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Tunnel Junctions Using Single Crystal Films of $YBa_2Cu_3O_{7-x}$ Superconductor

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Normal metal/insulator/superconductor tunnel junctions were fabricated using thin films of $YBa_2Cu_3O_{7-x}$ or $ErBa_2Cu_3O_{7-x}$ epitaxially grown on single crystals of $SrTiO_3$ by activated reactive evaporation method. The junctions using single crystal $YBa_2Cu_3O_{7-x}$(001) films on $SrTiO_3$(100) show single set of the peaks in dI/dV-V curve. For the tunneling perpendicular to the Cu-O planes, Δ (~4K)=10~12meV and $2\Delta/kT_c$=2.8~3.2 were obtained. Quasiparticle density of states $N_s(E)$ deconvoluted from the dI/dV-V curve indicates increase of the gap states with increasing temperature.

Introduction

The tunnel measurements of the Cu based oxide superconductors are expected to reveal the nature of high transition temperature superconductivity. Here we report the first measurements of planer quasiparticle tunnel junctions using single crystal thin film of (001)$YBa_2Cu_3O_{7-x}$(YBCO) with good quality in the surface, epitaxially grown on $SrTiO_3$(100). We also represent the resuls of junctions using (110)YBCO on $SrTiO_3$(110).

Recently we succeeded to prepare a single crystal YBCO on single crystal $SrTiO_3$ substrate by the activated reactive evaporation technique[1]. The low temperature process of the method (530~700°C) enables us to fabricate films with smooth surface and allows us to build tunnel junctions on it. Deconvoluted quasiparticle density of states $N_s(E)$ seen in the direction perpendicular to the Cu-O planes gives us peculiar aspects.

Experimental Details

The YBCO films with 1000Å thickness were prepared by coevaporation from individually controlled metal sources and by direct reaction with oxygen at the surface of the substrate. The oxygen incorporation during the growth of the film is significantly important for the crystal formation of YBCO. We made relatively high-pressure oxygen environment near the substrate (10^{-2}Torr). The process involves the introduction of oxygen plasma (10^{-5} Torr during the deposition) by RF oscillation between the evaporation sources and the substrate. In order to adjust the oxygen content in the as-deposited films, they were in-situ oxidized below the growth temperatures by introducing oxygen gas at the pressure of about 200 Torr into the evaporation chamber.

As an insulator, aluminum oxide (AlO_x) was evaporated on the YBCO film in the oxygen atmosphere of 5×10^{-4} Torr. We attempted to prepare several junctions with different thickness of the insulator and found that a 30 Å thick AlO_x did not act as a barrier, probably due to pin holes. Therefore, we used 60 Å AlO_x for the junctions studied. Besides, in order to avoide a leak current, the side edge of YBCO was covered by 500 Å AlO_x.

For a top normal metal electrode, a Pt

or Ag film with 1000 Å thickness was deposited. Since all the patterning processes were carried out through the metal masks (without any chemical etching or ion bombardment), the deterioration of the film quality was expected to be minimized.

To examine the surface quality of the YBCO on $SrTiO_3(100)$ as a superconductor, we prepared the ultra-thin YBCO film with 100 Å thickness. We found that even such an ultra-thin film exhibits the superconducting transition at 82K[2]. Besides the direct contact between the YBCO and a metal shows no contact resistance. Therefore we believe the quasiparticle tunnel junction using the YBCO film reflect the bulk nature of the superconductor.

The current across the tunnel junction was measured using a constant voltage circuit and then the differential conductance was computed. In the measurements, the polarity of the applied voltage V is defined as that in the superconducting film against the normal metal.

Results and Discussion

The junctions using good quality single crystal YBCO films on $SrTiO_3(100)$ never show clear steps like that in the Bardeen-Cooper-Schrieffer(BCS) theory in the I-V curve, but show small peaks around 10meV in the dI/dV-V curve at $\sim$4K. The typical results at 4.6K for the junction where the single crystal YBCO film has transition temperature T_c=87K with transition width $\Delta Tc(10\text{-}90\%)=3.7K$ and resistivity $\rho=7\times10^{-5}\Omega cm$ at T_{conset} are seen in Fig.1. These data lead gap parameter $\Delta(4.6K)=10\pm2meV$ and the coupling constant $2\Delta/kT_c=2.8\pm0.3$ in the direction perpendicular to the Cu-O planes of YBCO. The values of the coupling constat for the YBCO which we have measured so far in the same manner are between 2.8 and 3.2 equal or less than the value of the weak coupilng limit of the BCS theory[3].

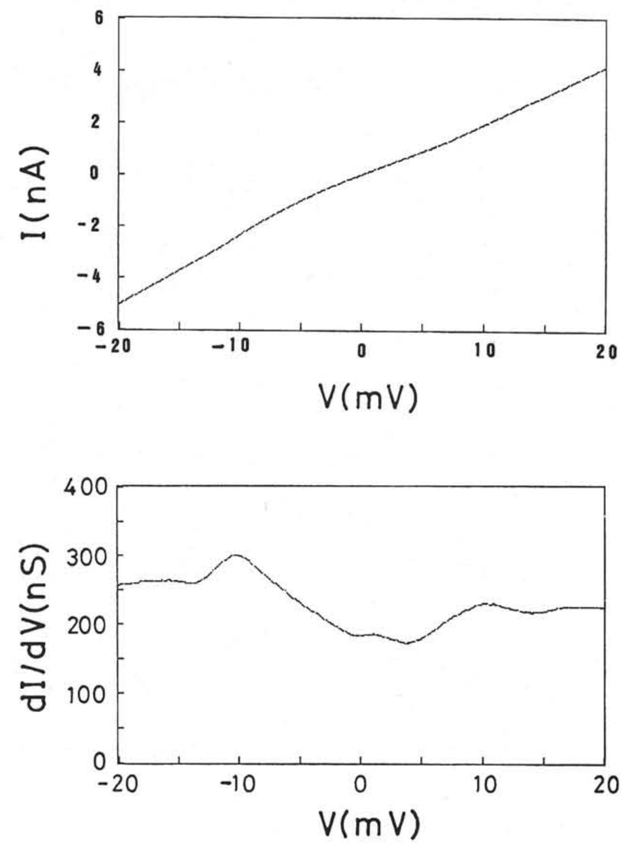

Fig.1 Tunnel current and the differential conductance as a function of applied voltage at 4.6K for the sample where $YBCO(001)/SrTiO_3(100)$ has T_c=87K with ΔT_c=4K.

The tunnel differential conductance between a normal metal and a superconductor with quasiparticle density of states $N_s(E)$ at a temperature T can be expressed by

$$\left(\frac{dI}{dV}\right)_T = \frac{G_n}{e}\int_{-\infty}^{\infty} N_s(E)\frac{\partial}{\partial V}f(E-eV,T)dE\ , \qquad (1)$$

where G_n and $f(E-eV,T)$ are the tunnel conductance in normal states and the Fermi function respectively. We assume in (1) that the density of states in the normal conductor and the tunnel matrix element are constant in the energy region of the experiments.

$N_s(E)$ at various temperatures were extracted directly from the data by deconvoluting (1). These are shown in Fig.2. The deconvoluted $N_s(E)$ is quite different from the BCS density of states. There are

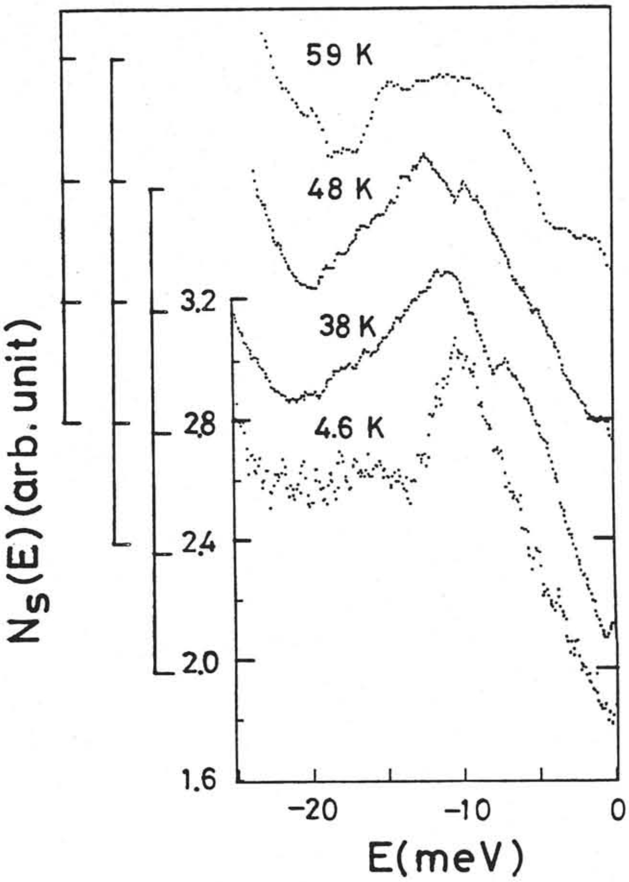

Fig.2 Deconvoluted quasiparticle density of states $N_s(E)$ of YBCO below the Fermi level at various temperatures observed in the direction perpendicular to the Cu-O planes.

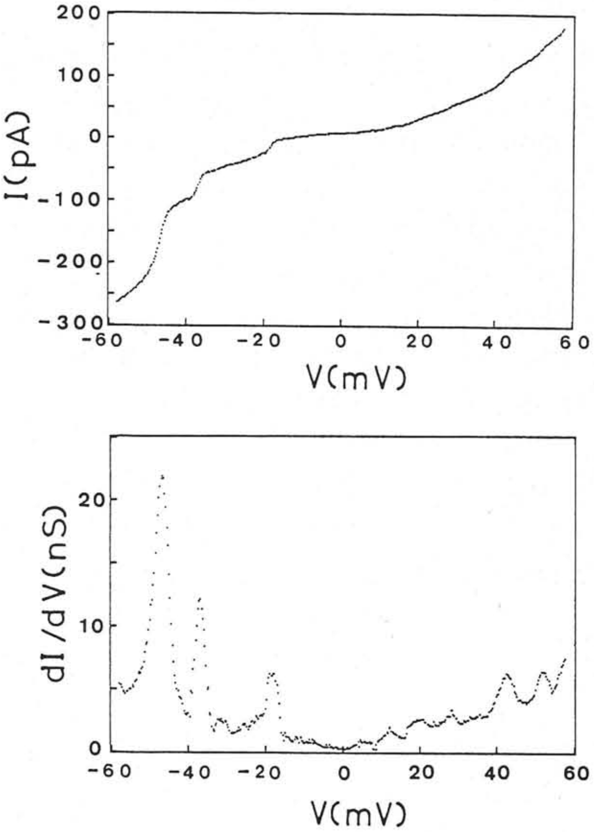

Fig.3 Tunnel current and the differential conductance as a function of applied voltage at 4.7K for the sample where EBCO(110)/$SrTiO_3$(110) has T_c=30K with T_c=40K.

many states at E_f. Here we cannot rule out the effect of leak currents on the $N_s(E)$. The peak structure at $|\Delta|$ becomes broad and the gapstates increase with increasing temperature. Such a feature may be qualitatively explained by the lifetime broadening model with temperature dependent broadening parameter which has been found in the superconductor $Pb_{0.9}Bi_{0.1}$ by Dynes et al[4]. However we note that too many excess states at E_f can not be explained quantitatively by the model. The temperature dependence of Δ which seems to be nearly constant 10meV at least below T/T_c=0.7 taking account of broadness of the value resembles to that in the BCS theory.

The junctions using the YBCO epitaxially grown on $SrTiO_3$(110) usually show regularly spaced multipeak structure in the dI/dV-V curve. Such a feature becomes clearer for the samples with the YBCO film posessing lower transition temperature Tc, wider transition width Tc and higher resistivity above Tc. The typical results at 4.7K are shown in Fig.3 for the junction using $ErBa_2Cu_3O_{7-x}$ on $SrTiO_3$(110) which has T_c=30K, ΔT_c(10-90%)=40K and ρ =7x10^{-3} Ωcm at T_{conset}. We observe the obvious steps in the I-V curve. This eventually produces very sharp and regularly spaced multipeaks in the dI/dV-V curve.

The step structure in the supercurrent

tunneling characteristics found by Coon and Fiske[5] is very similar to our observations. They found that the I-V curve of the Josephson junction in an applied field of a few gauss becomes steplike. These steps are associated with resonant electromagnetic modes of the junction, which act as an open-ended cavity. The lowest and the highest modes are set by the junction dimensions and by the gap parameter respectively.

Indeed, heterogeneous structures imagined from the low quality of the superconducting films suggest the Josephson junctions involved in the films.

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