Size effects in the conductivity of thin-film bridges of high-temperature superconductors

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The effect of the dimensions (w,l) of film bridges on their electrical conductivity is linked with the existence of large-scale percolation processes, with a correlation radius L much greater than the grain size a. A time-varying Josephson effect is observed in such bridges under the conditions $\xi(0) \ll a < w, l < L$.

Granular high-temperature superconducting films are of particular interest for research on the physics of diordered superconducting systems. The usual properties of these films in comparison with those of films of conventional superconductors[1,2] stem primarily from the short coherence length $\xi(0)$, which is such that the ratio of $\xi(0)$ to the typical grain size a ($\sim 1\ \mu$m) is 10^{-3}–10^{-4}. Because of this circumstance, the properties of the films are governed by a set of Josephson weak links between grains over a wide temperature range, from $T \to 0$ up to the critical temperature.[3] A Josephson medium of this sort has a percolation mechanism for its conductivity because of both the statistical scatter in the properties of the grain-grain links and the sizes of the grains,[4] on the one hand, and the specific effect of thermal fluctuations on Josephson weak links,[5] on the other. The distinctive features of the percolation current flow in

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such a medium should become most obvious as the dimensions of the medium decrease.

We have studied the electrical resistance of thin-film bridges of $YBa_2Cu_3O_{7-\delta}$. The original films were synthesized on BaF_2 substrates by magnetron sputtering[6] and had grain sizes of 0.5–3 μm and thicknesses of 0.5–1 μm. The surface resistivities $R_\square$ of the films at 300 K ranged from a few ohms to tens of ohms. From each film which we studied we fabricated a family of bridges by a photolithographic technique. The widths of these bridges ranged from 5 to 200 μm, and the ratio of the bridge length l to the bridge width w ranged from 1 to 10. After the fabrication, and after a cement containing silver was applied to the contact areas, some of these bridges were annealed in oxygen. This annealing had no qualitative effect on the results found in this study.

Figure 1 shows the characteristic temperature dependence of the resistance, $R_\square(T)$, for a family of bridges of various dimensions fabricated from the same $YBa_2Cu_3O_{7-\delta}$ film. The temperature at which the transition to the superconducting state begins, T_{c0}, are the same for the entire family of bridges. This agreement is evidence that the photolithography does not alter the properties or composition of the bridge material. In the low-temperature part of the transition the dependence $R_\square(T)$ is exponential, $\log R_\square \sim -(T_{c0} - T)^\alpha$, with an exponent $\alpha = 1$–1.5 for the various bridges. With decreasing bridge width, $R_\square$ increases, and the sharp exponential decay of $R_\square(T)$ is replaced by a more gradual decay. In general, these changes in the magnitude and behavior of $R_\square(T)$ become particularly obvious as the bridge width falls below ~ 100 μm. A variation of the bridge length l at $l \gtrsim 100$ μm has no substantial effect on $R_\square$. With decreasing w, $l < 50$–100 μm, the scatter in the values of $R_\square$ measured for the various realizations of the bridges increases. In order to reduce this scatter, we carried out measurements of $R_\square$ for bridges with $l \gg w$.

For the bridges with dimensions w, $l < 50$–100 μm, Josephson properties are exhibited; these properties are quite apparent even if w and l are substantially larger than the grain size a in the film. The inset in Fig. 1 shows the evolution of the current-

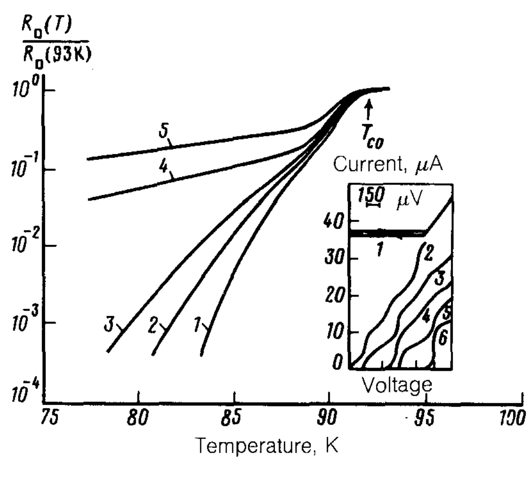

FIG. 1. Temperature dependence of the surface resistivity, $R_\square(T)$, of bridges fabricated from a $YBa_2Cu_3O_{7-\delta}$ film and having the following dimensions $w \times l$ (in microns): *1*—196×2000; *2*—94×1000; *3*—45×500; *4*—13×70; *5*—6×16. The inset shows current-voltage characteristics of a bridge with 6×6 μm with increasing power of a microwave signal at a frequency of 74 GHz. Curves *3*–*6* have been shifted 150 μV with respect to each other. $T = 5$ K.

voltage characteristic of a bridge with dimensions $6\times 16\ \mu$m during the application of a microwave signal at a frequency $f = 74$ GHz at $T = 5$ K. As the radiation power is increased (curves 1–6), there is an oscillatory change in the critical current I_c and in the current steps I_n, which arise at voltages $V_n = nhf/2e$, $n = 1,2,3,\ldots$. These oscillations are characteristic of an approximately sinusoidal current-phase relation in the bridge. The Josephson steps on the current for this bridge were observed as the temperature was raised to 60 K. As the bridge dimensions were increased (w, $l \sim 20$–50 μm), the Josephson current steps became less apparent, and their oscillations in the microwave field either shrunk or disappeared completely.

The observed size effects can be interpreted on the basis of the model in Ref. 5, according to which a film is a network of grain-grain Josephson weak links which vary in the value of the critical current I_{ci} and thus have exponentially different resistances $R_i \sim \exp(-\hbar I_{ci}/ekT)$. Taking the approach outlined by Shklovskiĭ and Éfros,[7] one can show that in the low-temperature part of the superconductivity transition the resistivity $R_\square(T)$ of a film is proportional to $\exp(-\hbar I_{cm}/ekT)$, where I_{cm} is the smallest critical current in an infinite cluster of weak links with $R_i \leqslant R_m$, which are responsible for the current percolation in the film.[5] We observed a similar temperature dependence $R_\square(T)$, with $I_c \sim (T_{c0} - T)^\alpha$, for all of the films that we studied. Figure 2 shows the temperature dependence $I_c \sim (T_{c0} - T)^\alpha$ with $\alpha \approx 1$ and 1.5 for the bridges of the various widths. The correlation radius L of the infinite cluster in the film is far larger than the size of the grains. With decreasing transverse dimension, $w < L$, the formation of an infinite cluster is hindered, and the resistance of the film increases: $R_\square \approx R_\square(\infty)\exp[(a/w)^{1/\nu}]$ (Ref. 7), where $R_\square(\infty)$ is the surface resistivity of a film with $w \gg L$, ν is the critical index of the correlation radius, and $B(T)$ is a constant which increases with increasing scatter in the resistances R_i in the original network.

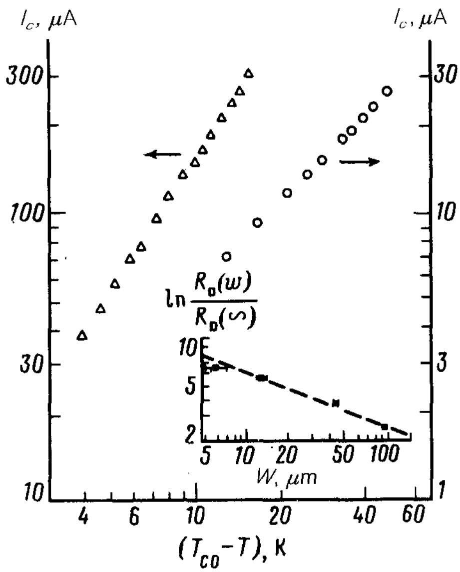

FIG. 2. Temperature dependence of the critical current of bridges with two widths w. Δ—70 μm; ○—6 μm. The inset shows $\ln[R_\square(w)/R_\square(\infty)]$ versus w for a family of bridges at $T = 83$ K. The dashed line is the theoretical functional dependence with $\nu = 2.5$.

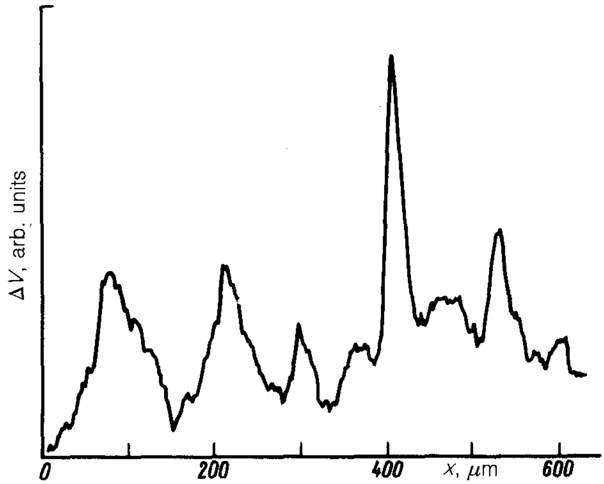

FIG. 3. Results of a local laser probing of the $YBa_2Cu_3O_{7-\delta}$ film which was the starting point for the family of bridges for which results are shown in Fig. 1.

The inset in Fig. 2 shows the experimental behavior of $\ln[R_\square(w)/R_\square(\infty)]$ as a function of w in double logarithmic scale; from this plot we can determine the index ν (Ref. 7). It turns out that an increase in $R_\square$ of the bridges with decreasing w is described by the theoretical function $R_\square(w)$ with $\nu = 2.5 \pm 0.5$ with $R_\square(\infty) = R_\square$ (194 μm).

We used the method of local laser probing to estimate the length scales of the percolation processes in these films.[8] Figure 3 shows the spatial variation of the voltage, $\Delta V(x) \sim [I(dR/dT)\Delta T_x]$, across the film during a slight local heating ($\Delta T \ll T$, $T = 84$ K) of the film by the beam from a He–Ne laser at point x. The current is obviously concentrated in a few highly conducting channels, which are separated from each other by an average distance $\sim 100\ \mu$m. We thus can estimate the correlation radius to be $L \sim 100\ \mu$m for the original $YBa_2Cu_3O_{7-\delta}$ film. This value of L explains our observation of Josephson properties for the bridges with w, $l < L$: Changes in the dimensions w and l smaller than the correlation radius of the infinite cluster promote the selection of a single weak link in a bridge.

These results are evidence of large-scale ($L \gg a$) percolation processes in granular films of superconductors which have extremely short coherence lengths $\xi(0) \ll a$, of an exponential increase in the resistance of the film bridges with a decrease in their transverse dimensions $w < L$, and of the possibility of using a Josephson weak link in bridges with dimensions $\xi(0) \ll a < w$, $l < L$.

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[1]D. U. Gubster *et al.* (editors), *Inhomogeneous Superconductors*, 1979, 1980.
[2]E. A. Antonova and V. L. Ruzinov, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 323 (1988) [JETP Lett. **48**, 355 (1988)].

[3]J. R. Clem, Physica C **153–155**, 50 (1988).
[4]E. Z. Meĭlikhov and Yu. V. Gershanov, in: *Superconductivity, No. 3*, 1988, p. 55.
[5]A. S. Afanas'ev *et al.*, Fiz. Nizk, Temp. **15**, 322 (1989) [Sov. J. Low Temp. Phys. (to be published)].
[6]Yu. V. Gulyaev *et al.*, Pis'ma Zh. Tekh. Fiz. **14**, 761 (1988) [Sov. Tech. Phys. Lett. **14**, 761 (1988)].
[7]B. I. Shklovskiĭ and A. L. Éfros, *Electronic Properties of Semiconductors*, Springer-Verlag, New York, 1984.
[8]A. P. Perov, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 327 (1986) [JETP Lett. **43**, 422 (1986)].

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