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SUPERCONDUCTING ENERGY GAP OF SINGLE-CRYSTAL $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ BY ELECTRON TUNNELING

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We report measurements of the superconducting energy gap in a $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ single crystal using point contact electron tunneling. We show data related to the energy gap spectra in these new ceramics. The energy gap was determined to be around 27-32 meV. The results give values for the ratio 2Δ (T=4.6 K)/k_BT_c (80 K) of between 7.8 and 9.3. The data also reveal a reproducible structure at energies of 67 and 120 meV.

Since the discovery of the new ceramic superconductors in 1986 and of the new families in 1988 there have been many attempts to observe one of the most characteristic features of the superconducting state; the energy gap. Two different techniques have mainly been used; infrared spectroscopy and electron tunneling. Tunneling is, perhaps, the most direct technique to observe the energy gap in superconductors. In the past, it was used with notable success by Giaever [1] and other workers in the field [2]. Very soon after Giaever's discovery, with the support of theoretical models [3] it was clear that the important information that tunneling provides is directly related to the size of the energy gap and the electron density of states. Once the strong coupling theory appeared to explain discrepancies with the BCS model, McMillan and Rowell [2,4] were able, using computational techniques, to invert the Eliashberg gap equations to find how the decorations of the experimental dI/dV curve can be related to the excitation spectra. Thus tunneling results can be used to find, among a wealth of information, the coupled functions $\alpha^2(\omega)F(\omega)$ which, in turn, give information about the electron-electron interaction and the phonon density of states. With all this amount of information that could be extracted from tunneling experiments, it is very clear that tunneling is the best probe of the superconducting state.

In the new ceramic superconductors much tunneling data has been obtained in the last two years; the conclusion so far is that the resulting data show poor tunneling characteristics which are difficult to understand. One general claim is that, in these materials, the granular behavior, the rapid oxygen loss, and surface degradation create problems which are immediately reflected in noisy data and little reproducibility. With all these problems there are no reliable measurements of the energy gap values, and the important ratio $2\Delta/k_BT_c$ oscillates from values characteristic of the weak coupling limit 3.5, to values close to 20 [5] in the very strong limit, according to conventional theories of superconductivity. So the conclusion is that tunneling measurements in the new ceramic materials are difficult, and many of the problems may be related to the surface quality which has a dramatic influence on the tunneling measurements.

In this paper we report tunneling measurements using single crystals of $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$, which were grown from mixtures of powders of their respective oxides and carbonates (in alumina crucibles) melted at 950°C in air, and then cooled at a rate of 1°C/h to below 650°C. Platelet-like crystals were obtained with typical dimensions of $1\times1.5\times0.3$ mm^3. Resistivity vs. temperature characteristics show critical transition temperatures at $T_c(R=0)=80$ K. X-ray

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diffraction data indicated a single phase with basal planes (00n) being perpendicular to the platelets plane. Tunneling measurements were made at 4.6 K using a closed-cycle refrigerator. In order to isolate the vibrations of the refrigerator, the tunnel junctions were suspended by the four spring wire electrodes used to do the measurement. The sample chamber was filled with He gas to produce a good thermal equilibrium with the sample. The tunnel junctions were formed by driving a tungsten needle into the surface of the Bi-single crystal in the (001) face. The reason for driving in the tungsten point was to avoid the surface problems already discussed and observed in many experiments [5]. The tungsten needle was sharpened using an electrochemical etching process until the tip was smaller than 50 μm. Au wires were also tried but the best results were obtained using the tungsten points.

Differential resistance dV/dI of the W–$Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ point contact tunnel junctions were obtained from 1 kΩ to several hundred kΩ. However the best and clearest results were found with dV/dI (zero bias) of the order of 30–50 kΩ. Fig. 1 shows the I–V, dV/dI and d^2V/dI^2 characteristics measured at $T=4.6$ K, using standard tunneling electronics as described by Adler et al. [6]. Attempts to measure tunnel junctions with $dV/dI \leq 3$ kΩ clearly display a large zero bias anomaly conductance peak. This anomaly has very often been observed but its physical interpretation is still a point that deserves major analysis. Tunnel junctions with large values of dV/dI display noisy characteristics. Fig. 2 shows $(dI/dV)_s$ and $(dI/dV)_N$ vs. V curves, the normal characteristic was obtained at a temperature of 100 K above T_c. Δ can be determined from the I–V characteristics of the tunnel junction, by different methods which depend on whether the junction is N–I–S or S–I–S. For our type of tunnel junction (N–I–S), one can fit the I–V characteristic, for $V>\Delta$, using the BCS expression at $T=0$; $R_nI(V)=(V^2-\Delta^2)^{1/2}$ (in this equation R_n is the high voltage junction resistance). This procedure avoids the problem of assigning Δ to the peak in the dI/dV characteristic, which could be affected by gap smearing or by the leakage current due to imperfect tunnel junctions. Another and perhaps better criterion is to compare the calculated and experimental curves of $G(V)$ and to choose the value of Δ which gives the best fit. According to those two criteria and using a smeared BCS density of states as proposed by Dynes et al. [7], to account for lifetime effects, in which $N_s(E)=\mathrm{Re}[(E-i\Gamma)/((E-i\Gamma)^2-\Delta^2)^{1/2}]$, from fig.

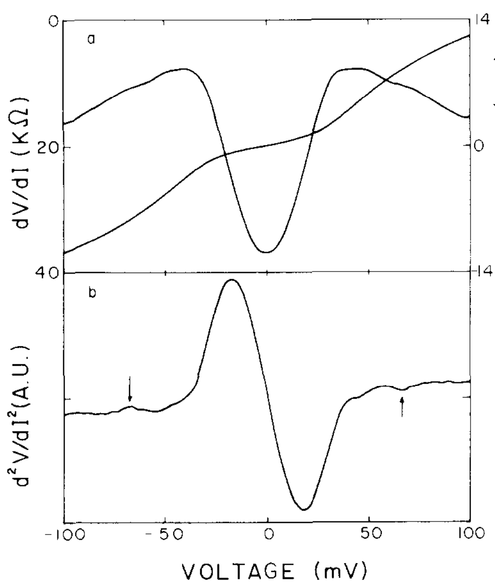

Fig. 1. Characteristic curves of a tunnel junction at $T=4.6$ K, formed by a tungsten point and a single crystal of $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$. a) I–V and dV/dI–V, b) d^2V/dI^2–V, note the peak structure at about ±67 meV.

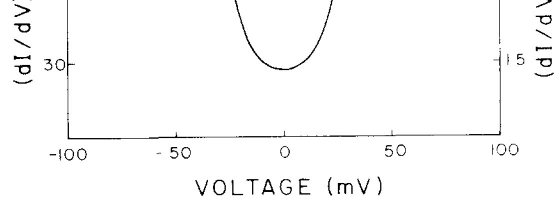

Fig. 2. (dI/dV)'s vs. V curves in the superconducting and normal state, (dI/dV)'s vs. V curves in the superconducting and normal state, (dI/dV_s) was measured at $T=4.6$ K and $(dI/dV)_N$ at $T=100$ K.

3 and the I–V characteristics of fig. 1a, we determined an energy gap value of $27 \leq \Delta \leq 32$ meV. and a value for the smearing parameter $\Gamma = 10$ meV. From this value the ratio $7.8 \leq 2\Delta/k_B T_c \leq 9.3$ was obtained. Fig. 1b exhibits an interesting feature which is clearly observed at about ± 67 meV. in the d^2V/dI^2 curve. Figs. 4 and 5 also show dI/dV's at high energies. In fig. 4 an asymmetrical structure is noted with average value of ± 120 meV. In fig. 5 we show data taken from 0 to 500 meV. This figure shows no additional structure after 120 meV. Attempts to measure the temperature dependence of the energy gap was impossible because of the low stability which is characteristic of point contact tunnel junctions. It is worthwhile mentioning that of the many tunnel junctions measured, only a few of them gave the very clean structures shown in figs. 1 to 5, and the rest of them gave characteristics without a clear indication of energy gap and with all kinds of peaks at different energy positions. However, the results reported here are reproducible and were taken from different sets of measurements. All data was filtered using a Fourier transform digital filter [8].

In all data shown in this paper, we can observe that the zero bias conductance in the superconducting state does not reach zero; which is indicative of a leakage current. To evaluate that current, or in other words, those contributions to dI/dV due to the non-tunneling process, it is convenient to use the

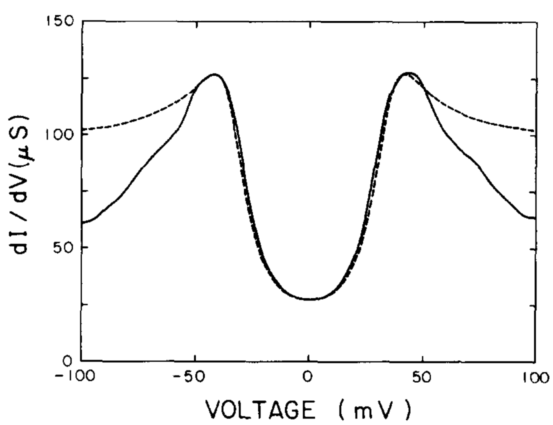

Fig. 3. The experimental $(dI/dV)_s$ characteristic of a tunnel junction (continuous line), and the theoretical density of states given by: $N_s = \mathrm{Re}[(E - i\Gamma)/((E - i\Gamma)^2 - \Delta^2)^{1/2}]$ (dashed line), with $\Gamma = 10$ meV, and $\Delta = 32$ meV.

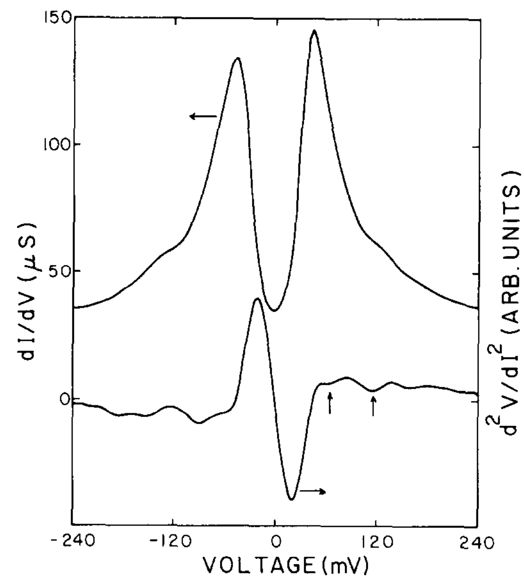

Fig. 4. dI/dV–V and d^2V/dI^2–V characteristics of the tunnel junction at higher energies, which show peaks at ± 67 meV and at ± 120 meV.

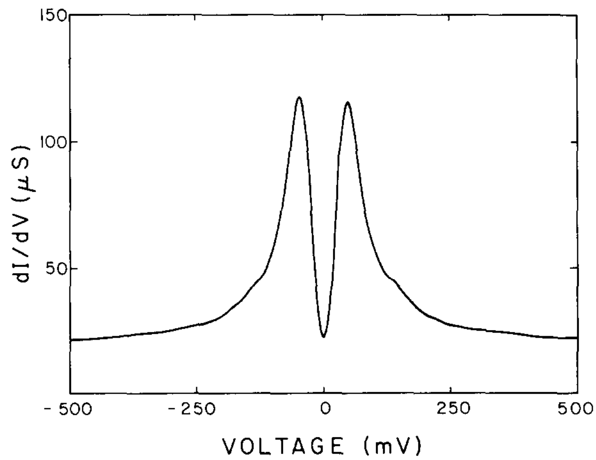

Fig. 5. dI/dV vs. voltage curve of the junction at higher voltages.

McMillan and Rowell criteria [4]. In this case it is necessary to take the ratio of the conductance at zero bias in the superconducting state to that in the normal state, which for our experiment is difficult to evaluate, because we would have to take the normal state at the same temperature that we are using to compare with the dV/dI in the superconducting state.

It is interesting to point out some characteristics of our data: first the curves display, in the superconducting state, a well defined gap-like feature. Second, the high voltage $(dI/dV)_s$ vs. V characteristic is a decreasing function of voltage, which was already observed by other authors [9]. They indicated that this behavior is consistent with a normal density of states which is strongly energy-dependent and that is peaked near the Fermi level. However, in our normal-state experimental data, we always observed very conventional behavior, namely the expected parabolic dependence on voltage as described by Brinkman, Dynes and Rowell [10]. While the $(dI/dV)_N$ characteristic was taken at a relatively high temperature (100 K), we would expect the normal density of states to be only slightly modified and therefore the background conductance should be unchanged compared to the superconducting data.

In several recent works [11–13] the general trend for the ratio $2\Delta/k_BT_c$, in Bi-compounds as in the 1:2:3 superconductors, indicates ratios around 7 which in the framework of the Eliashberg theory is in the very strong limit. Also, according to other results, the general belief is that the temperature dependence of the gap is of the BCS-type as has been reported [11,12,14,15]. It is important to observe that the reproducible structure at 67 and 120 meV. can be indicative of the interaction concerning the basic mechanisms of the superconducting state in these materials [16,17]. In a recent paper Marsiglio and Carbotte [18] propose another possible contribution to form the superconducting state besides the usual electron–phonon interaction. In particular they used an excitonic contribution together with the electron–phonon interaction to explain superconductivity in high-T_c materials. It is interesting to observe that in that case the appropriate λ value has an excitonic contribution at higher energies of the order of 70 meV.

In summary the important results of this paper are:

1) Tunneling characteristics of dI/dV vs. V show features that indicate the energy gap which has a value of $27 \leq \Delta \leq 32$ meV.
2) We find that clean structures for the gap can be observed with tunnel junctions formed by W–$Bi_2Sr_2CaCu_2O_{8+\delta}$, where a tungsten tip is driven into the surface of the single crystal so avoiding surface problems.
3) Clear structure that yield information of possible excitations were found at 67 and 120 meV.
4) The value of the ratio $7.8 \leq 2\Delta/k_BT_c \leq 9.3$ is indicative of very strong coupling according to conventional superconducting theory.

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