# Negative magnetoresistance of *p*-Ge in the region of the Mott hopping conductivity

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The magnetoresistance of *p*-Ge samples ($N_{\text{Ga}} = 1.9 \times 10^{17}$ cm$^{-3}$) with various degrees of compensation ($K = 0.23$–$0.95$) has been studied in the hopping-conductivity region. In weak magnetic fields the negative magnetoresistance results from an increase in the state density near the Fermi level and appears only at a high degree of compensation, at which the Mott conductivity sets in.

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The negative magnetoresistance observed in heavily doped and compensated *n*-Ge at liquid-helium temperature can be explained at a qualitative level by an increase in the state density of an impurity band at the Fermi level in a magnetic field.[1]

In an effort to observe the negative magnetoresistance in the hopping-conductivity region of *p*-Ge and to determine how the degree of compensation influences the magnitude of the effect, we have studied *p*-Ge samples with a constant concentration of the main impurity, gallium ($N \cong 1.9 \times 10^{17}$ cm$^{-3}$), and with various degrees of compensation: $K = 0.23$, 0.55, 0.71, 0.85, and 0.95 (samples 1–5, respectively). The doping was carried out by the method of neutron transmutation doping,[2] which produces a highly homogeneous dopant distribution over the volume of the semiconductor. Inhomogeneities of this distribution have a strong effect on the magnetoresistance. From the temperature dependence of the resistivity, $\rho(T)$, in the low-temperature range we concluded that a hopping conductivity with a constant activation energy was exhibited by samples 1 and 2, while samples 4 and 5 exhibited a hopping conductivity with a variable activation energy. Sample 3 exhibited a transition from a constant activation energy to a variable one below 3 K.

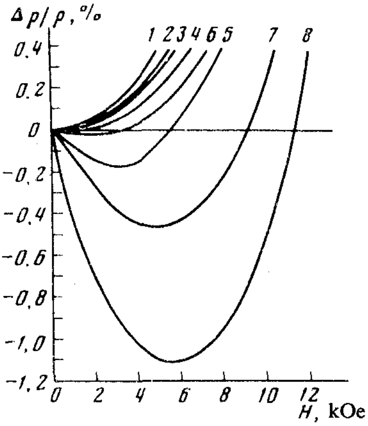

FIG. 1. Magnetoresistance of samples with various degrees of compensation. 1—0.23; 2—0.55; 3, 6—0.71; 4, 7—0.85; 5,8—0.95. $T$,K: 1–5—4.2; 6–8—1.9.

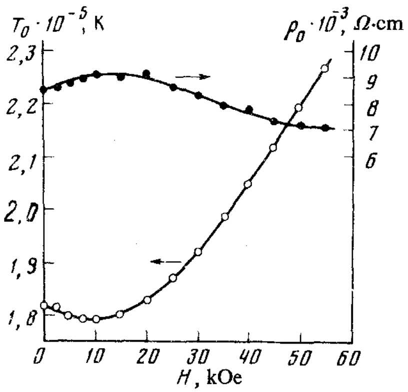

FIG. 2. Dependence of $\rho_0$ and $T_0$ on the magnetic field for sample 5.

Measurements of the transverse magnetoresistance over the temperature range 1.5–4.2 K revealed (Fig. 1) only a positive magnetoresistance for the samples with low degrees of compensation (samples 1 and 2), while sample 5, with the highest degree of compensation, exhibits a negative magnetoresistance. In samples 3 and 4, a negative magnetoresistance appears only at $T \lesssim 2$ K and $T \lesssim 4$ K. The absolute value of the negative magnetoresistance increases with decreasing temperature. As the magnetic field is increased, the negative magnetoresistance becomes positive. A negative magnetoresistance of $p$-Ge has thus been observed for the first time in the region of the hopping conductivity involving shallow impurities. The appearance of a negative magnetoresistance is directly related to the appearance of a Mott conductivity with a variable activation energy. This situation is evidently general in nature, since a negative magnetoresistance is also observed upon the appearance of a Mott conductivity in uncompensated $n$-Ge subjected to uniaxial compression.[3]

For sample 5, in which the negative magnetoresistance is most pronounced, the temperature dependence of the resistivity over the range 1.5–4.2 K is described well at various fixed values of the magnetic field $H$ by the Mott law[4]

$$\rho(T, H) = \rho_0(H) \exp\left(\frac{T_0(H)}{T}\right)^{1/4}; \quad T_0(H) = \frac{\beta}{g(\mu, H)\, a^3(H)},$$

where $\rho_0(H)$ and $T_0(H)$ are the parameters of the Mott law, $g(\mu, H)$ is the state density in the impurity band at the Fermi level, $a(H)$ is the effective carrier-localization radius at the impurity center, and $\beta$ is a numerical factor.

Figure 2 shows the field dependences $\rho_0(H)$ and $T_0(H)$. The only reason for a negative magnetoresistance in weak fields ($H \leqslant 10$ kOe) is seen to be the decrease in $T_0(H)$, which is caused by a corresponding increase in the state density $g(\mu, H)$, since the localization radius $a(H)$ can only decrease in a magnetic field, leading to a positive magnetoresistance in a strong field (we will not discuss the positive magnetoresistance in this letter).

The increase in the state density at the Fermi level can be explained as follows: In semiconductors with a high degree of compensation, the Fermi level lies at the tail of the state density, where there is a certain concentration of pairs of centers at which the localized carriers are coupled by an antiferromagnetic exchange interaction $J$. This is the situation if $\Delta J/J < 2$ and $T < J/k$ (Ref. 5), where $\Delta J$ is the average scatter in the coupling energies between the magnetic moments of the carriers localized at sufficiently low temperatures, and $k$ is the Boltzmann constant. A magnetic field causes a paramagnetic shift of the Fermi level, and also most of the impurity-center levels which are not coupled by an antiferromagnetic interaction, and it splits the energy levels of the antiferromagnetic pairs. As a result of the splitting, the levels of centers with carrier spins oriented opposite the field come to lie near the Fermi level, thereby increasing the state density $g(\mu, H)$. For this reason, the negative magnetoresistance is observed only in the highly compensated samples, i.e., only if there is a hopping conductivity with a variable activation energy (of the Mott type), for which the state density near the Fermi level plays an important role.

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