Anomalous superconducting response and nonactivating tunneling in high-resistance metastable states of GaSb

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(Submitted 3 June 1993)
Zh. Eksp. Teor. Fiz. **104**, 3217–3231 (September 1993)

Distinguishing features of metastable high-resistance states produced in GaSb by annealing a quenched high-pressure phase are a very low conductivity σ which furthermore varies little with temperature (since $\Delta\sigma \propto T^{1/2}$) and an anomalous superconducting response below the superconducting-transition temperature T_c (exponential decrease of the conductivity σ). This aggregate of properties can be explained within the framework of a granulated-metal model with granules having a branched fractal surface. The large capacitance between these granules makes the Coulomb-energy changes in tunneling negligibly small, i.e., makes the tunneling non-activating.

1. INTRODUCTION

Superconductivity in high-resistance materials is strongly influenced by two circumstances, the peculiarities of the metallic (M-) state near the localization threshold and the spatial inhomogeneity of the material. This makes the study of the superconducting (S-) transition one of the most effective methods of investigating metal-insulator (M-I) transitions.

Let us discuss briefly the first of these circumstances.

High resistance is evidence of a decreased density of delocalized carriers or of a strong disorder. The two factors are usually simultaneously present, and both lead in the normal state to localization.[1,2] If a superconducting (S-) transition can take place in the medium, a competition sets in between the localization and the superconductivity. In two-dimensional ($2D$) materials this competition leads to S-I transitions. The main features of these transitions have been described both theoretically[3] and experimentally.[4] The situation in $3D$ materials is not so clear.

According to the results of a number of theoretical studies[5–7] of the behavior of the S-transition temperature T_c in the vicinity of the Anderson transition, a growth of the disorder degrades the superconductivity, i.e., lowers T_c, which can reach zero either while still in the M-state, or on the I-side of the M-I transition. In the former case the growth of the disorder leads to a sequence of S-M-I states at $T=0$. In the second case one can expect sequences of S-I states. These two variants are represented by curves *1* and *2* of Fig. 1, where the ordinate is the temperature T and the abscissa is a parameter describing the state of the material along the I-M line; this parameter can be, for example, the sample conductance G (see Fig. 1). The latter means here actually the reciprocal of the resistance, $G_T=[R(T)]^{-1}$ at a certain fixed temperature $T>T_c$. Note that the M-I transition itself is represented on this diagram by a point, since it is defined only at $T=0$ (Ref. 8).

It is quite probable, however, that the tendency of T_c to zero is not the only possible consequence of the increased disorder. According to Ref. 9, if the electronic characteristics undergo sufficiently strong spatial fluctuations the order parameter does not become self-averaged and the superconductivity becomes inhomogeneous, while the S-regions are initially produced in the form of individual drops. The feasibility of such a scenario was also confirmed by experiments on a highly resistive metastable CdS alloy.[10] The results of these experiments are shown in Fig. 1 by curve *3* with its return point. The physical interpretation of this curve is quite simple: the normal conductivity on any vertical line $G=\text{const}$ on the I side of the diagram should become hopping at sufficiently low temperature, and the pairing should delocalize the carriers to form S states.

The assumption made in Ref. 9 that the spatial fluctuations near the threshold are significant leads to the second factor that influences decisively the S transition, the spatial inhomogeneity. We have in mind here inhomogeneity on a scale much larger than atomic. The best known object of this type, whose superconductivity has long been under study, is granulated metal with M-grains separated by I-shells. The bottleneck of charge transport in granulated metal is the tunneling between grains. This process is qualitatively similar to the elementary act of hopping conductivity, hopping of a local carrier from one impurity center to another, except that instead of a center with an isolated level we have an M-grain with a multitude of levels separated by intervals $\delta\varepsilon$ determined by the grain size. From the standpoint of realizing an M-I transition, a granulated metal is therefore conceptually similar to a semiconductor with disordered impurities. This is particularly clear from an analysis of the conduction mechanism in the I-region.[11] Charge tunneling from one grain to another produces an energy change of the order of

$$\varepsilon \approx \delta\varepsilon + e^2/2C, \tag{1}$$

where C is the capacitance between the grains. Charge transport is therefore an activated process, just as carrier

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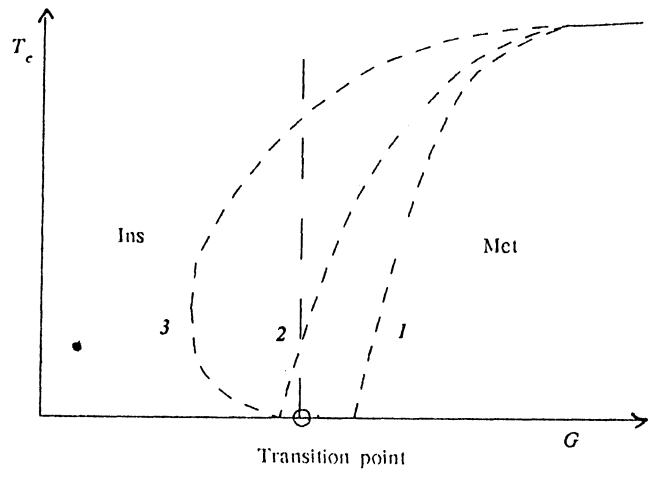

FIG. 1.

jumps from one center to another in hopping conduction.[12] The presence of Coulomb interaction leads in both cases to a specific dependence of the conductivity σ on T:

$$\sigma \propto \exp[-(T/T_0)^{1/2}]. \quad (2)$$

At the same time, the S-properties of granulated and uniformly disordered materials can differ quite strongly. Probably the first granulated material used to investigate the S-transition properties was granulated aluminum.[13] The parameter in the sample group was the resistance R at 4.2 K, which is essentially equivalent to the G_T introduced above. The following was observed:

1. The temperature T_c depends little on the parameter G_T.

2. The form of the transition curve $R(T)$, on the contrary, depends strongly on G_T; although the T_c point is reliably identified on the curves, no real S-state with $R=0$ is reached starting with certain G_T.

3. After dropping close to T_c in a certain G_T interval, the $R(T)$ curve reaches a constant value, even though it had a negative derivative at $T > T_c$.

4. A quasireentrant transition is observed, wherein R no longer decreases below T_c and begins to increase sharply.

5. The S-response gradually vanishes when G_T decreases.

The large number of events contained in the above list makes already the S-transition a sensitive device for the study of the vicinity of an M-T transition. It is therefore of interest to find new systems with a large range of variation of G and to investigate the evolution of an S-transition in them.

New possibilities along these lines are provided by alloys in which it is possible, by using high pressure and quenching, to obtain a metastable M-phase that goes over when heated into a disordered I-phase.[14–16] Annealing in steps produces a number of intermediate states, in each of which one can investigate the transport properties at low temperatures. Such a transformation increases the specific volume, which is a decisive factor in the dynamics of the transformation and can generate fractal structures.[17] The I-phase produced is frequently x-ray amorphous: it has no long-range order and is therefore isotropic.

Even the earliest research with these alloys has shown that in their high-resistance states the S-response has a number of particularities.[18,19] In particular, in the GaSb alloy the resistance drop at the point T_c gives way in the high-resistance states to an increase of the resistance that sets in at the very same temperature. We report in the present article the results of an experimental investigation of this phenomenon.

2. EXPERIMENT

2.1. Procedure

GaSb is one of the systems that have at high pressures and temperatures an M-phase capable of being quenched and kept in a metastable state at liquid-nitrogen temperature for a long time. Heating converts this M phase into an x-ray amorphous I state, which is in turn also metastable, but is preserved a rather long time in a certain vicinity of room temperature.[16] If the composition is correctly chosen, the disordered I-state is homogeneous, i.e., has no foreign-phase inclusions.[16] A distinguishing feature of the GaSb system is that one regular compound of this type is also the stoichiometric $Ga_{50}Sb_{50}$.

A pellet of pressed GaSb powder, 5 mm in diameter and about 1.5 mm thick, was kept in a high-pressure chamber[14,15] at 70 kbar and 250 °C for about 24 hours. The sample was next cooled to nitrogen temperature at an average rate of about 20 °C/s, after which the pressure was lifted. According to the Debyegram, the result was a polycrystalline sample with crystal structure of the white-tin type.[14]

The pellet was clamped at nitrogen temperature in a holder by two pairs of gold wires of 0.5 mm diameter with pointed ends. These wires served also as electric contacts. The holder with the sample was placed in a cryostat in which the temperature could be varied from 1.2 to 300 K.

We were interested in a set of intermediate states between the initial metastable M-phase and the disordered I-phase. Transitions between states were effected by heating the sample to 155–160 K at which it was soaked for 5–10 min under the control of a continuously measured resistance which increased gradually. The soaking was interrupted in such a way that the sample resistance increased by a factor 2–3 at 6 K. No temperature-variation regime in the region below 120 K influenced the state of the sample, which could be measured for an unlimited time.

2.2. Results

Figure 2a shows the $R(T)$ curves for various states of the GaSb sample. Figure 2b shows for comparison an analogous set of curves previously obtained[18] for CdSb. All the curves in both sets are normalized to the values of R at $T=6$ K. The parameter q tagging the curves indicates the state of the sample and its value is

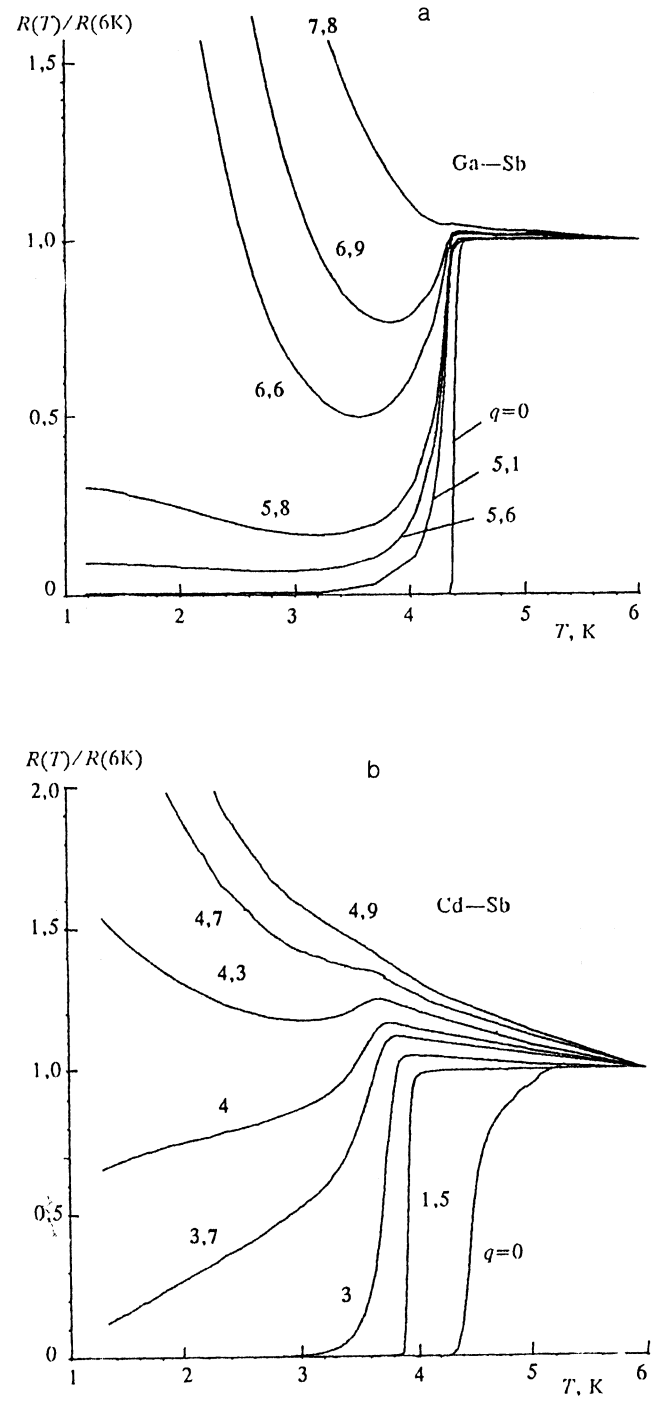

FIG. 2. Evolution of superconducting response in the alloys Ga–Sb (a) and Cd–Sb (b) in various states of the samples. All the $R(T)$ curves are normalized to the resistance at $T=6$ K. The parameter q is defined by Eq. (3).

$$q=\lg(R/R_{\text{in}})_{T=6\text{ K}}, \tag{3}$$

where R_{in} is the sample resistance in the initial state. It can, of course depend not only on the material but also on the particular sample, for example, quenched under pressure at a different rate. The differences between the two materials are nonetheless quite instructive. The initial values of the resistivity $1/\sigma$, corresponding to $q=0$, are usually of the order of 10–100 $\mu\Omega\cdot$cm. Values of q from 2 to 3 correspond therefore to the minimal Mott conductivity[1]

$$\sigma=(e^2/\hbar)k_{\text{F}}$$

for the minimally reasonable Fermi wave vectors k_{F}, while for $q=4$ to 5 one should expect an M-I transition. This transition does indeed take place in CdSb, for which it was determined by extrapolating the $\sigma(T)$ dependence from $T>T_c$ to $T=0$. The extrapolation is usually made in the coordinates $(\sigma,T^{1/n})$, where this dependence is described by a straight line[20,21]

$$\sigma(T)=\sigma(0)+\alpha T^{1/n},\quad n=2\quad\text{or}\quad 3. \tag{4}$$

This makes it possible to set each state in correspondence with the quantity $\sigma(0)$ and single out the state $\sigma(0)=0$ which is located directly on the transition. This procedure yielded for CdSb a critical value $q\simeq 4$ (Ref. 22). As seen from Fig. 2b, the S-response changes character changes just near this value of q and vanishes altogether at $q\simeq 5$. Thus, the S response from CdSb behaves in the absence of a magnetic field in exactly the same manner as for granulated aluminum.

The S response of a GaSb alloy behaves differently. Its relative value does not decrease with increase of q, and the response reverses sign instead (curve marked 7, 8). Further increase of q (to 8, 9) does not alter the character of the curve—see Fig. 3.

An increase of the resistance of a granulated metal below the S-transition was also observed earlier,[23–25] but mainly in the I-region, where the normal resistance above T_c is activated and varies in accordance with Eq. (2). In the case of GaSb, as seen from Fig. 3, the resistance above T_c varies as the power law (4), a variation usually regarded as an attribute of the M-state or at least of a critical state.[10] It is evident here from extrapolation of the straight lines (4) that an increase of q does not lead to an M-I transition, although the absolute values of the dimensionless conductance

$$g=(\hbar/e^2)G \tag{5}$$

is lower than the critical value of g_c for $3D$-materials[26]

$$g_c=\pi^{-3}\approx 3.2\cdot 10^{-2},\quad G_c=7.8\cdot 10^{-6}\,\Omega^{-1}. \tag{6}$$

The absolute values of g and $\partial g/\partial T$ which can be determined from Fig. 3 must be approached with caution: transfer of the contacts to another place on the sample in a state $q=8,9$ with a decrease of a distance between them did not only change R more strongly than expected, but also changed the relation between $g(0)$ and $\partial g/\partial T$. This question calls therefore for further experimental study. It can be stated, however, that an increase in the resistance of the material does not produce at $T>T_c\approx 4$ K any formal indication of a transition into an I-state. Another incontrovertible fact is that in a sufficiently large temperature interval R varies with temperature at $T>T_c$ as the power law (4) which is indicative of a strongly disordered metal, rather than the exponential law (2).

All the experimental data that follow pertain to the highest of the reached states, with $q=8,9$.

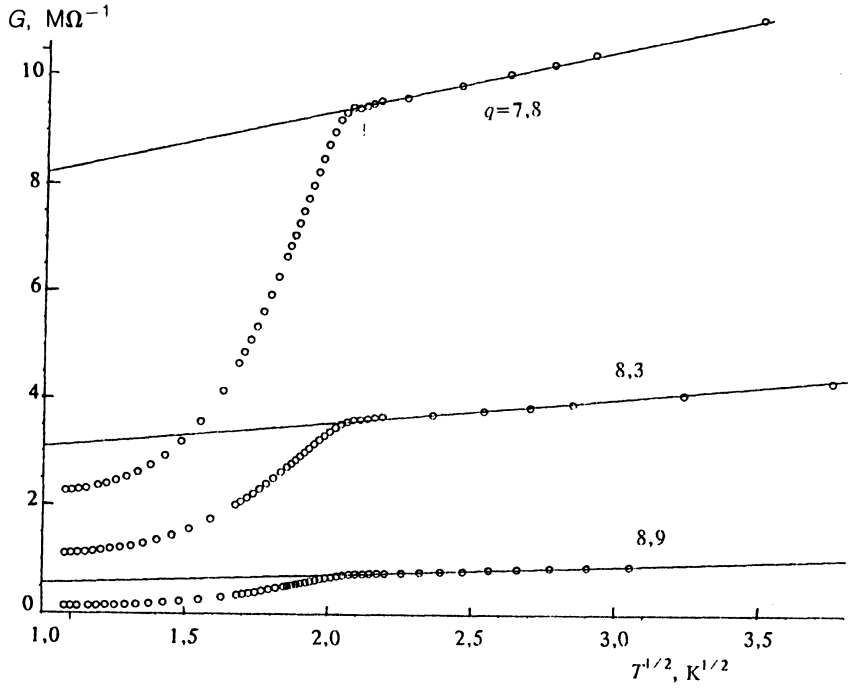

FIG. 3. Temperature dependence of the conductivity of three high-resistance states of a sample.

Figure 3 may give an impression that the $g(T)$ curves tend to a finite value as $T \to 0$. This is due, however, to the nonlinearity of the current-voltage characteristics (IVC), a nonlinearity that is stronger the lower the temperature. Figure 4 shows plots obtained for different measurement currents, i.e., in different electric fields. Since the kink on the curves is not shifted along the T axis, it can be stated that the difference between the curves is not due to overheating of either the sample or the electron gas. It is due exclusively to the direct influence of the electric field on the conduction process. Analysis of the current-voltage characteristic can therefore be used to explain the physical nature of the phenomenon (see the next section).

The fact that the observed decrease of the conductivity is due to superconductivity can be proved by eliminating this decrease by a magnetic field. As seen from Fig. 5, no signs of a change in the character of the conductivity at the point T_c in a 5 T field can be seen on the $R(T)$ curve. The dynamics of destruction of this state is seen from the magnetoresistance curve plotted for 1.27 K (see Fig. 6). Since

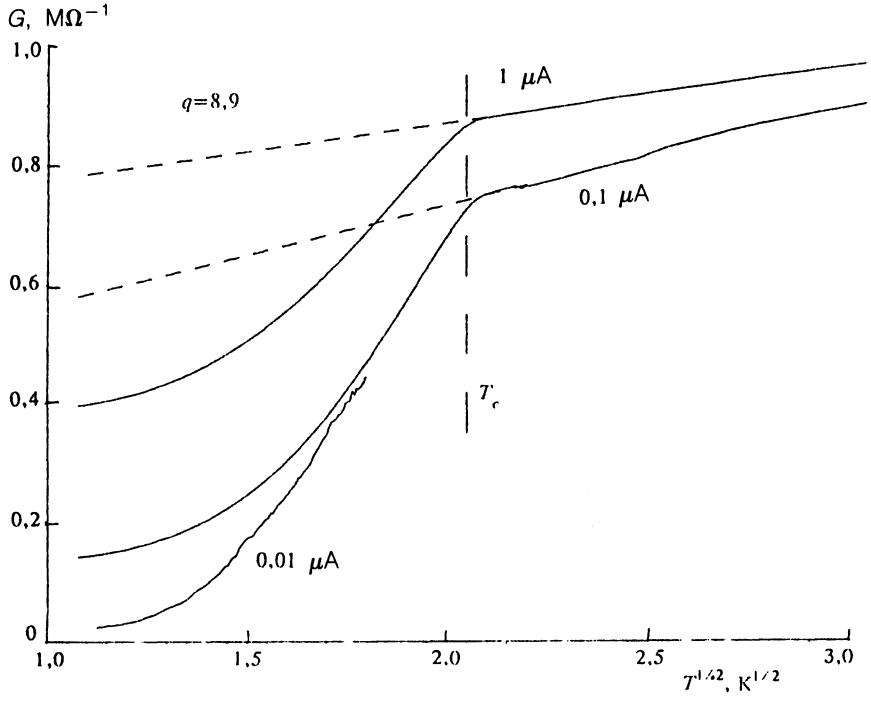

FIG. 4. $G(T^{1/2})$ plots for one and the same state of the sample but for different measurement currents.

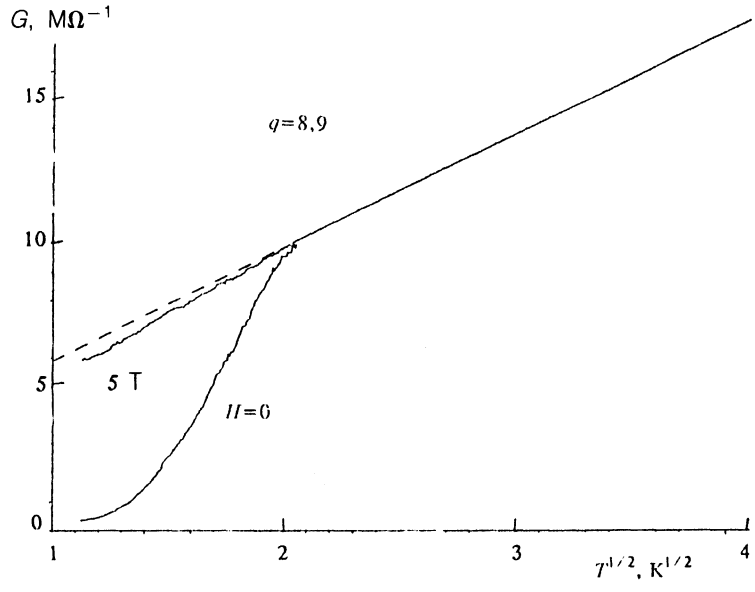

FIG. 5. Reconstruction, by a magnetic field, or "normal" conductivity of a highly resistive state of a sample. Dashed—continuation of the $G(T^{1/2})$ straight plot of the experimental data at $T > T_c$. The data in Figs. 5–8 were obtained in the same sample state, $q=8.9$, as in Figs. 3 and 4, but at shorter distances between the contacts.

$R(T,0)$ increases as $T \to 0$ and $R(T,H)$ tends to a constant if H is large enough, their ratio can be made even larger by lowering the temperature (and the measurement current). On the contrary, if $T > T_c$ there is practically no magnetoresistance at all: applying a 5 T field at 4.24 K leaves the resistance unchanged to within 0.1%. Note that a gigantic negative magnetoresistance of the same order as in Fig. 6 was observed earlier in granulated aluminum in the vicinity of the M-I transition.[27]

3. DISCUSSION

We attempt below to use the known elements to construct a rough model containing the following crucial facts:

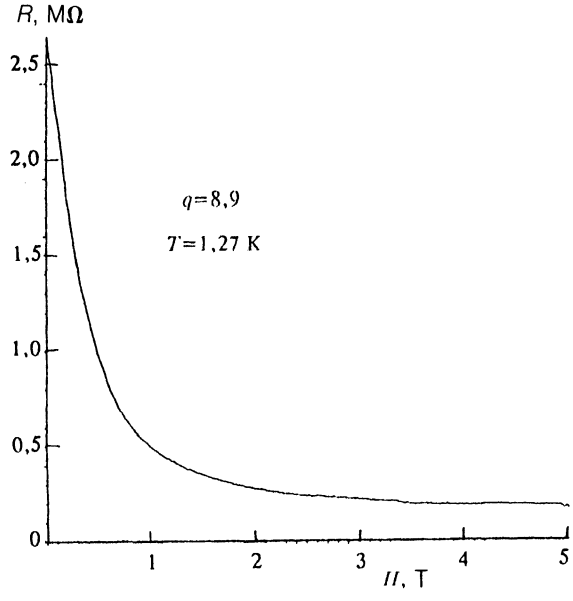

FIG. 6. Giant negative magnetoresistance at $T=1.27$ K.

1. An anomalous response of the material to a superconducting transition—the increase of the resistance at $T < T_c$—indicating that the material cannot be regarded as a homogeneous metal.

2. A $\sigma(T)$ temperature dependence of type (4) above T_c, indicative of M-state in the vicinity of the M-I transition.

3. A dependence, patently unrelated to overheating of the electron system, of the conductance $g(T)$ on the electric field.

4. Finite, albeit small, values of $g(0)$ obtained by extrapolating the $g(T)$ dependence to $T=0$ from the region $T > T_c$, without indications that this extrapolation can lead to a value $g(0)=0$.

We have already mentioned that a sign reversal of the change of the electric resistance of a material at temperatures lower than T_c is possible in principle and has already been observed in granulated material.[23,24] The explanation proposed in Ref. 23 presupposes that the conductivity is controlled in normal as well as S-states by tunneling between grains, but that the tunneling requires the activation energy (1) which is of the order of or larger than the gap energy Δ. These assumptions hold for our problem, except for one—the activation character of the tunneling processes. We shall hereafter neglect in (1) the size quantization compared with the Coulomb energy, which will be identified with the activation energy.

We choose in lieu of the granulated model a layered structure consisting of alternating M- and I-layers, with a current flowing perpendicular to the layers. Let the layers be so thin that the current through the I-layers is due exclusively to tunneling between the M-banks, and the M-layer resistance r_M is much lower than the tunnel resistance, so that the total resistance r of an M-I-M structure is due to the I-layers:

$$r = r_I + r_M \approx r_I \equiv r_{MIM}, \quad r_{MIM} = AN^2(\varepsilon_F), \tag{7}$$

where $N(\varepsilon_F)$ is the state density on the Fermi level in the M-layers and the constant A is determined by the thickness and by other parameters of the I-layer. Since the M-layer dimensions are not bounded, the capacitance C between them is infinite. The charge transport is therefore not connected with a change of the Coulomb energy.

Transition of M-layers into S- state can give rise to two tunnel-current types, single-particle and Josephson. Let the contact resistance r_I be so large that the Josephson current is suppressed by fluctuations.[28] The S-transition of the M-layers will then not affect the overall resistance of the structure in the immediate vicinity of the point T_c, since the single-particle tunnel current remains unchanged. However as the temperature drops and the gap $\Delta(T)$ broadens in the S-bank spectrum, the single-particle tunnel current begins to decrease. In the BCS model the single-particle tunnel current through a junction with a normal resistance r_I and at a voltage V is equal to[29]

$$I=(2/er_I)\exp(-\Delta/T)[2\Delta/(eV+2\Delta)]^{1/2}(eV+\Delta) \times sh(eV/2T)K_0(eV/2T), \quad (8)$$

where K_0 is a modified Bessel function of second order. As $V\to 0$ there appears in Eq. (8) a logarithmic divergence $I/V\propto\ln(2T/eV)$ which is due to the divergence of the electron-state density on the edge of the gap in the BCS model. Introducing a spread in the spectrum and thereby cutting off the divergence at a certain energy $\varepsilon_0\ll\Delta$, we obtain for the junction resistance

$$r_n\equiv r_{SIS}/r_{MIM} \approx\begin{cases}(T/\Delta)\exp(\Delta/T)/\ln(2T/\varepsilon_0), & T\gg\varepsilon_0,\\ (T/\Delta)\exp(\Delta/T), & T\ll\varepsilon_0.\end{cases} \quad (9)$$

To process our experimental data in accordance with this equation, we have used the ΔT dependence from the BCS theory, introducing the function

$$\delta=\Delta(T)/\Delta_0,\quad \Delta_0=1.76\ T_c, \quad (10)$$

and we have plotted the quantity

$$Y=[R(T)/R(4.2\text{ K})](\delta/T)\ln(2T/\varepsilon_0)$$

as a function of δ/T for temperatures $T<3.8$ K (see Fig. 7). The value of Δ_0 is then obtained from the slope of the straight line and from its intercept with the ordinate axis. The value of ε_0 was chosen to satisfy the condition that the difference between these values be as small as possible. For $\varepsilon_0=0.9$ K we obtained $\Delta_0=7.6$ K from the slope and $\Delta_0=9.2$ K from the intercept with the ordinate axis. According to the classical relation (10) we have from the BCS theory $\Delta_0=7.5$ K.

The reasons why the plot deviates at low temperatures from a straight line are not very clear. The most likely cause is the finite measurement current. At any rate, the deviations decrease when the measurement current is decreased.

Let us continue the examination of the experimental data in the framework of the "layered" model.

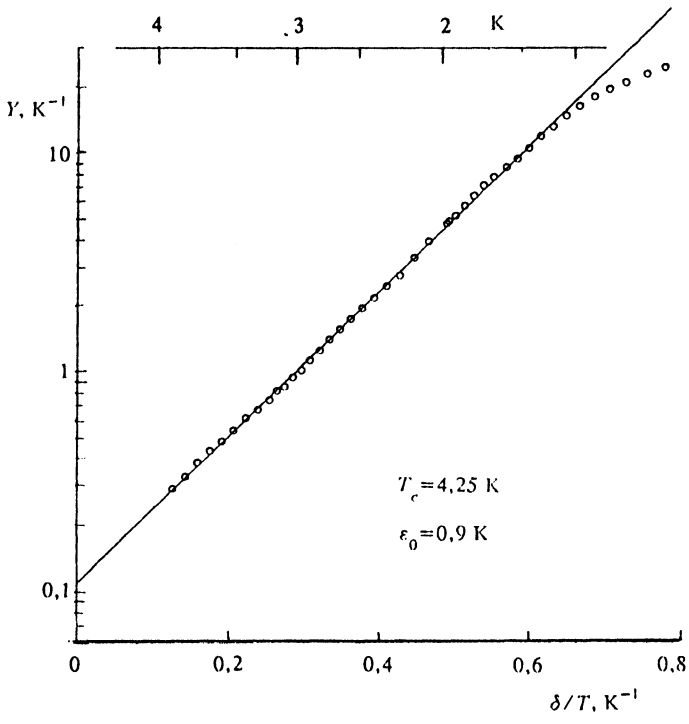

FIG. 7. Reduction of the experimental temperature dependence of the resistance, to determine the value of the superconducting gap from the $R(T)$ curve with $\partial R/\partial T<0$ (see the text).

Hence, according to our assumption (7) the M-layer resistance makes no substantial contribution to the total resistance of the material, the temperature dependence of $\sigma(T)$ above T_c can be attributed to the dependence of the density of states $N(\varepsilon_F)$ on T precisely in the M-layers. This dependence exists because of the *ee* interaction between the free carriers in a disordered medium. This interaction leads to the appearance of the following correction for $N(\varepsilon)$:

$$N(\varepsilon)/N_0(\varepsilon) =\begin{cases}1-\alpha_1(\gamma-|\varepsilon-\varepsilon_F|^{1/2}), & T\ll|\varepsilon-\varepsilon_F|\ll\hbar/\tau,\\ 1-\alpha_2(\gamma-T^{1/2}), & |\varepsilon-\varepsilon_F|\ll T\end{cases} \quad (11)$$

where $N_0\approx$const is the state density without allowance for the *ee* interaction, the constants $\alpha_1\sim\alpha_2\ll 1$ determine the value of the correction, and

$$\gamma\sim(\hbar/\tau)^{1/2},$$

where τ is the elastic relaxation time, which determines the diffusion and the interference in the M phase. Inasmuch as according to (7) the tunnel resistance contains a factor $N^2(\varepsilon_F)$, the temperature-dependent minimum of $N(\varepsilon_F)$ leads to the dependence (4) observed at temperatures higher than T_c.

It is known that the minimum of the density of states on the Fermi level leads to the so-called zero-bias anomalies of the characteristics at zero bias in M-I-M junctions.[32,33] The variation of the state density with energy is usually determined from the dependence of $\partial I/\partial V$

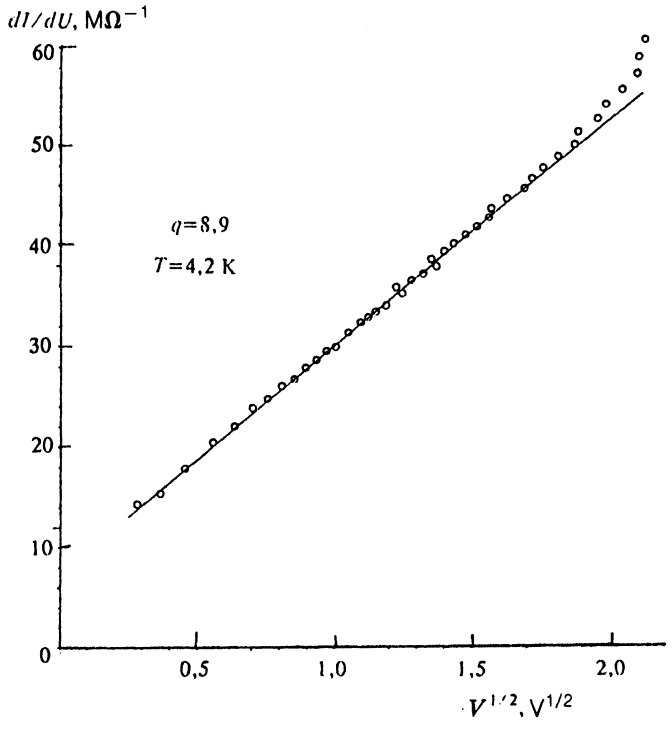

FIG. 8. Square-root dependence of the differential conductivity of a highly resistive state of a sample on the voltage applied to the sample.

on V. The current-voltage characteristic plotted at 4.2 K, i.e., for $T > T_c$, is shown in Fig. 8. The functional dependence

$$\partial I/\partial V = (\partial I/\partial V)_0(1+\beta V^{1/2}) \qquad (12)$$

is usually regarded as proof that the state density near the Fermi level varies with energy in accordance with (11). The equations (11) were obtained under the assumption that the correction is small,[31,32] but they probably remain valid also near the localization threshold.[33] It follows from Fig. 8 that the second term in (12) is in our case not small compared with the first, i.e., that the corrections are not small. Since it is assumed that the minimum of (11) takes place on both banks of the tunnel junctions, one might expect relation (12) to contain the next term that is linear in V. This, however, was not observed in experiment.

Finally, the "layered" model makes it possible to explain qualitatively also the fourth of the experimental facts listed above. Since the conductivity in this structure is not activated, it will remain finite for an arbitrarily small but finite tunneling probability in each structure period even at $T=0$.

A one-dimensional layered structure is too crude a model for an inhomogeneous $3D$ material. It is apparently possible, however, to construct also a three-dimensional structure model with an activationless tunnel conductivity. According to Eq. (1), this calls for large capacitances between the metallic granules. Imagine a $3D$ lattice with a period a having in its sites metal granules which instead of being spherical have the form of loose branched fractals with average branch sizes much larger than a. If the branches of these fractals are intertwined but have no metallic contacts anywhere, we obtain a structure that satisfies the requirements (note that the "branches" may be surfaces rather than lines).

A fractal branched model of an I-phase structure produced by a solid-phase transformation from a metastable M-phase, with increase of the specific volume, was constructed in Ref. 17. Owing to the increase of the volume, the onset of an I-phase nucleus leads to compressive elastic stresses that block the transition. Under these conditions the new phase is built-up of flat nuclei, with tensile stresses on their edges stimulating the transition (see also Ref. 34). As a result, the I-phase layers grow with practically no thickening, but do not intersect (owing to the interference between stresses from different growing layers). The branching continues until the distance h between the I-layers exceeds greatly their thickness d: $h \gg d$. At the same instant when h and d become of the same order, the entire sample volume becomes filled with intermixed M- and I-layers. The M-layers form one infinite cluster, and the I-layers form individual fractal clusters that cover the entire volume of the sample. Their concentration ν is equal to the concentration of the initial nuclei of the new phase. Just this first stage of the structure development was discussed in Ref. 17.

When approximate equality sets in, $h \approx d$, the elastic stresses become equalized and the I-layers start to merge one on the other. The structure is then converted into its inverse, an infinite insulating I-cluster and isolated fractal M-grains. Both are in the characteristic-size interval from $\nu^{-1/3}$ to h ($\approx d$). The M-grain concentration in this stage can also be assumed equal to ν. The surface of each M-grain

$$S \approx (\nu d)^{-1}, \qquad (13)$$

and the capacitance between two neighboring grains is

$$C \approx S/d \approx (\nu d^2)^{-1}. \qquad (14)$$

Taking for the estimate the average distance between nuclei

$$a = \nu^{-1/3} \approx 1\ \mu m \quad \text{and} \quad d \approx 20\ \text{Å},$$

we obtain in (1) a Coulomb energy of the order of 10^{-4} K.

Imagine a sample in the form of a cubic lattice of tunnel resistances r between fractal grains. Using again the value $a \sim 1\ \mu m$ to estimate the lattice period and assuming that the experimental value of the resistance R_L corresponds to a cube with dimension $L \approx 1$ mm, we get

$$r = R_L(a/L) \approx 10^8\ \Omega.$$

The large value of r points that the area S in (14) is not simultaneously the effective area of the tunnel junction. Since the gap d is known to vary from point to point, and the probability of tunneling through the element ds of the barrier is proportional to $\exp(-2\beta d) \leqslant 1$, where β is determined by the height of the barrier, the tunneling is through strips of small area. At the same time, the value of r accounts for the absence of Josephson currents.

Formation of an infinite I-cluster that emerges to the surface of the sample eliminates a large fraction of the tensile stresses, and the structure-evolution character is changed. The structure now consists of layers with gradually increasing thickness and possibly crushed M-granules. This process, naturally, is primarily manifested in the value of R_L and decreases the capacitance C only insignificantly. R_L will therefore increase, but the temperature dependence will remain quasimetallic, i.e., the power law (4) will remain in force.

4. CONCLUSION

The principal distinguishing feature of the evolution of metastable GaSb is that the S-response is inverted in it against the background not of an activation law but of a power law, of the type (4), for the normal conductivity: $\sigma \propto T^n$. The inversion of the S-response is evidence that the conductivity is governed by tunneling processes,[23] but at first glance this agrees poorly with the temperature dependences of the normal conductivity. A model of nonactivation tunneling of the charge between granules having branched surfaces was proposed to explain qualitatively the crucial experimental facts. The choice of appropriate parameters leads even to a quantitative agreement. This agreement, however, is hardly very instructive inasmuch as we are certainly dealing with rather small length scales.

For tunneling to be the principal conduction mechanism, the corresponding dimensions of the I regions should be of the order of tens of Angstrom. The widths of the M-layers is probably of the same order. Under these conditions the sample can hardly be regarded as a mechanical mixture of two phases. More natural is a quantum-mechanical approach positing a single unit sample. In this case, the model in question and the possibility of reconciling it with all the main experimental facts can be regarded as an indication of a classical analog of the quantum-mechanical system. Attempts should be made to formulate the system itself in terms of quantum diffusion, of a single order parameter, of non-phased Cooper pairs, etc. The main experimental task is a search for manifestation of "indivisibility" of this medium.

The experiments performed raise also the question of the feasibility, and under what conditions, of applying a scaling theory of the M-I transition[8,35] to a microscopically non-uniform medium. Annealing converts metastable M-phases into disordered I-phases[16] that are convenient objects for such investigations.

The authors are grateful to V. E. Antonov and E. G. Ponyatovskiĭ for help and interest in the work. This study was part of project 93-02-3271 of the Russia Fund for Basic Research and was supported by a grant from the American Physical Society.

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Translated by J. G. Adashko