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Phonon structure in the tunneling conductance of $Bi_2Sr_2CaCu_2O_8$

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Clear phonon structures were observed in the tunneling conductance of a $Bi_2Sr_2CaCu_2O_8$-GaAs junction. The spectral function of the electron-phonon interaction gives a value of 87.3 K for the critical temperature and 22.2 meV for half a gap. There is no particularly large phonon structure, and the high T_c cannot be attributed to a particular phonon mode in the electron-phonon mechanism. The gap edge structure is sharp, and an s-wave state is probable. However, if the angular distribution of the tunneling current is highly anisotropic we cannot definitely exclude a d-wave state.

There has been some dispute over the reliability of phonon structures in the tunneling conductance of high-T_c cuprates, and phonon structures have not contributed to a clarification of the mechanism of high-T_c superconductivity despite their importance to the electron-phonon mechanism,[1] except for lower-T_c oxides such as $Nd_{2-x}Ce_xCuO_4$ and $Ba_{1-x}K_xBiO_3$.[2] Vedeneev *et al.*,[3] Gonnelli *et al.*,[4] and our group[5] have reported the spectral function α^2F of the electron-phonon interaction for $Bi_2Sr_2CaCu_2O_8$ (Bi2212). In this paper, however, we will report on some experimental results which clearly demonstrate that the structures correspond to the phonon density of states, and present well resolved α^2F.

A tunneling junction was fabricated by strongly pressing a thin Bi2212 crystal, whose dimensions were 2 mm×5 mm ×0.1 mm, into a single crystal of GaAs doped with Zn as shown in the inset of Fig. 1. The Bi2212 single crystal was grown by the usual self-flux method. Sintered material of $Bi_{2.10}Sr_{1.90}Ca_{0.90}Cu_{2.10}O_x$ was melted at 1273 K for 6 h. It was cooled to 1018 K with the rate of 0.6 K/h and subsequently to 300 K with the rate of 120 K/h. The temperature gradient was 5.5 K/cm along the axis and 2~3 K/cm along the radius of the crucible. T_c was 89.3 K at midresistance with a transition width of 3 K. The single crystal was coated with epoxy resin until it was brought into contact with the GaAs. The coated Bi2212 crystal was cut with a razor in air at room temperature five minutes before the contact was made. Thus the surface of the Bi2212 was flashed to the air. Two copper lead wires had been attached to the Bi2212 with silver paint after evaporating the Au. Two copper lead wires had also been connected to the GaAs by ultrasonic soldering. The major improvements in this experiment compared to the previous ones are the thinness of the crystal and the coating of the crystal with epoxy resin. Except for these two points, the junction was fabricated and operated as was previously reported.[6] Tunneling electrons flowed in parallel with the CuO_2 plane from the GaAs to the Bi2212 under a positive bias. The current flowed macroscopically in parallel with the Cu-Cu (not Cu-O-Cu) direction.

Figure 1 shows dV/dI in relation to temperature. Structures due to superconductivity disappear above about 88 K. Hence T_c was determined to be 86±2 K, whereas the resistive transition temperature was 89±2 K. Small wiggles are seen at 4.2 K, but they are unclear above 21 K in dV/dI. Another feature to be noted is a jog at about 20 mV. This appears at every temperature below T_c at the same voltage, and as a result it appears as a shoulder just below the gap edge peak at 4.2 K. The zero-bias conductance was not zero at 4.2 K. Such a leakage current is inevitable for our junction composed of the heavily doped semiconductor. In fact the normalized zero-bias conductance was 0.59 at 2.1 K for a Pb-GaAs junction for which Pb phonons were clearly observed.[7] The whole structure appears on a broad background resistance peak which is not relevant to superconductivity, as already explained.[8]

The observed conductance must be normalized for deducing the α^2F by the McMillan-Rowell (MR) inversion procedure.[9] Since the exact normal-state conductance at 4.2 K is not known, it was approximated from that at 88 K as follows. At first 0.507 mS was subtracted from the observed conductance at 4.2 K to reduce the conductance to zero at zero bias. Next 0.340 mS was subtracted from the observed conductance at 88 K to make the normalized conductance unity at 200 mV. Thus shifted conductances are shown in

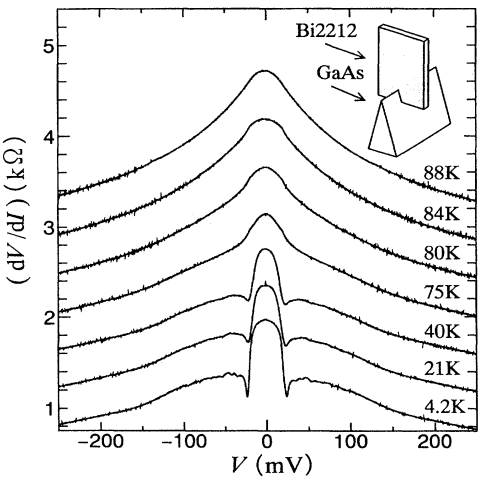

FIG. 1. Differential resistance dV/dI was plotted against voltage V in relation to temperature. The ordinate is for the lowest dV/dI curve. It was shifted upward by 0.4 kΩ each for the others. Inset is a schematic of the contact.

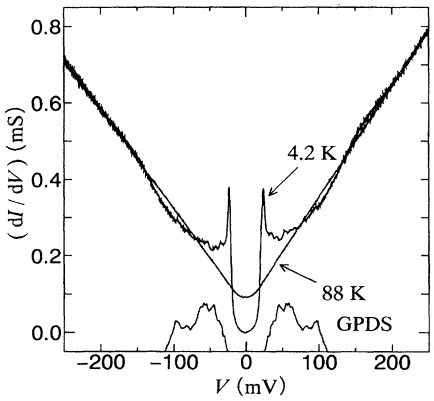

FIG. 2. The normalization procedure was illustrated. The subtracted conductances at 4.2 and 88 K were plotted together with the GPDS of Bi2212 (Ref. 10). These subtracted conductances were normalized. See the text.

Fig. 2 together with the generalized phonon density of states (GPDS) obtained by Renker *et al.*[10] The ratio of the depleted area to the accumulated area in the normalized dI/dV is 0.85 at negative bias and 0.61 at positive bias, indicating some uncertainty in the normalization procedure. Then we modified the normal-state conductance to make this ratio unity. At that time α^2F was similarly as large as the present one. Therefore we abandoned such a modification and adopted the previously obtained normalized conductance in order to make the situation as simple as possible. The MR procedure was applied to the averaged normalized conductance for both biases.

The averaged normalized conductance is shown in Fig. 3. There appear many structures in the phonon frequency range. The correspondence with GPDS is satisfactory as will also be shown in Fig. 4. Such structures had repeatedly been observed at the phonon positions for various junctions of

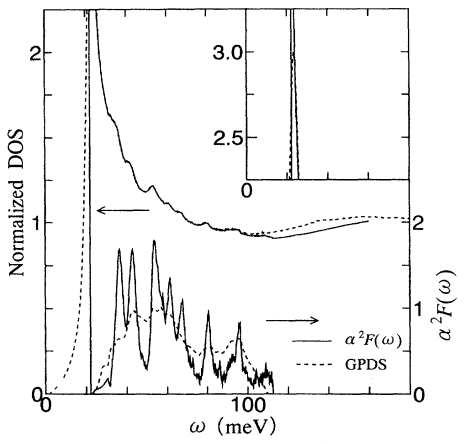

FIG. 3. The spectral function (lower solid line), GPDS (Ref. 10) (lower broken line), the averaged normalized conductance at 4.2 K (upper broken line), and the calculated normalized quasiparticle density of states at 0 K (upper solid line). Sharp edge peaks outside the frame were replaced to the upper right panel. The left-hand ordinate is both for normalized values of DOS and the conductance.

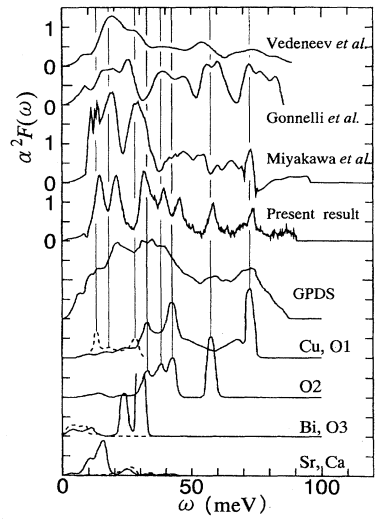

FIG. 4. Spectral functions obtained by Vedeneev *et al.* (Ref. 3), Gonnelli *et al.* (Ref. 4), Miyakawa *et al.* (Ref. 5), and the present result are compared with GDPS and the atomic vibrations (Ref. 10). O1; O in the CuO_2 plane, O2; apical O, O3; O in the Bi-O planes.

Bi2212, and they had shifted parallelly as temperature had been varied.[7,11,12] Occurrence of such structures either for evaporated junctions indicates that they are not extrinsic structures introduced during the mechanically contacting process.[7,12] The inelastic process[13,14] also produces a structure at the phonon position, but our structures are not the inelastic ones as explained in Ref. 15. Now compared with the previous conductance curves for Bi2212-semiconductor junctions[7,12] the gap edge structure is sharper for the present junction. And the resolution of the structures is better than the others ever to have been reported. Hence the correspondence with the GPDS structures are more evident as will be shown in Fig. 4. The sharp gap-edge structure may be due to better quality of the thin Bi2212 crystal at the contact. In our previous experiments, the gap-edge structure was not so sharp as this. Nevertheless the phonon structures were observed. If the gap value homogeneously distributes in a wider range than the phonon dispersion width, the structures will be smeared out. Therefore the observation of the phonon structures for previous junctions suggests that the distribution of the gap value was not homogeneous, or some nonohmic current flowed in the gap region and made the edge peak blunt. Such a nonohmic current was observed for normal-metal-semiconductor junctions within about 20 mV at lower temperatures.[8]

The α^2F is also shown in Fig. 3, together with the calculated quasiparticle density of states (DOS) for 0 K, and GDPS.[10] When the MR inversion procedure was applied, the gap-edge region within 9 mV from the peak was cut off because of its divergent property. The cut-off frequency for μ^* integral was 500 meV. The Coulomb repulsion μ^* and the calculated gap parameter $\Delta(0)$ are 0.11 and 22.2 meV, respectively. The integrated value of $\alpha^2F(\omega)$ is 52.5 meV and the calculated T_c is 87.3 K. T_c was calculated as previously reported.[16] Hence $2\Delta(0)/k_BT_c$ is 5.9. μ^* is as small as

0.11, but there is an uncertaity in μ^* due to the uncertainty in the normal-state conductance, and we cannot discuss this value. $\Delta(0)$ is also estimated from the phonon zero-frequency position and the gap-edge peak position, and is 24 ± 1 meV and 24 ± 0.5 meV, respectively. In the above analysis, dI/dV was assumed to be proportional to the electron density of states in the Bi2212. However, dI/dV may also be analyzed by using the Blonder-Tinkham-Klapwijk (BTK) theory.[17] In fact, the observed dI/dV was reproduced at every temperature except for 84 K by using the above obtained α^2F. The barrier strength parameter Z (Ref. 17) was 2.0 to 1.5 depending on the temperature. However, even for this analysis the subtraction of a certain constant conductance was necessary. Therefore the density of states analysis and the BTK analysis are essentially equivalent for the present junction, and the former analysis was executed.

The spectral function is compared with that obtained by Vedeneev *et al.*,[3] Gonnelli *et al.*,[4] and our own previous result[5] in Fig. 4, together with the component analysis of the vibrations made by Renker *et al.*[10] All of them have a more or less similar shape to GPDS. The correspondence with phonon modes is most clearly understood by comparing the present α^2F with the atomic vibration analysis[10] and with the mode analysis by Prade *et al.*[18] According to their analysis the Cu-O stretching mode occurs at about 72 meV, and an axial oscillation of the apical O occurs at about 57 meV. These two oscillations have been considered to be important factors in enhancing the electron-phonon interaction.[19] However the elimination of corresponding peaks from α^2F decreases T_c only by 3.3 K and 6.6 K, respectively. Since the contribution to T_c may be expressed by a parameter $\lambda_i=2\int d\omega_i\alpha^2F_i/\omega_i$, where ω_i is a frequency of the ith mode, our α^2F indicates that lower-frequency modes contribute much to T_c in accordance with the first-principles calculation by Cohen, Pickett, and Krakauer[20] and Rodriguez *et al.*[21] for $YBa_2Cu_3O_7$. Thus our α^2F indicates that there is no particular phonon mode which is solely responsible for high T_c and each of the modes makes an important contribution to the enhancement of T_c.

Let us now discuss the gap anisotropy. As seen from Fig. 3, the gap-edge conductance peak is very sharp and the calculated s-wave density of states almost reproduces it. To see whether another scattering mechanism other than phonons is operative, we introduced the Dynes' Γ (Ref. 22) into the expression for the density of states. It was found that Γ would have to be, if it were present, less than 1 meV at 4.2 K. The conductance curve below the gap edge may be modified by the gap distribution. If the order parameter is that of an s wave, the present result at 4.2 K constrains the distribution width to within 3 meV as long as the angular distribution of the tunneling current is isotropic. This width is smaller than the reported value.[23] Since the shape of the contact was not simple, the angular distribution could not be estimated. As for a d-wave order parameter[24] it cannot definitely be excluded if the current distribution is highly anisotropic.

In conclusion, we observed phonon structures in the tunneling conductance of Bi2212, and α^2F gives a value of 87.3 K for T_c. There is no particularly large structure in α^2F, and this indicates that high T_c is not attributable to a particular phonon mode in the electron-phonon mechanism. μ^* was 0.11. $\Delta(0)$ was 24 ± 1 meV, 22.2 meV, and 24 ± 0.5 meV from the phonon zero-frequency position, α^2F, and the gap-edge peak position, respectively. The first gap gives a value of 6.5 ± 0.4 for $2\Delta(0)/k_BT_c$, where T_c is 86 ± 2 K. The gap-edge structure was sharp enough to suppress the Dynes' Γ below 1 meV if such a parameter exists. If the order parameter is of the s type, which seems to be probable, its distribution width must be less than 3 meV if the current distribution is isotropic. A d-wave state cannot definitely be ruled out if the current distribution is highly anisotropic.

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