Characteristics of a strong field conductivity of inhomogeneous n-type Ge in magnetic fields

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(Submitted June 2, 1975)
Fiz. Tekh. Poluprovodn. 9, 2231–2234 (November 1975)

PACS numbers: 72.20.My

The present paper reports the results of measurements of the electrical conductivity in a magnetic field ($\sigma_H$), carried out at 80°K on dumbbell-shaped samples of n-type Ge grown along the [100] direction and characterized by resistivities $\rho_{300K} = \rho \cdot \Omega \cdot \text{cm}$ (samples A and B) and $\approx 12 \Omega \cdot \text{cm}$ (samples C and D). These samples were cut in a way that all the faces coincided with the {110} planes and the current flowed along the X axis, which was parallel to the [010], [001], [010], and [001] axes for samples A, B, C, and D, respectively. The magnetic field was rotated in a plane perpendicular to the current and it made an angle $\alpha$ with the [100], [100], [001], and [001] axes of these four samples.

In heating electric fields, samples A and D exhibited a dependence of $\sigma_H$ on the polarity of the magnetic field. The dependences of $\Delta \sigma_H(\alpha) = \sigma_H(\alpha + 180^\circ) - \sigma_H(\alpha)$ on the electric field $E$ in $H = \text{const}$ and on the magnetic field $H$ in $E = 500 \text{ V/cm}$ had maxima. Figures 1 and 2 show the dependences $\sigma_H$ on the angle $\alpha$ obtained for $E = 500 \text{ V/cm}$ and $H = 10 \text{ kOe}$, corresponding approximately to the maxima of the dependences of $\Delta \sigma_H(\alpha)$ on $E$ and $H$ for sample D. Since along the investigated directions of the current (i [100]) the effects odd in respect of $H$ should not be observed for homogeneous samples (see, for example, Refs. 1 and 2), we assumed that the dependence of $\sigma_H$ on the polarity of $H$ was due to the presence of inhomogeneities.

The inhomogeneity at right angles to the current gives rise to an inhomogeneity of the heating along this direction and to a hot-carrier field $E_T$, (see, for example, Refs. 3 and 4). If the Hall field $E_H$ has a nonzero projection along $E_T$, the total transverse field $E_T = E_H + E_T$, and therefore, the conductivity $\sigma_H$ should change when $H$ is reversed (see, for example, Ref. 2, where the same reasoning, pertaining to $E_H$ and the Sasaki field, are confirmed calculations). The maximum of $\Delta \sigma_H(\alpha)$ corresponds to the angle $\alpha$ for which $E_H \parallel E_T$, and $\Delta \sigma_H(\alpha) = 0$ corresponds to $E_H \parallel E_T$. Since in the case of weak heating the field $E_T$ in a slightly inhomogeneous semiconductor is proportional to $E^2 \tau^* T$ (here, $\tau^*$ is a characteristic time, which is identical with the energy relaxation time $\tau_E$ in one-valley semiconductors but is a combination of $\tau_E$ and of the intervalley scattering time $\tau$ in the case of many-valley semiconductors; the combination depends on the direction of the current and carrier density gradient), an increase of the applied field $E$ increases $E_T$ and $\Delta \sigma_H(\alpha)$. Since the intervalley redistribution, which makes $\Delta \sigma_H(\alpha) = 0$ for the direction of the current -- the greatest contribution to $E_T$ (Ref. 4), has a maximum when considered as a function of heating, we may expect a maximum also in the dependence of $E_T$ on $E$, which is the cause of the observed maximum in the dependence of $\Delta \sigma_H(\alpha)$ on $E$. Since $\Delta \sigma_H(\alpha)$ has its maximum at $E_H \sim E_T$, we can expect a maximum in the dependence of $\Delta \sigma_H(\alpha)$ on $H$.

However, it was unlikely that the growth inhomogeneities would be confined to a plane perpendicular to the current. In fact, measurements of the conductivity for $i > 0$ and $i < 0$ revealed rectifying current-voltage characteristics [$\sigma_H(i > 0) \neq \sigma_H(i < 0)$], which demonstrated...
the existence of an inhomogeneity also in the direction of the current [i.e., \( \rho = \rho(x, y, z) \)]. The latter gave rise to a non-carrier field \( E_{BC} \) (Ref. 4), i.e., \( E_{BC} = E_{BC1} + E_{BC2} \) was not confined to the plane perpendicular to \( i \), which enhanced the external field for one of the directions of the current and opposed it for the other direction. Figure 2 shows the dependence \( \alpha_{UB} \) for sample D for two directions of the current (\( E = 500 \) V/cm and \( H = 10 \) kOe), whereas Fig. 3 shows the dependence \( R(H = 0) \) on the field \( E \) (\( i > 0 \) and \( i < 0 \)) for samples A and B.

It is shown in Refs. 5 and 6 that if \( \partial p/\partial x = 0 \), then \( E_H = E_H(x) \) also because curl \( E = 0 \) and \( E_x = E_x(y) \) (here, \( y \perp H \)), i.e., the field \( E_x \) and the current are distributed inhomogeneously in a sample, being displaced toward one of the surfaces (for example, \( y = d \)). Reversal of the magnetic field alters the direction of displacement of the current (it is now shifted toward \( y = -d \)). If \( \partial p/\partial y = 0 \) or if \( p = p(y) \) is symmetric relative to the XYZ plane passing through the center of the crystal [this is true of sample B, for which \( \Delta \rho_H(x) = 0 \) for all values of \( x \)], a reversal of the magnetic field does not alter the current \( j \) whereas in the case of samples A and D the dependence \( p = p(y) \) causes this reversal to make a contribution to \( \Delta \rho_H(x) \). We can easily show that the contributions of these two effects to \( \Delta \rho_H(x) \) are greatest for \( H \parallel E_{BC} \) and vanish for \( H \parallel E_{BC} \). This makes it possible to explain qualitatively the dependences obtained in the present study and plotted in Figs. 1-3.

The investigated samples had a high resistivity and both momentum and energy were dissipated by interaction with lattice vibrations. Therefore, the inhomogeneity of \( \rho \) was primarily due to the inhomogeneity of the carrier density under constant-mobility conditions. It follows from Ref. 6 that in this case the conductivity \( \rho_H \) should exhibit no effects linear in respect of the magnetic field if there is no heating (see also Ref. 7). Heating due to an inhomogeneity in the distribution of carriers is inhomogeneous and then the mobility begins to depend on the coordinate and effects linear in respect of the magnetic field are observed, i.e., the dependence of \( \rho_H \) on the direction of the magnetic field appears in heating fields and this dependence is enhanced by an increase in \( E \) if the phonon scattering predominates.

These effects are not observed in nearly homogeneous samples, such as sample C in our study.

We shall conclude by pointing out that in the case of samples with \( \partial p/\partial x = 0 \) the criterion for the absence of the edge effects \( l/2d < 3 \) (Ref. 8) (here, \( l \) is the length of the sample and \( 2d \) is its width) is no longer valid because the length is not the actual physical length of the sample but the characteristic inhomogeneity length. Therefore, even in nonheating electric fields the samples with a non-square cross section \( d_1 = d_2 \) exhibit a dependence of the magnetoresistance on the rotation of the magnetic field through \( \pi/2 \) because of the change in the ratio \( l/d_1 \) where \( d_1 \) is the inhomogeneity length. The existence of an inhomogeneity at right angles to the current also gives rise to a dependence of \( \rho_H \) on the rotation of the magnetic field by \( \pi/2 \) in nonheating electric fields. All these dependences and the resistivity \( \rho(x, y, z) \) were investigated using probes, in addition to the dependences shown in Figs. 1-3, in order to find whether the effects odd in respect of \( H \) occurred in samples with inhomogeneities.

Although the experimental results obtained could be explained qualitatively by the presence of inhomogeneities, final conclusions could not be drawn without further theoretical and more detailed experimental studies of the influence of inhomogeneities on the transport phenomena.

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Translated by A. Tybulewicz