Tunneling-effect measurement of the energy gap in superconducting crystals of the Bi–Sr–Ca–Cu–O system

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The energy gap and its temperature dependence have been measured by a tunneling-effect method in single crystals of the Bi–Sr–Ca–Cu–O system. The results show that these samples contain two superconducting phases, with $T_c = 65$ and 28 K, for which the ratios $2\Delta(0)/kT_c$ are 7.1 and 7.0, respectively. An x-ray structural analysis confirms the presence of two single-crystal phases in the samples.

Maeda *et al.*[1] recently reported a new high-temperature superconductor, Bi–Sr–Ca–Cu–O, with superconducting transition temperatures T_c of 115 and 80 K, which differs from the 1–2–3 superconductors in that it lacks Cu–O chains. Using the procedure described previously,[2] we prepared several single crystals of the Bi–Sr–Ca–Cu–O system (BSCCO) and measured some of their characteristics. The BSCCO crystals had an area of 0.5×0.5 mm^2 and a thickness of 50 μm. The superconducting transition, measured by the usual four-contact resistive method, lay in the interval 74–87 K. The resistivity of the samples along the wide part was $\rho(90\text{ K}) = 100$–$200\ \mu\Omega\cdot$cm.

After these measurements were carried out, needles of single-crystal niobium were pressed against the plane surface of the BSCCO crystals at 4.2 K, and the characteristics of a BSCCO-Nb "point" tunnel junction were recorded. As in a previous study,[2] the test crystal was cracked by the needle in liquid helium, and a tunnel junction was produced directly on a fresh cleaved surface of the crystal. When we obtained stable and reproducible current-voltage characteristics for the tunnel junctions, we studied their temperature dependence over the range 4.2–150 K. Figure 1 shows a series of derivative *I-V* characteristics of the tunnel junctions at various tem-

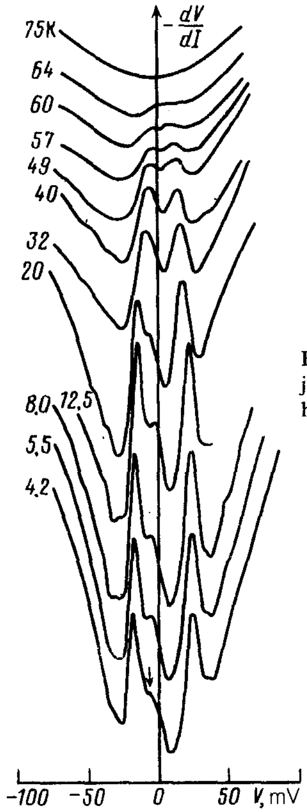

FIG. 1. The dependence $-dV/dI(V)$ for a (Bi–Sr–Ca–Cu–O)–Nb tunnel junction, recorded at various temperatures (the curve labels). The curves have been shifted along the vertical axis.

peratures (for clarity, the curves have been shifted along the vertical axis). As usual, the distance between the two main maxima on the curves recorded at $T = 4.2$, 5.5, and 8.0 K is equal to 2 $[\Delta(T)_{\rm Nb} + \Delta(T)_{\rm BSCCO}]$. After the Nb underwent a transition to the normal state (9.2 K), a determination of the value of Δ of the superconductor from the tunneling characteristics required matching the experimental and calculated state densities $N_T(V)$ near the gap for each temperature on the basis of the tunneling characteristics, under the assumption $N_T(V) = N(0)|V|/\sqrt{V^2 - \Delta^2}$. The latter dependence is not obvious for new superconductors, and we estimate the value of Δ at $T > 9.2$ K roughly from the maxima on the $dV/dI(V)$ curves. This approach introduced an error in the determination of the $\Delta(T)$ dependence, but it did make possible an accurate determination of the temperature at which the energy gap was "cut off." We adopted this temperature as T_c of the oxide superconductor.

It can be seen that this sample went into a normal state at $T \approx 65$ K in the vicinity of the tunnel junction, while the resistive method yielded $T_c \approx 80$ K.

Figure 2 shows values of $\Delta_{\rm BSCCO}$ for various temperatures as found from the data in Fig. 1 (the circles). The dashed line shows the dependence of $\Delta(T)/\Delta(0)$ on T/T_c according to the BCS theory. We see that the dependence $\Delta(T)$ deviates substantially

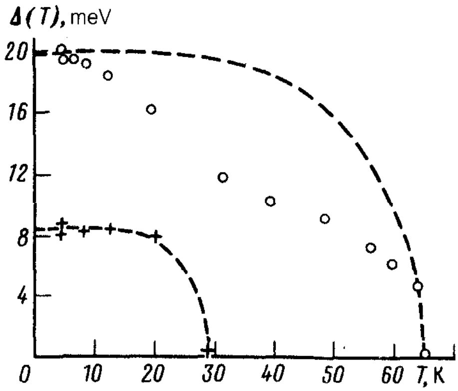

FIG. 2. Plots of $\Delta_{BSCCO}(T)$ (circles) and $\Delta'_{BSCCO}(T)$ (plus signs) for the two superconducting phases with $T_c = 65$ and 28 K.

from the theoretical prediction. A similar picture was observed by one of the authors in a previous study of the tunneling characteristics of superconducting compounds with an A15 lattice, containing phases with different values of T_c. Specifically, the curves in Fig. 1 have yet another "gap feature" (marked by the arrow), which vanished at 28 K. This feature is well resolved in Fig. 3.

The value of Δ'_{BSCCO} for the low-temperature phase is shown for various temperatures in Fig. 2 (the plus signs), along with the theoretical dependence of $\Delta'(T)/\Delta'(0)$ on T/T_c. As the temperature is raised, the measurements of D' come to agree much better with the theoretical BCS dependence $\Delta(T)$. On the other hand, because of a proximity effect, this phase greatly distorts the shape of the $\Delta_{BSCCO}(T)$ dependence. From these experimental results we found $\Delta_{BSCCO}(0) = 19.8$ meV and $\Delta'_{BSCCO}(0) = 8.5$ meV. These figures correspond to $2\Delta(0)/kT_c = 7.1 \pm 0.2$ and $2\Delta'(0)/kT_c = 7.0 \pm 0.2$. Since the coherence length of the metal-oxide superconductors is exceedingly short, the superconducting properties of these substances in the vicinity of the tunnel junction can be weakened significantly by the effect of the niobium oxide used as the tunnel barrier.

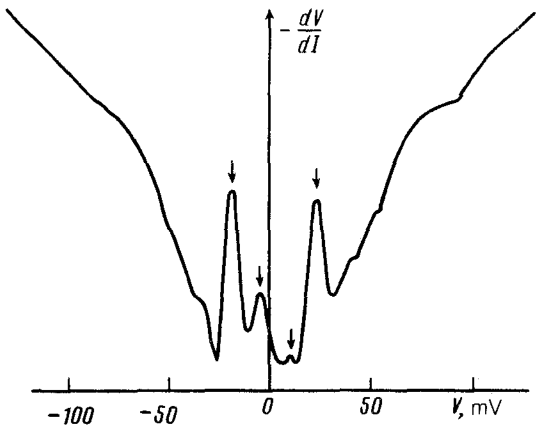

FIG. 3. The dependence $-dV/dI(V)$ for a (Bi–Sr–Ca–Cu–O)–Nb tunnel junction at $T = 4.2$ K with gap features from two phases in the sample.

An x-ray structural analysis of the samples studied by the tunneling method confirmed that they contained two single-crystal phases with lattice constants which agree with data in the literature.[3] The c axis ran perpendicular to the plane of the single-crystal wafers. Unfortunately, we were not able to prove unambiguously that the $\Delta(T)$ dependence for this new superconductor has the BCS shape, since we were not able to synthesize samples containing the high-temperature phase exclusively.

[1]H. Maeda, Y. Tanaka, H. Fukutomi, and T. Asano, Jpn. J. Appl. Phys. **27**, L209 (1987).
[2]S. I. Vedeneev, I. P. Kazakov, A. P. Kir'yanov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 306 (1988) [JETP Lett. **47**, 367 (1988)].
[3]Superconductivity News **1**, No. 8, 1 (1988).

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