On the observation of phase slip centers in high-temperature superconductors

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(Submitted 2 October 1990, resubmitted 15 November 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 12, 1255–1258 (25 December 1990)

The current-voltage characteristics of thin-film 1-2-3 superconducting cross links have been studied experimentally. The step-like behavior of the I-V characteristic of cross links is associated with the formation of a dynamical spatial structure of phase slip centers.

Following the development of high-temperature superconductors experimental data which can be used to clarify the microscopic picture of superconductivity in high-temperature superconducting materials have been collected. The study of nonequilibrium properties of the new superconductors, which have analogs in traditional superconductors and which can be explained in the microscopic theory, are of particular interest. In connection with this program, it is useful to consider the I-V characteristics of long, thin cross links (where the width W is comparable to the coherence length ξ and the penetration depth λ of a weak magnetic field), which may make it possible to reproduce features on the I-V characteristics typical of phase slip centers, which have been observed in cross links of traditional superconductors, but which have not yet been observed in high-temperature superconductors.

Cross links of length $L \sim 1$–4 mm were prepared by laser etching of polycrystalline 1-2-3 films of thickness 0.5–1 μm with resistivity 0.1 mΩ, which were obtained on ZrO_2 substrates using the technology described in Refs. 5 and 7. The method of preparing the cross links[8,9] allowed one to obtain cross links of width $W = 200$–500 μm by choosing the intensity and the exposure time to the radiation, thereby "softly" etching the sample and only partially disturbing the superconducting parameters of the film.

This problem has been studied in detail, both experimentally and theoretically, for helium superconductors in the case of one-dimensional[1,2] and two-dimensional[3,4] long cross links. The absence of experimental papers on high-temperature superconducting samples is probably due to the difficulty of preparing narrow ($W \leqslant 1$ μm) cross links from these materials.

In our opinion there is a way to overcome these difficulties. First, it is apparently not absolutely necessary to deal with narrow cross links. Recently, the behavior of the I-V characteristics of interest here was observed in both narrow and wide ordinary cross links.[4] Second, one can artificially "degrade" the parameters of attainable wide high-temperature superconducting cross-link films to obtain narrow current-carrying channels in them. As noted by us in Ref. 5 (see also Ref. 6), a "precursor" effect takes place in high-temperature superconducting materials, in which the diamagnetic transition is anticipated by transition into a state with zero resistance with respect to temperature. Because of this effect, one can assume that near T_c the transition to the superconducting state occurs in filamentary structures. In our view, the observation of interesting features in the I-V characteristics in wide high-temperature superconducting cross links is therefore not completely hopeless. In fact, our research shows that these features may be observed in high-temperature superconducting materials.

The performance curves of high-temperature superconducting cross links and the films used for their preparation are illustrated in Fig. 1. We see that the parameters of the cross links are somewhat degraded from those of the films. A cross link can acquire a certain residual resistance, which increases with decreasing width. For this reason, we chose cross links of width ~ 200 μm, although it is possible in principle to prepare cross links with widths ~ 30 μm by means of laser etching,[9] Figure 2 shows

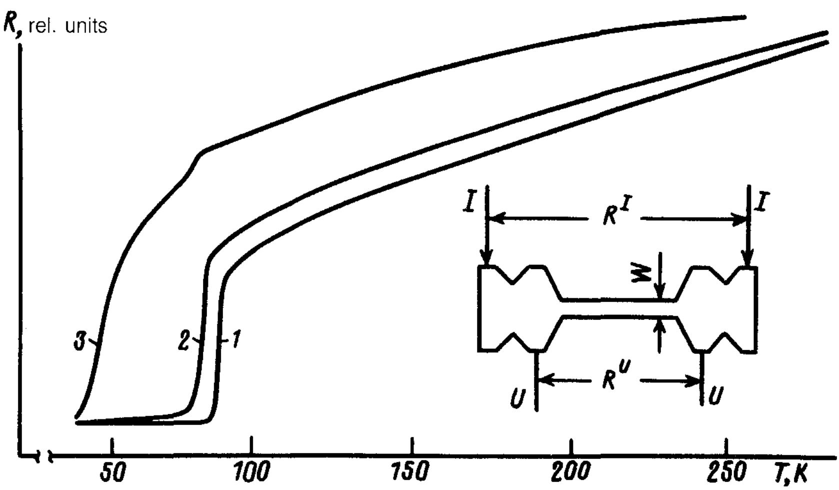

FIG. 1. Temperature dependence of the resistance at constant current of the samples: *1*—film, $T_c = 87$ K, $R^U_{300\ \mathrm{K}} = 49$ Ω, $R^I_{300\ \mathrm{K}} = 97$ Ω; *2*—cross link, $W \sim 200$–300 μm, $R^U_{300\ \mathrm{K}} = 166$ Ω, $R^I_{300\ \mathrm{K}} = 210$ Ω; *3*—cross link after exposure to a current pulse of $I \sim 100$ mA, $R^U_{300\ \mathrm{K}} = 507$ Ω, $R^I_{300\ \mathrm{K}} = 1445$ Ω. Inset: Schematic diagram of the sample.

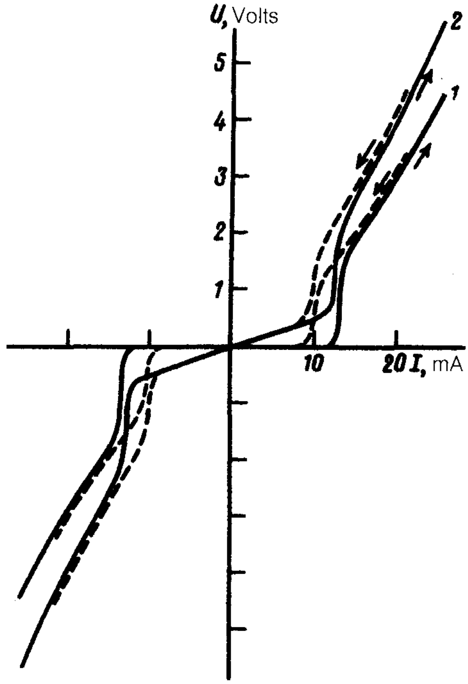

FIG. 2. Current-voltage characteristics of the samples at $T = 72$ K: *1*—film, *2*—cross link. The hysteresis on the curves is due to thermal superheating of the samples.

the I-V characteristics of films and the cross links prepared from them for the same temperatures. The I-V characteristics were recorded in the current-sweep mode using the standard four-probe method. The linear behavior of curve 2 in Fig. 2 near the origin characterizes the residual ohmic resistance of the cross links, which occurs during their preparation. In some samples this residual resistance disappears during cooling, while in others it remains down to very low temperatures. The I-V characteristics of the first series ($T_c = 30$ K) are shown in Fig. 3. Note the step-like form of the curves. The steps virtually disappear when the cross link is heated above 50 K. The curves shown in Fig. 3 were reproduced many times, where the interval between measurements could be more than a day. A similar behavior of the I-V characteristics of the other cross links was observed after their parameters were degraded by means of a slight current pulse ($I \leqslant 50$ mA over a period of one second). The original cross links were superconducting after laser etching at temperatures below 70 K and they had ordinary current-voltage characteristics before their parameters were degraded see curve 1 in Fig. 2. The cross links transformed rapidly into the normal state and became superheated. This procedure decreased T_c and steps appeared on some of the I-V characteristics. If after recording the I-V characteristic the cross link was subjected to a strong current pulse of order 100 mA over a period of about a second, then the sample became superheated and it completely transformed into the normal state. Curve 3 in Fig. 1 shows the dependence $R(T)$ of a cross link subjected to such a

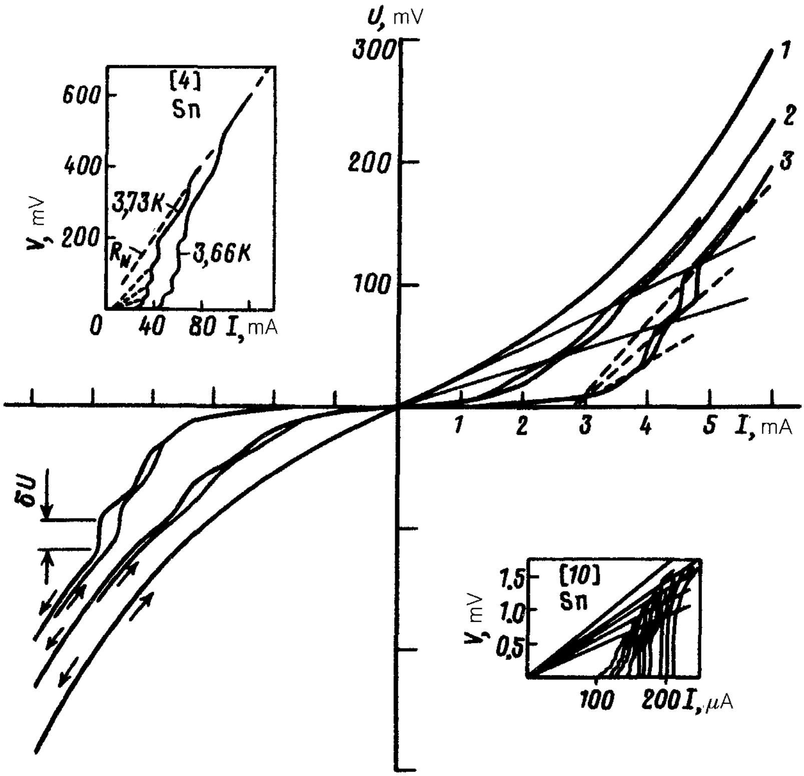

FIG. 3. Current-voltage characteristics of a cross link at $T = 66$ K (*1*), $T = 42$ K (*2*), and $T = 22$ K (*3*) in the current interval -6 mA$\leqslant I \leqslant +6$ mA. Inset: Curves from Refs. 4 and 10.

current pulse and hence this is the cause of the disappearance of the steps on the I-V characteristics.

We consider the detailed behavior of the current-voltage characteristics of the samples, from which we conclude that they have phase slip centers. The characteristic feature of the voltage steps shown in Fig. 3 is the intersection of the tangents of the curve segments following the voltage jumps at a single point on the current axis. This is the distinguishing feature of phase slip centers. We also point out a second feature of the series of steps: the curve segments of the I-V characteristics, which follow the voltage jump and which correspond to different temperature, lie on a single straight line that passes through the origin. For comparison, the corresponding curves from Ref. 4 and 10 are shown in the inserts to Fig. 3. We also note that the hysteresis in the current observed in Fig. 3 is nonthermal in nature. This is evident from the fact that the I-V characteristics of the cross links considered in the present study are completely reversible and reproducible in the current interval -6 mA$\leqslant I \leqslant +6$ mA (compare with Fig. 2).

The magnitude of the energy gap of the cross link was estimated from the voltage jumps of the I-V characteristics using the usual formula[4] $\Delta = \delta U \simeq 20$ mV (see Fig.

3). This is about half the value of the gap at $T = 0$ K for 1-2-3 superconductors.[11] This low value of the gap is possibly connected with its temperature dependence, and also with changes in the parameters of the film during the fabrication of the cross links using the available technology. In particular, the current-carrying filaments of the samples in our experiments could be linked with the low-temperature phase with a smaller value of Δ. This question should be further investigated.

In our view, it is thus possible to convert wide cross links into narrow channels either by an artificial decrease of the number of superconducting current paths by means of laser etching of high-quality 1-2-3 films during the fabrication of the cross links, or by degrading the parameters of wide cross links by means of a current pulse. In fact, we detected step-like behavior on the I-V characteristics of such samples analogous to that obtained from liquid-helium superconductors. This behavior is associated with the formation of spatial structures of phase slip centers.

The authors thank M. L. Ter-Mikaelyan for support of this work, A. M. Gulyan for fruitful discussions, and V. T. Tatoyan and Zh. K. Akopyan for overall assistance.

This work was completed as part of projects N79 and N:P-51 of the State Program on High-Temperature Superconductors and was supported by the State Scientific Council.

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Translated by J. D. Parsons