Electron-phonon coupling in BiSrCaCuO single crystals with different T_c values

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A tunneling study has been made of BiSrCaCuO single crystals with $T_c = 65$ K and 23 K. The spectral density of the electron-phonon coupling, $\alpha^2(\omega)F(\omega)$, has been reconstructed from the tunneling data through a numerical inversion of the Éliashberg equation for the gap. Comparison of these functions with each other and with the background spectrum $F(\omega)$ indicates a strong electron-phonon coupling and a governing role of this coupling in the formation of superconducting electron pairs.

In this letter we are reporting a continuation of a tunneling study[1] of single crystals of the high-temperature superconductor $Bi_2Sr_2CaCu_2O_{8-x}$ (BSCCO). In Ref. 1 our samples contained two phases, with superconducting transition temperatures $T_c = 65$ K and 28 K, for which the values of the ratio $2\Delta(4.2\text{ K})/kT_c$ were 7.1 and 7, respectively. We wish to stress that these values of T_c were found from the temperature dependence of the energy gap of the high-temperature superconductors, $\Delta(T)$. The superconducting transitions found for the BSCCO single crystals by the ordinary resistive method, on the other hand, lay in the region 74–87 K.

In Fig. 3 in Ref. 1 we can clearly see structure, at voltages above the BSCCO energy gap, which disappears when the samples undergo a transition to the normal state. In ordinary superconductors such structure on the derivative current-voltage characteristics would be linked with an electron-phonon coupling. Ignoring the anisotropy of this coupling, we have reconstructed the spectral density of the electron-phonon coupling, $\alpha^1(\omega)F(\omega)$, from the tunneling data.[2] We carried out a corresponding analysis of the results of tunneling studies of $La_{2-x}Sr_xCuO_{4-y}$ and $Eu_1Ba_2Cu_3O_7$ in Ref. 3. These results, and also data on the temperature dependence of the resistance, the Raman effect, and the photoluminescence—reported by other investigators—point to a strong electron-phonon coupling in the high-temperature superconductors. In an effort to determine the relationship between the electron-phonon coupling and T_c in oxide superconductors, we have attempted to compare the functions $\alpha^2(\omega)F(\omega)$ of the two BSCCO phases, with the high and low value of T_c

For the tunneling measurements we used BSCCO single crystals consisting of the high-temperature phase nearly exclusively and others consisting of the low-temperature phase exclusively. The procedures for synthesizing the samples and carrying out the tunneling experiments are described in Ref. 1. The energy gaps and the values of T_c for the two phases, found from the curves of $\Delta(T)$, were $\Delta^H = 20$ meV, $T_c = 65$ K and $\Delta^L = 7.2$ meV, $T_c = 23$ K, for the high-temperature and low-temperature phases, respectively. From these values we find a ratio $2\Delta(4.2\text{ K})/kT_c \approx 7$, as in Ref. 1.

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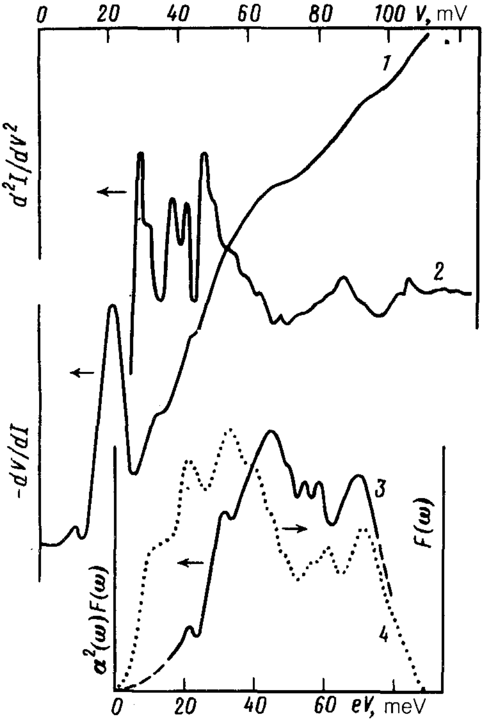

FIGS. 1 and 2. First (1) and second (2) derivatives of the current-voltage characteristics of BiSrCaCuO-Nb tunnel junctions fabricated from single crystals with $T_c = 65$ K and 23 K, respectively (at $T = 4.2$ K). 3—Spectral densities of the elecron-phonon coupling, $\alpha^2(\omega)F(\omega)$; 4—phonon spectrum $F(\omega)$ according to neutron-scattering data.

The upper parts of Figs. 1 and 2 show the first (1) and second (2) derivatives of the current-voltage characteristics of BSCCO-Nb "point" tunnel junctions ($T = 4.2$ K). The data in Fig. 1 correspond to a sample with $T_c = 65$ K, and the data in Fig. 2 to a sample with $T_c = 23$ K. The large maxima on curves (1) determine the sum $\Delta_{BSCCO} + \Delta_{Nb}$. At $eV > \Delta_{BSCCO} + \Delta_{Nb}$ we see some additional structure, whose general shape is the same in the two figures. Note in particular that in the case of the sample with $T_c = 23$ K this structure disappears at the transition to the normal state, so the disappearance of this structure at $T > T_c$ cannot be explained on the basis of a thermal smearing, as it might be in the case of samples with high T_c. This circumstance is further confirmation that this structure is related to an electron-phonon coupling in the high-temperature superconductor. (The structure of course remains when niobium goes into its normal state.)

To reconstruct the function $\alpha^2(\omega)F(\omega)$ from the tunneling data we need, along with the results in Figs. 1 and 2, the dependence $[-dV/dI(V)]_N$ for the normal state of the tunnel junction. This dependence must be measured at the same temperature as that at which the superconducting state is studied (for the normalization of the input

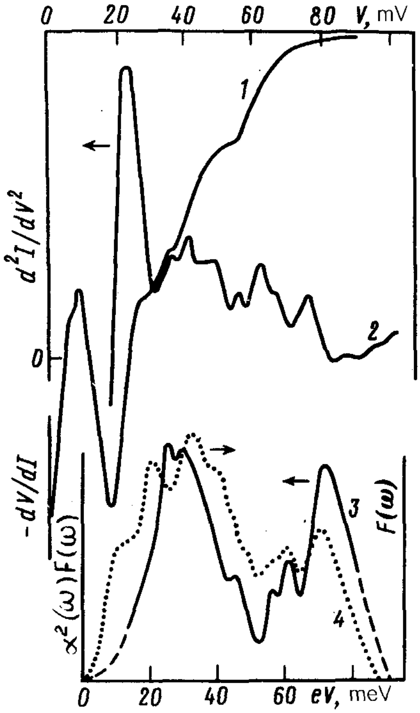

FIG. 2. (See Fig. 1 caption on previous page.)

data in the numerical calculations). In the case of a high-temperature superconductor, this condition cannot be satisfied by means of a magnetic field. Furthermore, we cannot use the dependence $-dV/dI(V)$ measured at $T > T_c$, since the conductivity of tunnel junctions based on high-temperature superconductors is very sensitive to the temperature, apparently because of the presence of unpaired electrons in these materials, even at $T \ll T_c$. We have studied the temperature dependence of the conductivity of tunnel junctions in high-temperature superconductors. We have reached the conclusion that $[-dV/dI(V)]_N$ can be approximated crudely by the dependence $-dV/dI(V)$ which is recorded at 4.2 K, but which has "gap" and "phonon" structural features. The solid lines (3) in the lower parts of Figs. 1 and 2 show the spectral density of the electron-phonon coupling, $\alpha^2(\omega)F(\omega)$, for the two BSCCO phases found through a numerical processing of the tunneling data, under the assumption which we just stated. As the program for the numerical calculations we used two stages of the program of Ref. 4 and one of the program of Ref. 5. The dotted lines (4) in these figures show the phonon spectrum $F(\omega)$ found for BSCCO at Karlsruhe from data on neutron scattering at $T = 5$ K (and graciously furnished to us by B. Renker, after the analysis of our tunneling data had been carried out). We see that the energy

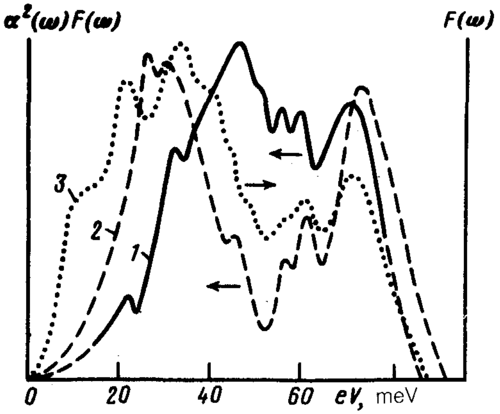

FIG. 3. The functions $\alpha^2(\omega)F(\omega)$ for samples with (1) $T_c = 65$ K and (2) 23 K, along with the phonon spectrum $F(\omega)$ (3).

positions of the maxima in the functions $\alpha^2(\omega)F(\omega)$ and $F(\omega)$ are the same, but the overall shape of the spectra is also the same in the case of the low-temperature phase of BSCCO. In previous research on simple superconductors, such a coincidence of these functions has been an unambiguous indication that electron-phonon coupling plays a governing role in the superconductivity mechanism. For clarity, the three spectra are shown together in Fig. 3. The vertical scales have been chosen in such a way that the amplitudes of the main peaks on the three curves are the same. The function $\alpha^2(\omega)F(\omega)$ shown by the solid line (1) corresponds to the sample with $T_c = 65$ K, the dashed line (2) corresponds to a sample with $T_c = 23$ K, and the dotted line (3) corresponds to the $F(\omega)$ phonon spectrum of BSCCO. For the first sample the $\alpha^2(\omega)F(\omega)$ spectrum is narrower and has no dip at 40–60 meV. This result can be taken as evidence of an intensification of the electron-phonon coupling in BSCCO at intermediate phonon frequencies with increasing T_c. It should be noted, however, that a corresponding change in the phonon spectrum itself, $F(\omega)$, has been observed[6] in the 1-2-3 high-temperature superconductors at the transition from the superconducting phase to the nonsuperconducting phase, so some accurate quantitative calculations are required for a more rigorous analysis. Because of the assumptions made above, we will not report numerical values for $\alpha^2(\omega)F(\omega)$, for the constant λ, or for the Coulomb pseudopotential μ^*. However, the amplitude of the phonon spectrum on the current-voltage characteristics of the tunnel junctions and the large value of the ratio $2\Delta/kT_c$ indicate a strong electron-phonon coupling and a large electron-phonon coupling constant λ in BSCCO. Since the phonon frequencies in this superconductor stretch up to 90 meV, the model of electron-phonon coupling could in principle predict the observed values of T_c in this oxide superconductor.

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