Anisotropic superconducting gap of Bi2Sr2CaCu2O8 : tunneling spectroscopy with STM

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Anisotropic superconducting gap of $Bi_2Sr_2CaCu_2O_8$: tunneling spectroscopy with STM

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The tunneling conductance was measured in the superconducting phase of $Bi_2Sr_2CaCu_20_8$ with use of the STM and the temperature dependence of magnetic field penetration depth was also investigated by the magnetization measurement. The obtained differential conductance is reduced to almost zero and flat near zero bias voltage indicating the finite gap on the whole Fermi surface, while a considerable gap anisotropy is found. The total conductance curve was explained by the anisotropic gap ranging from 10 meV to 30 meV. The temperature dependence of penetration depth is of the thermal activation type with the activation energy of 14 meV. These results indicate that the superconductivity in cuprate high T_C superconductor is given by the attractive interaction between electrons of the predominant s-wave symmetry mixed with the d-wave.

1. INTRODUCTION

In the past several years, the superconducting transition temperature T_C has been raised higher and higher in successively found cuprate materials. The origin of high T_C superconductivity has been attracting much interests from the discovery of cuprate material. A lot of experimental results have been accumulated and a variety of mechanisms have been proposed [1]. It is plausible from the NMR Knight shift behavior [2] and other experiments that the spin-singlet electron pair is formed in the superconducting phase. Accordingly it is a key for understanding of the mechanism of superconductivity to clarify the symmetry of pair wave function. The s-wave and d-wave are allowed for the pair symmetry.

It is accepted that the metallic conduction is born by electrons (holes) confined within the Cu-O layer in cuprate high T_C superconductor. It is also believed that the electron correlation is strong in the Cu-O layer. Therefore, it is an interesting problem which mechanism can overcome such a strong correlation. In the heavy fermion system, where the correlation is very strong, the pairing with the d-wave symmetry has been proposed from several kinds of experiments. In cuprate oxides as well, the NMR relaxation rate with gapless nature was reported [3]; the absence of coherence peak and the power law behavior in the low temperature. On the other hand, the temperature dependence of magnetic field penetration depth λ was described [4] rather by the BCS curve with a finite gap. The situation looks controversial.

The tunneling spectroscopic measurement is the most direct method for determination of the gap structure. However, existing results are different from experiment to experiment. In some cases, the tunneling conductance shows an extraordinary V-shape and don't supply fully reliable data. In this article we report the reliable tunneling result obtained in the electron tunneling spectroscopic measurement on single crystal of $Bi_2Sr_2CaCu_20_8$ with use of Scanning Tunneling Microscope (STM). We also describe the result of magnetic field penetration depth obtained at the same time and discuss the pair symmetry.

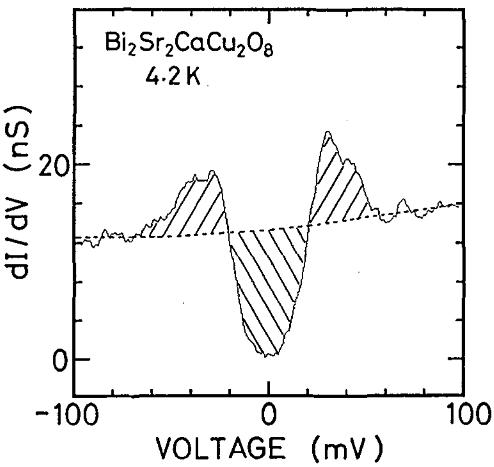
2. EXPERIMENTAL

Single crystals of $Bi_2Sr_2CaCu_2O_8$ were grown by the floating-zone method. The superconducting transition temperature T_C was determined from the midpoint of resistive transition as 87 K. In the STM measurement, the lateral surface perpendicular to the cleaved Bi-O surface was investigated at 4.2 K. The differential tunneling conductance was directly measured as a function of the applied voltage with use of a lock-in amplifier. The distance of tunneling tip from sample surface was maintained to be constant for the period of voltage sweep of typically 10 sec. The tunneling conductance was measured for several tip positions on the sample surface with varying the tip distance from the surface.

The magnetization measurement was carried out by the AC inductance method. Thin plate samples with a typical dimension of 1x2x0.2 mm^3 were investigated. In the lowest temperature of 4.2 K, nearly full Meissner fraction was confirmed. The temperature dependence of magnetic field penetration depth was obtained from the reduction of diamagnetic susceptibility, assuming that the field penetration is dominant along the perpendicular direction to thin plate.

3. RESULTS AND DISCUSSION

As we reported in the previous article [5], the tunneling conductance measured at the cleaved sample surface with the STM method varies its shape with changing the tip distance from the sample surface and gives the electronic density of states no more correctly. This behavior was attributed to the crystal structure consisting of the metallic Cu-O layer sandwiched by other non-metallic layers. Accordingly, it was expected that we can measure correctly the electronic density of states at the lateral surface, where the Cu-O layer appears on the surface directly. We obtained essentially the same conductance curve irrespective of the tip distance at every measured point on the lateral surface. Typical differential conductance curve is shown in Fig. 1. It shows a sharp drop near zero bias voltage associated with the superconducting gap structure. The enhancement at gap edges is also clear. For higher bias voltage, the differential conductance does not show the V-shape but is almost constant against the voltage. Total area of enhanced regions is equal to that of removed gap region, if we assume the normal conductance as a smooth curve shown as the broken line in Fig. 1. This assures that the state number is conserved between the normal and superconducting phases. These results strongly support that the observed tunneling conductance represents the electronic density of states in the superconducting phase correctly.



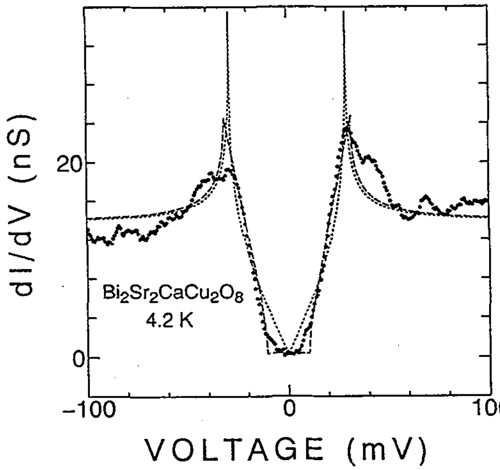


Fig. 1 Typical tunneling differential conductance observed at lateral surface at 4.2 K.

Fig. 2 Fitting of the conductance curve to the calculation for two kinds of anisotropic gap; dotted and broken lines represent the model for pure d-symmetry and that described by eq. (2), respectively.

Because the electron tunneling occurs within the very limited region at most a few atomic distances in the STM method, the wave number of tunneling electron is not conserved in each tunneling process. Accordingly we can measure only the total sum over the wave number space. The flat and nearly zero conductance region indicates that the superconducting gap is finite on the whole Fermi surface and suggests that the pair symmetry is predominantly of the s–wave. However the observed total conductance curve cannot be explained by the BCS density of states, even if we consider the life time broadening effect. We need to introduce some kind of anisotropy.

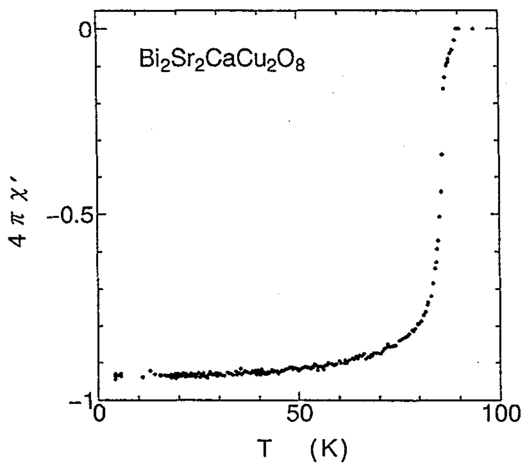
We investigate two anisotropic gap models in the following. For simplicity, we assume that the electronic band dispersion is isotropic and the gap amplitude is depending only on the direction in **k**–space. The essential structure of density of states, which appears near zero bias, is unchange for such a simplification. First model is the gap with pure d–wave symmetry described as,

$$\Delta=\Delta_0\cos 2\phi \ , \tag{1}$$

where Δ_0 is the maximum gap and ϕ is the azimuth in **k**–space. This gap has line nodes on the Fermi surface. We show the calculated density of states for this model with Δ_0=29 meV by the dotted line in Fig. 2. As seen in Fig. 2, the essential gap structure with line nodes appears in a linear density of states with energy at low energy region. The observed conductance curve is very different from this model calculation and it is not explained by the d–symmetry alone. Second model is described in the form of gap density function as,

$$D(\Delta)=\begin{cases} 1/(\Delta_{max}-\Delta_{min}) & \Delta_{min}\le\Delta\le\Delta_{max} \\ 0 & \Delta<\Delta_{min},\ \Delta>\Delta_{max} \ , \end{cases} \tag{2}$$

where Δ_{min} and Δ_{max} are the maximum and minimum value of gap, respectively. In this model, the gap value varies from Δ_{min} to Δ_{max} depending on the direction in **k**–space. The broken line in Fig. 2 shows the calculated curve for this anisotropic gap with Δ_{min}=10 meV and Δ_{max}=30 meV. The flat conductance near zero bias is reproduced satisfactorily. It is understood that the gap is predominantly of the s–wave symmetry, while it has a considerable anisotropy.



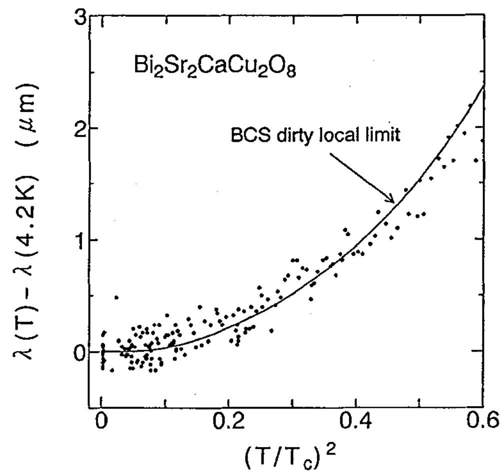


Fig. 3 Temperature dependence of the diamagnetic susceptibility.

Fig. 4 Magnetic field penetration depth against T^2. Solid line represents the BCS dirty local limit curve.

We investigated the temperature dependence of magnetic field penetration depth λ which is sensitive to the gap structure through the low energy excitation. In Fig. 3, we show the temperature dependence of the averaged susceptibility measured for thin plate sample. In the lowest temperature, almost perfect diamagnetism is observed and it indicates that the superconductivity occurs in bulk. In Fig. 4, is shown the temperature dependence of λ calculated from the averaged susceptibility by assuming that the field penetration is dominant along the perpendicular direction to the thin plate. As clear from Fig. 4, there is no power law behavior as expected from the gapless structure in the low temperature region. The temperature dependence is well fitted by the BCS dirty local limit curve with Δ=14 meV denoted as the solid line in Fig. 4. It is clear that the gap is finite on the whole Fermi surface. The estimated gap value is consistent with the minimum gap Δ_{min}=10 meV obtained from the present tunneling conductance and supports the tunneling result.

Our present result looks inconsistent with the gapless nature proposed by NMR measurement [3]. However, the absence of coherence peak in NMR relaxation rate does not necessarily exclude the s-wave, because an additional mechanism may cover the coherence peak even in the case of the s-wave symmetry. Non-thermal activation type temperature dependence may also be coming from another mechanism which is more effective in the low temperature region than that due to thermally exited electrons across the superconducting gap. Recently the gap anisotropy was observed by the angle-resolved photo emission experiment [6]. Although the resolution of photo emission measurement is not enough to determine the small gap value, their result is essentially consistent with the present tunneling result.

It is believed that the on-site Coulomb interaction in the Cu-O layer is fairly large in cuprate oxide. Therefore, it is suspected that the on-site attractive force can not become large to mediate the electron pairing. However, our results clearly show that the attractive interaction in cuprate superconductor has large isotropic component. In a naive picture, the isotropic interaction is the on-site one. It is open how the on-site attractive force overcomes the strong correlation. On the other hand, our observed gap has a considerable anisotropy. It is understood that the attractive interaction is predominantly s-wave mixed with d-wave.

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