Nonohmic hopping conductivity in semimagnetic semiconductor p-$Mn_xHg_{1-x}Te$

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A nonohmic hopping conductivity has been studied for the first time in semimagnetic semiconductors of the p-$Mn_xHg_{1-x}Te$ type. Features observed on the temperature and magnetic-field dependence of the current-voltage characteristics are linked with a transformation of acceptor states due to a carrier-ion exchange interaction.

Previous observations[1] have revealed that the hopping conductivity in a semimagnetic semiconductor results from two activation processes in a certain range of the concentration (N_A) of the acceptor impurity. This behavior differs from that of nonmagnetic semiconductors. The effect has been attributed to spin fluctuations in the spectrum of a magnetic polaron bound to an acceptor and to fluctuations in the radius of the state due to these spin fluctuations. Fluctuations of this sort should also be manifested in directed hopping-conductivity processes, which become significant in moderately strong electric fields E. There has been no theoretical or experimental study of transport processes for semimagnetic semiconductors under such conditions.

In this letter we are reporting a study of the current-voltage characteristics in the region of moderate electric fields, from the ohmic region of the current-voltage characteristic to the region in which impurity breakdown is manifested, for the group of samples studied in Ref. 1. For those samples, the hopping conductivity is characterized by two activation processes in weak electric fields. In an effort to avoid heating, we carried out measurements in pulses with a pulse length $\tau_{\text{pulse}} = 10$–20 s and a repetition frequency $f = 1$ kHz. Experiments were carried out at two temperatures, at which the hops were governed by different processes:[1] at 4.2 K, at which the transport occurs predominantly through excited spin states of a magnetic polaron at an acceptor, and at 1.6 K, at which the conductivity results from hops between lowest-lying states of a polaron. Figure 1 shows measured current-voltage characteristics of one of the samples.

At 4.2 K [Fig. 1(a)], and in the absence of a magnetic field, the ohmic dependence gives way to a region of a superlinear current-voltage characteristic, which is observed at fields from $E_1 \approx 50$ V/cm to $E_2 \approx 300$ V/cm. An impurity breakdown then sets in.[1)] In a magnetic field $H \perp E$ the boundary of the ohmic region and also the beginning of breakdown shift to lower values of E, leaving the current-voltage characteristic qualitatively similar to that in the case $H = 0$.

At 1.6 K, however, a nonmonotonic dependence of the derivative of the current-voltage characteristic arises: The ohmic region $(0 < E < 10$ V/cm) is followed by a

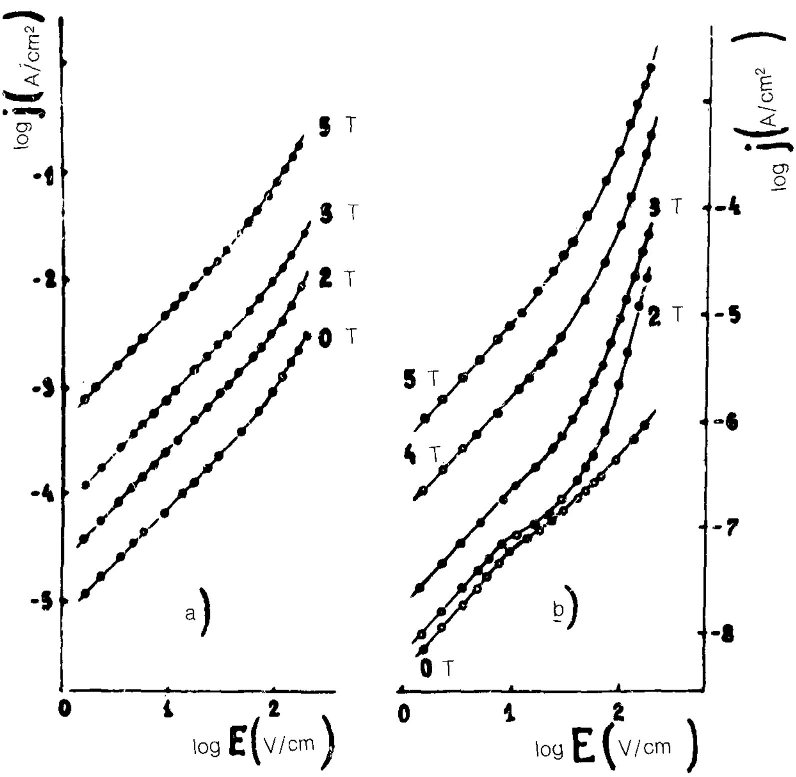

FIG. 1. Current-voltage characteristic of p-$Mn_{0.2}Hg_{0.8}Te$ measured at (a) 4.2 K and (b) 1.6 K. The curves are labeled with the value of the magnetic field.

sublinear region, which then gives way to a superlinear region [Fig. 1(b)]. In a magnetic field, the observed sublinearity decreases to the point that it disappears completely.

A superlinear current-voltage characteristic for the hopping conductivity is typical of the prebreakdown region of electric fields, even for nonmagnetic semiconductors. It stems from a substantial (in comparison with kT) change in the activation energy in an electric field, $\Delta\varepsilon = eEl$, over a hopping distance l. The sublinear current-voltage characteristic observed in a semimagnetic semiconductor at 1.6 K in comparatively weak fields E may be due to the mechanism of Refs. 2 and 3, which involves a directed percolation in an infinite cluster, through which the hopping process occurs, and the presence of "dead ends" in the cluster. Denoting by L the characteristic length of the dead ends, we note that under the condition $eEL > kT$ some of these dead ends, directed along the field, will act as traps for charge carriers and will thereby reduce the conductivity. Specifically, the observed decrease in the conductivity (Fig. 2) is described satisfactorily by the expression[3]

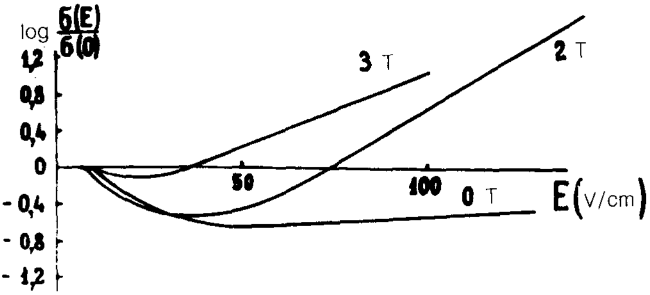

FIG. 2. Conductivity versus the electric field at various values of the magnetic field and at $T = 1.6$ K.

$$\sigma(E) = \sigma(0)\exp(-eEL/2kT), \qquad (1)$$

with $L = 4.6\times 10^{-6}$ cm. This value is close to the characteristic period of a percolation network, $L_0 = (1/3)(1.74N_A^{1/3}/a)^{\nu}N_A^{-1/3}$ (the critical index is $\nu\approx 1$, and a is the effective radius of the state of the impurity center).[3] A distinctive feature of semimagnetic semiconductors is seen in the dependence of the current-voltage characteristic on the magnetic field and stems from the known increase in a with increasing H and the concomitant decrease in L, which leads to a weakening of the $\sigma(E)$ effect in (1).

The absence of a sublinear current-voltage characteristic at 4.2 K does not contradict these estimates, since the role of the exponential factor in (1) is weakened in this case both because of the direct contribution of T and because of the comparatively large radius of the excited polaron states, which determine the hopping charge transport. The magnetic field makes an additional contribution to the increase in a (to the decrease in L), causing an increase in $\sigma(E)$ in this temperature interval.

In summary, the features observed on the dependence of the current-voltage characteristic on the magnetic field and the temperature can be explained in terms of a restructuring of acceptor states and in terms of spin fluctuations in the spectrum of exchange-coupled localized holes and magnetic ions.

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[1)] We will not consider in this letter the particular features of the breakdown characteristics, which warrant a separate study. We will instead restrict the discussion to the field region $E < E_2$.

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[2]V. V. Bryskin *et al.*, Fiz. Tverd. Tela (Leningrad) **22**, 1403 (1980) [Sov. Phys. Solid State **22**, 818 (1980)].

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