Advances in the criteria for dividing thin superconducting films into narrow and wide films

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The results of experimental investigations of the critical currents and certain nonequilibrium phenomena in thin Sn films of different width \( w \) are analyzed. Usually, thin superconducting films are divided into two groups: narrow channels \( w < \lambda_\perp \), and wide films \( w > \lambda_\perp \). A wide transitional region where the condition \( w > \lambda_\perp \) holds with a large margin and at the same time cannot be explained from the standpoint of the theory of the appearance of a vortex state has been found. This shows that the generally accepted criterion \( w \sim \lambda_\perp \) for dividing films into wide and narrow does not work. The transition into a wide-film regime, described by the existing theory of the vortex state, is fully completed only for \( w/\lambda_\perp(T) > 10−20 \).

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It is now generally accepted that thin superconducting films can be divided into narrow and wide films. Films whose width \( w \) and thickness \( d \) are smaller than the penetration depth \( \lambda_\perp(T) \) of a magnetic field and the coherence length \( \xi(T) \), which ensures a uniform distribution of the current over the film width and absence of vortex resistivity, are said to be narrow channels. Phase-slip centers (PSCs) appear when the current, exceeding the critical current \( I_{c,\perp}^{GL}(T) \) for Ginzburg-Landau (GL) depairing, flows in a narrow channel. These centers consist of the cores of size \( \sim \xi(T) \) and the diffusion tails on both sides of the core, having the length of the penetration depth of a longitudinal electric field into the superconductor. The order parameter \( \Delta \perp \) and the superconducting current \( I_c \) in the core of a PSC oscillate, and at certain moments \( \Delta \) and \( I_c \) vanish and the phase changes abruptly by \( 2\pi \). The frequency of the oscillations is determined by the Josephson ratio \( f_s = 2eV/h \).

Films whose width \( w > \lambda_\perp(T), \xi(T) \) are said to be wide [1]. In such films, due to the Meissner screening of the current-induced magnetic field, the current distribution over the width is nonuniform and exhibits sharp peaks at the edges. According to the Aslamazov-Lempitskiy (AL) theory [2], the resistive transition of a wide film is due to the instability of the current state when the edge current density reaches a value close to the critical current density \( f_c^{AL} \) in the GL theory. This instability results in the creation of vortices, whose motion generates voltage at the ends of the film. The corresponding critical current \( I_c^{AL} \) is small compared to \( I_c^{GL} \), since the current density in the bulk of the film is far from the critical value. On account of the motion and annihilation of the vortices, a second sharp peak in the current density forms at the center of the film. For certain value \( I_m \) of the current, the magnitude of this peak reaches a critical value \( f_c^{GL} \), which results in instability of the stationary flow of the vortices. In the AL theory, it was supposed that for \( I > I_m \), a film exhibits transition into the normal state.

The experimental investigations of resistive transitions in wide films, although qualitatively confirming the above-described picture of a nonuniform distribution of the current in subcritical and vortex states [3,4], have at the same time resulted in considerable refinement of the main assumptions of

\[ I_c^{AL} / I_c^{GL} = 1.5(\pi \lambda_\perp / w)^{1/2} \text{ (curve 2)} \]

FIG. 1: Reduced critical current density \( I_c / I_c^{GL} \) versus \( w/\lambda_\perp \) for the samples SnW5 ( ), SnW6 ( ), SnW7 ( ), SnW8 ( ), SnW9 ( ), SnW10 ( ); curve 2 – AL theoretical curve. The parameters of the films can be found in Ref. 4.

It turned out [4] that the vortex resistivity arises only in a film of sufficient width, \( w > 4\lambda_\perp \), while for \( I > I_m \) the film passes not into a normal state but rather to a vortex-free state with phase-slip lines (PSLs) – the two-dimensional analogues of PSCs. Even more unexpected, and prompting us to raise the question of the true criterion for a “wide film”, was the behavior of the temperature dependence of the critical current, shown in Fig. 1 for several samples as a dependence of the reduced current \( I_c / I_c^{GL} \) on the parameter \( w/\lambda_\perp \), which is proportional to \( 1 − T/T_c \). According to the AL theory, for \( w > \lambda_\perp \) this dependence should be described by a universal function of \( w/\lambda_\perp, I_c^{AL} / I_c^{GL} \) (curve 2). In the experiment, as seen from Fig. 1, this universality does indeed exist but only for very large values of \( w/\lambda_\perp \sim 10−20 \), which therefore should serve as the real criterion for a transition into the wide-film regime.

For smaller values of \( w/\lambda_\perp \), the behavior of the critical current is very peculiar. According to Ref. 4, samples with \( w/\lambda_\perp < 4 \) are narrow channels (in Fig. 1 the region to the left of the vertical straight line 1). In the interval between the vertical straight line 1 and the curve 2, there is a transitional region where the film is “quasi-wide” (a vortex section is present in the current-voltage characteristic (IVC) but the AL theory “does not work” yet). For the SnW10 film \(( w = 7 \mu m) \) the experimental current \( I_c \) for \( w/\lambda_\perp < 4 \) equals the computed value of \( I_c^{GL} \). As temperature decreases, i.e. \( w/\lambda_\perp \) increases, vortex resistivity arises and \( I_c \) drops rapidly
to a smaller value, which nonetheless reveals the temperature dependence close to \( I_c(T) \) that continues right up to a transition into regime described by the AL theory. This decrease of \( I_c \) is even more rapid for the SnW6 film (\( w = 17 \mu m \)), as a result of which the region of the transitional temperature dependence \( I_c \propto (1 - T/T_c)^{3/2} \) expands considerably. Finally, for the widest films SnW8 (\( w = 25 \mu m \)) and SnW5 (\( w = 42 \mu m \)), where a narrow-channel regime is not observed because of the extreme proximity of the corresponding temperature region to \( T_c \), the dependencies of \( I_c/I_c^{GL} \) on \( w/\lambda_\parallel \) are completely identical, and the width of the transitional region reaches saturation.

It should be noted that the observed wide transitional region, where the condition \( w > \lambda_\parallel \) holds with a large margin and at the same time the dependence \( I_c(T) \) is identical to the behavior of \( I_c^{GL}(T) \), cannot be explained from the standpoint of the AL theory of the mechanism of the appearance of the vortex state. A characteristic feature of this region is a sharp transition of \( I_c \propto (1 - T/T_c)^{3/2} \) to \( I_c^{AL}(T) \propto 1 - T/T_c \). Our numerical solution of the London integral equation \([2]\) for the current distribution over the film width for arbitrary values of \( w/\lambda_\parallel \) also shows the absence of a wide transitional region between \( I_c^{GL}(T) \) and \( I_c^{AL}(T) \) provided the critical current density \( j_c^{GL} \) is reached at the edge of the film at the point of the transition. This could signify that the condition for the appearance of vortices for \( w/\lambda_\parallel < 10 - 20 \) weakens because of the existence of a competing mechanism for the penetration of vortices into the film when the edge current density reaches some value \( j_c(T) \) smaller than \( j_c^{GL}(T) \). To explain the observed constancy of the value of \( I_c/I_c^{GL} \) in the transitional region, it must be assumed that as the temperature decreases the quantity \( j_c(T) \) increases more rapidly than \( j_c^{GL}(T) \), and is proportional to \( (1 - T/T_c)^2 \). At the point where they become equal, a transition occurs into the AL regime, which explains the sharpness of the crossover to the linear temperature dependence of \( I_c^{AL}(T) \) seen in Fig. 1. In principle, such a mechanism can be associated with edge microdefects, which have virtually no effect on the GL depairing current in the narrow-film regime, but they are a source of vortices in a wide film. At the same time the excellent quantitative agreement between the critical currents \( J_c(T) \), \( J_\mu(T) \) and the predictions of the AL theory for large values of \( w/\lambda_\parallel \) casts doubt on this supposition.

Other nonequilibrium phenomena, for example, the generation of electromagnetic oscillations with frequency lower than the Josephson frequency, also point to the inapplicability of the widely accepted criterion \( w \approx \lambda_\parallel(T) \) for a “wide film”. This phenomenon, called non-Josephson generation \([5, 6]\), arises when a certain current density \( j_c \) is reached, and this generation current density for narrow tin films (\( w \approx 1 \mu m \)) is 2.7 times higher than for wide samples with \( w > 20 \mu m \) at the same reduced temperature \( T/T_c = 0.99 \). Thus, for film width in the range \( 1 - 20 \mu m \), a smooth transition can occur from high to low generation current densities. To check this assumption, a film obtained in one deposition operation was used to prepare a series of samples with different width. The results of measurements of the generation current density \( j_c \) versus the width \( w \) of tin films at temperature \( T = 0.99T_c \) are presented in Fig. 2. It is evident that the center of the transition from a narrow to a wide channel corresponds to \( w \approx 12 \mu m \). Thus, from the standpoint of non-Josephson generation, tin films with width up to \( w \approx 5 \mu m \) can be treated as narrow channels, while they become “wide” only for \( w > 20 \mu m \).

A similar conclusion concerning the inapplicability of the widely accepted criterion \( w \approx \lambda_\parallel(T) \) \([1]\) for determining the boundary between narrow and wide films can also be drawn on the basis of an analysis of changes in the dependence of the critical current \( I_c \) on the power \( P \) of an external microwave field for films with different width \([7]\). Figure 3a shows the function \( I_c(P) \) in relative units for tin films of different width under identical experimental conditions. The descending sections of the curves \( I_c(P)/I_c(0) \) in Fig. 3a can be fit by the function \( I_c \propto (1 - P/P_c)^{\alpha} \). For the sample SnW10 (\( w = 7 \mu m \)), which at \( T/T_c = 0.99 \) is a narrow channel \([4]\), the dependence \( I_c(P)/I_c(0) \) is convex and, correspondingly, \( \alpha = 0.53 < 1 \). For the sample SnW6 (\( w = 17 \mu m \)) this dependence becomes concave and \( \alpha = 1.4 \) is larger than 1, while for the obviously wide film SnW5 (\( w = 42 \mu m \)) \( \alpha = 2.9 \). The dependence of the exponent of the fitting functions of the critical current versus the sample width, presented in Fig. 3b, shows that the value \( \alpha = 1 \) can be expected for a film of width \( w \approx 12 \mu m \), and the descending section of the function \( I_c(P) \) is a straight line. In other words, as the film width increases, the sign of the curvature of the descending sections of the curves changes, and a film with \( w \approx 12 \mu m \) is a boundary between quasi-narrow and quasi-wide samples, as in the case displayed in Fig. 2.

In summary, the result of the investigations of the critical currents and different nonequilibrium phenomena in thin films of different width make it possible to conclude that the widely accepted criterion \( w \sim \lambda_\parallel(T) \) for dividing films into wide and narrow does not work. The transition into the wide-film regime, described by the existing theory of the vortex state, fully occurs only for \( w/\lambda_\parallel > 10 - 20 \). It can be supposed that the simple criterion \( w > \lambda_\parallel \) does not work in practice because of the structural particularities of a Pearl vortex in a thin film, which is not a truly localized formation \([8]\). In contrast to an Abrikosov vortex in a bulk superconductor, its fields decrease with increasing distance not exponentially but rather in a power-law fashion. Specifically, Kogan \([9]\) has shown that the magnetic flux trapped by a single vortex in a thin film,
even at a distance $24\lambda_\perp$ from the vortex core, is 90% of the flux quantum. The ratio between the film width and the penetration depth of an electric field, which for $w/\lambda_\perp \sim 10$ is close to 1, can also play a certain role. The “anomalous” vortex state (transitional region) which we discovered and which arises in the interval $4 < w/\lambda_\perp < 10 - 20$ for the computed value of the edge current density $\propto (1 - T/T_c)^2$ much smaller than the depairing current density $j_{GL}^{GL}(T)$ draws attention also. The mechanism of the penetration of vortices into a film for such small edge currents and the reason why it vanishes for large values of $w/\lambda_\perp$ are not described by existing theories and have no explanation at the present time.

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