Superconducting gap and pseudogap in Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ 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$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ 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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (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$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ (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: yamadam@suzuki.kuee.kyoto-u.ac.jp
2 Present address: Department of Applied Physics, School of Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-0072, Japan
3 Present address: NTT Photonics Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
3. Results and discussion

Figure 1 shows $dI/dV$ – $V$ curves at various temperatures, $T$, for a nearly optimally-doped sample. We define the gap magnitude $2\Delta_{SG}$ for SG and $2\Delta_{PG}$ for PG as half the separation between the conductance peaks for $T < T_c$ and $T > T_c$, respectively. It is clearly seen that $2\Delta_{SG}$ gradually decreases with increasing temperature and finally disappears at $T_c$. Above $T_c$, $2\Delta_{PG}$ 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 $2\Delta_{SG}$ as a function of the $c$-axis resistivity at 300 K, $\rho_c(300 \text{ K})$, 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 $\rho_c$ for the Bi-2223 system decreases systematically with increasing doping, $T_c$ shows no doping dependence in the overdoped region [2], we use the value for $\rho_c(300 \text{ K})$ as a measure of the doping level. Therefore, Fig. 2 implies the doping dependence of $T_c$ and $2\Delta_{SG}$ when we regard the abscissa as the inverse of the doped carrier density. It is seen that $2\Delta_{SG}$ decreases from 80 meV to 53 meV as $\rho_c(300 \text{ K})$ 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 invariance with both the generic phase diagram of HTSC and the fundamental BCS relationship expected in the overdoped region between $T_c$ and $2\Delta_{SG}$.

The above mentioned anomalous relationship between $T_c$ and $2\Delta_{SG}$ 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 tunneling 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 $2\Delta_{SG}$, in which $T_c$ remains almost unchanged while $2\Delta_{SG}$ 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.

This work was partially supported by the Mitsubishi Foundation.

References