Energy spectrum of the semimagnetic zero-gap semiconductor $Hg_{1-x}Mn_xTe$ in a magnetic field

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The method of tunnel spectroscopy in a magnetic field was used to investigate the energy spectrum of the conduction band of the zero-gap semiconductor $Hg_{1-x}Mn_xTe$ ($0.005 \leqslant x \leqslant 0.04$) in the temperature range 1.8–40 K. It is shown that at low temperatures the exchange interaction of the free electrons with the magnetic moments of the matrix ions alters substantially the position of the *a*- and *b*-series of the Landau levels. A comparison is made with the theoretical calculation in the modified Pidgeon-Brown model. The field and temperature dependences of the parameter A, which describes the contribution of the exchange interaction, are determined, as is also the quantity $N_0\beta = 1.6$–1.8 eV.

INTRODUCTION

In semimagnetic semiconductors such as $Hg_{1-x}Mn_xTe$, in contrast to the solid solution $Hg_{1-x}Cd_xTe$, and increase of x not only changes the band gap and the effective mass, but also restructures substantially the energy spectrum in a magnetic field. This restructuring is due to exchange interaction between the band carriers and the localized magnetic moments of the Mn^{++} ions.[1] Allowance for this interaction shifts the energy positions of the Landau levels by an amount proportional to the magnetization, i.e., $\langle S_z \rangle$.[2,3] The energy increment has a different sign for different spin states, so that the spin splitting $g\mu_B H$ changes substantially (by several times), whereas the cyclotron energy $\hbar\omega$ is determined mainly by the usual band parameters. Since the magnetization depends on the temperature (T) the positions of the Landau levels and the value of the effective g-factor turn out to depend on T, so that with rising temperature, as $\langle S_z \rangle \to 0$, the spectrum of a semimagnetic semiconductor comes close to the spectrum of an ordinary semiconductor having the same band parameters. Thus, to study the contribution of the exchange interaction to the spectrum of a semimagnetic semiconductor in a magnetic field it is expedient to investigate not only samples with smoothly varying x, but also materials of fixed composition in a wide range of temperatures. This permits in fact the transition of the spectrum in a magnetic field to the normal state to be tracked and the singularities connected with the presence of localized magnetic moments to be unambiguously separated.

The oscillations of the interband ($\Gamma_6 \to \Gamma_8$) magnetoabsorption in $Hg_{1-x}Mn_xTe$ samples with smooth variation of the composition ($0.001 \leqslant x \leqslant 0.015$) were investigated in Refs. 2 and 4. It was shown that the exchange interaction alters substantially the spin splitting of the Landau levels of the conduction band Γ_8 and of the valence band Γ_6. Unfortunately, the measurements were made at only two temperatures, 4.2 and 2 K, and the temperature dependences of the observed effects in a wide range of temperatures were not investigated.

In Refs. 5–7 are reported results of measurements of Shubnikov–de Haas oscillations for certain compositions of zero-gap $Hg_{1-x}Mn_xTe$. It is known that to investigate the energy spectrum by this method in an appreciable energy band the measurements must be made on an assembly of samples of like composition but with different free-carrier densities, a task of some practical difficulty. This circumstance and the lack of detailed temperature measurements prevented the authors of Refs. 5–7 from obtaining convincing results.

The parameter $N_0\beta$ that describes the exchange interaction of the carriers of band Γ_8 with localized spins[2,3] was found in these studies to equal 0.65 eV,[8] 0.9 eV,[7] 1.2–1.4 eV,[5] 1.4 eV,[3] and 1.5 ev.[2] So large a spread in the values of this basic parameter points to a need for further investigations of the energy spectrum of the semimagnetic semiconductor $Hg_{1-x}Mn_xTe$.

Of great potential for the investigation of the electron spectra of semiconductors, including zero-gap ones, is tunnel spectroscopy in a magnetic field.[9–11] This method ensures high accuracy[12] and gets around many difficulties encountered in the traditional procedures; it is therefore natural to use it also for the investigation of semimagnetic semiconductors. We report here the results of an investigation, by this method, of the influence of exchange interaction on the spectrum of the conduction band Γ_8 of the zero-gap $Hg_{1-x}Mn_xTe$ in the temperature interval 1.8–40 K.

SAMPLES AND EXPERIMENTAL PROCEDURE

The investigations were performed on samples of the zero-gap semiconductor $p - Hg_{1-x}Mn_xTe$ with $0.005 \leqslant x \leqslant 0.04$ in magnetic fields up to 55 kOe. The composition was determined from the value of the energy gap $\varepsilon_g = \varepsilon(\Gamma_6) - \varepsilon(\Gamma_8)$ obtained by the tunnel spectroscopy method, in analogy with the procedure used in Ref. 11. The dependence of ε_g on the composition was the same as in Ref. 1.

The sample specifications were verified by measuring the dependences of the Hall effect and of the transverse mag-

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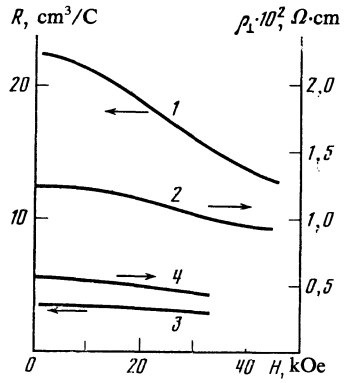

FIG. 1. Dependences of the Hall constant (1, 3) and of the tranverse magnetoresistance (2, 4) on the magnetic field at $T = 4.2$ K for samples No. 1 (1, 2) and No. 2 (3, 4).

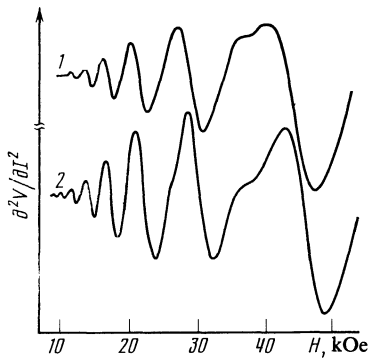

FIG. 3. Dependences of $\partial^2 V/\partial I^2$ on H for sample No. 1 in the orientation $\mathbf{H}\|\mathbf{I}$ at a bias voltage $V = 50$ mV and at different temperatures: 1—4.2 K; 2—1.8 K.

netoresistance ($\rho_\perp$) on the magnetic field at 4.2 K. The hall constant (R) of all the investigated samples is positive, starting with the very lowest magnetic field. The absence of an electron contribution to the Hall constant and the large value of $\mu_H = R\sigma$ (600–2500 cm^2/V·sec) are evidence that the acceptor band in our samples merged with the valence band, the Fermi level lies in the valence band (below the bottom of the conduction band), and the conduction is by the holes of the valence band. This conclusion concerning the location of the Fermi level is confirmed also by the tunnel-spectroscopy results which will be given below. Figure 1 shows typical plots of the Hall constant and of the transverse magnetoresistance vs the magnetic field. It can be seen that the Hall constant decreases with increasing field, while the conductivity increases. This behavior, in our opinion, is due to singularities of the spectrum of the heavy-hole band of a semimagnetic semiconductor in a magnetic field.[14] In this case the hole density $p = N_A - N_D$ must be determined from the Hall constant as $H \to 0$: $p = 1/eR_{H\to 0}$. The hole density determined in this manner varied in the investigated samples in the range $2\cdot10^{17} - 2\cdot10^{18}$ cm^{-3}.

The tunnel junctions were prepared by the procedure described in Ref. 11. A typical resistance of a tunnel junction in a 1.5 kOe field (after destruction of the superconductivity of the lead) is, at zero bias, 5–100 Ω. Measurements of $\partial V/\partial I$ as well as of the bias voltage (V) applied to the tunnel junction were made by a four-probe method.

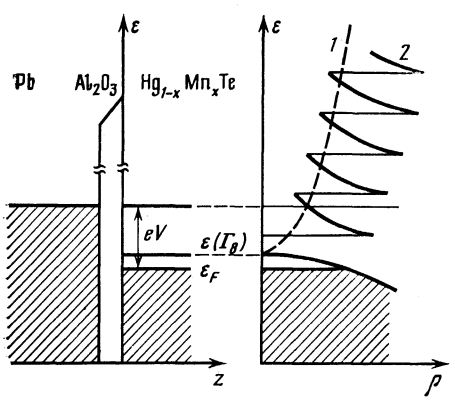

FIG. 2. Energy diagram of tunnel junction $p - Hg_{1-x}Mn_xTe - Al_2O_3 - Pb$ at a voltage $V > 0$ (the sign of the applied voltage corresponds to the sign of the potential on the semiconductor electrode). On the right is shown schematically the density of state in the semiconductor without a magnetic field (1) and in a magnetic field that is quantizing for the electrons (2).

TUNNEL-CONDUCTIVITY OSCILLATIONS IN A MAGNETIC FIELD

Figure 2 shows the energy diagram of a $p - Hg_{1-x}Mn_xTe - Al_2O_3 - Pb$ tunnel junction. A quantizing magnetic field H produces state-density maxima due to the quantization of the semiconductor spectrum. This leads to the appearance of oscillations in the dependences of $\partial V/\partial I$ and $\partial^2 V/\partial I^2$ on the applied bias at fixed H, as well as on H at fixed V (Fig. 3). Such oscillations, due to quantization of the conduction-band spectrum, were observed for all the investigated samples, but in the investigated range of magnetic fields we did not succeed in observing oscillations connected with the heavy-hole band. The measurements were performed both at a magnetic-field orientation $\mathbf{H}\|\mathbf{I}$ (the magnetic field is perpendicualr to the plane of the tunnel junction) and at $\mathbf{H}\perp\mathbf{I}$ (the magnetic field lies in the plane of the tunnel junction).

In sample No. 1 ($x = 0.025$; $N_A - N_D \approx 3\cdot10^{17}$ cm^{-3}), at low temperatures, in fields stronger than 35 kOe, and at orientation $\mathbf{H}\|\mathbf{I}$, we observed spin splitting of the oscillation maxima (Fig. 3). This sample was therefore used for the most detailed measurements of the temperature dependences of the tunnel-conductivity oscillations. We investigated in equal detail one of the samples in which no spin splitting was observed in the entire range of temperature and magnetic fields (sample No. 2, $x = 0.005$; $N_A - N_D \approx 2\cdot10^{18}$ cm^{-3}).

By measuring the dependences of the positions of the oscillation maxima on the magnetic field and on the voltage applied to the tunnel junction it is possible, in analogy with Refs. 9 and 11, to construct a level network that describes accurately, apart from the phase of the oscillations,[11] the energy shift of the Landau levels with increasing magnetic field. The results of such measurements for two magnetic-field orientations ($\mathbf{H}\|\mathbf{I}$ and $\mathbf{H}\perp\mathbf{I}$) are shown in Fig. 4 for sample No. 1 at $T = 1.8$ K. It can be seen that at $\mathbf{H}\|\mathbf{I}$ in strong magnetic fields a spin splitting of the Landau levels is observed in the entire investigated energy range, whereas at the other magnetic-field orientation ($\mathbf{H}\perp\mathbf{I}$), just as in the zero-

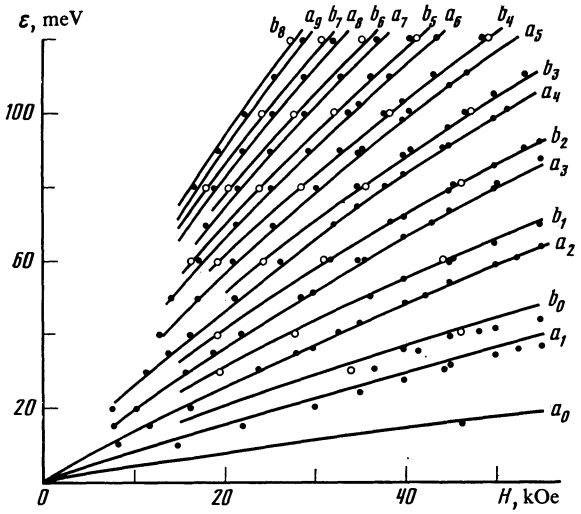

FIG. 4. Location of the oscillation maxima for sample No. 1 at $T = 1.8$ K: ●—H‖I; ○—H⊥I. Solid curves—calculation, in accord with REf. 2, using the parameters indicated in the text.

gap $Hg_{1-x}Cd_xTe$ (Refs. 11 and 13), no spin splitting is observed, and the oscillation maxima are connected with tunneling only in one set of spin sublevels. It is clear from Fig. 2 that by extrapolating the dependence of the Landau-level positions on the magnetic field to $H = 0$ we can determine the bias V_0 at which the electrons begin to tunnel from the Fermi level to the bottom of the conduction band of the semiconductor. Inasmuch as at $V = 0$ the Fermi levels of the metal and semiconductor coincide, the bias V_0 determines the semiconductor Fermi energy $\varepsilon_F = -eV_0$ reckoned from the bottom of the conduction band. In the extrapolation, the experimental relations were described by smooth curves of the form

$$H_n = A_n(V - V_0) + B_n(V - V_0)^2,$$

and V_0 was determined from the minimum of the mean square deflection of the experimental points from the calculated curves. This analytic expression describes well not only the Landau levels of a "Kane" semiconductor,[13] but, as shown by a special check, also the theoretical levels calculated with allowance for the exchange interaction[2]; the error of the extrapolation point was less than 0.5 meV. The experimental values of ε_F obtained in this manner have a somewhat larger error, ± (2–3) meV, and are negative for all samples, i.e., the Fermi level lies in the valence band, thus confirming the interpretation of the results of the measurements of the Hall effect. The values of the Fermi energy range from − 3 meV (for sample No. 1) to − 10 meV (for sample No. 2) and agree within the limits of errors with the values calculated from the hole density for a parabolic band with effective mass $m_n = 0.5\, m_0$.

From the set of levels shown in Fig. 4 we can determine not only the Fermi energy but, just as in $Hg_{1-x}Cd_xTe$ (Ref. 11), also the dependencies of the energy and of the effective mass on the quasimomentum, notwithstanding the contribution of the exchange interaction to the positions of the Fermi levels of the semimagnetic semiconductor. The reason is that the difference of the exchange-energy correction to the location of neighboring levels with the same spin direction is small compared with the cyclotron energy. The Landau levels for each spin series at a fixed energy level remain practically periodic in the recirpocal magnetic field, the value of the quasimomentum at the energy $\varepsilon = \varepsilon_F + eV$ is determined, with error not greater than 3%, from the formula[11]

$$k_{\varepsilon_F + eV} = 2e/c\hbar\Delta(1/H)_V, \tag{1}$$

while the effective mass at energy $\xi = \varepsilon_F + \frac{1}{2}(eV_n + eV_{n+1})$ is determined with error not greater than 5 % from the formula 11

$$m_e = \hbar eH/(eV_{n+1} - eV_n)c, \tag{2}$$

where $\Delta(1/H)_V$ is the period of the oscillations in the reciprocal magnetic field at a bias V; V_n and V_{n+1} are the biases at which oscillation maxima corresponding to neighboring Landau levels of one spin series are observed in a field H.

Figure 5 shows the experimental energy dependences of the electron effective mass, obtained from measurements at different orientations of the magnetic field and temperatures. As expected, the cyclotron effective mass does not depend on the field orientation or temperature (i.e., on the exchange interaction). To describe these dependencies we used the Kane three-band model with a spin-orbit splitting $\Delta = \varepsilon(\Gamma_8) - \varepsilon(\Gamma_7) = 1$ eV.[15] The best agreement between theory and experiment is reached for a momentum operator matrix element $p = 7.8 \times 10^{-8}$ eV·cm and $\varepsilon_g = -170$ meV for sample No. 1 and − 270 meV for sample No. 2. The theoretical curves with these parameters are also shown in Fig. 5. In the reduction we disregarded the contribution of the remote bands, since its effect on the dispersion law of the conduction band Γ_8 is small and, in addition, the γ parameters that describe the magnitude of this distribution are not known well enough even for HgTe (see, e.g., Refs. 16 and 17), in which, owing to the large ε_g, it should be the most sub-

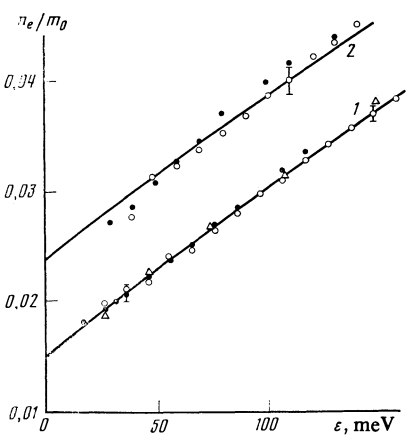

FIG. 5. Energy dependence of the electron effective mass for samples No. 1 (1) and No. 2 (2). Points—experimental data obtained from measurements at orientations H‖I (●) and H⊥I (○, △) and temperatures 4.2 K (○, ●) and 23 K (△). Solid curves—calculation in three-band Kane model with $P = 7.8$ eV·cm and $\varepsilon_g = -170$ meV (for sample No. 1) and $\varepsilon_g = 270$ meV (for sample No. 2).

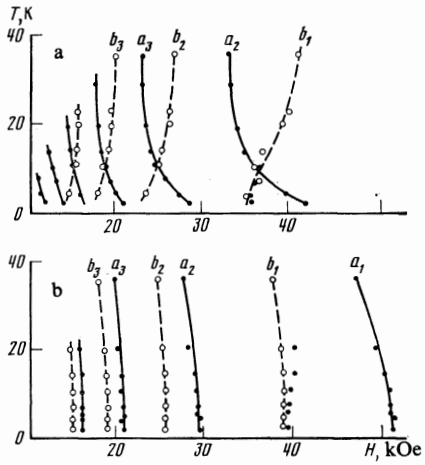

FIG. 6. Experimental dependence of the location of the oscillation maxima on the temperature for samples $Hg_{0.975}Mn_{0.255}Te$ (a) and $Hg_{0.93}Cd_{0.07}Te$ (b) at energy $\varepsilon = 50$ meV: ●—**H**‖**I**; ○—**H**⊥**I**.

stantial.

Using the dependence, taken from Ref. 1, of the energy gap ε_g on the composition, we determined the values of x given above for the samples investigated by us. The error in the determination of x is $\Delta x \approx 0.002$–0.003 and is due both to the inaccuracy of ε_g and to the scatter of the experimental points in the dependence of ε_g on x, given in Ref. 1.

It must be noted that the results described above, obtained at a single temperature, are qualitatively practically the same as for the nonmagnetic zero-gap semiconductor[11] $Hg_{1-x}Cd_xTe$. Only the energy dependence of the g factor, if the latter is determined from the distance between the nearest levels (see Fig. 4), will differ substantially from the Kane dependence. This is not surprising. Indeed, as already noted below, the peculiarities of a semimagnetic semiconductor should manifest themselves most strongly in the temperature dependences of the Landau-level positions. It is seen even from Fig. 3 that when the temperature changes from 1.8 to 4.2 K the splitting of the oscillation maxima changes. Figure 6a shows the temperature dependence of the positions of the oscillations in the entire investigated temperature range at an energy 50 meV reckoned from the bottom of the conduction band, for sample No. 1, both for **H**‖**I** and **H**⊥**I**.

To facilitate the interpretation of the observed dependences and to make it more reliable, we carried out a comparison with the analogous results obtained for $Hg_{1-x}Cd_xTe$, which has close band parameters in the same temperature interval (Fig. 6b). It can be seen from these figures that spin splitting of the oscillations is observed both in $Hg_{1-x}Mn_xTe$ and in $Hg_{1-x}Cd_xTe$ at low temperature and at the orientation **H**‖**I** in strong fields, and that the maxima at **H**⊥**I** coincide in location with one of the components at **H**‖**I**. With increasing temperature, this component, which is of lower amplitude, can no longer be resolved in both materials, and at **H**‖**I** only one maximum is left and its location is determined by another spin sublevel. The fundamental difference between the cited temperature dependences in $Hg_{1-x}Mn_xTe$ and $Hg_{1-x}Cd_xTe$ is that for $Hg_{1-x}Cd_xTe$ the positions of the maxima are practically independent of temperature (the small shift towards weaker fields with increasing T is due to the temperature dependence of ε_g), whereas for $Hg_{1-x}Mn_xTe$ the maxima at **H**‖**I** and **H**⊥**I** shift in opposite directions, and their location coincides at $T \approx 10$ K.

The interpretation of levels in $Hg_{1-x}Cd_xTe$ can be easily carried out by compariosn with the calculation in the three-band Kane model[11] (or, equivalently, in the Pidgeon-Brown model[18] with zero γ parameters). The levels on Fig. 6b are in fact designated in accordance with such an interpretation. It can be seen that the tunneling is into the states of the series b for the orientation **H**⊥**I** at all temperatures, and into the states of the series a for the orientation **H**‖**I** at high temperatures. Obviously, at high temperatures, when the contribution of the exchange interaction is small, the oscillation maxima in $Hg_{1-x}Mn_xTe$ can be interpreted by analogy with $Hg_{1-x}Cd_xTe$. It is seen from Fig. 6a that with decreasing temperature, i.e., with increasing contribution of the exchange interaction, the levels b_n and a_{n+1} move counter to one another, at $T \approx 10$ K their positions coincide, and with further lowering of the temperature they change places in such a way that the level b_n is higher in energy than level a_{n+1}.

This behavior of the Landau levels should lead to an anomalous temperature dependence of the oscillation amplitude, no longer described by the standard monotonic dependence determined only by the effective mass. Indeed, from Fig. 7, which shows the experimental temperature dependences of the oscillation amplitude for sample No. 1 at two orientations of the magnetic field, it can be seen that for **H**⊥**I** at $T \approx 10$ K, when the levels b_n and a_{n+1} coincide (Fig. 6), a maximum is observed, even for those energies and magnetic fields ($\varepsilon = 100$ keV, $H = 31$ kOe in Fig. 7b) at which no split-

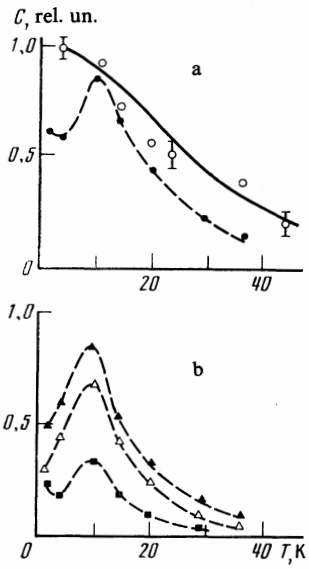

FIG. 7. Temperature dependence of the oscillation amplitude for sample No. 1 at energy 50 (a) and 100 meV (b): ○—**H**⊥**I**; the remaining points—**H**‖**I**: H in kOe: ○, ●, △—40; ▲—45; ■—31. Solid curve—theoretical dependence calculated in accord with Eq. (3) with $m_e/m_0 = 0.023$ (see Fig. 5).

ting could be discerened on the $(\partial^2 V/\partial I^2)(H)$ oscillation curve. In the orientation $\mathbf{H}\perp\mathbf{I}$, when the tunneling at all temperatures is only to states of the b series, the temperature dependence of the amplitude C is monotonic (Fig. 7a) and is described by the usual expression:

$$C(T)=C_0 T/\mathrm{sh}\,\frac{2\pi^2 k_B T}{\hbar\omega_c} \tag{3}$$

with the experimentally determined effective mass (Fig. 5). It must be noted that similar relations, obtained for $Hg_{1-x}Cd_xTe$ with nearly the same band parametes, are monotonic both for $\mathbf{H}\perp\mathbf{I}$ and $\mathbf{H}\|\mathbf{I}$, notwithstanding the spin splitting observed at $\mathbf{H}\|\mathbf{I}$ for the oscillation maxima.

Figure 8 shows the temperature dependence of the oscillation location for sample No. 2. For this composition ($x = 0.005$) the correction due to the exchange interaction is such that at low temperature the distance between levels b_n and a_{n+1} is small, and no splitting can be observed on the oscillation maxima. The behavior of the levels as the temperature is raised is qualitatively the same as in sample No. 1, but the temperature at which the positions of the levels b_n and a_{n+1} coincide is lower for sample No. 2, namely $T = 4$–6 K.

DETERMINATION OF THE EXCHANGE-INTERACTION PARAMETERS

It is known that the energy spectrum in the magnetic field of II–VI semiconductors and their solid solutions is well described at the point Γ in the Pidgeon-Brown model,[18] and the location of the Landau levels is determined by eigenvalues of an 8×8 matrix that breaks up, when the inversion asymmetry is neglected, into two 4×4 matrices, D_a and D_b, for the a- and b–series respectively. As shown in Refs. 2 and 3, to take into account the exchange interaction of the band electrons with the localized magnetic moments, it is necessary to add to the matrices D_a and D_b the matrices $\bar{D}_a$ and $\bar{D}_b$:

$$\bar{D}_a=\begin{vmatrix} 3Ar & 0 & 0 & 0\\ 0 & 3A & 0 & 0\\ 0 & 0 & -A & -2A\sqrt{2}\\ 0 & 0 & -2A\sqrt{2} & A\end{vmatrix},$$

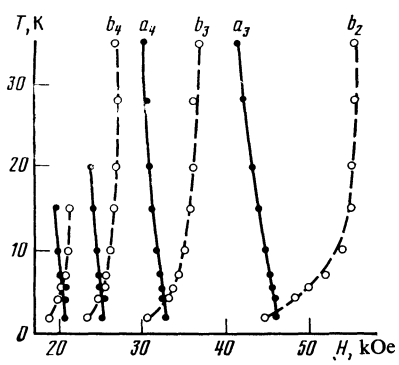

FIG. 8. Experimental temperature dependence of location of the oscillation maxima for sample No. 2 at energy $\varepsilon = 50$ meV: ●—$\mathbf{H}\|\mathbf{I}$; ○—$\mathbf{H}\perp\mathbf{I}$.

$$\bar{D}_b=\begin{vmatrix} -3Ar & 0 & 0 & 0\\ 0 & A & 0 & 2A\sqrt{2}\\ 0 & 0 & -3A & 0\\ 0 & 2A\sqrt{2} & 0 & -A\end{vmatrix}, \tag{4}$$

where $r = \alpha/\beta$ is the ratio of the exchange integrals on the wave functions of the bands $\Gamma_6(\alpha)$ and $\Gamma_8(\beta)$:

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

N_0 is the number of unit cells per unit volume, and $\langle S_z\rangle$ is the mean value of the z-component of the Mn^{++} spin.

Thus, neglecting the contribution of the remote bands, the location of the Landau levels at $k_z = 0$ is determined by four parameters: ε_g, P, r, and A. To describe our experimental results we shall use the values of ε_g and P determined above, and $r = -0.5$ (Ref. 2). From a comparison of the theoretical calcualtion in this model with the experimental position of the Landau levels we can determine the value of the parameter A, and the most reliable results are those obtained from measurements at low temperatures and in strong magnetic fields, when spin splitting of the oscillation maxima are observed at $\mathbf{H}\|\mathbf{I}$. As noted above, the location of the maxima agrees with the location of the Landau levels only accurate to the phase, but this does not prevent us from determining A, since the phase shift, while changing the lcoation of the maxima relative to the magnetic field, does not change the energy spacing of the neighboring maxima in a fixed field.

The values of the parameter A obtained in this manner for sample No. 1 at $t = 1.8$ K are -5.5, -6.6, and -7.8 meV in magnetic fields 30, 40, and 50 kOe, respectively. To calculate the location of the Landau levels in the entire range of the magnetic fields we must know A also at small H. It can be seen from (5) that the change of A with changing magnetic field is determined by the field dependence of $\langle S_z\rangle$, which was investigated in Ref. 19 by measuring the magnetization at $T = 2$ K for $Hg_{1-x}Mn_xTe$ at $x\leqslant 0.015$. It is shown in that reference that $\langle S_z\rangle$ is satisfactorily described by the expression

$$\langle S_z\rangle=-{}^5/_2(1-x)^{18}B_{5/2}[g\mu_B H/k_B(T+T_0)], \tag{6}$$

where $B_{5/2}$ is a Brillouin function and the factor $(1-x)^{18}$ takes into account the formation of the pairs of Mn^{++} ions. T_0 is a function of the composition, and extrapolation of the $T_0(x)$ dependence obtained in Ref. 19 to $x = 0.025$ yields a value $T_0 = 5$ K. Expressions (5) and (6) describe well the experimental values of A (H) cited above. The best agreement is obtained at $N_0\beta = 1.6$ eV.

By determining in this manner all the parameters needed for the calcualtion, we can compare the theoretical location of the Landau levels with the experimental ones (Fig. 4) in the entire magnetic-field range. For the phase ϕ (introduced in the same manner as in Ref. 11) we used in the calcualtion the value 0.6. The good agreement between the theory and the experiment is evidence, in our opinion, of the applicability of the employed model of Refs. 2 and 3.

From a comparison of the temperature dependence of

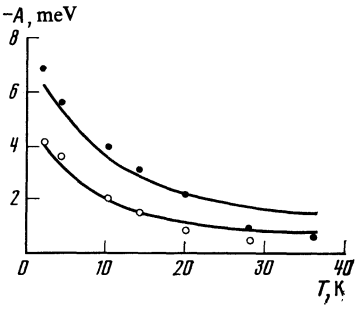

FIG. 9. Temperature dependence of the parameter A for sample No. 1: h in kOe: ●—37, ○—19. Solid curve—calculation in accord with expressions (5) and (6) with $N_0\beta = 1.6$ eV and $T_0 = 5$ K.

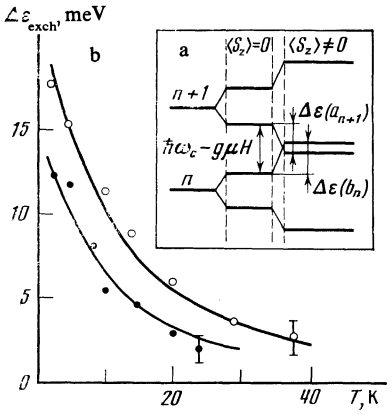

FIG. 10. a) Electron Landau-level scheme of zero-gap $Hg_{1-x}Mn_xTe$; b) temperature dependence of the total energy increment $\Delta\varepsilon_{exch} = |\Delta\varepsilon(a_{n+1})| + \Delta\varepsilon(b_n)|$; energy in meV: ○—50, ●—100. Solid curve—theoretical calcualtion with parameters indicated in the text.

the location of the oscillation maxima (Fig. 6a) with the calculation we determined the dependence of the parameter A on the temperature for sample No. 1 at two values of the magnetic field (Fig. 9). The same figure shows the theoretical curves calcualted from Eqs. (5) and (6). These curves fit well the experimental points at low temperatures. The cause of some discrepancy at high T may be that T_0 in (6) may generally speaking depend on the temperature.[20]

The measurement results for sample No. 2 (Fig. 8) allow us, just as for sample No. 1, to determine the parameter A and calculate the value of $N_0\beta$, found to equal 1.8 eV. It must be noted that we determine experimentally A with good accuracy, and obtain $N_0\beta$ from expression (5), using x, T_0, and the dependence (6) of $\langle S_z\rangle$ on H and T which are known with limited accuracy. This is apparently the cause of certain differences between the values of $N_0\beta$ determined for different samples.

It must be noted that in the reduction of the experimental results on tunneling we assume that the Fermi level is independent of the magnetic field and of the temperature. This assumption calls for further analysis, inasmuch as in semimagnetic semiconductors such as $p - Hg_{1-x}Mn_xTe$ the Fermi level can shift considerably with increasing magnetic field, even if it is located in the valence band at $H = 0$. The reason is that in these materials the upper Landau level b_{-1} shifts upwards in energy at an approximate rate $3A$ in weak fields, so that at low hole densities the ultraquantum level is reached already in relatively weak magnetic fields and the Fermi level begins to follow the level b_{-1}. An estimate of the magnetic field at which the ultraquantum level (H_0) is reached, on the basis of the $\varepsilon(k_z)$ dependence from Ref. 21 with an effective heavy-hole mass $m_h = 0.5\ m_0$, yields $H_0 \approx 70$ kOe for sample No. 1 and even a larger value for sample No. 2. Thus, the use of the assumption that the Fermi energy is independent of the magnetic field is justified under our experimental conditions.

CONCLUSION

The results reported in this paper show that the method of tunnel spectroscopy in a magnetic field is quite promising for the investigation of the energy spectra of semimagnetic semiconductors. This method allows the spectrum to be investigated with high accuracy in a wide range of energies. It is also single-band, unlike the classical method of interband magnetic absorption, so that the interpretation of the transitions is made considerably simpler and unambiguous and the results are more lucid.

The investigation of the tunnel-conductivity oscillations in a wide range of temperatures has shown that the exchange interaction of the band electrons with the localized magnetic moments of the Mn^{++} ions leads to the appearance of an energy increment to the location of the Landau levels. This increment has different signs for the a and b series. At low temperatures the levels a_{n+1} and b_n can change places (Fig. 10a). It is interesting to note that the total energy increment $\Delta\varepsilon_{exch} = |\Delta\varepsilon(a_{n+1})| + |\Delta\varepsilon(b_n)|$ decreases considerably with increasing energy (Fig. 10b), thus attesting to a substantial influence of the nonparabolicity on the contribution of the exchange interaction and indicating that the parabolic approximation cannot be used to calculate $\Delta\varepsilon_{exch}$.

We have shown that the theoretical model proposed in Refs. 2 and 3 describes well the spectrum of the conduction band Γ_8 of the zero-gap $Hg_{1-x}Mn_xTe$ in a magnetic field. Comparison of the theory with experiment has yielded the parameter $N_0\beta = 1.6$–1.8 eV.

Having determined $N_0\beta$, we can explain qualitatively why an investigation of a large number of $Hg_{1-x}Mn_xTe$ samples (about ten in the composition range

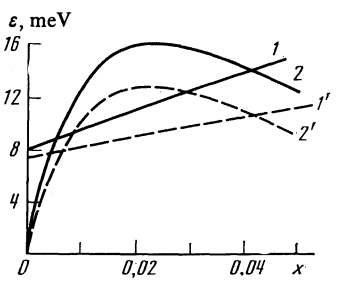

FIG. 11. Dependences of $\Delta\varepsilon_0 = \hbar\omega_c - g\mu_H H$ (1, 1') and $\Delta\varepsilon_{exch} = |\Delta\varepsilon(a_{n+1})| + |\Delta\varepsilon(b_n)|$ (2, 2') on the composition at two energies reckoned from the bottom of the conduction band: 50 meV (1,2) and 100 meV (1', 2'); $T = 4.2$ K.

$0.005 < x < 0.04$) enables us to observe reliably splitting of the oscillation maxima in only one of them—sample No. 1. The calculations show that the parameter ratio in the zero-gap $Hg_{1-x}Mn_xTe$ is such that splitting of the oscillation maxima at low temperature is determined almost always by the distance between the levels a_{n+1} and b_n (Fig. 10a), which is equal to

$$\Delta\varepsilon = \Delta\varepsilon_0 - \Delta\varepsilon_{exch} = (\hbar\omega_c - g\mu_B H) - (|\Delta\varepsilon(a_{n+1})| + |\Delta\varepsilon(b_n)|).$$

With increasing manganese content, both $\Delta\varepsilon_0$ and $\Delta\varepsilon_{exch}$ increase, but in such a way that the difference between them remains relatively small and goes through a maximum near $x = 0.02$ (Fig. 11), at which the best conditions are in fact realized for observation of the splitting of the oscillations. It is seen from the figure that this relation holds in a wide range of energies. Strictly speaking Fig. 11 is only illustrative, inasmuch as in the calculation the $\langle S_z \rangle$ dependence determined by (6) was extended, without good justification, to a composition region up to $x = 0.05$. Qualitatively, however, the features of the spin splitting in $Hg_{1-x}Mn_xTGe$ are correctly reflected. In our opinion, to investigate the contribution of the exchange interaction to the energy spectra of semimagnetic semiconductors in a wide range of densities of the paramagnetic impurity, it is of interest to study quaternary compounds of the $Hg_{1-x-y}Cd_xMn_yTe$ type, in which both $\hbar\omega_c$ and $g\mu_B H$, as well as the contribution of the exchange interaction, can be varied independently by varying the Cd and Mn concentrations.

[1]J. K. Furdina, J. Vac. Sci. Technol. **21(1)**, 220 (1982).
[2]G. Bastard, C. Rigaux, Y. Guldner, J. Mycielski, and A. Mycielski, J. de Phys. **39**, 87 (1978).
[3]M. Jaczynski, J. Kossut, and R. R. Galazka, Phys. St. Sol. (b) **88**, 73 (1978).
[4]G. Bastard, C. Rigaud, and A. Mycielski, *ibid.* **79**, 585 (1977).
[5]P. Buszewski, K. Szlenk, J. Kossut, and R. R. Galazka, *ibid.* **95**, 359 (1979).
[6]M. Jaczynski and W. Dobrowolski, *ibid.* **102**, 195 (1980).
[7]A. M. Sanadauer and P. Buszewski *ibid.* **109**, 167 (1982).
[8]K. Pastor, M. Grynberg, and R. R. Galazka, Sol. St. Commun. **29**, 739 (1979).
[9]D. C. Tsui, Phys. Rev. **B12**, 5739 (1975).
[10]L. P. Zverev, V. V. Kruzhaev, and G. M. Min'kov, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 402 (1979) [JETP Lett. **29**, 365 (1979)].
[11]L. P. Zverev, V. V. Kruzhaev, G. M. Min'kov, and O. É. Rut, Zh. Eksp. Teor. Fiz. **80**, 1163 (1981) [Sov. Phys. JETP **53**, 595 (1981)].
[12]O. É. Rut, V. V. Kruzhaev, and G. M. Min'kov, Fiz. Tverd. Tela **23**, 3212 (1981) [Sov. Phys. Soldi State **23**, 1869 (1981)].
[13]G. M. Min'kov, O. É. Rut, A. I. Luanin, and V. V. Kruzhaev, *ibid.* **24**, 356 (1982) [**24**, 203 (1982)].
[14]M. Doborowolska, W. Doborwolski, R. R. Galazka, and J. Kossut, Sol. St. Commun. **28**, 25 (1979).
[15]Y. Guldner, C. Rigaux, A. Mycielski, and Y. Couder, Phys. St. Sol. (b) **82**, 149 (1977).
[16]Y. Guldner, C. Rigaux, M. Grynberg, and A. Mycielski, Phys. Rev. **B8**, 3875 (1973).
[17]K. Pastor, M. Grynberg, and Y. Couder, Proc. III Int. Conf. Phys. of Narrow-Gap Semicond. Warszawa, 1977, p. 97.
[18]C. R. Pidgeon and R. N. Brown, Phys. Rev. **146**, 575 (1966).
[19]G. Bastard and C. Lewiner, J. Phys. **C13**, 1469 (1980).
[20]W. Dobrowolski, M. von Ortenberg, A. M. Sandauer, *et al.*, Proc. IV. Int. Conf. Physics of Narrow-Gap Semicond. Linz, 1981, p. 302.
[21]J. A. Gaj, J. Ginter, and R. R. Galazka, Phys. St. Sol. (b). **89**, 655 (1978).

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