Singularities of the superconducting transition during the destruction of superconductivity of a hollow cylindrical sample by a current

I. L. Landau

Institute of Physics Problems, USSR Academy of Sciences
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It was observed, in a study of the destruction of superconductivity of hollow indium cylinders by current, that the experimental current-voltage characteristics (CVC) differ significantly from those deduced on the basis of simple considerations.

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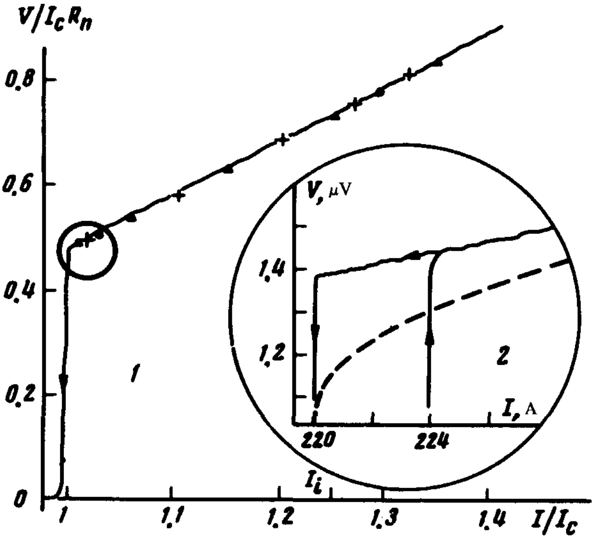
The measurements were performed on two single-crystal samples of indium with small tin impurity. The resistivity ratio $\rho_{300\,°K}/\rho_{0\,°K}$ was 1700 for sample and 3300 for sample II. Both samples had identical dimensions, outside diameter 8 mm, opening diameter 4 mm, length 55 mm. The method of preparing and mounting the samples, and also of obtaining and measuring strong current is described in[1]. The voltage picked off the potential contacts clamped to the central part of the sample was amplified by an F 118 nanovoltmeter and recor ed as a function of the current with an LKD4 automatic recorder. The sample temperature was monitored during the course of the measurements with Allen-Bradley thermometers glued to the internal surface of the sample; both openin in the sample were soldered closed after the installation of the thermometer, and the leads passed through hermetic glass bushings. This procedure made it possible to get rid completely of the errors connected with the uncertainty of t sample temperature even in the case when the sample was heated by the curre to a temperature higher than that of the helium bath.

Figure 1 shows, in a relative scale, the experimental current-voltage chara teristics (solid curves—obtained with automatic recorder, points—obtained by reduction of analog plots). The CVC region near I_c is shown in the same figure in the coordinates V and I. The overheating of the sample by a current (1—1.5 I_c was negligibly small at all temperatures.

The destruction of the superconductivity of the cylindrical sample by curren regardless of whether the sample is hollow or not, should begin when the magnetic field of the current and the outer surface of the sample reaches the critical value H_c, i.e., at a current $I_{c0} = cr_2H_c/2$ (r_2 is the radius of the outer surface of the sample). If the current flowing through the sample is large, one ty of intermediate state structure or another should be produced.[2–4] A very significant distinguishing feature of hollow samples is, however, the presence on the internal surface of the sample of a layer of two-dimensional mixed (TDM) states of type-I superconductors.[5,6] In the case when an intermediate state exists in the volume of the sample, the superconducting domains can directly emerge to the internal surface, whereas the normal ones should be covered by the TDM state. The dependence of the radius of the intermediate-state region



'IG. 1. 1) Dependence of V/I_cR_n on I/I_c (R_n is the sample resistance in the nor-
ıal state). Solid line—plot for sample II, $T=3.02$ °K, $I_c=89$ A; O—sample II, '$=3.361$ °K, $I_c=8.8$ A; ▲—sample II, $T=2.39$ °K, $I_c=218$ A; +—sample I, T 317 °K, $I_c=51$ A. 2) Dependence of V on I; sample II, $T=2.37$ °K. The dashed urve is a plot of the formula $V=(\rho L/2\pi r_2^2)(I+\sqrt{I^2-I_c^2})$.

ın the current is determined, just as in bulky samples, by the London form- .la[2] (see also[4]) $r_{in}=r_2\ (i-\sqrt{i^2-1})$, where $i=I/I_{c0}$. At $I>I_i=I_{c0}(r_1^2+r_2^2)/2r_1r_2$ r_1 is the radius of the opening), the radius of the intermediate-state structure ıecomes smaller than the radius of the opening in the sample, i.e., no inter- nediate state can exist in the volume of the sample at $I\geq I_i$ and the entire sam- ıle, with the exception of a thin TDM layer on its internal surface, should be in he normal state.

Since the sample resistance is determined only by the radius of the inter- nediate-state region, the CVC of a hollow sample at $I<I_i$ should coincide with he CVC of a bulk sample having the same diameter and the same resistivity ρ. 'hus, at $I<I_i$ the voltage on the sample is given, in accordance with[2], by

$$V=\frac{\rho L}{2\pi r_2^2}\left(I+\sqrt{I^2-I_c^2}\right),$$

, is the distance between the potential contacts. A plot of $V(I)$ in accordance ⁄ith this formula is shown dashed in Fig. 1; it should be noted that the value of , determined in the manner shown in Fig. 1 can differ somewhat from I_{c0} (see, .g., [7]). At $I>I_i$, if we neglect the thickness of the TDM layer, we can write $'=R_n(I-I_{\rm TDM})$, where $I_{\rm TDM}$ is the current flowing through the TDM layer and R_n s the sample resistance in the normal state. If $I_{\rm TDM}$ does not depend on the cur- 'ent flowing through the sample, then the CVC in this current region takes the orm of a straight line parallel to the CVC of the normal state. The experimen- al CVC (Fig. 1), however, are linear with good accuracy up to $I=I_c$, at which

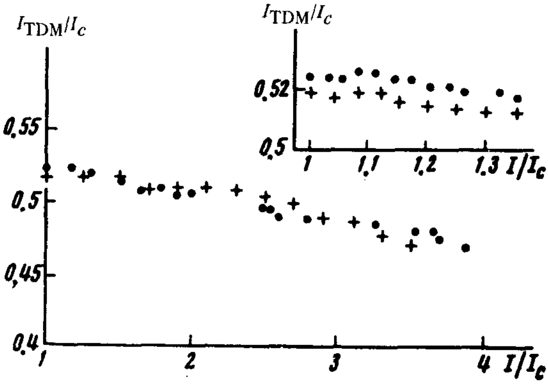


FIG. 2. Dependence of I_{TDM}/I_c. ●—sample I, $T=3.19\,°K$, $I_c=46$ A; △—sample II, $T=3.02\,°K$, $I_c=89$ A.

the sample resistance vanishes jumpwise. This shows that in this case there no intermediate state in the sample volume at any current.

If there is no intermediate state in the volume at $I<I_0$, then a simple calcul tion shows that the magnetic field, which is close to the critical value on the boundary of the TDM layer, decreases in the interior of the normal metal, where it has a minimum, and then increases to a value $2I/cr_2$ on the outer su face of the sample. The fact that destruction of this type takes place in our samples is quite interesting, since the wall thickness in these samples is quit large and accordingly the region in which the normal metal is in a supercoole state has quite appreciable dimensions in the case of small currents. In this situation, it would seem more natural for an intermediate state to be produce on the surface of the TDM layer, since this should lead to a gain of the free energy connected with the normal part of the sample. In other words, the TD state has turned out to be quite stable to the formation of an intermediate-stat structure on its surface.

In light of these results, it becomes understandable why no symptoms of th intermediate state were observed in an investigation of the structure of the T layer with the aid of microcontacts.[5] There is no doubt, however, that in sa ples with thicker walls the destruction of the superconductivity will be accompanied by formation of an intermediate state in the interior of the sample. Th an investigation of samples with $r_1 \ll r_2$ with the aid of microcontacts is of interest and should apparently lead to direct observation of the structure of the intermediate state that is produced when the superconductivity is destroyed b current.

It is possible to determine from the CVC also the value of the current in th TDM-state layer (Fig. 2). The quantity I_{TDM}/I_c is connected in the following manner with the magnetic field at the boundary between the TDM layer and th normal metal $\mathbf{H}^*$:

$$\frac{I_{TDM}}{I_c} = \frac{r_1}{r_2}\frac{I_{co}}{I_c}\left(1+\frac{d}{r_1}\right)\frac{H^*}{H_c} ,$$

ıere d is the thickness of the TDM-state layer; here, too, we took into ac-
unt the possible difference between I_c and I_{c0}. It is interesting that near I_c we
ve

$$\frac{I_{c0}}{I_c}\left(1+\frac{d}{r_1}\right)\frac{H^*}{H_c}=1.04\pm 0.02,$$

e., this quantity exceeds unity.

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