Critical currents of granular, superconducting films of small cross section

M.E. Gershenzon and V. N. Gubankov
Institute of Radio Engineering and Electronics, USSR Academy of Sciences

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The $J_c(T)$ dependence of granular Nb and NbN films near T_c is described by a theory developed for homogeneous, "dirty" superconductors, whereas for $T/T_c \lesssim 1 - [\xi(0)/g]^2$, where g is the granule size, the films behave like an ensemble of strongly bound granules.

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Recently, considerable attention has been focused on studying the properties of thin films of high-temperature superconductors, including films of niobium and its compounds. In addition to the prospects for their practical utilization,[1] a stimulus for studying such films lies in the growing interest in granular superconductors. Because of the high oxidizability of Nb, the films of Nb and its compounds consist of granules surrounded by an oxide layer; the dimensions of these granules are in the range 50–1000 Å, depending on the thickness of the film, its material, and the deposition method.[2,3] Until now, granular films in which the coherence length $\xi(0)$ greatly exceeds the granule size g have been studied thoroughly. This holds true, for example, in Al films sputtered in an oxygen atmosphere.[4] The short coherence lengths in the films of Nb and its compounds, which are attributable to intense scattering of electrons, make it possible to investigate the other limiting case—$\xi(0) \ll g$—and to trace the transition from $\xi(T) > g$ to $\xi(T) < g$ in the same sample by varying the temperature.

The use of thin Nb and NbN film of small cross section enabled us to correctly compare our results with those of the microscopic theory developed for homogeneous superconductors and to trace the transition from a region near the critical temperature T_c, where the critical currents are well described by the theory for homogeneous, "dirty" superconductors, to the temperature region where the films behave like an ensemble of strongly bound granules. Knowing the temperature at which this transition occurs, we can estimate the granule size and trace the dependence of g on the film thickness.

We have investigated thin (thickness $d = 400$–1000 Å) and narrow (width $W = 1$–5 μm) Nb and NbN films obtained by high-frequency sputtering. The resistive transition, in agreement with the fluctuation theory,[5] and the $T_c(d)$ dependence, which is quantitatively described by the theory of the proximity effect[6] with ~30-Å-thick surface layer with suppressed superconductivity for Nb and NbN, indicate that such films are highly homogeneous at much greater distances than $\xi(0)$.[7] The samples were produced by using photolithography followed by ionic etching. The parameters of several samples, which were determined using the standard method,[8] are given in Table I.

TABLE I

Sample No.	Material	W μm	d Å	$\lambda_\perp(0)$ μm	$\xi(0)$ Å	T^*/T_c	g Å
1	Nb	1	700	0.29	70	0.78	150
2	Nb	3	500	0.56	74,5	0.72	140
3	Nb	5	1000	0.23	87	0.87	240
4	NbN	1	500	8.4	39,5	0.75	80
5	NbN	1,5	500	9.8	42	0.75	85

Figure 1 shows the experimental dependences of the critical currents J_c of these samples on the quantity $W/\lambda_\perp$, which is a function of the temperature ($\lambda_\perp$ is the effective penetration depth of the magnetic field). The explicit temperature dependence of the critical current is shown in Fig. 2 for one of the samples (No. 4). A comparison with the theoretical temperature dependence $J_c^{gl}(T)=j_c^{gl}(T)(Wd)$ of the decoupling currents uniformly distributed over the sample cross section was carried out using the results of a numerical calculation of the $j_c^{gl}(T,l)$ dependences (l is the electron mean free path) obtained on the basis of the microscopic theory.[9] A good quantitative agreement between the experiment and the theory near T_c confirms the conclusion[4] that the theory of homogeneous, "dirty" supeconductors is applicable to granular superconductors with $\xi(T)\gg g$ and $k_F l \gg l$ (k_F is the Fermi wave number). As the temperature decreases, we can see that the experimental $J_c(T)$ dependence deviates from the theoretical dependence obtained for the decoupling currents that are uniformly distributed over the film cross section. This occurs for two reasons. First, for samples that are wide compared with $\lambda_\perp(0)$ the uniformity of the current distribution over the sample's cross section is perturbed at an appreciable distance from T_c. This occurs for $W/\lambda_\perp(T)\approx 1$, and for further decrease of the temperature the experimental $J_c(T)$ dependences are well described by the expression $J_c(T)=J_c^{gl}(T)\left(\frac{\lambda_\perp(T)}{W}\right)^{1/2}$ represented by a dashed line in Fig. 1, which corresponds to the $J_c(T)$ dependence for $W\gg\lambda_\perp(T)$ within an accuracy of a constant coefficient ~ 1 (Ref. 10). Second, we can see that for all the Nb and NbN samples studied, starting with a certain temperature T^*, an increase of $J_c(T)$ dependence slows down compared with the corresponding theoretical dependences obtained for homogeneous superconductors. Identical results were obtained with samples obtained by using the method described in Ref. 8, which have a considerably different edge geometry (a smooth thinning out of the film toward the edges). This confirms that the slowing of the rise in J_c is not due to the eddy mechanism for destruction of superconductivity because of elimination of the edge barrier at

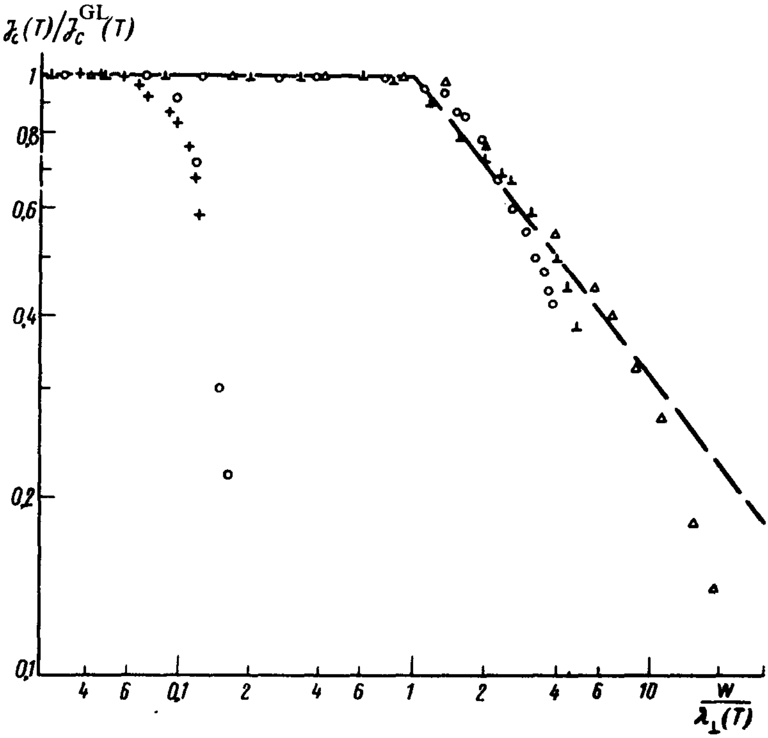

FIG. 1. The samples, whose parameters are listed in Table I are denoted by the following numbers: 1, ●; 2, ⊥; 3, Δ; 4, +; 5, ○.

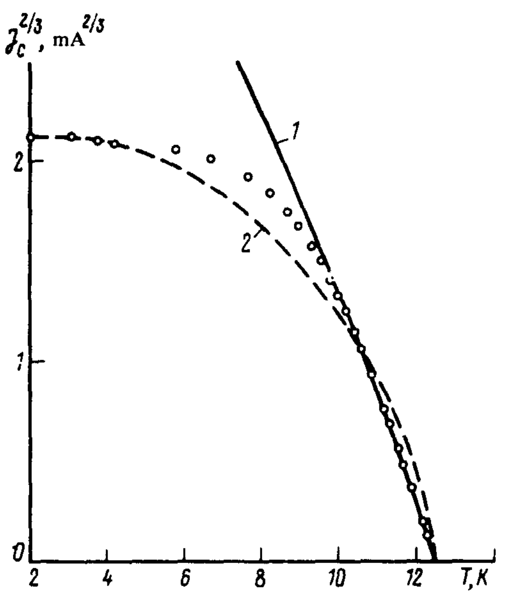

FIG. 2. $J_c^{2/3}(T)$ dependence for Sample No. 4. 1, $[J_c^{gl}(T)]^{2/3}$ dependence; 2, $[J_c^{AB}(T)]^{2/3}$ dependence.

$T \lesssim T^*$.

The observed shape of the $J_c(T)$ dependence can apparently be explained by the fact that the coherence length $\xi(T)$ at $T \approx T^*$ is comparable to the average size of the film granules. With a further decrease of the temperature the film behaves like an ensemble of granules with direct or tunnel conduction across the barriers between the granules, depending on the degree of oxidation of the granule surfaces. In fact, a transition from the region where $J_c(T)$ is quantitatively described by the theoretical $J_c^{gl}(T)$ dependence to the plateau region for $T \lesssim T_c$, which is identical to the Ambegaokar-Baratoff $J_c^{AB}(T)$ dependence for a tunnel Josephson junction,[11] can be observed in Fig. 2. A similar correspondence in the shape of $J_c(T)$ and $J_c^{AB}(T)$ for thin NbN films at low temperatures was observed in Ref. 1. It should be noted that a comparatively low resistivity of films in the normal state and high critical-current densities in the region of the plateau [$(1.5-3)\times 10^7$ A/cm^2 for Nb and $(4-5)\times 10^7$ A/cm^2 for NbN] indicate that the bonding between granules is strong.

A knowledge of the transition temperature T^* makes it possible to obtain estimates of the granule size. The g values obtained from the relation $g = \xi(T^*)$ and given in Table I agree with the literature data for the granule size in such films, which were obtained by direct methods.[2,3] It should be noted that an increase in the ratio T^*/T_c is observed with an increase in thickness of the Nb films, which indicates that the granules increase in size, in agreement with the results of Ref. 2.

Thus, a knowledge of the $J_c(T)$ dependences in granular films of high-temperature superconductors of small cross section makes it possible to trace the change in their properties as one goes from the case $\xi(T) > g$ to $\xi(T) < g$ and to obtain information about the structure of these films. It should also be noted that the two conditions $W \lesssim \lambda_\perp(T)$ and $g \lesssim \xi(T)$ must be satisfied simultaneously in order to produce decoupling currents in granular films that are uniformly distributed along the sample cross section.

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