Scanning tunnelling spectroscopy of an oxide superconductor $Bi_2Sr_2CaCu_2O_{8-\delta}$

1990 J. Phys.: Condens. Matter 2 9961

(http://iopscience.iop.org/0953-8984/2/49/020)

J. Phys.: Condens. Matter 2 (1990) 9961–9965. Printed in the UK

LETTER TO THE EDITOR

Scanning tunnelling spectroscopy of an oxide superconductor $Bi_2Sr_2CaCu_2O_{8-\delta}$

Koichi Ichimura†, Kazushige Nomura†, Fujio Minami‡ and Shunji Takekawa§

† Department of Physics, Hokkaido University, Sapporo 060, Japan
‡ Research Institute of Applied Electricity, Sapporo 060, Japan
§ National Institute for Research in Inorganic Materials, Tsukuba, Ibaraki 305, Japan

Received 16 October 1990

Abstract. We carried out a tunnelling spectroscopy measurement on a single crystal of superconducting oxide $Bi_2Sr_2CaCu_2O_{8-\delta}$ using a low temperature scanning tunnelling microscope. The superconducting gap parameter shows a spatial variation over a relatively small area (~10 nm). We obtained the energy gap parameter $\Delta(4.2\ K) = 26$ meV, the most observable value, and correspondingly $2\Delta/k_BT_c = 7$, larger than the BCS value. The shape of the $(dI/dV)-V$ curve suggests an anisotropy of the energy gap. Thermal smearing of the gap structure is observed below T_c. Temperature dependence of the gap parameter is consistent with BCS. Even above T_c the conductance curve is not flat.

Since the discovery of high T_c superconducting oxides, tunnelling spectroscopic studies have been carried out to determine the energy gap parameter Δ as a function of temperature; another motivation is to find a key to elucidate the mechanism of high T_c superconductivity from the tunnelling current–bias characteristics.

In various superconducting oxides larger values of Δ than are predicted by BCS have been found [1–5] for which no satisfactory explanation has been given. Values of $\Delta(T \ll T_c)$ determined by tunnelling spectroscopic techniques have shown a wide scatter. For instance, values varying from 6 to 11 have been assigned to $Bi_2Sr_2CaCu_2O_{8-\delta}$ [2–4].

Samples used in previous work were probably inhomogeneous. This and short coherence lengths contribute to the lack of a unified picture. We performed the tunnelling measurement on an oxide superconductor $Bi_2Sr_2CaCu_2O_{8-\delta}$ to study the local electronic states, using a low temperature scanning tunnelling microscope (STM).

This tunnelling method, which avoids direct contact between the sample and a counter-electrode (tip), enables us to obtain the local electronic density of states on an atomic scale at the sample surface without changing the latter's physical properties.

The tunnelling current I is given as a function of the bias voltage V between the tip and the sample by

$$I(V) \propto \int_{-\infty}^{+\infty} N_t(E)N_s(E+eV)(f(E)-f(E+eV))\,dE \tag{1}$$

where N_t and N_s are the electronic density of states for the tip metal and for the sample, respectively. If N_t is constant,

$$dI/dV \propto N_s(eV). \tag{2}$$

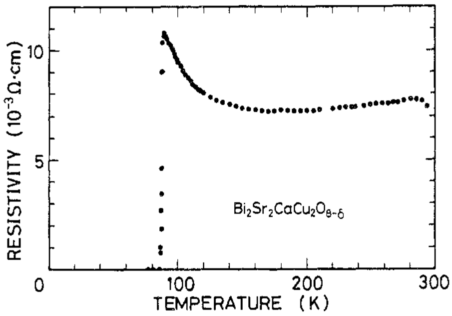

Figure 1. Temperature dependence of the resistivity of a single crystal of $Bi_2Sr_2CaCu_2O_{8-\delta}$.

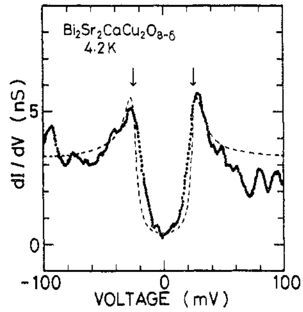

Figure 2. A typical (dI/dV)–V characteristic at 4.2 K. The broken curve shows a fit of the data to the broadened BCS density of states described by equation (3), with fitting parameters $\Delta = 25$ meV and $\Gamma = 3.5$ meV. In the region $|V| \leq \Delta$, the density of states is much enhanced compared with that of equation (3).

Therefore, from the tunnelling I–V characteristic one can study the local density of states of the sample material at the surface with the use of an STM. This technique is called scanning tunnelling spectroscopy (STS).

A single crystal of $Bi_2Sr_2CaCu_2O_{8-\delta}$ was used in this work because it sustains a more stable tunnelling current than La–Ba–Cu–O or Y–Ba–Cu–O. Tunnelling I–V characteristics were obtained and analysed in the temperature range 4.2 K to room temperature at different positions of the sample surface by scanning the tip.

Details of our low temperature STM apparatus are given elsewhere [6]. A scanning tip was made from Pt–Ir, the density of states of which is known to vary slowly near the Fermi level. A thin wire of this was mechanically sharpened and then electrochemically etched. The tip was attached to the top of a tube type actuator. Usually the movement of piezoelectric actuators is degraded at low temperatures. Nevertheless, we could control the distance between the sample and the tip, and scan the sample surface to within a range of 60 nm with our electronic devices.

In order to obtain a clean surface, the sample was cleaved along the Bi–O plane with adhesive tape just before being mounted in a STM unit. A metallic cell which contained the sample and the tip was filled with helium at low pressure acting as an exchange gas to achieve thermal equilibrium and control the temperature smoothly. The cell was immersed in liquid helium. In order to minimize the external vibration the helium dewar was mounted on a vibration isolator, which was equipped with air suspension. The helium dewar was immersed in liquid nitrogen in another outer dewar on the floor.

To investigate the local density of states, the tunnelling bias voltage, in the form of a 15–30 s triangular wave, was swept by a function generator, and the tunnelling current was measured. During the voltage sweep, the distance between the sample and the tip was kept constant by turning off the electronic feedback circuit, which controlled the distance between the tip and the sample. Both voltage and current signals were recorded by a digital memory scope, and transferred to the memory of a computer. Differential tunnelling conductance was calculated numerically from the I–V curve as a function of the bias voltage.

Figure 1 shows the resistivity of the sample measured after the STM study. The resistivity decreases slightly with decreasing temperature above 150 K, and increases with decreasing temperature in the range from 150 K to 90 K. Below 89 K the resistivity decreases rapidly. We obtained the superconducting critical temperature $T_c = 87$ K as the midpoint of the resistive transition with a transition width of 3 K.

A typical (dI/dV)–V curve at 4.2 K is shown in figure 2. It is essentially symmetric at the Fermi level ($V = 0$) and qualitatively similar to the BCS density of states. No noticeable structure, which would correspond to some special excitation, was observed below 200 mV. In order to determine the gap parameter Δ precisely, we tried to fit it to the broadened BCS density of states [7], which takes into account the quasi-particle lifetime broadening as

$$N_S(E) = \mathrm{Re}\,(E - i\Gamma)/[(E - i\Gamma)^2 - \Delta^2]^{1/2}\, N_N(E) \tag{3}$$

where N_S and N_N are the density of states for superconducting and normal states, respectively, and Γ is the quasi-particle lifetime broadening parameter. We consider that the effect of thermal smearing is also included in Γ, although in principle the thermal smearing should be treated by the distribution function in equation (1). In figure 2 the broken curve is the fit of our data to equation (3) with fitting parameters $\Delta = 25$ meV and $\Gamma = 3.5$ meV. At present, equation (3) should be regarded as a fitting function to determine Δ because we have not found an explicit interpretation of Γ.

As we discuss below, Δ shows a spatial variation with scanning along the sample surface. We obtained $\Delta(4.2\ \mathrm{K}) = 26$ meV as the most observable value. For $T_c = 87$ K we obtain $2\Delta/k_BT_c = 7$. It should be emphasized that the above value was obtained without greatly disturbing the sample surface (compared with point-contact techniques which do) because our measurement was performed without direct contact between the tip and the sample. Our present value of 7 is in agreement with the reported values of $2\Delta/k_BT_c$, which are in the range 6 to 11 for $Bi_2Sr_2CaCu_2O_{8-\delta}$ [2–4], and is still much larger than the BCS value (3.5) in the weak coupling limit. It is even larger than that of a strong coupled superconducting metal, e.g. Pb ($2\Delta/k_BT_c = 4.6$). A large value of $2\Delta/k_BT_c$ might suggest that $Bi_2Sr_2CaCu_2O_{8-\delta}$ is a strong coupling superconductor. No satisfactory explanation has been proposed for the large Δ, not only in $Bi_2Sr_2CaCu_2O_{8-\delta}$ but also in other oxide superconductors.

As shown in figure 2, the (dI/dV)–V curve deviates from the calculated BCS density of states with lifetime broadening (broken curve). In particular, in the region $|V| \leqslant \Delta$, the density of electronic states is larger than that given by equation (3). As Ebisawa *et al* [8] calculated, in anisotropic superconductors the density of states inside the gap is enhanced much more than in cases in which the gap is isotropic. It is probable that the I–V curve observed in our experiments is indicative of an anisotropy of the gap; the system may be a d-wave superconductor.

In order to profile the spatial variation of electronic states, we measured (dI/dV)–V characteristics at various positions of the sample surface by scanning the tip. The typical results are shown in figure 3. Labels A, B, C and D correspond to fixed positions at the sample surface. Points A, B and C are aligned in that order, and CD is normal to AC. The lengths of AB, BC and CD are about 30 nm. Both the (dI/dV)–V curve and the gap parameter Δ vary in space. We confirmed that the (dI/dV)–V curve at a position is reproduced repeatedly even when scanning from different positions. The tip did not touch the sample directly and so the variation of Δ is not due to damage inflicted on the sample by the tip. We tried to map the spatial variation of the tunnelling conductance by maintaining a voltage at the gap edge. We failed to establish whether or not the spatial variation of Δ is periodic, because the variation of the tunnelling conductance was very

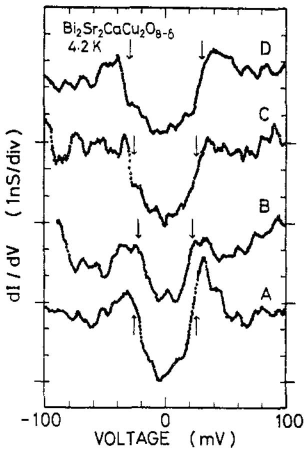

Figure 3. Spatial variation of the (dI/dV)–V characteristic at 4.2 K. Labels A, B, C and D correspond to the fixed positions at the sample surface. A, B and C are aligned in the order, and CD is normal to AC. The lengths of AB, BC and CD are ~30 nm. Arrows indicate the width of 2Δ. Δ = 26, 23, 26 and 30 meV for A, B, C and D, respectively.

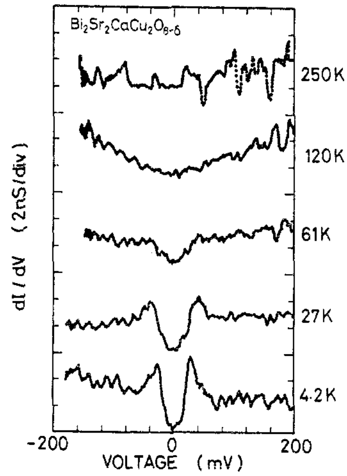

Figure 4. (dI/dV)–V characteristics at various temperatures. Below T_c thermal smearing of the gap structure is observed with increasing temperature. Even above T_c the conductance curve is not flat.

small. Nevertheless, we can conclude that Δ varies from 22 meV to 30 meV with changing position at the sample surface. The characteristic length of this variance Δ is of the order of 10 nm.

Vieira *et al* [1] found, using an STM, that the superconducting gap varies with the position at the sample surface in $Bi_4Ca_3Sr_3Cu_4O_{1.6+\delta}$. Their results are qualitatively consistent with ours in that Δ varies over a short length scale. It is noteworthy that the same conclusion is reached for different materials. The short range variation (about 10 nm) of the gap parameter is related to the short coherence length, of the order of several nanometers, and inhomogeneity of these materials. That explains why published values of Δ show a large scatter [2–4].

Figure 4 shows (dI/dV)–V characteristics at various temperatures. At low temperatures, the superconducting energy gap is clearly observed. As the temperature rises, the structure of the energy gap becomes smeared and disappears at about T_c.

The temperature dependence of Δ, which is obtained from fitting the (dI/dV)–V curve to equation (3), is shown in figure 5. In this figure all data are plotted irrespective of the tip position. When the temperature is varied, the tip position at the sample surface is changed by the thermal expansion of the actuator. The large scatter in figure 5 is a result of the position dependent Δ value as discussed above. The solid curve is the BCS prediction with $\Delta(4.2\ K) = 26$ meV and $T_c = 87$ K. At low temperatures the gap parameter is almost constant, and tends to decrease with increasing temperature. At T_c Δ becomes zero. As found from the figure, the temperature dependence of Δ is qualitatively consistent with the BCS theory.

As shown in figure 4, the (dI/dV)–V curve is not flat even above T_c, but the differential conductance is likely to vary linearly with voltage. The conductance curve becomes almost flat above about 200 K. Such a linear conductance has been observed

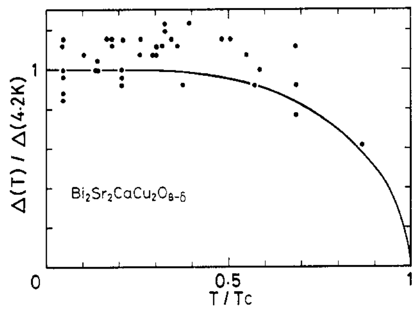

Figure 5. The normalized gap parameter $\Delta(T)/\Delta(4.2\ \mathrm{K})$ against the reduced temperature T/T_c, where $\Delta(4.2\ \mathrm{K}) = 26$ meV and $T_c = 87$ K. The solid curve shows the BCS prediction.

in other oxide superconductors Bi–Sr–Ca–Cu–O [2, 3] and Nd–Ce–Cu–O [5]. It should be noted that the nearly linear conductance is observed in non-contact tunelling (vacuum gap). Verma *et al* [9] proposed that the system is a marginal Fermi liquid, which shows the bias dependent conductance. They did not explain the temperature variation of the conductance curve, however. Kirtley *et al* [10] pointed out that the linear conductance in their $La_{2-x}Sr_xCuO_4$–In junction is due to inelastic electron tunnelling, and not to the density of states structure. In our experiements, the tip and the sample are separated by a vacuum gap (helium gas at low pressure); it is therefore difficult to predict the inelastic electron tunnelling. A satisfactory explanation is sought.

In summary, in a single crystal of $Bi_2Sr_2CaCu_2O_{8-\delta}$, we found the spatial variation of Δ over a short range, 10 nm, using a STM. This variation is attributed to both the short coherence length and inhomogeneity of this material. We obtained $\Delta(4.2\ \mathrm{K}) = 26$ meV and correspondingly $2\Delta/k_BT_c = 7$, which is much larger than the BCS value. The shape of the conductance curve suggests an anisotropy of the energy gap. The observed temperature dependence of the gap parameter is consistent with BCS. Voltage dependent conductance is observed even above T_c.

We would like to thank Professor T Sambongi for valuable discussions and critical readings of our manuscript. We are also indebted to Dr T Okada and Dr T Takase of Olympus Optical Co Ltd for their useful advice on the STM.

References

[1] Vieira S, Ramos M A, Vallet-Regi M and Gonzalez-Calbet J M 1988 *Phys. Rev.* B **38** 9295–8
[2] Ekino T and Akimitsu J 1989 *Phys. Rev.* B **40** 6902–11
[3] Ikuta H, Maeda A, Uchinokura K and Tanaka S 1988 *Japan. J. Appl. Phys.* **27** L1038–40
[4] Miyakawa N, Shimada D, Kido T and Tsuda N 1990 *J. Phys. Soc. Japan.* **59** 2473–82
[5] Ekino T and Akimitsu J 1989 *Phys. Rev.* B **40** 7364–7
[6] Nomura K and Ichimura K 1989 *Solid State Commun.* **71** 149–52; 1990 *J. Vac. Sci. Technol.* A **8** 504–7
[7] Dynes R C, Narayanamurti V and Garno J P 1978 *Phys. Rev. Lett.* **41** 1509–12
[8] Ebisawa H, Isawa Y and Maekawa S 1987 *Japan. J. Appl. Phys.* **26** L992–4
[9] Verma C M, Littlewood P B, Schmitt-Rink, Abrahams E and Ruchenstein A E 1989 *Phys. Rev. Lett.* **63** 1996–9
[10] Kirtley J R and Scalapino D J 1990 *Phys. Rev. Lett.* **65** 798–800