)$ is governed there by four factors: influx of electrons that have become cooled in the course of diffusion via emission of phonons, first optical and then acoustic; recombination, the rate of which depends on the concentration n; the gradient ∇n, which is the consequence of the preceding two factors; and the electric field.

Since no external field was applied to the sample in the measurements of the field E_{GH}, it remains to assume that the electron heating that leads to the change of the function $f(\epsilon)$ and to inversion of the oscillations of the field E_{GH} is due to the internal field.

To check on this assumption, we performed the experiment illustrated in Fig. 1. The pump intensity I was chosen so small that the initial $E_{GH}(H^{-1})$ curves with the external circuit open was inverted, i.e., corresponded to the heated electrons (curve A). Merely closing the circuits between the illuminated and unilluminated sides of the sample through small resistors, which decreased the field E_G, returns the curve to its normal shape almost completely—the minima of E_{GH} at the resonances were restored (curve 0). Application of an additional potential difference directed opposite to the internal field E_G (with the negative pole on the unilluminated surface—upper curves) has completed this "normalization process." A voltage of opposite polarity, added to E_G, as expected, restored the maxima (lower curves).

Within the framework of the model described above, the results of the experiment is explained in quite natural fashion. The presence of initial heating of the electrons by the field E_{GH} makes it possible, by applying an external field of opposite direction, to cool the electron subsystem, despite the current flowing through the sample. The remaining carriers should be heated by this external field, and this probably causes the low-temperature breakdown on the upper curve. At the same time, the fact that this explanation is natural serves as an additional argument favoring the model itself, which explains the inversion of the magnetic-impurity oscillations in photoexcited p-germanium on the basis of the concept of absolute negative conductivity.[1]

[1]V. F. Elesin, Zh. Eksp. Teor. Fiz. 55, 792 (1968) [Sov. Phys. JETP 28, 410 (1969)].

[2]V. F. Gantmakher and V. N. Zverev, Zh. Eksp. Teor. Fiz. 70, 1891 (1976) [Sov. Phys. JETP 43, 985 (1976)].

[3]V. F. Gantmakher and V. N. Zverev, Zh. Eksp. Teor. Fiz. 71, 2314 (1976) [Sov. Phys. JETP 44, in press (1976)].