Determination of the gap in Bi–Sr–Ca–Cu–O (2:2:1:2-phase) superconducting whiskers by tunneling spectroscopy

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The current–voltage characteristics of break junctions in Bi–Sr–Ca–Cu–O whiskers (the 2:2:1:2 phase), with a transition temperature $60 \leqslant T_c \leqslant 81$ K, have been studied experimentally. These *I-V* characteristics have a gap structure which is easily reproducible. From it one can determine the gap parameter Δ fairly accurately. In the interval of transition temperatures T_c studied, the ratio $2\Delta(0)/kT_c$ for the Bi–Sr–Ca–Cu–O (2:2:1:2) whiskers is 7.1 ± 0.2. The temperature dependence of the gap, $\Delta(T)$, agrees satisfactorily with the formal BCS theory.

It is difficult to determine the properties of the superconducting state of Bi–Sr–Ca–Cu–O whiskers[1–4] because of the small dimensions of these entities. In particular, no data have been reported on the gap parameter Δ or its temperature dependence. Because of the fairly high structural quality of whiskers, such results might lead to more accurate values of the ratio $2\Delta(0)/kT_c$ for Bi–Sr–Ca–Cu–O compounds (Refs. 5–11).

In this letter we are reporting the first (to the best of our knowledge) determination of the gap Δ in the superconducting state and its temperature dependence $\Delta(T)$ for Bi–Sr–Ca–Cu–O whiskers with the structure of the 2:2:1:2 phase.

The whiskers of series i-3a, 72L, and 73K studied in these experiments (Table I) were grown by a method approximately the same as that described in Ref. 4. The whiskers were grown on the surface of specially prepared plates whose structure had been rendered amorphous, in flowing oxygen, during cooling from 880 °C to 850 °C. The whiskers had a clearly defined ribbon shape. The width of the ribbon was 10–200 μm, its thickness 1–5 μm, and its maximum length $\approx$4 mm. The **c** axis was directed perpendicular to the plane of the ribbon.

The whiskers of the WKK series (Bi–Sr–Ca–Cu–O, 2:2:1:2 phase; Table I) were prepared at Humboldt University by the procedure described in Ref. 2.

To fabricate tunnel junctions we used the technique of producing break junctions

TABLE I.

Curve	T, K	Δ, meV	Γ, meV	Δ^*, meV
1	70	16.3	3.3	16.3
2	72	14.7	3.3	15.3
3	74	13.0	3.5	13.5
4	76	10.5	4.5	12.2

Here Δ^* is the gap calculated from the distance (V^*) between the peaks in the dynamic conductance.

in samples at liquid-helium temperature.[12] The mechanical apparatus for generating the microfissure and the technique for mounting the samples are described in Refs. 10 and 11. Before creating the microfissure in a whisker, we measured the temperature dependence of its resistance, $R(T)$, in order to determine the transition temperature $T_c(R=0)$. The values of $T_c(R=0)$ are reproducible quite well for the whiskers of each series (Table I).

We established that a stratification along the **ab** plane usually occurs during the generation of a microfissure in a whisker. As a result, there is a significant overlap of the halves of the whisker after the break. Just after the microfissure appears, when the contact resistance R_n is ≈ 1–$10\ \Omega$, the single-frequency branch of the current–voltage characteristic near the gap voltage $V_g=2\Delta/e$ either passes through a region of a vertical growth of the current (the dashed line in Fig. 1a) or becomes S-shaped (the solid line in Fig. 1a). The latter result may be due to an injection of nonequilibrium quasiparticles into the contact region, which would lead to a decrease in the size of the gap.[20] The regions with a vertical current rise in the region of the gap voltage have been seen previously on the current–voltage characteristics of break junctions in polycrystalline Bi–Sr–Ca–Cu–O:Pb samples.[14,15] They probably indicate the existence of a sharp peak in the density of states at the gap boundary. Note that low-resistance junctions of this sort are very sensitive to the position of the adjusting micrometer. We believe that they probably correspond to the case in which the quasiparticle tunneling current flows in the **ab** plane.

Upon a further deformation of the substrate with a whisker, we observe a transition to high-resistance junctions with $R_n=10$–$1000\ \Omega$, with current–voltage characteristics which are considerably stabler with respect to the micrometer position (Fig. 1b). In the latter case, there is a slippage of the two halves of the ruptured whisker along the **ab** plane as the junction is adjusted, and the tunneling current is probably directed along the **c** axis.

The gap structure on the current-voltage characteristic of the high-resistance junctions is smeared to a considerably greater extent than that of junctions of the first type. The size of the gap parameter, Δ, however, shows no significant sensitivity to the value of the junction resistance R_n (Fig. 1). In the case of high-resistance junctions, the gap parameter Δ was calculated on the basis of the Dynes model.[16] Figure 1b shows theoretical I-V and $dI(V)/dV$ characteristics (the dashed curves). These calculations used the following parameter values: $T=4.2$ K, $\Delta=21.1$ meV, $\Gamma=6$ meV, and $R_n=1780\ \Omega$ ($\Gamma=\hbar/\tau$ is a smearing parameter). It is possible that the large

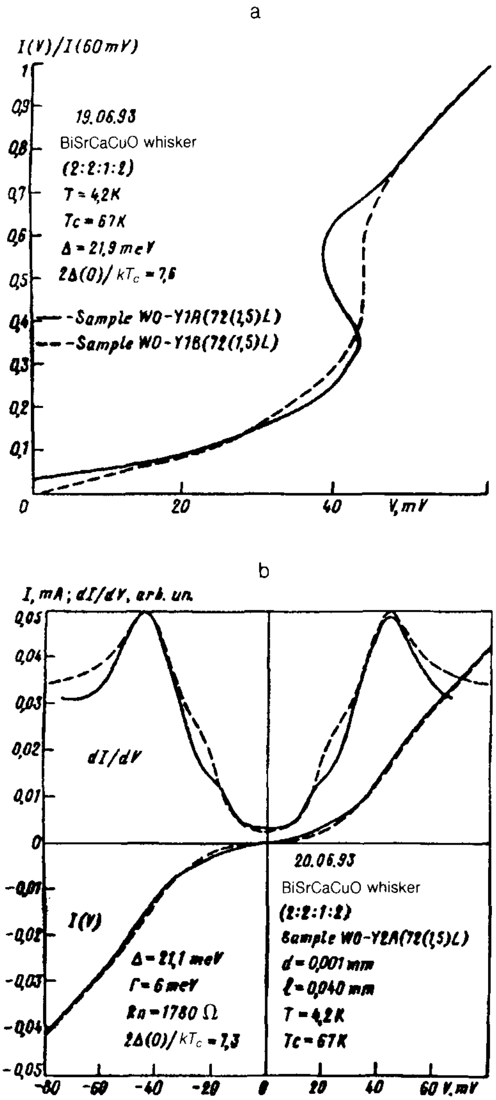

FIG. 1. a: Current–voltage characteristics of break junctions in a Bi–Sr–Ca–Cu–O whisker (the 2:2:1:2 phase) of series 72L (T_c=67 K) at T=4.2 K, normalized to the current I(60 mV). Dashed line—WO-Y1B junction; solid line—WO-Y1A junction, Δ=21.9 meV, 2 $\Delta(0)/kT_c$=7.6. b: $I(V)$ and $dI(V)/dV$ characteristics of a break junction in a Bi–Sr–Ca–Cu–O whisker (2:2:1:2 phase) of series 72L (sample WO-Y2A, T_c=67 K) at T=4.2 K. Solid curves—Experimental; dashed curves—calculated from the Dynes model with the parameter values Δ=21.1 meV, Γ=6 meV, and R_n=1780 Ω, 2Δ(0)/kT_c=7.3, d=0.001 mm, and l=0.040 mm.

theoretical values of the smearing parameter Γ are a consequence of a defectiveness of the cryogenic cleaved surface and do not unambiguously characterize the smearing of the bulk density of states.

We attribute the current–voltage characteristics of the low-resistance junctions (Fig. 1a) to tunneling in the **ab** plane, while we attribute the current–voltage characteristics of the high-resistance junctions (Fig. 1b) to tunneling along the **c** direction. If this interpretation is correct, then at this point there is no need to speak of any significant anisotropy of the gap in Bi–Sr–Ca–Cu–O. Note that the information which has been published on the anisotropy of the gap (and which is based on tunneling measurements) is at the moment extremely contradictory.[6,8,17] As was mentioned earlier, the value of the gap parameter Δ(4.2 K), which can be determined with a

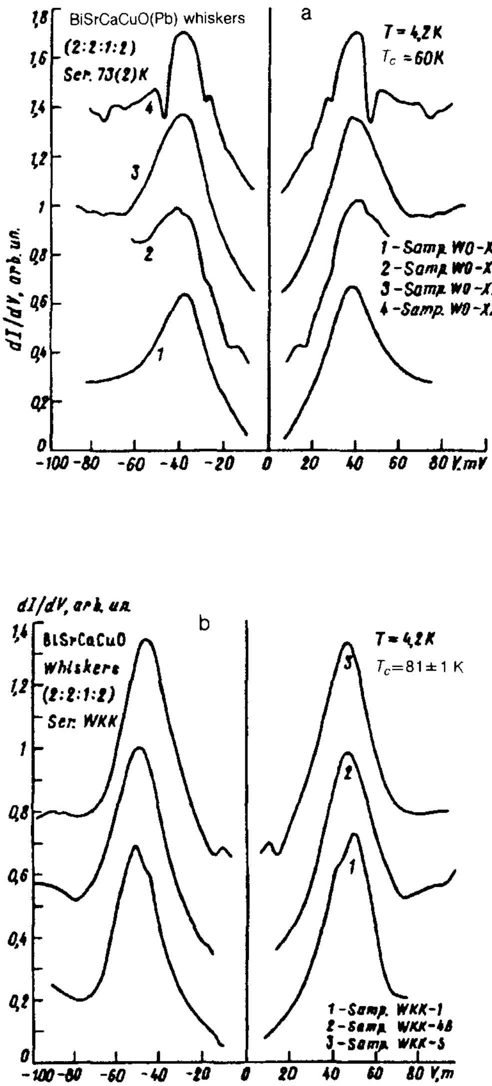

FIG. 2. $dI(V)/dV$ characteristics of break junctions in four Bi–Sr–Ca–Cu–O:Pb (2:2:1:2) whiskers. a—Series 73K (T_c $=60\pm1$ K) at $T=4.2$ K; b—series WKK ($T_c=81\pm1$ K) at $T=4.2$ K.

satisfactory accuracy from the distance (V^*) between local maxima of the dynamic conductance of the S–I–S junction ($V^*=4\Delta/e$) at $\Gamma/\Delta \leqslant 0.2$, is quite reproducible for whiskers of a given series (Figs. 2 and 3). As T_c is approached, this simple method of determining Δ from the smeared $dI(V)/dV$ characteristics of the S–I–S junctions is not sufficiently accurate, because of the rapid decrease in Δ. As a result, there is always a temperature interval in which the relation $\Gamma/\Delta > 0.2$ holds. This circumstance was pointed out in Ref. 10. The accuracy with which Δ is determined near T_c can be improved by comprehensive calculations of normalized $(dI/dV)_s/(dI/dV)_n$ characteristics on the basis of the Dynes model (see the inset in Fig. 3). It follows from the table in the Fig. 3 caption that the discrepancies between the values of the gap found from the Dynes model (Δ) and those found from the distance

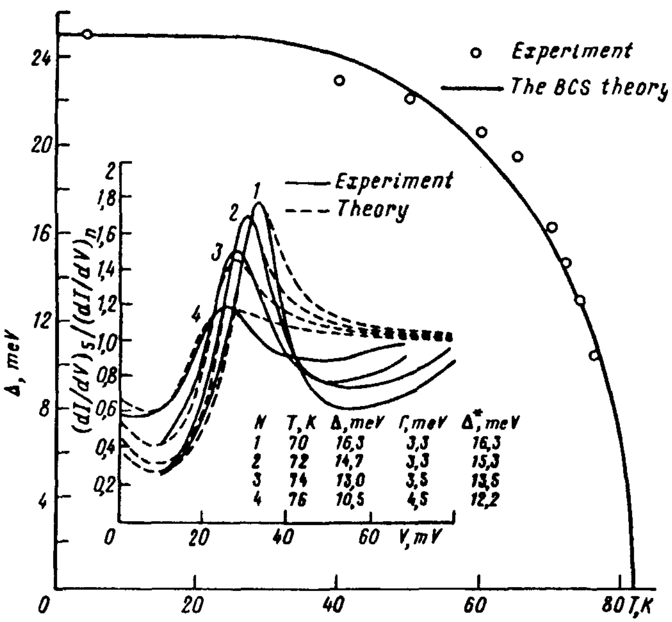

FIG. 3. Temperature dependence of the gap, $\Delta(T)$, of a Bi–Sr–Ca–Cu–O (2:2:1:2) whisker of series WKK (sample WKK-4, $T_c=82$ K, $\Delta(0)=25$ meV). Solid line—BCS theory; points—experimental. The inset shows $(dI/dV)_s/(dI/dV)_n$ characteristics of a break junction in a Bi–Sr–Ca–Cu–O whisker (2:2:1:2 phase) of series WKK [sample WKK-4, $T_c=82$ K, $\Delta(0)=25$ meV] at temperatures near the transition temperature. Solid lines—Experimental; dashed lines—calculated from the Dynes model with the values of the parameters Δ and Γ listed in Table I.

between the maxima of the dynamic conductance (Δ^*) become significant only at $T/T_c \geqslant 0.9$.

Figure 3 shows the temperature dependence of the gap for a whisker of the WKK series with $\Delta(0)=25$ meV and $T_c=82$ K. In a first approximation, this dependence agrees with the theoretical curve (the solid line in Fig. 3), found with the help of the expression of Ref. 18: $\Delta(T)=\Delta(0)\tanh[\Delta(T)T_c/\Delta(0)T]$ [in reduced coordinates, the results of a calculation of $\Delta(T)$ from this formula are essentially the same as the BCS dependence].

It can be seen from Table I that over the interval of transition temperatures studied, $60 \leqslant T_c \leqslant 82$ K, the ratio $2\Delta(0)/kT_c$ for Bi–Sr–Ca–Cu–O (2:2:1:2) whiskers is, on the average, 7.1 ± 0.2 (the results in Table I are averages over the three samples in each series).

Note that it is not possible to completely merge with the experimental $(dI/dV)_s/(dI/dV)_n$ characteristics on the basis of the Dynes model (see Fig. 1b and the inset in Fig. 3; see also Refs. 5 and 6). The reason may be the significant "distortions" of the energy dependence of the bulk density of states (in comparison with the classical BCS function), caused by, for example, a strong electron–phonon

TABLE II.

#	Series	$\Delta(0)$, meV	T_c, K	$2\Delta(0)/kT_c$
1	i–3a	18.4 ± 0.5	60 ± 1	7.1 ± 0.3
2	73K	18.7 ± 1.0	60 ± 1	7.2 ± 0.5
3	72L	21.1 ± 1.0	67 ± 1	7.3 ± 0.5
4	WKK	24.2 ± 1.0	81 ± 1	6.9 ± 0.4

interaction,[19,20] the existence of which was pointed out in Refs. 21 and 22. There are a limited number of theoretical[19,20,23] and experimental[5,6,15] studies of the deviation of the energy dependence of the tunneling density of states from the standard BCS dependence. However, it is too early to draw any definite conclusions.

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