# Effect of localized states near the metal-insulator transition on the conductivity and magnetoconductivity of strongly doped *n*-germanium

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It is shown that 1) in the range of impurity concentrations $1.4 N_c < N < 3N_c$, it is possible to determine from the results of measurements of the magnetoconductivity in Ge⟨As⟩ the value of the critical index of the metal-insulator transition; 2) the Yosida-Toyozawa effect in doped semiconductors can appear only in a narrow range of concentrations $N_c < N < 1.4N_c$, when, because of the disorder in the system, localized and delocalized states can exist near the Fermi level.

It can now be said with certainty that in the case $K_F l \gg 1$ (where $K_F$ is the quasimomentum at the Fermi surface, and $l$ is the mean free path) the anomalous magnetoresistance in doped semiconductors is due to quantum corrections to the kinetic coefficients which are associated with suppression of interference of elec-

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tronic wave functions in a magnetic field on self-intersecting trajectories.[1-3] As the impurity concentration is decreased and $N_c$—the concentration corresponding to the transition from the metallic state to the insulating state—is approached, the degree of disordering increases and $l$ and $K_F$ decrease, so that $K_F l \ll 1$. In this case, because of the disordered arrangement of impurities, there can be a situation in which for part of the impurities the Hubbard repulsion energy will exceed the Fermi energy $E_F$; as a result, singly occupied states with uncompensated spins appear. Thus, in a disordered system in direct proximity of the metal-insulator transition point (MIT), there can be a situation in which the localized states will exist together with the delocalized states near the Fermi level $E_F$.

In this paper, we shall present experimental results demonstrating the effect of localized electronic states on the magnetoconductivity and electrical conductivity of strongly doped $n$-germanium in the region of the metal-insulator transition.

According to the theory,[4] localized spins must have an appreciable effect on the temperature dependence of the conductivity $\sigma(T)$: for the three-dimensional case, the temperature correction to the conductivity, which is proportional to $T^{1/2}$ in the region $K_F l \gg 1$, transforms into a dependence of the type $\sigma \sim T^{1/3}$. As regards the magnetoresistance, the anomalous effect due to the quantum corrections to the kinetic coefficients is suppressed in the critical region due to the small spin relaxation time. On the other hand, an opportunity arises for observation of negative magnetoresistance resulting from the suppression of spin-dependent scattering in a magnetic field (Yosita-Toyozawa effect[5]).

Figure 1 shows the dependence of the magnetoconductivity $\Delta\sigma_0$ on the impurity concentration in specimens of uncompensated $n$-Ge⟨As⟩. The value of $\Delta\sigma_0$ was determined for values of the temperature and magnetic field $H_0$ for which $\frac{4DeH}{\hbar c}\tau_\phi \gg 1$ (where $D$ is the coefficient of diffusion of electrons, and $\tau_\phi$ is the phase relaxation time of the wave function due to inelastic collisions). In this case $\Delta\sigma$ is proportional to $H^{1/2}$.[2,3] It is evident from the figure that as $N$ approaches $N_c$ (for Ge⟨As⟩ $N_c \simeq 3.5 \times 10^{17}$ cm$^{-3}$),[7] $\Delta\sigma_0$ continuously decreases, vanishing at the transition point. We assume that this is related to the scaling nature of the change in the conductivity

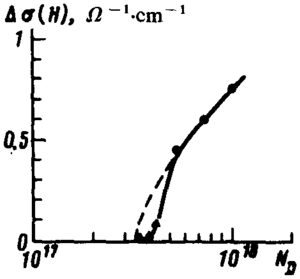


FIG. 1. Dependence of $\Delta\sigma(H)$ on the impurity concentration with $H = 4$ kOe and $T < 0.5$ K. ▲ - Data from Ref. 6; with $N = 4\times10^{17}$ cm$^{-3}$, $K_F l \simeq 0.5$.

near MIT[8]:

$$\sigma = \sigma_{min} ( ^{N}/_{N_c} - 1)^{\nu}, \qquad (1)$$

where $\nu$ is the critical index of the transition, and $\sigma_{\min}$ is the Mott minimum conductivity, since if (1) were not satisfied, then for $\frac{4DeH}{c\hbar}\tau_{\phi} \gg 1$ the quantity $\Delta\sigma_0$ must have the same value, irrespective of the impurity concentration (at least in the region where the condition $K_F l \gtrsim 1$ is satisfied).

From the study of the behavior of the conductivity on the metallic side of the transition[9] and the localization length of the wave function on the insulator side,[10] it follows that $\nu = 0.55 \pm 0.10$. It also follows from these studies that the dependence (1) is satisfied in a broader range of concentrations (on the metallic side up to $N = 2$–$3N_c$) than under the rigid requirements of applicability of the scaling theory of localization. An analysis of experimental data in Fig. 1 showed that $\Delta\sigma_0$ plotted as a function of $N$ is also described by expression (1) with $\nu = 0.5 \pm 0.1$ and $\Delta\sigma_0^{\min} = 0.55$ $\Omega$·cm (where $\Delta\sigma_0^{\min}$ is the magnetoconductivity at minimum metallic Mott conductivity), which within the error limits of the measurements agree satisfactorily with the previously obtained value of $\nu$. It is interesting to note that for specimens closest to the transition, the quantity $\Delta\sigma_0$ is much smaller than the value that is expected from expression (1) (shown in Fig. 1 by the dashed line). It is reasonable to attribute this difference to the appearance of localized spins, which suppress, as noted above, the interference effect of anomalous magnetoresistance. This result agrees with Ref. 11, where it is shown that near a metal-insulator transition, both localized and delocalized states can occur simultaneously at the $E^F$ level. It also agrees with experiments on the measurement of the magnetic susceptibility[12] and specific heat.[13]

Higher compensation leads to an increase in the disorder and intensification of localization effects. For this reason, the appearance of localized spins can be observed in a compensated material in a broader range of concentrations near MIT on

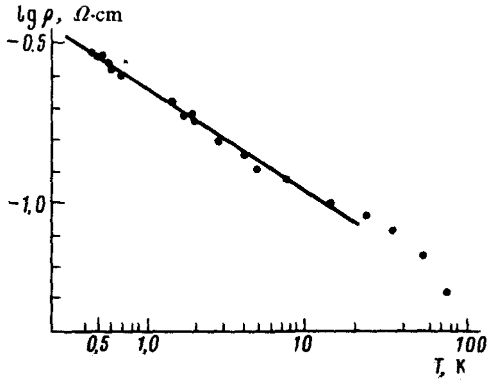


FIG. 2. Temperature dependence of the resistivity for a Ge⟨As⟩ sample with $N_{\mathrm{As}} = 5 \times 10^{17}$ cm$^{-3}$ and $K = 40\%$.

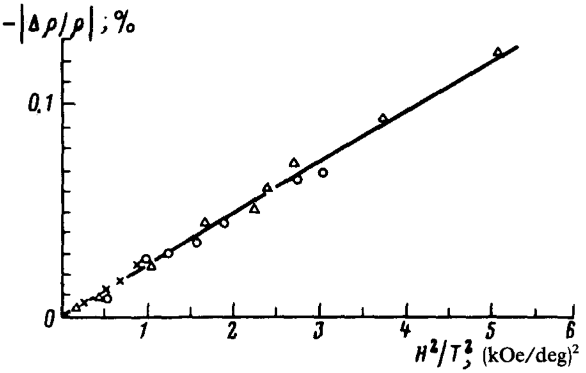


FIG. 3. Dependence of $\Delta\rho/\rho$ on $H^2/T^2$ for Ge⟨As⟩ with $N = 5\times10^{17}$ cm$^{-3}$ and $K = 40\%$; 3.0 K (×), 2.0 K (O), 1.55 K($\Delta$).

the metallic side. Figure 2 shows the temperature dependence of the resistivity $\rho(T)$ of a $n$-Ge⟨As⟩ specimen with concentration $N = 5\times10^{17}$ cm$^{-3}$ and degree of compensation $K = 40\%$. As is evident from the figure, $\rho \sim T^{-0.32\pm0.02}$.[1)] Since the dependence $\sigma = (\rho)^{-1} \sim T^{1/3}$ indicates the presence of localized magnetic moments, the magnetoresistance of this specimen can be described by the Yosida-Toyozawa formula:

$$-\frac{\Delta\rho}{\rho} = C\,\mathrm{th}^2(\mu H/kT), \tag{2}$$

where $C$ is a constant that depends on the localized-spin concentration and on the density of states at the level $E_F$; in the region of saturation of the magnetoresistance we have $C \cong |\Delta\rho/\rho|_{\mathrm{sat}}$.

The experiment has shown that in fields up to $H \simeq 3.5$ kOe the negative magnetoresistance is proportional to $H^2/T^2$; here $g = 1.57$ (Ref. 15) and $\mu = \mu_B$, where $\mu_B$ is the Bohr magneton, and $C \simeq 2\%$ (Fig. 3). It should be noted that in contrast to the situation where $N \gg N_c$ and $\Delta\sigma$ is isotropic with respect to the orientation of $H$ relative to the orientation of the specimen,[16] at $N \sim N_c$ an anisotropy should be observed in $\Delta\sigma$, which is attributable to the anisotropy of the $g$-factor.

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[1)] The presence of this type of dependence in the sample with these parameters was pointed out in Ref. 14.

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