Excess current and the dynamics of vortices in broad superconducting films

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The nature of the excess current in the current-voltage characteristics of broad superconducting films is investigated. It is shown that the excess current and the electric field present inside the superconductor are caused by a transition to an inhomogeneous resistive state with phase slippage lines. The behavior of the I-V characteristics in a magnetic field supports a model which predicts that the vortex dynamics should not depend on the normal component of the current produced by the phase slippage lines.

1. INTRODUCTION

Interest has increased recently in the dynamics of the mixed state in thin ($d \lesssim \xi$) and broad ($W \gg \lambda_\perp$) superconducting films.[1–8] In addition to some novel properties of uniform flux flow,[1] processes have also been studied[2–8] in which the transport current causes vortices to enter in a nonuniform way. The possible generation of thermal[3] and normal[4] domains in the mixed state has been considered, in addition to generation of the localized resistive states known as phase slippage lines (PSL).[5–8] In all cases the I-V characteristics are found to have a jump which is associated with an inhomogeneous transition of the film into a normal ($E \neq 0$, $\Delta \equiv 0$) or resistive ($E \neq 0$, $\Delta \neq 0$) state. The form of the I-V characteristics alone thus does not permit one to ascertain unambiguously whether the resistive state is due to phase slippage or to the formation of normal domains. In the present work we carried out experiments that make it possible to distinguish thermal effects from time-dependent relaxation phenomena in a superconductor. These studies shed light on the mechanism responsible for the observed excess current $I_{\rm exc}$ on the I-V characteristic, which is of the form $V = R_N (I - I_{\rm exc})$, where I is the normal current, R_N is the film resistance in the normal state, and $I_{\rm exc}$ is a constant independent of the voltage.

The excess current was studied previously in ScS and SN point contacts and in narrow superconducting channels.[9,10] In all cases, the excess current was associated with pulsations in the flow of the supercurrent, i.e., with the properties of the inhomogeneous resistive state. However, I-V characteristics resembling those for contacts carrying an excess current can also be produced by the expansion of a normal domain. This follows from some of our model experiments in which we artificially generated a moving thermal domain whose diameter depended on the amount of power supplied. The conditions required to generate such thermal domains in broad films were found, and the critical power P_k and the heat transfer coefficient α for heat flow from the film to the substrate + helium system were determined. We used these results to select the experimental conditions so that thermal effects in the resistive state of the superconductor were negligible.

We found that under conditions of effective heat transfer, weak spots at the edges of the film facilitated the generation of PSLs but did not determine the individual characteristics of the individual lines (localized resistive states). This suggests that the electric field and excess current associated with the PSLs might stem from the existence of local self-oscillatory solutions of the two-dimensional time-dependent equations describing the super-conductivity. Finding these solutions is even more difficult than in the familiar theory of phase slippage centers (PSC) for a one-dimensional channel. We carried out some experiments in order to develop a qualitative model; they revealed that the nonequilibrium processes are localized within a narrow core in the PSL. Outside the core, fluxoids can flow and substantially alter the excess current on the I-V characteristic. In addition, the possible coexistence of Abrikosov vortices and PSL's was analyzed qualitatively.

The fact that an elecric field penetrates a finite distance l_E into a superconductor plays a key role in the theory of phase slippage centers.[9,11] Because of the field penetration, the density of the superfluid component is depressed within a distance $\pm l_E$ of a PSC, so that it becomes more difficult to generate new PSC's. As a result, the transition of a long channel to the resistive state occurs in discrete stages. The finite penetration depth of the electric field inside a superconductor plays a similar role in the formation of resistive states with phase slippage lines. The slippage lines form due to the growth of instability in the vortex flux. If a PSL forms in the presence of an electric field, the latter discourages the further spread of vortex instability to the rest of the superconductor, because the normal component of the current induced by the PSL does not alter the velocity of the vortices.[12] In this respect the vortex dynamics in the inhomogeneous (PSL) state differs significantly from a homogeneous flux,[13] for which the vortex velocity is determined by the total transport current.

2. THERMAL EFFECTS IN THE *I-V* CHARACTERISTICS OF BROAD FILMS

We studied aluminum, tin, and indium films of characteristic thickness $d = 30$–89 nm, width $W = 0.05$–1 cm, and length $L = 1$ cm. Films with resistance $R_\square = 1 - 10\,\Omega$ were grown by sputtering the metals in vacuum ($3 \cdot 10^{-5}$ torr), and traps cooled by liquid nitrogen removed oil and water from the system. The temperature of the glass substrates varied from 77 to 300 K, and a shield attenuated the external magnetic field to 10^{-3} Oe.

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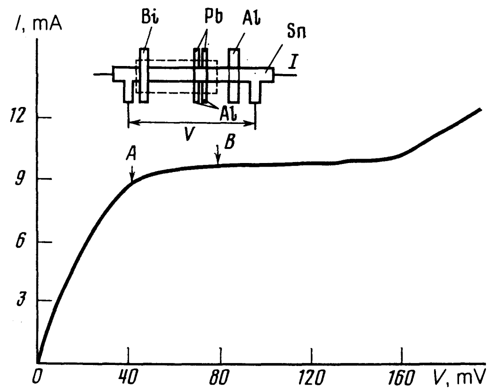

FIG. 1. Structure of the film specimen for studying the propagation of a thermal domain in a superconductor (tin film). The I-V characteristic shows the expansion of the domain from the heater (bismuth film) toward the Al–Al_2O_3–Pb tunnel thermometer measuring the temperature in the domain. Points A and B show the start of domain motion and the instant when it passed below the thermometer, respectively. The critical current I^* for thermal instability [Eq. (2)] was $I^* = 9$ mA.

We measured the temperature to which the resistive regions were heated in order to verify that the resistive state was due to phase slippage rather than to the formation of normal domains. We also measured the energy gap for films in the dissipative current state. Moreover, when heat transfer from the film was accompanied by bubbling we were able to visually observe thermal domains under an optical microscope. The primary goal of the experiments was to find the critical specific heating powers at which the resistive portion of the film heats up enough to cause a transition to the normally conducting state. This enabled us to allow for thermal processes in designing and analyzing the experiments.

We used tin films as models for the formation and dynamics of the dissipative regions. Each film (Fig. 1) was supplied with separate voltage and current contacts and was heated by an external (bismuth) film heater which was isolated from the Sn film by an SiO layer. The temperature was measured by an Al–Al_2O_3–Pb tunnel junction which was electrically isolated from the tin film and located a distance of 6 mm from the heater. The film also served as one of the layers in the Al–Al_2O_3–Sn tunnel junction, which was used to measure the size of the energy gap.

An Al–Al_2O_3–Pb tunnel junction served as the thermometer; it was fabricated so that its area was equal to the area of a section of the Sn film. The temperature measurements exploited the strong temperature dependence of the resistance $R_t(T)$ of S-I-N tunnel junctions. The thermometer was calibrated in terms of helium vapor pressure, and we used an ac bridge to measure the resistance of the contact. The maximum sensitivity was 0.01% when the voltage across the contact was 100 μV. The temperature coefficient $\gamma = d\ln R_t(T)/dT$ of the tunnel junction was equal to 6 for $3\ \mathrm{K} > T > 2\ \mathrm{K}$; this enabled us to measure temperature changes $\Delta T < 0.01$ K.

We used the heater to generate a resistive region in the superconducting film. The width of the region was initially equal to the width of the heater but increased when the transport current reached a critical value I^*. The movement of the domain was reflected on the I-V characteristic as an increase in the differential resistance of the film and could also be detected visually from the motion of the region of bubble boiling. The temperature in the domain was recorded as it passed beneath the tunnel thermometer. The instant when this happened was recorded from the change in the thermometer resistance and also visually, by noting when the leading edge of the bubble boiling region passed through. The I-V characteristic in Fig. 1 shows the currents at which the domain reached the tunnel thermometer (these give the corresponding temperature changes). The curve in Fig. 1 was recorded at the temperature $T_0 = 3.815$ K of the helium bath; the temperature of the superconducting transition for the thin film was $T_c = 3.925$ K, while the temperature in the domain was $T_D = 3.98$ K. This shows that the domains must have been in the normal state. However, one cannot rule out the possibility that the temperature was not distributed uniformly over the area of the domain because in our experiments the tunnel junction was considerably longer than the characteristic thermal length,

$$\lambda_T = (\varkappa d/\alpha)^{1/2} \approx 1.6 (T/\alpha R_\square)^{1/2}\ [\mu\mathrm{m}], \tag{1}$$

where $\varkappa$ is the thermal conductivity, α is the heat transfer coefficient, and d is the thickness of the film. The Wiedemann-Franz law was assumed in deriving (1). For the values $\alpha = 0.8\ \mathrm{W\cdot cm^{-2}\cdot deg^{-1}}$ found in our experiments (see below) for $T = 3.86$ K and $R_\square = 4\ \Omega$, we obtain $\lambda_T \approx 1.5$ μm.

Measurements of the order parameter using the Al-Al_2O_3-Sn tunnel contact revealed that when the domain passed under the contact, its resistance was equal to the normal resistance to within $\sim 0.1\%$. This indicates that no large regions with a nonzero order parameter were present in the domain, i.e., the latter was heated to a temperature $T > T_c$.

The similarity of the I-V characteristics to those for films making a discrete transition to the resistive state[5,6] is noteworthy (Fig. 2). The similarity is especially pronounced for films with a nonuniform heat transfer. We used the structure sketched in Fig. 2 as a model for this situation. The tin superconducting film was equipped with a system of leads which enabled us to pass a transport current either through or bypassing the heater (a Bi film sputtered into a gap in the Sn film). A normal domain formed in the film when the current through contacts 2, 2′ was sufficiently high. The domain propagated along the film but slowed down as it approached the voltage leads 3–5. An additional current was required to keep the domain moving, and in this case the domain jumped onto the next section of the film. The number of jumps on the I-V characteristic produced in this way was equal to the number of film sections bounded by the voltage leads, while the differential resistances of the sections saturated at values close to the corresponding resistances for a film in the normal state.

This result indicates that inhomogeneities in the film (e.g., the voltage contacts) can block the spread of a normal region in a current-carrying superconductor. When no current passed through the heater, the I-V characteristic for a film with a lead supplying current to contacts 3–2′ "cut off"

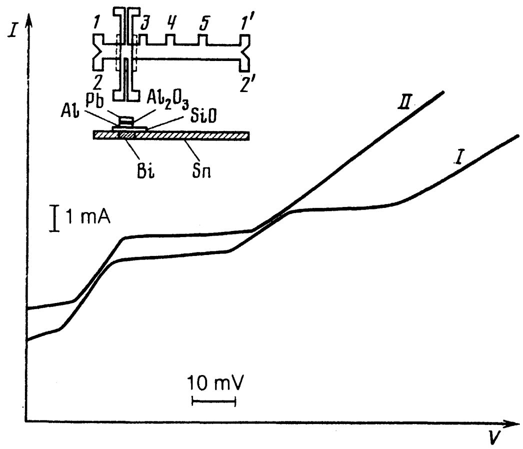

FIG. 2. The steps in the I-V characteristics reflect the jump-like propagation of the thermal domain along an inhomogeneous specimen. Current was supplied to the contacts 2, 2′. Curves I and II show the voltage recorded from leads 3, 1′ and 4, 1′, respectively. The insert shows the position of the bismuth heater and Al–Al_2O_3–Pb thermometer used to measure the heat transfer coefficient α. The measurement temperature was $T = 0.987\ T_c$.

and approached the I-V characteristic for the normal state of the corresponding film section. The cirtical cutoff was much larger than the heater current required for thermal instability. We note that the current leads in the film junctions often acted as a massive contact to produce such a heating. This was confirmed by visual observations of the normal zone as it left the contact region. Of course, in this case the measurements did not reflect the actual processes occurring in the film.

To find the specific powers corresponding to thermal instability in the superconducting films we measured the heat transfer coefficient $\alpha = \Delta P(\Delta T\Delta S)^{-1}$, where ΔP is the power evolved in a film of area ΔS, and ΔT is the corresponding heating of the film section relative to the temperature of the helium bath. The heating ΔT was measured by a tunnel temperature sensor fabricated directly above the Bi heater. The thermometer and heater were separated by an SiO layer of thickness $d \sim 30$ nm, and the areas of the heater and tunnel contact were equal. Because the heater was isolated, we were able to specify a calibrated amount of heating power. Because of the condition $\lambda_T \ll W$, it is reasonable to suppose that the area of the heat transfer region was equal to the area of the heater. We measured α in a wide temperature interval $4.2\ \mathrm{K} > T > 1.5$ K. The experimental data give $\alpha = 0.8\ \mathrm{W/(K \cdot cm^2)}$ for our films when $T > T_\lambda = 2.18$ K. For $T < T_\lambda$ and specific powers less than $0.3\ \mathrm{W/cm^2}$, α was $\mathrm{W \cdot K^{-1} \cdot cm^{-2}}$. As noted above, this value of α corresponds to a thermal length $\lambda_T = 1 - 2\,\mu$m. We can use these data to calculate the current I^* at which thermal instability develops, i.e., above which a normally conducting nucleus in the superconductor spreads throughout the entire film. Taking the resistivity of the resistive section equal to the normal value and using the power conservation condition

$$\frac{2\alpha\Delta T}{\Delta S} = \frac{R_\square (I^*)^2 \Delta X}{W(W\Delta X)}, \quad \Delta S = W\Delta X$$

we find that

$$I^* = W(2\alpha\Delta T/R_\square)^{1/2}. \qquad (2)$$

Here ΔX is the length of the resistive region along the direction of the current, and $\Delta T = T_c - T_0$.

Our analysis of the thermal processes enable us to find conditions under which a PSL does not regenerate into a normal domain. The chief requirement is that the threshold current I_{vi} for vortex instability should be much less than I^*. One can decrease I_{vi} by coating the edges of the film with a normal metal so as to decrease the height of the edge barrier to the influx of vortices (see,e.g., Ref. 7). One can also decrease I_{vi} by applying an external magnetic field normal to the film.

3. EFFECTS OF TEMPERATURE AND MAGNETIC FIELD ON THE EXCESS CURRENT

The steps in the I-V characteristics for aluminum films are shown in Fig. 3. For these films the threshold current for thermal instability calculated by Eq. (2) is $I^* = 20$ mA, which is much larger than the operating currents for the I-V curves. Thermal effects can thus be neglected. The initial portions of the I-V curves (Fig. 3) consist of sections on which the differential resistance is either constant or a multiple $R^{(N)} = NR_0$ of R_0, and the current depends linearly on the voltage: $V = R^{(N)}\ (I - I_{\rm exc}^{(N)})$. Here $I_{\rm exc}^{(N)}$ is the current otained by extrapolating the slope of the Nth section of the I-V characteristic to the voltage $V = 0$ (it is the "excess" current for this section). As N increases, so does $I_{\rm exc}^{(N)}$, which approaches the value $I_{\rm exc}$ of the excess current observed at high voltages. The start of each section is accompanied by a voltage jump δV which is equal to a multiple of the energy gap for the superconductor: $\delta V = N\Delta(T)/e$, where $N = 1,2,3,...$ is the same integer as in the relation $R^{(N)} = NR_0$. We thus conclude that the formation of an individual localized region is accompanied by a voltage jump $\delta V \approx \Delta/e$, and the differential resistance increases by R_0. We measured the temperature dependences $\delta V(T)$ and $\Delta(T)$ in order to verify that δV was an integer multiple of the energy gap. The order parameter for the film was measured using an Al–Al_2O_3–Pb tunnel contact. The results of these experiments are shown in Fig. 4. We see that the temperature de-

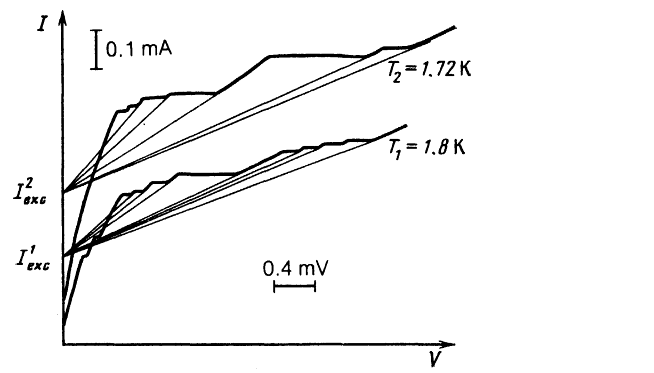

FIG. 3. I-V characteristics for an Al film containing localized resistive regions; $T_c = 1.85$ K, $R_\square = 4$ Ohm, $d = 30$–40 nm.

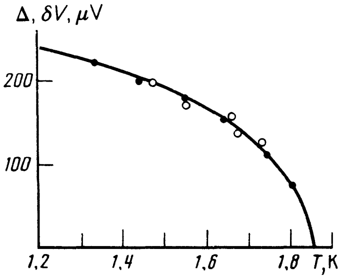

FIG. 4. Temperature dependence $\Delta(T)$ of the energy gap for an Al film (●) and the size of the voltage jumps δV (○) for the specimen in Fig. 3. The solid curve shows the dependence $\Delta(T)$ given by the BCS theory.

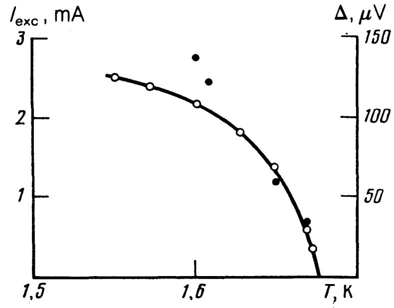

FIG. 6. Temperature dependence of the order parameter $\Delta(T)$ (○) and excess current I_{exc} (●) for the Al film in Fig. 5.

pendence $\Delta(T)$ of the order parameter for the film is predicted by the BCS theory, and the same is true for $\delta V(T)$.

The observed inhomogeneous transition into the resistive state, which is reflected in the discrete structure of the *I-V* characteristics, cannot be attributed to the generation and dynamics of a normal domain, because the power evolved in the latter is much less than the critical power. However, we are still not justified in concluding that the inhomogeneities are resistive in nature, because it is not ruled out that the order parameter might vanish in some small portion of the resistive region. We analyzed this possibility by carrying out tunnel measurements of the energy gap of films in the resistive state. Figure 5 shows a sketch of the specimen. The resistance of the Al–Al_2O_3–Pb junction was chosen so that the tunnel current for contact voltages $eV \approx \Delta_{Pb} - \Delta_{Al}$ was high enough to take the film into the resistive state.

The tunnel measurements revealed that the order parameters for the Al films remained unchanged, although the differential resistance of films in the resistive current state was equal to the normal value. The measurements (Fig. 5) were made in a magnetic field $H_\perp = 18$ Oe$\ll H_{c\perp}$. Similar curves were also recorded in zero magnetic field at temperatures close to the critical point. The value Δ for films in the dissipative current state agree closely with the equilibrium order parameter given by the BCS theory. This fact, together with the steep *I-V* dependence (typical for *S-I-S* tunnel contacts) at bias voltage $eV = \Delta_{Al} + \Delta_{Pb}$ (Fig. 5), shows that no large regions of normal phase were present within the tunnel junction.

Analysis of the *I-V* characteristics shows that the excess current is given by the expression

$$I_{exc} = q\Delta(T)/eR_0, \tag{3}$$

where the constant $q \sim 1$ and R_0 is the differential resistance of a single phase slippage line. We verified Eq. (3) in a wide temperature range by experimentally measuring the temperature dependence of the order parameter and the excess current I_{exc} [Fig. 6; $\Delta(T)$ was recorded by the tunnel method]. We found that I_{exc} deviates appreciably from (3) at low temperatures and in the immediate vicinity of the critical point, $T/T_c > 0.98$. In addition, (3) fails for transverse magnetic fields $H_\perp < 0.5\ H_{c\perp}$, for which the *I-V* characteristic

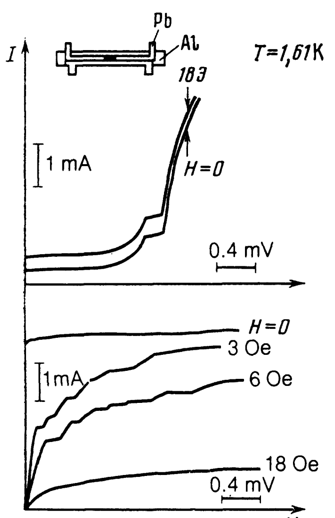

FIG. 5. *I-V* characteristics for an Al–Al_2O_3–Pb tunnel junction and for an Al film in transverse magnetic fields $H_\perp = 0$ and $H_\perp = 18$ Oe. Both curves are shown to the same scale. The insert shows the configuration of the specimen; $T/T_c = 0.961$, $H_{c\perp} = 116$ Oe, $T_c = 1.675$ K.

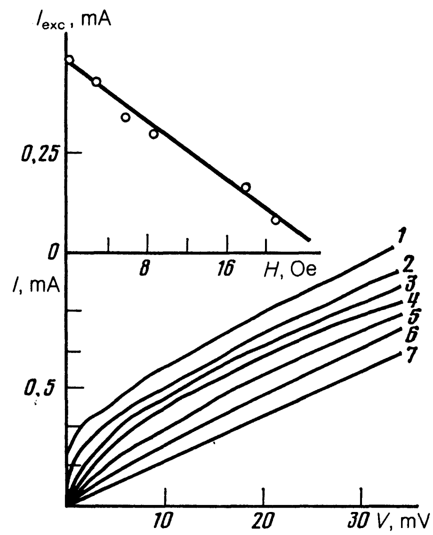

FIG. 7. *I-V* characteristics for an Al film in a transverse magnetic field $H_\perp$, $T/T_c = 0.994$. $H = 0$ (1), 3(2), 6(3), 9(4), 18(5), and 21(6) Oe; 7) *I-V* dependence for $T > T_c$. The insert shows how the excess current I_{exc} depended on $H_\perp$ when a voltage $V = 25$ mV was applied to the specimen; $H_{c\perp} \approx 33$ Oe, $T_c = 1.82$ K.

was found to shift parallel to itself with increasing field at large biases (Fig. 7). Here the critical field $H_{c\perp}$ can be estimated by the formula

$$H_{c\perp}=\frac{\Phi_0}{2\pi\xi^2}\approx 2.3\cdot 10^{-4}\frac{(T_c-T)}{l}\ [\mathrm{Oe}],\quad \Phi_0=\frac{\pi\hbar c}{e},$$

where l (in cm) is the mean free path. For aluminum films we used the expression

$$l_{\mathrm{Al}}=4.2\cdot 10^{-12}(R_\square d)^{-1}\ [\mathrm{cm}]\tag{4}$$

for l_{Al}, which gives $l_{\mathrm{Al}}=0.5-15$ nm. The corresponding critical fields $H_{c\perp}$ are given in the captions to Figs. 5 and 7. These figures show that for weak fields $H_\perp<0.5H_\perp$, I_{exc} decreases almost linearly with increasing magnetic field. This behavior of the *I-V* characteristics can be attributed to the features of the vortex dynamics in the electric field produced by the phase slippage lines.

4. DISCUSSION

We conclude from the experiments that a transition of the film to an inhomogeneous resistive state is responsible for the behavior of the *I-V* characteristics. This state is characterized by the presence of an electric field in the interior of the superconductor; the order parameter vanishes only at certain points in the film, and then only at certain times. This is suggested by the fact that the voltage jumps in the *I-V* curves are all integer multiples of a common small value, by the presence of an excess current, by the finding that the differential resistances of the linear portions of the *I-V* characteristics are the same as for the normal state, and by the fact that the absolute value of the order parameter near the resistive state is almost equal to the equilibrium value $\Delta_{\mathrm{BCS}}(T)$.

The Josephson relation $\hbar\omega_J=2$ eV holds quite generally[9] for any localized resistive state; here V in the time average of the voltage generated by the material in the localized state, and ω_J is the pulsation frequency of the order parameter. For example, if the resistive state is produced by a moving row of Abrikosov vortices, e.g., then the points at which $|\Delta|$ vanishes lie on a line which is normal to the transport current and intersects the axis of the fluxoids. The voltage generated by a single row of vortices is $V=\pi\hbar u_L/ea$, where u_L is the velocity of the fluxoids and a is the distance between them.

The experimental data are consistent with a PSL model in which $|\Delta|$ vanishes (as in a row of vortices) at isolated points that move along a phase slippage line, i.e., one which is normal to the transport current and intersects the broad side of the film. The Josephson pulsation frequency satisfies $\hbar\omega_J=2e\delta V\gtrsim 2\Delta$. The pulsations in the supercurrent and in the energy gapwidth are therefore localized in a narrow channel whose length equals the width of the film and whose width is of order $\xi(T)\ll l_E$. The excess current deduced from the *I-V* characteristics satisfies the empirical expression (3), where R_0 determines the penetration depth of the electric field into the superconductor: $l_E=WR_0/2R_\square$. For superconducting Al films, the relaxation time τ_Q to electron-hole equilibrium deduced from the experimental data on R_0 using the formula $l_E=(D\tau_Q)^{1/2}$ was $\tau_Q=10^{-8}$–10^{-7} s (here the diffusion coefficient is $D=v_F l/3$, where v_F is the Fermi velocity of the electrons). This spread in τ_Q is in all probability due to the different conditions under which the films were fabricated; the values τ_Q are in satisfactory agreement with available published data.[9,11] We did not detect any appreciable temperature dependence of τ_Q in the experiments (Figs. 3–6). To compare these results with the predictions of the SPC theory for phase slippage centers in Ref. 9, we note that in our case the film thickness was always greater than ξ and $\lambda_\perp$:

$$W\gg\lambda_\perp=\frac{0.83R_\square}{T_c-T}\ [\mu\mathrm{m}]\gg\xi(T),$$

$$\xi(T)=\left(\frac{1.38l_{\mathrm{Al}}}{(T_c-T)}\right)^{1/2}\ [\mu\mathrm{m}],$$

where the mean free path l_{Al} (in μm) is given by Eq. (4). The transport current I was much less than the depairing current $I_{\mathrm{GL}}{}^c$:

$$I\ll I_{\mathrm{GL}}{}^c\approx\Delta^2(T)W/eTR_\square L_0,$$

where $L_0=1.53^{1/2}\xi(T)$, and we assume that in the resistive state the current is distributed uniformly over the film cross section.

The relations

$$l_E\gg l_\varepsilon=(D\tau_\varepsilon)^{1/2}\gg\xi(T),\qquad I\gg I_{\mathrm{exc}}\sim\frac{\Delta(T)}{eR_0}\ll I_{\mathrm{GL}}{}^c(T),$$

where τ_ε is the energy relaxation time for the quasiparticles, were satisfied throughout the temperature interval for which phase slippage lines were observed. On the other hand, the quantitative results of the PSC theory were obtained by solving equations[11] valid under the stringent conditions ($\xi\gg l$)

$$l_\varepsilon\ll\xi(T)\ll l_E,\quad j\gg j_{\mathrm{GL}}{}^c,\quad W\lessdot\xi.\tag{5}$$

For Al films with $R_\square=1$–10 Ohm, these inequalities can be satisfied only for temperatures in the inaccessibly narrow range $T_c-T<10^{-3}T_c$. The width of this interval is comparable to the width ΔT_f of the fluctuation smearing $R(T)$ of the transition, $\Delta T_f\sim T_cR/R_c$, $R_c=4.12$ kohm. Since conditions (5) were not satisfied, we cannot expect that the experimental value of the excess current (3) will agree quantitatively with the expressions in the PSC theory. On the other hand, the observed dependence $I_{\mathrm{exc}}\sim\Delta/eR_0$ is characteristic of contacts in which two superconductors are connected by a narrow bridge[10]; in such contacts the mechanism by which quasiparticles of energy $\varepsilon<\Delta$ transport current across the contact is responsible for the excess current I_{exc}. This suggests that the excess current in a phase slippage line may be generated by a similar mechanism within the core of the PSL, where the order parameter is locally depressed.

We now use the PSL model proposed above to analyze how the vortex dynamics is affected by the nonequilibrium state produced by processes in a PSL. The problem simplifies due to the pronounced difference between the characteristic frequencies Ω and ω_J. A vortex lattice moving at velocity u_L has characteristic frequencies $\Omega\lesssim u_L/\xi$. The velocity for stable motion of Abrikosov vortices is bounded[14] by u^*,

$u_L < u^* = (D/\tau_Q)^{1/2}$. The condition $\hbar\Omega < \hbar\Omega^* \ll \Delta$ is thus always satisfied for vortices, i.e., the Josephson oscillation frequency ω_J in a PSL is much higher than the characteristics frequencies Ω for the vortices. The small parameter Ω/ω_L makes is possible to analyze the dynamics of the PSL and vortices independently. Up to corrections of order Ω/ω_J, the vortex motion cannot alter the phase jump frequency in the PSL nor (consequently) the steady-state electric field E generated in the superconductor by the nonequilibrium processes in the core of the phase slippage line. Coversely the field E, which is independent of the vortex motion, has no effect on the velocity of the vortex lattice and little influence on the viscosity coefficient. This fact makes it possible to explain the observed behavior of the I-V characteristics in a magnetic field (Fig. 7). We express the I-V characteristic of a film containing phase slippage lines in the form

$$V_{\mathrm{PSL}} = R_N(I - I_{exc}) \equiv R_N I_{\mathrm{PSL}}^N, \tag{6}$$

where I_{PSL}^N is the quasiparticle current produced by the steady-state field of the PSL's. If (as discussed above) the vortices do not appreciably disturb the phase slippage processes in the PSL's, then they must also leave unchanged the voltage generated by the PSL at a fixed transport current I. The voltage developed across a PSL at current I is thus given by the same expression (6) as when no vortices are present. However, the vortex velocity u_L can depend only on a component of the total current I, because I_{PSL}^N is independent of u_L. The voltage generated by a lattice of vortices is thus equal to

$$V_f = R_f(I - I_{\mathrm{PSL}}^N) \equiv R_f I_{exc},$$

where R_f is the flux resistance. In our approximation, the vortices serve merely as an addition phase-jump channel, and the resultant I-V characteristic takes the form $V = V_f + V_{\mathrm{PSL}} = R_N(I - \tilde{I}_{\mathrm{exc}})$, where $\tilde{I}_{\mathrm{exc}}$ is the experimentally observed effective excess current, i.e., the superfluid component of the total transport current:

$$\tilde{I}_{exc} = I_{exc}(1 - R_f/R_N). \tag{7}$$

Here $I_{\mathrm{exc}} R_f/R_N$ is the part of the normal current component due to the electric field generated by the motion of the vortices. We verified (7) by using the experimental values of the flux resistance $R_f(H_\perp)$ in a fixed magnetic field; these values were found from the initial portions of the I-V characteristics (Fig. 7). Good agreement was obtained for low critical pinning currents and for magnetic fields $H_\perp < 0.5\, H_{c1}$.

5. CONCLUSIONS

We have shown that the order parameter near a PSL coincides with its equilibrium value and determines the excess current $I_{\mathrm{exc}} \sim \Delta e R_0$ on the I-V characteristics in the absence of a magnetic field. The observed dependence of I_{exc} on the magnetic field was explained using a model in which the vortex motion is postulated to have little effect on the nonequilibrium processes in the "hot" core of the PSL.

According to the latest theory the resistive state, i.e., the generation of an electric field in the interior of a superconductor, is due to various phase slippage mechanisms. Therefore, the voltage across a PSL (as across any resistive object) must be related to the frequency ω_J of 2π phase jumps by the Josephson formula $\hbar\omega_J = 2\mathrm{eV}$. The voltage generated by a single PSL was typically $\sim\Delta/e$; the corresponding frequencies $\hbar\omega_J \sim \Delta$ are thus much greater than the reciprocal of the energy relaxation time in the superconductor. The inequality $\omega_J \tau_\varepsilon \gg 1$ means that the electron subsystem must be heated significantly in a PSL. Nevertheless, we showed in Secs. 2 and 3 that the superconductor is not heated appreciably, and the order parameter is equal to its equilibrium value nearly everywhere in the film. The "hot" core of the PSL must thus be much smaller than the diameter of the resistive region, which depends on the penetration depth $l_E \gg \xi(T)$ of the electric field. Our experiments also imply another important property of the PSL's—their I-V characteristics are identical, i.e., they are independent of the conditions under which the PSL was formed. This indicates that the size of the voltage steps on the initial portions of the I-V characteristics is the same for all the localized resistive regions, and that their differential resistances are also equal.

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