Motion of vortices in bridge structures made from high-T_c superconductors

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(Submitted 13 January 1989; resubmitted 5 April 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **49**, No. 10, 559–562 (25 May 1989)

A coherent motion of vortices in bridge structures made from high-T_c superconductors has been observed when a transport current flows through them and when a microwave radiation in the millimeter wavelength range is applied to them.

The manifestation of Josephson properties in bridge structures made from high-T_c metal oxide superconductors with a constriction, whose size is much greater than the coherence length (ξ), is explained by several authors[1-3] by the presence of weak coupling between the grains of the high-T_c superconductor. It is assumed that only one Josephson grain junction is operating in a bridge structure.

We have shown experimentally that the phenomena characteristic of Josephson junctions, e. g., the appearance of current steps on the current-voltage characteristics which stem from the synchronization of the self-radiation of a Josephson junction by an external signal, may occur in a bridge structure made from a high-T_c superconductor because of the presence of another physical mechanism for the generation of an alternating current in a junction; specifically, because of the coherent motion of the fluxoids (vortices) caused by the transport current I and by the application of microwave radiation. We note that these phenomena in bridge structures made from ordinary superconductors (In, Sn, etc.) have been studied extensively.[4,5] The distinctive features of the bridge structures made from high-T_c superconductors is that in them not only the Abrikosov vortices[4,5] but also the Josephson vortices and hypervortices[6] can be formed and set in motion.

The test samples were square bars made from a Y–Ba–Cu–O ceramic measuring $6\times2.5\times0.5$ mm, at the center of which the constriction was cut out: a bridge structure of length $L = 150$–200 μm, width $W = 150$–200 μm, and thickness $d \leqslant 100$ μm. The grain size of the ceramic was $a \approx 1$ μm. The I-V characteristic of the samples was measured by the four-contact method in the autonomous regime and with an imposition of a microwave radiation with various frequencies over a broad temperature interval T from 300 K to 4.2 K.

Figure 1 shows the I-V characteristics of one of the test samples for various temperatures. We see that the behavior of the I-V characteristic of a bridge structure is typical of a weak coupling with a direct conductivity: There is no hysteresis over a broad temperature interval, and at high voltages, $V \gtrsim 1$ mV, we see an appreciable excess current; i.e., the I-V characteristic reaches a plateau which is displaced relative to $V = IR_N$ by an amount $I_{ex} \gtrsim I_c$. At low temperatures, $T \lesssim 17$ K, the I-V characteristic exhibits several sloping current plateaus. It should be pointed out that the I-V

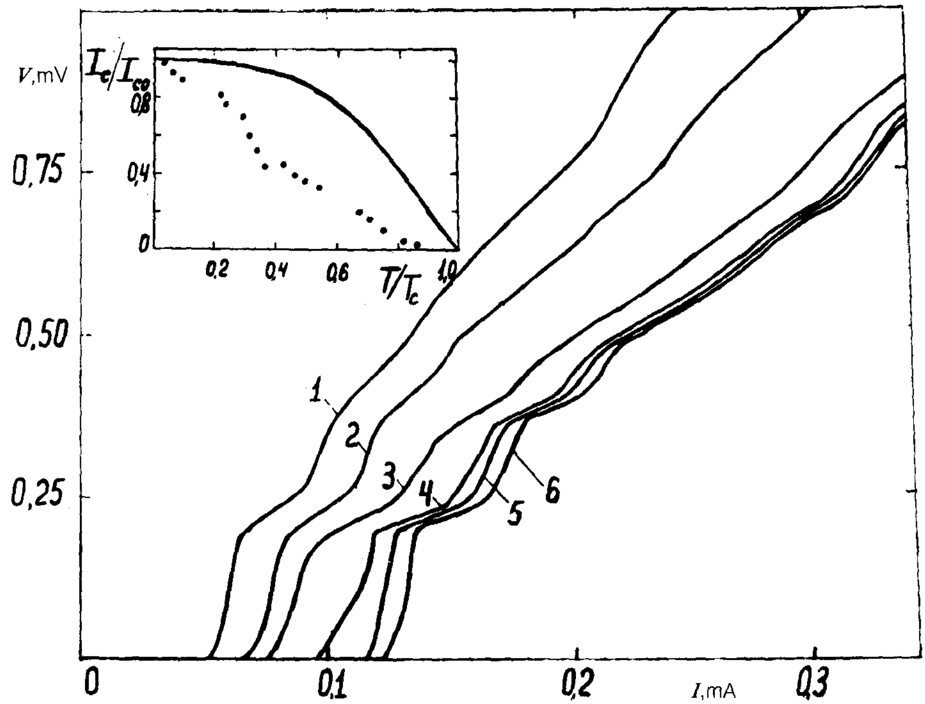

FIG. 1. The I-V characteristics of the bridge structures at various temperatures T: 1—25.1 K; 2—23.5 K; 3—22.6 K; 4—17.3 K; 5—5.0 K; 6—4.2 K. The inset shows the experimental $I_c(T)$ dependence normalized relative to $I_{c0}(T = 4.2\ K)$. The solid line represents the theoretical dependence for the Josephson tunnel junctions.

characteristic of a bridge structure, in contrast with the classical Josephson junctions, is asymmetric relative to $I = 0$ (not shown in Fig. 1) and that the degree of asymmetry changes with changing temperature.

The temperature dependence of the critical current I_c of a bridge structure is shown in the inset in Fig. 1. The solid line represents the theoretical dependence $I_c(T)$ of a Josephson tunnel junction,[7] determined on the basis of the BCS theory. We see that the experimental $I_c(T)$ dependence differs dramatically from the theoretical dependence. The experimental results differ even greater from the theoretical results of Kulik and Omel'yanchuk[8] for a Josephson junction with a direct conductivity. In several experimental studies (see, e.g., Refs. 9–11) such $I_c(T)$ curves for the test samples have been explained in terms of the granular structure of the high-T_c superconducting materials.

Figure 2 shows the I-V characteristics of the same bridge structure for various values of the applied microwave power P_e of frequency $f_e = 36$ GHz at 4.2 K. As can be seen in the figure, an increase in P_c leads to a decrease in I_c and to the appearance of structural features on the I-V curve in the form of horizontal current steps. The

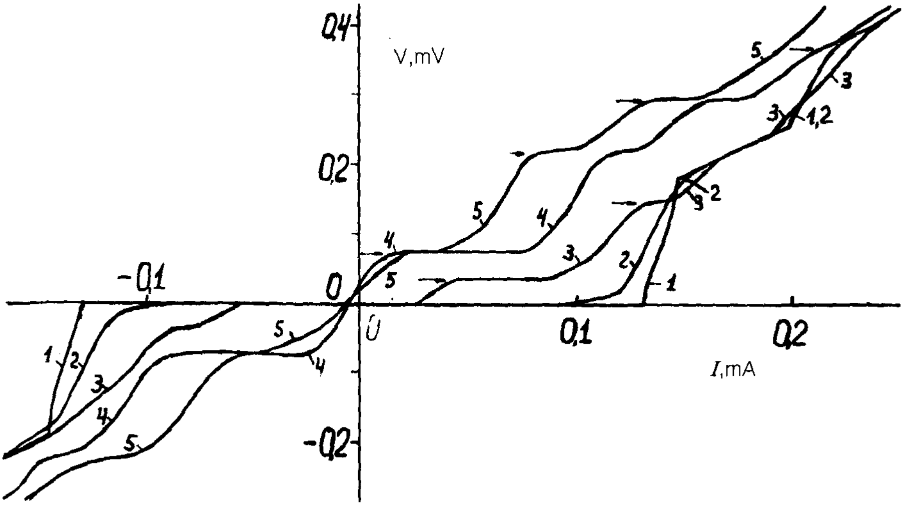

FIG. 2. The I-V characteristics of the bridge structure at 4.2 K for various microwave power levels with microwave frequency $f_e = 36$ GHz (1—without microwave radiation; 2–5—in a microwave field with various attenuations): 2—40 dB; 3—35 dB; 4—26 dB; 5—15 dB. The arrows show the current steps $n/m = 1/2$, 1, 2, 3, 4, and 5.

voltages corresponding to the current steps on the I-V characteristics are related to the frequency f_e by the Josephson relation $V_{n,m} = (n/m)(hf/2e)$, where n is an integer corresponding to the synchronization of self-radiation of the bridge structure by the nth harmonic of the applied signal, and m is an integer corresponding to the synchronization of self-radiation by the mth subharmonic. In contrast with an ideal Josephson junction, the I-V characteristics of the bridge structures we have studied exhibit subharmonic steps as a result of the application of microwave radiation, suggesting that the current-phase relation does not have a sinusoidal shape.[12]

The half step ($n = 1$, $m = 2$) appears at much lower values of P_e than those at which the main steps appear ($m = 1$). As P_e is raised, we see a more pronounced asymmetry of the I-V characteristic with respect to current than that which occurs as a result of varying the temperature. The P_e dependence of I_c and of the harmonic steps differs considerably from the quasi-oscillatory dependence characteristic of Josephson junctions,[12] but is, on the whole, similar to that observed earlier for moving Abrikosov vortices in long bridge structures made of tin.[5]

The vortical nature of the nonlinearity of the bridge structure in the granular high-T_c superconductors is consistent with the plot of I_c vs the static magnetic field H_e obtained by us. A dependence of the type $\sin H_e/H_e$, which is characteristic for Josephson junctions,[12] was not observed, however. A pronounced hysteresis was observed when H_e was varied inversely. Such a behavior of $I_c(H)$ and the asymmetry of the I-V characteristic suggest that bridge structures contain vortices, even in the absence of I, because of the small value of the lower critical magnetic field H_{c1} which, from the estimate $H_{c1} = 2\pi I_c / cW$, is 0.45 Oe. The sloping plateaus on the I-V characteristic are attributable to the motion of a fixed number of vortices in the bridge structure.[5]

The experimental results presented here are therefore evidence that bridge structures made from a high-T_c superconductor are inhomogeneous and that they contain magnetic field vortices. The structure of a vortex depends on the relationship among ξ, the penetration depth λ_L, and the Josephson magnetic field penetration depth λ_J. For the values typical of the given high-T_c superconductor $\xi = 1.5$ nm, $\lambda_L = 150$ nm, and the superconducting current density $j = 10^4$ A/cm^2, which determines the value $\lambda_J = 10$ μm, we have, according to the classification of Ref. 6, a hypervortex in the bridge structure without a region in which the order parameter is suppressed, as is the case in Josephson vortices, and the magnetic field penetration depth is much greater than the size of a single Josephson junction (which is on the order of a). As a result, all the irregularities of the structure of the bridge material have only a slight effect on the vortex motion (weak pinning) and the bridge structure is characterized by a viscous vortex flow induced by the transport current.[13] The application of a weak electromagnetic field causes vortex synchronization and the appearance of current on the I-V characteristics of the Josephson steps. In such high-T_c superconducting bridge structures electromagnetic self-radiation can be seen directly.

We wish to thank M. E. Gershenzon, A. V. Zaĭtsev, N. G. Pogosyan, and M. I. Faley for a useful discussion of the results of this study.

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Translated by S. J. Amoretty