Mutual conversions between the superconducting and insulating phases in metastable high-resistance states of the alloy $Ga_{50}Sb_{50}$

V. F. Gantmakher, V. N. Zverev, V. M. Teplinskiĭ, and I. I. Barkalov
Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Moscow Oblast

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The temperature dependence of the resistance, $R(T)$, of the alloy GaSb has been measured in various stages of the transition of the metastable high-pressure metallic phase into the disordered insulating state. These stages span a range of more than eight orders of magnitude in terms of the absolute value of R. In the low-resistance states of the sample, a superconducting transition is observed at $T \simeq 4.6$ K. In the high-resistance states, this transition is replaced by a sharp increase in the resistance, i.e., by a transition to an insulating state, at the same temperature.

The evolution of the superconducting (S) transition as the metal-insulator (M–I) transition is approached has been under study for a long time now. In 3D materials one usually observes a quasireentrant (qrS) transition:[1,2] As the sample becomes an insulator, i.e., as the localization threshold is approached, the S transition first stretches out and then fails to go to completion. Right after the initial decrease in the resistance R, a further reduction of the temperature is accompanied by a renewed increase in R.

The simplest classical explanation for this behavior of the function $R(T)$ is based on the existence of isolated inclusions, whose S transition shunts the surrounding matrix regions. The renewed growth of R then simply reflects the temperature dependence of the conductivity of the unshunted part of the matrix. Theoretical models which have been developed also assume that the material has a granular structure, and they treat the Coulomb interaction between charged grains[3,4] or the properties of Josephson junctions between grains[5,6] as being of paramount importance.

However, our previous experiments[2] have revealed indications that a qrS transition may possibly occur in a uniformly disordered material also. We have accordingly undertaken an effort to compare the temperature dependence $R(T)$ above the onset of the qrS transition and below it, where R increases with decreasing T. We are reporting the results of that comparison here.

The alloy $Ga_{50}Sb_{50}$, which was used in these experiments, is one of a group of alloys which can be produced in a metastable M phase by means of high pressure. Heating converts this phase into a disordered I phase.[7–9] By carrying out the annealing for specified times, one can produce several intermediate states, in each of which it is possible to measure the temperature dependence of the resistance at low temperatures. This was the approach which we took in previous studies of the transport properties

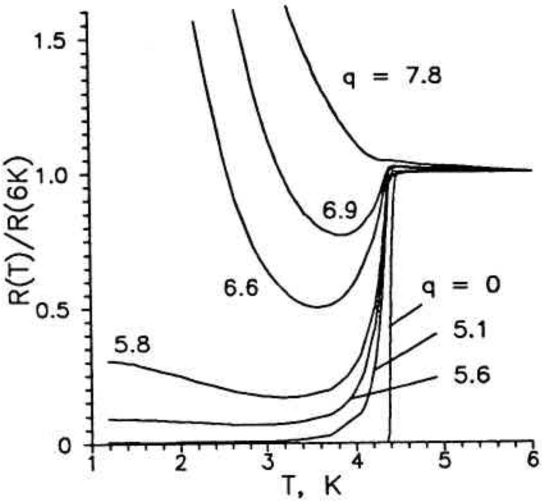

FIG. 1. $R(T)$ curves normalized to the resistance at $T = 6$ K, in various states of the sample. The parameter q is defined by expression (1).

of $Zn_{43}Sb_{57}$ (Ref. 10) and $Cd_{43}Sb_{57}$ (Ref. 11). Analysis of the evolution of $R(T)$ in these alloys revealed that the conversion proceeds in different ways. In the Zn–Sb alloy, fractal structures of the I phase appear in the first stage; they cause a thinning and entanglement of current lines.[12] For the Cd–Sb alloy there is reason to believe that we are dealing with a quasiuniform progressive conversion of the material into the I phase.[11]

The Ga–Sb alloy apparently converts in a fractal manner. At any rate, after we raised the initial resistance of the sample by a factor of 10^8(!) (the original resistivity ρ was on the order of 100 $\mu\Omega\cdot$cm), we did not reach the state which might be called the "I state" on the basis of the formal results of an extrapolation of the dependence $\sigma(T)\equiv\rho^{-1}(T)$ to $T=0$ (cf., Ref. 11 for example). Determining the nature of the disordering process appears to be a matter for future research; here we focus on the evolution of the S transition.

Figures 1 and 2, which show the same experimental data in different coordinates, describe the essence of this effect. We characterize the state of the sample by means of the parameter q,

$$q=\log(R/R_{\text{in}})_{T=6\text{ K}}, \tag{1}$$

where R_{in} is the resistance of the sample in its initial state. It can be seen from the plot of $R(T)$ that the first four orders of magnitude in the change in R are not accompanied by changes in the S transition. This result confirms that the conversion affects only part of the sample. There are no substantial changes in the physical properties of those regions in which the S transition persists, but their volume shrinks rapidly, and their topology becomes more complex. Such a process can be described by, for example, a fractal model.[12] An increase in q to 5 gives rise to tails on the transition and then to a qrS transition:[1,2] The resistance, without reaching zero, begins to rise with decreasing temperature. However, as can be seen from the q = 7.8 curve, there is no

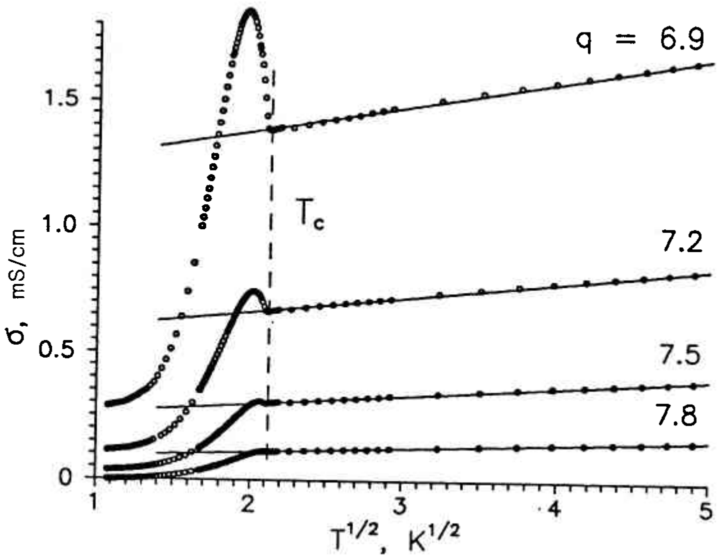

FIG. 2. Conductivity $\sigma(T)$ at temperatures $T < 25$ K in various states of the sample. Above T_c, the $\sigma(T)$ dependence is described well by function (2).

"natural" S response at all in the high-resistance states: A transition does occur at the temperature T_c, but the resistance increases, rather than decreases, over the entire temperature range $T < T_c$.

As Fig. 2 shows, at $T > T_c$ and at sufficiently large q, the changes in the conductivity are proportional to $T^{1/2}$. This result agrees with the arguments based on quantum corrections to the conductivity due to a weak localization and an *ee* interaction.[13] Comparing the $\sigma(T)$ dependence at $T < T_c$ with the function

$$\sigma_0(T)=\sigma_0(0)+\alpha T^{1/2}, \tag{2}$$

which is an extrapolation of the function $\sigma(T)$ from the region $T > T_c$, we find that the difference $\sigma(T) - \sigma_0(T)$ changes sign at a certain T^*. Let us adopt the value $\sigma_0(0)$ as a characteristic of the state of the sample, and let us plot the temperatures T_c and T^* against it. We find three regions in the (σ_0, T) plane, which may be called M, S, and I regions (Fig. 3).

We are speaking a bit loosely in using these labels, since the material evolves through several nonuniform states, as was mentioned above. The simplest assumption is that we have a clear division of the material into M and I phases. Since there is no infinite M cluster in this stage of the conversion, the current lines intersect an M–I–M–I... sequence of regions at $T > T_c$ and therefore an S–I–S–I... sequence at $T < T_c$.

Let us assume that the resistance of the I regions, R_I, is of a tunneling nature: $R_I \equiv R_{MIM}$. Although R_M vanishes abruptly at the point of the resistance transition of the M regions, there is essentially no change in the total resistance of the circuit if

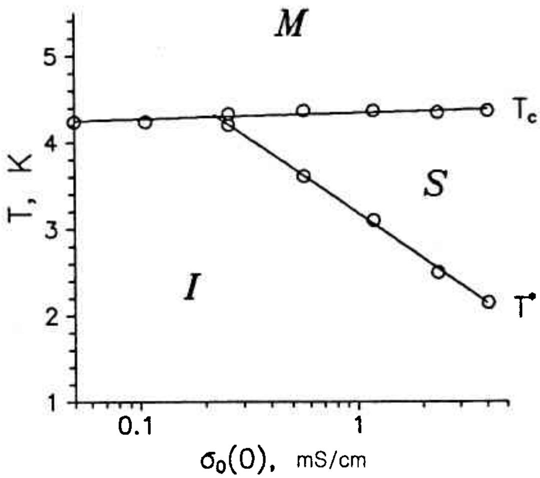

FIG. 3. Diagram illustrating the changes in the electronic properties of the alloy $Ga_{50}Sb_{50}$ at low temperatures in the course of the conversion of the metastable state.

$$R_I \gg R_M. \tag{3}$$

At temperatures $T \ll T_c$, however, the tunneling resistance R_{SIS} may be very large, satisfying $R_{SIS} \gg R_{MIM}$, so the observed effect would result.

The validity of this explanation should be tested by measuring the effect of a magnetic field and an applied voltage. However, we can already see a weak point in these arguments. If tunneling is to be the major mechanism for the conductivity of the I region, its corresponding size d_I should not exceed several tens of angstroms. Introducing the resistivities ρ_I and $\rho_{M'}$, we can put inequality (3) in the form

$$\rho_I d_I \gg \rho_M d_M, \tag{4}$$

where d_M is the size of the M regions along the current lines. We should assume that in states with $q > 7$, in which the dc response at the point T_c changes sign, and inequalities (3) and (4) hold, the quantities d_I and d_M are of the same order of magnitude. Under such conditions the sample could hardly be thought of as a mechanical mixture of two phases. It is more natural to take a quantum-mechanical approach, dealing with the sample as a whole. The insulating state may then turn out to be a consequence of an effect such as a spin density wave or phase stratification,[14] or it may be a crystal of electron pairs.[15] In this connection, we might note the suggestion by Paalanen *et al.*,[16] that there is a finite order parameter and that Cooper pairs exist on the I side of the S–I transition in the 2D case.

A similar effect—a crossover from a resistance decrease at the point of the phase transition to an increase, due to changes in experimental conditions—has been observed[17] in the quasi-1D conductor $TaSe_3$. The similarity is even more striking when we note that the dimensionality of the conducting regions in the fractal structure may be fairly low. However, the nature of the effect observed in $TaSe_3$ has not been finally resolved.

In summary, as the metastable metallic state of the alloy $Ga_{50}Sb_{50}$ transforms into progressively higher-resistance states, its dc response at the point of the electronic phase transition changes sign; i.e., the sharp decrease in resistance gives way to a sharp growth. The circumstance that these two processes begin at the same temperature indicates some internal linkage between them. If the observed effect is a superposition of two processes in different components of a multiphase system, then these processes have the same physical origin.

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