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Superconducting Gap, Pseudogap, and Fermi Surface of Bi2201: High Energy- and Momentum-Resolution Photoemission Study

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We have performed a systematic high energy (7-11 meV) and momentum (0.01 Å $^{-1}$) resolution angle-resolved photoemission spectroscopy (ARPES) on superstructure-free $Bi_{1.80}Pb_{0.38}Sr_{2.01}CuO_{6-\delta}$ with various dopings. All the samples from overdoped T_c=0K to underdoped T_c=18K possess a large hole-like Fermi surface centered at X point, whose volume shows a systematic evolution with doping. The superconducting gap exhibits a $d_{x^2-y^2}$-like anisotropy with a typical gap value of 10-15 meV. By comparing with $Bi_2Sr_2CaCu_2O_8$, we found that the size of superconducting gap and the ARPES spectral feature near E_F are well scaled with the maximum T_c (T_c^{max}). This suggests that the superconducting properties are characterized by T_c^{max} irrespective of the number of CuO_2 layers or the structural modulation in BiO layer.

The Fermi surface (FS) and the superconducting gap of high-T_c superconductors (HTSCs) have been intensively studied by angle-resolved photoemission spectroscopy (ARPES) on $Bi_2Sr_2CaCu_2O_8$ (Bi2212). The $d_{x^2-y^2}$-like superconducting order parameter [1–3] and the pseudogap above the superconducting transition temperature (T_c) [4–7] revealed by ARPES have been regarded as key features of HTSCs to approach the high T_c mechanism. A recent ARPES study using higher photon energies, on the other hand, has raised a question to the so-far believed hole-like FS in HTSCs, proposing an electron-like FS centered at Γ point [8]. It is still unknown how the double CuO_2 layers and the incommensurate superstructure in the BiO layer affect the electronic structure and consequently the superconducting properties. In contrast to Bi2212, Pb-substituted $Bi_2Sr_2CuO_6$ (Bi2201) has only one CuO_2 layer per unit cell with any structural modulation in the Bi(Pb)O layer[9]. It is thus very important to perform ARPES measurements on Pb-substituted Bi2201 to check the universality of the key features observed so far in Bi2212 as well as to obtain an insight to the Fermi-surface topology free from the structural modulation. In this paper, we report a systematic ultrahigh-resolution ARPES study on $Bi_{1.80}Pb_{0.38}Sr_{2.01}CuO_{6-\delta}$ with various dopings (underdope (UD) T_c=18K, 19K to overdope (OD) T_c=13K, 0K). We found that the FS retains its hole-like character for all the doping levels. We have succeeded in observing the superconducting gap as well as the pseudogap above T_c. By comparing the present experimental results on Bi2201 with those on Bi2212, we found that the

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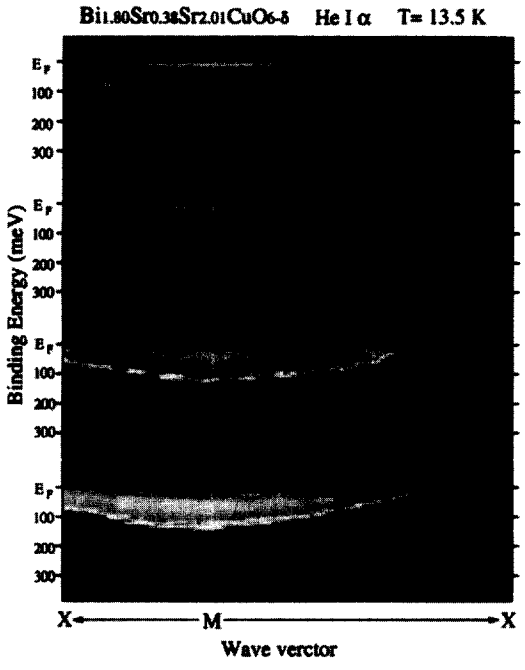

Figure 1. ARPES intensity map along MX cut of $Bi_{1.80}Pb_{0.38}Sr_{2.01}CuO_{6-\delta}$ with various dopings (OD $T_c = 0$K, 13K to UD $T_c = 19$K, 18K). Bright area corresponds to the high ARPES intensity. The Fermi momentum (k_F) is shown by arrows from OD 0K (k_F=0.1π) to UD 18K (k_F=0.15π).

superconducting properties are characterized by the maximum T_c (T_c^{max}) of each compounds, irrespective of the number of CuO_2 layers or the structural modulation in the crystal.

Single crystals of Pb-substituted Bi2201 ($Bi_{1.80}Pb_{0.38}Sr_{2.01}CuO_{6-\delta}$) were grown by the traveling-solvent floating-zone (TSFZ) method. Details of sample preparation are described elsewhere[9]. The T_c of samples was determined by the magnetic susceptibility measurement (UD T_c=18K, 19K, OD T_c=13K, 0K, where 0K means that the sample does not show any signature of superconductivity down to 4K.). ARPES measurements were performed using a SCIENTA SES-200 spectrometer with a high-flux discharge lamp and a toroidal grating monochromator. We used the He Iα resonance line (21.218 eV) to excite photoelectrons. The energy and angular (momentum) resolutions were set at 7-11 meV and 0.25 ° (0.01 Å $^{-1}$), respectively. The Fermi level (E_F) of the sample was referenced to a gold film evaporated onto the sample substrate and its accuracy is estimated to be better than 0.4 meV.

Figure 1 shows the photoelectron intensity map of $Bi_{1.80}Pb_{0.38}Sr_{2.01}CuO_{6-\delta}$ measured along MX cut at 13.5K. In all the samples, a dispersive feature centered at M point is clearly observed. It reduces the intensity on approaching X point from M point, indicating the Fermi-level crossing in this direction [10–12]. The Fermi momentum ($_F$) determined by the $|\nabla_k n(\mathrm{k})|$ method [13] is shown by arrows. We find that k_F is gradually shifted toward X point when the doping level is decreased ($k_F = 0.1\pi$ for OD 0K, k_F=0.15π for UD 18K)[14]. The present result thus clearly shows that the volume of FS systematically changes with doping but the topology retains its hole-like character for all the doping levels from OD 0K to UD 18K.

Figure 2 shows ARPES spectra of superconducting samples in the very vicinity of E_F measured at each k_F at 13.5K, compared with that of gold reference. The leading edge of ARPES spectrum is systematically shifted with doping. The leading edge of OD 13K sample seems to almost coincide with that of gold with a very small positive (toward higher binding energy) shift of 1 meV. Since the measurement temperature (13.5K) is almost the same as the T_c of the sample (13K), this suggests that the superconducting gap is almost closed around T_c or a small pseudogap may open above T_c. In contrast to OD samples, the ARPES spectra of UD 18K and 19K show a remarkable leading-edge shift relative to the gold reference. We have also measured ARPES spectra along the (0, 0)-(π, π) cut and confirmed that no superconducting gap opens within the accuracy of the present measurement. This is consistent with the previous ARPES report [12] and indicates that Bi2201 has also a $d_{x^2-y^2}$-like superconducting gap as Bi2212 [1–3]. In order to estimate the size of superconducting gap in UD 18-19K samples, we have simulated the spectra with the BCS spectral function by taking into account the finite energy resolution and the finite temperature effect (Fermi-Dirac function at

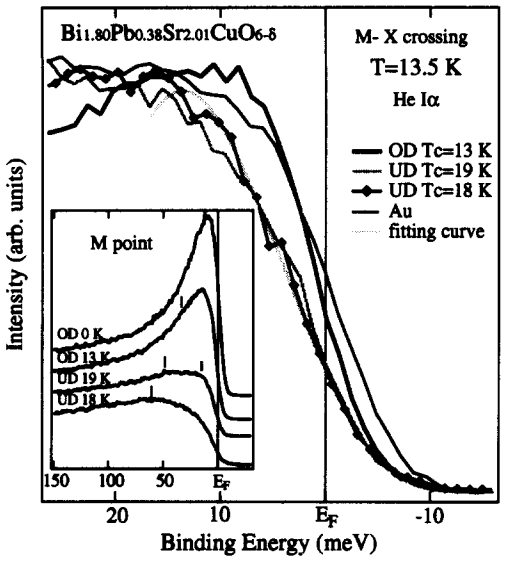

Figure 2. ARPES spectra of superconducting samples in the very vicinity of E_F at 13.5K measured at each Fermi momentum (k_F) along MX cut compared with a gold reference and a result of numerical simulation to estimate the superconducting gap. Inset shows the spectra at M point.

13.5K). The result is shown with gray line. We find that the leading edge of the ARPES spectrum is well fitted by the simulation, while the higher-binding energy region is not well reproduced probably because the incoherent part and the back ground in ARPES spectrum are not included in the simulation. The estimated gap size of UD 19K sample is 14 ± 1.5 meV. This value is relatively small compared with a typical value for Bi2212 with the same hole concentration (40-45 meV)[15–17] reflecting the difference in the T_c, namely the strength of pairing interaction. It is remarked here that the ratio of the gap size (40-45 meV / 14 meV = 2.9-3.2) is similar to the ratio of the maximum T_c (T_c^{max}) for each compound (90K (Bi2212) / 23K (Bi2201) ~3.9). This suggests a certain scaling for the characteristic energy of the superconducting property.

Inset shows the doping dependence of ARPES spectrum at M point. We find that overall spectral evolution with hole doping are very similar to that of Bi2212 [18]. We find a small hump-like structure around 50 meV in the spectra of UD 18K and UD 19K as denoted by bars. This structure is very similar to the hump structure seen in underdoped Bi2212 [18], suggesting that their origins are the same. It is noted that the energy scale near M point of Bi2201 is distinctly smaller in comparison with that of Bi2212. When we compare the energy scale between Bi2212 and Bi2201 from the energy position of the hump-like structure in each ARPES spectrum (Bi2201 UD 19K and Bi2212 UD 75K), we obtain the ratio of 3.8 (=190 / 50). Surprisingly, this value is almost the same as that of the T_c^{max} (90K (Bi2212) / 23K (Bi2201) = 3.9), suggesting an energy scaling in the ARPES spectrum near E_F between Bi2201 and Bi2212.

We have measured the temperature dependence of ARPES spectrum and found that the leading-edge shift relative to E_F still remains even above 20K [19], suggesting that a pseudogap opens in Bi2201 as in Bi2212 [4–7]. Although we could not observe the accurate temperature at which the pseudogap closes (T^*) because of a relatively fast degradation of the sample surface at high temperatures, it is speculated that a similar T^*-doping relation stands in Bi2212 and Bi2201. In fact, the in-plane resistivity of optimally doped Bi2201 shows a deviation from T-linear behavior at 42K [9] which is 1.9 times higher than the T_c, while that of optimally doped Bi2212 is 150K which is 1.7 times higher than the T_c [20]. These two values (1.9 and 1.7) are more or less the same. Since the in-plane resistivity is closely related to opening of the pseudogap, these experimental results suggest a similar T^*-doping phase diagram for both Bi2201 and Bi2212. We also find here that the ratio of T^* deduced from the in-plane resistivity between Bi2212 and Bi2201 (150K (Bi2212) / 42K (Bi2201)~3.6) is almost equal to that of T_c^{max} (~3.9). This suggests that the characteristic energy of pseudogap properties is also scaled with T_c^{max}. This is supported by the experimental fact that the pseudogap is smoothly connected to the superconducting gap and seems to have the same origin [6,12].

We show comparison of characteristic energies

Table 1
Comparison of various energies between Bi2201 and Bi2212.

Energy	Bi2201	Bi2212	Ratio
S. C. gap Δ (meV)	14 ± 1.5	40-45 [17]	3.1
Hump energy (meV)	50 ± 10	190 ± 20 [18]	3.8
$T^*_{\text{resistivity}}$ (K)	42 [9]	150 [20]	3.6
T_c^{max} (K)	23 [9]	90	3.9

of the superconducting and pseudogap properties between Bi2201 and Bi2212 in Table 1. As clearly seen, the size of superconducting gap, the energy position of a hump structure in ARPES spectrum, and T^* at which the in-plane resistivity deviates from the T-linear dependence are well scaled with $T_c{}^{max}$. This clearly indicates that the superconducting and pseudogap properties are essentially the same in both Bi2212 and Bi2201 irrespective of the number of CuO_2 layers or the structural modulation in the BiO layer, and their characteristic energies are well scaled with $T_c{}^{max}$, namely the strength of pairing interaction.

In summary, we have performed an ultrahigh-resolution ARPES study on superstructure-free Pb-substituted Bi2201 with various dopings. We found that the FS retains its hole-like character for all the doping levels. Superconducting gap with the size of 10-15 meV is observed in UD samples. The ARPES spectral feature near E_F and its doping dependence of Bi2201 are quite similar to those of Bi2212 while the energy scale is remarkably different. We found that the superconducting gap and pseudogap properties are well scaled with the maximum T_c of the respective compounds. All these indicate that key superconducting properties observed so far in Bi2212 are universal in Bi-system HTSCs irrespective of the number of CuO_2 layers or the structural modulation in the BiO layer.

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