Anomalous magnetoconductivity of strongly doped p-type germanium

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It is shown that the anomalous positive magnetoresistance of p-Ge is qualitatively and quantitatively described by theory without taking into account interaction between the holes. It is found that as the temperature decreases, the negative magnetoresistance of uniaxially deformed p-Ge goes over into the anomalous positive magnetoresistance.

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The new theory of magnetoconductivity of strongly doped semiconductors,[1] based on electron-electron interaction and quantum corrections to the kinetic coefficients, is at present subjected to careful experimental verification. The behavior of magnetoconductivity $\Delta\sigma$, predicted theoretically both for two-dimensional and three-dimensional conductivity, was discovered in n-Ge.[2-4] This paper is concerned with the analysis of experimental data in degenerate p-Ge.

In p-Ge, as is well known, an anomalous positive magnetoresistance (APMR) is observed. This magnetoresistance has the same temperature and impurity concentration dependence as the negative magnetoresistance (NMR) in n-Ge.[5] APMR is explained theoretically[1] taking into account: 1) the complex structure of the valence band; 2) the interaction between holes. When there is not deformation, the expression for $\Delta\sigma$ ignoring the classical PMR, has the following form[1]:

$$\Delta\sigma(H) = -\frac{e^2}{8\pi^2\hbar} f\left(\frac{4DeH}{\hbar c}\tau_\varphi\right)\left(\frac{eH}{\hbar c}\right)^{1/2}\left[1+\frac{1}{4}\beta(T)\right]+\frac{1}{16}\Delta\sigma^{(1)}, \quad (1)$$

where

$$\Delta\sigma^{(1)} = -C(T)\frac{e^2}{2\pi^2\hbar}\left(\frac{eH}{\hbar c}\right)^{1/2}\varphi\left(\frac{2DeH}{\pi cT}\right), \quad f(x) = \begin{cases} 0.605 & x \gg 1 \\ x^{3/2}/48 & x \ll 1 \end{cases}$$

$$\varphi(z) = \begin{cases} 1.9 & z \gg 1 \\ 0.33 z^{3/2} & z \ll 1 \end{cases}, \quad x \equiv \frac{4DeH}{\hbar c}\tau_\varphi, \quad z \equiv \frac{2DeH}{\pi c T}$$

D is the diffusion coefficient; τ_φ is the relaxation time for the phase of the wave function due to inelastic collisions; $\beta(T)$ is the Maki-Thompson correction; and the remaining notations are conventional. The term $\Delta\sigma^{(1)}$ is related to the interaction between holes. The sign of $\Delta\sigma^{(1)}$ is determined by the sign of the effective interaction constant $C(T)$. In the case of attraction, $C(T)<0$, while for repulsion, $C(T)>0$. In our case, $\beta(T)$ and $C(T)<1$. In order to compare these results with theory at $T=4.2$ K, we studied $\Delta\sigma$ p-Ge ⟨Ga⟩ with $p=1.6\times10^{19}$ cm^{-3} and $\rho=1.249\times10^{-3}$. The diffusion coefficient D was calculated using the equation $D=2/3\ \epsilon_F\ \mu/e$, where ϵ_F is the Fermi energy, and, μ is the mobility of holes. In determining ϵ_F, the effective mass of the density of states for holes is assumed to be equal to 0.388 m_0, where m_0 is the mass of a free electron. In our case, $D\cong12$ cm^2/s, while $\tau_\varphi\cong T^{-3/2}\sim10^{-11}$ s^3. Figure 1 shows the experimental vaules of $\Delta\sigma$ as a function of H. Here, the classical PMR, which was determined experimentally at high T, where the APMR can be ignored, was taken into account. Substituting the values obtained for D and τ_φ into (1), we find that $x\gg1$ already for $H\geqslant3$ kOe, while $z\gg1$ only for $H>50$ kOe. In this case, in the range of H studied, where $z\cong1$, the interaction between holes can be ignored, so that the experimental data must be compared with the theoretical dependence constructed according to (1) for strong fields without appealing to the interaction effect (Fig. 1). It is evident from Fig. 1 that the theoretical dependence $\Delta\sigma$ satisfactorily describes the values obtained experimentally, if the origin of coordinates is shifted by an amount $\Delta\sigma_0$.[1)]

The behavior of $\Delta\sigma$ in p-Ge under uniaxial compression provides an additional check of the theory. In the presence of strain as is well known, the degeneracy of the valence band is lifted. The split valence band becomes ellipsoidal, which leads to a small anisotropy in the diffusion coefficient. For example, under compression along (100), the coefficient of anisotropy of the Hall mobility along the principal axes of the ellipsoid will be $\mu_\parallel/\mu_\perp\cong1.6$.[6] When the strain-induced splitting of doubly degenerate, with respect to spin, bands is greater than ϵ_F, the theory[1] predicts a change in the sign of the effect from a positive to a negative anomaly. In this case, the expression for $\Delta\sigma$ in deformed germanium, taking into account the anisotropy in D, will be[1]

$$\Delta\sigma_{ik}=\frac{D_{ik}}{D_a}\frac{e^2}{\pi^2\hbar}\left(\frac{eH}{\hbar c}\frac{D_c}{D_a}\right)^{1/2}\left\{-\frac{1}{2}\left[1+\frac{1}{2}\beta(T)\right]f\left(\frac{4DeH}{\hbar c}\tau_\varphi\right)\right.$$
$$\left.+\frac{3}{2}\left[1-\frac{1}{2}\beta(T)\right]f\left(\frac{4DeH}{\hbar c}\frac{1}{\tau_{s0}^{-1}+\tau_\varphi^{-1}}\right)\right\}+\Delta\sigma_{ik}^{(1)},\tag{2}$$

where $\Delta\sigma_{ik}^{(1)}=-C(T)(e^2/2\pi^2)D_{ik}/D_a[(eH/\hbar c)(D_c/D_a)]^{1/2}\varphi(2D_ceH/\pi cT)$, τ_{s0} is the relaxa-

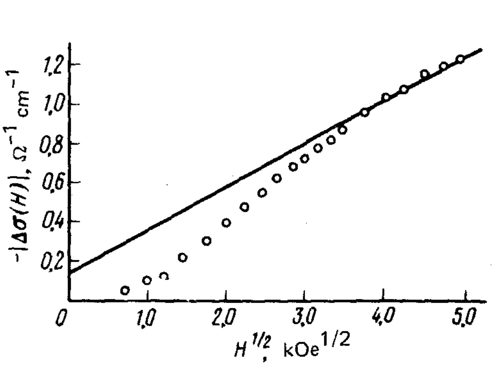

FIG. 1. $\Delta\sigma$ as a function of $H^{1/2}$ for $p=1.6\times10^{19}$ cm^{-3} at $T=4.2$ K; the straight line is constructed according to (1) ignoring the interaction between holes.

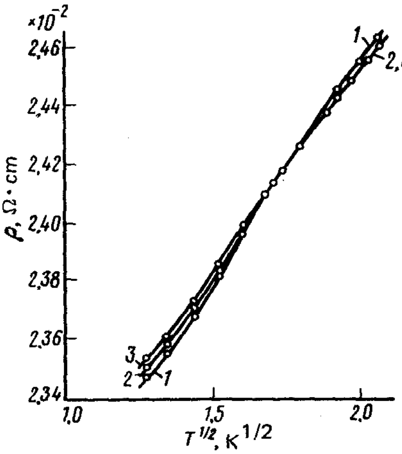

FIG. 2. The T dependence of $\Delta\sigma$ of deformed p-Ge ($p = 6 \times 10^{17}$ cm^{-3}, $\chi = 3.9$ T/cm^2): 1) $H = 0$ kOe; 2) $H_{\parallel} = 5$ kOe; 3) $H_{\perp} = 5$ kOe.

tion time of the spin orbital interaction, D_{ik} is the diffusion coefficient tensor, $D_c^2 = D_{\perp}(D_{\perp}\cos^2\theta + D_{\parallel}\sin^2\theta)$, $D_a = (D_{\parallel}D_{\perp}^2)^{1/3}$ and θ is the angle between the directions of the uniaxial compression and the magnetic field. It follows from (2) that for $\tau_{s0} \gg \tau_{\varphi}$ (this occurs with deformation) the second term in the curly brackets turns out to be greater than the first term. This can finally lead to a change in sign, i.e., to NMR if $|\Delta\sigma_{ik}^{(1)}|$ is a small quantity. However, as the temperature is decreased, $|\Delta\sigma_{ik}^{(1)}|$ increases, which must again change the sign of the effect; i.e., APMR arise with $C(T) > 0$.

In order to check the results of the theory, we studied the T dependence of ρ of deformed p-Ge for two mutually perpendicular directions H. The specimens with an acceptor concentration $p = 6 \times 10^{17}$ cm^{-3} (compensation was not introduced deliberately) were oriented with their long face along the direction (100). The strain was applied along the long face. The magnetic field was parallel ($H_{\parallel}$) and perpendicular ($H_{\perp}$) to the direction of strain. We shall estimate for our case the values of H and T for which NMR may be expected. For $\rho = 2.13 \times 10^{-2}$ $\Omega \cdot$ cm, we find that $D_{\perp} \cong 5.5$ cm^2/s ($H_{\perp}$) and $D \cong 9.0$ cm^2/s ($H_{\parallel}$). Substituting the values obtained into (2), we find that $T = 4.2$ K and $H = 5$ kOe, $\Delta\sigma_{ik} > 0$. Figure 2 shows ρ as a function of T for $H = 0$ kOe and $H = 5$ kOe. In the region 4.2-3.0 K, for $H_{\perp}$ and $H_{\parallel}$, NMR is indeed observed.[2)]

Let us examine the nature of the T dependence of ρ for a compressed p-Ge specimen.

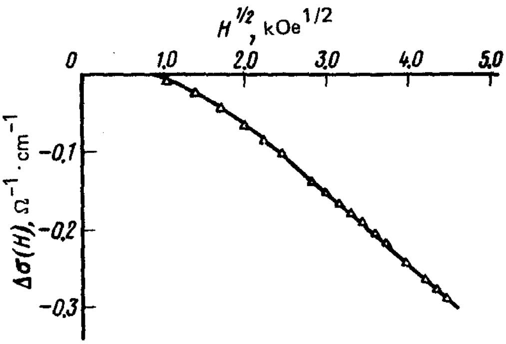

FIG. 3. The H dependence of $\Delta\sigma$ of deformed p-Ge ($p = 6 \times 10^{17}$ cm^{-3}, $\chi \parallel (111)$, $\chi = 3.9$ T/cm^2) at $T = 1.6$ K.

It is evident from Fig. 2 that as the temperature is reduced, NMR is replaced by anisotropic PMR. Here, $|\Delta\sigma|$ for $H \geqslant 5$ kOe is proportional to $H^{1/2}$, in qualitative agreement with Ref. 1 (Fig. 3). It should be noted that interaction between holes with an interaction constant $C(T)>0$ is not the only thing that leads to APMR, but spin splitting of free holes in the magnetic field also leads to APMR.[8] In both cases, theory predicts APMR of the same order of magnitude, proportional to H^2 in weak fields and $H^{1/2}$ in strong fields. However, these theories predict different behavior for $\Delta\sigma^{(1)}$ relative to the magnitudes of D and the g factor for free holes. It follows from Ref. 1 that $|\Delta\sigma^{(1)}|$ with $z \cong 1-2$ will increase with increasing D and will not depend on the g factor. It follows from Ref. 8 that $|\Delta\sigma^{(1)}|$ will decrease with increasing D and increase with increasing g factor. Taking into account only the D anisotropy in our case leads to anisotropy of the magnetoresistance with $K=1.4$, where $K=\Delta\sigma_{\perp}/\Delta\sigma_{\parallel}$. If, on the other hand, we keep in mind the anisotropy of the g factor of free holes of deformed p-Ge ($g_{\perp}/g_{\parallel}=1.5$), then for $g\mu H \lessgtr kT$ we find $K=2$.[8] The last value of the APMR anisotropy coincides with the experimental value.

In conclusion, I thank A. G. Aronov, B. L. Al'tshuler, I. S. Shlimak, and T. A. Polyanskiĭ for discussing the problems touched upon in this paper.

[1)]The origin of $\Delta\sigma_0$ is related to taking into account the next term in the expansion of the function $f(x)$ in strong magnetic fields. I am grateful to T. A. Polyanskaya for bringing this to my attention.

[2)]The observation of NMS in uniaxially compressed p-Ge was first reported in Ref. 7.

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