The nature of "anomalous" magnetic reluctance in heavily doped *p*-type germanium

A. N. Ionov

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

(Submitted 28 November 1978)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 1, 76–79 (5 January 1979)

We show that a transition due to uniaxial compression from an "anomalous" positive to negative magnetic reluctance in *p*-Ge is explained by a change in sign of the exchange interaction between the spins of the free holes and localized spins.

PACS numbers: 71.20. + c, 71.70.Gm, 72.20.My

In 1963, it was reported[1,2] that an "anomalous" positive magnetic reluctance (PMR) had been observed in heavily doped *p*-Ge⟨Ga⟩ in the range of helium temperatures. At that time, it was shown that the "anomalous" PMR has the same temperature and concentration dependences as negative magnetic reluctance (NMR), observed in germanium with metallic conductivity. The assumption was expressed that in both types of germanium the "anomalous" magnetic reluctance has the same cause which until now has remained unexplained.

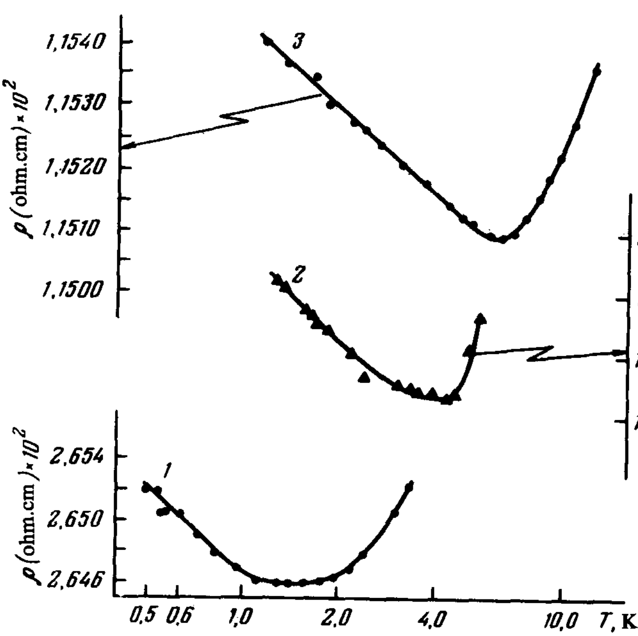

FIG. 1. Temperature dependence of resistivities of *p*-Ge with dopant concentrations: 1—4.6×10^{17} cm^{-3}; 2—1.1×10^{18} cm^{-3}; 3—1.6×10^{18} cm^{-3}.

We propose that the nature of the "anomalous" magnetic reluctance in doped germanium beyond the Mott transition on the metallic conductivity side is due to the increase in the density of the states at the Fermi level in a magnetic field, because the Kondo effect[3] is observed in the temperature dependence of the conductivity of such materials:

$$\rho_{ex} \sim \rho_0 \left[1 - \frac{4J}{N} \xi(\epsilon_F) \ln \frac{\epsilon_F}{KT}\right], \quad (1)$$

where ρ_{ex} is the value of the resistivity due to the exchange interaction ; ρ_0 is the value of resistivity in the first Born approximation; $\xi(\epsilon_F)$ is the density of the states at the Fermi level; ϵ_F is the Fermi energy; N is the impurity concentration; J is the exchange integral; K is the Boltzmann constant; and T is the temperature. The sign of the "anomalous" magnetic reluctance depends on the sign of J. According to this model, the transition from the "anomalous" PMR to the NMR under the effect of uniaxial compression that was observed in p-Ge[4] may be due to a change in the sign of J. However, the temperature dependence of ρ_{ex} should then necessarily change: instead of increasing with a decrease in temperature it should, on the contrary, decrease.

For an experimental verification of this hypothesis, germanium doped with gallium without prior compensation was selected with the carrier concentration from 2×10^{17} cm^{-3} to 1.5×10^{18} cm^{-3}.

Figure 1 shows the low-temperature conductivity of the samples. It can be seen that in all samples, starting at some temperature, the resistivity increases in accordance with Eq. (1). The temperature at which the conductivity minimum is observed shifts toward higher temperatures, with an increase in the concentration of the dopant; moreover, the temperature dependence of the conductivity is described by Eq. (1) with $J<0$. Figure 2 presents the temperature dependence of the conductivity for the p-Ge under conditions of uniaxial compression along the direction [100] at the sample pres-

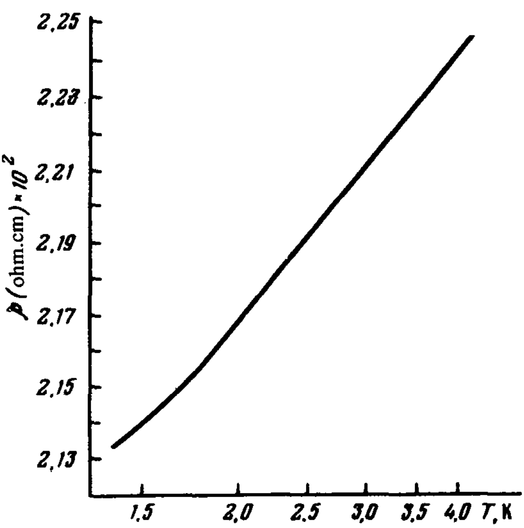

FIG. 2. Temperature dependence of resistivity of p-Ge ($N_a = 5.5\times10^{17}$ cm^{-3}) under conditions of uniaxial compression ($\chi = 4.2$ T/cm^2) along the direction [100] (I mA ∥ [100]).

sure at which the NMR is observed. Clearly, the temperature dependence of the conductivity actually changes sign and is now described by Eq. (1), but with $J > 0$.

In our opinion, the cause for the change in the sign of the exchange integral is the following. From the theory of the Kondo effect, it is known that the exchange integral J is the sum of two parameters:[5]

$$J = J_0 - J_m,$$

where J_0 is the result of a direct exchange interaction, and it is always positive, while J_m is the result of lumping the wave functions of the free carriers and the localized magnetic moments, which yields a negative contribution to J. Depending on the balance of these parameters, the total value of the exchange integral will be either positive or negative. Applying uniaxial compression and increasing the overlap between the wave functions, we increase the direct exchange interaction, which can lead to the final result and to a change in the sign.

In conclusion, the author thanks R.V. Parfen'ev and R. Rench for their help in the experiment, I.S. Shlimak for discussion of the results, and S.M. Ryvkin for his attention and interest in the work.

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