CHANGE IN THE RESISTANCE OF TIN FILMS UPON THE DESTRUCTION OF THEIR SUPERCONDUCTIVITY BY A CURRENT[1)]

A. P. SMIRNOV, V. N. TOTUBALIN, and I. S. PARSHINA

A. F. Ioffe Physico-technical Institute, Academy of Sciences, U.S.S.R.

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It was found that the process of destroying the superconductivity of tin films, $(3-8)\times 10^{-5}$ cm thick, occurred over a wide range of currents. The criteria of criticality of the current are discussed. If the critical current is defined as that which appears when the resistance reaches a certain value, the temperature dependence of the critical current has the form given by Eq. (1), right down to 2.9° K.

SAMPLES. METHOD OF MEASUREMENT. RESULTS

KOLCHIN et al.[1] described a number of phenomena discovered in an investigation of the destruction of the superconductivity of thin tin films by current pulses of various waveforms and durations. In the present paper, we give in greater detail the results obtained from an investigation, in the temperature range 1.7—4.2° K, of the change in the resistance of tin films under the action of square current pulses having a duration of 0.4 μsec and a rise time of 0.05 μsec.

We investigated samples 5—10 mm long, 0.1—0.3 mm wide, and $(3-8)\times 10^{-5}$ cm thick. The samples were prepared by the evaporation of tin from an alundum crucible in 10^{-6} torr vacuum onto polished glass, cooled to a temperature of −70° C.[2] At room temperature, the resistance of the samples R_{293} was 6—30 Ω, but at liquid helium temperature the resistance $R_{4.2}$ decreased to 0.4—1.5 Ω so that $\gamma = R_{293}/R_{4.2} = 14-30$. The residual resistance of the initial material was $\rho = R_{4.2}/R_{293} = (2-5)\times 10^{-5}$.

A generator of the GI-4M type was used as the source of the current pulses. The measurements were carried out using a two-beam oscillograph (type DÉSO-1), which recorded simultaneously the current through the sample and the voltage across it. The resistance was found from the ratio of the voltage and current signal amplitudes. At a bath temperature of 4.2° K, when the sample was in the normal state, the amplification of the oscillograph channels was adjusted so that the amplitudes of the signals corresponding to the current through the sample and the voltage across it were equal at the maximum current through the sample. The equality of the signal amplitudes was not affected by a change in the current. Special attention was paid in the measurements to the stability of the amplification in both the oscillograph channels and to their linearity. These measures made it possible to estimate the resistance with an error of less than 4%. The measurement error of the relative change R_{sn}/R_n did not exceed 1% and was governed by the width of the electron beam of the oscillograph.

Typical oscillograms of the destruction of the superconductivity by a current are given in Fig. 1. All the investigated samples exhibited the following type of destruction of the superconductivity. At a fixed bath temperature (below the critical temperature), the resistance of a sample was zero up to a certain value of the current. For currents greater than this value, the resistance of the sample rose slowly during the action of the current pulse (Figs. 1a and 1b). Beginning at certain current amplitudes in the pulse, the resistance rose only when the current increased but remained steady during the action of the pulse (Figs. 1c and 1d). In order to reduce the average heating of the samples, the measurements were carried out using pulses with a large off-duty factor, equal to 25,000. Current pulses of long duration produced excessive heating of the films even during the pulse itself (Fig. 1e). The step-like nature of the dependence of the resistance on the current, mentioned in[1], was manifested in the oscillograms by the fact that the rise of the voltage across the sample during the action of a

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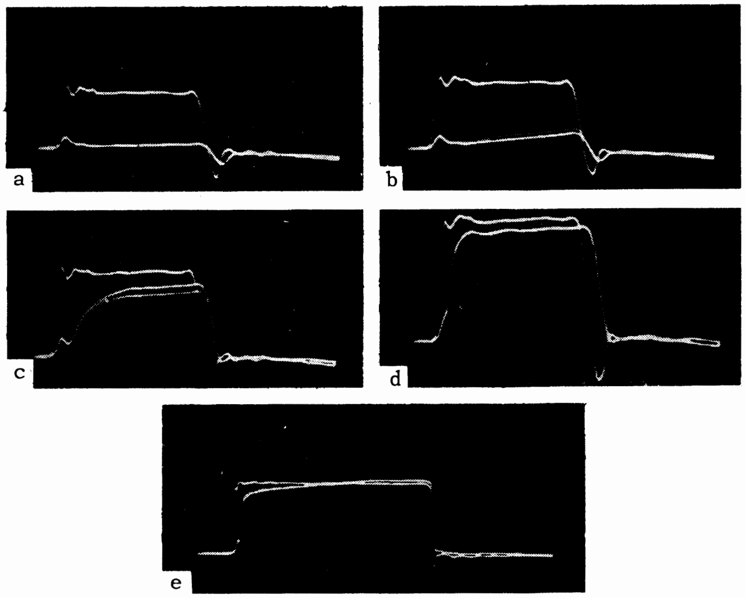

FIG. 1. Current and voltage pulse oscillograms for a sample: a)-d) $\tau_{pul} = 0.4$ μsec; e) $\tau_{pul} = 5.0$ μsec; I_a = 430 mA, I_b = 510 mA, I_c = 630 mA, I_d = 880 mA, I_e = 1100 mA.

pulse could occur in several ways (Figs. 1b and 1c), and by the sudden change in the voltage when there was a slight change in the current through the sample. It should be mentioned that at currents considerably greater than the current at which the resistance appeared, the amplitude of the voltage signal across a film was always smaller than that of the current signal in the oscillograms of all the investigated samples. With cooling, this difference increased.

From the oscillograms, we obtain the dependences of the resistance of a sample on the current for various temperatures, defining the resistance of a film as the ratio of the voltage across it to the current passing through it (at the end of a current pulse). Figure 2 shows part of a family of R(I) curves for one of the samples in the temperature range from T_c to 1.7° K. It is clear from Fig. 2

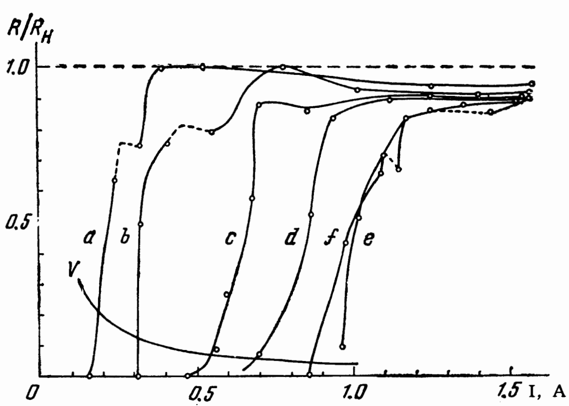

FIG. 2. Dependence of the resistance of a sample on the current at various temperatures ($T_a > T_b > \ldots > T_f$).

that the resistance increases at first very rapidly with the current; this is followed by a region of relatively slow change in the resistance with the current. Over a wide range of currents, the resistance does not reach its value in the normal state. The resistance of the films, measured by the dc potentiometric method, does not change in the temperature region from 4.2° K to T_c, so that one would not expect the residual resistance to decrease with further cooling.

Although the durations of the pulses were short, nevertheless, the dependences R(I) obtained could not be regarded as fully isothermal, particularly when high currents flow through a sample. During the action of a single pulse, the film became hotter than the bath. This caused the heating of the helium next to the film. Since the volume expansion coefficient of helium is very high,[3] this thermal shock produced oscillations in the helium, which indicated that the samples were overheating with respect to the bath. (A detailed report will be given in a separate paper of the results of an investigation of the generation of sound in helium when the normal phase appears in films under the action of current pulses.)

The evolution of the Joule heat governs, to a great extent, the kinetics of the development of the intermediate state. Even at pulse durations such as $\tau = 0.4$ μsec, the growth of the normal phase takes place by a domain mechanism due to the motion of a temperature front, as mentioned in [4,5]. This is evident from the kinks in the voltage curves for a film through which a constant current is passing (Fig. 1c).

ANALYSIS OF THE RESULTS AND DISCUSSION

To analyze the process by which the superconductivity is destroyed, we used the dependences of the resistance of a sample on the current passing through it, obtained by analysis of the oscillograms. A number of characteristic features of the destruction process were discovered.

1. In all the investigated samples, the resistance R_{sn} restored by the current was, at high current densities, less than the resistance R_n of the film in the normal state. During cooling, there was a tendency for the resistance R_{sn} to decrease. This was probably a property of the intermediate state, which was formed when the superconductivity was destroyed in planar samples. The change in the resistance in the process of destruction occurred over a wide range of currents. A reduction in the pulse duration widened the range of the currents in which the destruction of the superconductivity occurred.

2. The film resistance passed through a maximum before reaching the value R_{sn}. This was a feature of planar samples and was not found in cylindrical ones.[5] In the curves given here, the maximum can be seen clearly only at some temperatures. This is due to the method of analysis of the results: the resistance was determined at the end of a pulse, and the possibility of observing a resistance maximum depended on the moment of recording. When a sample was cooled, its resistance maximum shifted to the beginning of the pulse. Since the resistance maximum appeared only in the planar samples, it was obviously related to the redistribution of the current in the process of destruction of the superconductivity.

3. The temperature dependences of the critical current were plotted for different samples (Fig. 3) from the obtained dependences of the resistance of the films on the current at various bath temperatures. It should be pointed out that the choice of criterion which determines the critical current I_c alters greatly the nature of the temperature dependence of this quantity. The critical current may be defined as the current under the action of which a certain fraction of the resistance, say, $0.3R_n$, is established. This criterion gives a parabolic temperature dependence for the critical current of the type

$$I_c = I_0[1 - (T/T_c)^2], \qquad (1)$$

right down to 2.9° K. The same temperature dependence of the critical current is obtained in this range of temperatures if the critical current is regarded as the current which flows at $0.2R_n$, or even $0.5R_n$, but, of course, the value of I_0 is different in Eq. (1). At lower temperatures, there is some departure from the parabolic law (curve b in Fig. 3).

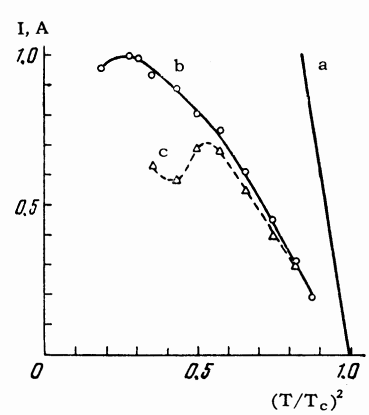

FIG. 3. Temperature dependences of the critical current: a) for bulk metal; b) for a film, according to $I_c = I(R/R_n = 0.3)$; c) for a film, according to $I_c = I_{V=const}$.

For comparison, Fig. 3 includes a parabola (curve a) plotted for a bulk sample. To establish a scale in the calculation of the critical current, it was assumed that the current on the surface of a film was distributed uniformly and that

$$H_j = 0.4\pi j_{surf} = 0.2\pi I / w,$$

where w is the width of the film. The lower values of the critical current may be due to some distribution of the current across the film.[6] It has been mentioned in the published literature that the critical current should increase considerably if the edge effects are eliminated, for example, in the case of a planar sample with a superconducting screen placed close to it.[7] Allowance for the distribution of the current across the film was made in accordance with Rhoderick's work,[8] who reported experimental data confirming the existence in a film of a distribution of the type

$$j(x) = j_0[1 - (2x/w)^2]^{-1/2}, \qquad x < w/2$$

(for the case when $d \approx \lambda$, $w \gg \lambda$, so that $wd \gg \lambda^2$) which, at a distance of $a\lambda^2/2d$ from the edge, goes over into the distribution

$$j(x) = j\left(\frac{w}{2}\right)\exp\left[\frac{-d}{a\lambda^2}\left(\frac{w}{2} - x\right)\right],$$

so that

$$j(w/2) = \frac{j(0)}{\lambda}\sqrt{\frac{wd}{2a}}e^{1/2},$$

where w is the width of the film, d is the film thickness, λ is the depth of penetration, a is a coefficient of the order of unity, x is a running coordinate, measured from the middle of the film,

j_0 is the current density in the middle of the film, and $j(w/2)$ is the current density at the edge of the film.

We may assume that in the investigated samples the beginning of the process of destruction of the superconductivity occurs when the surface density of the current at the edges of the film $j(w/2)$ reaches the critical current density for bulk metal at a given temperature. This makes it possible to estimate the penetration depth λ_j when the superconductivity of films is destroyed by a current. For the investigated films, it was found that in the temperature range where I_c was proportional to H_{cm}, $\lambda_j = 2 \times 10^{-4}$ cm. Kuang Liu Cheng, who used the average free-energy density as the critical parameter,[9] found $\lambda_j = 10^{-4}$ cm.

The critical current can be determined from the "trace" resistance, as has usually been done in the published work, i.e., by recording the appearance of a certain voltage Δv across the sample. In this case, the critical currents are given by the intersection of the family of R(I) curves by the hyperbola $RI = \Delta v$ (cf. Fig. 2). This method of recording may not only give low values of the critical current, compared with the values obtained by determining the critical current from the appearance of some fraction of the resistance, but it may also change the temperature dependence of the critical current, which will differ considerably from the parabolic dependence near T_e. The "trace" resistance criterion may lead to the appearance of "singularities" at some temperatures. The appearance of these singularities and their nature depend on the sensitivity of the apparatus and on the form of the R(I) curves.

Curve c in Fig. 3 illustrates the appearance of such a singularity when a family of R(I) curves (curve b in Fig. 2) is intersected by the hyperbola $RI = \Delta v$. It is interesting to note that the same nature of the temperature dependence of the critical current has been observed in ring-shaped tin films using measurements of the current decay by an induction method, as reported by Mercereau and Crane.[10]

4. In the determination of the critical current from the value of the resistance, the temperature dependences of the critical current are governed also by the moment at which the resistance is recorded. This is because the transition time, i.e., the time during which a certain fraction of the resistance appears, depends on the current amplitude in the pulse.[1,11] As the current amplitude increases, the time necessary to reach a certain value of the resistance decreases, the overheating of the film decreases, and the process of destruction of the superconductivity is governed less and less by the motion of the temperature front in the sample.[5,12] When the duration of the pulse is less or even comparable with the relaxation time of heat along the film and to the substrate, we may observe an adiabatic transition process,[13] which makes it necessary to increase the current in order to achieve the transition.[14] In this case, the kinetics of the destruction of the superconductivity by a current is different, and the heat evolved in the normal regions does not govern the growth of the normal phase and does not affect the destruction of the superconductivity. However, the development of the process of destruction of the superconductivity may be affected considerably by eddy currents.[15] Analysis of the cited papers leads to the conclusion that on destruction of the superconductivity by current pulses of 100—400 nsec duration, the overheating can be neglected only in the initial stage of the destruction of the superconductivity when $R_{sn} < 0.3R_n$ but over a relatively wide range of temperatures.

5. At some values of the current, a step-like rise in the resistance or several transition paths were observed. In Fig. 2, these regions are shown by dashed lines, which represent the maximum value of the resistance. The process of destruction of the superconductivity may even reduce the resistance when there is an increase in the current over a narrow range. Such a change in the resistance has been observed both in measurements using long-duration pulses (100—500 μsec) and in dc measurements near T_c.[1] This observation is a characteristic feature of the destruction of superconductivity, representing the development of the intermediate state in unscreened planar samples, and associated with a redistribution of the current across the film during the process of destruction of the superconductivity. Since our measurements with 400 μsec pulses were not isothermal for $R_{sn} > 0.3R_n$, slight oscillations of the film temperature from pulse to pulse could have produced, due to this feature, a sudden change in the resistance when there was an increase in the current or several transition paths, as shown by the oscillograms (Figs. 1b and 1c).

6. It should be mentioned that there is a considerable departure of the critical current from the parabolic law of Eq. (1). It is possible that this departure is due to differences in heat transfer and is associated with the strong temperature dependence of the properties of helium, which also affect nonstationary processes.[13] The reduction in the depth of penetration λ_j (in the intermediate state) with temperature may also lead to a depar-

ture from the parabolic law because this reduction increases the ratio of the current density at the film edges with respect to the average density through the film (cf. Subsection 3 above). In such a case, there should not be any departure for cylindrical samples. However, there are grounds for assuming that this phenomenon, noted in Hagedorn's paper,[16] is associated with the electron-pair breakup, due to the temperature dependence of the effective film thickness.[17]

A more detailed investigation into the reason for the departure of the temperature dependence of the critical current from a parabola is now being undertaken.

[1] Kolchin, Mikhaĭlov, Reĭnov, Rumyantseva, Smirnov, and Totubalin, JETP **40**, 1543 (1961), Soviet Phys. JETP **13**, 1083 (1961).

[2] Grigor'ev, Mikhaĭlov, Reĭnov, Rumyantseva, and Smirnov, PTÉ, No. 3, 133 (1962).

[3] Fizika nizkikh temperatur (Low Temperature Physics), IIL, 1959.

[4] J. W. Bremer and V. L. Newhouse, Phys. Rev. Letters **1**, 282 (1958).

[5] Hartlin, Wertheimer, and Graham, Can. J. Phys. **42**, 1282 (1964).

[6] R. F. Broom and E. H. Roderick, Proc. Phys. Soc. (London) **79**, 586 (1962).

[7] Newhouse, Bremer, and Edwards, Proc. Inst. Radio Engrs. **48**, 1395 (1960).

[8] E. H. Rhoderick and E. M. Wilson, Nature (London) **194**, 1167 (1962).

[9] Kuang Liu Cheng, J. Appl. Phys. **35**, 1302 (1964).

[10] J. E. Mercereau and L. T. Crane, Phys. Rev. Letters **9**, 381 (1962).

[11] Crittenden, Cooper, and Schmidlin, Proc. Inst. Radio Engrs. **48**, 1233 (1960).

[12] N. E. Alekseevskiĭ and M. N. Mikheeva, JETP **38**, 292 (1960), Soviet Phys. JETP **11**, 211 (1960).

[13] F. B. Hagedorn, Phys. Rev. Letters **12**, 322 (1964).

[14] J. W. Duijvestijn, IBM J. Res. Dev. **3**, 132 (1959).

[15] A. B. Pippard, Phil. Mag. **41**, 243 (1950).

[16] F. B. Hagedorn, Bull. Am. Phys. Soc. **8**, 232 (1963).

[17] P. Fulde and R. A. Ferrell, Phys. Rev. **131**, 2457 (1963).

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