Antiferromagnetic interaction of conduction electrons with local magnetic moments in $Pb_{1-x}Mn_xTe$

M. P. Boĭko, A. V. Nikorich, and M. É. Guerrero
Institute of Applied Physics, Academy of Sciences of Moldova, 270028, Kishinev

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Kondo anomalies have been observed in the kinetic properties of *n*-type $Pb_{1-x}Mn_xTe$ ⟨In⟩ at $T < 50$ K. Varying the carrier density by IR illumination made it possible to rule out a possible effect of the band relief. The observed anomalies can therefore be attributed to the antiferromagnetic nature of the interaction of conduction-band electrons with local magnetic moments.

That the Mn–Mn interaction is of an antiferromagnetic nature in the semimagnetic semiconductors with the general formula $(IV)_{1-x}Mn_x(VI)$ has now been solidly established through measurements of the magnetic susceptibility,[1] a study of the transition to a spin-glass phase,[2] and other experiments. The Mn–Mn interaction is dominated by a superexchange through anions, i.e., involving the valence shells of the chalcogen. The kinetic characteristics depend primarily on an interaction of a different type, specifically, the interaction of carriers with localized manganese *d* electrons. The constants of this interaction, e.g., for manganese-doped lead telluride,[3,4] have different signs for carriers from the valence band and from the conduction band: $J_v < 0$ but $J_c > 0$. This difference between the signs of J_v and J_c should lead to qualitatively different kinetic characteristics for electrons and holes. In particular, with $J > 0$ at low temperatures, a scattering of carriers by local magnetic moments accompanied by spin flip may be manifested.[5] However, previous low-temperature measurements of transport effects have been carried out on *p*-type samples[2,6] or on *n*-type samples with a low manganese concentration.[7] Our purpose in the present study was to learn about carrier scattering in *n*-type $Pb_{1-x}Mn_xTe$ with high manganese concentration.

Galvanomagnetic characteristics of semimagnetic semiconductors $Pb_{0.95}Mn_{0.05}Te$ with 0.5 at. % In were measured over the temperature range 4.2–100 K and at magnetic fields up to 6 T. The single-crystal bars were grown by the Bridgeman method. The manganese concentration was monitored by ac polarography. The samples were cut and etched by the standard procedures. Their geometric dimensions were $0.5 \times 0.5 \times 5$ mm. Measurements were carried out on four samples, cut from the central parts of two bars. Since the electrical properties of all the samples turned out to be very nearly the same, we will report data on only one sample here. In accordance with Ref. 8, the composition of the alloy was chosen in such a way that the indium-stabilized Fermi level was near the bottom of the conduction band at low temperatures. The use of indium as a dopant makes it possible not only to lower the electron density but also to vary this density by applying IR light. As the IR source we used a carbon resistor held 5 cm above the sample and heated by a current up to 30–70 K. The highest densities of nonequilibrium photoelectrons for the various samples of this alloy were $n = (4–7) \times 10^{17}$ cm^{-3}.

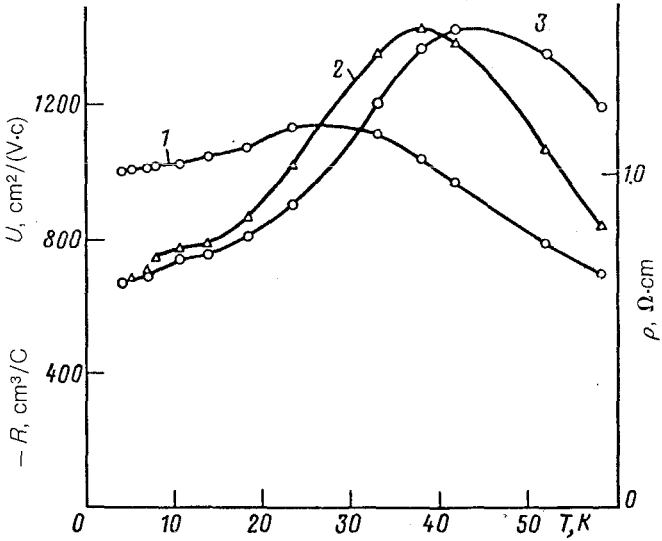

FIG. 1. Temperature dependence of (1) the resistivity, (2) the Hall coefficient, and (3) the mobility of a sample of $Pb_{0.95}Mn_{0.05}Te$ with 0.5 at. % In.

Figure 1 shows the temperature dependence of the resistivity, the Hall coefficient, and the mobility. The reason for the nonmonotonic shape of the $\rho(T)$ and $R(T)$ curves is a shift of the stabilized Fermi level into the band gap as the temperature is raised. Similar $R(T)$ curves had been recorded in PbTe⟨In⟩ in Ref. 9, in which case a minimum density was observed at $T \sim 300$ K. A new result is the nonmonotonic temperature dependence of the mobility U. The $U(T)$ curve has a maximum at $T = 40$ K and then a decrease at lower tempertures. The field dependence of the Hall voltage at low temperatures has an unusual shape (Fig. 2). The experimental value of the Hall

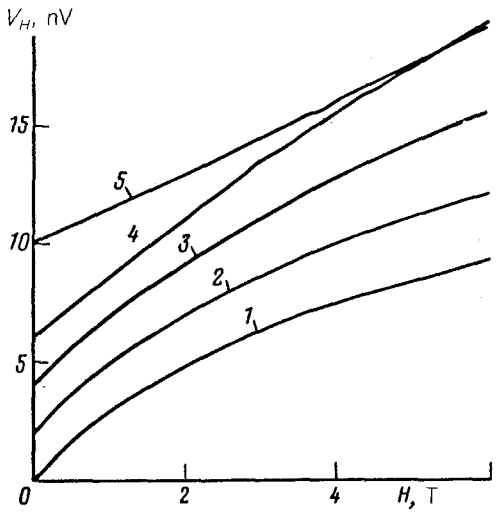

FIG. 2. Field dependence of the Hall voltage of a $Pb_{0.95}Mn_{0.05}Te$ sample with 0.5 at. % In. The current through the sample is 1 mA. 1—$T = 4.2$ K; 2—10.7; 3—23.4; 4—33.0; 5—51.9 K. Lines 2–5 have been shifted 2, 4, 6, and 10 mV, respectively, along the y axis.

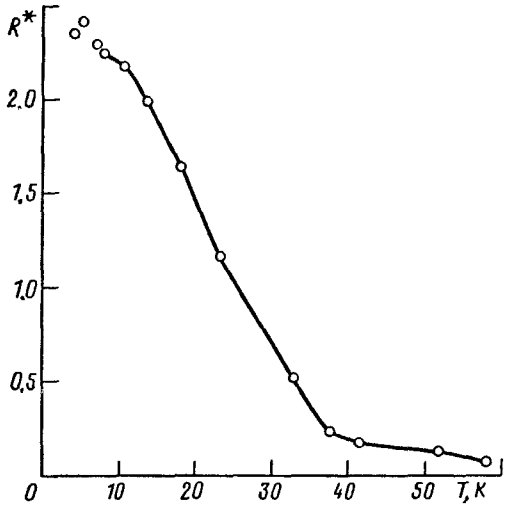

FIG. 3. Temperature dependence of R^* of a $Pb_{0.95}Mn_{0.05}Te$ sample with 0.5 at. % In.

voltage is the sum of two terms: $V_H = V_1 + V_2$, where V_1 is the ordinary Hall voltage, which is a linear function of the magnetic field, and V_2 is an additional voltage. In weak fields this additional component has the behavior $V_2 \sim H$; ad H is raised, it reaches saturation. The ratio $R^* = [R(0) - R]/R$[where $R(0)$ is the experimental value of the Hall constant at $H = 0$, and R is the ordinary Hall constant $R = 1/en$, found from the slope of dV_H/dH in a field of 6 T] characterizes the relative value of the additional Hall component. It follows from the temperature dependence $R^*(T)$ in Fig. 3 that the additional Hall component is seen at the same temperatures as the anomalous $U(T)$ dependence.

The $U(T)$ and $V_H(T,H)$ characteristics found have the typical Kondo shape. The positive value of dU/dT is an analog of the well-studied increase in the resistance with decreasing temperature in metal alloys with dilute magnetic moments. It is explained in terms of a corresponding increase in the intensity of scattering accompanied by spin flip. The reason for the onset of an additional Hall component at low temperatures in dilute alloys is a manifestation of an asymmetric scattering by local magnetic moments in a magnetic field.[10] The various features of the Hall characteristics of metal alloys have received less study. For the slightly degenerate systems with dilute magnetic moments which are of interest here, there has been no detailed analysis of the field dependence or the temperature dependence of the Hall coefficient. Nevertheless, we will draw from the results of Ref. 10 for a qualitative illustration of the features of the $V_H(H,T)$ dependence observed in the present study. The Hall coefficient as $H \to 0$ is written in the form

$$R(0) = (1/en)(1 - \alpha), \tag{1}$$

where α is a complex function of the spin-spin exchange constant J, the spin–orbit exchange constant λ, the concentration (C_i) of local magnetic moments, the Fermi energy E_f, the dopant spin S, the temperature, and several other parameters. It is given

by

$$\alpha \sim \frac{C_i \lambda}{kTE_f^2} S(S+1)\Phi(J,S). \tag{2}$$

In strong fields, for values of λ which are moderately large, the Hall constant tends toward its normal value. Since we have $R^* = \alpha$ in the notation of Ref. 10, we can assume that relations (1) and (2) give a qualitatively correct description of the features of the Hall characteristics of n-$Pb_{1-x}Mn_xTe$. We repeat that we are dealing with only a qualitative correspondence here, but it is sufficient for drawing the conclusion that we are seeing a manifestation of an asymmetric scattering by local magnetic moments of manganese atoms at low temperatures. In particular, it follows from (2) that R^* should decrease with increasing carrier density. As we have already mentioned, the application of IR light made it possible to vary the carrier density. As the density was increased to $n = 3\times 10^{17}$ cm^{-3}, R^* decreased to a value of 0.7 at $T = 4.2$ K. The fairly high values of R^* at $n > 10^{17}$ cm^{-3} means that we can rule out the possibility that the anomalies in $U(T)$ and $V_H(H,T)$ result from a localization of carriers due to fluctuations of the band relief. The same conclusion is implied by the circumstance that the derivative dU/dT retains its sign during the IR illumination. Furthermore, with an increase in the density of nonequilibrium photoelectrons at $T < 20$ K, we observe an increase in the resistivity with decreasing temperature, which is a consequence of a weakening of the $R(T)$ dependence.

The low-temperature kinetic properties of n-$Pb_{1-x}Mn_xTe$ which have been measured in the present study are evidence of a fundamental difference between the transport properties of n-type and p-type alloys. The reason, as we mentioned earlier, is the difference between the signs of the exchange constants for electrons and holes. The constants J_v and J_c differ in sign in the alloys $Hg_{1-x}Mn_xTe$ also. Consequently, n-type samples may exhibit anomalies similar to those observed in the present study.

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