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Superconducting gap of heavily underdoped copper oxide superconductor $(Bi,Pb)_2Sr_2(Ca,Y)Cu_2O_{8+\delta}$

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ABSTRACT

The heavily underdoped $(Bi,Pb)_2Sr_2(Ca,Y)Cu_2O_{8+\delta}$ single crystals were successfully grown by conventional floating zone technique with a very slow growth rate of 0.20 mm/h. The superconducting gap of prepared single crystals was investigated by means of laser induced ARPES measurement. We found that the superconducting gap was kept almost unchanged from optimally doped region, $T_c = 92$ K, to heavily underdoped region, $T_c \sim 12$ K. The result suggest that the pair-formation-energy in underdoped region is similar to that in optimally doped region, and the superconducting temperature is presumably suppressed by the pseudogap which increase with decreasing hole concentration.

1. Introduction

The collective excitation leading to the formation of Cooper pairs in copper oxide high T_c superconductors has not been identified yet even after the intensive researches in the last three decades. We consider that the investigation into the temperature, momentum, and carrier concentration dependences of the superconducting gap is one of the most important researches for revealing the mechanism of Cooper pair formation in high T_c superconductors because it is directly related with the superfluid density that represents the order-parameter of superconducting phase. We should also recognize that the pairing gap is observable only in the nodal region because the pseudogap, that prevents the Cooper pair formation, exists in antinodal region even in superconducting state [1].

Recently, we have determined the carrier concentration dependence of superconducting gap in $Bi_2Sr_{2-x}RE_xCuO_{6+\delta}$ (RE = La, Sm, and Nd) (Bi2201), which is characterized by the single CuO-plane in the unit structure, by means of ultra high energy-resolution laser induced angle resolved photoemission spectroscopy technique (laser-ARPES). As a result, we found that the *d*-wave symmetry of the superconducting gap around nodal region persists regardless of the carrier concentrations. Besides, the size of the superconducting gap shows the maximum value over a wide carrier concentration range of $0.16 < p < 0.26$ (holes/Cu) in the underdoped region. The critical temperature T_c decreases with decreasing carrier concentration from $p = 0.3$ holes/Cu. This tendency was caused mainly by the development of the pseudogap around antinodal region.

In this study we employed $(Bi,Pb)_2Sr_2(Ca,Y)CaCu_2O_{8+\delta}$ (Bi2212), in which doubly stacked CuO_2 planes exist in the unit structure, and possesses much higher $T_c^{max} \sim 92$ K than ~35 K of Bi2201. The superconducting gap observable around the nodal direction was investigated in detail and compared with the previously measured one of Bi2201.

2. Experimental procedure

The high quality single crystals of heavily underdoped and optimally doped $(Bi,Pb)_2Sr_2(Ca,Y)CuO_{8+\delta}$ (Bi2212) samples were successfully prepared by using the conventional floating zone (FZ) technique with a very slow growth rate of 0.20 mm/hour. The sizes of single crystals were typically lager than $\sim 3 \times 5 \times 0.1\ mm^3$ in dimension. A conventional X-ray diffraction (XRD) measurement was performed for single crystals and polycrystalline powders prepared from the crashed single crystal. Then, we confirmed that there is no impurity phase in the single crystals.

The carrier concentration of each sample was controlled by both the partial substitution of Y for Ca and the annealing under various conditions. The critical temperature was determined from the tem-

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perature dependence of magnetic susceptibility using the Vibrating Sample Magnetometer (VSM) option in a Physical Properties Measurement System (PPMS) manufactured by Quantum Design Inc. The doping conditions were determined from the value of the Seebeck coefficient at T = 290 K which is often used as a measure of T_c [2–5]. The Seebeck coefficient was measured using a self-made system installed in PPMS [6].

We employed the laser-ARPES for revealing the carrier concentration dependence of the superconducting gap for $(Bi,Pb)_2Sr_2(Ca,Y)Cu_2O_{8+\delta}$. All the samples were cleaved at low temperature, T = 6 K under the ultra high vacuum atmosphere of ~10^{-11} Torr. The laser-ARPES measurement was performed at T = 6 K with a laser of $h\nu$ = 7 eV. Despite that the momentum range capable of being observable is limited much smaller than the First Brillouin zone, the very high energy resolution below 1 meV allowed us to precisely investigate the superconducting gap near the nodal direction.

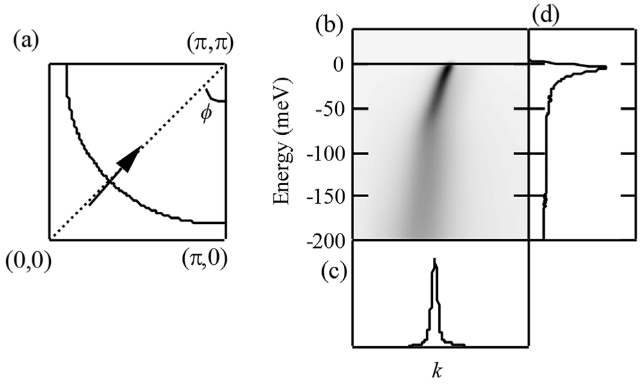

Fig. 1. (a) A schematic of Brillouin-Zone quadrant. (b) The laser-ARPES spectra of UD12 along the nodal region (solid arrow in (a)) at T = 6 K. (c) The momentum distribution curve (MDC) at $E = E_F$ in (b). The peak position represents the Fermi momenta k_F. (d) The energy distribution curve (EDC) at $k = k_F$ in (b).

3. Results

In this study, two heavily underdoped and one optimally doped Bi2212 were prepared. These samples were named according to the doping state and T_c in this paper as UD12, UD17 and OP92, which represent an underdoped sample with T_c = 12 K, 17 K and the optimally doped one with T_c = 92 K, respectively.

We performed the laser-ARPES measurement for these three samples. Fig. 1b shows the ARPES spectra measured for UD12 at T = 6 K along the nodal direction, $\phi \sim 45^\circ$, as typical example. Here ϕ represent the Fermi surface angle, and $\phi = 0^\circ$ and 45° represent the nodal and antinodal direction, respectively. The Fermi momenta k_F were determined from the peak in the momentum distribution curve (MDC) at E_F (see in Fig. 1c). The energy distribution curve (EDC) of a given k_F was shown in Fig. 1d.

To estimate the superconducting gap, all the EDC spectra were symmetrized at $E = E_F$ so as to make the resulting spectra free from the Fermi-Dirac distribution function. Fig. 2a–c show the symmetrized EDC spectra around the nodal region for UD12, UD17 and OP92, respectively. The splitting of the peak at k_F was clearly observable in Fig. 2a–c except for the nodal direction, $\phi \sim 45^\circ$. The energy-width of gap was determined as the energy difference between the two peaks. Notably the energy width of gap increased with increasing value of $|\phi - 45^\circ|$.

Being apart from the nodal direction, the EDC spectra were loosing the spectrum weight around E_F due to the influence of the pseudogap as shown in Fig. 3a. In order to precisely estimate the superconducting gap, we removed the effect of the pseudogap from the EDC spectra by assuming the shape of pseudogap is a Lorentz

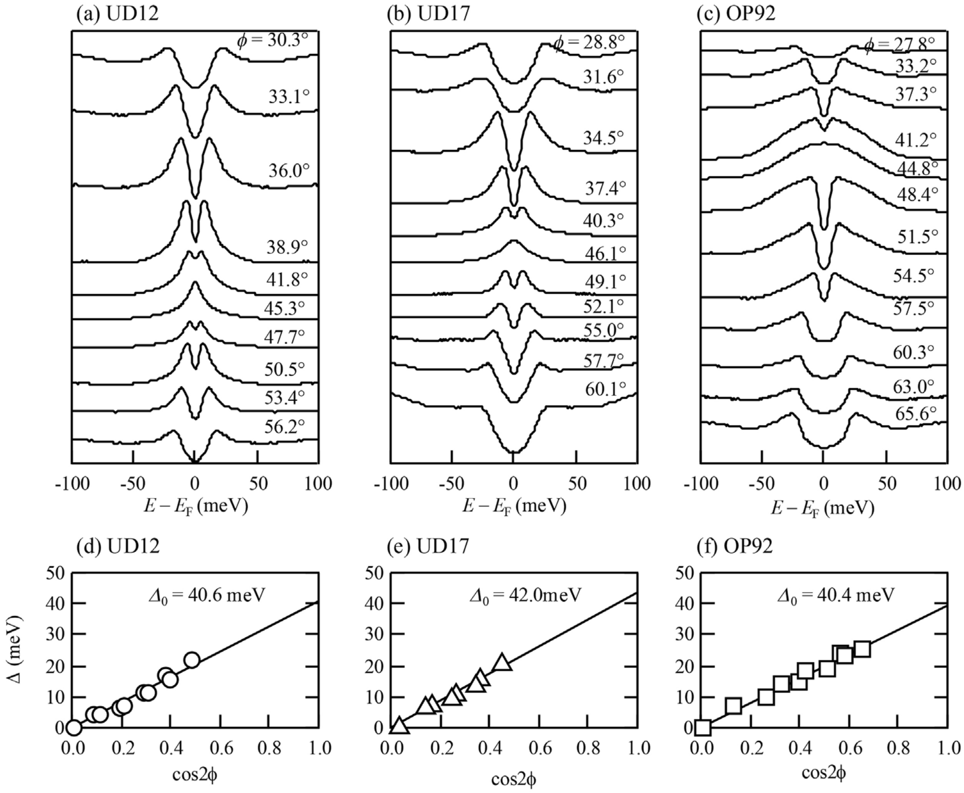

Fig. 2. (a)–(c) The energy distribution curve (EDCs) symmetrized at E_F of UD12, UD17 and OP92, respectively. Here ϕ represents Fermi surface angle. (d)–(f) Gap sizes determined from (a) to (c) respectively are plotted as functions of $|\cos(2\phi)|$. The solid lines denote the simplest d-wave gap function fits, $\Delta(\phi) = \Delta_0|\cos(2\phi)|$.

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