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STM Study of Anisotropic Superconducting Gap of Bi-Based Oxides

Koichi Ichimura[a], Kazushige Nomura[a] and Shunji Takekawa[b]

[a]Department of Physics, Hokkaido University, Sapporo 060, Japan
[b]National Institute for Research in Inorganic Materials, Tsukuba, Ibaraki 305, Japan

The electron tunneling study was done on both $Bi_2Sr_2CaCu_2O_8$ and $Bi_2Sr_2CaCu_{2-x}Ni_xO_8$ with use of STM and temperature dependence of the magnetic field penetration depth was also investigated. The tunneling conductance obtained at the lateral surface of single crystal of $Bi_2Sr_2CaCu_2O_8$ indicates the finite gap on the whole Fermi surface, while the considerable anisotropy is found. The temperature dependence of the penetration depth is of the thermal activation type. These results indicate symmetry of the pair wave function is the predominant s-wave mixed with the d-wave. For $Bi_2Sr_2CaCu_{2-x}Ni_xO_8$, any clear energy gap structure was not found in the tunneling conductance at the cleaved surface. The penetration depth exhibits the T^2 temperature dependence.

1. INTRODUCTION

A lot of studies have been done in order to clarify the mechanism of high-T_c superconductivity since its discovery. From these experiments, it is established that spin-singlet electron pairs are formed in this superconductivity. At a recent stage, attentions are paid to the symmetry of the pair wave function which is directly connected with the origin of the attractive force responsible for the superconductivity.

The electron tunneling spectroscopy is the most useful method in investigation of the pair symmetry. However, reported tunneling results are not reliable enough to discuss the pair symmetry. Here, we present the reliable tunneling spectroscopic result carried out on $Bi_2Sr_2CaCu_2O_8$ with use of STM [1] and discuss the pair symmetry. Preliminary result for $Bi_2Sr_2CaCu_{2-x}Ni_xO_8$ is also presented.

2. RESULTS AND DISCUSSION

Single crystals of $Bi_2Sr_2CaCu_2O_8$ were grown by the floating-zone method. The superconducting transition temperature was determined as 87 K from the mid-point of resistive transition. Single crystals of $Bi_2Sr_2CaCu_{2-x}Ni_xO_8$ with T_c=75 K grown by the flux method were also used. Spectroscopic measurements were carried out with the STM apparatus at 4.2 K. For $Bi_2Sr_2CaCu_2O_8$, the lateral surface of a single crystal perpendicular to the cleaved Bi-O surface was investigated. The magnetic field penetration depth was obtained by the AC magnetization measurement.

The tunneling conductance curve at the cleaved surface exhibits the dependence on the tip distance from the sample surface [2] and is no more proportional to the electronic density of states. On the other hand, at the lateral surface where Cu-O plane appears on the surface, the conductance curve is independent of the tip distance. Figure 1 shows a typical differential conductance obtained at the lateral surface at 4.2 K. Essentially same curves are obtained irrespective of the tip position on the surface. These curves are reproduced when the tip distance is varied. The sharp reduction of the conductance associated with the superconducting gap and the enhancement at the gap edge are clearly found. If we assume the normal conductance by a smooth interpolation, the area of enhanced region is equal to that of reduced one. This assures the conservation of electronic state number between the normal and superconducting state. Therefore, the conductance at the lateral surface represents the electronic density of states correctly.

In the STM method, the tunneling conductance is given by the total sum over every wave number, because of the locality of the region through which the tunneling occurs. The obtained conductance is reduced to almost zero and flat near zero bias voltage and it indicates that the gap is finite on the whole Fermi surface. This suggests the s-wave symmetry for the pair wave function. However, the obtained curve is not well fitted by the BCS density of states, even if the life time broadening effect is taken into account. Finite conductance inside the gap

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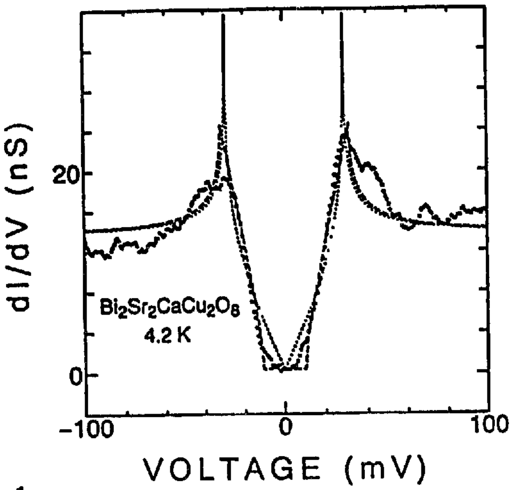

Fig. 1.
Tunneling conductance with model calculations.

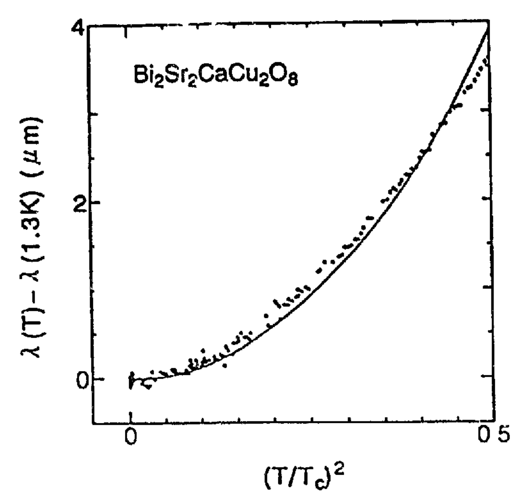

Fig. 2.
Temperature dependence of the penetration depth.

edge indicates a considerable gap anisotropy. The dotted line in Fig. 1 represents the calculated density of states for a d-wave with line nodes of the gap. It is obvious that the obtained curve can not be explained by the pure d-wave model. The broken line in Fig. 1 represents the density of states calculated for another anisotropic model, in which the gap Δ varies from 10 to 30 meV depending on the direction in k-space. The obtained conductance in the mid-gap region is well fitted by the model. Such a gap anisotropy is consistent with the angle-resolved photoemission result by Shen *et al.* [3], although they insisted the gapless We deduce that they obtained zero gap because of the relatively poor resolution of the photoemission spectroscopy.

In order to confirm the result of the tunneling spectroscopy, we also measured the magnetic field penetration depth. The temperature dependence of in-plane penetration depth λ_{ab} is of the thermal activation type suggesting the finite gap, as shown in Fig. 2. Additionally, we found that this behavior is well fitted by the temperature dependence, represented by the solid line in Fig. 2, calculated from the density of states used in the fitting of the tunneling conductance (the broken line in Fig. 1). It should be emphasized that the temperature dependence of λ_{ab} is consistent with the result of the STM spectroscopy. Naively, the finite gap indicates a large s-wave component in the attractive interaction, while a considerable anisotropy may due to the contribution of a d-wave. It is deduced that the attractive interaction with the mixed symmetry of s- and d-wave plays an important role in the high T_c superconductivity.

The cleaved surface of single crystal of $Bi_2Sr_2CaCu_{2-x}Ni_xO_8$ was also investigated. The shape of the conductance curve varies depending on the tip distance as in the case of $Bi_2Sr_2CaCu_2O_8$ [2]. However, any sharp reduction associated with the superconducting gap was not found, even if the tip position on the surface is varied. The randomness in Cu-O layer introduced by Ni-doping occurs the depairing and the life time broadening of the electronic level. Consequently, the superconducting gap structure is somewhat smeared. However, it is not excluded that the absence of gap structure is due to low Meissner fraction (10-20%) in this sample. Further investigation is needed. The temperature dependence of λ_{ab} exhibits the T^2 dependence. We point out the possibility that the T^2 dependence is caused by the finite density of states inside the gap induced by impurity doping.

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