# Destruction of superconductivity in thin narrow films by a current

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We study the conditions for the destruction of superconductivity by a current in thin (440–800 Å) narrow (1–2 μ) Sn films. It is demonstrated that in the absence of a magnetic field the measured critical currents agree with those estimated on the basis of the condition of suppression of the edge potential barrier. In accordance with the phenomenological theory,[6] in films with even edges the suppression occurs when the current density at the edges becomes equal to the pair-breaking current density. At temperatures for which the current is uniformly distributed over the cross section, the pair-breaking current in films with even edges can be attained experimentally. In films with strong edge defects the critical currents decrease as a result of penetration of the vortices through local low spots of the barrier. It is shown that the nature of vortex pinning in films is altered in a magnetic field.

## INTRODUCTION

It is known that the transition from the superconducting to the normal state under the influence of current in thin films can be connected with two circumstances. The first is the intense destruction of the electron pairs when the superconducting condensate reaches critical velocity. The problem of determining the critical current of a film (the pair-breaking current) was solved for this case by Ginzburg and Landau[1,2] for the temperature region close to the critical $T_c$, and also by Maki[3] and by Ovchinnikov[4] for the entire region $T < T_c$. The second circumstance is the possibility of formation of a mixed state owing to the entry of vortices into the film. In a magnetic field perpendicular to the plane of the film, a vortex structure is produced in a sufficiently thin type-I superconducting film[5]. When transport current is made to flow, the magnetic field referred to above is the field produced by the current, and the entry of the vortices is possible at a current much smaller than the pair-breaking current[6,7]. An important role in the determination of the start of the vortex motion is played by edge phenomena.[6,8]

The critical currents of thin superconducting films of finite width have been the subject of many experimental studies (see, e.g. the bibliography of Chap. V in the book by Chopra[9]). In all probability, however, only Hunt[10] reported the results of investigations of the pair-breaking current, although the lack of data concerning certain parameters makes it impossible even in this case to compare correctly the experimental results with the theory, and also casts doubts on the validity on certain assumptions made by him (in particular, the assumed uniform current distribution in a wide temperature range).

The difficulties in the interpretation of the experimental data were caused to a considerable degree by the onset of a mixed state in the thin films. This theory was developed relatively recently by Shmidt[8] and Likharev[6].

The purpose of the present study was an experimental investigation of the destruction of superconductivity by current in narrow thin films, and to ascertain the feasibility of realizing the pair-breaking current $I_c^{GL}$. This problem reduces in fact to a study of the conditions that hinder the formation of a mixed state, particularly before the current in the film reaches the value $I_c^{GL}$.

## EXPERIMENTAL PROCEDURE

The investigated objects were thin narrow films of Sn. The width w of most films was 1—2 μ and was chosen with an aim at maintaining a uniform current distribution in the cross section, at least in the immediate vicinity of $T_c$. The procedure for the production of such narrow films consisted in the following (see also[11]). A layer of tin 1.5—2 μ thick (foil) was sputtered on a quartz-crystal substrate. Long strips, several hundred microns wide, were cut from the obtained foil. The tin strips were slotted with a razor blade over the entire width. A film of desired thickness was then sputtered on the substrate. After the sputtering, the foil strips, which served as masks, were removed with tweezers. The result was a film having the indicated width and a length up to 500 μ. The described procedure excluded the possibility of appreciably decreasing the film thickness at the edges. The edge defects in the better films were less than 0.3 μ in size. The sputtering was at an approximate pressure $2 \times 10^{-6}$ mm Hg at a rate ~100 Å/sec.

To compare the results, we investigated also relatively wide films (w ~ 200 μ), which were obtained by sputtering through a standard mask. The conditions for the sputtering of the narrow and wide films were identical, but in the latter case the thickness could be smaller at the edges, owing to the possible lower sputtering rate. The edge defects in the broad films measured ~2—3 μ.

We measured the dependence of the critical current on the temperature and on the magnetic field $H_\perp$ perpendicular to the film plane, and also the dependence of the film resistance on the parallel and perpendicular electric fields. The measurements were made in the temperature interval 2—4° K. The temperature measurement accuracy was 0.002° K. The measuring current used to plot the superconducting transition curves as functions of resistance in a magnetic field or of the temperature did not exceed 10 μA. The resistance width of the transitions, between the levels 0.9 and 0.1 of $R_{4.2}$ (the film resistance at T = 4.2° K) was usually (3—6) $\times 10^{-2}$° K.

The critical current $I_c$ was determined from the current-voltage characteristics (CVC) of the films, being the current at which the voltage on the film reached 0.1 μV. The current $I_c$ flowing when the restored resistance reaches a constant level $(5 \times 10^{-5}) R_{4.2}$ did not exceed the current measured at the 0.1 $\mu$V level by more than 5%.

The critical temperature was determined by extrapolating the plot of the critical current against temperature to zero. The film resistance at $T_c$, determined in this manner, was $(0.2-0.3)R_{4.2}$.

The critical parallel field $H_{c\parallel}$ and perpendicular field $H_{c\perp}$ were determined from the $R(H_\parallel, H_\perp)$ plots. The critical field was taken to be the field at which the film resistance was restored to its value at $T = T_c$ in the absence of the field.

The parameters of typical investigated films are listed in the table.

The film thickness was determined from measurements of the room-temperature resistance $(R_{300})_{\square}$ and the residual resistance $(R_{4.2})_{\square}$ of a square surface area [12] and from optical measurements with an interference microscope. In addition, the thicknesses of some films were determined from the measured critical magnetic fields $H_{c\perp}$ and $H_{c\parallel}$ near $T_c$ [7,12]. All methods yielded values of d that agreed within 15%.

The residual electron mean free path $l$ was estimated from the values of $R_{300}$ and $R_{4.2}$, using the mean free path $l_f$ in pure bulky tin at 300° K ($l_f$ = 95 Å [12]):

$$l=l_f[R_{300}/R_{4.2}-1]. \qquad (1)$$

The mean free path in all films was less than the coherence length of pure tin, $l < \xi_0$. In addition, the relation $l \sim d$ was satisfied, indicating that boundary scattering played the predominant role.

The coherence length $\xi$ was determined from measurements of $H_{c\perp}$ as a function of T near $T_c$ [13]:

$$\xi(T)=\left[\frac{\Phi_0}{2\pi T_c}\frac{1}{|dH_{c\perp}/dT|}\right]^{1/2}\left(1-\frac{T}{T_c}\right)^{-1/2}, \qquad (2)$$

where $\Phi_0$ is the magnetic-flux quantum. For certain films, the coherence length was determined also from the function $H_{c\parallel}(T)$ [14]. These values agreed well with one another. In those cases when $l$ was $\approx 0.1\,\xi_0$, the values of $\xi$ calculated from the formula for the "dirty" limit [13] exceeded those obtained from magnetic measurements by not more than 15–20%. This discrepancy, which was noted also earlier [14], may be due to the approximate character of the estimate of $l$ from (1).

The depth of penetration of the perpendicular magnetic field $\delta_\perp$ into the film was calculated from the measured residual resistance $(R_{4.2})_{\square}$ by means of the formula [15]:

$$\delta_{\perp[\mu]}=0.83(R_{4.2})_{\square}[\text{ohm}]/(T_c-T)\,[°\text{K}]. \qquad (3)$$

The table lists the values of $\xi(0)$ and $\delta_\perp(0)$ obtained formally from (2) and (3) at T = 0.

Before we change over to an exposition and discussion of the experimental results, we note two circumstances.

Film Parameters

| Film No. | w, μ | d, Å | $T_c$, °K | $(R_{300})_{\square}$, Ω | $(R_{4.2})_{\square}$, Ω | $l$, Å | $\xi(0)$, Å | $\delta_\perp(0)$, Å |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.2 | 480 | 3.86 | 2.60 | 0.32 | 680 | 690 | 700 |
| 2 | 1.6 | 420 | 3.78 | 3.30 | 0.72 | 350 | 630 | 1600 |
| 3 | 2.0 | 690 | 3.70 | 2.00 | 0.40 | 380 | 800 | 900 |
| 4 | 155 | 630 | 3.76 | 2.00 | 0.24 | 700 | 650 | 520 |

1) The condition $d < \xi$ was satisfied in the entire temperature interval ($\delta = (\delta_\perp d/2)^{1/2}$ is the depth of penetration of the magnetic field into a bulky sample of the film material). The condition that the current be uniformly distributed over a width $w \lesssim \delta_\perp$ was satisfied for the narrow films at $T \gtrsim 0.94T_c$.

2) It is known [5] that a film in a perpendicular magnetic field behaves like a type-II superconductor if $\xi < \delta_\perp$. Under the experimental condition this relation held true for all films.

## EXPERIMENTAL RESULTS AND DISCUSSION

1. Let us consider and discuss first the temperature dependences of the critical currents in the absence of a magnetic field.

Figure 1 shows the temperature dependences of $I_c$ of narrow films with even edges. Near $T_c$ they are well approximated by the function $(T_c - T)^{3/2}$. When the temperature is lowered, $I_c$ decreases more slowly, in proportion to $(T_c - T)$. The change of the $I_c(T)$ is more clearly pronounced in Fig. 2.

Figure 3 shows a plot of $I_c(T/T_c)$ for a narrow film with strong edge defects (characteristic dimension of

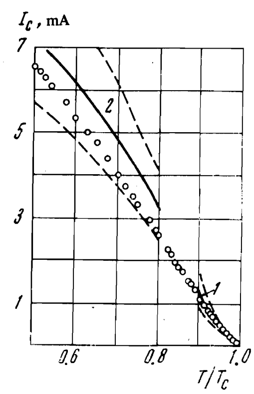


FIG. 1

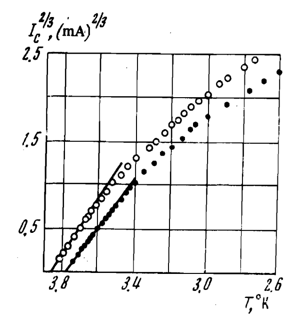


FIG. 2

FIG. 1. Temperature dependences of theoretical current of film No. 1; ○—experimental values. Curve 1—theoretical plot of $I_c^{GL}$ in the range $(1.0-0.9)T_c$; curve 2—$I_c^{non}$ in the range $(0.8-0.5)T_c$. The dashed lines are plots of the same quantities but with allowance for the uncertainties connected with the possible errors in the determination of the film parameters.

FIG. 2. Plots of $[I_c(T)^{2/3}]$; ○—experimental values for film No. 1; ●—for film No. 2. Solid lines—theoretical plots of $[I_c^{GL}(T)]^{2/3}$ for these two films.

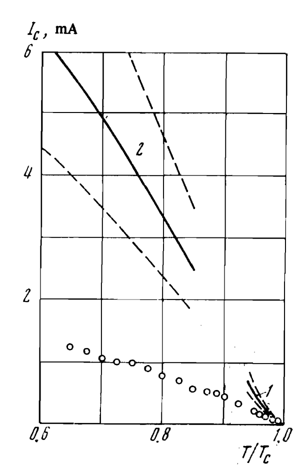


FIG. 3. Temperature dependences of the critical current of film No. 3: ○—experimental values. Curve 1—theoretical plot of $I_c^{GL}$; curve 2—plot of $I_c^{non}$. The dashed lines denote the same plots but with allowance for the uncertainties connected with the errors in the determination of the film parameters.

defects $\Delta w = 0.7\ \mu$). This relation is well approximated in the entire temperature interval by $T_c - T$.

The principal difference (apart from the dimensions) between the investigated films was in the conditions on the edges, owing to the presence of defects of diverse dimensions and shapes. It seems to us that the differences in the character of superconductivity destruction in our experiment is determined to a considerable degree by boundary conditions.

The question of the critical current of superconducting films is closely related with the question of the state produced when the current exceeds the critical value. As is known[6,8], the edge potential barrier present in the sample prevents the production of the mixed state. Likharev[6] has shown that the transection of the film by vortices is energywise favored when an arbitrary small transport current flows, but is possible only when the barrier is suppressed. Galaĭko has shown[16] that the barrier is suppressed in a superconductor when the current density on the edge reaches the critical value $j_c^{GL}$ given by the Ginzburg-Landau theory. This condition turned out to hold for films with even edges[6], at least accurate to a small coefficient. According to the theory[6], when the current is uniformly distributed over the width of the film, the barrier is suppressed only if the current is equal to the pair-breaking current. The details of the transition to the normal state are not clear in this case, since the velocity of superconducting condensate reaches its critical value at the same time[1)], but it should be noted that the transition takes place only after the order parameter is noticeably lowered by the current.

It follows from the data of the preceding section that in narrow films near $T_c$ the current distribution over the cross section is uniform. The expression for the pair-breaking current is then[13]

$$I_c^{GL} = \frac{c\Phi_0}{6\sqrt{3}\pi^2}\frac{w}{\xi\delta_\perp}. \tag{4}$$

It is seen from Figs. 1 and 2 that the theoretical and experimental values of $I_c^{GL}$ and $I_c$ of a narrow film with even edges are in agreement up to $0.9T_c$.

The slower growth of $I_c$ with further decrease of temperature is typical of narrow films with even edges. This slowing down cannot be attributed to edge defects, since they are small in this case. Estimates of the conditions of heat transfer from the film to the helium bath, as well as the experimental data (the agreement between the critical currents measured by the pulsed[2)] and static methods, the absence of a strong increase of $I_c$ on going through the λ point), allow us to state that the "parasitic" effects capable of heating the film are small in the entire investigated temperature region, and have likewise practically no effect on the value of $I_c$. What is fundamental, however, is the fact that in the region $T \sim 0.9T_c$ the value of $\delta_\perp$ becomes equal in magnitude with the width w, and that with further lowering of the temperature the current distribution over the cross section becomes uneven.

If the current in the film is unevenly distributed, it is no longer possible to realize uniform pair breaking. In this case, when the current increases the current density will reach the value of the pair-breaking current density at the edge of the film and suppress the barrier; in the remaining sections of the film, where the density of the superconducting densities is not yet equal to zero, vortex motion sets in. Thus, even if the conditions on the edges of the film are ideal (i.e., in the absence of defects that cause local lowering of the barrier[7,8]) the critical current is always smaller than the pair-breaking current at $\delta_\perp < w$.

Larkin and Ovchinnikov[17] have shown that if the current is much smaller than $I_c^{GL}$ and the conditions $d \ll \xi$, $\delta_\perp$ and $\delta_\perp \ll w$ are satisfied, the current density on the edge of the film j(w/2) is connected with I in the following manner:

$$j(w/2) = I/\sqrt{\pi w \delta_\perp}\, d. \tag{5}$$

As shown in[18], the critical density of the pair-breaking current, calculated in[3,4], is close to $j_c^{GL}$ even when the deviation from $T_c$ is appreciable, provided that the value of $\delta_\perp(T)$ used in (4) is calculated from the microscopic theory, and $\xi(T) = \xi(0)(1 - T/T_c)^{-1/2}$. When these last remarks are taken into account we can obtain from (5) a reasonable estimate of the critical current by equating j(w/2) and $j_c^{GL}$:

$$I^{\text{non}} = \frac{c\Phi_0}{6\sqrt{3}\pi^{3/2}\xi}\sqrt{\frac{w}{\delta_\perp}}. \tag{6}$$

It is seen from Fig. 1 that at $T/T_c \lesssim 0.8$ there is agreement between the experimental values of the critical current and those obtained from (6). A similar agreement is observed also for other films with even edges.

In films with strong edge defects, the critical currents, as can be seen for example from Fig. 3[3)], are smaller than the values obtained from (4) and (6), and agree for most films with those estimated[6,7] from the vortex model, if it is assumed that the vortices begin to penetrate through the local defect regions under the condition $\delta w \approx \Delta w$ ($\delta w$ is the barrier width). For some films, however, the critical currents estimated from this condition are smaller by a factor 1.5–2 than the experimentally observed ones. It can be assumed that in the latter case the vortices penetrate at a current smaller than $I_c$, but are halted by interaction with the volume defects that are inevitably present in the films and play the role of pinning centers[4)].

We proceed now to describe and discuss the results of experiments in a magnetic field, which suppresses, like the transport current, the edge potential barrier of the film.

The conditions for the suppression of the barrier in a film by a magnetic field were considered theoretically by Shmidt[8] and by Likharev[6] for parallel and perpendicular fields, respectively. They analyzed the dependence of the vortex energy in the film on the coordinate and on the magnitude of the magnetic field, and determined the characteristic magnetic field in which qualitative changes of this dependence take place. These are the field $H_{c1}$ starting with which the existence of a vortex in the film becomes energywise favored, and the field $H_s$ at which the barrier is completely suppressed. However, the absence of a superconducting current at $H_\perp > H_s$ is not obvious beforehand, since the vortices penetrating into the film can be halted by pinning centers in the volume.

Figure 4 shows the plots of $I_c(H_\perp)$ of a narrow film with even edges. In the analysis of these relations it is possible to separate three regions of $H_\perp$. In relatively weak fields, $I_c$ depends little on $H_\perp$. The growth of the

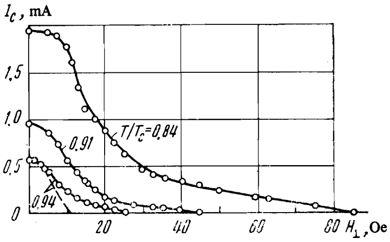


FIG. 4. Plot of $I_c(H_\perp)$ for film No. 1. Dashed line—theoretical plot of formula (10).

field then leads to a noticeable lowering of $I_c$. Finally, with further increase of $H_\perp$, the critical current again depends little on the field, $I_c$ has a "tail" that drops slowly with increasing field.

Let us estimate the current at which the barrier is suppressed, recognizing that in the presence of $H_\perp$ the current distribution over the cross section becomes uneven even if the condition $w \ll \delta_\perp$ is satisfied. If $d < \xi$, $\delta$ and $w < \delta_\perp$ the superconducting-current density satisfies the relation

$$j = -\frac{cA_c}{4\pi\delta^2}(1-a^2)a, \tag{7}$$

where $a = A/A_c$ is the normalized vector potential, $A_c = \Phi_0/2\pi\xi$. It can be assumed that $a = a_0 + a_1 x$ ($a_0$ is the normalized vector potential in the absence of $H_\perp$, $a_1 = 2\pi\xi H_\perp/\Phi_0$, and x is the transverse coordinate), since the vector potential of the current field is much smaller than $a_0$.

Equating $j(w/2)$ to $j_c^{GL}$ we obtain (at $x = w/2$)

$$(1-a^2)a = 2/3\sqrt{3}, \tag{8}$$

whence $a_0 + a_1 w/2 = 1/\sqrt{3}$.

We now determine the current I:

$$I = d\int_{-w/2}^{w/2} j\,dx = a_0 w d\frac{cA_c}{4\pi\delta^2}\left[1 - a_0^2 - \left(\frac{w}{2}a_1\right)^2\right]. \tag{9}$$

Dividing (9) by the current in the absence of the field, taking (8) into account, and introducing $h = wa_1/2$, we obtain

$$I_c^h/I_c^{GL} = 3\sqrt{3}h^3 - 6h^2 + 1. \tag{10}$$

The plot of (10) is shown in Fig. 4 for the temperature at which the current distribution over the section is uniform at $H_\perp = 0$.

We see that in the region of weak fields, the experimental values of $I_c$ coincide with those calculated from (10), but with further increase of the field $I_c^h$ becomes smaller than $I_c$. We note that the field at which the critical current should vanish according to (10) coincides with $H_s$ if the Ginzburg-Landau nonlinearity is taken into account. Since the vortices penetrate into the film even in the absence of the transport current, at least in the region $H_\perp \geq H_s$, the presence of a superconducting current in this case is evidence that the vortices are pinned by the defects in the volume. Thus, whereas in fields $H_\perp \ll H_s$ the vortices are pinned by the edges of the film, owing to the presence of the barrier, and a transition from the Meissner to the dynamic mixed state is realized when the critical current is reached, in strong fields ($H_\perp > H_s$) the barrier is fully suppressed at I = 0 and the critical current is determined by the start of the development of the vortical instability, due to the detachment of the vortices from the pinning centers in the volume (i.e., a transition is realized from the static to the dynamic mixed state). In the intermediate region ($H_\perp \lesssim H_s$), as follows from (10), the barrier is completely suppressed by a sufficiently weak current, and as seen from Fig. 4, an increase of the current first (at $I = I_c^h$) produces a transition from the Meissner mixed state to the static one, and then (at $I = I_c$) to the dynamic mixed state.

The pinning of the vortices on the edges in films with strong edge defects is weaker, and therefore the behavior of $I_c(H_\perp)$ of such films depends to a greater degree on the effectiveness with which the vortices interact with the defects in the volume. Indeed, the vortex penetration in the film takes place in this case in a field $H_\perp^{\Delta w}$ at which the barrier width decreases to Δw. Even in the absence of transport current, the value of $H_\perp^{\Delta w}$ calculated in accord with[6] for films with strong edge defects is much smaller than either $H_s$ or the field at which the superconducting current vanishes. The plots of $I_c(H_\perp)$ of such films are similar (first sharp decrease of $I_c$ with increasing current, following by a slower decrease) to those already described earlier[9,10], at any rate under the condition $w \gg \delta_\perp$.

## CONCLUSIONS

1. We have measured the critical currents of thin ($d < \xi$, $\delta < \delta_\perp$) narrow tin films. We observed that in narrow films with even edges, in the temperature interval $(1.0-0.9)T_c$, where the condition $w \lesssim \delta_\perp$ is satisfied, pair-breaking current is realized. In the case $w > \delta_\perp$, the unevenness of the current distribution over the cross section comes into play, and the measured values of the critical current agree well with those estimated with allowance for the unevenness of the distribution over the cross section[17], under the condition that the pair-breaking current has been reached on the edge of the film.

2. We have investigated the influence of edge defects on the temperature dependence of $I_c$. We show that $I_c$ of films with large edge defects are much smaller than $I_c^{GL}$ and $I_c^{un}$. This is due to the local lowering of the edge potential barrier by the defects and to the formation of a mixed state at relatively weak currents. The results agree well with the conclusions of the phenomenological theory[6].

3. We have investigated the influence of $H_\perp$ on the conditions for the formation of a normal phase. We show that whereas in a weak field ($H_\perp \ll H_s$) and in films with even edges the vortex pinning takes place on the edges, and a transition from the Meissner to the dynamic mixed state takes place at $I = I_c$, in a strong field ($H_\perp > H_s$) the vortices are pinned on defects in the volume, and $I_c$ is determined by the conditions for the transition from the static to the dynamic mixed state. In the intermediate region ($H_\perp \lesssim H_s$) it is possible, by increasing the current, to change from the Meissner to the static mixed state, and subsequently to the dynamic mixed state.

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[1)]In all probability, the statement that the destruction of the superconductivity in the film takes place in the absence of vortices is valid, strictly speaking, only when $w < \xi$, i.e., in the immediate vicinity of $T_c$.

[2)]The pulse duration was 1 μsec and the repetition period 0.5 msec.

[3)]In wide films, the condition $\delta_\perp \ll w$ is satisfied in practically the entire region below $T_c$, and we have $I_c/I_c^{non} \ll 1$ even near $T_c$; for example, for film No. 4 we have $I_c/I_c^{non} \approx 0.1$ at $T = 0.99\ T_c$.

[4)]In films, these pinning centers may be not only structure defects but also local regions of reduced thickness.


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166