Nonohmic hopping conductivity in strong electric and magnetic fields

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A nonohmic hopping conductivity stimulated by a strong electric field in an amorphous insulator Si_3N_4 in a magnetic field at low temperatures has been studied for the first time. Several new effects have been discovered.

1. The specific properties of amorphous Si_3N_4: high localized state density within the mobility gap and strong scattering of charge carriers excited to the conduction band, make it an interesting candidate for studying nonohmic conductivity in electric and magnetic fields. The conductivity of Si_3N_4, however, has so far been studied only

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at temperatures $T > 77$ K. At $T > 300$ K the current transport in Si_3N_4 is linked with the Frenkel-Pool effect.[1]

2. In the present experiments we have studied the direct-current conductivity of an amorphous Si_3N_4 in the temperature interval 2–450 K in longitudinal and transverse magnetic fields up to 70 kOe and in an external electric field up to 8 mV/cm. Two types of samples were studied: type A samples, comprised of SiO_2 and Si_3N_4 layers 60 Å and 400 Å thick and type B samples, consisting of SiO_2, Si_3N_4, and SiO_2 layers 60 Å, 370 Å, and 80 Å thick, respectively. The various types of samples differ in the technology of fabrication of Si_3N_4 film. It was established in Ref. 2 that a thick SiO_2 layer blocks the hole component of the current and that the conductivity of the samples is determined exclusively by the Si_3N_4 layer.

3. All the structures studied by us have qualitatively identical temperature dependences of the conductivity (current) at $H = 0$. Figure 1 shows a typical temperature dependence of the current J across the layers in various fields H for a type-A sample. The high-temperature ($T > 100$ K) part of the curve, which corresponds to the activa-

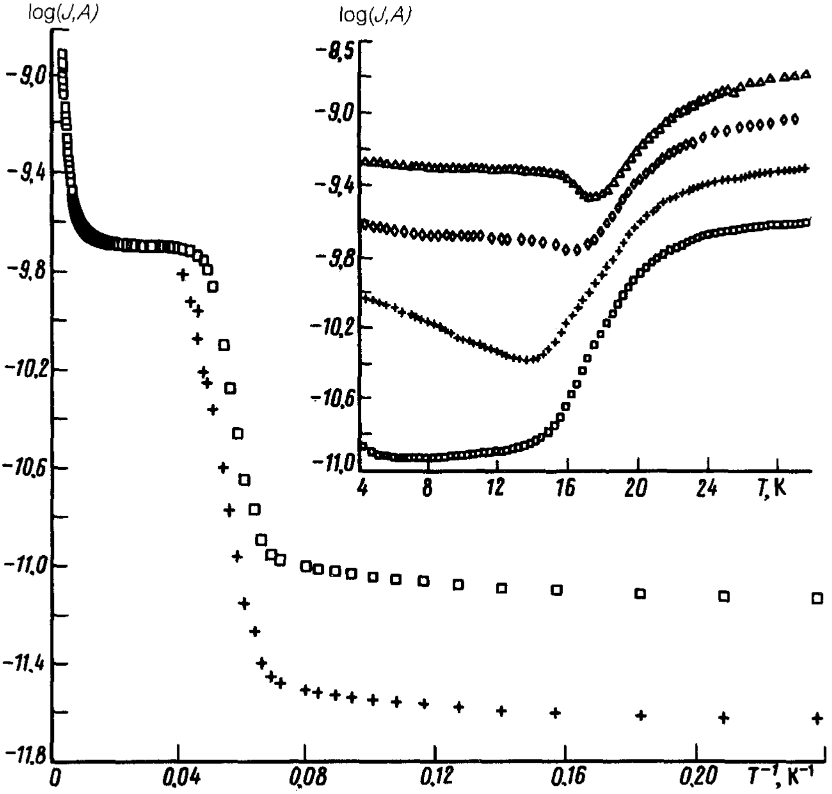

FIG. 1. Dependence of log J on the reciprocal of the temperature $1/T$ in magnetic fields $H = 0$ (□) and $H = 20$ kOe (+). Inset—a plot of log J versus T at the following voltages on the sample: -32 V (□); -33 V (+); -34 V (◇); -35 V (△).

tion nature of the conductivity, characterizes the depth of the energy levels of the localized states in Si_3N_4, whose maximum value is ~1 eV. In the temperature region $30\ K < T < 100\ K$ the conductivity is nearly independent of the temperature. Upon further lowering of the temperature, the conductivity initially decreases sharply and then reaches values which are nearly independent of T. At these temperatures ($T < 12$ K) the current may either increase or decrease with decreasing T when different voltages are applied to the sample (see the inset in Fig. 1).

4. The characteristic feature of the samples is an inordinately strong dependence of the conductivity on the magnetic field. For type-A samples the conductivity does not depend on H at $T > 30$ K (Fig. 1). At lower temperatures the current decreases rapidly even in relatively weak fields H when a constant voltage U is applied to a type-A sample. The current in this case decreases more rapidly at higher voltages on the sample (Fig. 2). It is important to note that the H dependence of the current is only slightly sensitive to the orientation of H, and the longitudinal magnetoresistance is slightly greater than its transverse magnetoresistance. At low temperatures the magnetoresistance of type-B samples behaves analogously. At $T \approx 20$ K, however, the magnetoresistance of type-B samples, in contrast with type-A samples, reverses its sign and at higher temperatures these samples reveal a negative magnetoresistance (see Fig. 3). The absolute value of the negative magnetoresistance increases rapidly in weak fields and at H on the order of several kilo-oersteds it reaches a maximum (the inset in Fig. 3). The negative magnetoresistance near the saturation point is ~6% of the magnetoresistance in the absence of a magnetic field at $T = 30$ K and it continues to decrease to 1% at $T = 250$ K.

5. The inset in Fig. 2 is a plot of the conductivity as a function of the voltage on the sample in $\ln\sigma - U^{-1/4}$ coordinates in various magnetic fields. Those parts of the curves which correspond to lower voltages fit well on the straight line in these coordinates. With increase of U, the slope changes characteristically at a certain U^* and the kink in the magnetic field shifts toward stronger electric fields.

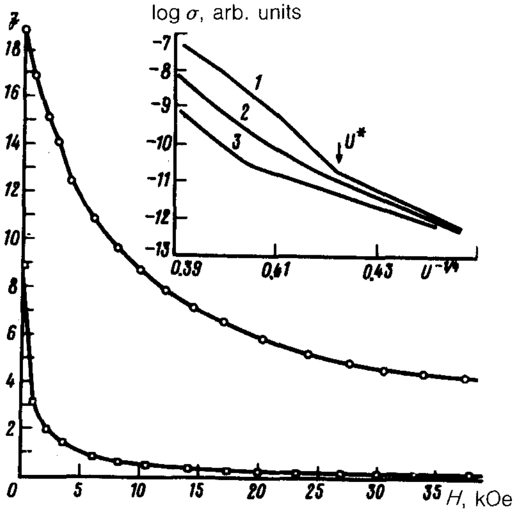

FIG. 2. A plot of the current J on the magnetic field H. ○—The values of the current (in pA) at a voltage of -32.5 V on the sample; □—the values of the current (in nA) at a voltage of -40 V on the sample. Inset—a plot of the conductivity versus the voltage U on the sample in $\log\sigma - U^{-1/4}$ coordinates in various magnetic fields: 1—$H = 0$; 2—$H = 5$ kOe; 3—$H = 25$ kOe.

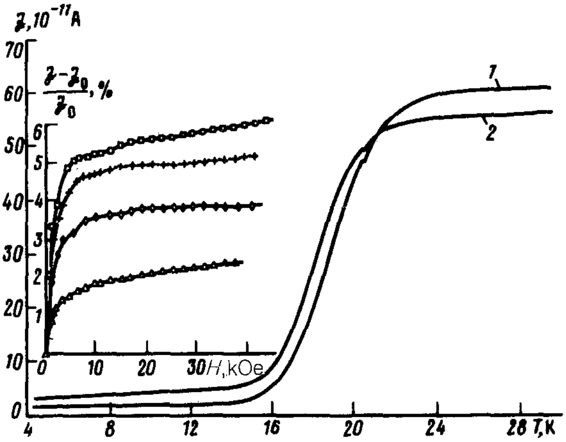

FIG. 3. A plot of the current J flowing through a type-B sample versus the temperature T for two values of the magnetic field: 1—$H = 20$ kOe; 2—$H = 0$. At $T \approx 20$ K the positive magnetoresistance becomes a negative magnetoresistance. The voltage on the sample is -25 V. Inset—the variation of $\Delta J/J_0$ (in %) in a type-B sample in a magnetic field at various temperatures: □—30 K; + —78 K; ◇—98 K; △—180 K. The voltage on the sample is -25 V.

6. The exponentially strong H dependence of J (Fig. 2) at low temperatures, the characteristic features of this dependence indicated above, and the nature of the dependence of the conductivity on the electric field strength (the inset in Fig. 1) are evidence in favor of the fact that at these temperatures the current transport in Si_3N_4 is based on the hopping mechanism with a dissipative tunneling in a strong electric field. It is quite conceivable that at these temperatures we are seeing here a nonactivated hopping current transport with an emission of phonons or long-wave photons during each hop.[3]

7. The presence of negative magnetoresistance in Si_3N_4 is difficult to explain in terms of the model[4] developed for the weak localization region near the mobility threshold. A much more likely reason for the appearance of negative magnetoresistance is, from our point of view, the scattering of electrons by paramagnetic centers with a spin flip.[5] As the estimate based on the method of Ref. 5 shows, the concentration of paramagnetic centers in Si_3N_4 need be only 10^{18} cm^{-3} in order to account for a 6% negative magnetoresistance, consistent with the conclusions of Ref. 6.

8. In summary, it appears that two competing effects can participate in forming nonohmic magnetoresistance of thin insulating Si_3N_4 films in strong electric fields: dissipative tunneling, which accounts for the increase of the resistance in a magnetic field, and scattering by paramagnetic centers, which decreases the electrical resistance.

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