Investigation of electric and magnetic properties of the semimagnetic semiconductors $Hg_{1-x}Mn_xTe$ at low and infralow temperatures

N. B. Brandt, V. V. Moshchalkov, A. O. Orlov, L. Skrbek, I. M. Tsidil'kovskiĭ,[1)]

and S. M. Chudinov

Moscow State University

(Submitted 23 June 1982)
Zh. Eksp. Teor. Fiz. **84**, 1050–1074 (March 1983)

The temperature and field dependences of the Hall coefficient and of the resistivity of the zero-gap p-type semimagnetic semiconductors (SMSC) $Hg_{1-x}Mn_xTe$ ($0<x\leqslant 0.075$) are investigated in magnetic fields up to 40 kOe and at temperatures $0.04\leqslant T\leqslant 20$ K. The temperature dependences of the magnetic susceptibility in weak magnetic fields ($H\sim 0.5-100$ Oe) are measured with the aid of SQUID. When the temperature is lowered to the region $T<4$ K, a significant growth of the Hall coefficient (by 2 to 70 times) is observed simultaneously with a decrease of the resistivity by 1.5 to 6 times. A model is proposed to explain the anomalies of $R(T)$ and $\rho(T)$, which are attributed to an increase in the mobility μ_c of the electrons of the conduction band at low temperatures, owing to binding of ionized donors D^+ and acceptors A^-, which have captured an excess electron, into neutral D^+–A^- complexes. In samples in which the dominant contribution to the conductivity is made by carriers from the impurity acceptor band, a local maximum is observed against the monotonic temperature dependence $R(T)$ in the interval $0.15\leqslant T\leqslant 0.7$ K. The position of the maximum corresponds to the temperatures at which a kink is observed on the $\chi(T)$ curve. The amplitude of the maximum decreases with increasing field H in which the Hall coefficient was measured, and vanishes at $H>200$ Oe. The temperature of the kink on the $\chi(T)$ curve also decreases with increasing field. The singularities of $\chi(T)$ and $R(T)$ point to a transition of the zero-gap SMSC $Hg_{1-x}Mn_xTe$ into spin glass. Thus, the phase diagram of the magnetic properties of $Hg_{1-x}Mn_xTe$ is more complicated than previously assumed, and a spin-glass phase exists not only at $0.17<x<0.36$ [S. Nagata *et al.*, Phys. Rev. **B22**, 3331 (1980)], but also at lower concentrations x: $0<x\lesssim 0.075$. Under the action of hydrostatic compression, which induces inversion of the Γ_8 and Γ_6 bands at $p=p_i$ and opens a direct gap at $p>p_i$, the temperature of the transition from the paramagnet to spin glass decreases sharply and no local maximum is observed on the $R(T)$ plot at $p>p_i$. This seems to indicate that a substantial role in the establishment of a long-range exchange interaction in SMSC is played by virtual interband transitions via the zero gap.

PACS numbers: 72.20.My, 75.30.Cr, 75.30.Kz, 72.20.Jv

INTRODUCTION

A semimagnetic semiconductor (SMSC)[1] is usually referred to as a semiconducting matrix in which a magnetic impurity is disolved. The impurity content is usually varied in a wide range, from densities 10^{-5}–10^{-4} at.%, typical of classical Condon systems of the type Au⟨Mn⟩, Cu⟨Fe⟩, etc. up to the densities of magnetic semiconductors. As a rule, the initial semiconducting material is a compound whose band structure has been thoroughly investigated, so that the matrix of the initial semiconductor can be used as a reference and principal attention can be paid to effects due to the introduction of the magnetic component.

Practically all the SMSC investigated to date are II-VI compounds with the component II replaced by a transition element M, and constitute solid solutions of the type $A_{1-x}{}^{II}M_xB^{VI}$. Among the compounds $A_{1-x}{}^{II}M_xB^{VI}$, the ones investigated in greatest detail were $Hg_{1-x}Mn_xTe$, $Hg_{1-x}Mn_xSe$, and $Cd_{1-x}Mn_xTe$. In these systems the change of the concentration of the magnetic component (in this case Mn) causes a smooth rearrangement of the energy spectrum, similar to that produced, e.g., by replacement of Hg with Cd in ternary solid solutions $Hg_{1-x}Cd_xTe$ makes it possible to change the relative positions of the terms Γ_8 and Γ_6 and the size of the gap $\varepsilon(\Gamma_6)$–$\varepsilon(\Gamma_8)$.

In a zero magnetic field, the energy spectrum of the SMSC $Hg_{1-x}Mn_xTe$ is rearranged with increasing x (Refs. 2 and 3), just as in the system $Hg_{1-x}Cd_xTe$, when the cadmium concentration is increased. The most substantial difference between SMSC and ordinary semiconductors is connected with the exchange interaction of the carriers with the uncompensated magnetic moments of the Mn^{2+} ions, which manifest themselves most strongly when SMSC are investigated in a magnetic field.

The most interesting unsolved problems in the physics of SMSC are, in our opinion, the following: 1) the problem of the interaction of the magnetic ions of variable density in the matrix of a semiconductor[4,5] whose band spectrum can vary in a wide range—from zero-gap to inversion, such as HgTe with $0<\varepsilon(\Gamma_8)-\varepsilon(\Gamma_6)\lesssim 300$ meV, to a direct one of the type InSb with $0\leqslant\varepsilon(\Gamma_6)-(\Gamma_8)\lesssim 1$ eV; 2) the problem of impurity states in SMSC, particularly in zero-gap ones, which is closely connected with investigations of impurity states in zero-gap semiconductors of the HgTe type.

 0038-5646/83/030614-10$04.00

The specific feature in the study of problems 1) and 2) in a zero-gap SMSC is that their spectrum contains small (1–10) K) characteristic energy parameters. For example, in the p-type zero-gap SMSC $Hg_{1-x}Mn_xTe$ this is the activation energy (20–50 K) of the acceptor states and the width Γ of the impurity acceptor band ($\Gamma \sim 1$–10 K). In addition, the characteristic energy of the interaction of the magnetic ions with one another may turn out to be quite small if their number in the matrix is small enough.

From this point of view, to solve the problems 1) and 2) a most promising approach is provided by experiments performed at the lowest possible temperatures, including the region of infralow temperatures, when kT becomes negligibly small compared with the characteristic energy parameters. To our knowledge, however, the number of studies in which this requirement might have been satisfied is very small.[6,7]

In this connection, on the basis of the results of Refs. 6 and 7, we present here a detailed investigation of the temperature and field dependences of the Hall coefficient $R(T)$ and of the resistivity $\rho(T)$ in the temperature interval $0.04 \leqslant T \leqslant 20$ K. In a weak magnetic field $0.5 < H < 100$ Oe, the SQUID method was used to measure the temperature dependences of the magnetic susceptibility $\chi(T)$ at $0.04 \lesssim T \lesssim 3$ K.

EXPERIMENTAL PROCEDURE

Infralow temperatures were obtained with the aid of the He^3–He^4 dissolution refrigerator of the SHE firm (USA), which makes it possible to operate in a continuous cooling regime down to ~ 30 mK. The basic principles of the operation of the refrigerator are described in Ref. 8. To obtain magnetic fields up to 70 kOe, a superconducting cable solenoid was used with a constant 1 kOe/A. For more accurate measurements in weak magnetic fields (to prevent effects connected with a "frozen-in" field), a two-layer superconducting solenoid is used with a constant 59 Oe/A. The initial samples were mounted on a cold finger connected to the dissolution chamber of the refrigerator. To decrease the heating by eddy currents, the cold finger was assembled of a large number of copper wires insulated from one another. Hydrostatic pressure up to 15 kbar was produced in a high-pressure chamber made up of heat-treated beryllium bronze BrB-2 by the Itskevich method.[9] To operate at infralow temperatures, the high-pressure chamber was connected to the dissolution chamber of the refrigerator with the aid of a special red-copper holder constructed in such a way that there were no closed conducting loops in a plane perpendicular to the magnetic field. The pressure was determined from the temperature of the superconducting transition of a tin pickup placed directly in the channel of the high-pressure chamber.

The temperature of the mixture in the dissolution chamber was varied in the range $0.05 < T < 2$ K with the aid of a carefully calibrated GRT germanium thermometer. To measure the lowest temperatures, a magnetic thermometer was used: a high-frequency SQUID was used to determine the magnetic susceptibility of cerium-magnesium nitrate. The temperature of the samples on the cold finger and in the high-pressure chamber was measured with a Speer type carbon thermometer located in the immediate vicinity of the samples–either on the cold finger or on the working part of the high–pressure chamber. It was established that the resistance of this thermometer in the temperature interval $0.03 < T < 5$ K does not depend on the magnetic-field intensity up to 70 kOe. To prevent overheating of the thermometer, its resistance was measured by a four-probe method using an ac PCB bridge (of the SHE firm) with a very low excitation level (10^{-12} W).

The differential magnetic susceptibility was measured with the aid of an RF Zimmerman SQUID. The sample was placed in one of the coils of the superconducting transformer on the outer side of the dissolution chamber of the refrigerator. An external-feedback system was used (the unbalanced signal detected by the SQUID, used as the null indicator, is compensated for by a feedback signal that is fed from the electronic circuitry of the SQUID through an inductive coupling directly to the superconducting transformer). This made it possible to measure separately both the real and imaginary parts of the unknown impedance. To compensate for the SQUID signal, a biphase detector and a precision ac bridge (RBU of the SHE firm) was used. The measurements were performed in a magnetic field enclosed in a superconducting niobium cylinder (the cooling trapped either the z-component of the external field of the earth, $H_z < 0.5$ Oe, or the field produced by the superconducting solenoid). The sensitivity of the procedure was 10^{-7} cm^3/g at $H \sim 0.5$ Oe.

TABLE I.

Sample No.	x, % Mn	$N_{D^+}\cdot 10^{-18}$, cm^{-3} [13]	$N_A = N_{D^+} - n_c \times 10^{-18}$, cm^{-3}	$n_c \cdot 10^{-18}$, cm^{-3} [13]	σ_i(4.2 K), $\Omega^{-1}\cdot$cm^{-1}	σ_c(4.2 K), $\Omega^{-1}\cdot$cm^{-1}	ε_F, MeV [13]	ε_g, MeV [13]	$\frac{\mu_c(0.1\text{ K})}{\mu_c(4.2\text{ K})}$ expt.	$\frac{N_{D^+}+N_{A^-}}{n_c}$ theor	T_{SG}, mK
13	2	3	0.7	2.3	9	14.6	4.2	165	–	–	225
11	3.4	3	1.8	1.2	13	20	4.0	110	–	–	250
1	3.6	4	3.34	0.66	5.7	4.3	–	–	14.5	11.2	240
2	3.6	4	3.4	0.7	5.6	4.3	–	–	13.5	10.5	250
7	5.5	1	0.39	0.61	1	53.7	5.6	47	4.0	2.3	360
6	6.5	1	0.4	0.6	1.4	73.1	7.8	26	4.1	2.4	–
9	7	1	0.58	0.42	1.3	8.1	8.0	20	12.9	3.8	620
10	7.5	–	–	–	–	–	–	0	20.0	–	550

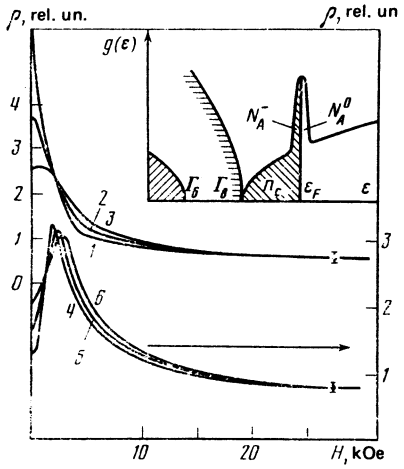

FIG. 1. Field dependences of resistivity $\rho(H)$ of samples No. 11 (left scale, curves 1, 2, and 3) and No. 2 (right scale, curves 4, 5, and 6) at the following temperatures: 250 mK—curves 1 and 4; 350 mK—2 and 5; 700 mK—3 and 6. The inset shows the band structure of the zero-gap SMSC $Hg_{1-x}Mn_xTe$.

ANOMALOUS CHANGE OF THE RESISTANCE OF $Hg_{1-x}Mn_xTe$ IN A MAGNETIC FIELD

All the $Hg_{1-x}Mn_xTe$ investigated in the present study were p-type samples with zero band gap (see the table). It is known[10] that in zero-gap semiconductors, including the zero-gap SMSC $Hg_{1-x}Mn_xTe$ ($0<x<0.075$), the impurity acceptor band is resonant (Fig. 1, inset), inasmuch as the acceptor states land in the band of allowed values of the conduction band Γ_8. Therefore at low temperatures the Fermi level ε_F is fixed in the acceptor band and two groups of carriers contribute to the current transport: the conduction electrons (index c) and the holes of the impurity acceptor band (index i) with respective mobilities μ_c, μ_i and densities n_c, n_i.

The Fermi energy ε_F of the p-type zero-gap SMSC $Hg_{1-x}Mn_xTe$ amounts to 4–5 meV.[11] Therefore at temperatures $T \lesssim 40$–50 K the electron gas is degenerate, and distinct Shubnikov-de Haas oscillations were observed in all the samples investigated in the present study; the period of these oscillations was practically independent of temperature at $0.1 < T < 4.2$ K. The table lists the values of the Fermi energy ε_F and of the gap parameter $\varepsilon_g = \varepsilon(\Gamma_8) - \varepsilon(\Gamma_6)$, taken from Ref. 12, in which the same samples were investigated at temperatures $T \gtrsim 1.6$ K.

A unique identifying feature of p-type single crystals of $Hg_{1-x}Mn_xTe$, which decides the relation between n_c, μ_c and n_i, μ_i, are the dependences of the transverse resistivity $\rho_\perp$ on the magnetic field H (Fig. 1) and the field dependences of the Hall voltage $U_H(H)$ (Fig. 2).

From the experimental $U_H(H)$ and $\rho_\perp(H)$ curves it is possible to determine all the four parameters n_c, μ_c, n_i, and μ_i.[12] Only three equations are needed for this purpose, since the concentration n_c can be easily determined from the period $\Delta(1/H)$ of the quantum oscillations.[13] The first two equations are given by the expressions for the Hall coefficient R in a weak magnetic field $H \to 0$ and for the conductivity σ:

$$R_{H\to 0} = -e\frac{\mu_c^2 n_c - \mu_i^2 n_i}{\sigma^2}, \tag{1}$$

$$\sigma = e(\mu_c n_c + \mu_i n_i). \tag{2}$$

In the limit of strong magnetic fields, at which the Lorentz magnetization of the mobile electrons of the conduction band causes their mobility to become negligibly small, one can assume with sufficient accuracy that as $H \to \infty$ (usually at $H \gtrsim 30$ kOe) we have

$$R_{H\to\infty} \approx 1/en_i. \tag{3}$$

In addition to (1)–(3) we can use for samples with $\sigma_c \gtrsim \sigma_i$, for which the sign of R is reversed in a magnetic field $H = H_i$, the following equation:

$$\frac{\mu_c^2 n_c}{1+(\mu_c H_i)^2} - \frac{\mu_i^2 n_i}{1+(\mu_i H_i)^2} = 0. \tag{4}$$

The values of n_c, μ_c, n_i and μ_i determined at $T = 4.2$ K from the experimental $U_H(H)$ dependence using Eqs. (1)–(4), as well as the conductivities σ_c for the band Γ_8 and σ_i for the impurity acceptor band are listed in the table. The procedure of finding these parameters is described in greater detail in Refs. 11 and 12.

For samples with $\sigma_c \gg \sigma_i$ the Hall coefficient $R_{H\to 0} < 0$, and with increasing H the sign of R is reversed and the magnetoresistance which is positive at $H \ll H_{max}$ becomes negative in a magnetic field $H \gg H_{max}$ (Fig. 1). With decreasing temperature, the absolute value of $R_{H\to 0}$ increases (Fig. 2), and the maximum on the $\rho(H)$ curves shifts towards weaker magnetic fields. At the same time, the resistivity ρ in a zero magnetic field also decreases with decreasing temperature, (Fig. 1).

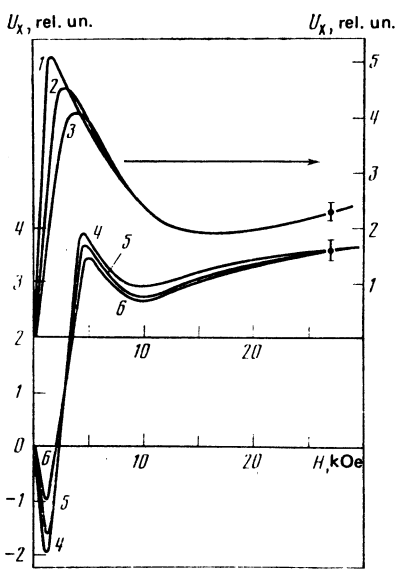

FIG. 2. Field dependences of the Hall voltage $U_H(H)$ of samples No. 11 (right scale, curves 1, 2, and 3) and No. 2 (left scale, curves 4, 5, and 6) at temperatures 250 mK (curves 1 and 4), 350 mK (2 and 5) and 700 mK (3 and 6).

We assume that the decrease of $\rho(H)$ at $H \geqslant H_{max}$ is due to the increase of the conductivity σ_i in the impurity band in the magnetic field. Indeed, as shown in Ref. 11, in the longitudinal magnetoresistivity $\rho_\parallel$, which is determined in the entire range of the magnetic fields by the sum of the contributions made to the carrier conductivity by the impurity band and the conduction band ($1/\rho_\parallel = \sigma_i + \sigma_c$), there is no section with decreasing $\rho(H)$, or else it is very weakly pronounced. On the other hand, the decrease of the transverse magnetoresistivity ρ takes place in that region of fields where the contribution of σ_c becomes negligibly small because of the Lorentz magnetization of the electrons of the conduction band.

With increasing conductivity σ_i relative to σ_c, the decrease of $\rho(H)$ becomes more pronounced, and sections of negative magnetoresistivity appear in external fields (see Fig. 1): the maximum shifts to the left in the H scale. At sufficiently large ratio σ_i/σ_c, there even arises a situation (see the curves in the upper part of Fig. 1) when $\rho(H)$ has no maximum and the decrease of $\rho(H)$ begins at $H = 0$. The qualitative change of the shape of the $\rho(H)$ curves with changing σ_i/σ_c is accompanied also by a transformation of the field dependence of the hole coefficient $R(H)$: at large σ_i/σ_c, the sign of $R(H)$ is not reversed (see the curves in the upper part of Fig. 2).

The sections with decreasing $\rho(H)$, which were observed also earlier for $Hg_{1-x}Mn_xTe$ (Refs. 14 and 15) do not appear for the semiconductors $Hg_{1-x}Cd_xTe$, which have a similar energy spectrum at $H = 0$. Therefore the anomalous behavior of $\rho(H)$ can be naturally attributed to the presence of the magnetic component.[11,14,15]

We can point to at least two causes that can explain the anomalously large value of the negative magnetoresistivity.

In Ref. 11, the main source of the decrease of the resistivity was taken to be the decrease of the probability of scattering of the impurity-band holes as a result of the ordering of the magnetic moments of the manganese by the magnetic field (a correlation was established between the behavior of the $\rho(H)$ curves and the values of $g\mu_B H/kT$, where g is the g-factor and μ_B is the Bohr magneton).

The authors of Ref. 15 believe that the cause of the decrease of the resistivity may be the broadening of the impurity band in the magnetic field, owing to the decrease of the ground-state energy ε_A of the acceptors. Let us examine in some detail this mechanism of the change of $\rho(H)$. In SMSC, in contrast to ordinary semiconductors, an important role in the make-up of the energy spectrum is played by the exchange interaction of the valence electrons of the Γ_8 band with the $3d^5$ electrons of the Mn^{2+} ions. This interaction leads to a splitting of the fourfold degenerate valence band Γ_8. The value of the splitting B is determined by the exchange integral β, by the average z-component of the spin of the manganese ions $\langle S_z \rangle$, by the number N_0 of the unit cells per unit volume, and by the concentration of the manganese x:

$$B = {}^1/_6 N_0 \beta \langle S_z \rangle x. \tag{5}$$

The band parameters of $Hg_{1-x}Mn_xTe$ are such that in moderately strong magnetic fields (at $L \gg a_h$, where L is the magnetic length and a_h is the Bohr radius of the heavy holes), a situation is realized in which the splitting of the valence band on account of the exchange interaction is much larger than the distance between the Landau levels of the valence band ($B \gg \hbar\omega_c$, where ω_c is the cyclotron frequency). Under these conditions, the acceptor energy $\varepsilon_A(H)$ is determined mainly by the parameters of the highest of the split valence bands. The calculations show that the effective mass of this highest of the bands of $Hg_{1-x}Mn_xTe$ is small enough and the energy $\varepsilon_A(H)$ becomes lower than ε_A^0 (Ref. 15). As a result, a decrease of the acceptor activation energy should be observed (and is observed[15]) in $Hg_{1-x}Mn_xTe$ at $L \gg a_h$. In stronger fields ($L \ll a_h$) in SMSC, just as in ordinary semiconductors, an important role is assumed by the compression of the acceptor wave functions by the magnetic field, and the energy $\varepsilon_A(H)$ should increase.[15]

The decrease of the energy ε_A in the region of moderately strong magnetic fields corresponds to an increase of the radius of the localized acceptor states, i.e., to a strengthening of the overlap of the wave functions of the impurities. This can serve as the reason for the decrease of the resistance of $Hg_{1-x}Mn_xTe$ with increasing H in the region of conduction over the impurity states.[15]

The negative magnetoresistivity connected with the decrease of ε_H with increasing H depends substantially on the character of the conduction over the impurity band. Unfortunately, on the basis of the available experimental data it is impossible to draw directly any conclusion on the nature of the conduction over the impurity band in the employed region of magnetic fields. This is due, on the one hand, to the fact that in $Hg_{1-x}Mn_xTe$ of p-type the impurity band is resonant, and therefore at $H = 0$ the main contribution to the conductivity is made by the light carriers in the Γ_8 band, and on the other hand to the anomalous dependence of the radius a_h of the impurity states on the magnetic field. It is possible to determine the mechanism of the conduction over the impurity acceptor band only by using theoretical estimates of the critical density N_M of the Mott metal-insulator transition:[16]

$$N_M^{1/3} a_h \approx 0.2, \tag{6}$$

where $a_h = \hbar^2 \varkappa / m^*_h e^2$ (Ref. 16, p. 256 of Russian translation), m^*_h is the effective mass, and $\varkappa$ is the dielectric constant. For HgTe we have $N_M \approx (0.7\text{–}1) \times 10^{18}$ cm^{-3} (Ref. 17). Inasmuch as in accordance with the data of Refs. 12 and 13 the acceptor density in the investigated samples does not exceed 10^{17} cm^{-3}, it can apparently be assumed that the conduction over the impurity band has at $H = 0$ an activation origin. Thus, the contribution of the mechanism of Ref. 15 to the negative resistance can be quite large.

It must be borne in mind that explanations of the anomalously large negative magnetoresistivity $\rho_1(H)$, given both in Ref. 11 and in Ref. 15, are qualitative and to estimate the contribution of each of the mechanisms of Ref. 11 and Ref. 15 it is necessary to have concrete theoretical calculations of the conduction over the impurity band in the SMSC.

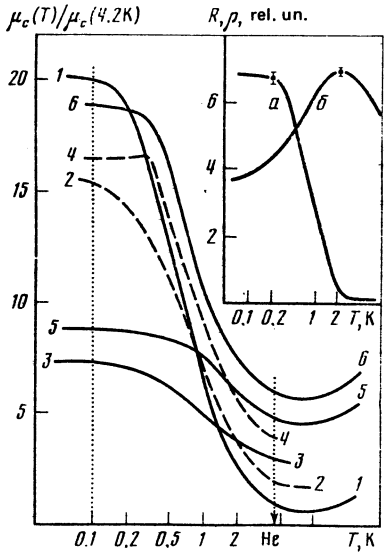

FIG. 3. Temperature dependences of $\mu_c(T)/\mu_c$ (4.2 K) for samples No. 10—curve 1, No. 1—2, No. 7—3, No. 2—4, No. 6—5, No. 9—6. Curves 2–6 are shifted along the ordinate axis by 1–5 units, respectively. The inset shows the temperature dependences of $R_{H\to 0}(T)$ (curve *a*) and $\rho(T)$ (curve *b*) for sample No. 1.

ANOMALOUS CHANGE OF THE RESISTIVITY $\rho(H=0)$ AND OF THE HALL COEFFICIENT $R(H\to 0)$ OF $Hg_{1-x}Mn_xTe$ AT INFRALOW TEMPERATURES

It was noted above that in the investigated zero-gap SMSC there was observed in the region $T\leqslant 4$–6 K (with decreasing temperature) a substantial decrease (by several times) of the resistivity $\rho(H=0)$, with simultaneous increase of the Hall coefficient $R_{H\to 0}$ by 2–70 times (see inset of Fig. 3 and the sections in Figs. 1 and 2 for $H=0$). This effect takes place at sufficiently low temperatures, when the condition $kT\ll\varepsilon_F\approx 40$–50 K is satisfied and the period of the quantum oscillations, which determines the electron density n_c, is practically independent of temperature.[7,11]

The anomalous change of the Hall coefficient $R(T)$ and of the resistivity $\rho(T)$ when the temperature is decreased all the way to ~ 0.08 K is observed under conditions when the value of the temperature smearing kT of the occupation boundary is negligibly small compared both with ε_F and with the width Γ of the impurity acceptor band. It is therefore natural to assume that the densities n_c and n_i do not change in this temperature region, and that the observed effect is due to a change in the mobility μ_c and (or) μ_i. Since it was shown in Ref. 7 that the anomalies of $\rho(T)$ in the *p*-type zero-gap SMSC $Hg_{1-x}Mn_xTe$ are distinctly observed in the case $\sigma_c\gg\sigma_i$ under the condition $R(T)\approx$ const, it is most probable that an increase of $\mu_c(T)$ takes place as $T\to 0$.

In fact, inasmuch as for all the investigated samples (see the table) the relations $n_i\mu_i^2\ll n_c\mu_c^2$ are satisfied, but $n_i\mu_i\sim n_c\mu_c$, we can neglect in the numerator of the right-hand side of (1) the term $n_i\mu_i^2$. We then obtain from (1) the following expression for the mobility $\mu_c(T)$:

$$\mu_c(T)\approx\sigma(R/en_c)^{1/2}. \tag{7}$$

The temperature dependences of $\mu_c(T)$ determined for different samples of $Hg_{1-x}Mn_xTe$ from the experimental curves $R(T)$ using formula (7) are shown in Fig. 3.

What can cause such a substantial increase of the mobility $\mu_c(T)$ ($[\mu_c(0.1)\text{ K}/\mu_c(4.5\text{ K})]\approx 4$–20 when the temperature is lowered from 4.2 to 0.08 K)? The dominant scattering mechanism in doped semiconductors is scattering by ionized impurities. It is therefore natural to attribute the increase of $\mu_c(T)$ with decreasing temperature to the decrease in the number of charged scattering centers that limit the mobility $\mu_c(T)$ at $T\to 0$.

In the *p*-type zero-gap SMSC $Hg_{1-x}Mn_xTe$ (see the inset of Fig. 1) there are two types of charged center. The first are the positively charged remnants D^+ of the donor atoms, inasmuch as in gapless semiconductors of the HgTe type the donor states are always delocalized.[10] Electrons that depart with N_{D^+} donor atoms fill the conduction band Γ_8 and in part the impurity acceptor band:

$$N_{D^+}=n_c+N_{A^-}. \tag{8}$$

The second type are the acceptors A^- which have captured an excess electron. They correspond to occupied states in the acceptor band and constitute negatively charged scattering centers. We note that in zero-gap semiconductors of the HgTe type the acceptors A^- are constantly present, whereas in the case of an ordinary semiconductor they correspond to an excited state with a short lifetime.

The unoccupied state in the impurity bands are neutral acceptors A^0 (see the inset in Fig. 1). A typical density N_{A_0} or N_{A^-} in the investigated samples amounts to $\leqslant 10^{17}$ cm^{-3} (Ref. 13), which in the case of HgTe is less than the critical Mott density $N_M\sim 10^{18}$ cm^{-3} (Ref. 17).

Though this statement is based on a rather rough estimate, it allows us to assume that conduction in $Hg_{1-x}Mn_xTe$ over the impurity band is activating. If this is indeed so, at sufficiently low temperatures the current transport over the acceptors is via hopping conduction within the limits of one Hubbard subband. In this case one can propose the following mechanism of low-temperature change of the electron mobility in the conduction band.

At not very low temperatures $kT\gtrsim\Gamma$ the hopping conduction consists of electron hops from a certain center A^- to a neighboring neutral acceptor A^0. In this situation, therefore, the lifetime τ of the excess electron on the acceptor is short. When the temperature is lowered, $kT\leqslant\Gamma$, a transition takes place from the regime of hopping to neighboring centers A^0 (ε_3 process) to hopping conduction with variable length of the hop (VRH—variable range hopping), when each elementary act of current transport is connected with a hop not to the neighboring center A^0, but to a farther but closer in energy acceptor A^0, the distance to which increases with decreasing temperature.[16]

In fact, the possibility that the considered hopping-conduction mechanism is applicable to SMSC $Hg_{1-x}Mn_xTe$ calls for an additional confirmation, since the acceptors form a resonant impurity band, and consequently constant transitions of the electrons from the conduction bands to the acceptors A^0 and back are allowed. However, since the density of states in the conduction band Γ_8 is always small, only a negligible fraction of the energy can go over simultaneous-

ly to the conduction band. Therefore the application of the concepts usually employed for bound acceptor states to resonant acceptor states seems apparently to be justified.

For the ε_3 process, the average distance from A^- to D^+ does not change in first-order approximation in the transition $A^- A^0$, inasmuch as the excess electron from the A^- centers hops over to neighboring centers A^0 that are separated from the considered donor by approximately the same distance. At the same time, VRH conduction is characterized by electrons hopping to remote centers A^0, therefore these hops are connected with performance of work to overcome the Coulomb attraction of the electron by the donor D^+ closest to the acceptor A^- from which the excess electron hops over.

The Coulomb attraction by the ionized donor D^+ contributes by the same token to an increase in the lifetime of the excess electron on the acceptor, i.e., of the state A^-. In this situation the probability of formation of a single neutral complex made up of D^+ and A^-, a complex which is the remainder of the donor D^+ and the acceptor A^0 closest to it, unified by a common electron shell (by an "excess electron") increases strongly. In other words, at low temperatures $kT \leqslant \Gamma$ neither on the donor remainder D^+ nor on the neutral acceptor A^0 is the depth of the potential well sufficient for electron localization, but at the same time the "combined" potential energy made up of both centers D^+ and A^0 may turn out to be sufficient to localize the excess electron and to produce a neutral D^+–A^0 complex.

The formation of the neutral complexes begins at a certain characteristic temperature $kT^* \approx \Gamma$, below which the probability of hopping over from one center A^- to another decreases sharply.

The mechanism of binding the donors D^+ and of the acceptors A^- and of production of neutral complexes should operate in a sufficiently wide temperature interval because of the random distribution of the impurities, and it can be apparently used not only in a gapless SMSC $Hg_{1-x}Mn_xTe$, but also for arbitrary zero-gap semiconductors of the HgTe type doped with acceptors. It is possible that it is precisely the formation of D^+–A^- neutral dipoles which explains the increase observed in $Hg_{1-x}Cd_xTe$ (Ref. 18) of the conductivity and of the Hall coefficient with decrease in temperature. We note that the conditions realized in p-type zero-gap semiconductors ($N_A > N_D$) are unique for the formation of neutral complexes D^+–A^- and for the associated increase in the electron mobility. Indeed, owing to the fact that in zero-gap semiconductors the acceptor level lies above the bottom of the conduction band, while the donors are ionized even as $T \to 0$, the electron density in the conduction band is finite and is practically independent of T at $\varepsilon_F = \varepsilon_A$ all the way to the lowest temperatures. In $Hg_{1-x}Cd_xTe$ and $Hg_{1-x}Mn_xTe$, in addition, at low temperatures usually $n_c \ll N_A + N_D$, and it is this which leads to the condition $d \ll \lambda$, which is necessary for the appearance of D^+–A^- pairs in the scattering as a unit (d is the characteristic dimension of the neutral complex and λ is the de Broglie wavelength of the electrons in the band Γ_8).

In ordinary not too strongly doped semiconductors, when the impurity levels are located in the forbidden gap, $\rho(T)$ is determined as $T \to 0$ by the strong (exponential) decrease of the electron density (in n-type samples) or hole density (in p-type samples). If, however, the sample is strongly doped and the electron (hole) density remains constant as $T \to 0$, it is impossible to satisfy the condition $d \ll \lambda$ in the case of weak compensation $n = N_D (p = N_A)$. This condition can be satisfied for strong compensation, but strong compensation leads to localization of the electrons in the impurity potential, and, as a consequence, to an exponential increase of $\rho(T)$ as $T \to 0$.

We note that for SMSC, including $Hg_{1-x}Mn_xTe$, there exists one more factor contributing to stabilization of the excess electron on the acceptor. This factor is connected with the presence, in the SMSC, of uncompensated magnetic moments, namely, in p-type SMSC is possible autolocalization of an excess electron on an acceptor, i.e., stabilization of the A^- state), inasmuch as at sufficiently low temperature the exchange interaction of this electron with the moments, say, of the Mn^{2+} ions contributes to polarization of the latter and to production at the A^- acceptor of a potential well of sufficient depth, which ensures localization of the excess electron.[15] Autolocalization of an excess electron on an acceptor in SMSC is similar to formation of a bound magnetic polaron in magnetic semiconductors.[5]

Regardless of whether the localization of the excess electron on the acceptor is due to polarization of the magnetic moments of Mn^{2+} or to Coulomb attraction of an ionized donor, in any case the stabilization of the A^- state in $Hg_{1-x}Mn_xTe$ contributes to formation of neutral D^+–A^- complexes, and this in turn, should lead to an increase of the mobility.

In experiment (Fig. 3), for samples with different densities N_D and N_A, an increase of the mobility μ by a factor 3.5–20 is observed when the temperature is lowered from 4.2 to 0.1 K, and notice must be taken of one empirical relation: the increase of the mobility manifests itself more strongly the larger the contribution to the electric conductivity by the impurity-band conduction, i.e., the larger the ratio σ_i/σ_c.

Such a correlation between the ratio $\mu(0.1)/\mu(4.2)$ and σ_i/σ_c can be explained within the framework of the model proposed above for the formation of D^+–A^- neutral complexes. In fact, as $T \to 0$ out of $N_{D^+} + N_{A^-} = n_c + 2N_{A^-} = N_{ch}$ charged centers, n_e positively charged centers remain after binding of N_{A^-} negative acceptors with the same number of ionized donors. If it is assumed that the mobility μ_c is determined mainly by the density of the charged scattering centers (e.g., in accordance with the Brooks-Herring formula), the anomalous growth of the mobility $\mu(0.1\ \text{K})/\mu(4.2\ \text{K})$ can be estimated in first-order approximation by the relation

$$\frac{\mu_c(0.1\ \text{K})}{\mu_c(4.2\ \text{K})} \approx \frac{N_{ch}(4.2\ \text{K})}{N_{ch}(0.1\ \text{K})} \approx \frac{n_c + 2N_{A^-}(4.2\ \text{K})}{n_c}. \qquad (9)$$

Comparison with the experimental data shows a good qualitative agreement. We note (see Fig. 3 and Table I) that as a result of the anomalous growth of $\mu_c(T)$ the Hall mobility in

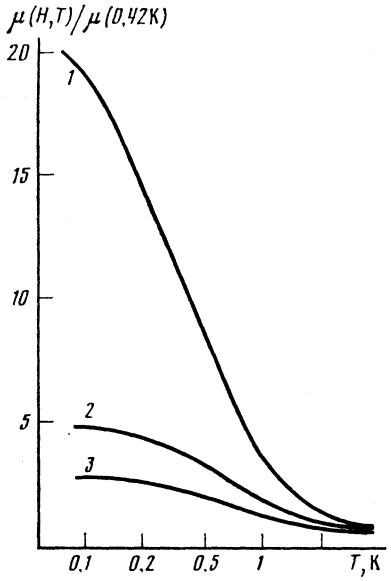

FIG. 4. Temperature dependences of the mobility $\mu(H, T)$ calculated from Eq. (7) for different magnetic fields: 1—$H = 50$ Oe, 2—200, 3—1000 for sample No. 10.

the investigated samples reaches values $(0.2–2)\times 10^6$ cm^2/V sec at $T = 0.1$ K.

In a magnetic field (Fig. 4) the increase of $\mu_c(T)$ is suppressed, and in a field $H > 5–10$ kOe, when the main contribution to the current transport is made by carriers of the impurity acceptor band, only a weak change of $R(T)$ and $\rho(T)$ is observed. This result confirms the assumption made above that the growth of the Hall mobility $\mu = R(H\to 0)\sigma(H = 0)$ is due to the change of the mobility μ_c of the electrons of the conduction band Γ_8.

TRANSITION OF ZERO-GAP SMSC $Hg_{1-x}Mn_xTe$ INTO SPIN GLASS.

The features of the interaction of the magnetic moments in semiconductors were considered by Bloembergen and Rowland,[19] who have shown that in semiconductors the indirect exchange on account of virtual transitions from the valence band to the conduction band between magnetic ions located at points R_i and R_j has an oscillatory dependence on the distance R_{ij}. However, the magnetic interaction in semiconductors differs from the spin density RKKY oscillations by a factor $\exp\{-(2m'\varepsilon_g)^{1/2}R_{ij}/\hbar\}$ (m' is the effective mass at the bottom of the conduction band and ε_g is the width of the forbidden band). Owing to the exponential damping of the magnetic interaction in semiconductors with $\varepsilon_g \neq 0$ it is difficult to expect a long-range indirect exchange, so that only interactions of neighboring magnetic moments is significant.[19] At the same time, for zero-gap semiconductors, including for the SMSC $Hg_{1-x}Mn_xTe$, the argument of the exponential is equal to zero, and shown by Bastard and Lewiner,[21] who used the Bloembergen-Rowland method for the concrete system $Hg_{1-x}Mn_xTe$, the effectiveness of the virtual interband transitions is large. Therefore, in $Hg_{1-x}Mn_xTe$ ($0 < x \leqslant 0.075$), despite the possibility of establishment of RKKY oscillations because the density of the free carriers is low, formation of spin glass is nevertheless possible.[6] On the other hand, in SMSC with low concentration of the magnetic component, the formation of spin glass can be due to the mechanism proposed in Refs. 22 and 23. The point is that the real distribution of the Mn atoms in $Hg_{1-x}Mn_xTe$ (Ref. 23) differs substantially, even at $x = 0.3$, from the randomly large relative content of the pairs, triads, and other "elementary" clusters, consisting of Mn atoms. Consequently, within the limits of each of such elementary cluster the condition for minimization of the magnetic interaction of the Mn ions imposes contradictory requirements on the optimal orientation of the magnetic moments, which in final analysis are "frozen in" randomly with decreasing temperature. Such a model of spin-glass formation is called frustration and, in contrast to the Bastard-Lewiner model, it is not directly connected with the character of the energy spectrum of the SMSC, including the value of the forbidden gap.

Thus, the transition of the zero-gap SMSC $Hg_{1-x}Mn_xTe$ into spin glass, observed in Ref. 6, can be due either to the effectiveness of the virtual interband transitions via $\varepsilon_g = 0$, or to the "cluster" mechanism.[22,23] It was therefore of interest to investigate this transition in greater detail. To this end, we investigated samples of the zero-gap SMSC $Hg_{1-x}Mn_xTe$ with Mn densities different from those used in Refs. 6 and 23, and with different values of the ratio σ_i/σ_c. In addition to the $\chi(T)$ dependences we investigated also the temperature dependence of the Hall coefficient $R_{H\to 0}(T)$.

First (see Figs. 6 and 7 below), just as in Ref. 6, at sufficiently low temperatures we observed anomalies of $\chi(T)$ and $R_{H\to 0}(T)$, which are typical[24,25] of the transition into spin glass. These anomalies manifest themselves most clearly in samples with a dominant contribution to the electric conductivity σ from the impurity-band carriers with $\sigma_i \gtrsim \sigma_c$. A feature of such samples is the increase of the resistivity with decreasing temperature (Fig. 5), whereas in the case $\sigma_c \geqslant \sigma_i$ the value of ρ decreases.

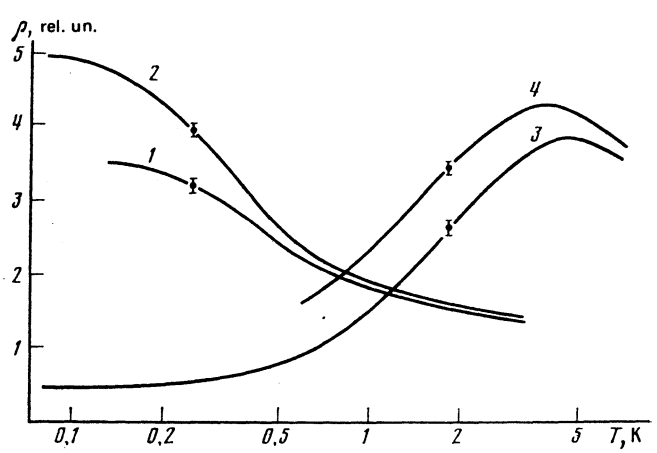

FIG. 5. Temperature dependences of the resistivity $\rho(T)$ (curves 2 and 3) and of the magnetoresistivity $\rho(H, T)$ at $H = 500$ Oe (curves 1 and 4) for samples 11 ($\sigma_i > \sigma_c$, curves 1 and 2) and No. 9 ($\sigma_i < \sigma_c$, curves 3 and 4).

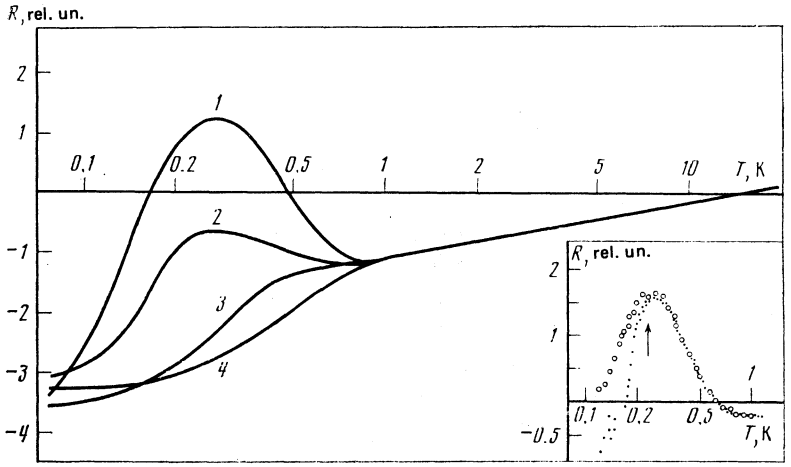

FIG. 6. Temperature dependences of the Hall coefficient $R(T)$, measured for sample No. 11 in different fields: 1—50 Oe, 2—100, 3—200, 4—500. The inset shows the temperature dependence of $R(T)$ in a 50-Oe field. The switching of H was carried out at $T > T_{SG}$ (light circles) and $T < T_{SG}$ (dark circles). The arrow marks the temperature T_{SG} determined from the position of the kink on the $\chi(T)$ curve.

The Hall coefficient (Fig. 6, curve 4) of single-crystal $Hg_{1-x}Mn_xTe$ changes little in the region $T < 10$ K with decreasing T, down to temperatures at which a local maximum appears on the $R_{H\to 0}(T)$ curves. The amplitude of this maximum is larger the weaker the magnetic field in which the quantity R is measured.[26] In a magnetic field $H > 200$ Oe, this local maximum is completely suppressed.

The anomalies of the Hall effect are accompanied by the appearance of a characteristic kink on the plots of $\chi(T)$ against temperature at $T = T_{SG}$ (Fig. 7). With increasing external magnetic field (Fig. 7, curves 2, 3, 5) the temperature T_{SG} decreases, and the amplitude of the peak at $T = T_{SG}$ on the $\chi(T)$ curve decreases. We note also that the form of the $R_{H\to 0}(T)$ curve depends substantially on the temperature at which the switching of the magnetic field H was carried out, in the region $T < T_{SG}$ or at $T > T_{SG}$ (see the inset of Fig. 6).

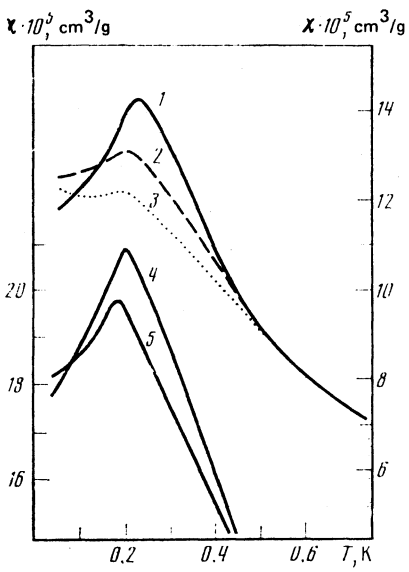

FIG. 7. Temperature dependences of the magnetic susceptibility $\chi(T)$ for sample No. 11 (right scale, curve 1—$H = 0.5$ Oe, 2—50, 3—100) and for sample No. 13 (left scale, curve 4—$H = 0.5$ Oe, 5—50).

The reason for this effect is that in the former case the locally frozen-in magnetic moments of Mn^{2+} cannot follow completely the change of the direction of the vector **H**.

We shall dwell now in somewhat greater detail on the T–x phase diagram for the SMSC $Hg_{1-x}Mn_xTe$ (Fig. 8). The spin-glass phase which is produced[22,23] at $0.17 = x_c \leqslant x < 0.4$ (x_c is the percolation threshold) is due to direct exchange interaction of the neighboring Mn ions. As established in the present paper, the SMSC $Hg_{1-x}Mn_xTe$, being zero-gap semiconductors, also go over into spin glass at $0 < x \leqslant 0.075$. Inasmuch as in this case the intermediate compositions $0.075 < x < 0.17$ were not investigated (for lack of high-grade $Hg_{1-x}Mn_xTe$ single crystals), it is perfectly natural to raise the question of how to draw the P–S (paramagnet–spin glass) boundary on the (T–x) diagram: by regarding the region S as consisting of two parts (the dashed lines in Fig. 8) or of one part (dotted line in Fig. 8).

In the first case, the P–S transition is due to the Bastard-Lewiner mechanism, and in the second to the cluster mechanism.[22,23] To determine the role of each of these mechanisms

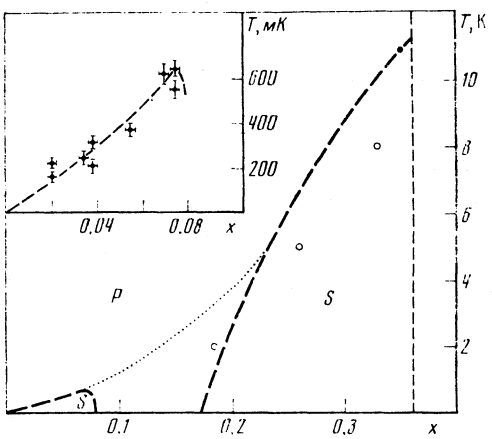

FIG. 8. (T–x) phase diagram of the magnetic state of $Hg_{1-x}Mn_xTe$. Region P—paramagnetic phase, S—spin glass. Dark circles—from Ref. 22, light circles—from Ref. 22 for the SMSC $Hg_{1-x}Mn_xSe$. The inset shows the data of the present paper.

in the formation of spin glass in the zero-gap SMSC $Hg_{1-x}Mn_xTe$ and to assess the possibility of existence of a correlation between the size of the gap ε_g and the transition temperature T_{SG}, we have performed in the present study a preliminary set of experiments at a pressure p in which the shift of the temperature T_{SG}, determined from the position of the maximum on the $R_{H\to 0}(T)$ curve in the region $p \lesssim 15$ kbar, was determined for samples 11 and 13 under the action of hydrostatic compression.

INFLUENCE OF PRESSURE ON THE ZERO-GAP SMSC IN THE SPIN-GLASS PHASE

In zero-gap semiconductors of the HgTe type hydrostatic compression shifts the Γ_6 level upward in energy scale relative to Γ_8. Therefore the gap $\varepsilon_g = \varepsilon(\Gamma_8) - \varepsilon(\Gamma_6)$ first decreases, and then at $p = p_i$ the terms Γ_6 and Γ_8 are inverted (ε_g vanishes) and in the region $p > p_i$ the direct gap $\varepsilon_g = \varepsilon(\Gamma_6) - \varepsilon(\Gamma_8)$ opens up at a rate $\partial\varepsilon_g/\partial p = 10$–$15$ meV/kbar.[27] Thus, by using the pressure as the external parameter that varies the energy spectrum, it is possible to transform the SMSC $Hg_{1-x}Mn_xTe$ into a semiconductor of the InSb type with a direct gap at the point Γ of the Brillouin zone.

Single-crystal samples of $Hg_{0.966}Mn_{0.034}Te$ (No. 11) and $Hg_{0.98}Mn_{0.02}Te$ (No. 13), for which at $p = 0$ in a field $H < 200$ Oe, the plot of $R_{H\to 0}(T)$ has a maximum connected with the P–S transition, were mounted respectively across and along the high-pressure chamber channel,[9] which was secured with the aid of a special cold finger (a red-copper yoke) on the dissolution chamber of the refrigerator. The procedure of the galvanomagnetic investigations under pressure at infralow temperatures is described in detail in Ref. 28.

At pressures $P = 2.5$ kbar; $p_2 = 5.3$; $p_3 = 7.6$; $p_4 = 12.0$ on sample #1 and $p_1 = 4.3$ kbar; $p_2 = 10.0$; $p_3 = 10.8$; $p_4 = 14.7$ on sample #13, we measured the temperature dependences of $R_{H\to 0}(T)$ and $\rho(T)$ in the temperature region up to ~ 100 mK. At pressures p_1–p_3 one observes on the $R_{H\to 0}(T)$ a maximum, and the temperature corresponding to this maximum depends little on the pressure. No local maxima were observed at $p = p_4$. The resistivity ρ constantly decreased when the pressure was increased from p_1 to p_3, and at $p = p_4$ its value again increased. This behavior of ρ is evidence of opening up of a direct gap, induced by pressure, in the SMSC $Hg_{1-x}Mn_xTe$.

On the basis of the analysis of the $R_{H\to 0}(T)$ variation under pressure it is apparently possible to state that the P–S transition of the SMSC $Hg_{1-x}Mn_xTe$ depends on the structure of the energy spectrum. In fact, so long as this SMSC remains a zero-gap semiconductor, the $R_{H\to 0}(T)$ curve has a maximum that points to a P–S transition. As soon as the Γ_6 and Γ_8 bands are inverted ($p > p_i$) the P–S transition vanishes, at least in the region $T \geqslant 150$ mK.

Thus, the existence of a spin-glass phase is apparently due to the long-range indirect exchange interaction of the Mn^{2+} ions, via a mechanism of virtual interband transitions through the zero gap in the gapless SMSC $Hg_{1-x}Mn_xTe$,[20,21] and not via frustration which does not depend on ε_g. The mechanism of the virtual transitions becomes ineffective at $p > p_i$, when the exchange interaction of the Mn ions becomes short-range as a result of the exponential dependence on the gap ε_g.

Preliminary data obtained under pressure give grounds for assuming that on the (T–x) phase diagram there exist two regions S (see Fig. 8). Nonetheless, if we take into consideration the possibility of cluster formation at small x (Ref. 23), as well as the latest data,[29] in which a smeared transition of the wide-band SMSC $Cd_{1-x}Mn_xTe$ ($x = 0.01$ and $x = 0.05$) to the spin-glass phase via the cluster mechanism[22,23] was observed in the temperature region $0.01 \lesssim T \lesssim 0.1$ K, it is impossible to reject completely the probable existence of a unified region S on the phase diagram (the dotted line in Fig. 8) without studying the intermediate compositions $0.075 < x < 0.17$ and without detailed experiments under pressure.

CONCLUSION

In the investigation of the electric and magnetic properties of the p-type zero-gap SMSC $Hg_{1-x}Mn_xTe$ it was established that: 1) when the temperature is lowered a substantial increase is observed in the mobility of the electrons of the conduction band. 2) This effect correlates with the ratio σ_i/σ_c and it is explained by the decrease, at low temperatures, of the concentration N_{ch} of the charged centers on account of binding of the positive donors D^+ and the acceptors A^-, which capture the excess electron, into neutral D^+–A^- complexes. 3) The zero-gap SMSC $Hg_{1-x}Mn_xTe$ go over at $T = T_{SG}$ into the spin-glass phase. The transition is most distinctly observed in samples with $\sigma_i > \sigma_c$ and is revealed by the presence of a local maximum on the $R_{H\to 0}(T)$ curve at the same temperatures at which a kink is observed on the $\chi(T)$ plot. 4) The temperature T_{SG} of the samples $Hg_{0.966}Mn_{0.034}Te$ and $Hg_{0.98}Mn_{0.02}Te$ is strongly decreased by a pressure $p \gtrsim p_i$ corresponding to inversion of the bands Γ_8 and Γ_6 and to a transition to a normal spectrum with $\varepsilon_g > 0$, thus attesting to the effectiveness of virtual interband transitions in zero-gap SMSC $Hg_{1-x}Mn_xTe$; these transitions can lead to establishment of a long-range oscillating exchange interaction between the Mn^{2+} ions at $0 < x \leqslant 0.075$.

In conclusion, the authors are sincerely grateful to A. A. Abrikosov, B. L. Gel'mont and B. B. Ponikarov for discussion of the results, to A. N. Taldenkov for help with the measurements at infralow temperatures, to V. Giriat for supplying the high-grade single-crystal $Hg_{1-x}Mn_xTe$ samples.

[1)]Institute of Metal Physics, Urals Scientific Center, USSR Academy of Sciences, Sverdlovsk.

[1]R. R. Galazka, 14th Int. Conf. Semicond. Inst. Phys. Conf. Ser. **43**, 133 (1979).
[2]G. Bastard, G. Rigaux, Y. Guldner, *et al.*, Phys. Rev. **B24**, 1961 (1981).
[3]M. Dobrowolska, W. Dobrowolski, M. Otto, T. Dietl, and R. R. Galazka, Proc. 15th Int. Conf. Semicond. J. Phys. Soc. Jpn **49**, Suppl. A, 815 (1980).
[4]J. A. Gay, *ibid.* p. 797.
[5]P. Kuivalainen, J. Sinkkonen, K. Kaski, and T. Stubb, Phys. Stat. Sol. (b)

94, 181 (1979).
[6]N. B. Brandt, V. V. Moshchalkov, L. Skrbek, A. N. Taldenkov, and S. M. Chudinov, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 326 (1981) [JETP Lett. **35**, 401 (1981).
[7]N. B. Brandt, I. M. Tsidil'kovskiĭ, V. V. Moshchalkov, B. B. Ponikarov, L. Skrbek, *et al.*, Fiz. Nizk, Temp. No. 6 (1982) [Sov. J. Low Temp. Phys. No. 6 (1982)].
[8]O. V. Lounsmaa, Experimental Principles and Methods Below One Degree Kelvin, Academic, 1974.
[9]E. S. Itskevich, Prib. Tekh. Eksp. No. 4, 148 (1963).
[10]B. L. Gel'mont and M. I. D'yakonov, Zh. Eksp. Teor. Fiz. **62**, 713 (1972) [Sov. Phys. JETP **35**, 377 (1972)].
[11]A. B. Davydov, V. V. Ponikarov, and L. M. Tsidil'kovskiĭ, Phys. Stat. Sol. (b). 101, 127 (1980).
[12]B. B. Ponikarov, Candidate's dissertation, Sverdlovsk, 1981.
[13]A. B. Davydov, B. B. Ponikarov, and I. M. Tsidil'kovskiĭ, Fiz. Tekh. Poluprov. **15**, 881 (1981) [Sov. Phys. Semicond. **15**, 504 (1981)].
[14]R. T. Delves, Proc. Phys. Soc. 87, 809 (1966).
[15]A. Mycielski, J. Mycielski, C. Rigaux, *et al.*, Ref. 3, p. 811.
[16]N. F. Mott, Metal-Insulator Transitions, Barnes & Noble, 1974.
[17]V. Radhakrishnan and P. C. Sharma, Phys. Rev. **B23**, 3004 (1981).
[18]D. G. Arapov, F. I. Akhmedov, A. B. Davydov, and I. M. Tsidil'kovskiĭ, Fiz. Tekh. Poluprov. **16**, 54 (1982) [Sov. Phys. Semicond. **16** (1982)].
[19]N. Bloembergen and T. J. Rowland, Phys. Rev. **97**, 1679 (1955).
[20]G. Bastard and C. Lewiner, Phys. Rev. **20**, 4256 (1979).
[21]G. Bastard and C. Lewiner, J. Phys. Lett. **40**, L177 (1979).
[22]G. D. Khattak, C. D. Amarasekara, S. Nagata, R. R. Galazka, and P. H. Keesom, Phys. Rev. **B23**, 3553 (1981).
[23]S. Nagata, R. R. Galazka, D. P. Mullin, H. Akbazadeh, G. D. Khattak, *et al.* Phys. Rev. **B22**, 3331 (1980).
[24]S. P. McAllister, J. de Phys. **39**, C6-893 (1978).
[25]V. Canella and J. A. Mydosh, Phys. Rev. **B6**, 4220 (1972).
[26]B. H. Verbeer, G. J. Niewenhuys, H. Stoker, and J. A. Mydosh, J. de Phys. **39**, C6, 917 (1978).
[27]I. M. Tsidil'kovskiĭ, Zonnaya struktura poluprovodnikov (Band Structure of Semiconductors), Nauka, 1979.
[28]S. M. Chudinov, Doctoral dissertation, Moscow State Univ., 1979.
[29]M. A. Novak, S. Oseroff, and O. G. Symko, Physica **107B**, 313 (1981).

Translated by J. G. Adashko