# Manifestation of features of the density of states of a high-$T_c$ superconductor on the current–voltage characteristics of Bi–Sr–Ca–Cu–O:Pb tunnel structures

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The current–voltage characteristics and $dI(V)/dV$ characteristics of tunnel break junctions in single-crystal Bi–Sr–Ca–Cu–O:Pb samples (the 2212 phase) have been studied at a temperature of 4.2 K. The $I-V$ curve has regions with a negative resistance at bias voltages $V$ in the intervals 2–4 mV and 38–40 mV. These regions are linked with features in the density of states which stem from the layered structure of this high-$T_c$ superconductor.

The assertion that high-$T_c$ superconductivity is of a quasi-2D nature is finding a progressively firmer foundation.[1] Correspondingly, the models of high-$T_c$ superconductors which are attracting the most interest are those in which the layered structure of these compounds is taken into account directly. Tachiki *et al.*[2-4] have shown, for example, that the layered structure is responsible for some characteristic properties of the vortex structure in the mixed state, pinning, and the fine structure on the current–voltage characteristics of tunnel junctions which are observed experimentally.[5,6] Working in a modified version of the model of Tachiki *et al.*, Abrikosov[7] has explained why the threshold for the onset of a Raman satellite depends on the polarization of the light.

A knowledge of such properties as the density of states near the Fermi level and the energy gap is important for reaching an understanding of the mechanism for the superconductivity of the high-$T_c$ superconductors. Tunneling spectroscopy is an effective method for determining the properties of the superconducting state. The most convenient devices for accurately determining the gap parameter $\Delta$ are SIS tunnel junctions.[8] Attempts to fabricate good SIS junctions on the basis of high-$T_c$ superconductors run into serious difficulties, because the surfaces of these superconductors lose their superconducting properties under ordinary conditions, and the coherence length $\xi$ and the mean free path $l$ are both small. These difficulties can be overcome by using bicrystal boundaries, grain boundaries, or cryogenic break junctions[8] as natural barriers.

In the present study we used a natural barrier which arises at a cleaved surface upon the generation of a microfissure in Bi–Sr–Ca–Cu–O:Pb single-crystal samples

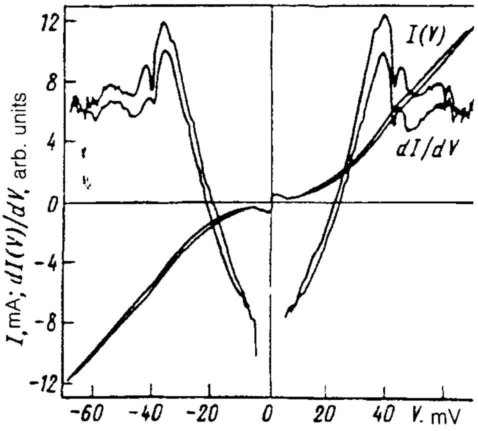

FIG. 1. $I$–$V$ and $dI(V)/dV$ characteristics of a break junction in a Bi–Sr–Ca–Cu–O:Pb single-crystal sample at $T=4.2$ K (sample LIL-877-1A).

(this is the 2212 phase) at liquid-helium temperatures. Thin single-crystal samples with typical dimensions $0.15 \times 0.5 \times 2.0$ mm were mounted on a cross-shaped stage made of foil-wrapped fiberglass with the help of an indium–gallium solder. The microcrack was generated in the sample at liquid-helium temperature by deforming the stage with the sample by means of a micrometer screws. The current–voltage characteristics of the tunnel junctions were studied with the help of an experimental apparatus which measured the changes in the conductivity, $\Delta\sigma \geqslant 10^{-4}$ S, at modulation levels ranging from 30 $\mu$V to 3 mV. This apparatus detects the harmonics of the current (or the voltage) generated by the low-resistance sample upon a modulation of the voltage across the sample. The specified modulation level is automatically maintained with high precision. The current–voltage characteristics of the tunnel junctions are measured at a fixed voltage and a constant modulation level. The superconducting transition temperature is estimated by measuring the temperature dependence of the resistance of the sample, $R(T)$. The superconducting transitions for these test samples lie in the range 70–78 K. The width of the transition is 5–11 K, indicating that these samples are inhomogeneous. The product of the critical Josephson current $I_c$ and the resistance of the junction in its normal state, $R_n$, is $4.5 \leqslant I_c R_n \leqslant 27.0$.

Figure 1 shows $I$–$V$ and $dI(V)/dV$ characteristics of a break junction in sample LIL-877-1A at 4.2 K. The presence of a Josephson current indicates that the barrier is comparatively thin. Nevertheless, the current–voltage characteristic has an excess current at subgap bias voltages, and there is a bump or knee in the excess current at $V \sim 2\Delta/e$. There is a significant blurring of the gap structure. The $I$–$V$ characteristic found here has a region with a negative slope at low voltages, $eV \sim 2$–$4$ meV.

The magnitude of the gap parameter $\Delta$ of these samples was found from the distance ($V^*$) between the peaks in the dynamic conductance on the $dI(V)/dV$ characteristic of the junction. The values found for $2\Delta/kT_c$ and $\Delta$ in the present study are $\sim 5.5$–$7.7$ and 16.9–25.1, respectively, in satisfactory agreement with the results of other studies.[9]

Figure 2 shows $I$–$V$ and $dI(V)/dV$ characteristics of a break junction in sample LIL-877-1G at 4.2 K. There is a region with a negative resistance on the $I$–$V$ char-

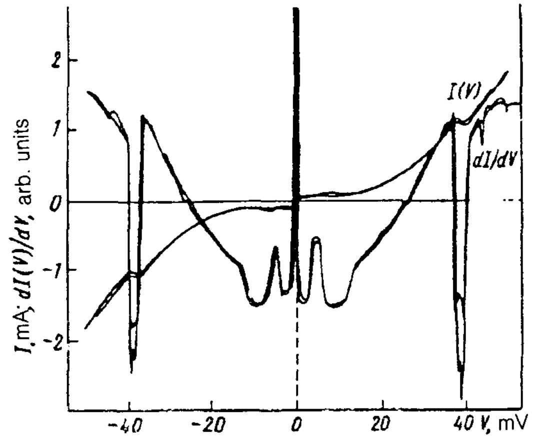

FIG. 2. $I$–$V$ and $dI(V)/dV$ characteristics of a break junction in a Bi-Sr-Ca-Cu-O:Pb single-crystal sample at $T=4.2$ K (sample LIL-877-1G).

acteristic at bias voltage $eV\sim 38$–40 meV. Abrikosov[7] has discussed a model in which the high-$T_c$ superconductor consists of an alternation of layers of two types: 1) layers with an electron attraction and an effective mass $m_1$ of the usual magnitude (these are superconducting layers); 2) layers in which there is no electron attraction, and the effective mass $m_2$ is large (these are normal layers). Working in this model, Abrikosov derived the density of states. The result differs from that of conventional superconductors in that it does not have a square-root singularity at $\epsilon=\Delta$. There are two logarithmic singularities, at $\epsilon_1=t^2/\Delta$ and $\epsilon_2=\sqrt{\Delta^2+2t^2}$, where $t$ is an energy parameter characterizing the overlap of the wave functions of the superconducting and normal layers. Our suggestion that the anomalies on the current–voltage characteristic are related to features in the density of states of the high-$T_c$ superconductor introduces a new element in the method for determining the energy gap $\Delta$ in the high-$T_c$ superconductors. Comparing the experimental values $eV_1$ and $eV_2$ with the theoretical values $t^2/\Delta$ and $\sqrt{\Delta^2+2t^2}$ of the parameters of the structural features, we find $\Delta=e(-V_1+\sqrt{V_1^2+V_2^2})$. For the parameter $t$ we find values 6–9 meV, which correspond fairly well to the Abrikosov condition $t\ll\Delta$.

Figure 3 shows possible types of junctions in an SIS structure based on a layered high-$T_c$ superconductor according to the Abrikosov model. Figure 3a corresponds to the case in which there are superconducting layers of high-$T_c$ superconductor on each side of the barrier. The tunneling current is due primarily to transitions of electrons from the superconducting layer of the high-$T_c$ superconductor on the left into the superconducting layer on the right, if we assume that the probability for tunneling out of the other layers is small. According to the diagram in Fig. 3a, the tunneling current is zero at $T=0$ if $eV<2\Delta$, and it increases in the interval $2\Delta\leqslant eV<\Delta+\epsilon_2$ (the density of states diverges logarithmically at $eV=\sqrt{\Delta^2+2t^2}$). In the interval $\Delta+\epsilon_2\leqslant eV<2\epsilon_2$, there is a nonohmic increase in the tunneling current, due to the behavior of the density of states at $eV=2\epsilon_2$. This increase may be the reason for the appearance of the knee on the current–voltage characteristic, which has been seen

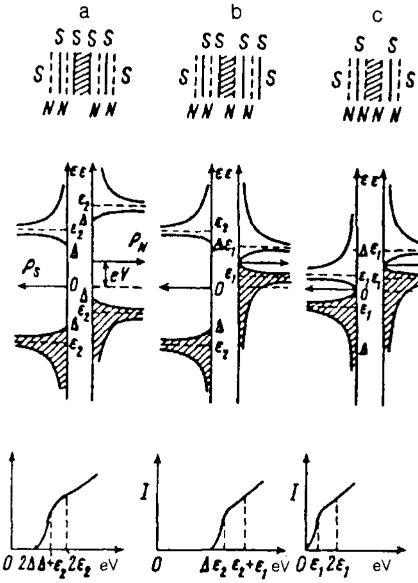

FIG. 3. Possible types of junctions in a (high-$T_c$ superconductor)–insulator–(high-$T_c$ superconductor) system, diagram for calculating the tunneling current, and suggested form of the current–voltage characteristic. a—Junction of superconducting layers of high-$T_c$ superconductors; b—junction of superconducting and normal layers of a high-$T_c$ superconductor; c—junction of normal layers of a high-$T_c$ superconductor.

repeatedly by Ponomarev's group at Moscow State University. At $eV \gg 2\epsilon_2$, the $I$–$V$ curve becomes Ohm's law.

When there is a superconducting layer of a high-$T_c$ superconductor on one side of the junction, and a normal layer on the other side (Fig. 3b), the tunneling current is zero at $eV < \Delta$. It increases in the interval $\Delta \leqslant eV \leqslant \epsilon_2$ and becomes Ohm's law at $eV \gg \epsilon_1 + \epsilon_2$. Here again there is a knee at bias voltages $\epsilon_2 \leqslant eV \leqslant \epsilon_2 + \epsilon_1$.

The rate of increase of the tunneling current changes at $eV = \epsilon_1$ and $eV = 2\epsilon_2$. In these cases there are normal layers of high-$T_c$ superconductor on both sides of the junction (Fig. 3c). At $eV > \epsilon_2$, the rate of increase in the current falls off, and at $eV \gg \epsilon_2$ the $I$–$V$ curve becomes Ohm's law.

If we assume that in the actual situation there is a superposition of current–voltage characteristics corresponding to the cases shown in Fig. 3, then we conclude that the resulting characteristic will exhibit changes in the rate of increase of $I$ at $eV$ values of $\epsilon_1$, $2\epsilon_1$, $\Delta$, $\epsilon_2$, $\epsilon_3$, $2\Delta$, $\epsilon_4$, and $2\epsilon_2$, where $\epsilon_3 = \epsilon_1 + \epsilon_2$ and $\epsilon_4 = \Delta + \epsilon_2$. At $T \neq 0$, thermal excitations arise in the system, and regions with a negative resistance appear on the $I$–$V$ curve at $eV = \epsilon_1$ and $eV = \epsilon_2$.

As Abrikosov has pointed out,[7] the structural features in the density of states at $\epsilon = \epsilon_1$ and $\epsilon = \epsilon_2$ can easily be smoothed over by inhomogeneities of the sample. This circumstance would explain why these features are not regularly observed on the current–voltage characteristics of tunnel junctions. The superconducting current flowing through the junction must also be taken into account in order to carry out a thorough analysis of the tunneling at the SIS junction.

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