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 tin films of different width w are analyzed. Ordinarily, 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 less 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 width of the film and absence of vortex resistivity, are said to be narrow channels. Phase-slip centers (PSC) appear when a current exceeding the critical current $I_c^{GL}(T)$ for Ginsburg-Landau depairing flows in a narrow channel. These centers are nuclei of size $\sim\xi(T)$ and the diffusion "tails" on both sides of a nucleus are of the order of the penetration depth of a longitudinal electric field into the superconductor. The order parameter Δ and the superconducting current I_s in the nucleus of a PSC oscillate, and at definite times Δ and I_s vanish and the phase changes abruptly by 2π. The frequency of the oscillations is determined by the Josephson ratio $f_J=2\ \mathrm{eV}/nh$, where $n=1,2,\ldots$.

Films whose width $w>\xi(T)$, $\lambda_T(T)$ are said to be wide.[1] In such films, because of 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–Lempitskiĭ (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 j_c^{GL} in the GL theory. This instability results in the creation of vortices, whose motion generates a voltage at the ends of the film. The corresponding critical current I_c^{AL} is weak compared with I_c^{GL}, since the current density in the volume of the film itself 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 some value of the current I_m the magnitude of this peak reaches a critical value j_c^{GL}, which results in the instability of the stationary flow of the vortices. In the AL theory, it was supposed that for $I>I_m$ a film transitions into the normal state.

The experimental investigations of resistive transitions in wide films, which, 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 A. L. Okazalos' theory[4] that the a resistive transition 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 a vortex-free state with phase-slip lines (PSL)—the two-dimensional analogues of PSC. 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, displayed in Fig. 1 for several samples as a dependence of the reduced current I/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 $w/\lambda_\perp$: $I_c^{AL}/I_c^{GL}=1.5(\pi\lambda_\perp/w)^{1/2}$ (curve 2). In the experiment, as one can see from Fig. 1, this universality does indeed exist but only for very large values of $w/\lambda_\perp\sim10-20$, 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 on the 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

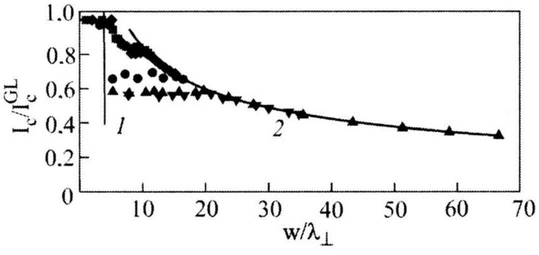

FIG. 1. Reduced critical current density I_c/I_c^{GL} versus $w/\lambda_\perp$ for the samples SnW5 (▲), SnW6 (●), SnW8 (▼), SnW9 (♦), SnW10 (■); curve 2—AL theoretical curve. The parameters of the films can be found in Ref. 4.

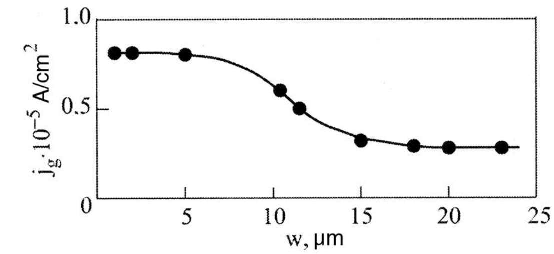

FIG. 2. Generation current density versus the Sn film width at $T/T_c=0.99$.

and I_c drops rapidly to a smaller value, which nonetheless possesses a temperature dependence close to $I_c^{GL}(T)$ 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 ($w=17$ μm), 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 ($w=25$ μm) and SnW5 ($w=42$ μm), where a narrow-channel regime is not observed because of the extreme proximity of the corresponding temperature region to T_c, the dependences of I_c/I_c^{GL} on $w/\lambda_\perp$ 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 $w>\lambda_\perp$ 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 $I_c \sim (1-T/T_c)^{3/2}$ to $I_c^{AL}(T) \sim (1-T/T_c)$. Our numerical solution of the London integral equation[2] for the current distribution over the width of the film for arbitrary values of $w/\lambda_\perp$ also shows the absence of a wide transitional region between $I_c^{GL}(T)$ and $I_c^{AL}(T)$ provided that 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 $w/\lambda_\perp < 10-20$ 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 $j_c(T)$, less 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, seen in Fig. 1, of the crossover to the linear temperature dependence of $I_c^{AL}(T)$. 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 $I_c(T)$, $I_m(T)$ and the predictions of the AL theory for large values of $w/\lambda_\perp$ 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 $w \geqslant \lambda_\perp(T)$ for a "wide film." This phenomenon, called non-Josephson generation,[5,6] arises when a definite current density j_g is reached, and this generation current density for narrow tin films ($w \approx \xi \approx 1$ μm) is 2.7 times higher than for wide samples with $w > 20$ μm at the same reduced temperature $T/T_c=0.99$.[6] Thus, for film width in the range 1–20 μm, a smooth transition can occur from high to low generation current densities. To check this supposition, 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_g versus the width w of tin films at temperature $T=0.99T_c$ are presented in Fig. 2.[6] It is evident that the center of the transition from a narrow to a wide channel corresponds to $w \approx 12$ μm. Thus, from the standpoint of non-Josephson generation, tin films with width up to $w \approx 5$ μm can be treated as narrow channels, while they become "wide" only for $w > 20$ μm.

A similar conclusion concerning the inapplicability of the widely accepted criterion[1] $w \approx \lambda_\perp(T)$ 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 nondescending 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 ($w=7$ μm), which at $T/T_c=0.99$, is a narrow channel,[4] the dependence $I_c(P)/I_c(0)$ is convex and, correspondingly, $\alpha \approx 0.53 < 1$. For the sample SnW6 ($w=17$ μm) this dependence becomes concave and $\alpha \approx 1.4$ is greater than 1, while for the obviously wide film SnW5 ($w=42$ μm) $\alpha \approx 2.9$. The dependence of the exponent α 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 $w \approx 12$ μm, 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 $w \approx 12$ μm 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 $w \sim \lambda_\perp$ 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 $w/\lambda_\perp > 10-20$. It can be supposed that the simple criterion $w > \lambda_\perp$ does not work in practice because of the structural particularities of a vortex in a thin

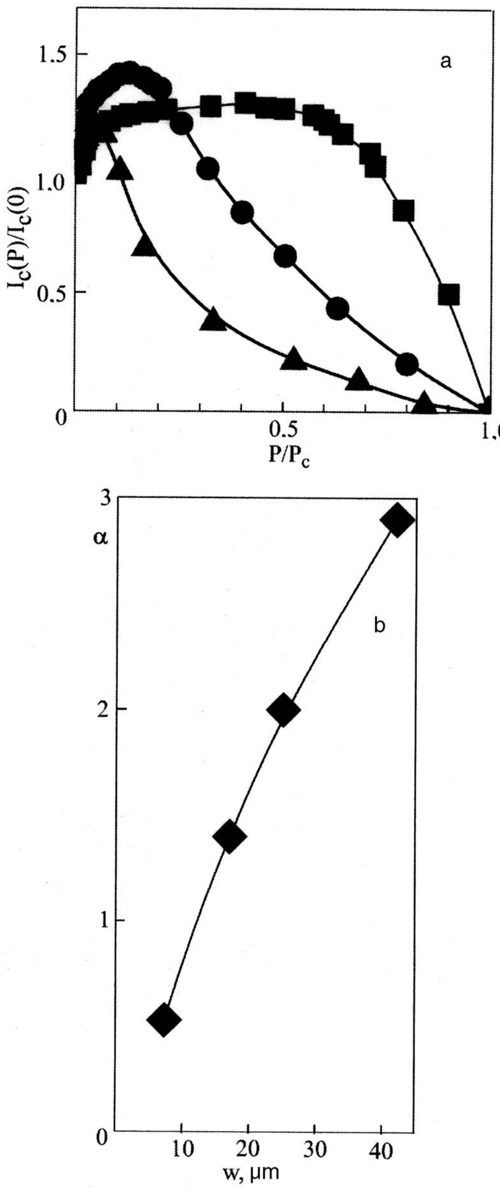

FIG. 3. Relative critical current $I_c(P)/I_c(0)$ versus the reduced irradiation power P/P_c for different tin films: SnW5 (▲), SnW6 (●), and SnW10 (■) (a) and the exponent α of its fitting function versus the width w of the sample at 9.2 GHz at $T/T_c \approx 0.99$ (b).

film, which is not a truly localized formation:[8] in contrast to an Abrikosov vortex, its fields in a bulk superconductor decrease with increasing distance not exponentially but rather in a power-law fashion. Specifically, Kogan has shown that the magnetic flux trapped by a single vortex in a thin film, even at a distance $24\lambda_\perp$ from the nucleus vortex, 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 definite 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 less than the depairing current density $j_c^{GL}(T)$ 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 modern theories and have no explanation at the present time.

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