Manifestation of spin fluctuations in the hopping conductivity of semimagnetic semiconductors

A. E. Belyaev, Yu. G. Semenov, and N. V. Shevchenko
Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR

(Submitted 3 November 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 11, 623–625 (10 December 1988)

Experiments reveal that in a certain interval of impurity concentrations the hopping conductivity of semimagnetic semiconductors results from two activation processes. The effect is explained in terms of spin fluctuations in the spectrum of a bound magnetic polaron at an acceptor and the fluctuations in the state radius which stem from these spin fluctuations.

We would like to discuss the features of hopping processes which have been seen experimentally in semimagnetic semiconductors in measurements of the temperature dependence (over the range 1.5–50 K) and the magnetic-field dependence (0–5 T) of the resistivity ρ and the Hall coefficient R_H of p-$\mathrm{Hg}_{1-x}\mathrm{Mn}_x\mathrm{Te}$ samples ($0.09 \leqslant x \leqslant 0.16$).

A variation of the composition (x) from 0.16 to 0.09, like an increase in the acceptor concentration N_A from 10^{16} to 10^{17} cm^{-3}, reduces the energy of the acceptor states, ϵ_1, from 8 to 3 meV. On the basis of this parameter, we can classify all the samples in one of two groups (Fig. 1).

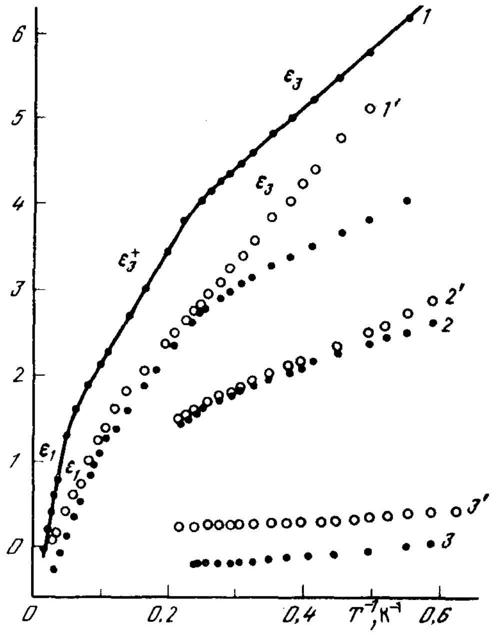

FIG. 1. Temperature dependence of the resistivity of p-$\mathrm{Hg}_{0.88}\mathrm{Mn}_{0.12}\mathrm{Te}$ samples in various magnetic fields. ●—$(N_A - N_D) = 6\times10^{16}$ cm^{-3}; solid line—theoretical; ○—$(N_A - N_D) = 2\times10^{17}$ cm^{-3}. B, T: 1, 1′) 0; 2, 2′) 2; 3, 3′) 5.

0021-3640/88/230675-03$01.00

a) $\epsilon_1 = 5$–8 meV. For this group, a sublinear dependence $\log\rho(T^{-1})$ is observed in the hopping-conductivity region. Specifically, as T is lowered, the region with the energy $\epsilon_3{}^+$ is replaced by a weaker dependence, with ϵ_3. In a magnetic field B, both $\epsilon^+{}_3$ and ϵ_3 decrease, and at high values of B the distinction between $\epsilon^+{}_3$ and ϵ_3 disappears. The region with $\epsilon^+{}_3$ cannot be interpreted as an ϵ_2 conductivity. We believe that assertion is verified by the fact that the temperature dependence $R_H(T)$ has an inflection point at $T \approx 8$ K, which gives way to a sharp decrease. For most of the samples, a coefficient R_H could not be measured at all at temperatures $T \leqslant 4.2$ K.

b) $\epsilon_1 = 3$–4 meV. For this group the hopping conductivity is characterized by a constant activation energy over the entire T range studied (there is no well-expressed inflection point).

A two-exponential temperature dependence $\log\rho(T^{-1})$ in the hopping-conductivity region is not observed in semiconductors with similar band characteristics which do not contain a magnetic component. The suppression of this effect in magnetic fields which eliminate spin fluctuations might indicate that the effect is of a spin-fluctuation nature, but an analysis of the role played by spin fluctuations in the temperature dependence of the hopping conductivity in semimagnetic semiconductors has shown[1] that at $\epsilon_3 > T$ the magnetic-polaron effect does not influence the temperature dependence of the probability for activation processes associated with a charge transfer along shallow donors in an ideal paramagnetic semiconductor. This is a quite general result, and it can be extended quite easily to a hopping along acceptors for a real semimagnetic semiconductor (i.e., when we take spin-spin coupling into account). It should be noted here that the average rate of the hops of the charge carriers, $\overline{W}_{ij}$, is much lower than the rate at which a magnetic polaron is formed, τ_p^{-1}. Specifically, estimates based on the equations of Ref. 2 yield $\overline{W}_{ij} \sim 10^6$–$10^7$ s^{-1}, in comparison with $\tau_p^{-1} \sim 10^9$ s^{-1} (Ref. 3).

We thus see that spin fluctuations in the energy spectrum cannot by themselves explain the observed features on the $\rho(T)$ curve. Furthermore, the spectrum of magnetic-polaron states of an acceptor in a cubic semimagnetic semiconductor has several structural features, among which we wish to single out the following one. The effective angular momentum of a hole localized at an acceptor, $S_h = 3/2$ (here and below, we are ignoring cubic-anisotropy effects), which corresponds to two possible polaron states, has projections $S_{hz} = m_h = 3/2$ and $1/2$ onto the z direction, the direction of the local magnetization caused by the exchange interaction of the hole and the magnetic ions. The ground state of the polaron corresponds to $m_h = 3/2$, at which value the contribution of the exchange interaction with magnetic ions to the change in the energy and thus to the effective radius of the polaron state is at a maximum.

The excited state of the polaron ($m_h = 1/2$) corresponds to a much smaller exchange energy and thus a much larger state radius. We also note that the T-independent factor in the expression for the hopping probability W_{ij} is proportional to[2] $\exp(-1.73/N_A^{1/3}a)$, i.e., is an exponentially sharp function of the state radius (a) of the hydrogen-like shallow center. In view of the approximate nature of these estimates, we will also approximate the wave function of a polaron at a neutral acceptor by an exponential function with a state radius a_{m_h}, which depends on the spin state of the hole, $|m_h\rangle$. As a result, the probability for a hop, which is related to the overlap of the wave functions of the excited states of a polaron with $m_h = 1/2$, may be substantially greater than the probability with $m_h = 3/2$. Because of this difference, at a high temperature it will be favorable for a polaron to await fluctuations to an excited state and then hop to an acceptor which is in the same spin state and which has no hole. The probability for this process is $\sim\exp(-[\Delta + E]/T)$, where Δ is the difference in the energies of the ground state of an occupied acceptor, i, and of an acceptor which has no hole, j, when spin interactions are ignored, and E is the magnitude of the spin splitting of the 3/2 and 1/2 states. At low temperatures, on the other hand, the conductivity will be dominated by hops between ground states of the acceptor, with a probability $\sim\exp(-\Delta/T)$.

Restricting the discussion to the qualitative aspects of this question, we can simplify by replacing the distribution function of the exchange-coupled hole and magnetic ions by discrete levels which correspond to projections $m_h = \pm 3/2, \pm 1/2$. As justification for this replacement we can cite the spectrum of the Raman scattering by an acceptor in a semimagnetic semiconductor which was calculated in Ref. 4. We ignore the comparatively weak exchange splitting of the $\pm 1/2$ states and the more highly excited state, $-3/2$, which is active in the anti-Stokes component of the Raman scattering, again with a small energy shift. With this set of excited states we associate an energy level separated from the ground state by an amount E. For the hopping probability in this model we then find

$$\overline{W}_{ij} = \frac{\alpha+\beta}{1+\exp(-E/T)}[\alpha\exp(-\Delta/T) + \beta\exp-(\Delta+E)/T], \tag{1}$$

where α and β are matrix elements of the probabilities for photoinduced hops for the ground and excited states of the hole, respectively. The case $\alpha = \beta$ is described by a single-exponential curve, with an activation energy Δ, in complete accordance with Ref. 1.

Using (1), we can find a comprehensive description of $\rho(T)$ in the hopping-conductivity region (line 1 in Fig. 1) with $\Delta = 1.5$ meV, $E = 1$ meV, and $\beta/\alpha = 95$. The latter ratio prevails at $N_A = 6\times 10^{16}\ \text{cm}^{-3}$ and $E_A^0 = 7$ meV if the effective radius of the ground state of the bound magnetic polaron, $a_{+3/2}$, is smaller by a factor of 1.5 than $a_{+1/2} \approx a_A$.

The polaron effect weakens in a magnetic field, so the difference between the activation energies in the two temperature ranges should decrease. The polaron effect also weakens with an increase in N_A, which leads to an increase in the radius of the acceptor state. Both of these effects agree qualitatively with the experimental data.

[1] A. S. Ioselevich, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 148 (1986) [JETP Lett. **43**, 188 (1986)].

[2] B. I. Shklovskiĭ and A. L. Éfros, Electronic Properties of Doped Semiconductors, Springer-Velag, New York, 1984.

[3] T. Dietl and J. Spalek, Phys. Rev. Lett. **48**, 355 (1982).

[4] C. Benoit a la Guillaume, Physica **146B+C**, 1-2, 234 (1987).

Translated by Dave Parsons