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Singularities of the destruction of the conductivity of a cylindrical indium sample by a current

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Results are presented of the measurement of the temperature dependence of the hysteresis in the case when the superconductivity of a cylindrical indium sample is destroyed by current. The large value and the strong temperature dependence of the hysteresis, as well as the fact that the superconductivity is restored when the current is decreased to values lower than the current I_{c0} determined by the Silsbee rule, are in agreement with the assumption that an intermediate state with a Gorter structure exists in the sample.

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An investigation was made of the destruction of the superconductivity of a cylindrical indium sample by a current. It turns out that the destruction does not occur at all in a manner that might be suggested on the basis of a periodic London structure of the intermediate state[1] or its modifications.[2,3] In particular, at low temperatures this process takes place with practically no hysteresis, and when the temperature is raised the hysteresis is substantially increased. Restoration of the superconductivity sets in at currents lower than the critical value $I_{c0} = cr_0H_c/2$ (r_0 is the sample radius and H_c is the critical magnetic field) determined from the Silsbee rule.

EXPERIMENT

The measurements were made on a single-crystal indium sample. The sample diameter was 3.6 mm and the length 70 mm, grown from the melt in a glass tube and its crystallographic orientation was not determined. The resistance ratio obtained by extrapolating the results of measurements above the critical point to $T = 0$ in accord with the rule $R = R_0 + \alpha T^5$ amounted to 1.4 $\times 10^5$.

The experimental setup is shown in Fig. 1. The current through sample 2 was produced by current transformer 4 with superconducting windings, and was measured with an inductive meter 3 by the procedure described in Ref. 4. At temperatures close to critical, experiments were also made in which the current was fed to the sample from outside the dewar. For a more accurate monitoring of the temperature, the sample 2 was placed inside a vacuum jacket 1. The sample temperature could be monitored during the measurements with an Allen-Bradley thermometer T, which could be glued to the sample. The lead current conductors 5 were soldered to the sample with Wood's alloy and were axially symmetrical near the sample. The vacuum jacket was hermetically sealed by a flange joint with an indium gasket 6. The current inside the vacuum jacket was fed through lead wires 8 of 3 mm diameter. The wires were passed inside thin-wall stainless-steel tubes 7 and

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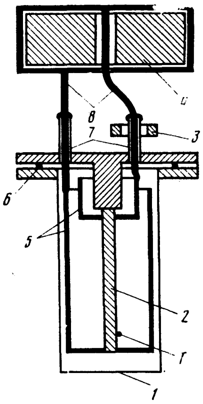

FIG. 1. Experimental setup: 1—vacuum jacket, 2—sample, 3—current-measuring pickup, 4—transformer core, 5—lead-foil current leads, 6—indium vacuum gasket, 7—stainless steel tubes, 8—lead wires.

were soldered; no electric insulation was needed in this case, since the stainless-tube resistance is incomparably larger than the sample resistance.

The described experiments consisted of measuring the current-voltage characteristics of the sample. To this end, two potential contacts separated by 54 mm were clamped to the sample. The voltage on the sample was measured with an F-118 nanovoltmeter and could be plotted with an x-y recorder as a function of the current through the sample. In addition, measurements were made of the surface impedance of the sample; the pickup was a coil of 50-μm copper wire in the form of a solenoid with approximate length 12 mm, placed in the central part of the sample. This coil served as the inductance element of the tank circuit of an RF oscillator; the change of the oscillator frequency, which is proportional to the change of the imaginary part of the surface impedance, was the measured quantity.

In the preliminary experiments we measured also the dependence of the sample critical field on the temperature. These measurements were made in the same instrument, but before the current leads were soldered to the sample. The value of H_c was determined from the instant of the transition of the sample to the normal state upon increase of the longitudinal magnetic field. The longitudinal field was produced with a solenoid placed over the vacuum jacket (1 in Fig. 1). The solenoid was equipped with correcting coils, and the inhomogeneity of the magnetic field over the sample length did not exceed 0.5%. The instant of the transition of the sample to the normal state was determined from measurements of the surface impedance. The sample temperature was determined from the resistance of a carbon thermometer calibrated separately in each helium experiment. The accuracy with which $H_c(T)$ was measured was about 0.5% in the temperature interval 1.2 – 3.3 K (the critical temperature of indium is 3.4 K). It was verified in special experiments that the magnetic field that could be frozen in an indium vacuum-seal ring and in the winding of the superconducting solenoid did not lead to noticeable errors in the determination of H_c.

The earth's magnetic field was cancelled out with two Helmholtz coils, accurate to ~0.02 Oe.

MEASUREMENT OF SAMPLE VOLTAGE WITH THE AID OF A SUPERCONDUCTING TRANSFORMER

The use of a superconducting transformer as a current source uncovers additional possibilities for the measurement of the sample voltage. We examine therefore in somewhat greater detail the operating principle of the current transformer (see Fig. 2). The investigated sample 2 is part of a closed superconducting circuit 3 around a soft-steel core 1 (the core in these experiments was a toroid with cross section ~4 cm^2). Coil I wound on the core has several hundred turns of 50 NT superconducting wire and serves as the primary winding of a transformer whose secondary is the lead loop with the sample. In view of the negligible resistance of the sample, the time constant of such a transformer exceeded 10 min. At temperatures below critical and at currents lower than I_c, the entire secondary loop was superconducting and the current through the sample was $I = N_1 i$ (where i is the current through the primary winding of the transformer and N_1 is the number of turns in the winding). If the superconductivity of the sample is partially destroyed by the current or if the measurements are made at $T > T_c$, then to maintain a constant current in the sample circuit it is necessary to vary the current in the primary winding in such a way that a magnetic flux is maintained continuously in the secondary loop.

Since the entire secondary loop, with the exception of the sample, is always superconducting, the rate of change of the magnetic flux in this loop is $d\Phi/dt = -cV$, where V is the voltage drop across the sample. The magnetic permeability of soft steel is $\mu \gg 1$, so that it can be assumed that the entire magnetic flux is concentrated in the core of the current transformer. The rate of change of the magnetic flux in the core, however, can be easily measured. We determined $d\Phi/dt$ with a special measuring coil (II in Fig. 2), which was also wound onto the core of the superconducting transformer. The voltage on the measuring coil is $V_2 = -c^{-1}N_2 d\Phi/dt$) ($N_2$ is the number of turns of the measuring coil), so that V_2 is N_2 times larger than the potential drop on the sample. The only real restriction on N_2 is the condition is $R_w N_2^2 \ll R_{in}$ (where R_w and R_{in} are respectively the sample resistance and the input resistance of the measuring unit). In our case the measuring coil had 200 turns of thin copper wire.

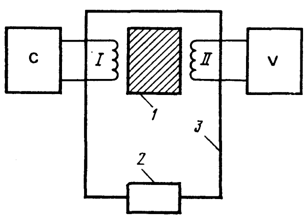

FIG. 2. Diagram of current transformer: 1—transformer core 2—sample, 3—superconducting secondary-winding loop; I—primary winding of transformer, II—measuring winding; C—current-control unit, V—F-118 nanovoltmeter.

This procedure makes it quite easy to measure the very small voltages produced on the sample by passage of a weak current. On the other hand, it must be borne in mind that in this case one measures the total potential difference in the secondary winding, including the potential difference across the junctions of the current leads with the sample. In our experiments the leads were soldered to the sample with Wood's alloy, which is itself superconducting at helium temperatures; nevertheless, the contact between the Wood's alloy and the indium could have a noticeable resistance.

It is quite difficult to determine the junction resistance directly. If the sample is superconducting, the resistance of the junctions is at any rate smaller by a factor of a thousand than the sample resistance in the normal state, but it must be kept in mind that the junction resistance can depend on the temperature and on the current through the sample, and becomes noticeable when the superconductivity of the sample is destroyed. To estimate the junction resistance we have therefore measured the voltage across the sample, using the current transformer simultaneously with the traditional method of recording the voltage between the potential contacts. It makes sense to perform such measurements only at relatively large currents, when the voltage on the potential contacts is high enough to be measured.

Figure 3 shows the current-voltage characteristics of the sample, plotted by both methods at various temperatures, including a temperature below critical. It is seen from this figure that although the sample resistance depends quite strongly on the temperature and on the magnetic field of the current flowing through the sample, the ratio of the voltages on the additional winding and between the potential contacts remains constant at the measurement accuracy. We can thus conclude from these results that the junction resistance is low compared with the sample resistance (otherwise it would be necessary to assume that the dependence of the junction resistance on the temperature and on the magnetic field coincide with that of the resistance of pure indium.

It should be noted, however, that in measurements below the critical temperature there is some difference between the dependences of the voltage on the sample current obtained by the two methods. Thus, at currents lower than I_c, the voltage measured with the transformer decreases with decreasing current at a noticeably slower rate than the voltage on the potential contacts. It appears that the cause of this effect is that some magnetic flux is frozen in near the junctions, and the normal regions connected with this flux are set in motion by the current, and it is this which produces the small potential difference in the sample circuit. When the current is decreased, these normal regions are fixed in place and the potential difference vanishes.

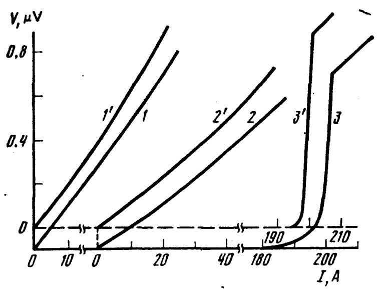

FIG. 3. Current-voltage characteristics of sample. Curves 1′—3′–voltage measured across the potential contacts, 1—3–voltage measured with the special winding of current transformer (these curves were recorded with the voltmeter sensitivity decreased by a factor 250). Curves 1, 1′ —T = 4.2 K, curves 2, 2′ —T = 3.56 K, curves 3, 3′ —T = 1.26 K.

MEASUREMENT RESULTS

Figure 4 shows the sample current-voltage characteristic obtained at T = 3.16 K. It is seen that the destruction of the superconductivity is accompanied by a noticeable hysteresis. We note here also that with increasing current the superconductivity was destroyed gradually, i.e., the region of the steep voltage growth has a certain width. On the contrary, when the current was decreased below a certain value the decrease of the sample voltage was jumplike; it was possible to stop the variation of the current at this point, and then the sample voltage decreased as a function of the time. The curve obtained with increasing current was perfectly reproducible (the repeated plots were superimposed to form a single line). On the other hand the voltage jump with decreasing current could shift to one side or the other. This form of the hysteresis loop indicates that it was precisely the superconducting transition that was delayed relative to the equilibrium situation.

Another interesting circumstance is the strong temperature dependence of the hysteresis (Fig. 5). Thus, the hysteresis practically disappears with decreasing temperature. The magnitude of the hysteresis was determined also from the plots of the surface impedance against the current through the sample. Both methods yielded identical results. At temperatures above 3.1 K the measurements were made also with current fed to the sample from an external source.

The strong dependence of the sample resistance on the temperature and on the magnetic field did not make it possible to determine with any degree of accuracy the size of the resistance jump at $I = I_c$, and no such data are cited here.

As already noted, to exclude possible thermal effects

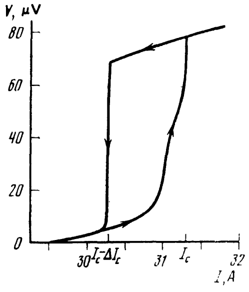

FIG. 4. Current-voltage characteristic (the voltage was measured on the transformer winding); T = 3.16 K.

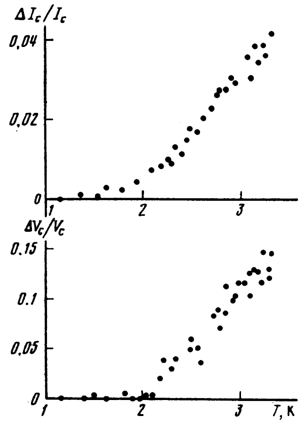

FIG. 5. Temperature dependence of the hysteresis. Upper curve—current, lower—voltage.

the sample temperature was monitored in the course of all the experiments. The change in the critical magnetic field ΔH_c as a result of the overheating of the sample by the current was negligibly small, $\Delta H_c/H_c \lesssim 10^{-3}$, and the random temperature fluctuations were even an order of magnitude smaller.

Since the $H_c(T)$ dependence was determined for the very same sample, it was of interest to compare the experimental value of the destruction current with the value of I_{c0} determined by the Silsbee method. The results of this comparison are shown in Fig. 6. The accuracy of the measurement of both H_c and of the destruction current was about 0.5%, so that I_c/I_{c0} is thus accurate to ~0.01. At temperatures near 3 K the restoration of the superconductivity takes place at currents lower than I_{c0}. This result agrees with the measurements of Posada and Rinderer[5] for tin samples. They have shown that in the purest samples (when the thermal effects can apparently be neglected), the superconductivity is destroyed at currents close to I_{c0} and the superconductivity is restored with decreasing current at lower currents.

DISCUSSION OF RESULTS

It was shown earlier[6] that when the superconductivity of a cylindrical sample is destroyed by a current a Gorter structure of the intermediate state[7,8] should result. The Gorter structure is a system of coaxial cylindrical superconducting and normal layers that move towards the sample axis; as a result, superconducting regions on the sample axis vanish and new ones are produced

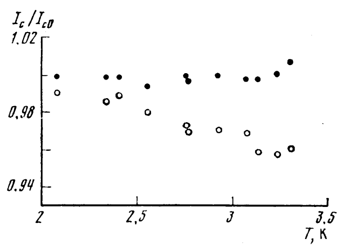

FIG. 6. Temperature dependence of the currents needed to destroy (•) and restore (○) the superconductivity, expressed in units of I_{c0}.

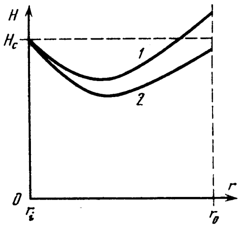

FIG. 7. Schematic distribution of the magnetic field in the normal part of the sample outside the intermediate-state region: curve 1—$I > I_{c0}$, curve 2—$I < I_{c0}$; r_i—radius of the intermediate-state region.

near the surface. The distribution of the magnetic field outside the region of the intermediate state in the case of a Gorter structure takes the form shown schematically in Fig. 7.

The magnetic field, which equals H_c on the boundary of the intermediate-state region, decreases towards the interior of the normal part of the sample, reaches a certain minimum $H = H_{min}$, and then increases towards the sample surface. As the boundary of the intermediate state moves towards the sample axis, H_{min} decreases until, finally, a new superconducting layer is produced in the region of the minimum of the magnetic field. The inner boundary of the superconducting layer begins immediately to move towards the sample surface, and only after some time, when the currents become redistributed in the normal part of the sample, does the outer boundary of the new superconducting layer also begin to move towards the sample axis.

We examine now the process of formation of the new superconducting layer in somewhat greater detail. The creation of the layer takes place at the minimum of the magnetic field, where $H = H_{min} < H_c$; on the other hand, the magnetic field should equal the critical value on the interface between the superconducting layer and the normal metal. This means that the layer boundary should move even at the instant of its creation at a velocity that ensures equality of the magnetic field to the critical value on the phase separation boundary. The condition $H = H_c$ on the layer boundary means that at the instant of the layer creation an additional current with surface density $c(H_c - H_{min})/4\pi$ should flow in the superconducting layer, and since the redistribution of the currents in the normal metal is quite slow, an additional current $-c(H_c - H_{min})/4\pi$ appears in the normal metal on the outer side of the superconducting layer (the minus sign means that the current is directed opposite to the current in the sample).

The speed of the outer boundary of the superconducting layer can be determined in the usual manner from the requirement of continuity of the tangential component of the electric field (see Ref. 9):

$$\mathbf{E} = c^{-1}[\mathbf{v} \times \mathbf{H}]; \tag{1}$$

here v is the velocity of the phase separation boundary, and $\mathbf{E}$ and $\mathbf{H}$ are the values of the electric and magnetic fields on the boundary. In this case $\mathbf{v} \perp \mathbf{H}$ and $|\mathbf{H}| = H_c$, so that condition (1) can be rewritten in the form

$$v = cE/H_c, \tag{2}$$

with

$$E=\rho(j_n+j_1), \quad (3)$$

where ρ is the resistivity of the normal metal, j_n is the current density in the normal part of the sample prior to the onset of the sperconducting layer, and j_1 is the density of the additional currents flowing in the normal metal as a result of the production and motion of the superconducting layer. The quantity j_1 is a function of the distance from the boundary of the superconducting layer and of the time elapsed from the instant of production, the directions of j_1 and j_n being opposite.

An equation for j_1 can be easily obtained from Maxwell's equation curl $\mathbf{E} = c^{-1}\partial H/\partial t$, if we take the curl of both sides and recognize that curl $\mathbf{H} = 4\pi\mathbf{j}/c$ and $\mathbf{E} = \rho\mathbf{j}$. Thus,

$$\text{rot rot } \mathbf{j}_1 = -\frac{4\pi}{c^2\rho}\frac{\partial \mathbf{j}_1}{\partial t}. \quad (4)$$

In our case the problem is axially symmetrical, but if we neglect the curvature of the superconducting layer (this can be done when the changes of the layer radius during the considered processes are small compared with this radius), then Eq. (4) can be rewritten in the form

$$\frac{\partial^2 j_1}{\partial x^2} = \frac{4\pi}{c^2\rho}\frac{\partial j_1}{\partial t}; \quad (5)$$

the coordinate xx is reckoned from the outer boundary of the superconducting layer towards the interior of the normal metal.

To find the function $j_1(x, t)$ by solving Eq. (5) we must also specify the initial and boundary conditions. If we assume that the production of the superconducting layer takes place instantaneously in the form of a thin cylindrical surface of radius r_1, then

$$j_1(x,0) = -\frac{c(H_c - H_{min})}{4\pi r_1}\delta(x). \quad (6)$$

Assuming as before that the changes of the layer radius are small, we can use the following boundary condition:

$$\int_0^{r_0} j_1(x,t)\,dx = \text{const}. \quad (7)$$

Our problem is thus similar to that of the diffusion of a thin layer of matter coated on a bulky sample.

An exact solution of this problem entails considerable mathematical difficulties and would be meaningful only in the presence of more accurate measurements of the dependence of the sample resistance on the current. It must be recognized here also that the equations given above are valid only in the case of a local connection between the electric field and the current density. But the electron mean free path in the investigated sample is not small, i.e., the conditions for the local relation are not satisfied. Qualitatively, however, the foregoing analysis remains valid at any ratio of the mean free path to the sample dimensions.

Thus, the outer boundary of the superconducting layer will move first after its production towards the sample surface; this is accompanied by a redistribution of the currents in the normal part of the sample, and in particular, by a decrease of j_1 at $x = 0$; only then will the condition $j_\perp(0, t) = -j_n$ be satisfied, the outer boundary of the layer will stop, and will subsequently move towards the sample axis. If we denote by r_{max} the radius of the superconducting layer at the instant of stopping, then this quantity is the maximum (with respect to time) radius of the Gorter structure. We note that $r_{max} > r_1$ [see (6)], and the difference $r_{max} - r_1$ is larger the larger the difference between H_{min} and H_c.

If the current in the sample exceeds I_{c0}, then $r_{max} < r_0$. At $I < I_{c0}$ the sample can go over into the superconducting state either if $r_{max}/r_0 = I/I_{c0}$ or if the nucleus of the superconducting phase is produced on the sample surface. In either case the restoration of the superconductivity can occur at currents noticeably lower than critical. It is difficult to identify the particular method whereby the superconductivity is restored in a real sample, since on the one hand it is easier for the nucleus to be produced on the sample surface than in the volume, and on the other hand the magnetic field in the volume of the normal metal is weaker than on the sample surface.

The current at which the superconductivity of the sample is restored is determined in the case of a Gorter structure by the degree to which the normal metal should be supercooled for nucleation of the superconducting phase. When the temperature is lowered the surface tension on the phase separation boundary is decreased, and consequently the degree of the required supercooling of the normal is decreased. Thus, the observed temperature dependence of $\Delta I_c/I_c$ and the fact that the superconductivity is restored at currents lower than I_{c0} agree with the assumption that a Gorter structure of the intermediate state exists.

I am grateful to Yu. V. Sharvin and A. F. Andreev for a discussion of the questions touched upon in this article.

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