Current transport mechanism in high-T_c superconducting Josephson junctions on bicrystals

I. I. Vengrus, M. Yu. Kupriyanov, O. V. Snigirev, A. G. Maresov, and S. I. Krasnosvobodtsev

M. V. Lomonosov Moscow State University, Russian Academy of Sciences, 119899 Moscow, Russia

The mechanism for the transport of the normal component of the current in high-T_c superconducting Josephson junctions on a bicrystal substrate has been studied experimentally. At high voltages, the behavior of the conductance of the junctions as a function of the voltage and the temperature agrees well with the behavior predicted by the theory of Glazman and Matveev for structures in which the conductivity results from inelastic resonant tunneling through a finite number of localized states. © *1994 American Institute of Physics.*

High-T_c superconducting Josephson junctions on bicrystal substrates have an advantage over high-T_c superconducting structures of other types (SNS and edge junctions with an interlayer of semiconducting metal oxides) in that their transport properties are much more nearly uniform. For example, the scatter in the critical currents I_c and the normal resistances R_n within the substrate is usually less than 30%, while in other structures this figure ranges from 100 to 500%.

Nevertheless, study of the noise characteristics of individual junctions and also of inferferometers based on them reveals sources of an intense $1/f$ excess noise. At voltages $V > I_c R_n$, the noise sources are primarily fluctuations of the voltage across the normal resistance of the junctions.[1,2] Their characteristic cutoff frequency, $f_0 \approx 500–1000$ Hz, is essentially an order of magnitude higher than that of low-T_c superconducting Josephson junctions with the same normal resistance.

This large difference may stem from a different—non-ohmic—nature of the normal conductivity of high-T_c superconducting junctions. It has been shown[3–5] that the primary mechanism for the transport of the normal current in high-T_c structures with interlayers of their semiconducting metal oxides is inelastic resonant tunneling through localized states in the material of the interlayer. In junctions based on bicrystal substrates, local stresses near the boundary are quite capable of giving rise to regions with a lowered oxygen content and a hopping normal conductivity, which gives rise to a more intense $1/f$ noise.

In the present letter we show that a hopping mechanism for transport of the normal current is indeed operating in junctions on bicrystal substrates.

The Josephson junctions were fabricated from bicrystal SrTiO$_3$ substrates.[6] The halves of the substrates were rotated symmetrically with respect to the "seam," i.e., the line of the junction, to create a misorientation angle of 36°. Thin YBa$_2$Cu$_3$O$_7$ films were
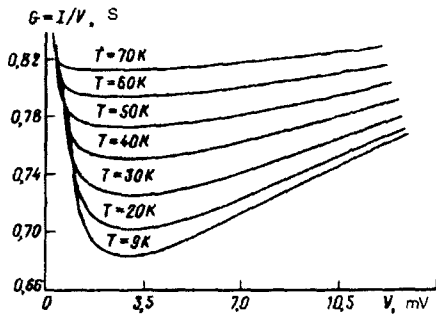
FIG. 1. Conductance of a high-T_c superconducting Josephson junction on a bicrystal substrate versus the voltage at various working temperatures.

deposited by laser evaporation of a target prepared by the standard procedure from a mixture of powdered oxides of the elements making up the high-T_c superconducting ceramic.

The quality of the samples was monitored by measuring the temperature dependence of the resistance and magnetic permeability of the superconducting film. The superconducting transition temperature of the samples was $T=90–92$ K in most cases, and the transition width was $\Delta T=0.2–0.3$ K.

The Josephson junctions were fabricated by forming in the film a structure with a microbridge which intersected the line of the seam. For this purpose we used either a laser scribing method[6,7] or standard photolithography with a subsequent etching of the structure in 0.1% HNO_3. The width of the bridges was usually 5–10 μm, so the critical current of the junctions at 77 K, at a film thickness of 0.3–0.5 μm, had values in the range 50–100 μA. These currents correspond to a critical current density $j_c \leqslant 10^4$ A/cm^2. The critical current of the superconducting electrodes under the same conditions was higher by a factor of 1.5 or 2, on the average.

Current–voltage characteristics of the resulting junctions were measured by the standard four-probe method. Figure 1 shows some typical curves of the conductance of one of four junctions studied, at various temperatures. At essentially all values of T, there is a deviation from Ohm's law $[G=I/V=\mathrm{const}(V)]$ at high voltages. The deviation increases with decreasing transition temperature. Among the various mechanisms which would cause a deviation of G from Ohm's law, that which fits the experimental data best is the model of a hopping conductivity through a finite number of localized states, as proposed by Glazman and Matveev.[8] In particular, it follows from their model that the primary mechanism for the transport of the normal current through the material of the interlayer with a semiconducting conductivity may be an inelastic resonant tunneling though a finite number of localized states. The presence of two localized states in a resonant channel is sufficient to cause the conductance to behave as a function of the temperature and the field in the manner typical of this process:

$$G = \Big(\langle G_1 \rangle + \langle G_2(T,0) \rangle + \langle G_2(0,V) \rangle \Big) V, \quad \langle G_1 \rangle \propto \frac{S}{\alpha^2}(g\alpha^3 E_0)\exp\left\{ -\frac{d}{\alpha} \right\}, \qquad (1)$$
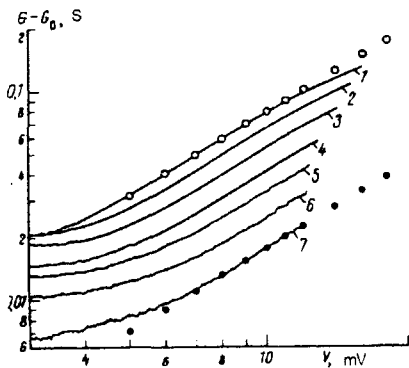
FIG. 2. Voltage dependence of the nonlinear part of the conductance at the temperatures $T=9$, 20, 30, 40, 50, 60, and 70 K (curves 1–7, respectively). The circles are points which lie on the $GV^{4/3}$ approximating curves.

$$\langle G_2(0,V)\rangle \propto \frac{S}{da}(2gda^2eV)^2\left[\frac{E_0\lambda_{ep}}{eV}\exp\left\{-\frac{d}{a}\right\}\right]^{2/3} \propto V^{4/3}, \quad T \ll eV, \tag{2}$$

$$\langle G_2(T,0)\rangle \propto \frac{S}{da}(2gda^2T)^2\lambda_{ep}\left[\frac{E_0\lambda_{ep}}{T}\exp\left\{-\frac{d}{a}\right\}\right]^{2/3} \propto T^{4/3}. \tag{3}$$

Here S and d are the effective area and the thickness of the weak-link region, g and E_0 are the density and characteristic energy of the localized states in the material of the interlayer, λ_{ep} is the dimensionless constant of the electron–phonon interaction, and a is the effective radius of a localized state. The factors (S/a^2) and (S/da) in Eqs. (1)–(3) determine the number of statistically independent conducting channels which contain respectively one and two localized states. The reason for the difference between these coefficients is that in the former case the effective radius of the channel is governed by the size of an individual localized state, a. When there are two localized states in a channel, this radius depends on the distance ($\sqrt{da}$) over which these localized states may be displaced spatially in the direction parallel to the boundaries without any substantial decrease in the conductance of the channel. The factors (ga^3E_0), $(2gda^2T)^2$, and $(2gda^2eV)^2$ are the probabilities for the formation of the corresponding conducting channels. For a channel with a single localized state, this probability is proportional to the volume of the weak link occupied by the localized state. For channels with two or more localized states, this probability depends on the portion of the energy (T or eV) which an electron can exchange with its surroundings in the course of the tunneling. It also depends on the spatial volume which they occupy. The last factors in (1)–(3) determine the conductance of an optimum channel:

$$\left(\exp\left\{-\frac{d}{a}\right\}\right), \quad \lambda_{ep}\left[\frac{E_0\lambda_{ep}}{T}\exp\left\{-\frac{d}{a}\right\}\right]^{2/3}, \quad \lambda_{ep}\left[\frac{E_0\lambda_{ep}}{eV}\exp\left\{-\frac{d}{a}\right\}\right]^{2/3}.$$

Figures 2–4 show the results of a comparison of the experimental data found here with predictions of the Glazman–Matveev theory.

In the first step of the data analysis we determined the voltage-independent part of the conductance $[G_0 = \langle G_1\rangle + \langle G_2(T,0)\rangle]$, requiring the formation of the broadest range of voltages in which $\langle G_2(V)\rangle$ is a power function of the applied voltage. The solid curves in Fig. 2 are plots of this type found at various temperatures, shown in logarithmic scale.
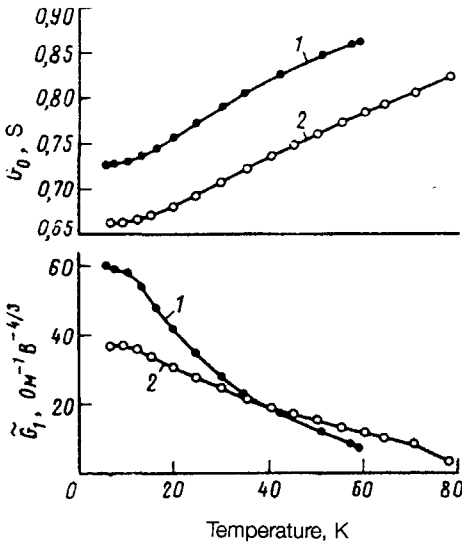
FIG. 3. Temperature dependence of the coefficients G_0 and $\tilde{G}$, which determine the behavior of the conductance as a function of the applied voltage, as found through an analysis of the current–voltage characteristics of samples 71 and 331-1 (curves 1 and 2, respectively).

The circles in the same figure are points which lie on straight lines corresponding to the theoretical behavior $\langle G_2(V) \rangle = \tilde{G}(T)V^{4/3}$. We see that there is a satisfactory agreement between the experimental and theoretical behavior over a broad voltage range. The deviations at low voltages are caused by the presence of a superconducting component of the current in the junction. At high voltages, the increase in $\langle G_2(V) \rangle$ with the voltage slows down because of a local heating of the junction region.

Specifically, in follows from the temperature dependence of the coefficients G_0 and $\tilde{G}$ in Fig. 3 that $\tilde{G}$ falls off with increasing temperature. The deviations from the $V^{(4/3)}$ law at high voltages with decreasing absolute value of the proportionality factor $\tilde{G}$ are thus due to a local increase in the junction temperature.

The temperature dependence of the coefficient G_0 also agrees reasonably well with expressions (1) and (3). It follows from Fig. 4 that, in addition to the temperature-independent component $G_{00} = \langle G_1 \rangle$, there is a term proportional to $T^{4/3}$ over a broad temperature range.
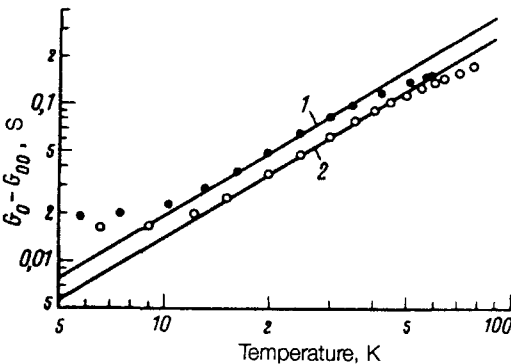

FIG. 4. Temperature dependence of the quantity $\langle G_2(0,T) \rangle = G_0 - G_{00}$ as found for samples 71 and 331-1 (curves 1 and 2, respectively). The solid lines are plots of a theoretical $T^{4/3}$ law.

Unfortunately, the Glazman–Matveev theory makes only qualitative predictions. It generates no quantitative results which might be used to extract further information, e.g., on the number of localized states in the material of the interlayer, N_{eff}. Nevertheless, since the conductance component G_{00}, which is independent of the temperature and the voltage, is governed by elastic and inelastic tunneling through one localized state in a current-conducting channel, we can estimate the number of such channels, N_{eff}, by working from the Larkin–Matveev theory.[9] For the elastic component G_{00} this theory predicts

$$(G_{00})_{eff} = \pi^2 \frac{S}{a^2}(ga^3E_0)\frac{e^2}{\pi\hbar}\langle D\rangle = \frac{e^2}{\pi\hbar}N_{eff}, \tag{4}$$

Here $e^2/\pi\hbar$ is the conductance of an optimum channel, and $\langle D\rangle \propto \exp\{-d/a\}$ is the probability for its realization, which is governed by the effective transmission of the barrier. Taking the electron–phonon interaction into account in the course of inelastic resonant tunneling through localized states, we find, at temperatures below the Debye temperature, only some very slight temperature corrections to $\langle D\rangle$, regardless of the strength of this interaction.[10] We can thus use (4) to estimate the total number of elastic and inelastic resonant channels which are involved in the transport of the normal current through the junction. For typical values $G_{00} \approx 1$ S we find from (4)

$$N_{total} = \frac{\pi\hbar}{e^2}\langle G_1(0)\rangle \approx 10^4. \tag{5}$$

This value is essentially an order of magnitude larger than the corresponding estimates found for edge junctions with a PBCO interlayer.[3–5]

From this study we can draw the unambiguous conclusion that a hopping mechanism of a conductivity through a finite number of localized states in a conducting channel is operating in high-T_c superconducting Josephson junctions on bicrystal substrates. The number of these channels is essentially an order of magnitude larger than for other types of high-T_c junctions. This large number is responsible for the good reproducibility of the transport properties over a single substrate. It leads to the generation of an intense $1/f$ excess noise.

[1] R. Gross and B. Mayer, Physica C **184**, 235 (1991).
[2] M. Kavasaki et al., Phys. Rev. Lett. **69**, 1065 (1992).
[3] C. Stolsen et al., Long-range Proximity Effect in Shallow Step Josephson Junctions, Preprint, 1994.
[4] A. A. Golubov et al., Ext. Abstracts of 4th M^2S-HTSC International Conference (Grenoble, France, 1994).
[5] T. Satoh et al., Current Transfer Mechanism in YBaCuO/PrBaCuO/YBaCuO Ramp Edge Junctions, Preprint, 1994.
[6] I. I. Vengrus et al., Sverkhprovodimost' (KIAE) **6**, 1730 (1993).
[7] A. A. Bliablin et al., SPIE **1723**, 46 (1992).

[8] L. I. Glazman and K. A. Matveev, Zh. Eksp. Teor. Fiz. **94**, 332 (1988) [Sov. Phys. JETP **67**, 1276 (1988)].
[9] A. I. Larkin and K. A. Matveev, Zh. Eksp. Teor. Fiz. **93**, 1030 (1987) [Sov. Phys. JETP **66**, 580 (1987)].
[10] L. I. Glazman and R. I. Shekhter, Zh. Eksp. Teor. Fiz. **94**, 292 (1988) [Sov. Phys. JETP **67**, 163 (1988)].

Translated by D. Parsons