Superconducting gap and pseudogap in $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ by short-pulse interlayer tunneling spectroscopy

Yoshiharu Yamada [a,1], Kenkichi Anagawa [a], Takenori Fujii [b,2] Takao Watanabe [b,3], Azusa Matsuda [b], Takasada Shibauchi [a], Minoru Suzuki [a]

[a] *Department of Electronic Science and Engineering, Kyoto University, Kyoto 606-8501, Japan*

[b] *NTT Basic Research Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan*

Abstract

We have measured the superconducting gap, pseudogap and their doping dependence of CuO_2 trilayer high-T_c superconductor $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ by short-pulse interlayer tunneling spectroscopy. While both gaps exhibit temperature dependence similar to those for the bilayer system, their doping dependence behaves differently from that of T_c, presenting an anomalous relationship between T_c and the gap magnitude. In the overdoped region, T_c remains almost unchanged from its optimum value irrespective of doping, while the gap decreases with increasing doping. This is suggestive of inequivalent hole doping in the inner and outer planes, which is thought to occur in trilayer systems.

Key words: interlayer tunneling spectroscopy; Bi-2223; superconducting gap; pseudogap; doping dependence

1. Introduction

Although extensive studies have been conducted on high-T_c superconductors (HTSC), there is still no general consensus about its origin. Among various physical properties, the quasiparticle density of states (DOS), and its temperature and doping dependence are the most essential clue in the quest for the mechanism. For the quasiparticle DOS observation, interlayer tunneling spectroscopy (ITS) is effective in that it provides a high energy resolution and is unobstructed from surface effects. Indeed, ITS studies have revealed that the temperature and magnetic field dependences of the superconducting gap (SG) and the pseudogap (PG) are significantly different, leading to an implication that both gaps are distinct in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) system. If such a gap structure is essential in HTSC, it is imperative to observe a similar gap structure in different series of HTSC. For this reason, we have applied the ITS measurements of the gap structure for the $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) CuO_2 trilayer system, whose TSFZ single crystals were recently grown successfully [1].

In Bi-2223, it was reported that T_c is pinned at the optimum value in the overdoped region [2]. With regard to this anomalous behavior of T_c, the relationship between T_c and SG, and its doping dependence particularly attract our interest in this Bi-2223 system.

2. Experimental

For the ITS experiments, we fabricated very small and thin mesas on a cleaved surface of Bi-2223 single crystals. The crystals were annealed in vacuum or in flowing oxygen to control the doping level. The mesa

[1] E-mail: y_yamada@suzuki.kuee.kyoto-u.ac.jp

[2] Present address: Department of Applied Physics, School of Science and Engineering, Waseda University, 3-4-1 Ookubo, Shinjyuku, Tokyo 169-0072, Japan

[3] Present address: NTT Photonics Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan

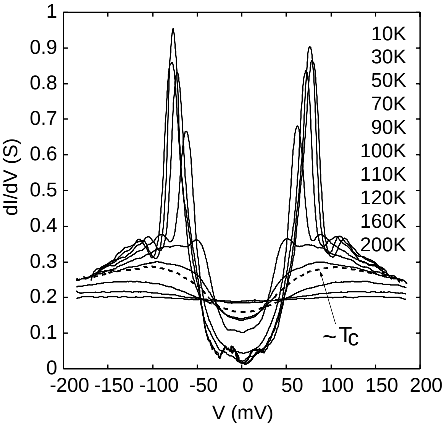

Fig. 1. $\mathrm{d}I/\mathrm{d}V - V$ curve at various temperatures for nearly optimum doped sample.

thickness was controlled by the ion milling time to have a typical value of 19 nm, which corresponds to approximately 10 intrinsic Josephson junctions. The mesa lateral size was approximately 10 μm$\times$10 μm. We adopted the three-terminal configuration at the expense of contact resistance, because the heat-flow channel through the mesa top electrode is most effective and essential to reduce the self-heating. Current-voltage characteristics were measured by the short-pulse method to reduce the self-heating further [3]. Current pulses used were 1 μs wide at a duty of 0.08 %.

3. Results and discussion

Figure 1 shows $\mathrm{d}I/\mathrm{d}V - V$ curves at various temperatures, T, for a nearly optimally-doped sample. We define the gap magnitude $2\Delta_{\mathrm{SG}}$ for SG and $2\Delta_{\mathrm{PG}}$ for PG as half the separation between the conductance peaks for $T < T_{\mathrm{c}}$ and $T > T_{\mathrm{c}}$, respectively. It is clearly seen that $2\Delta_{\mathrm{SG}}$ gradually decreases with increasing temperature and finally disappears at T_{c}. Above T_{c}, on the other hand, $2\Delta_{\mathrm{PG}}$ is almost T-independent. This contrasting difference in T-dependence between SG and PG suggests that they are different order parameters as in the case of the Bi-2212 system [3].

Figure 2 shows T_{c} and $2\Delta_{\mathrm{SG}}$ as a function of the c-axis resistivity at 300 K, ρ_c(300 K), for different doping levels. Values for $\rho_c(T)$ were calculated from the mesa resistance measured. T_{c} was determined from the resistive transition of $\rho_c(T)$. Since ρ_c for the Bi-2223 system decreases systematically with increasing doping, while T_{c} shows no doping dependence in the overdoped region [2], we use the value for ρ_c(300 K) as a measure of the doping level. Therefore, Fig. 2 implies the doping dependence of T_{c} and $2\Delta_{\mathrm{SG}}$ when we regard the abscissa as the inverse of the doped carrier

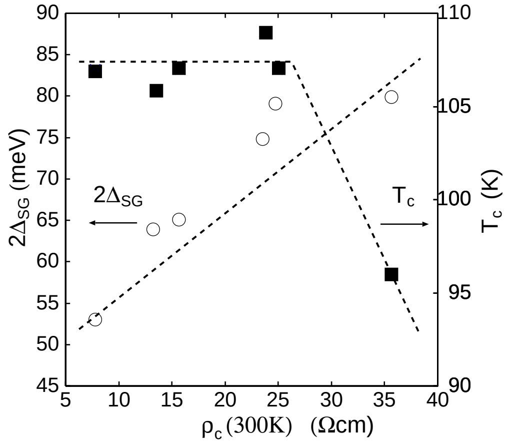

Fig. 2. T_{c} and $2\Delta_{\mathrm{SG}}$ at 10 K as a function of ρ_c at 300 K. Dashed lines are the guides for the eyes. ρ_c(300 K) is inversely proportional to doping. The optimum doping corresponds to ρ_c(300 K)=25$\sim$30 Ωcm approximately.

density. It is seen that $2\Delta_{\mathrm{SG}}$ decreases from 80 meV to 53 meV as ρ_c(300 K) decreases (with increasing doping). On the other hand, T_{c} remains unchanged at the optimum value of 107 K in the overdoped region. This is at variance with both the generic phase diagram of HTSC and the fundamental BCS relationship expected in the overdoped region between T_{c} and $2\Delta_{\mathrm{SG}}$.

The above mentioned anomalous relationship between T_{c} and $2\Delta_{\mathrm{SG}}$ is explained in terms of inequivalent doping, which is thought to occur in CuO_2 multilayered systems [2]. In line with this scenario, it occurs that excess carriers are doped mostly into the outer CuO_2 planes and the carrier density of the inner CuO_2 planes are almost fixed against doping. Then it follows through the tunnelng proximity effect that the gap magnitude decreases with increasing doping, which results from overdoped outer planes, and T_{c} to be observed remains fixed at the maximum value of the optimally doped inner planes.

In conclusion, we have measured SG and PG for Bi-2223 and their doping dependence by ITS. The measurements have revealed an anomalous relationship between T_{c} and $2\Delta_{\mathrm{SG}}$, in which T_{c} remains almost unchanged while $2\Delta_{\mathrm{SG}}$ decreases with increasing doping. This behavior is explained in terms of both inequivalent doping and the proximity effect between inner and outer CuO_2 planes.

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