Activationless hopping conductivity along the states of the Coulomb gap in a-Si⟨Mn⟩

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A hopping charge transfer along localized states in the region of a Coulomb gap in strong electric fields has been studied. Experimental observation of 3D systems has shown for the first time that activationless hopping conductivity changes with increasing field strength F in accordance with $\sigma(F) \sim \exp[-(F_0/F)^{1/2}]$.

The nonresistive hopping conductivity in the presence of a parabolic Coulomb gap in the spectrum so far has virtually been ignored and the data[1,2] found in the literature are rather contradictory. The theoretical predictions of Refs. 1–4 can be summarized as follows. Since there is a spread in the energy levels of the impurity in the disordered semiconductors, the electron absorbs a phonon as it hops from one localized state to another. This situation gives rise to an activation nature of hopping conductivity. In a strong electric field ($F > F_c = kT/ea$, where k is the Boltzmann constant, T is the temperature, e is the electron charge, and a is the localization length) the electrons participating in the hops acquire an energy necessary for executing the hop, not due to the thermal phonons but rather due to the electric field. The conductivity in this case no longer depends on the temperature (it becomes a conductivity without an activation energy) and increases with increasing field in accordance

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with

$$\sigma(F) \sim \exp[-(F_0/F)^X]. \quad (1)$$

The exponent X is determined by the behavior of the state density $g(E)$ near the Fermi level E_F. $X=\frac{1}{2}$ if the spectrum has a parabolic gap; $X=\frac{1}{4}$ if $g(e) = \text{const} \neq 0$. The results of the measurement of the conductivity of the a-Ge⟨Cu⟩ films have shown[1] that although the Coulomb gap is seen in the temperature dependence of σ in the resistive part of the current-voltage characteristic, the conductivity in strong electric fields is consistent with Eq. (1), where $X=\frac{1}{4}$. This discrepancy between the experimental results and the theoretical predictions has made it necessary to study the nonresistive conductivity in other systems with a Coulomb gap.

Because of the breakdown of the impurity, it is difficult in strong fields to measure σ of semiconductors doped with an impurity with shallow levels. A target for studying should therefore be a material with deep levels, whose concentration is large enough for the Coulomb gap to appear in the spectrum. Such a material is an amorphous silicon (a-Si) doped with Mn. The method used to synthesize the samples and the properties of the a-Si⟨Mn⟩ samples corresponding to the resistive part of the I-V characteristic were described in Refs. 5 and 6, in which it was shown that the conductivity of a-Si⟨Mn⟩ is given by

$$\sigma(T) \sim \exp[-(T_0/T)^{1/2}], \qquad T_0 = 1.4e^2/k\kappa a, \quad (2)$$

where κ is the dielectric constant of the system. The exponential function (2) corresponds to the activation hopping conductivity along the states of the Coulomb gap.[7] We give the results of an experimental study of an activation-free hopping conductivity of a-Si⟨Mn⟩ with a concentration of Mn $N=8$ at.% in fields $F \leqslant 11$ kV/cm. To

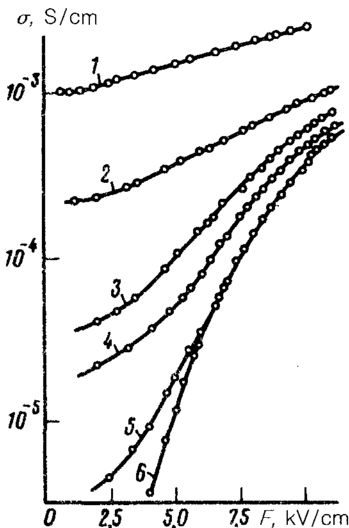

FIG. 1. Dependence of σ on F at various temperatures. 1—21 K; 2—15.5 K; 3—10.7 K; 4—8.5 K; 5—6.2 K; and 6—4.7 K.

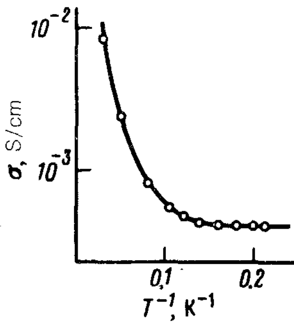

FIG. 2. Temperature dependence of the conductivity at $F = 11$ kV/cm.

prevent heating of the samples during the measurements, we applied a pulsed voltage to them.

The results of the measurement of $\sigma(F)$ at various temperatures are shown in Fig. 1. At $F > 1$ kV/cm we have an essentially nonresistive conductivity which increases exponentially with increasing field. At temperatures $T < 8$ K and fields $F \geqslant 6.6$ kV/cm the curves of $\sigma(F)$ for different temperatures merge into one curve. Figure 2 shows the temperature dependence of the conductivity for an electric field strength $F = 11$ kV/cm. We see that at low temperatures the conductivity becomes activationless. The field dependence of the conductivity in the activationless regime ($F \geqslant 6.6$ kV/cm at $T = 6.2$ K and $F \geqslant 5$ kV/cm at $T = 4.7$ K) in this case is approximated by Eq. (1) with $X = \frac{1}{2}$ and $F_0 = 7.3 \times 10^5$ V/cm (Fig. 3) and does not become linear in the coordinates $(\ln \sigma, T^{-1/4})$.

In the case of a hopping transfer of a charge the action of the electric field reduces to a decrease in the activation energy W (whose value is determined by the character-

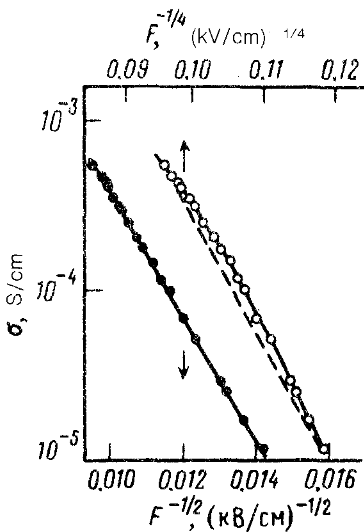

FIG. 3. Conductivity vs the electric field at $T = 4.7$ K. $F \geqslant 5$ kV/cm in the coordinates $\ln \sigma$, $F^{-1/2}$ and $\ln \sigma$, $F^{-1/4}$.

istic energy of the Coulomb interaction of the charges dispersed along the length of the hop R) by the amount ϵFR. The probability for tunneling between two localized states therefore is given by

$$p \sim \exp\left(-\frac{2R}{a} - \frac{W - eFR}{kT}\right). \tag{3}$$

In the activationless regime the activation energy vanishes and the hops occur over a typical distance R given by the relation[2]

$$\frac{e^2}{\kappa R} - eFR = 0. \tag{4}$$

Using (3) and (4), we easily see that the probability for activationless tunneling is

$$p \sim \exp[-(F_0/F)^{1/2}], \tag{5}$$

where

$$F_0 \approx kT_0/ea. \tag{6}$$

Here T_0 is the same parameter as that in expression (2). The experimental data obtained by us make it possible to find several important characteristics of the material under study: the localization length of electrons and the dielectric constant of the medium. Setting, in accordance with Ref. 5, $T_0 = 1000$ K and using the value $F_0 = 7.3\times10^{15}$ V/cm determined by us, we find from (2) and (6) the value $a = 10.5$ Å and $\kappa = 26$.

A conceptual understanding of the divergence between κ and a as the insulator-metal transition is approached (as the Fermi level E_F approaches the percolation threshold E_P) is now being developed in the physics of disordered systems. We have found previously that the divergence of these parameters in $a = \text{Si}\langle\text{Mn}\rangle$ is described by the expressions

$$a = a^* \left(\frac{E_P - E_F}{\Omega}\right)^{-1/2}, \tag{7}$$

$$\kappa = \kappa^* \left(\frac{E_P - E_F}{\Omega}\right)^{-1,7}, \tag{8}$$

where $\Omega = 0.12$ eV is the width of the impurity band of Mn in $a = \text{Si}$, $a^* = 3.5$ Å (Ref. 6), and $\kappa^* = 12$. Setting[8] $E_p - E_F = 0.07$ eV for $N = 8$ at.%, we find $a \approx 7$ Å and $\kappa \approx 37$, in reasonable agreement with the results obtained by us.

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