Thermally induced resistive domains in thin superconducting indium films

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(Submitted 10 February 1982)
Zh. Eksp. Teor. Fiz. **83**, 684–698 (August 1982)

A phenomenological theory describing localized resistive regions in superconducting thin films is used to introduce the concept of elementary resistive domains which are analogs of phase slip centers characteristic of superconducting thin channels and microbridges. The main feature of elementary resistive domains is the same as that of phase slip centers: energy dissipatation in the domains occurs in a region of width $2l_E$, where l_E is the depth of penetration of a longitudinal electric field into the superconductor. It is shown that the number of jumps in the current-voltage characteristic of a film with a domain, recorded under constant-current conditions, is a function of the parameters of the film and is independent of the thermostat temperature. An estimate of l_E is obtained using the experimental current-voltage characteristics of elementary domains and allowing for the inhomogeneous distribution of the current across the film width. Experiments are reported in which resistive domains (including elementary ones) are induced by heaters in the form of evaporated copper films. Characteristic features of domains formed in the presence of a heater include a wide range of currents in which such domains exist, and their disappearance on switching off the heater if the value of the transport current does not exceed a certain critical value, the threshold nature of the excitation at low rates of heat flow, etc. The mechanism of formation of these superdomains is explained schematically and experiments are considered for the separate determination of the currents responsible for the appearance of domains.

PACS numbers: 73.60.Ka, 74.30.Ci, 74.70.Gj

I. INTRODUCTION

The appearance of resistive domains in superconducting thin films during the passage of a transport current is associated with the penetration into a thin film of the lines of force of a magnetic field in the form of vortices or flux tubes.[1] The first vortex appears at the point of location of a defect strongest in the sense of reduction of the potential barrier which a vortex has to overcome. When such a vortex enters a film, it begins to travel at right angles to the direction of flow of the current. It is followed by the next vortex, etc. This creates a chain of moving vortices in a film and the distance between them decreases on increase in the current.

From the moment of formation of a vortex chain the temperature T_m at the center of motion of the flux deviates from the thermostat temperature T_0, i.e., a thermal or resistive domain is formed. An increase in the transport current may increase the temperature T_m not only smoothly, but also—as shown below—in jumps, giving rise to temperature instabilities. The case of a temperature instability resulting in the formation of a normal region was considered by us earlier.[2]

It should be noted that domains formed in a wide (of the order of 1 cm) film free of normal regions are analogs of the so-called phase slip centers. In fact, phase slip centers are characterized by the fact that, at certain points, the modulus of the order parameter of a superconductor $|\psi|$ vanishes periodically. This is also observed in the motion of vortices in resistive domains since any point in a domain is intersected periodically by the core of a vortex where $|\psi| = 0$. We can therefore speak of a spatial wave of the modulus of the order parameter traveling at right-angles to the direction of flow of the current.

Phase slip centers appear most clearly in narrow superconducting strips and microbridges,[3–5] but they do occur also in wide films but at thermostat temperatures very close to a critical value T_c (Ref. 1) at which the vortices are so large that they no longer fit across the film.

When the temperature T_0 is lowered, the vortex size decreases and phase slip centers transform continuously into resistive domains. Vortices then begin to "sense" inhomogeneities of a sample and domains become pinned at these inhomogeneities. This strong influence of inhomogeneities makes the domain structure (in contrast to phase slip centers) nonperiodic. Inhomogeneities also give rise to a large difference between the currents corresponding to the appearance of the individual domains.

The absence of periodicity and the differences between the appearance currents are characteristic not only of resistive domains, but also of phase slip centers provided we ensure an inhomogeneity of a microbridge, as has been done—for example—by Dolan and Jackel.[6] They localized one of the phase slip centers and identified its appearance current by making a small cut in a microbridge and thus increasing the density of the transport current at this point. This procedure enabled Dolan and Jackel to carry out accurate measurements of the difference between quasiparticle potential and the chemical potential of the Cooper pairs within a nonequilibrium region near an induced phase slip center.

The same method can be used to induce domains also in wide films. However, when films are evaporated in poor vacuum (and such films were investigated by us) there is no need to make deliberate cuts. Such films contain a sufficient number of intrinsic defects and inhomogeneities which can act as the vortex introduction centers. Moreover, we may expect that in any region along a film of length of the order of the region of the temperature drop λ_T (which is the thermal size of a domain) we can find an inhomogeneity of one or another size and, consequently, we can in principle create a resistive domain. However, difficulties are encountered in investigations of the properties of a domain which must be excited in a strictly defined region in a sample. If such a region does not contain a "strong" inhomogeneity, a simple increase of the current results in the appearance of a domain in this region when a film already contains many other domains distorting its properties or a domain does not appear at all because the region in question becomes normal or resistive on expansion of a neighboring domain.

We used heaters of width $l_1 < \lambda_T$ to induce in a given region of a film an isolated resistive domain which was stable in a wide range of transport currents and free of the influence of other domains.

We detected domains by recording the current-voltage characteristics of a sample.

PREPARATION OF SAMPLES AND EXPERIMENTAL METHOD

In the final analysis the role of an inhomogeneity at the edge of a wide film or a cut in a microbridge is to lower the edge potential barrier to the penetration of vortices, because the height of the potential barrier decreases on increase in the current density. But there is another factor which determines the barrier height and this is the temperature. Consequently, if at the edge of a film we create a sufficiently small (of size less than λ_T) heat source, we can then readily control a resistive domain without exerting a significant influence on the rest of the sample.

Such a heat source need not be located at the edge of a film because diverging vortices of opposite signs can appear also at the center of a film, although the probability of such appearance is less because the density of the current at the center is less. The feasibility of introduction of vortices at the center of a film is confirmed by the observation that the current-voltage characteristics reflecting the presence of resistive domains in planar films are not qualitatively different from the current-voltage characteristics of cylindrical thin films which have no edges (see Ref. 1). The only difference is that in cylinders the trajectories of the vortex motion are not segments of straight lines but circles. Such a structure resembles a two-dimensional mixed state which appears on the internal surface of a hollow cylinder and represents a system of annular phase slip regions.[7] Such regions have a definite period measured along the cylinder axis and this is a consequence of the complete homogeneity of the cylinder.

Vortices may enter a sample at certain points in a film and they can also be pinned at various centers, which prevents formation of a domain.

We can enhance the mechanism of introduction of vortices by weakening the pinning effect and thus increasing the effectiveness of heating by placing a heater along the whole trajectory of vortex motion, i.e., across a film.

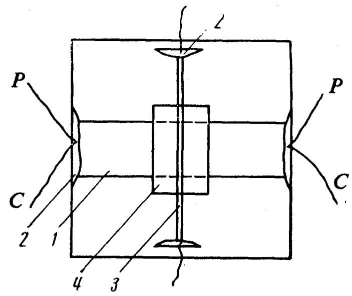

FIG. 1. Schematic diagram of a sample used to study domains induced with the aid of a heater.

Figure 1 shows schematically one of our samples. These samples were prepared by evaporation on a glass substrate in 10^{-4}–10^{-5} Torr vacuum of an indium film 1 of thickness $d \approx 1000$–3000 Å, length $\mathscr{L} \approx 1$–2 cm, and width $L \approx 0.3$–0.5 cm. Indium contacts 2 were deposited first on a substrate (before the evaporation of a film) and both current (C) and potential (P) leads were attached there.

A copper heater 3 of micron thickness and width $l_1 \sim 10^{-3}$–10^{-2} cm was evaporated across the indium film. Numerical estimates indicated that λ_T should be of the order of 10^{-2} cm for films ~ 1000 Å thick with a resistivity $\rho \approx 10^{-5}$ Ω·cm and a Ginzburg–Landau parameter $\varkappa \approx 1$. Therefore, in practically all the cases we were able to satisfy the condition $l_1 \lesssim \lambda_T$, and in some cases even the inequality $l_1 \ll \lambda_T$.

Electrical contact between the indium and copper films was prevented and the proximity effect was avoided by separating these films with a silicon oxide layer 4 of thickness ~ 100 Å.

When a sample was immersed in liquid helium and cooled to a temperature below the critical value, its current-voltage characteristic was recorded during the flow of different currents I_h through the heater. The small transverse cross section of the copper film and its correspondingly high resistance (~ 100 Ω) ensured local heating essential in the process of inducing a resistive domain at currents ~ 10 mA.

The current-voltage characteristics were recorded using the four-probe method under constant-current and constant-voltage conditions. Special attention was paid to the control of the current-voltage characteristics in the case of periodic switching on and off the current through the heater. These characteristics were recorded at T_0 both above and below the λ point of He. The experimental investigation was carried out on 10 samples. All their characteristics and the response exhibited by them to a heat flux from the heater were basically the same, i.e., there was no conflict with the phenomenological model proposed in Ref. 8 or with the ideas put forward in the present paper.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Elementary resistive domains

Before we describe the experimental results, we shall introduce the concept of elementary resistive domains. According to a phenomenological model proposed by the authors earlier,[8] when the dimensions of r_D of defects at which domains appear in superconducting thin films are much smaller than λ_T, the properties of domains must be described using a heat balance equation of the type[2,9,10]

$$\frac{d}{dx}K(T)\frac{dT}{dx}+Q(T)-W(T)+F(T)\delta(x)=0, \qquad (1)$$

in which an important role is played by the term $F(T)$ associated with a local inhomogeneity. The notation used in Eq. (1) is as follows: x is the coordinate along the film length, $K(T)$ is the thermal conductivity, $Q(T)$ and

$$W(T)=h(T)(T-T_0)/d$$

are functions of homogeneous heat evolution and heat transfer to the ambient medium, and $h(T)$ is the heat transfer coefficient. The term $F(T)$ for composite superconductors is treated most fully in Ref. 11. In the case of superconducting thin films this term should be modified[8] allowing for dissipative processes associated with the flow of a magnetic flux. One of the central features of the model of Ref. 8 is a calculation of an electric field E which appears inside a domain, $E(0)$, and in the homogeneous part of the sample, E_0. It should be pointed out that the fall of E from $E(0)$ to E_0 occurs in a characteristic length l_E which is defined by a diffusion-type equation and is associated with the relaxation of electron-like branches of the energy spectrum of excitations.[12–14]

Using the standard method for solving equations with a δ function and applying suitable boundary conditions, we can separate Eq. (1) into an equation which describes the distribution of the temperature in a domain along a sample and which contains just one unknown temperature (which is the temperature at its center T_m) and another equation for T_m which equates the generalized local heat evolution function $V(T,j)$ to the reduced function describing heat transfer to the thermostat $G(T)$. Following Ref. 8, we shall find it convenient to introduce reduced temperatures

$$\zeta=1-T/T_c, \quad \zeta_m=1-T_m/T_c, \quad \zeta_0=1-T_0/T_c,$$

so that $G(T)$ becomes $\zeta_0-\zeta$. The function $V(\zeta,j)$ (here, j is the current density) is described by a much more complex expression. The dependences of this function on ζ are plotted in Fig. 2 for three different values of the current density $j_3>j_2>j_1$. This equation can be solved conveniently by a graphical method. The abscissas of the points of intersection of $V(\zeta,j)$ and $\zeta_0-\zeta$ give ζ_m. However, not all the points of intersection of $\zeta_0-\zeta$ and $V(\zeta,j)$ are stable. Out of those shown in Fig. 2 the points $\tilde{\zeta}_2$ and ζ_4 are stable because in the case of a fluctuation-like increase in temperature the system goes over to a region where the rate of heat transfer to the ambient medium is greater than the rate of heat evolution and, consequently, the system returns to the initial state; such cooling again ensures that the rate of heat evolution is greater than the rate of heat transfer to the ambient medium and the system returns to the previous state.

The points $\zeta_1(j_2)$ and $\tilde{\zeta}_3$ are stable only when temperature is lowered. The absolutely unstable points are not shown in Fig. 2. We can see that on increase in the transport current (exactly as in the process of recording a current-voltage characteristic) the reduced temperature ζ_m first has the

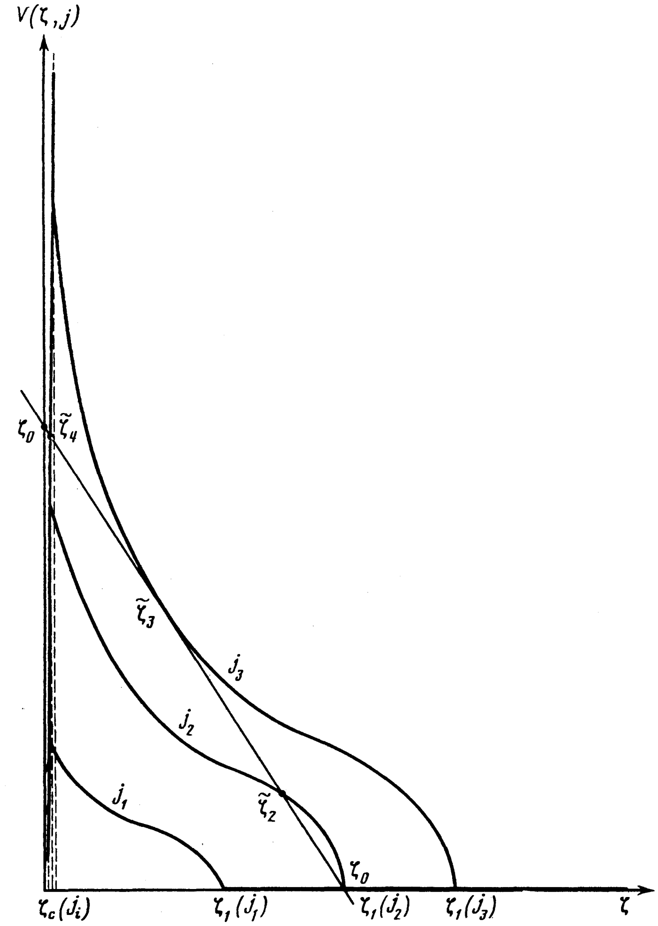

FIG. 2. Graphical solution of the equation for a local heat balance in a film with a domain. The straight line $\zeta_0-\zeta$ is the reduced function representing heat transfer to the ambient medium and $V(\zeta,j)$ is the generalized function of local heat evolution for three values of the current $j_3>j_2>j_1$. The abscissas of the points of intersection of $\zeta_0-\zeta$ and $V(\zeta,j)$ give ζ_m which is the temperature at the center of a resistive domain. When the current is j_1 there is no domain and we have $\zeta_m=\zeta_0$; the currents j_2 and j_3 correspond to the onset of thermal instabilities. At these instabilities the system switches abruptly from the point $\zeta_1(j_2)$ to $\tilde{\zeta}_2$ and from $\tilde{\zeta}_3$ to $\tilde{\zeta}_4$.

value ζ_0 and then it falls abruptly to $\tilde{\zeta}_2$ at a current $j=j_2$. This is followed by a smooth fall of ζ_m and finally at $j=j_3$ there is a second jump when the curve $V(\zeta,j)$ comes in contact with the straight line $\zeta_0-\zeta$ at a point $\tilde{\zeta}_3$. The jumps in ζ_m correspond to changes in the voltage as exhibited by the current-voltage characteristic of a sample.[1)] After the second jump the reduced temperature ζ_m lies first in a narrow interval near ζ_c:

$$\zeta_c=\frac{j}{j_c} \quad (\zeta_c-\zeta_m\ll\zeta_c); \quad j_c=\frac{j_c(T)}{1-T/T_c},$$

where $j_c(T)$ is the critical current for the appearance of dissipation in a defect-free film. This means that the motion of the flux is established in a domain localization region of the order of l_E and there is no normal state in this region.

At high values the reduced temperature ζ_m approaches a constant value[2)] $\zeta_k=(\zeta_0\gamma/\alpha)^{0.444}$. The current-voltage characteristic of a domain becomes linear and it is governed entirely by the quantity[3)] $l_E=\lambda_E/\zeta_k^{1/4}$:

$$U=2E_p l_E(\zeta_p-\zeta_k), \quad (2)$$

where $E_p=\rho j_p$; $\zeta_p=j/j_p$; j_p is the pinning current.

At a higher value of the current we find that a nonlinear term associated with λ_T begins to contribute to U:

$$U'=2E_p\lambda_T\zeta_p\zeta_c/(\zeta_0^2-\zeta_T\zeta_p\zeta_c)^{1/2}, \quad (3)$$

where $\zeta_T=j/j_T$; $j_T=T_c h(T)/2dE_p$. In the linear part of the current-voltage characteristic of a domain the domain resistance R_0 and the excess total current I_0.

$$R_0=2\lambda_E\rho/\zeta_k^{1/4}, \quad I_0=j_p dL\zeta_k, \quad (4)$$

are functions of the thermostat (ambient medium) temperature and of the parameters of the sample as a whole, i.e., they are constant for every domain. As a rule, the linear sections of the current-voltage characteristics of different domains overlap and, for a certain value of the current, a sample may contain several identical (which will be called elementary) resistive regions which are manifested in the current-voltage characteristic of the whole sample by a series of linear regions of different resistances and which emerge from the same point on the current axis. Such a current-voltage characteristic is typical of superconducting thin channels and microbridges. This confirms the correctness of the analogy between phase slip centers and resistive domains.

The current-voltage characteristics of wide films, resembling the characteristics of narrow superconducting channels, were described in Ref. 15. The film materials were aluminum and tin evaporated on substrates made of quartz single crystals to which heat was transferred several orders of magnitude faster than to glass substrates. A general approach for the understanding of a resistive state due to destruction of superconductivity by current flowing in films of different width was mapped out qualitatively in Ref. 15.

The dashed curve in Fig. 3 represents the current-voltage characteristic of sample In-1 corresponding to $\zeta_0=0.3$. We can clearly see resistive regions with

$$R_i=nR_0, \quad (5)$$

corresponding to $n=6$, 7, and 8 and to $R_0=1.8\times10^{-2}\ \Omega$. The transition regions between them exhibit two characteristic jumps.

If we know the value of R_0, we can estimate λ_E. However, it should be pointed out that Eq. (4) gives R_0 and I_0 only in the case of a homogeneous distribution of the current over the film width. When a film is in a superconducting state the current is not distributed homogeneously across its width:

$$j=I/\pi d[y(L-y)]^{1/2}, \quad (6)$$

where y is the running coordinate across the film; I is the total current.

It is logical to assume that in the case when the width of a resistive region $\sim l_E$ is very small, time is insufficient for the current passing through this region to become homogeneous and its distribution inside the domain still obeys Eq. (4), which is valid everywhere except for regions of width $\lambda_\perp=\lambda^2/d$ near the film edges.[1] Here, λ is the depth of penetration of a magnetic film. In the intervals $[0,\lambda_\perp]$ and $[L-\lambda_\perp, L]$ the current density can be assumed to be constant and equal to $I/\pi(\lambda_\perp L)^{1/2}$. The domain resistance R_0 is easily calculated by finding the component of this dissipated power which is a quadratic function of the current:

$$W=\frac{4\rho\lambda_E I^2}{\pi^2 d\zeta_k^{1/4}L}\left[\ln\frac{L}{\lambda_\perp}+1\right]. \quad (7)$$

In the case of sample In-1 the effective mean free path of electrons is $0.014\ \mu$, and we also have $\lambda_\perp=0.02\ \mu$, $L=0.3$ cm, and $\zeta_k=2.7\times10^{-2}$, so that Eq. (7) gives

$$R_0=13.2\rho\lambda_E/dL. \quad (8)$$

If ρ is expressed in terms of the resistance of a sample in its

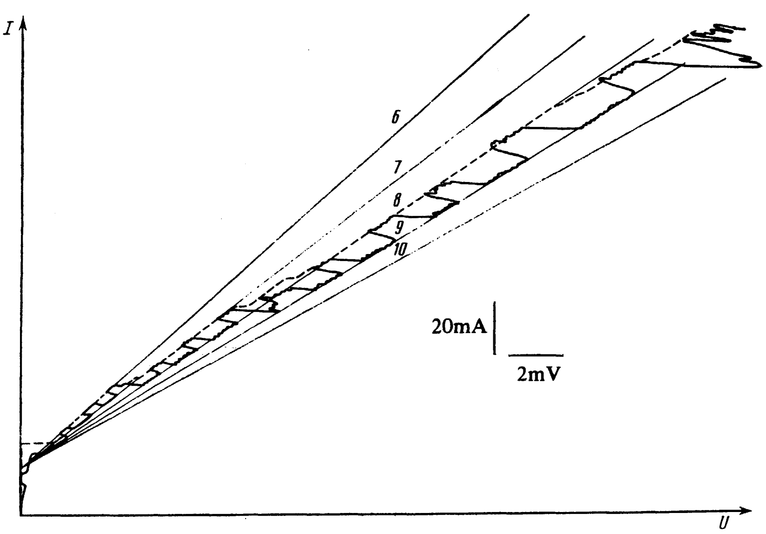

FIG. 3. Current-voltage characteristics of sample In-1 recorded under constant-current conditions. The thin lines represent resistive states corresponding to the presence of 6–10 elementary domains in a sample. The dashed curve is the current-voltage characteristic in the absence of a current through a heater. The formation of free elementary domains is accompanied by two voltage jumps. The continuous thick curve illustrates formation of an additional elementary domain when the current through a heater is switched on and then off. All domains, including the induced one, are characterized by the same resistance and the same excess current.

normal state $R = 2.33\ \Omega$, we find that $\lambda_E = R_0\mathscr{L}/13.2R = 9\times10^{-4}$ cm. This value agrees well with λ_E found directly by measurements on thin samples carried out by Clarke[16] and with the results of other investigations (see, for example, Ref. 17).

An estimate shows that $\lambda_T/\lambda_E = 11$, i.e., we can assume that $\lambda_T \gg \lambda_E$. This is important for the model[8] of resistive states (see also Ref. 2).

The deviation of the current-voltage characteristics in Fig. 3 from linearity observed at high currents is due to the appearance of a nonlinear term in the expression for U [see Eq. 3]. We can see from Eq. (8) that the influence of inhomogeneity of the distribution of the current across the width of the film on the current-voltage characteristic of a sample is manifested by an increase (in the case of sample In-1 with $L/\lambda_\perp = 1.5\times10^5$. The increase is by a factor exceeding six) of the resistance of an elementary resistive domain. If the current in a film is distributed homogeneously, which is typical of narrow channels and microbridges, the current-voltage characteristic of a resistive domain in its linear region is

$$U = \frac{2\rho l_E}{dL}(I - I_0),$$

exactly as in the case of phase slip centers (see Refs. 3 and 4). This is a further confirmation of the common origin of these centers and resistive domains.

2. Thermally induced domains

The temperature distribution in a domain in the direction along a sample (Ref. 2) is

$$|x| = \int_T^{T_m} \frac{dT'K(T')}{[2S(T')]^{1/2}}, \qquad S(T) = \int_{T_0}^{T} dTK(T)[W(T) - Q(T)]. \tag{9}$$

Since at some value of T_0 the quantities $S(T)$ and $K(T)$ are constant along the length of the sample and are independent of j, then all the differences between domains which appear at various points for different values of the current are concentrated in T_m (or in ζ_m).

In contrast to Ref. 11, the constancy of the electrical and thermal characteristics along a film is not in conflict with a strong inhomogeneity of a sample in the sense of a reduction in the potential barrier impeding the introduction of vortices, because the barrier-lowering defects are much less than the film width, $r_D \ll L$, and because the quantities $K(T)$, $\rho(T)$, $h(T)$, etc., are averaged over a large number of similar inhomogeneities along L.

The value of ζ_m is found by solving the following equation (see Ref. 8):

$$(\zeta - \zeta_0)^2 = L^2(\zeta, j) + B(\zeta, j);$$
$$L(\zeta, j) = F(\zeta, j)\frac{1}{2T_c}\left(\frac{d}{Kh}\right)^{1/2}, \tag{10}$$

where $L(\zeta, j)$ is a term which is associated with a local heat evolution at the point where a barrier is lowered and $B(\zeta, j)$ is the heat evolved because the temperature near a domain becomes higher than ζ_c, which corresponds to the onset of homogeneous flow of the flux. At high currents we have $L \propto j$, and $B \propto j^2$.

We shall now consider a domain which appears because of heating. Introduction of a heater of length $l_1 \ll \lambda_T$, is mathematically equivalent to the addition to $F(T)$ or $L(\zeta, j)$ of a term L' which is independent of j and ζ. Since, according to Eq. (10), the presence of a heater simply alters ζ_m dependence on ζ_0, it is convenient to compare a domain with a heater carrying a current j and a domain without a heater with the same value of j but with a different effective thermostat temperature ζ_0^*. The value of ζ_0^* is found formally from the system of equations

$$(\zeta_0 - \zeta)^2 = [L' + L(\zeta, j)]^2 + B(\zeta, j), \quad (\zeta_0^* - \zeta)^2 = L^2(\zeta, j) + B(\zeta, j). \tag{11}$$

We find from Eq. (11) that

$$\zeta_0^* = \zeta_0 - [(L + L')^2 + B]^{1/2} + (L^2 + B)^{1/2}. \tag{12}$$

We can readily see that at low values of j, when $\zeta_m < \zeta_c$ and $B = 0$, we have $\zeta_0^* = \zeta_0 - L'$, whereas in the case of high currents, when $L^2 + B \gg 2LL' + L'^2$, we find that $\zeta_0^* = \zeta_0$.

For intermediate values of the current the value of $\zeta_0 = 0.3$ is a complex function of j or $\zeta_c = j/j_c$. The dependence of $\zeta_0^*(\zeta_c)$ is plotted in Fig. 4 (curve 4) for $\zeta_0 = 0.3$. Figure 4 represents the $\zeta_c - \zeta_0$ diagram (on a logarithmic scale) of a single domain with $\gamma = 10^{-7}$, $\lambda_T = 10\lambda_E$, and $\alpha = 1$, and it gives a full description of its properties because ζ_0 and j (or ζ_c) are the only independent parameters in our experiments.

The shaded region corresponds to the linear part of the current-voltage characteristic of a domain. It is located below straight line 1 where $\zeta_c = (\lambda_E/\lambda_T)\zeta_0$, and this corresponds to equality of the linear and nonlinear terms in U [see Eqs. (2) and 3], but above curve 2 which is characterized by the fact that $\zeta_c = \zeta_k$, is true on this curve. Line 3 represents the lower limit of the existence of a domain.

Using this diagram, we can follow the stages of formation of a resistive domain at any thermostat temperature. By way of example, we shall consider the case when $\zeta_0 = 10^{-2}$. If the current through a film is increased from zero, a domain appears only if the current is $j = j_c\zeta_{c1}$. At higher currents a temperature instability is observed. In the range $j_c\zeta_{c3} < j < j_c\zeta_{c4}$ the current-voltage characteristic of this instability is linear.

It is clear from Fig. 4 that in the case of low values of ζ_0 the current-voltage characteristic does not have a linear region, whereas if ζ_0 is large, the current-voltage characteristic is linear already at the moment of nucleation of a domain. All these observations are supported by numerous experimental data. Some of them are described in our preceding paper.[8]

The diagram in question can easily be used also to describe a domain with a heater characterized by a dependence $\zeta_0^*(j)$. Curve 4 gives the "phase" trajectory of a domain with heating for $L' = 0.29$. Deviation of curve 4 from the vertical $\zeta_0 = 10^{-2}$ at low values of j begins at a moment when ζ_m becomes equal to ζ_c (this point is not identified in Fig. 4). At

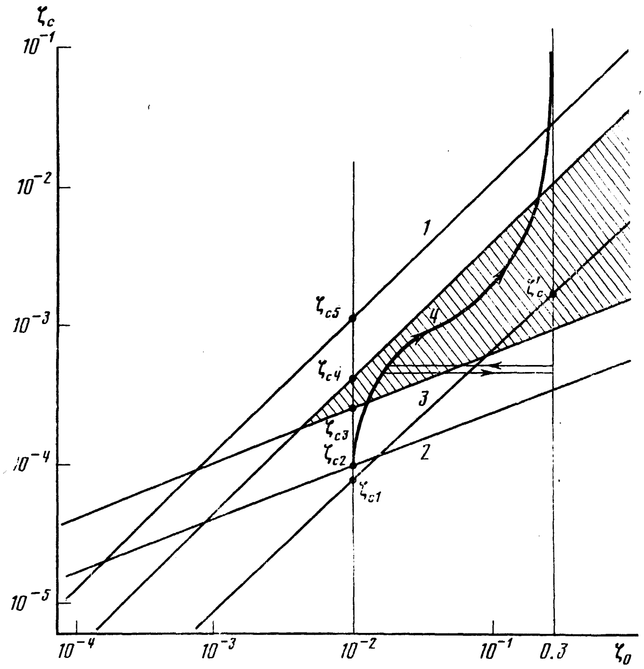

FIG. 4. "Phase" $\zeta_c - \zeta_0$ diagram of a resistive domain plotted on a logarithmic scale. The shaded region corresponds to linearity of the current-voltage characteristics of a domain. The thin vertical lines represent "phase trajectories" of a domain at different thermostat temperatures. The continuous curve is the "phase trajectory" of the same domain observed during heating and characterized by $\zeta_0 = 0.3$ and $L' = 0.29$ when the effective thermostat temperature depends on the current. The arrows are changes in the state of a domain due to brief switching off of a heater. The domain disappears only when a current falls to $j < \zeta'_c f_c$.

high currents, curve 4 approaches smoothly another vertical corresponding to $\zeta_0 = 0.3$.

We can identify several important features of a domain which appears in the presence of a heater and which distinguish it from a free domain.

1. In the presence of a heater a domain appears at much lower (sometimes by one or two orders of magnitude) currents. This is particularly important for the excitation and investigation of isolated domains, because it is when the nearby current is high that many other resistive regions distorting strongly the properties of the investigated media appear in a system.

2. The current-voltage characteristic of a domain observed in the presence of a heater is linear, in contrast to a free domain, over a wide range (sometimes extending over an order of magnitude) of transport currents (Fig. 4). In this connection it should be pointed out that the linearity of the current-voltage characteristic in the shaded region of Fig. 4 does not represent ideal behavior because a change in the current alters the effective thermostat temperature ζ_0^*, whereas the resistance R_0 and the excess current I_0 of the current-voltage characteristic of a domain depend weakly on ζ_0^*:

$$R_0 \propto \zeta_0^{*0,111}, \quad I_0 \propto \zeta_0^{*0,444},$$

so that the deviation from linearity can then be frequently ignored.

3. When a heater is switched off, ζ_0^* becomes equal to ζ_0 (as represented by thin horizontal lines with arrows in Fig. 4). When the transport current becomes less than $\zeta'_c j_c$ (Fig. 4), a domain disappears. It follows that passage of a current through a heater allows us to excite and annihilate a domain at any moment convenient for the experiment in question. The thick continuous curve in Fig. 3 represents pulsed excitation of an elementary domain in sample In-1 due to brief passage of a current 10 mA through a heater. Each heat pulse induces a new resistive state in a film and increases the quantity n in Eq. (4) by unity. This creates new states with $n = 9$ and $n = 10$.

Up to now we have considered the anology between elementary domains and phase slip centers concentrating our attention particularly on the linear region of the current-voltage characteristic of a domain. However, the part preceding the linear region is equally important. Investigations of the nonlinear region have shown that the current-voltage characteristic of an induced domain has all the properties of the characteristic free domains. At low values of ζ_0^* the properties are fully reversible, but at higher values of the effective temperature of a thermostat a hysteresis appears and voltage jumps are observed under constant-current conditions; at moderate currents the voltage jump is preceded by a linear region of the current-voltage characteristic, at higher currents the jump disappears, and so on (see Ref. 8).

Figure 5b shows a series of the current-voltage characteristics of sample In-2 obtained for different heat fluxes

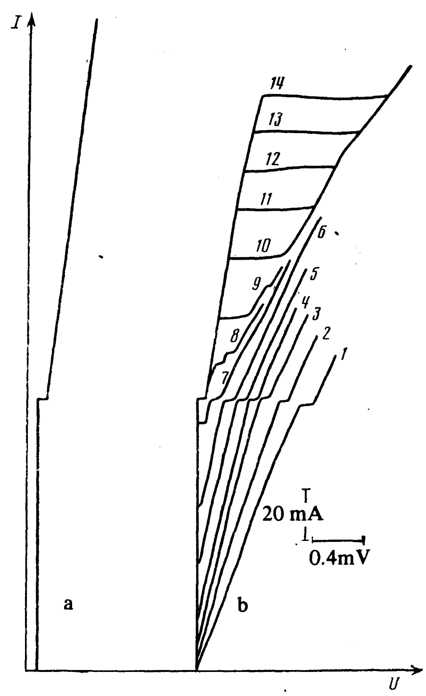

FIG. 5. a) Current-voltage characteristic of sample In-2 in the absence of a current through a heater. The current step corresponds to the appearance of a free domain. b) Current-voltage characteristics of sample In-2 obtained for different heat fluxes from a heater (in units of 10^{-2} W): 1) 9.45; 2) 7.98; 3) 5.92; 4) 5.01; 5) 4.62; 6) 4.37; 7) 4.2; 8) 4.05; 9) 3.99; 10) 3.9; 11) 3.83; 12) 3.79; 13) 3.75; 14) 3.71. The current-voltage characteristics of an induced domain are obtained by subtracting curve a from the curves b. The current-voltage characteristic of an induced domain has all the properties of the characteristic of free resistive regions.

from a heater. The current-voltage characteristic of an induced domain can be deduced simply by subtracting (along the voltage axis) curve 5a, representing the current-voltage characteristic of a free domain created in the same film, from any of the curves in Fig. 5b. Only the forward branches of the current-voltage characteristics are shown in Fig. 5, but nevertheless they illustrate some of the features discussed above. Moreover, curves 8 and 9 show clearly splitting of a current step into two (in the succeeding current-voltage characteristics the second step is weak). Curve 1 represents a transition of a part of an induced domain to the normal state. It is also worth noting that at all heat fluxes the height of a step due to a free domain remains practically constant. This means that an excited domain has almost no significant influence on the step.

We have shown above that we have $\zeta_0^* = \zeta_0 - L'$ until a thermal instability of a domain is observed. Consequently, in the case of the critical current I_1 corresponding to the entry of the first vortex into a sample (see Ref. 8), the dependence $I_1(L'_c - L')$, where L'_c is some fixed value of the heat flux, corresponds to the dependence $I_1(\zeta_0^*)$ for an induced domain or $I_1(\zeta_0)$ for a free domain, i.e., it is linear. This is confirmed by the results plotted in Fig. 6 for sample In-2.

The process of formation of an induced domain depends on the cryogenic liquid surrounding a film. If this film is He I, the switching on of a heater is accompanied by strong noise oscillations of the voltage associated with a transition of the sample to the regime of unstable bubble boiling (these oscillations are flattened out in Fig. 3). This makes it difficult to investigate the influence of small heat fluxes on a film.

If at a fixed value of the heater current I_h the temperature T_0 is reduced below the λ point of He^4, a domain is no longer excited because of a strong increase in the rate of heat transfer by the superfluid component of helium. However, there are no fundamental difficulties preventing the formation of a domain in He II: all that is necessary is to increase the power of a heat source. Noise oscillations are observed in He II only at very high fluxes from a heater. Consequently, it is possible to study the formation of induced domains in the case of low values of L' when $\zeta_0^* \approx \zeta_0$ [see Eq. (12)]. If then ζ_0 is sufficiently high, the excitation of a domain has a definite threshold.

Figure 7 shows the current-voltage characteristic of sample In-3 recorded at a constant scanning rate under near-

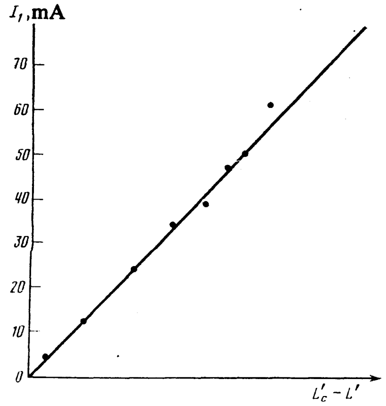

FIG. 6. Dependence of the current I_1 corresponding to the appearance of the first vortex of an induced domain on the reduced heat flux from a heater $L'_c - L'$; here, L'_c is the flux corresponding to $I_1 = 0$.

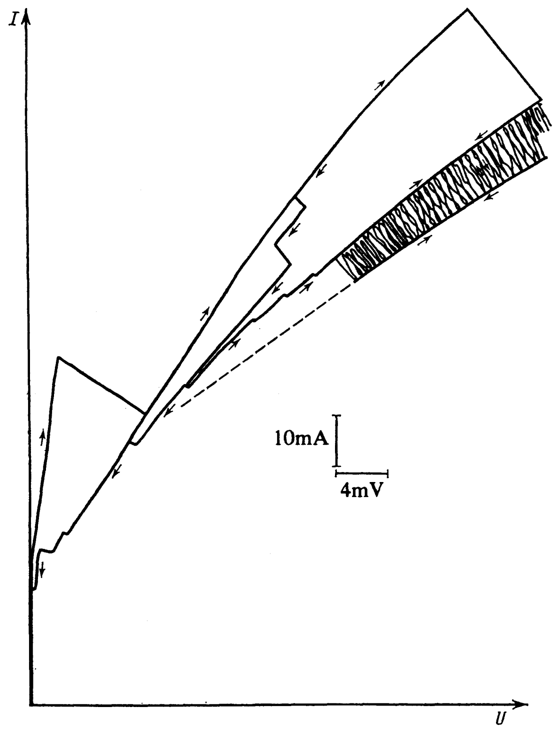

FIG. 7. Current-voltage characteristic of sample In-3 recorded at a constant scanning rate under conditions close to the constant-voltage regime when the current through a heater is switched on and off periodically. The parts of the characteristic obtained by increasing and then reducing the voltage are identified by arrows. The complex structure of the characteristic of resistive states indicates the appearance of numerous free domains in a sample immersed in He II. The results demonstrate the threshold nature of the excitation of a domain when a film is subjected to a small heat flux.

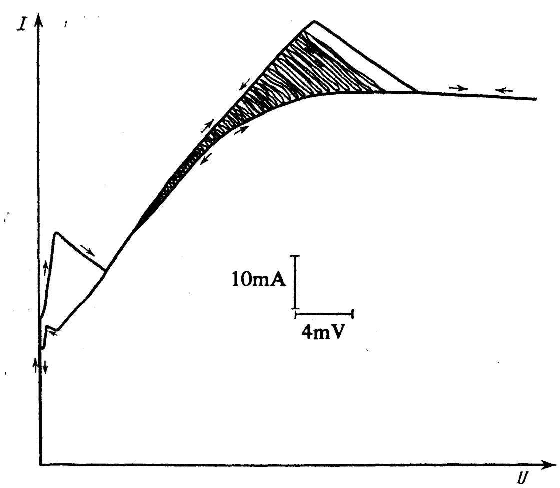

FIG. 8. Current-voltage characteristic of film In-3 observed when a localized heat flux acts periodically. Arrows identify the direction during recording of the characteristics. A sample is immersed in He I. The conditions are close to the constant-voltage regime. If the current exceeds a certain value, a domain does not disappear even when a heater is switched off. The envelopes of the pulsating structure are obtained by plotting the current-voltage characteristic with the heat source continuously switched on (lower curve) or switched off (upper curve).

constant-voltage conditions. The current is passed through a heater in the form of pulses separated by equal time intervals. We can see that the range of currents and voltages in which a domain is induced is limited by the load curve when the current is ≈ 90 mA. Under constant-current conditions the range of existence of a domain is limited by the horizontal line $I = \text{const}$ (Fig. 4).

It follows from the "phase" trajectory of a domain with $\zeta_0 = 0.3$ and $L' = 0.29$ (see also the $\zeta_0 - \zeta_c$ diagram in Fig. 4) that when a heater is switched off, a domain disappears only if $j < \zeta_c' j_c$. If $\zeta_c > \zeta_c'$, a domain continues to exist stably even in the absence of heating. This is demonstrated in Fig. 8 which shows the current-voltage characteristic of sample In-2 obtained in He I by periodic switching on and off the heater current I_h. When the transport current I exceeds 87 mA, a domain becomes stabilized and heating has practically no effect. In this case a sample is subject to a large heat flux and ζ_0^* differs considerably from ζ_0. For this reason the current-voltage characteristic of a domain is strongly nonlinear in the high-current range.

3. Separation of interacting superdomains on the basis of the current

In the preceding sections we have considered mainly domains which appear at defects of size $r_D \ll l_E$. When $r_D \gg l_E$, resistive regions appear in a film and these exceed an elementary domain in respect of size. In all probability, this is how a region with $R \approx 6R_0$ appears in sample In-1 (Fig. 3). Moreover, domains located at a distance $\sim \lambda_T$, interact with one another. This interaction appears primarily because a domain which has already been formed heats the region of the appearance of the next domain. In this case the appearance of one domain because of heating of neighboring regions and in the presence of suitable defects in these regions may give rise to a large resistive region, called a superdomain, with a resistance several hundreds of times greater than R_0.

Such superdomains appear most readily at high currents when the flux near a defect flows over distances $l \gg l_E, l \sim \lambda_T$; a normal region can then appear inside a superdomain. At relatively high currents a film splits into several (typically up to 10, see Refs. 1 and 2) superdomains. They interact thermally with one another. Frequently at high values of the transport current a resistive region which appears first heats so much the neighboring regions that it excites there superdomains and these merge when the whole sample is converted to the normal state. The forward branch of the current-voltage characteristic then exhibits one large voltage jump (line 1 in Fig. 9).

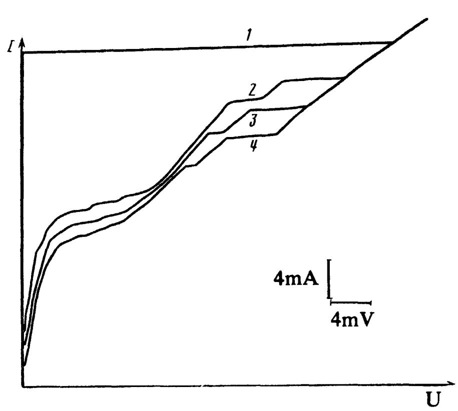

FIG. 9. Current-voltage characteristics of sample In-4 obtained for different values of the heater current I_h (mA): 1) 0; 2) 0.3; 3) 0.4; 4) 0.5. The results illustrate how to separate superdomains on the basis of the current.

If a heater is placed near superdomains which appear after the first one, the potential barriers can be reduced at the points of nucleation of these superdomains and thus they can appear at low currents without altering significantly the appearance current of the first superdomain. The forward branch of the current-voltage characteristic then exhibits a multitude of steps. Such a separation of superdomains on the basis of the current in sample In-3 is demonstrated in Fig. 9. The resistance of each of them is equal to the resistance of between 100 and 300 elementary resistive domains.

CONCLUSIONS

The results obtained in the present investigation indicate that the phenomenological model of resistive domains proposed by us earlier[8] leads in a natural manner to the concept of an elementary domain which is a linear analog of phase slip centers in thin channels and microbridges. However, the analogy is incomplete because phase slip centers are isothermal, whereas the appearance of an elementary domain and its stabilization are related fundamentally to the possibility of localization of overheating. In the linear part of the current-voltage characteristic the quantitative value of the resistance of an elementary domain is the same as of one phase slip center, but T_0 should be replaced with T_m.

Interesting possibilities for the investigation of nonequilibrium phenomena in superconducting films are provided by the process of inducing resistive regions (including elementary ones) thermally with the aid of a heater. The behavior of such regions is also described well by the model put forward by us in Ref. 8. However, the induced domains now have a number of advantages compared with free domains and are more convenient for performing a variety of experiments. A full picture of the behavior of domains cannot be obtained without considering the problems associated with the motion of a boundary between superconducting and resistive regions, and also the possibility of generation of traveling single domains. Equally interesting would be a study of the interaction of domains with one another and of the forces governing the pinning of domains to defects in films.

[1]The dependence $V(\zeta, j)$ shown in Fig. 2 is not universal. It varies somewhat from one sample to another. Consequently, the characteristics of films with a domain may exhibit one voltage jump or none. Moreover, the number of jumps may vary for the same sample depending on T_0, decreasing as T_0 approaches to T_c.

[2]Here, α is a characteristic dimensionless parameter of a sample responsible for the repulsive force of the vortices and γ is a parameter representing the nonisothermal behavior in recording of the current-voltage characteristics. For the films in question we have $\alpha \sim 1-10^{-1}$, and $\gamma \sim 10^{-5} - 10^{-7}$.

[3]In general, we find that $l_E = \lambda_E / \zeta^{\nu}$, where the relaxation of the unbalance of the branches due to the electron–phonon interaction corre-

sponds to $\nu = 1/4$, whereas in the case of the relaxation mechanism of Kulik and Gogadze[13,14] we have $\nu = 0$. Within the framework of the phenomenological model used by us, the value of $\nu = 1/4$ agrees better with the experimental results.

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Translated by A. Tybulewicz