New mechanism of penetration of vortices into current-saturated superconducting films

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An analysis is made of a transition to a resistive state occurring under the action of the transport current in wide $w \gg \lambda_\perp$ (w is the width and $\lambda_\perp$ is the effective depth of penetration of a magnetic field) superconducting films. It is shown that the presence of internal defects ensures, in contrast to the models used earlier, that vortex pairs penetrate the film. A theoretical calculation is made of the conditions for the penetration of a magnetic flux by determining the distribution of the superfluid velocity near a region of size $l \ll \lambda_\perp$ where the order parameter is depressed. A calculation is made of the critical pair-penetration current. A method is developed for creating inhomogeneities on the basis of the proximity effect and experiments on the internal penetration of vortices are reported. The distributions of the transport and Meissner currents across the film width are found by a method based on the characteristics of formation of resistive domains. Variation of the heat transfer conditions in the course of internal penetration of vortices is used to reconstruct the temperature profiles of resistive domains of different origin.

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INTRODUCTION

The process of destruction of the supeconducting state is fairly homogeneous films of micron dimensions has been investigated quite thoroughly.[1–4] A model has been proposed and confirmed experimentally by methods which included visual observations [3,4]: according to this model the superconductivity is destroyed by the penetration, through the film edges, of flux vortices or tubes carrying respectively one or several magnetic flux quanta Φ_0. The edge potential barrier hindering penetration plays the dominant role in this mechanism. Obviously, this model is generally applicable also to wide films.[5] Nevertheless, numerous experiments have shown that many features of the appearance of the resistive state in such films cannot be accounted by this model. We shall therefore suggest below a mechanism of the penetration of vortices via internal inhomogeneities.[1)] We shall establish the conditions for controlled realization of this mechanism. We shall use the characteristics of the mechanism in the experimental determination of the distributions of the Meissner and transport currents across a film, of the law describing the fall of temperature in the vicinity of newly formed resistive domains, and of the temperature profiles in regions of strong overheating of a sample (see also Ref. 7).

FUNDAMENTALS OF THE EXPERIMENTS

The general features of the penetration of vortices into a film via an internal defect are illustrated in Fig. 1. This figure gives a transverse cross section of a film along a line passing through an inhomogeneity (inset).

If a film is homogeneous, the lines of force of the magnetic field are effectively expelled from the film (a). In the presence of a defect these lines are distorted (b). When the density of the current at a point B becomes sufficient for the destruction of the superconducting state at this point, the lines of force collapse (c) forming two vortices of opposite signs which begin to travel immediately in opposite directions under the action of the Lorentz force (d). As soon as these vortices travel a sufficient distance from the point B, a second pair penetrates the film, and so on. The result of such a periodic process is a chain of vortices (e) along a line AA' in this film: some of these vortices move toward one edge of the

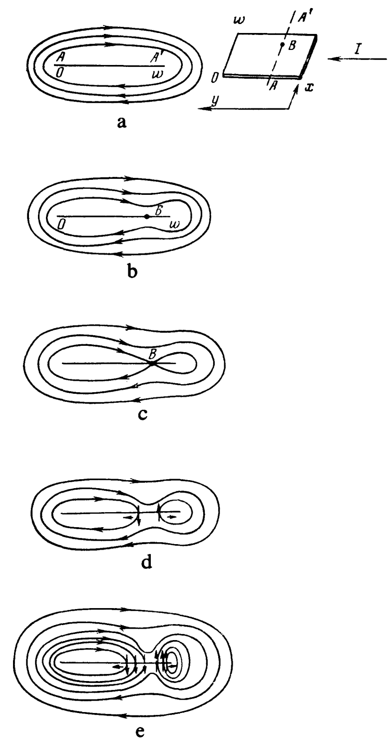

FIG. 1. Penetration of a magnetic flux into a superconductor at an internal defect (B) when the transport current reaches its critical value. Decaying currents (vortices) circulate around the lines of force intersecting a sample and contracting under the action of the Lorentz force at the edges. These vortices form in pairs with opposite signs.

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sample and others toward the other edge. An important feature of this mechanism is the sensitivity of the potential barrier preventing the penetration of vortices to the local density of the current at the position of the defect (inhomogeneity).

One of the early indications supporting this mechanism were the experiments carried out on cylindrical (edge-free) aluminum and tin films,[5] which revealed the appearance of localized resistive regions at currents much lower than the Ginzburg depairing current I_d.

New information on the destruction of the superconducting state was provided by investigations of thin planar films in weak normal magnetic fields H.

It was found that in the presence of a magnetic field a change in the direction of the transport current flowing through the film altered the absolute critical values of the current I_{ci} at which chains of vortices penetrated the film at specific (i) places. Figure 2 shows the experimental points representing the dependences $I_{c+,-}(H)$ obtained for a part of an indium film, where the subscripts $+$, $-$ denote the opposite directions of the current. The close approach of the dependences $I_{c+,-}(H)$ to linearity demonstrates the sensitivity of the potential barrier to the total current density at the point of location of a defect which facilitates penetration of vortex chains and it is explained by the fact that for one direction of the transport current the Meissner (j_m) and the transport (j_t) components of the total current density $j = j_m + j_t$ are added, whereas for the direction they are subtracted.

Following the results of Likharev,[8] we can show that in the case of wide films characterized by $\lambda_\perp/w \ll 1$ ($\lambda_\perp$ is the effective depth of penetration of a magnetic field into a film and w is the film width) the derivative $|dI_{ci}/dH|$ is constant in a wide range of fields and is independent of the quantity

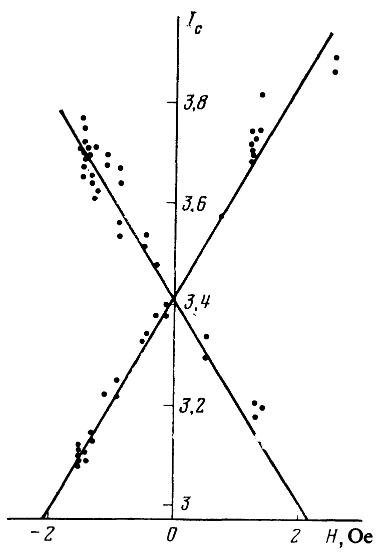

FIG. 2. Dependence of the critical current of a film (in milliamperes) with a defect on the applied magnetic field plotted for different directions of the transport current ($+$, $-$). The branch with $dI_c/dH > 0$ (I_{c-}) corresponds to the subtraction of the Meissner transport components of the total current density in the region of an inhomogeneity, whereas the branch with $dI_c/dH < 0$ (I_{c+}) corresponds to the addition of these current densities.

apart from the position of the defect or cavity relative to the center of the film.[2)] Even the depression of the order parameter by the inhomogeneity can affect only the value of I_{ci} but not its derivative with respect to the field. Consequently, if during the flow of the current the only mechanism of vortex penetration is via the edge defects, then all the resistive domains should have the same value of dI_c/dH, which is positive or negative depending on the side of the film through which a magnetic flux is entering. However, measurements on granulated films evaporated in poor vacuum ($\sim 10^{-3}$–10^{-4} Torr) fail to give this picture. In general, the derivative dI_{ci}/dH has a different value at each point of penetration of vortices. It follows that vortices do indeed enter via internal defects.

THEORETICAL DESCRIPTION

We shall obtain quantitative relationships by considering a film of thickness d for which the London penetration length of a magnetic field is $\lambda \gg d$. This situation is encountered most frequently in the experiments and it is found that $\lambda_\perp = \lambda^2/2d$. We shall assume that a defect represents a region of a depressed order parameter and that its radius is $\xi \ll l \ll \lambda_\perp$ (here, ξ is the coherence length). We shall also assume that this defect is sufficiently strong so that in its vicinity the order parameter is reduced to zero. This is not an essential assumption but it is very natural since only strong inhomogeneities or defects are manifested first in the experiments and, moreover, this assumption simplifies significantly the calculations. The London equations relating the magnetic induction to the current density $\mathbf{j} = en_s\mathbf{v}$ can be written in the form

$$\text{curl}\,\mathbf{B} = (4\pi/c)\,\mathbf{j}; \qquad mc\,\text{curl}\,\mathbf{v} = -eB. \tag{1}$$

Eliminating induction $\mathbf{B}$ from the relationships in Eq. (1) and bearing in mind that the second equation applies only inside the sample, we obtain the following equation for the description of the distribution of the superfluid velocity $\mathbf{v}$:

$$\text{curl}\,\mathbf{v} = \frac{1}{2\pi\lambda_\perp}\int dr'^2 \frac{[\mathbf{r}-\mathbf{r}', \mathbf{v}(\mathbf{r}')]}{|\mathbf{r}-\mathbf{r}'|^3}(1-\theta_D(\mathbf{r}')), \tag{2}$$

where the spherical function $\theta_D(\mathbf{r})$ allows for the fact that in the vicinity of the defect the order parameter and, consequently, the value of n_s vanishes: $\theta_D = \theta(l^2 - |\mathbf{r} - \mathbf{r}_D|^2)$.

Equation (2) must be supplemented by the relationship $\text{div}\,\mathbf{j} = 0$. Moreover, we shall make a number of simplifying assumptions. A defect can be located at any point $\mathbf{r}_D$ in the investigated film but not closer than the distance $\lambda_\perp$ from the edge. Since in the case of a defect-free film the scale of variation of $\mathbf{v}_0$ with the transverse coordinate x is the width w (excluding the region near the edges), it follows that to within terms of the order of $\sim \lambda_\perp/w \ll 1$ we can seek solutions of Eq. (2) in the form

$$\mathbf{v} = \mathbf{v}_0(x) + \mathbf{u}(x, \mathbf{r}-\mathbf{r}_D).$$

The dependence on the first coordinate in $\mathbf{u}$ is slow (the scale of variation is w), whereas the dependence on the second coordinate is fast, so that for $|\mathbf{r} - \mathbf{r}_D| \gg \lambda_\perp$ we have $|\mathbf{u}| \ll |\mathbf{v}_0|$. Therefore, we can ignore the dependence on x in $\mathbf{u}$ and assume simply that $x = x_D$. When such assumptions are made, we readily obtain the following equation for $\mathbf{u}(r) \equiv \mathbf{u}(x_D, r)$ valid in the region $|\mathbf{r}| \gg l$:

$$\operatorname{rot} \mathbf{u} = \frac{1}{2\pi\lambda_\perp} \int dr'^2 \frac{[\mathbf{r}-\mathbf{r}', \mathbf{u}(\mathbf{r}')]}{|\mathbf{r}-\mathbf{r}'|^3} - \frac{l^2}{2\lambda_\perp} \frac{[\mathbf{r}, \mathbf{v}_0(x_D)]}{r}. \quad (3)$$

A solution of Eq. (3) is the following relationship expressed in terms of radial coordinates r and φ:

$$\mathbf{u}(r, \varphi) = -\frac{l^2 v_0(x_D)}{4\lambda_\perp} \left[\mathbf{e}_r \frac{\sin\varphi}{r} + \mathbf{e}_\varphi \cos\varphi \frac{\partial}{\partial r} \right] \times \int_0^\infty \frac{d\tau}{(\tau+1)^{1/2}} \exp(-\tau^{1/2} r/\lambda_\perp). \quad (4)$$

We can easily show that the relationship (4) is satisfied under all the assumptions made above. In fact, if $r \gg \lambda_\perp$, we find from Eq. (4) that

$$\mathbf{u}(r, \varphi) = -\frac{l^2 \lambda_\perp v_0(x_D)}{2r^3} [\mathbf{e}_r \sin\varphi - 2\mathbf{e}_\varphi \cos\varphi]. \quad (5)$$

Consequently, the influence of a defect is local so that at distances $|\mathbf{r}| \sim \lambda_\perp$ the velocity is perturbed only by a small amount $\sim (l/\lambda_\perp)^2$. This important circumstance allows us to ignore the influence of defects on one another if they are separated by distances $|\mathbf{r}| \gg \lambda_\perp$. Unfortunately, although the relationship (3) does give a correct description of the lines of flow of the current and the order of magnitude of u in a region $|\mathbf{r}| \approx l$, the result for this region is quantitatively somewhat underestimated. In determining the critical value of the current for the nucleation of a vortex pair the region $|\mathbf{r}| \approx l$ is the most important. However, in the vicinity of this region we can determine the distribution of $\mathbf{v}$ to within terms $\sim l/\lambda_\perp$ from Eq. (2):

$$\mathbf{u}(r, \varphi) = v_0(x_D) \{ (1 - (l/r)^2) \mathbf{e}_r \sin\varphi + (1 + (l/r)^2) \mathbf{e}_\varphi \cos\varphi \}. \quad (6)$$

This relationship allows us to find the critical value of the current I_c associated with a given defect. We can do this by equating the attractive force between two vortices of opposite signs to the force of their repulsion by the current that flows around the defect. The latter force is maximal for $r = l$ and $\varphi = 0, \pi$. Clearly, this is the condition for the disappearance of a barrier preventing the penetration of a pair of vortices in the presence of a given current. Bearing in mind that[8]

$$j(x_D) = If(x_D) = I/\pi w (1 - \xi_D^2)^{1/2}, \quad (7)$$

where $\xi_D = 2x_D/w$, we obtain the following expression for I_c:

$$I_c = \frac{c\Phi_0 w d}{64\pi\lambda^2 l} (1 - \xi_D^2)^{1/2}. \quad (8)$$

It is interesting to consider also the ratio of I_c to the current I_{c0} corresponding to the penetration of vortices into a homogeneous film (see Ref. 5):

$$I_c/I_{c0} = \frac{1}{4g\varkappa} \left(\frac{\pi w d}{l^2} \right)^{1/2} (1 - \xi_D^2)^{1/2}, \quad (9)$$

where $\varkappa$ is the Ginzburg-Landau parameter and g is a constant of the order of unity (the expression for g in terms of an integral is given in Ref. 5). Strictly speaking, the relationship (8) is valid if $1 - \xi_D^2 \gg \lambda_\perp / w$ (for x_D far from the edges), but qualitatively this relationship should be satisfied also near the edges. Substituting $1 - \xi_D^2 = l/w$ for the edge defects, we find that

$$I_c^k / I_{c0} = \alpha \left(\frac{d}{l} \right)^{1/2} \frac{1}{\varkappa}, \quad (10)$$

where α is a numerical coefficient of the order of unity.

Equation (10) was first derived for the edge defects in Ref. 5 from purely qualitative considerations. The dependence of the ratio I_c^k/I_{c0} on $\varkappa$ was also confirmed experimentally in Ref. 5.

It follows from the above discussion that from the experimental point of view the ideal defects are those characterized by $l \ll \lambda_\perp$. However, in practice it is very difficult to suppress the order parameter in such a small region without disturbing the geometry of a sample. In fact, serious mathematical difficulties are encountered in describing the penetration of vortices into inhomogeneities characterized by $l \gtrsim \lambda_\perp$. Therefore, it is not possible to determine accurately the upper limit of the value of l at which the region of the order parameter is suppressed can be regarded as an internal inhomogeneity. Clearly, if l is sufficiently large, a film can be regarded as a parallel combination of two samples. Then, the conditions for the penetration of vortices at the edges of an inhomogeneity will be identical to the conditions for the penetration to the opposite edges of a film and the mechansim of destruction of the superconducting state can be reduced to the usual form.[1,4]

EXPERIMENTAL METHOD

The conditions for the penetration of a flux were ensured by the proximity effect using evaporated copper "points" with diameters 5×10^{-3}–3×10^{-2} cm. Granulated thin films (~ 1000 Å) of $\approx 7 \times 10^{-1}$ cm width were investigated. They were formed by evaporating high-purity indium or lead on glass substrates in 10^{-3}–10^{-4} Torr vacuum.

The film thickness was monitored during evaporation by a quartz resonator and it was measured with an MII-4 interferometer. Evaporation of the copper "points" (of thickness of the order of 1 μ) took place after the formation of an oxide layer on the surface of a film. This ensured the necessary degree of depression of the order parameter.

The granularity (grain structure) of the films ensured a high homogeneity of the electrical and thermal parameters (they were averaged over a large number of grains) and a high rate of heat evolution in the resistive state, which—in combination with the poor heat transfer to the glass substrate—gave rise to prominent singularities in the current-voltage characteristics which appeared on penetration of the flux. Moreover, an analysis of the results was simplified by the highly developed theoretical description of the electrodynamics of granulated systems.[9]

It should be pointed out that evaporation of copper "points" on indium made it possible to form samples which were unaffected by storage in air, but in this case the order parameter was not depressed so strongly. This had the effect that the current corresponding to the penetration of vortices at artificial defects was sufficient for the penetration of a magnetic flux via random inhomogeneities. In this case the current-voltage characteristics exhibited a large number of "stray" singularities and identification of the ones of interest to us presented difficulties. Moreover, a system of this kind was sensitive to weak fluctuations of the current and temperature, so that reliable results could be obtained only by making a large number of measurements and recording sometimes several thousands of the current-voltage characteristics for a single film. Lead films behaved much better. They were not affected as strongly by the influence of fluctuations and they exhibited practically none of the stray singularities in the current-voltage characteristics, but exposure to air even for half an hour destroyed completely the film in the vicinity of the copper "points". The nature of this effect was not quite clear. It was likely that the copper particles were capable of penetrating the dense oxide layer on Pb and thus facilitate the contact between the film and oxygen. Samples consisting of lead films evaporated on top of copper "points" located directly on a glass substrate were found to be much more stable. In this case the access of oxygen from the copper side was prevented.

Figure 3 shows the general form of the investigated samples. Inhomogeneities were created on one side of a film because the distribution of the transport current across a film was symmetric and simultaneous penetration of vortices from both sides complicated an analysis of the pattern of destruction of the superconducting state. The separation between the points along and across a sample was kept constant and this was monitored with a measuring microscope. The "points" or islands were evaporated simultaneously through a mask. This ensured the same degree of depression of the potential barrier by all the inhomogeneities.

Some samples had an additional potential contact which was used in separate investigations of the various groups of inhomogeneities. The finished films were placed in a cryostat inside a small solenoid. One should point out that indium samples were sensitive to the fields H of the order of the terrestrial field, whereas lead films showed no changes in the current-voltage characteristics on application of fields H up to 40 Oe. Therefore, detailed investigations in weak magnetic fields were carried out only on indium films.

The current-voltage characteristics of the samples were recorded by the four-probe method under constant-current conditions. The temperature in a thermostat was usually selected to be low so that penetration of the first vortex immediately gave rise to a temperature instability.[10] This ensured the appearance of clear and unsmeared voltage steps in the current-voltage characteristics and each of these steps represented a single inhomogeneity. The current-voltage characteristics were recorded under various heat transfer conditions: films were immersed in superfluid liquid helium (He II), in normal helium (He I), or exposed to helium vapor.

A total of 10 samples was investigated. Their behavior was qualitatively similar and it fitted the ideas put forward above.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4a shows the current-voltage characteristic of one of the lead samples obtained at a temperature slightly below the λ point of He. Penetration of vortices at each of the defects was accompanied by the appearance of a corresponding voltage jump in the characteristic. The number of jumps represented the number of inhomogeneities created in this lead film. To a high degree of accuracy we could assume that the resistive domains formed at the points of penetration of the magnetic flux did not interact with one another thermally in superfluid helium, i.e., a domain formed earlier did not heat additionally the next domain (this would have reduced the critical current of the second domain). The terrestrial magnetic field did not affect the current-voltage characteristic of the sample so that we could assume the Meissner current was weak compared with the transport current and that the distribution of the latter across the film width was given by Eq. (7) where x_D should be replaced with x.

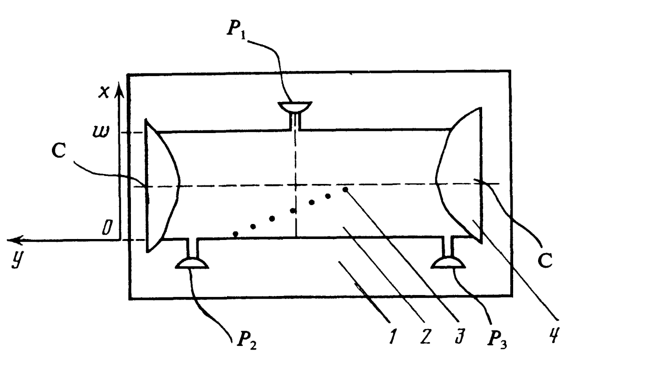

FIG. 3. Schematic representation of the investigated samples: 1) glass substrate; 2) indium or lead films; 3) copper "points"; 4) indium or lead-indium contacts. The letters C are used for the current terminals and P_{1-3} are the potential terminals. The additional potential terminal P_1 makes it possible to separate newly formed resistive domains into two groups.

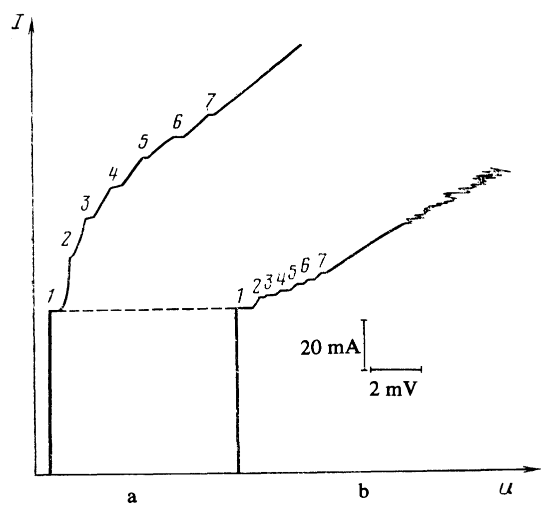

FIG. 4. Current-voltage characteristic of a lead film with seven copper "points" recorded at thermostat temperatures above and below the λ point of He: a) $T_0 = 2.17$ K; b) $T_0 = 2.2$ K. When the sample is immersed in helium I (b), resistive domains interact with one another thermally. The lower rate of heat transfer (compared with the case a) to the thermostat and the higher dissipated power causes bubble formation in the helium and creates noise-like voltage jumps.

Since the density of the transport current was higher at the edges, all the inhomogeneities reduced equally the order parameter and penetration of vortices at a local defect required the attainment of a specific (in this case the same in all cases) current density j_c, so that each inhomogeneity could be set to correspond to a voltage step in the current-voltage characteristic: a step closer to the center corresponded to a higher current.

Knowing the positions of the inhomogeneities, we were able to reconstruct quite simply the experimental distribution of the transport current [i.e., to find the function $f(x)$ of Eq. (7)], because

$$j_c = j_t(x_i) = I_{ci} f(x_i)$$

indicated that $f(x_i) = j_c / I_{ci}$, where I_{ci} are the values of the critical currents on the current-voltage characteristic corresponding to different (i) defects. It should be noted that reconstruction of the distribution of j_t for the indium samples, when the destruction of the superconducting state required much lower currents, could be performed only if the terrestrial magnetic field was first thoroughly screened.

The points in Fig. 5 represent the reconstructed distributions $j_t(x)$ for indium and lead films of different thicknesses. The thin continuous curve corresponds to Eq. (7). Clearly, the greater the thickness of the sample, the closer the distribution of the transport current to the theoretical curve. This can be explained by the fact that the boundaries of the films evaporated through masks are far from sharp. The degree of the influence of this factor decreases for greater thicknesses. For comparison, Fig. 5 shows the width of the "smearing"zone of the boundary (l') for one of the indium samples (▬).

It should be pointed out that although the theoretical nonuniformity of the distribution of the transport current across the film width was predicted some time ago (see Ref. 11), the previous checks have been made by indirect methods: using a magnetic field created near a sample,[11] employing boiling of helium,[12] etc. The most precise is the method based on the direct measurement of the vortex velocity proportional to the local current density.[4] However, complex apparatus is required in such measurements. The method developed by us is direct and at the same time simple to apply.

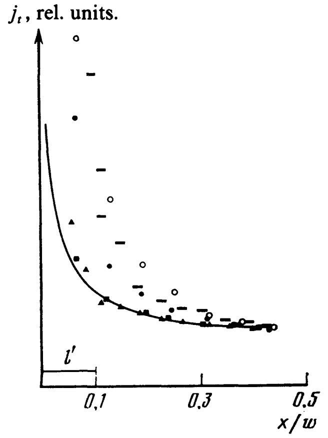

FIG. 5. Reconstructed distribution of the transport current across the width of a film plotted for five samples of different thickness: ○) Pb, $d = 400$ Å; ●) Pb, $d = 800$ Å; ▲) Pb, $d = 1500$ Å; ■) Pb, $d = 2000$ Å; ▬) In, $d = 800$ Å. The thin curve is the theoretical dependence. The deviation from this dependence is due to the "smearing" of the edges. For comparison, the smearing (l') is shown for one of the films (▬).

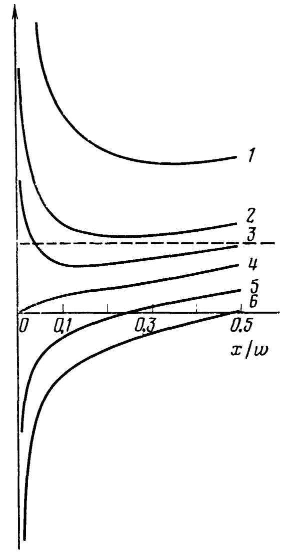

FIG. 6. Distribution of the total current density j across the film width plotted for different ratios of the Meissner and transport components: $j_{t|x=0} = -Aj_{m|x=0}$; here, A has the following values: 1) 3.5; 2) 2; 3) 1.5; 4) 1; 5) 0.5; 6) 0. This illustrates the possibility of penetration of vortices (for $H \neq 0$) at defects closer to the middle of the sample.

The pattern of destruction of the superconducting state of films with defects in the absence of an external magnetic field is fairly simple, but the application of H may complicate it greatly. Figure 6 shows the distribution of the total density in one half of the films, obtained for various values of the field. Curve 1 corresponds to $H \approx 0$, curve 4 corresponds to the equality of j_m and j_t at the edge of a sample, and curve 6 represents the case when j_m was considerably higher than j_t. When on attainment of a critical value I_{ci} the ratio of I and H was such that curve 4 was obtained, then—as demonstrated in Fig. 6—the subsequent increase of the current resulted in penetration of vortices first at defects located in the middle of the film and then at those closer to the edge, in contrast to the situation without the field. In intermediate fields the destruction of the superconductivity should occur first at the edge inhomogeneities, then at those located at the center, and finally at those between the center and the edges. For some of the indium samples such a distortion of the destruction pattern was produced by magnetic fields of the order of the terrestrial field. This made it difficult to analyze the current-voltage characteristics recorded in the absence of magnetic screening.

However, good screening from external fields made it possible not only to reduce the destruction pattern of the superconducting state of thin films to the simplest case and to determine accurately the form of the function $f(x)$ [see Eq. (7)], but also to reconstruct the distribution of the Meissner current across the film width. It was sufficient to record a current-voltage characteristic in a magnetic field, find the distribution of the total current density $j(x)$, and then subtract $j_t(x)$ found from a characteristic recorded in the absence of a field. Our experimental results showed that the correspondence between $j_m(x)$ and the theoretical dependence was reasonable (see Ref. 8).

Additional possibilities were provided by changes in the heat transfer conditions. As soon as the thermostat temperature rose above the λ point of helium, a resistive domain in a lead sample began to heat the point of nucleation of the next domain, etc. The current-voltage characteristic changed in a radical manner (Fig. 4). It should be pointed out that the temperatures at which the current-voltage characteristics of Figs. 4a and 4b were recorded differed by just 0.03 K, so that the value of the first critical current was not affected.

Knowing the critical currents I_{ci} in the absence of the thermal effect and the temperature dependence $I_{ci}(T)$, which in this case could be calculated quite accurately using the Parmenter model[9] or measured experimentally (such measurements were basically in agreement with the model of Ref. 9), we could use the values of I_{ci} for a medium with poor heat transfer to determine the overheating at the points of location of each inhomogeneity (Fig. 7). Then, if the defects were located at the same distance along the film length, we could reconstruct readily the temperature distribution in the vicinity of any resistive domain recalling[10] that in the fully formed state the temperature at the center of a peak remained constant (very close to the critical value T_c) in a wide range of currents. The temperature peaks were the same near each inhomogeneity so that the difference between the degrees of overheating of the domains n and $n+1$ should give the absolute temperature of the first resistive domain at the point of location of the $(n+1)$-th domain. The inset in Fig. 7 shows a reconstructed temperature distribution.

Figure 8 gives the temperature profiles of domains obtained at different thermostat temperatures and for different

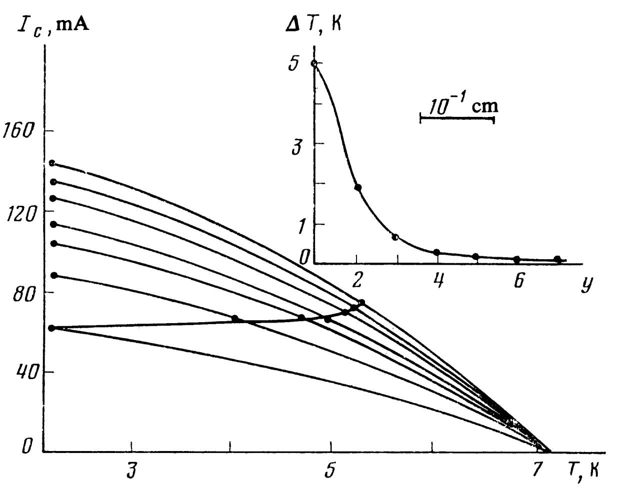

FIG. 7. Procedure for finding the temperature profile of the first resistive domain from the dependences $I_{ci}(T)$ for a film with seven inhomogeneities ($i = 1, 2, \ldots, 7$). The experimental points (●) were obtained by recording current-voltage characteristic of a sample at the moment of transition of liquid helium from the superfluid to the normal state. The inset shows the temperature profile of a domain.

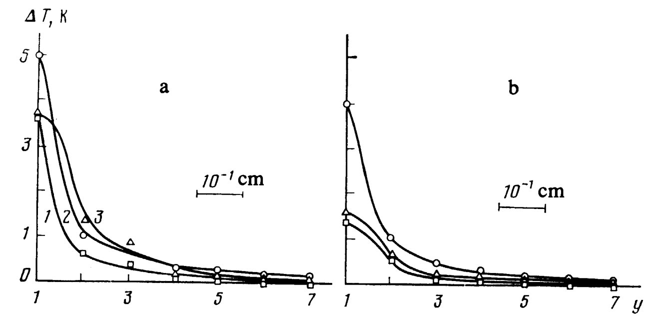

FIG. 8. Reconstructed coordinate dependences of the superheating temperature for resistive domains in two lead samples (a, b) in the case of different thermostat temperatures and different thermal environments: a1) $T_0 = 3.57$ K, liquid He I; a2) $T_0 = 2.2$ K, liquid He I; a3) $T_0 = 3.57$ K, He vapor; b1) $T_0 = 3.25$ K, liquid He I; b2) $T_0 = 5.6$ K, He vapor; b3) $T_0 = 3.58$ K, He vapor. The domain profiles are wider in the vapor environment.

heat transfer conditions in the case of two other lead samples. Clearly, the temperature peaks broadened considerably when helium vapor was used.

We have considered so far vortex penetration into a perfectly homogeneous film. The presence of a macroscopic inhomogeneity (which could be weak) across a sample could result in localization of a large resistive domain. Its description within the framework of a phenomenological model[10] was insufficient. When the localization associated with the smallness of the regions of vortex penetration and with the mechanism of thermal stabilization (due to the formation of a channel with a depressed order parameter in the superheated region) is ignored against the localization background established by a macroinhomogeneity, then the situation is the same as that described by Gurevich and Mints.[13,14]

In this case when a domain of this kind appears near evaporated copper "points," then against the temperature background the penetration of a magnetic flux at the positions of induced inhomogeneities occurs at other (lower) values of the current.

This give rise to a basically different heating pattern of the regions of nucleation of "control" domains. Each subsequent location is superheated less than the preceding one. However, this is not a serious obstacle and by determining the currents corresponding to the appearance of control domains from the nature of the current-voltage characteristic we can easily reconstruct the temperature profile of a Gurevich-Mints domain. However, if the current-voltage characteristic is not recorded when a sample is immersed in superfluid helium or if the induced inhomogeneities are sufficiently close to one another, then the thermal influence of domains must be allowed for in the calculations.

Experiments showed that the profiles of the domains localized at macroinhomogeneities were qualitatively similar to the profiles of the domains that appeared at microdefects in a homogeneous film. This confirmed the possibility of providing a unified description of various thermal domains.

One should also add that our results demonstrated a possible use of the films with deliberately induced regions of a depressed order parameter for the determination of the profiles of external temperature gradients. Granulated systems have a sufficiently high stability and can ensure reliable results after relatively simple calibration procedure and suitable measurements.

We shall consider one other important aspect. All the thermal calculations were carried out in the approximation that ignored the temperature distribution across the film width. This is justified in the case of large domains because within such a domain the current becomes redistributed toward uniform distribution and the rate of heat evolution (which is a function of the vortex velocity and, consequently, of the current density) remains practically constant throughout the whole path of a vortex. However, if the range of motion of a magnetic flux is narrow, the current inside it does not become redistributed and the temperature near the edges are higher, as found in Ref. 12. In this case the relevant corrections should be made to the calculations.

CONCLUSIONS

The experimental results obtained on the process of destruction of the superconducting state in thin films by the transport current are explained by proposing a mechanism of penetration of vortices via internal defects. A method is developed for creating sufficiently effective defects or inhomogeneities that ensure the necessary degree of depression of the order parameter. The main feature of the mechanism, which is the sensitivity of a potential barrier hindering the penetration of vortices to the local current density at the position of a defect, is used in a number of experiments to reconstruct the distributions of the transport and Meissner currents across the width of a sample and to find the temperature profiles of resistive domains of different kinds. It is important to note that the characteristics of domain formation are used as the investigation method. Naturally, this method has a very limited range of validity. For example, a singularity responsible for a sharp voltage step at the moment of penetration of the first vortex ceases to appear in sufficiently strong magnetic fields, when (because of the smallness of the transport current) the evolution of heat along the line of motion of a vortex is below the threshold value. On the other hand, as soon as the Meissner current becomes of the order of the transport current, minima of the Meissner j_m and transport j_t current densities in the regions of depressed order parameters establish conditions favoring effective capture of vortices. Static mixed state regions, similar to those predicted by Kupriyanov and Likharev[15] for homogeneous films, then appear near defects. Some experimental aspects of such an island magnetic structure are discussed in Ref. 16. The appearance of a static mixed state alters the distribution of the currents in a film and distorts greatly the mechanism of penetration of vortices at internal defects.

[1)]In the case of homogeneous films the formation of vortex pairs is not possible in the interior.[6]

[2)]We can quite readily understand, in the qualitative sense, the dependence of the degree of influence of the field on the position of an inhomogeneity. If the inhomogeneity is located at the edge, the Meissner component of the current is maximal at the edge and the degree of influence is greatest, whereas if the inhomogeneity is located at the center of the film, we find that $j_m = 0$ applies irrespective of the value of H and there is no influence of the magnetic field.

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