RAPID COMMUNICATIONS

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Break-junction tunneling measurements of the high-T_c superconductor $Y_1Ba_2Cu_3O_{9-\delta}$

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Current-voltage tunneling characteristics in a high-critical-temperature superconducting material containing predominately $Y_1Ba_2Cu_3O_{9-\delta}$ have been measured using the break-junction technique. Sharp gap structure was observed, with the largest superconductive energy gap measured to be $\Delta = 19.5 \pm 1$ meV, assuming a superconductor-insulator-superconductor junction. This energy gap corresponds to $2\Delta/k_BT_c = 4.8$ at $T = 4$ K, for a critical temperature of 93 K (midpoint of the resistive transition).

Since the discovery of high-critical-temperature ($T_c \simeq 90$ K) superconductivity in the Y-Ba-Cu-O system,[1] a number of experimental techniques have been used to study these new superconducting compounds. This Rapid Communication reports tunneling measurements in this high-T_c superconductor using the relatively new break-junction technique.[2] These measurements were made on a bulk sample with the predominant superconducting phase $Y_1Ba_2Cu_3O_{9-\delta}$ (where δ indicates an undetermined amount of oxygen deficiency), with T_c onset at 95 K and $R = 0$ at 91 K. Variations of the energy gap, Δ, along with the gap structure were observed as the junction was set and reset; the largest energy gap was 19.5 ± 1 meV. For a critical temperature of 93 K (midpoint of the resistive transition),[3,4] this value of the energy gap corresponds to $2\Delta/k_BT_c = 4.8$, which is larger than would be expected from the BCS prediction of $2\Delta/k_BT_c = 3.5$. This value is consistent with strongly coupled superconductors.

The break-junction technique used in this study has the potential for providing details of the quasiparticle states in the new high-T_c materials. In a break junction, tunneling occurs across the fracture of a *bulk* sample. A small piece of bulk material is electromechanically fractured under liquid helium, and the freshly fractured surfaces are adjusted to form a tunneling barrier with the helium as the insulator. A break-junction sample may be a single crystal, polycrystal, or sintered pellet. The break-junction method has been useful in providing tunneling data in the La-Sr-Cu-O superconductor system,[5,6] along with other tunneling studies using the point-contact technique[7,8] and the scanning tunneling microscope.[9,10] Unlike these other tunneling techniques, the break-junction technique gives access to the tunneling characteristics of the interior of bulk samples; it is not restricted to a surface layer that may not be representative of the bulk material.

The sample with an overall composition of $Y_2Ba_2Cu_3O_x$ was prepared from Y_2O_3, $BaCO_3$, and CuO powders sintered in the pressed-pellet form. The synthesis of the Y-Ba-Cu-O_x compounds is reported elsewhere.[4] The majority phase is the superconducting $Y_1Ba_2Cu_3O_{9-\delta}$ phase, recently identified,[3,11-13] with a small addition of the semiconducting phase Y_2BaCuO_5. The resistive (10%–90%) transition temperature is 94–92 K, and $R = 0$ at 91 K. Filaments with dimensions of $1 \times 1 \times 20$ mm^3 were cut from a sintered 1-in. disk for preparing break junctions. The measurements were performed using a break-junction apparatus designed for dipping in liquid-helium storage dewars ($T = 4$ K). First derivatives of the *I-V* curves were taken, using the standard lock-in technique with a modulation voltage of 1 mV.

The *I-V* characteristics of the $Y_1Ba_2Cu_3O_{9-\delta}$ break junctions changed as the junctions were mechanically set and reset. This is similar to the characteristics observed in the La-Sr-Cu-O system.[5,6] We think that this phenomenon was due to sample inhomogeneity, since break-junction measurements on pure Pb and Sn indicate low-leakage, quasiparticle tunneling independent of junction setting. As a junction was set and reset, tunneling probably shifted between different points within the fracture, thus sampling different materials.

Figure 1 shows the predominant type of *I-V* charac-

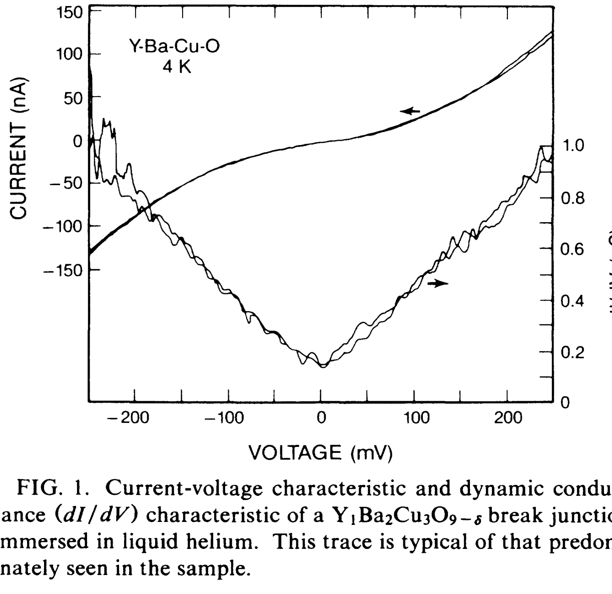

FIG. 1. Current-voltage characteristic and dynamic conductance (dI/dV) characteristic of a $Y_1Ba_2Cu_3O_{9-\delta}$ break junction immersed in liquid helium. This trace is typical of that predominately seen in the sample.

teristic and its associated dynamic conductance curve. Two traces are shown corresponding to increasing and decreasing bias voltage. This *I-V* curve shows little structure and is nonlinear, with a nearly quadratic dependence (nearly linear dynamic-conductance trace). This type of behavior has been observed in most of the tunneling measurements of La-Sr-Cu-O.[5-10] As pointed out by Kirtley *et al.*,[9] this is consistent with the model of Zeller and Giaever,[14] which treats tunneling in a system of small superconducting grains separated by insulating material. The nonlinearity of the *I-V* curve decreased at low junction resistances (less than about 100 kΩ). This curvature is not apparent at low bias in pure Pb or Sn break junctions, implying that its cause is inherent to the high-T_c compounds Y-Ba-Cu-O and La-Sr-Cu-O.

An *I-V* characteristic showing strong gap structure was obtained after resetting the junction several times. The data shown in Fig. 2 indicate low-leakage tunneling between superconducting electrodes. Conductance peaks at −39 and +39 mV clearly define a tunneling energy gap. If the materials on either side of the junction are identical, and the junction is formed in the superconductor-insulator-superconductor (SIS) configuration, then $4\Delta/e = 78$ mV or $\Delta = 19.5$ meV. This is consistent with previous interpretations of point-contact data on the La-Sr-Cu-O system.[5-10] We have not observed a tunneling gap larger than the one reported, indicating that we are observing SIS tunneling. However, we cannot rule out that the actual junction may be in the superconductor–insulator–normal-conductor configuration, in which case the gap would be nearly twice as large.

The peaks in the dynamic conductance (dI/dV) traces at the gap edges are broad (between 16 and 24 meV wide at half maximum), as shown in Fig. 2. Also, there is a strong negative peak in the dynamic conductance trace within 15 to 30 meV of the gap edge. If the normal-state conductance varies smoothly from low bias to high bias, this represents a large negative deviation from normal-state conductance. Additional structure may exist beyond the gap edges, but was too small to be detected in these measurements.

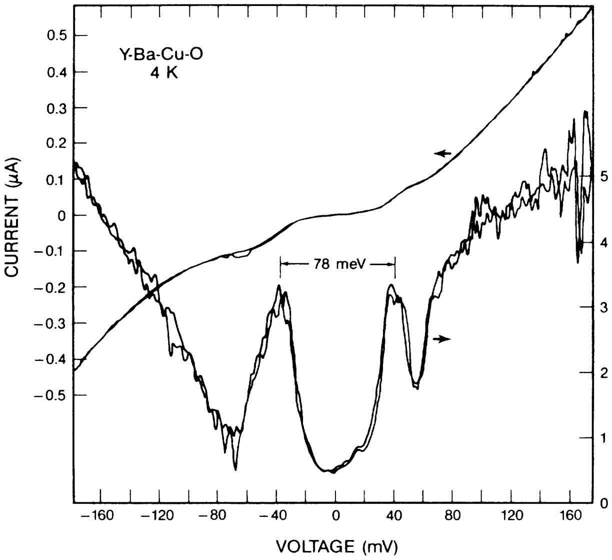

FIG. 2. Current-voltage characteristic and dynamic conductance (dI/dV) showing superconducting gap structure typical of the largest measured in the $Y_1Ba_2Cu_3O_{9-\delta}$ break-junction sample.

In summary, a direct measure of the superconductive energy gap in $Y_1Ba_2Cu_3O_{9-\delta}$ gives us some information concerning the mechanism of superconductivity in this high-critical-temperature superconductor. The relatively large gap of 19.5 ± 1 meV gives a value of $2\Delta/k_BT_c$ of 4.8, which is consistent with the values of strongly coupled superconductors.

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