Possibility of comparing the tunneling density of states of BiSrCaCuO (2212) with the BCS model

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Current-voltage characteristics of S–I–S tunnel junctions fabricated from high-quality BiSrCaCuO (2212) single crystals have been measured. A method is proposed for extracting the tunneling density of states $N(E)$ from experimental data. Allowance is made for a finite quasiparticle lifetime. The functions $N(E)$ which have been found can be described well by the BCS model if one additional parameter, Γ, is introduced. The temperature dependence of the energy gap 2Δ is the BCS $2\Delta(T)$ dependence with a ratio $2\Delta(0)/(k_BT_c)$ of 6.7 ± 0.3.

Numerous measurements of the energy gap 2Δ in the high-T_c superconductor $Bi_2Sr_2Ca_1Cu_2O_{8+v}$ (BSCCO), carried out in various laboratories, have confirmed our own data quite accurately.[1,2] Values of $2\Delta(4.2\ K)$ were found in Refs. 1 and 2 from the maximum of the differential conductance $dI/dV(V)$ of BSCCO–Nb tunnel junctions, as in the case of ordinary low-temperature superconductors. The junctions were fabricated *in situ* on freshly cleaved surfaces of BSCCO single crystals at 4.2 K. These stringent conditions in the preparation of the tunnel junctions increased the probability for obtaining data corresponding to the bulk material. Nevertheless, the experimental $dI/dV(V)$ curves which we found in Refs. 1 and 2, as well as curves found in subsequent studies, differ sharply from those which had been found previously for tunnel junctions made of simple superconductors. The curves are greatly smeared in most cases. At a zero bias voltage V, there is a large additional conductance (up to 50% of the conductance at $eV > \Delta$). A dip is observed beyond the gap peak, while the conductance of the junction at $eV > \Delta$ depends strongly on V. So far, the results of tunneling studies of $Y_1Ba_2Cu_3O_7$ cannot be reproduced well, and they are difficult to interpret. These differences and several other unusual properties suggest that an unconventional mechanism may be responsible for the superconductivity in the high-T_c superconductors.

However, our recent experiments [3,4] have shown that, as the quality of the BSCCO single crystals is improved, all the anomalies in the differential conductance of the tunnel junctions decrease substantially. It was recently found [5] that the same tendency prevails in the case of $Y_1Ba_2Cu_3O_7$. In the present letter we attempt to show that the experimental results on the tunneling density of states of high-quality, single-phase, perfect BSCCO single crystals can be described in the BCS model. The single crystals of BSCCO (the 2212 phase) used in the present experiments were grown from molten solution [4]. The crystals were platelets with dimensions up to 3 × 3 × 0.2 mm. The chemical composition was found by microanalysis to correspond to the formula $Bi_{2.4}Sr_{1.5}Ca_{0.9}Cu_{2.2}O_{8+v}$. An x-ray study of the crystals revealed a block structure; the

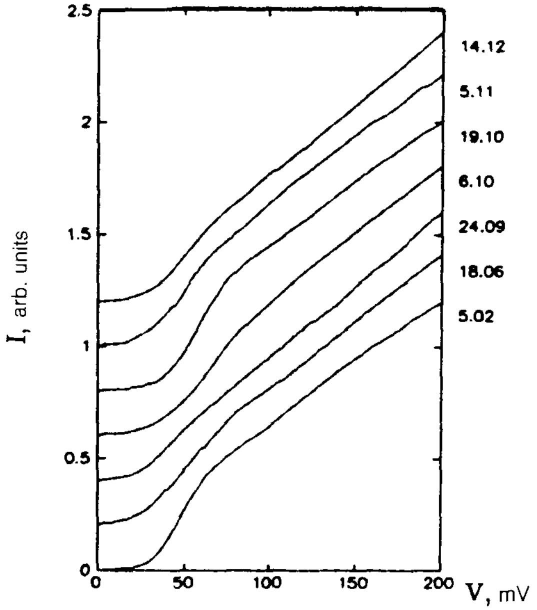

FIG. 1. Current-voltage characteristics of BSCCO–BSCCO tunnel junctions fabricated from seven single crystals with various values of T_c. The characteristics have been normalized to the peak value of the current and have been displaced uniformly along the vertical axis. $T = 4.2$ K.

blocks are 100–200 μm in size and have a disorientation of 1°–2°. The c axis runs perpendicular to the plane of the crystal. The lattice constants are $a=b=5.39$ Å, $c=30.731$ Å. The values of T_c and ΔT_c, measured by the resistance method and from the rf susceptibility, were found to be $T_c = 75$–81 K (in terms of the transition onset) and $\Delta T_c(10\%$–$90\%) = 6$–12 K. The resistivity is $\rho(90 \text{ K}) = 40$–50 $\mu\Omega \cdot$cm, and the derivative of the resistivity with respect to the temperature is $d\rho/dT = 0.3$–0.4 $\mu\Omega \cdot$cm/K (Ref. 4).

For the tunneling measurements we used symmetric (S–I–S) BSCCO–BSCCO tunnel junctions of the break-junction type [6]. Before the measurements, gold films were deposited on the crystal in the regions in which the current and potential leads were to be attached. This measure reduced the contact resistance to [7] 1–0.01 Ω. The crystal was mounted on a flexible substrate. This substrate made it possible to bend the crystal by means of a high-precision instrument in liquid helium to the point that a microfissure formed in the plane perpendicular to the a–b plane of the crystal, and a tunneling current arose. The tunneling current along the a–b plane in this geometry was always greater than the current along the c axis, because of the pronounced anisotropy of the conductivity and the coherence length, despite the stepped relief of the cleaved surface. By adjusting the pressure on the substrate, we were able to change the resistance of the tunnel junction. The best results were obtained on tunnel junctions with a resistance of 1–10 kΩ at $eV > 2\Delta$.

Figure 1 shows current-voltage (I-V) characteristics of tunnel junctions fabricated from seven single crystals with various values of T_c. The measurement temperature T was 4.2 K in all cases. The I-V characteristics have been normalized to the maximum current and shifted uniformly along the vertical axis. We see that these curves are reproducible quite well and demonstrate that the tunnel junctions are of relatively high quality. At $eV > 2\Delta$, the I-V characteristics are linear, with slight deviations from linearity at high voltages. Since these deviations are different for different tunnel junctions, even for those formed in the same single crystal, the change in the differential conductance at $eV \gg 2\Delta$ is probably due to a change in the transmission of the tunnel barrier as the energy varies. The conductance at a zero bias voltage for the better tunnel junctions is 3×10^{-2} of the value of the conductance at $eV > 2\Delta$. The experimental curves of dI/dV versus V corresponding to these curves usually do not have the dip just beyond the conductance peak which has always been seen previously in tunneling studies of BSCCO. The structure at phonon energies is also reproducible quite well. The only features which distinguish our $dI/dV(V)$ curves from the tunneling conductance predicted by the BCS model are the finite conductance at a zero bias voltage and the smeared gap feature. In recent work it has become customary to follow the Dynes approach [8] of attributing these two factors to a finite lifetime of the quasiparticles and of dealing with this point by introducing an imaginary part Γ in the quasiparticle energy $E-i\Gamma$. The BCS density of states then becomes[8]

$$N(E)=\mathrm{Re}\{(E-i\Gamma)/[(E-i\Gamma)^2-\Delta^2]^{1/2}\}. \tag{1}$$

To compare our experimental data with this formula, we smoothed $dI/dV(V)_s$ curves measured at $T = 4.2$ K and normalized them to the differential conductances in the normal state, $dI/dV(V)_n$, measured at $T > T_c$. Break junctions are mechanically unstable, so for those tunnel junctions for which we were unable to measure $dI/dV(V)_n$ at $T > T_c$ we found curves of $dI/dV(V)_n$ from the curves of $dI/dV(V)_s$ by smoothing out the gap features, as in Ref. 3. In this procedure it is necessary to obey a sum rule, and the result must coincide with the curve of the conductance in the superconducting state at high voltages. The shape of the $dI/dV(V)_n$ curves found in this manner turned out to be approximately the same as the $dI/dV(V)_n$ curves measured at $T > T_c$ for other tunnel junctions. Using Δ, Γ, and the magnitude of the conductance shunting the tunnel junction as parameters, we made a least-squares fit of the expression

$$\frac{dI(V)}{dV}=\frac{d}{dV}\int_0^V N(E)N(E-eV)dE \tag{2}$$

(for the derivative of the tunneling current with respect to the voltage) to the normalized experimental differential conductances $dI/dV(V)$, by analogy with Ref. 3. In this manner we found Δ and Γ for each tunnel junction. All the curves could be described well by expression (2), but the best agreement was found for crystals 24.09 and 14.12 with $\Delta_1 = 18.5$ meV, $\Gamma_1 = 5.8$ meV and $\Delta_2 = 23.8$ meV, $\Gamma_2 = 5.5$ meV, respectively. The shunting conductance (the leakage current) turned out to be less than 0.5% of the conductance at high voltages in all cases.

To find the experimental tunneling density of states of BSCCO and to compare it with the theoretical density, we solved the inverse problem: We selected a function $N_e(E)$, approximately the same as (1), which was capable of describing the experimental data on $dI/dV(V)$ on the basis of expression (2). The selection criterion was

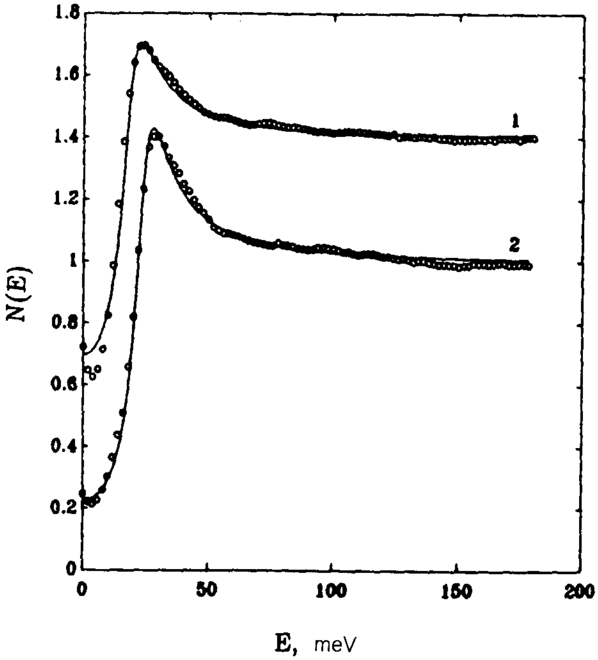

FIG. 2. Points: Tunneling density of states for two single crystals, 24.09 (*1*) and 14.12 (*2*), found by fitting expression (2) to the experimental data. Solid lines: Calculated from expression (1) with the parameter values $\Delta_1 = 18.5$ meV, $\Gamma_1 = 5.8$ meV and $\Delta_2 = 23.8$ meV, $\Gamma_2 = 5.5$ meV. Curve *1* and the corresponding experimental data have been shifted upward a distance of 0.4 along the vertical axis.

to minimize the sum of the weighted standard deviations of $N_e(E)$ from (1) and of $dI/dV(V)$ from (2) with $N(E) = N_e(E)$ from the experimental results. The points in Fig. 2 show the results found through the solution of this problem for two single crystals, 24.09 (1) and 14.12 (2). Shown for comparison are two curves calculated from expression (1) with the parameter values $\Delta_1 = 18.5$ meV, $\Gamma_1 = 5.8$ meV and $\Delta_2 = 23.8$ meV, $\Gamma_2 = 5.5$ meV (curve *1* and the corresponding experimental data have been shifted upward a distance of 0.4 along the vertical axis). The smooth curve in Fig. 3 is the calculated differential conductance $dI/dV(V)$ corresponding to the density of states $N(E)$ shown by the points in Fig. 2 (curve *1*). Also shown here are experimental results on $dI/dV(V)_s$. We see that the experimental curve lies on top of the theoretical curve everywhere except in a small region near zero, where the Josephson effect influences the measurements. The good agreement of these curves demonstrates the validity of the density of states $N(E)$ which we have found for BSCCO. In this figure we can also clearly see, on both curves, the knee at the voltage corresponding to one gap energy Δ. On the theoretical curve this knee is caused by the finite value of the density of states $N(E)$ at $E = 0$. The presence of the corresponding feature on the experimental curves may imply that the nonzero conductance $dI/dV(V)_s$ at a zero bias voltage results from a finite density of states at the Fermi surface inside the

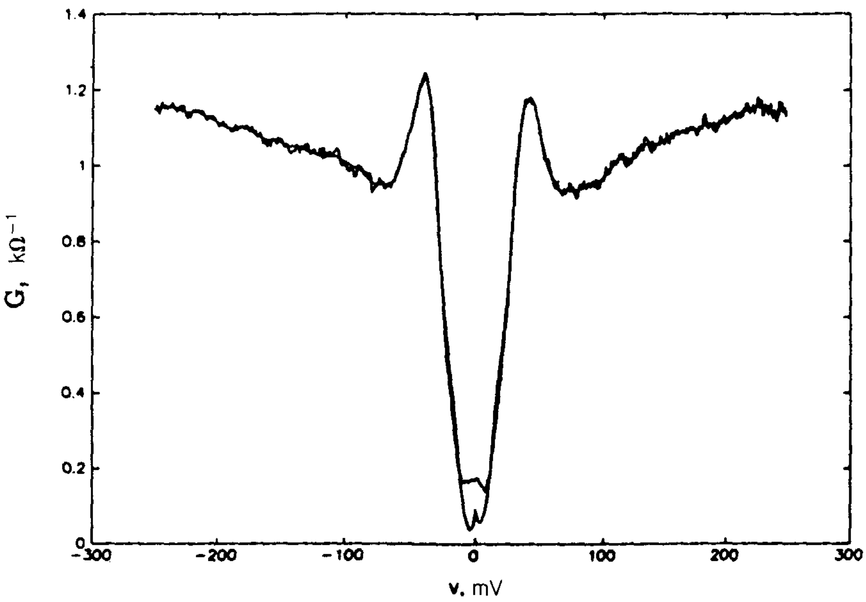

FIG. 3. Experimental curve of $dI/dV(V)_s$ for a BSCCO–BSCCO tunnel junction fabricated from single crystal 24.09, along with the theoretical differential conductance $dI/dV(V)$ (smooth curve) corresponding to the density of states $N(E)$ shown by points *1* in Fig. 2.

BSCCO gap in the *a–b* plane, rather than from a low quality of the tunnel junction.

Finally, we measured the temperature dependence of the BSCCO energy gap, 2Δ, for two of the seven single crystals, plotting curves of $dI/dV(V)$ at various temperatures. In both cases the gaps "closed" at temperatures close to the onset of the superconducting transition. Values of $\Delta(T)$ and $\Gamma(T)$ were found with the help of an expression analogous to (2), in which the nonzero temperature was taken into account. As in other studies (e.g., Ref. 9), the plot of $\Delta(T)/\Delta(0)$ vs T/T_c has the shape of the BCS plot of $\Delta(T)$, and the experimental points agree within the error with the temperature dependence $\Delta(T)$ for Pb and Pb_7Bi_3 — superconductors with a strong electron–phonon coupling, for which the values of the ratio $2\Delta(0)/k_BT_c$ are [10] 4.67 and 4.86, respectively. The values of the ratio $2\Delta(0)/k_BT_c$ for these two crystals are 6.5 ± 0.3 and 6.9 ± 0.3. The smearing parameter $\Gamma(T)$ is independent of the temperature (in contrast with Ref. 11) all the way to $T \simeq 0.9T_c$; it increases sharply at high temperatures.

In summary, we regard the results of this study as evidence that the data from tunneling studies of high-quality BSCCO single crystals can be described in the BCS model if a single parameter, Γ, is introduced. It is apparently also possible to explain the presence of this parameter by assuming that there is a finite density of states in the energy gap of BSCCO.

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