The passage of a constant transport current exceeding the critical value gives rise to a spatially inhomogeneous resistive state in a superconducting film. A special feature of this state is the existence of an energy gap in the spectrum of quasiparticle excitations, i.e., the existence of a superconducting current, and also of a normal dissipative current giving rise to a voltage drop. A narrow film of width $W$ less than the coherence length $\xi(T)$ splits into localized resistive regions known as the phase-slip centers. The experimental results were found to be in good agreement with the theory when the mechanism of mixing of electron-like and hole-like branches of the quasiparticle spectrum was governed by the elastic scattering of the excitations. This was one more experimental confirmation that a phase-slip line is a two-dimensional analog of a phase-slip center.

An experimental investigation was made of the temperature dependence of the first step of a phase-slip line in a thin superconducting tin film. The depth of penetration of a nonequilibrium longitudinal electric field into the superconductor was determined near the critical temperature. A comparison was made with theoretical investigations of one-dimensional structures containing phase-slip centers. The experimental results were found to be in good agreement with the theory when the mechanism of mixing of electron-like and hole-like branches of the quasiparticle spectrum was governed by the elastic scattering of the excitations. This was one more experimental confirmation that a phase-slip line is a two-dimensional analog of a phase-slip center.

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The depth of penetration $l_E$ of a nonequilibrium longitudinal electric field determines the resistance $R_0$ to the flow of the current of a single phase-slip center and a phase-slip line, where

$$R_0 = 2\rho_n l_E/ W d,$$

where $\rho_n$ is the resistivity in the normal state and $d$ is the film thickness. In a more or less homogeneous film the above expression can be rewritten in the form

$$R_0 = 2R_n l_E/ L,$$

where $R_n$ is the resistance in the normal state and $L$ is the length of the whole film.

The temperature dependence $R_0(T)$ can be used to judge the temperature dependence of $l_E$. Information on the depth of penetration of the electric field can be obtained also directly by microprobe located near a single phase-slip center and a phase-slip line. The depth of penetration of the electric field is governed by various mechanisms of relaxation of the difference between the populations of electron- and hole-like branches of the energy spectrum of a superconductor. They include an inelastic mechanism of electron-phonon collisions, an "elastic" mechanism in the case of a sufficiently strong current $j_s$ of the condensate, and other "elastic" mechanisms involving the scattering by paramagnetic impurities and the anisotropy and inhomogeneity of the energy gap. Different mechanisms have different temperature dependence. An experimental investigation of the dependence $l_E(T)$ can be used to determine which mechanism is active in a given situation.

As demonstrated in many theoretical and experimental investigations, an inhomogeneous distribution of the longitudinal field in a phase-slip center is formed primarily by the inelastic electron-phonon scattering processes. In this case the depth of penetration of an electric field into a superconductor with an energy gap is

$$l_E^0 = \sqrt{D\tau_Q} = \sqrt{D\tau_c \frac{4kT}{\pi\Delta}},$$

where $\Delta$ is the energy gap, $D = (1/3)v_F l$ is the electron diffusion coefficient ($v_F$ is the Fermi velocity and $l$ is the mean free path), $\tau_Q$ is the relaxation time of the asymmetry of the populations of the branches of the quasiparticle spectrum, and $\tau_c$ is the relaxation time. Near $T_c$ in the case of the inelastic mechanism we have

$$l_E^0 = A(D\tau_c)^{1/2}(1 - \tau)^{-1/4},$$

where $A$ is the numerical coefficient of the order of unity, $\tau = T/T_c$, and $T_c$ is the critical temperature.

It is shown in Refs. that another mechanism of penetration of an electric field is the elastic scattering of excitations resulting in mixing of the electron and hole branches of the spectrum. It is important if we allow for the finite velocity of flow of the superconducting condensate. At temperatures somewhat further from $T_c$ these processes may predominate over the inelastic mechanism. The depth of penetration of an electric field in the case of the elastic scattering mechanism is

$$l_E^{el} = \frac{\pi\varepsilon}{P_s \Delta \sqrt{2}},$$

where $P_s$ is the numerical coefficient of the order of unity, $\varepsilon$ is the penetration depth of the electric field into the superconductor, $\Delta$ is the energy gap, and $P_s$ is the penetration depth of the electric field into the superconductor.
where $P_s$ is the superfluid momentum and $\varepsilon$ is a characteristic energy. Near $T_c$, we obtain

$$l_{E}^{\ell} = B(\zeta_0 l)^{1/2}(1 - \varepsilon)^{-1}, \quad (6)$$

where $B$ is a numerical coefficient of the order of unity and $\zeta_0$ is the coherence length of a pure superconductor. The limiting conditions for the realization of the elastic and inelastic case are found theoretically in Ref. [4]. The inelastic mixing mechanisms can be neglected if

$$l_{E}^{\ell} << l_{E}^{\ast} \quad (7)$$

In the case of a homogeneous sample, we have

$$(1 - \varepsilon) >> \left[ \frac{\hbar}{\tau_{e} k T_c} \right]^{2/3} \quad (8)$$

It follows from the above inequality that when the temperature shifts somewhat from $T_c$, the elastic processes of mixing of electron and hole branches of the quasiparticle spectrum may predominate in such a homogeneous sample. Moreover, the condition (8) depends on the energy relaxation time $\tau_e$. Theoretical estimates of $\tau_e$ are given in Ref. [4], but the experimental values of $\tau_e$ are subject to a large scatter. Therefore, at a given temperature we may have the same mixing mechanism in different samples.

Phase-slip centers have been investigated quite thoroughly both theoretically and experimentally [1, 2], but there are practically no theoretical studies of phase-slip lines. These lines have the following properties: 1) motion of vortices until the first phase-slip line is formed; 2) creation of a magnetic field by the transport current (in the case of phase-slip centers this field is ignored because of the small width of the films). This makes it difficult to analyze phase-slip lines theoretically. The temperature dependence of the resistance of these lines has not yet been investigated sufficiently thoroughly. Even in the case of phase-slip centers the early treatments of Tinkham et al. [3] failed to detect a temperature dependence of the differential resistance of these centers. This dependence was however observed subsequently [11, 12]. In the case of wide films the temperature dependence of the differential resistance of a phase-slip line was first investigated by us [12] and we found that the depth of penetration of an electric field is governed by the inelastic scattering mechanism.

Variation of the initial data of a sample allows us to consider the elastic mechanism. The temperature dependence of the resistance of a phase-slip line under the elastic scattering conditions is the subject to the present paper. We prepared samples with a much lower resistivity $\rho_0 = 8 \times 10^{-7} \Omega \cdot \text{cm}$ than used by us in Ref. [12], which made it possible to widen the temperature range of the existence of phase-slip lines until they were transformed into resistive domains, which increased the probability of a realization of the elastic case. Moreover, in the case of the new samples the time $\tau_e$ was several times longer than in the study reported in Ref. [12].

Our samples were tin films $d \approx 2000 \, \text{Å}$ thick, $W = 70 \, \mu\text{m}$ wide, $L = 2 \, \text{mm}$ long and $R_n \approx 1.14 \, \Omega$. They were formed by thermal evaporation on silicon substrates kept at room temperature. Weak spots (cuts) at side boundaries of a film strip were formed to facilitate the appearance of isolated phase-slip lines. The current-voltage characteristic was recorded at different temperatures of a helium bath near $T_c \approx 3.91 \, \text{K}$. This characteristic was stepped and it consisted of a series of linear regions with a differential resistance which was a multiple of the resistance $R_0$ of a single phase-slip line, similar to that reported in Ref. [12].

The temperature dependence of the resistance of the first phase-slip line (Fig. 1) was qualitatively similar to the temperature dependence reported by us earlier [12]. However, in the present case, single phase-slip lines were manifested less clearly in the current-voltage characteristic and merging of several phase-slip lines usually occurred. The appearance of the first step due to a single phase-slip line near the critical current and critical temperature was observed for samples with a strong inhomogeneous boundary (the dimensions of the inhomogeneity were less than the depth of penetration of an electric field). The main difference was that the resistance of a phase-slip line had a stronger temperature dependence (Fig. 1) in the isothermal interval, which was $\approx 3.86 \div 3.90 \, \text{K}$ in our case.

The results of a quantitative analysis obtained for one of our samples are presented in Fig. 2. The temperature
Hence, we found the experimental value with the slope scale. The experimental points fitted well a straight line $\tau$ of this line intersected the ordinate at $\ln M$ dependence of the dimensionless resistance $R_0/1\Omega$ on $(1-\tau)$ in the isothermal interval was plotted on a logarithmic scale. The experimental points fitted well a straight line with the slope $\approx -1$ and the continuation (extrapolation) of this line intersected the ordinate at $\ln M \approx -8.26$. Hence, we found the experimental value $M_{exp} \approx 2.59 \times 10^{-4} \Omega$. Assuming that

$$l_E^\tau = B(\xi_0 l)^{1/2} (1-\tau)^{-n}, \quad (9)$$

we obtained experimental value of the resistance

$$R_0^{exp} = R_n \frac{2l_E}{L} = M(1-\tau)^{-n}, \quad (10)$$

where

$$M = \frac{2R_n B(\xi_0 l)^{1/2}}{L} , \quad (11)$$

$\xi_0 = 2.3 \times 10^{-5}$ cm is the coherence length of tin and $l = 2 \times 10^{-5}$ cm is the mean free path in the tin film obtained from $\rho_n l \approx 1.6 \times 10^{-11} \Omega \cdot \text{cm}^2$.\[12\]

A comparison of the experimental value of $M_{exp}$, deduced from Fig. 2, with $M \approx B(2.44 \times 10^{-4}) \Omega$, deduced from (11) indicated that the numerical coefficient was $B \approx 1$. Therefore, the depth of penetration of an electric field found from the experiment results was given by Eq. (9), where $B \approx 1$ and $n \approx 1$. This was in agreement with the theoretical predictions and with the experimental results obtained for narrow films in which phase-slip centers formed. In the elastic case characterized by $\nu_E^\tau > \nu_E^\nu$ we could estimate the energy relaxation time $\tau_e$. This time was of the order of $10^{-9}$ s, which was close to the value found in Ref. $[10]$, when both (elastic and inelastic) scattering mechanisms were active under the conditions of formation of phase-slip centers. This value of $\tau_e$ was several times greater than that used in Ref. $[12]$, where the inelastic mechanism was observed.

We thus demonstrated for the first time that in the case of wide films containing phase-slip lines, when the transport current was slightly higher than the critical value, the elastic relaxation mechanism of the imbalance of populations of the electron- and hole-like branches of the quasiparticle spectrum of excitations could predominate and govern the depth of penetration of an electric field and, consequently, the temperature dependence of the resistance of a phase-slip line. This resistance was governed by $l_E$, exactly as in the case of narrow films containing phase-slip centers.

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