Crossover from superconductivity to a negative magnetoresistance in a Cd–Sb alloy near the localization threshold as the temperature is lowered

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The evolution of the superconducting response in various stages of the amorphization of a metastable metallic phase of the alloy $Cd_{43}Sb_{57}$ has been studied. This amorphization is accompanied by a metal–insulator transition. On the insulator side of the transition, a superconducting response is observed in fields $H < 1.5$ T at $T \gtrsim 3$ K. At $T < 1$ K, this superconducting response gives way to a negative magnetoresistance characteristic of a hopping conductivity.

The influence of a localization threshold on superconductivity is a problem with several aspects. One is the question of the phase transitions which occur with increasing disorder at absolute zero[1-5] ($T=0$). According to the theory of Refs. 1–3, a transition from a superconducting state (S) can occur to either a metallic state (M) or an insulating state (I). In the first case, an increase in the disorder leads to the state sequence S–M–I at $T=0$; in the second case it leads to the sequence S–I.

A second aspect is the problem of how the disorder affects the superconducting transition temperature T_c. It has been shown in several theoretical papers[6-9] that a disorder degrades the superconductivity, i.e., lowers T_c. The pertinent question, however, is the extent to which this assertion remains valid in the immediate vicinity of the localization threshold. According to Bulaevskiĭ *et al.*,[10] if the spatial fluctuations of the electronic characteristics are sufficiently large, the superconducting order parameter does not undergo a self-averaging, and the superconductivity becomes inhomogeneous. The S regions arise first as separate droplets, and the S transition becomes a percolation transition.[11]

Two conclusions can be drawn from the results of Bulaevskiĭ *et al.* First, we would expect that an increase in the disorder near the localization threshold would have its greatest effect on the width of the S transition, rather than on the position of its onset, T_{c0}. Second, the fundamental inhomogeneity of the S state near the M–I transition should reduce the differences between an initially homogeneous material and an inhomogeneous, e.g., granular, material.

Experimental data on the behavior of the S transition near the localization threshold in 3D materials have been reported in many places (see, for example, the papers cited in Ref. 12). It turns out that in the critical region the onset temperature of the S transition, T_{c0}, is often quite insensitive to the degree of disorder,[5,13-15] and the resistance $R(T)$ may never vanish. Instead, it may assume a constant value[5,14] at

$T \ll T_{c0}$, or it may go through a minimum and then increase again[4,13,15] (a reentrant transition[13,16]).

A Coulomb interaction between charged grains,[17,18] a temperature-induced change in the properties of the tunneling barrier in Josephson junctions,[19] and a dissipation at these junctions[20] have all been considered as causes of a reentrant transition. All these factors are specific to a granular material. However, it would seem that the behavior of a granular superconductor would not be greatly different from that of a homogeneous superconductor near the localization threshold.

In the present study we were interested in the S transition near the localization threshold in a homogeneous material. By varying the temperature, we observed a correlation between the superconducting response and the conductivity type on the I side of the threshold. Specifically, as the hopping conductivity becomes predominant with decreasing temperature, the superconducting response which existed at higher temperature disappears.

The experiments were carried out on the alloy $Cd_{43}Sb_{57}$ during the decomposition of the metastable high-pressure phase.[21] At liquid-nitrogen temperature the initial metastable phase is an M phase; it goes into an S state at $T \approx 5.3$ K. Heating to room temperature causes an irreversible transformation of the M phase into an amorphous I phase. By carrying out the heating in increments, one can interrupt this process and obtain, in a given sample, a sequence of quasistable intermediate states at temperatures below room temperature. This procedure and the transport properties of the set of states obtained as a result are described in detail in Ref. 15. These states differ in their resistance (by six orders of magnitude) and their temperature dependence.

Using another sample, we repeated the procedure described in Ref. 15, focusing on the evolution of the superconducting transition. Analysis of the transport in the normal state, e.g., the fact that the conductivity $\sigma(T)$ has a temperature dependence

$$\sigma = \sigma(0) + \alpha T^n \tag{1}$$

with $n = 1/3$, leads to the conclusion that we are dealing with an initially homogeneous material.[22] (The results for $T > 5$ K are essentially the same as those of Ref. 15.)

Figure 1 shows curves of $R(T)$ at low temperatures $T < 6$ K for the sequence of states of the sample. The curve labels are the values of the logarithm of a normalization constant,

$$q = \log(R/R_0)_{T=6\text{K}}, \tag{2}$$

where R_0 is the resistance of the sample in its initial state. The information gleaned from these curves is collected in Fig. 2. The set of all these states has been partitioned somewhat arbitrarily into four intervals here. In the first interval (A) the form of the transition is characteristic of a polycrystalline material with internal stress, defect clusters, etc. In interval B, the curve of the S transition becomes narrow, as would be typical of an amorphous material.[23] It appears that the structural amorphization has already occurred by this stage and that the subsequent evolution of the states is a consequence of changes primarily at the electronic level, e.g., the formation of covalent bonds. In interval C, some tails appear on the transition curves. Curves of the S

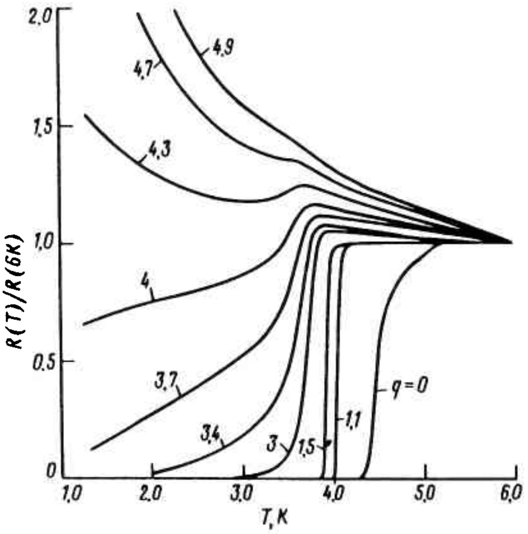

FIG. 1. Superconducting response on the two sides of the localization threshold in a Cd–Sb alloy. The curve labels are the values of the state parameter q, defined in (2).

transition with this shape have been seen for disordered materials in several places. This shape is usually linked with percolation structures.[24] Finally, in interval D, a region with $\partial R/\partial T<0$ appears on the $R(T)$ curves at $T<T_{c0}$. The boundary between intervals C and D coincides exactly with the M–I transition as determined from the vanishing of the free term in (1) (Refs. 15 and 22). The weak R dependence of T_{c0} near the M–I transition is evidence in support of the conclusions reached by Bulaevskiĭ *et al.*[10]

The experimental data below refer to the state with $q=4.9$.

Figure 3 shows curves of $R(H)$ recorded in this state at various temperatures.

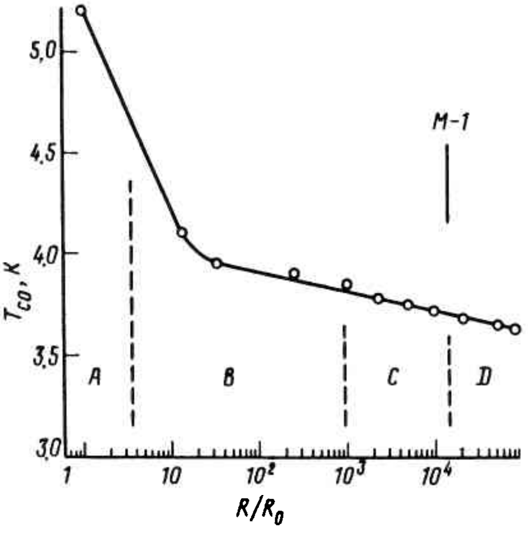

FIG. 2. Onset temperature of the transition versus the resistance in the normal state.

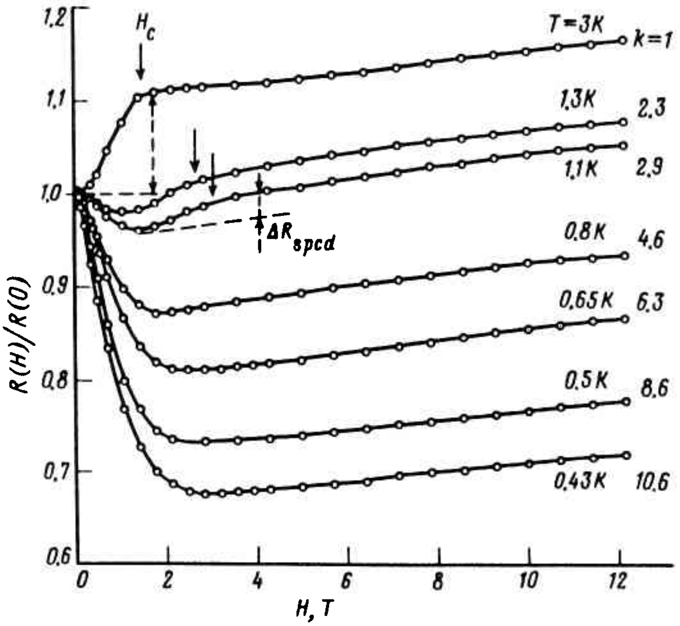

FIG. 3. Curves of $R(T,H)$ for various values of T, normalized to the value of $R(T,0)$, for the state with $q=4.9$. The curves are labeled with the value of T and of the normalization factor $k=R(T,0)/R(3K,0)$. The arrows on the three curves at the top mark the field H_c which destroys the superconducting response.

The curve at the top ($T=3$ K) is completely normal in shape: There is a sharp increase in the resistance in weak fields $H<H_c$, which can be attributed to a destruction of the superconductivity (or, more precisely, the destruction of whatever superconductivity remained), and there is a positive magnetoresistance in strong fields. At lower temperatures, however, a region with a negative magnetoresistance appears on the "superconducting" part of the curve. As the temperature is lowered, the negative magnetoresistance increases, and the traces of the destruction of superconductivity by the magnetic field disappear. The curves for $3.5\text{ K}>T>2\text{ K}$ and for $T<0.8$ K are in a sense inverses of each other: Those in one group show an increase in the resistance with the magnetic field, while those in the other group show a decrease, by a third at $T=0.4$ K. The transition to a positive magnetoresistance, which is independent of the temperature, occurs at roughly the same field, $H\approx 2.5$ T.

It is natural to suggest that the negative magnetoresistance is the result of a field-induced destruction of the quantum interference in the tunneling of carriers in the course of hopping-conductivity processes.[25] According to theoretical work, the changes in the conductivity here may be large:[26]

$$\sigma(H)-\sigma(0)\sim\sigma(0).$$

However, a negative magnetoresistance on this scale (about 50%) in the case of a hopping conductivity has previously been observed exclusively in two-dimensional

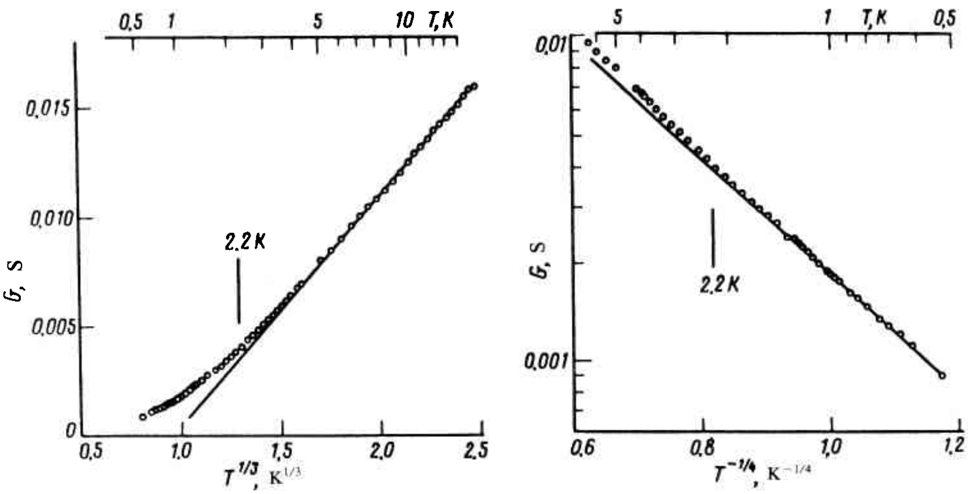

FIG. 4. Temperature dependence of the conductivity in the state with $q=4.9$. These results demonstrate a change in the type of conductivity.

settings.[27] In 3D materials, the effect has previously been considerably more modest, about 1% (Refs. 28 and 29). The negative magnetoresistance observed here thus requires further study.

There is also indirect evidence that the conductivity in this state is a hopping conductivity at low temperatures. In the critical region, by which we mean near the *M–I* transition but at a nonzero temperature, the resistance is described by expression (1), on both the *M* and *I* sides of the transition.[15] In the *I* state, however, the resistance should sooner or later go into a hopping regime as the temperature is lowered. In the state with $q=4.9$ which we are discussing here, this crossover from the critical scaling regime in (1) to the hopping regime apparently occurs at $T\approx 2$ K. The situation can be seen in Fig. 4, which shows the temperature dependence in a field $H=4$ T, at which the superconductivity is definitely destroyed. In the series of experiments which we have described in this letter, the accuracy was not sufficient for distinguishing a power $n=1/3$ from 1/2 in expression (1) (cf. Ref. 15) or for distinguishing $m=1/4$ from 1/2 in

$$\sigma \propto \exp[-(T_0/T)^m], \tag{3}$$

which describes a hopping conductivity. Nevertheless, it is possible to distinguish the behavior in (1) from that in (3) and to estimate the boundaries of the temperature intervals in which the two types of behavior prevail. This has been done in Fig. 4. The position of the boundary between the critical and hopping regimes agrees well with the temperature at which the nature of the curves in Fig. 3 changes.

In summary, a Cd–Sb alloy has been used as an example to demonstrate a correlation between a change in conductivity regime, from critical to hopping, and the disappearance of the superconducting response. As the temperature is lowered, the initial system of electron wave functions changes. In the new basis, the superconducting interaction either is negligible or is not manifested in an electromagnetic response.

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