Enhanced Superconducting Gaps in the Trilayer High-Temperature Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ Cuprate Superconductor

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We report the first observation of the multilayer band splitting in the optimally doped trilayer cuprate Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ (Bi2223) by angle-resolved photoemission spectroscopy. The observed energy bands and Fermi surfaces are originated from the outer and inner CuO$_2$ planes (OP and IP). The OP band is overdoped with a large d-wave gap around the node of $\Delta_0 \sim 43$ meV while the IP is underdoped with an even large gap of $\Delta_0 \sim 60$ meV. These energy gaps are much larger than those for the same doping level of the double-layer cuprates, which leads to the large $T_c$ in Bi2223. We propose possible origins of the large superconducting gaps for the OP and IP: (1) minimal influence of out-of-plane disorder and a proximity effect and (2) interlayer tunneling of Cooper pairs between the OP and IP.

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It has been well known that on of the most efficient ways to increase the critical temperature ($T_c$) of high-$T_c$ cuprate superconductors (HTSCs) is to increase the number of neighboring CuO$_2$ planes ($n$). $T_c$ of the optimally doped region ($T_{c,\text{max}}$) generally increases from single layer ($n = 1$), double layer ($n = 2$), to triple layer ($n = 3$) and then decreases for $n \geq 4$ [1]. In order to explain the $n$ dependence of $T_c$, several mechanisms have been proposed. According to the theory of tunneling mechanism of Cooper pairs between the CuO$_2$ planes, $T_{c,\text{max}}$ should increase with increasing $n$ [2]. Furthermore, if one takes into account the charge imbalance between the planes and the existence of competing order, $T_{c,\text{max}}$ takes a maximum at $n = 3$ [3], in agreement with the experiment. Meanwhile, $T_c$ tends to increase with next-nearest-neighbor Cu-Cu hopping parameter $t'$, which increases with the number of CuO$_2$ planes [4]. Also, $T_c$ increases with decreasing degree of out-of-plane disorder [5,6]. However, it has been unclear which parameter governs the $n$ dependence of $T_{c,\text{max}}$ because of the lack of detailed knowledge about the electronic structure of the multilayer cuprates.

So far, angle-resolved photoemission spectroscopy (ARPES) studies have been performed for multilayer cuprates such as double-layer Bi2212 [7–9] and four-layer Ba$_2$Ca$_3$Cu$_4$O$_8$F$_2$ (F0234) [10,11], and have revealed the splitting of band dispersions and Fermi surfaces (FSs). In Bi2212, hybridization between the two CuO$_2$ planes causes band splitting into the bonding and antibonding bands [7]. The ARPES study on F0234 has indicated band splitting due to the different hole concentrations of the outer and inner CuO$_2$ planes [10,11], where the maximum superconducting (SC) gap was $\sim 60$ meV, approximately twice as large as that of the smaller one. However, in the case of triple-layer Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+\delta}$ (Bi2223) which has the highest $T_{c,\text{max}}$ (= 110 K) among Bi-based HTSCs, band splitting and multiple FSs have not been identified in the previous ARPES studies [12–14]. To clarify the role of the multiple CuO$_2$ planes for the highest $T_c$, it is important to observe the multiband of triple-layer HTSCs and to compare the electronic structure with those of single- and double-layer cuprates.

In the present Letter, with aid of high-quality single crystals and bulk sensitivity in low-photon-energy ARPES, we have successfully observed the band splitting of Bi2223 and have revealed that the outer (OP) and inner CuO$_2$ plane (IP) have different doping levels and different gap magnitudes. Furthermore, the SC gaps for the OP and IP are very large compared to those for the same doping levels of Bi2212, which leads to the high $T_{c,\text{max}}$ in Bi2223. We shall discuss the origin of the large SC gaps for the OP and IP and the highest $T_c$ of triple-layer cuprates in relation to the multi-CuO$_2$ layers.

Single crystals of optimally doped Bi2223 ($T_c = 110$ K) were grown by the traveling solvent floating zone method [15]. ARPES experiments were carried out at BL 9A of the Hiroshima Synchrotron Radiation Center ($h\nu = 6.6–12.9$ eV, circularly polarized light), BL 5–4 of the Stanford Synchrotron Radiation Laboratory ($h\nu = 18.5$ eV, linear polarized light), BL 28A of the Photon Factory ($h\nu = 45$ eV), and the University of Tokyo (He I $\lambda h\nu = 21.218$ eV). The total energy resolution
curve's at OP and IP bands deduced from the momentum distribution for successfully resolved, and the intensity of OP is enhanced 11

20 meV/C6

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surfaces are observed corresponding to the outer CuO2 planes. Since there are three neighboring CuO2 planes, one would expect to observe three bands which come from two OP and one IP bands, as indicated by t-t'-t''-J model calculation [18].

The fact that we observed only two bands implies that the two OP bands, i.e., the bonding and antibonding OP bands, are nearly degenerate. In fact, the FWHM of the momentum distribution curve for the OP band at E_F, ~0.011 Å⁻¹, is significantly larger than that of the IP band ~0.0074 Å⁻¹, suggesting that two unresolved OP bands exist. The FWHM of the IP band is nearly the same as that of the bonding or antibonding band in Bi2212, 0.0065 Å⁻¹ [9], indicating its single-component nature. Even in the off-nodal region, splitting of the OP band has not been observed, possibly due to the small interlayer hopping [19]. The Fermi momentum (k_F) positions for the OP and IP have been determined by the minimum-gap locus in the SC state [20]. The k_F's were fitted by the tight-binding model, yielding the values of tight-binding parameters −t'/t ≈ 0.26 (OP) and −0.29 (IP), if the third-nearest-neighbor hopping parameter is assumed to be −t''/t = 0.5 [4]. The hole concentration for the OP and IP bands deduced from the FS areas are ~23% and ~7%, respectively. The average hole concentration is ~18% taking into account the number of CuO2 layers.

We show dispersions in the SC state for the OP and IP bands, respectively, from the nodal to off-nodal cuts in Figs. 2(a) and 2(b). The gap energies for both bands are very different, as in the case of P0234 (n = 4). The gap magnitudes for the OP and IP bands have been estimated from the peak position of the symmetrized energy distribution curve at each k_F fitted to the phenomenological model [21,22]. The momentum dependence of the gap magnitude for OP is almost simple d wave, Δ0[cos(ka) − cos(k, a)]/2 with Δ0 ~ 43 meV, as shown by a straight line in Fig. 2(c). On the other hand, the gap for the IP band deviates from the simple d wave around the antinode ~(π, 0). The gap size is characterized by two parameters Δ0 ~ 60 meV around the node and Δ* ~ 80 meV in the antinodal region, where Δ0 and Δ* are defined by the linear extrapolation of the gap magnitude to the antinode [1 cos(ka) − cos(k, a)]/2 = 1], as shown in Fig. 2(c). The deviation of the gap anisotropy from the simple d wave is known to be prominent in underdoped cuprates, which is called “two-gap behavior” [22–25]. These observed gap anisotropies are in accord with the doping levels of the OP and IP estimated from the FS areas. Judging from the present result on the gap of OP, Δ0 ~ 43 meV, one can conclude that the previous ARPES result Δ0 ~ 40 meV for Bi2223 reflected the OP band due to the employed photon energies of ~22 eV [12–14,26].

Δ0 and Δ* for La2–x,SrxCuO4 (LSCO, n = 1), Bi2212 (n = 2), and Bi2223 (n = 3) are plotted as functions of hole doping in Fig. 3. Hole concentrations for the OP and

FIG. 1 (color online). (a),(b) Intensity plots of ARPES spectra for Bi2223 at E = ±20 meV in momentum space. Two Fermi surfaces are observed corresponding to the outer CuO2 plane (OP) and inner CuO2 plane (IP). Superstructures due to the Bi-O layer modulation are indicated by SS. (c),(d) Band dispersions in the nodal direction corresponding to red arrows in (a) and (b), respectively. (e) Relative intensities of the OP and IP bands as functions of photon energy. For hν = 7.65 eV [(a),(c)], the OP band spectra are enhanced while for hν = 11.95 eV [(b),(d)], the IP band is enhanced.
the doping level of Bi2212. In spite of its heavily overdoping, the OP and IP are very large compared to those for the same LSCO and Bi2212. The interpo-
lated values of the next-nearest-neighbor hopping parameter $-t'/t$ which has correlation with $T_{c,\text{max}}$ [4], $\sim 0.26$ for OP, and $\sim 0.29$ for IP, is larger than those of the single-layer ($-t'/t \sim 0.15–0.2$) [27,28] and double-layer ($-t'/t \sim 0.24$) [29] cuprates; (2) out-of-plane disorder effect is small in IP because IP is protected from the out-of-plane disorder by the OP, and therefore, IP is ideally flat [5]; and (3) interlayer tunneling of Cooper pairs between OP and IP may enhance the SC order parameter [3].

In Fig. 4, we test the correlation between $T_{c,\text{max}}$, SC gap $\Delta_0$, $-t'/t$ at optimal doping ($x \sim 0.16$) [30], and $\Delta^*$ in the underdoped region ($x \sim 0.07$) [31] for the single-layer (Bi2201, LSCO), double-layer (Bi2212), and triple-layer (Bi2223) HTSCs. One can see a remarkable correlation between $\Delta_0$ and $T_{c,\text{max}}$, that is, $T_{c,\text{max}}$ is nearly proportional to $\Delta_0$. On the other hand, $T_{c,\text{max}}$ and $\Delta^*$ shows only weak correlation compared with $T_{c,\text{max}}$ versus $\Delta_0$, $-t'/t$ shows some correlation with $T_{c,\text{max}}$, but not so strong as $T_{c,\text{max}}$ versus $\Delta_0$. In this context, it is interesting to point out that $\Delta^*$ is weakly dependent on $-t'/t$, and therefore the large $\Delta^*$ of IP can be explained by its large $-t'/t$ value as shown in the inset of Fig. 4 [32]. Such a dependence of $\Delta^*$ on $-t'/t$ has been predicted by a $t$-$t'$-$J$ model calculation [34].

The out-of-plane disorder may enhance $\Delta^*$ [25,35], however, the large $\Delta^*$ of IP cannot be explained by this effect since IP is protected from the out-of-plane disorder.

In Bi2223, $\Delta_0$ for IP is very large possibly due to the protection from the out-of-plane disorder by the presence of OPs. $\Delta_0$ for OP is also larger than that in overdoped Bi2212 despite the influence of the out-of-plane disorder to the same extent as in the case of Bi2212. This unusually large $\Delta_0$ of IP can be explained by a proximity effect from IP with the very large $\Delta_0$ [36]. Such a proximity effect would in turn reduce the $\Delta_0$ of OP. The fact that the $\Delta_0$ of IP is nevertheless very large means that the “original” $\Delta_0$ of IP was even larger, or that the proximity effect did not reduce the $\Delta_0$ of IP. Finally, we consider the interlayer tunneling of Cooper pairs which enhances the SC order parameter and hence $T_c$ [3]. In the single-layer cuprates, the tunneling of interlayer Cooper pairs observed by opti-
[30] For $n = 3$, values interpolated between IP and OP have been used.
[31] We have plotted the $\Delta^*$ values for LSCO and Bi2212 at $x \sim 0.06$ in Fig. 3.
[32] As for the $-t'/t$ of Bi2212 in the inset of Fig. 4, we have plotted the extrapolated value at $x \sim 0.06$ from $-t'/t \sim 0.24$ at $x \sim 0.16$ (Ref. [29]) and $\sim 0.20$ at $x \sim 0.1$ (Ref. [33]).