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

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The present paper reports the results of measurements of the electrical conductivity in a magnetic field (σ_H), carried out at 80°K on dumbbell-shaped samples of n-type Ge grown along the [100] direction and characterized by resistivities $\rho_{300°K} \approx 6\ \Omega \cdot cm$ (samples A and B) and $\approx 12\ \Omega \cdot cm$ (samples C and D). These samples were cut in such a way that all the faces coincided with the $\{110\}$ planes and the current i 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 α with the [100], [100], [001], and [001] axes of these four samples.

In heating electric fields, samples A and D exhibited a dependence, not observed for samples B and C (or for samples A and D in nonheating fields), of the conductivity σ_H on the polarity of the magnetic field. The dependences of $\Delta\sigma_H(\alpha) = \sigma_H(\alpha + 180°) - \sigma_H(\alpha)$ on the electric field E in H = const and on the magnetic field H in E = 500 V/cm had maxima. Figures 1 and 2 show the dependences σ_H on the angle α obtained for E = 500 V/cm and H = 10 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 ($i \parallel \langle 100 \rangle$) 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 σ_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_{∇_1} (see, for example, Refs 3 and 4). If the Hall field E_H has a nonzero projection along E_{∇_1}, the total transverse field $E_\perp = E_H + E_{\nabla_1}$ and therefore, the conductivity σ_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 α for which $E_H \parallel E_{\nabla_1}$ and $\Delta\sigma_H(\alpha) = 0$ corresponds to $E_H \perp E_{\nabla_1}$. Since in the case of weak heating the field E_{∇_1} in a slightly inhomogeneous semiconductor is proportional to $E^2\tau^*\nabla\sigma$ (here, τ^* is a characteristic time, which is identical with the energy relaxation time τ_ε in one-valley semiconductors but is a combination of τ_ε and of the intervalley scattering time τ in the case of many-valley semiconductors[4]; this combination depends on the direction of the current and carrier density gradient), an increase of the applied field E increases E_{∇_1} and $\Delta\sigma_H(\alpha)$. Since the intervalley redistribution, which makes – for this direction of the current – the greatest contribution to E_{∇_1} (Ref. 4), has a maximum when considered as a function of heating,[2] we may expect a maximum also in the dependence of E_{∇_1} 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 $E_H \sim E_{\nabla_1}$, 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

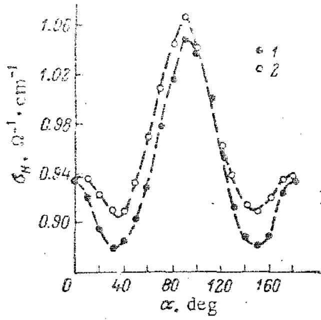

Fig. 1. Dependence of the conductivity σ_H on the angle α for sample A: 1) $0° \le \alpha \le 180°$; 2) $180° \le \alpha \le 360°$.

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 hot-carrier field E_{∇_2} (Ref. 4), (i.e., $E_\nabla = E_{\nabla_1} + E_{\nabla_2}$ 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 $\sigma_H(\alpha)$ 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 $\partial\rho/\partial x \neq 0$, 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 $\partial\rho/\partial y = 0$ or if $\rho = \rho(y)$ is symmetric relative to the XZ plane passing through the center of the crystal [this is true of sample B, for which $\Delta\sigma_H(\alpha) = 0$ for all values of α], a reversal of the magnetic field does not alter the current,[5,6] whereas in the case of samples A and D the dependence $\rho = \rho(y)$ causes this reversal to make a contribution to $\Delta\sigma_H(\alpha)$. We can easily show that the contributions of these two effects to $\Delta\sigma_H(\alpha)$ are greatest for $H \perp E_{\nabla_1}$ and vanish for $H \parallel E_{\nabla_1}$. 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 ρ 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 σ_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[4] 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 σ_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.

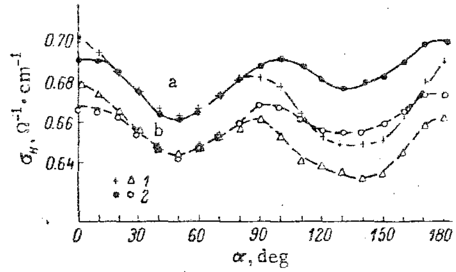

Fig. 2. Dependence $\sigma_H = f(\alpha)$ for sample D: a) $i > 0$; b) $i < 0$; 1) $0° \le \alpha \le 180°$; 2) $180° \le \alpha \le 360°$.

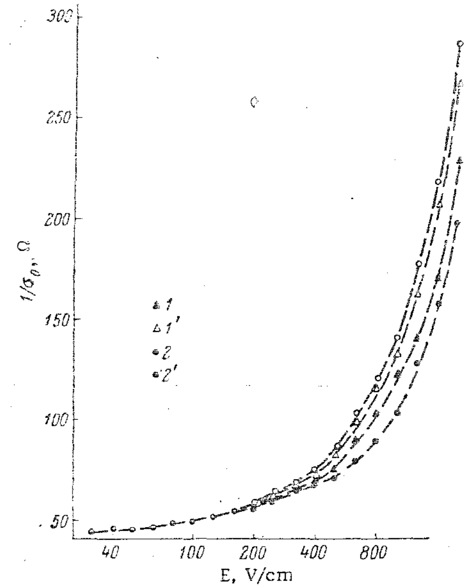

Fig. 3. Electric-field dependences of the resistance of sample A (1, 1') and B (2, 2'): 1, 2) $i > 0$; 1', 2') $i < 0$.

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 $\partial\rho/\partial x \neq 0$ the criterion for the absence of the edge effects $l/2d \ge 3$ (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 nonsquare cross section ($d_1 \neq d_2$) 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_i, where d_i is the inhomogeneity length. The existence of an inhomogeneity at right angles to the current also gives rise to a dependence of σ_H on the rotation of the magnetic field by $\pi/2$ in nonheating electric fields.[8] 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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