

# Induction of phase-slip lines in a thin, wide superconducting film by an rf electromagnetic field

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The appearance of phase-slip lines, induced by an rf field, was observed experimentally in wide superconducting films in which the destruction of superconductivity by a dc current is associated with the formation of phase-slip lines. The characteristics of the separation of the film into superconducting and nonuniform, isothermal, nonequilibrium regions (phase-slip lines) under electromagnetic irradiation were studied.

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1. When a current exceeding the critical current ( $I > I_c$ ) flows through a thin superconducting film at temperatures close to the critical temperature ( $T < T_c$ ), phase separation of the film into superconducting and spatially localized, nonequilibrium regions is possible. In narrow films whose width is less than the coherence length [ $w < \xi(T)$ ], these regions, in which the modulus  $|\Delta|$  of the order parameter of the superconductor periodically vanishes and the phase of the order parameter changes by  $2\pi n$  ( $n$  is an integer), are called phase-slip centers (PSC).<sup>1</sup> At temperatures close to  $T_c$  and with good heat transfer, wide films [ $w > \xi(T)$ ] can form nearly isothermal, nonequilibrium, nonuniform regions (phase-slip lines), whose length  $2l_E$  is equal to twice the penetration depth of a longitudinal electric field into the superconductor.

The appearance of phase-slip centers has been studied extensively.<sup>1</sup> The main experimental studies of phase-slip lines (PSL) are presented in Ref. 2. We know of only one theoretical work on the formation of PSL during the passage of a dc current through a film.<sup>3</sup> The discovery of “nitrogen” superconductors has renewed interest in the development of devices that operate on the basis of the switching from the superconducting state to the resistive state. The formation of PSL is a possible realization of the resistive state. In wide films there exist, besides PSL, magnetic flux lines. The motion of flux lines can influence the dynamics of PSL and the PSL themselves can influence the dynamics of the flux lines.<sup>4</sup> The experimental investigations of PSL performed thus far do not completely explain the physics of such lines. It follows from Refs. 2, 5, and 6 that PSL in wide films are similar to PSC in narrow films. The I-V characteristics of samples containing PSL have a step character and consist of a series of linear sections, whose resistance is a multiple of the resistance of a single PSL, i.e.,  $R \cong nR_0$ . The resistance to current flow of a single PSL (just as a PSC) is  $R_0 = 2\rho_n l_E / wd$ , (Refs. 1 and 2) where  $\rho_n$  is the normal-state resistivity of the film, and  $d$  is the thickness of the film.

The penetration depth of an electric field is determined by different mechanisms of the relaxation of the unbalance of the populations of the electron- and hole-like branches

of the quasiparticle spectrum of the superconductor. In theoretical studies these mechanisms for PSC were investigated in, for example, Refs. 7 and 8. In Refs. 5 and 6 the cases in which both branches of the spectrum are mixed as a result of inelastic electron-phonon collisions and the so-called elastic mechanism, which is the dominant mechanism when the condensate current is sufficiently strong, were studied experimentally in wide films. The investigation of the temperature dependence of the PSL resistance makes it possible to determine which mechanism of hole-electron conversion leads to the appearance of a nonuniform electric field in the superconductor plays the main role. The dynamics of PSL in wide films irradiated with high-frequency radiation has still not been studied experimentally. Our objective was to conduct such a study.

2. The samples consisted of tin films of width  $w = 70 \mu\text{m}$ , thickness  $d \sim 1000 \text{ \AA}$ , and length  $L = 2 \text{ mm}$ . The films were thermally deposited on polished silicon substrates. A sample was placed in an 8-mm waveguide. The plane of the substrate was parallel to the electric component of the 30 GHz electromagnetic field. The dc I-V characteristics of the sample were recorded at temperatures close to the critical temperature with different irradiation power levels. We note that in tuning the radiation generator the maximum output power  $P_{\text{max}}$  was changed in each new series of measurements. We calculated the resistance of a PSL according to the slope of the first visible (sometimes second and third) linear section of the I-V characteristic which was close to the critical current.

3. To determine the mechanism of the penetration of a nonuniform longitudinal field into a superconducting film, we investigated the temperature dependence of the resistance of the first phase-slip line with no irradiation. This dependence was nonmonotonic, just as in Ref. 5. In the isothermal region, the resistance was determined by the penetration depth of the electric field  $l_E = \sqrt{D\tau_Q} = \sqrt{D\tau_\epsilon 4kT/\pi|\Delta|}$ , where  $D$  is the diffusion coefficient,  $\tau_Q$  is the relaxation time of the asymmetry of the populations of the branches of the quasiparticle spectrum, and  $\tau_\epsilon$  is the inelastic electron-phonon scattering time. Then  $l_E = g(D\tau_\epsilon)^{1/2}(1-t)^{-1/4}$  near  $T_c$ , where  $t = T/T_c$  and  $g \approx 1$ . For our samples with a mean free path  $l \approx 300 \text{ \AA}$ ,  $T_c \approx 3.9 \text{ K}$ ,  $\tau_\epsilon \approx 3 \times 10^{-10} \text{ s}$ , and  $\rho_n l \approx 1.6 \times 10^{-11} \Omega \cdot \text{cm}^2$ , (Ref. 5) the temperature dependence of  $l_E$ , determined from  $R_0(T)$ , was close to that presented above. For our films, the penetration of the longitudinal electric field in the isothermal region is therefore associated mainly with the inelastic electron-phonon mechanism of balancing of the populations of the electron- and hole-like branches.

4. Similar results were obtained for different films in all series of measurements. For this reason, only the characteristic and most detailed dependences from different series are shown in the figures. Figure 1 shows the I-V characteristic of one sample as a function of the irradiation power at a temperature close to  $T_c$ . The I-V characteristic of the unirradiated sample, including two steps, is shown in the inset in Fig. 1. As the power increases, at first the critical current can increase. This could be associated with the stimulation of superconductivity.<sup>10</sup> At some power ( $\approx -24 \text{ dB}$ ) the critical current is appreciably suppressed and vanishes in an interval of several dB. We call the power  $P_c$  at which  $I_c = 0$  the critical power. The resistance  $R_0$  remains virtually constant at a power lower than  $P_c$ . The initial section of the I-V characteristic for  $P > P_c$  is linear and there is virtually no hysteresis in the I-V characteristic recorded in both directions. Despite the absence of a critical current, the step structure of the I-V characteristic remains up to the irradiation power at which the resistance of the film is equal to the normal-state resis-

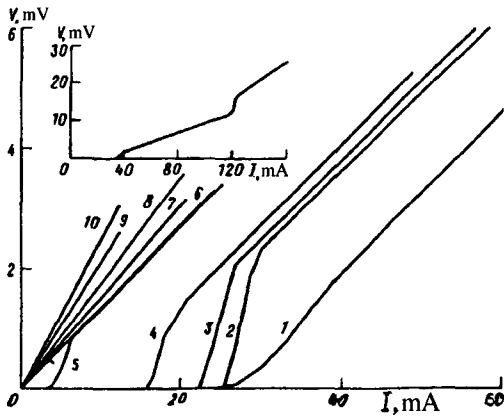


FIG. 1. Initial sections of the I-V characteristic with irradiation power in the range of suppression of the critical current and increase in the resistance of the first linear section from  $R_0$  to  $\approx 2R_0$ . Curve 1—70 dB, 2—24 dB, 3—23 dB, 4—20 dB, 5—19.3 dB, 6—19.1 dB, 7—17.3 dB, 8—16.4 dB, 9—15.4 dB, 10—13.9 dB (damping in decibels).  $T=3.89$  K,  $P_c/P_{max}=-19.1$  dB,  $\omega/2\pi=30$  GHz. Inset: I-V curve of a sample with no irradiation, including two PSL steps;  $T=3.87$  K.

tance. Similar I-V characteristics were also observed with no stimulation of superconductivity.

5. Figure 2 shows the normalized resistance  $R/R_0$  as a function of the relative irradiation power  $P/P_{max}$ , where  $R$  is the resistance of the first, linear section, which is close to the critical current, of the I-V characteristic. The resistance  $R_0$  is the resistance of a single PSL with no irradiation. In the case of no critical current the resistance was

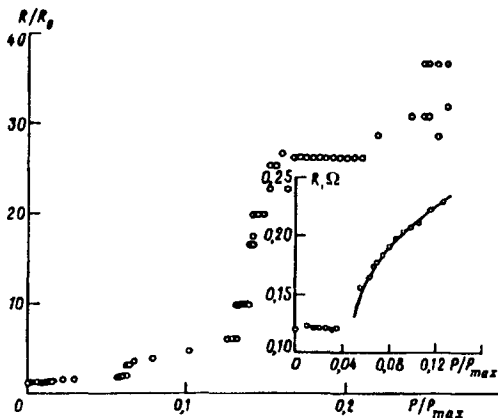


FIG. 2. Normalized resistance of the first visible PSL step near  $I=0$  as a function of the relative irradiation power.  $T\approx 3.88$  K,  $R_0\approx 0.12$   $\Omega$ ,  $P_c/P_{max}\approx 0.01$ . Inset: Resistance of the film as a function of the relative irradiation power for  $R$  from  $R_0$  to  $\approx 2R_0$ .  $T\approx 3.88$  K,  $R_0\approx 0.12$   $\Omega$ ,  $P_c/P_{max}\approx 0.05$ . Solid line:  $R=R_0+b(P/P_{max}-P_c/P_{max})^{1/2}$ , where  $b\approx 0.4$   $\Omega$ . This power dependence was measured in the next series of measurements, so that the value of  $P_{max}$  is different.

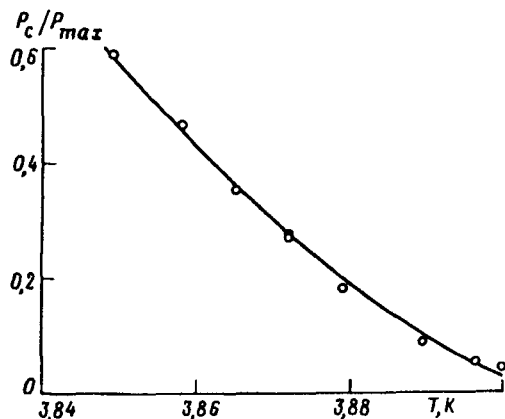


FIG. 3. Temperature dependence of the relative critical power at temperatures close to the critical temperature;  $T_c \approx 3.9$  K. Solid line:  $P_c/P_{max} = h(1 - T/T_c)^{3/2}$ , where  $h \approx 300$ .

determined near a current close to zero. The measurements were performed in the temperature range where dc overheating phenomena are weak, i.e., in the isothermal region. As the power increases, the normalized resistance increases, mainly by a jump, and after the jump it equals an integer. The small nonuniqueness of the dependence is explained by the fact that in repeated measurements there was a scatter in the powers at which a jump onto the  $n$ th step occurred. Moreover, at some powers the probabilities of states with the  $n$  and  $n + m$  PSL, where  $n$  and  $m$  are integers, were close. The sample jumped from one state into another. Separate points corresponding to the second or third visible linear step are also shown in Fig. 2. In some power intervals the resistance of the first, close to zero, step increased continuously, and then made a more or less distinct jump to a state with  $n$  PSL. We constructed the experimental curve of the resistance versus  $P/P_{max}$  in the interval where the resistance increases continuously from  $R_0$  up to values  $\leq 2R_0$  for one of the samples (Fig. 2, inset). These data can be approximated by a root function  $R = b(P/P_{max} - P_c/P_{max})^k + R_0$ , where  $k \approx 0.5$ , and  $b$  is a constant. Such dependences were also obtained for other films.

6. A phase separation into superconducting and nonequilibrium regions (PSL), which is induced by high-frequency irradiation, has thus been observed for the first time in wide superconducting films. The "high-frequency" separation is similar to the "current" separation. The possibility of "high-frequency" separation when superconductivity is stimulated in narrow channels was described in Ref. 11. To clarify the physical picture of the process and to compare it with the theory of Ref. 11 and the experiment of Ref. 12 for narrow films, where PSC are formed, we constructed the temperature dependence of the relative critical power  $P_c/P_{max}(T)$ . Near  $T_c$  this dependence has the form  $P_c/P_{max} \sim (1 - T/T_c)^{3/2}$  (Fig. 3). However, it is close to a linear dependence at temperatures farther away from the critical temperature and for somewhat higher powers. In this case the isothermal state could be disrupted. The temperature dependence  $P_c/P_{max} \sim (1 - T/T_c)^{3/2}$  agrees with the following experimental results: 1) The critical current  $I_c(0)$  with no irradiation and the critical power  $P_c/P_{max}$  have the same tempera-

ture dependence near  $T_c$  and 2) the critical current  $I_c(P/P_{\max})$  with irradiation is roughly a linear function of the power near  $T_c$  and  $P$  close to  $P_c$ .

At a temperature very close to  $T_c$  and low power, however, this dependence had the form  $I_c(P/P_{\max})=I_c(0)-c(P/P_{\max})^{1/2}$ , where  $c$  is a constant. In Ref. 13 the power dependence  $I_c(P/P_{\max})$  at low power was close to quadratic. Instabilities of different nature which result in the destruction of superconductivity have a different temperature dependence of the critical power. In Ref. 11 the relative critical power of the high-frequency separation of a film under conditions of stimulation of superconductivity in narrow films is proportional to  $1-T/T_c$ . In the case of an instability as a result of the pair-breaking current  $P_c \sim (1-T/T_c)^3$ , for flux-line motion  $P_c \sim (1-T/T_c)^2$ , and in a strong parallel field  $P_c \sim 1-T/T_c$ .<sup>14</sup> In Ref. 13  $P_c \sim 1-T/T_c$  for a thin film with a transport current and microwave irradiation, disregarding transparency. Very close to  $T_c$  other temperature dependences of  $P_c$  can be expected because of the nonequilibrium nature of the gap. The theories of Refs. 11 and 13 are concerned with uniform films which transform at the critical irradiation power  $P_c$  into the normal state<sup>13</sup> or into a nonuniform state with phase separation into PSC, the nonequilibrium regions immediately filling the sample along its entire length with a definite period.<sup>11</sup> In our case, just as in Ref. 12, the number of PSL which are formed on the nonuniformities of the film increases systematically with increasing irradiation power above  $P_c$ . However, the temperature dependence  $P_c(T)$  is different from the dependences presented in Refs. 11–14.

#### 7. There are several differences:

1) The transition from the power at which the critical current is first suppressed to the power at which the average critical current  $I_c=0$  is extended and its width is  $\approx 5$  dB (Fig. 1), while in Ref. 12 the width of this transition is  $\approx 0.5$  dB. The transition region depends on the absolute irradiation power and can be large for other measurements.

2) The resistance of a single PSL  $R_0 \sim I_E$  most likely does not change with an increase in power at the irradiation frequency 30 GHz, and the resistance  $R$  at the first step of the I-V characteristic of a sample with a PSL increases as a result of the appearance of new PSL. In Ref. 12 the resistance  $R_0$  of the irradiated sample decreased by 30%. It follows from the power-independence of  $R_0$  that the temperature dependence of  $R_0$  is also not related to the high-frequency irradiation at this frequency. Irradiation thus has no effect on the realization of the inelastic mechanism of relaxation of the unbalance of the populations of the electron- and hole-like branches of the quasiparticle spectrum.

3) In addition to a discrete increase of the resistance as a function of the power, there are also regions where  $R$  increases continuously (Fig. 2, inset). The increase of the resistance from  $R_0$  up to values  $\approx 2R_0$  can be explained by a gradual appearance of a second PSL. This process is associated with the production of Abrikosov flux lines by an rf magnetic field. The motion of these flux lines under the action of the measuring current gives an additional contribution to  $R$ . The experimental power dependence of this contribution has the form

$$R_{\text{flow}} = R - R_0 = b(P/P_{\max} - P_c/P_{\max})^{1/2},$$

where  $b$  is a constant. The power  $P_c$  at which the critical current vanishes is most likely equal to the power at which the flux lines start to move. The motion of the flux lines

produced by the rf electromagnetic field probably terminates with the formation of another PSL. However, many subsequent PSLs are formed by a jump without the participation of flux lines. Suppression of the order parameter could be another cause of the continuous growth of  $R$ . In this case  $\delta R = R - R_0 \sim \delta I_E \sim \delta \Delta / \Delta \sim \bar{A}_\omega^2 \sim P$ , (Ref. 15), where  $\bar{A}_\omega$  is the average amplitude of the magnetic vector potential of the electromagnetic field. According to our ideas, we worked at lower powers. Measurements with no irradiation were performed in the interval of isothermality of PSL. Hysteresis also did not occur at low irradiation powers, so that the continuous growth of the resistance from  $R_0$  up to  $\approx 2R_0$  on the first linear section is most likely not associated with thermal superheating.

8. In summary, phase separation, induced by an rf field with power above the critical power  $P_c$ , on phase-slip lines was observed in wide superconducting films. Near the critical temperature the power is  $P_c \sim (1 - T/T_c)^{3/2}$ . As the power increases, the resistance of the film increases, on the whole, by an amount that is a multiple of the resistance  $R_0$  of a single PSL with no irradiation, and this increase is associated with the successive formation of new PSLs. The resistance  $R_0$  and therefore the time-averaged value of the penetration depth of a longitudinal electric field do not depend on the irradiation power at 30 GHz. There is an additional contribution to the resistance of the sample  $\delta R \sim (P/P_{\max} - P_c/P_{\max})^{1/2}$  which could be associated with the motion of flux lines in an rf field.

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