Effect of pressure on the magnetoconductivity of heavily doped n-type germanium

A. N. Ionov and I. S. Shlimak

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

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Experiments reveal that the magnetoconductivity in n-type germanium depends on the intensity of the intervalley electron scattering. The anisotropy of the magnetoconductivity is shown to result from an anisotropy of the diffusion coefficient.

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Al'tshuler *et al.*[1] and Kawabata[2] have derived a theory which attributes the anomalous magnetoconductivity $\Delta\sigma(H) = \sigma(H) - \sigma(0)$ in semiconductors exhibiting a metallic conductivity to quantum-mechanical corrections to the kinetic coefficients. According to this theory, the magnetoconductivity in the three-dimensional case is

$$\Delta\sigma(H) = \frac{e^2}{2\pi^2\hbar}\, f\left(\frac{4DeH}{\hbar c}\tau_\varphi\right)\left(\frac{eH}{\hbar c}\right)^{1/2} \qquad (1)$$

$$f(x) = \begin{cases} 0.605 & x \gg 1 \\ x^{3/2}/48 & x \ll 1 \end{cases},$$

where D is the diffusion coefficient, H is the magnetic field, and τ_φ is the characteristic time for the phase relaxation of the wave function caused by inelastic collisions. The rest of the notation is standard. It can be seen from (1) that in a magnetic field with $x \ll 1$ the magnetoconductivity $\Delta\sigma$ increases with increasing D. In multivalley semiconductors, if we may ignore intervalley electron scattering, the contributions of different valleys to the magnetoconductivity are additive; i.e.,

$$\Delta\sigma(H) = \sum_i \Delta\sigma^i_{\alpha,\beta}(H)$$

$$\Delta\sigma_{\alpha,\beta} = \frac{D_{\alpha,\beta}}{D_a}\,\frac{e^2}{2\pi^2\hbar}\left(\frac{eH}{\hbar c}\,\frac{D_c}{D_a}\right)^{1/2} f\left(\frac{4D_c eH}{\hbar c}\tau_\varphi\right) \qquad (2)$$

(the sum is over nonequivalent ellipsoids), where[1)] $D_c^2 = D_\perp(D_\perp \cos^2\theta + D_\parallel \sin^2\theta)$, θ is the angle between the axis of the ellipsoid and the magnetic field, $D_{\alpha,\beta}$ is the diffusion coefficient tensor, and $D_a = (D_\parallel D_\perp^2)^{1/3}$.

In the absence of scattering, $\Delta\sigma(H)$ is thus anisotropic. In the case of intense scattering, on the other hand, the contributions of different valleys reduce to that of a single valley with an average diffusion coefficient, so that $\Delta\sigma(H)$ is isotropic.

In an effort to test the conclusions of this theory, we have studied the magnetoconductivity of n-type germanium doped with different donor impurities (As and

Sb). Experiments were carried out without an applied pressure and during a uniaxial compression (χ) along a [111] axis. It has been established elsewhere that n-type germanium has four nonequivalent ellipsoids in [111] directions. These particular impurities were chosen because they offer different intensities of intervalley scattering; in the case of the As impurity, the value of $|\Psi(0)|^2$ is high for an electron donor, so that there is intense intervalley scattering. The impurity concentrations were $N_{As} = 5 \times 10^{18}$ cm^{-3} and $N_{Sb} = 2 \times 10^{18}$ cm^{-3}; these concentrations correspond to roughly the same doping level, which is determined by the parameter Na^3, because of the difference in the first Bohr radii ($a_{As} = 40$ Å, $a_{Sb} = 60$ Å). The samples were not deliberately compensated. They were oriented with their long face along a [111] direction. The effect of intervalley scattering on the magnetoconductivity can be ignored if[1]

$$4eD_{\parallel,\perp} H \tau_v / \hbar c \gg 1, \tag{3}$$

where $D_{\parallel,\perp}$ is the electron diffusion coefficient along ($\parallel$) or across ($\perp$) the major axis of the ellipsoid, and τ_v is the relaxation time of the intervalley scattering. For the present case we have $\tau_v \sim 3 \times 10^{-13}$ s and $\tau_v \sim 4 \times 10^{-11}$ s for Ge⟨As⟩ and Ge⟨Sb⟩, respectively.[3] Adopting an anisotropy coefficient[4] $K = \mu_\perp/\mu_\parallel \approx 5$ ($\mu_{\perp,\parallel}$ are the transverse and longitudinal mobilities), we find $D_\parallel \approx 7$ cm^2/s for As and $D_\parallel \approx 10$ cm^2/s for Sb. Substituting in these values, we find that condition (3) holds for Sb even in weak magnetic fields, $H \geqslant 0.5$ kOe, while for As it holds only at $H \geqslant 20$ kOe. In fields of a few kiloersteds we may thus ignore intervalley scattering in the case of Ge⟨Sb⟩, but this is not possible in the case of Ge⟨As⟩. These results imply the following for conditions without uniaxial compression: 1) The contributions of the four ellipsoids to the magnetoconductivity will be summed for Ge⟨Sb⟩; i.e., the value of $\Delta\sigma$ for a Ge⟨Sb⟩ sample will be higher than that of a Ge⟨As⟩ sample at given values of the temperature and the magnetic field. 2) For Ge⟨As⟩, the magnetoconductivity should be isotropic, in contrast with Ge⟨Sb⟩, where an anisotropy of $\Delta\sigma(H)$ has been observed experimentally (in Ref. 2, for example). Both of these conclusions have been confirmed in the present experiments. It can be seen from Fig. 1 that $\Delta\sigma$ in the case of Ge⟨Sb⟩ is 11 times that in the case of Ge⟨As⟩ for samples with identical doping level. From Fig. 2, which shows $\Delta\sigma_\parallel$ and $\Delta\sigma_\perp$ for a Ge⟨As⟩ sample with

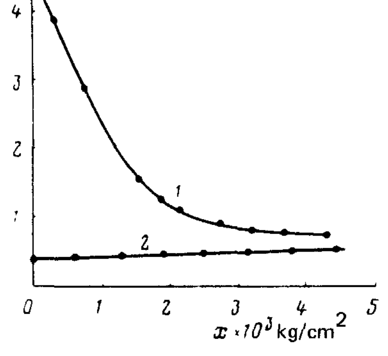

FIG. 1. Dependence of the magnetoconductivity at $H = 10$ kOe on the applied pressure. 1—Ge⟨Sb⟩; 2—Ge⟨As⟩.

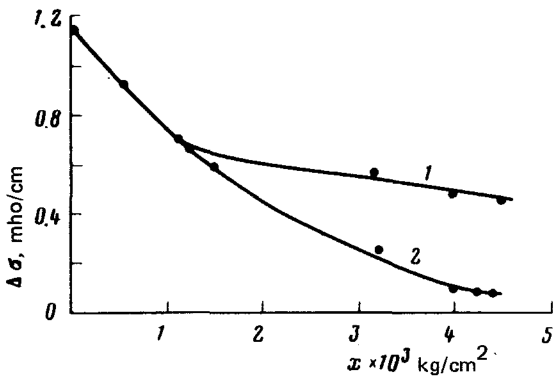

FIG. 2. Dependence of the magnetoconductivity on the applied pressure for various magnetic field directions ($H = 5$ kOe). 1–$H \parallel [111]$; 2–$H \perp [111]$.

$N_{As} = 1.3 \times 10^{10}$ cm^{-3}, we see that in the absence of pressure ($\chi = 0$) we have $\Delta\sigma_{\parallel} = \Delta\sigma_{\perp}$.

What happens upon uniaxial compression along a [111] axis? We know that in this case one valley will move downward along the energy scale, while the other three will rise. At sufficiently high pressures, at which there is a saturation of the piezoresistance, the Fermi level will lie in a single valley. For Ge⟨Sb⟩, this assertion means that the contribution of the three upper ellipsoids to the magnetoconductivity will disappear, and $\Delta\sigma(H)$ should decrease. This is, in fact, what is observed experimentally (Fig. 1). For Ge⟨As⟩, the change in the energy positions of the ellipsoids caused by the pressure does not substantially change the magnetoconductivity. In this material, in the absence of a pressure, the contributions of the different valleys do not add up; instead, they essentially reduce to the contribution of a single valley, with an average diffusion coefficient, because of the frequent scattering. The entire change in the magnetoconductivity in this material results from a change in the diffusion coefficient. Experimentally in this case we do in fact observe a slight increase in $\Delta\sigma(H)$. It should also be expected that the values of $\Delta\sigma$ in these samples should be approximately equal at large values of χ, and again this is what we observe experimentally (Fig. 1).

If only a single valley is participating in the conductivity, the magnetoconductivity $\Delta\sigma$ should be anisotropic because of the anisotropy of the diffusion coefficient, and this assertion includes the case of Ge⟨As⟩. This effect is illustrated by Fig. 2. We see that under saturation conditions the piezoresistance is $\Delta\sigma_{\parallel}/\Delta\sigma_{\perp} \cong 7$. It follows from expression (2) that $\Delta\sigma_{\parallel}/\Delta\sigma_{\perp} = D_{\perp}/D_{\parallel}$. Substituting in the values of $D_{\perp}$ and $D_{\parallel}$, we find $\Delta\sigma_{\parallel}/\Delta\sigma_{\perp} \approx 5$, in approximate agreement with the experimental value. In summary, all the anisotropy of the magnetoconductivity is a consequence of the anisotropy of the diffusion coefficient, as predicted by the theory of Ref. 1.

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[1)]There was an error in the expression for D_c in Ref. 1: the symbols $D_\perp$ and $D_\parallel$ in the parentheses should be interchanged.

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