Direct evidence of two gaps in underdoped Bi2212

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Abstract. This short paper summarizes the results we presented at the LEHTSC2007 conference. Recent doping and temperature dependence of angle-resolved photoemission data of underdoped superconducting cuprate $Bi_2Sr_2CaCu_2O_8$ (Bi2212) have revealed the presence of two energy scales exhibiting distinct behaviours [1,2]. One, which dominates the antinodal region, increases with underdoping and does not show obvious temperature dependence across Tc. This is a behaviour known for more than a decade and considered as the general gap behaviour in the underdoped regime. The other, which dominates the near-nodal regime, does not increase with less doping and opens near Tc via a BCS-like temperature dependence. This is a behaviour not previously observed in the single particle spectra. We propose a momentum space picture of these two energy scales or energy gaps that could resolve the seemingly contradictory gap measurements among different experimental techniques. Our results have also further constrained the theory for high-Tc superconducting cuprates.

1. Introduction

Two decades after the discovery of first high temperature superconductors, the microscopic mechanism of high-Tc superconductivity remains elusive. One of the most mysterious and characteristic phenomena in high temperature superconductors is so called "pseudogap" which exists well above Tc over a wide range of compositions and temperatures in the phase diagram [3]. The origin of this pseudogap and its relation to the superconducting gap are believed to hold the key for understanding the mechanism of high-Tc superconductivity. Early angle-resolved photoemission (ARPES) measurements in the antinodal region [4] and electron tunneling experiments from lightly underdoped samples [5] suggested that the pseudogap has similar characteristics to the superconducting gap below Tc. This is consistent with the idea that the pseudogap is a precursor to the $d_{x^2-y^2}$ superconducting state but lacks the phase coherence of pairs. In this scenario, below Tc, where the phase coherence of pairs is established, the pseudogap smoothly evolves into the superconducting gap. In addition, the magnitude of this gap was found via ARPES [6,7], thermal conductivity [8], and tunneling measurements [9] to increase as the doping is reduced. However, the characteristic energy scales obtained by Andreev reflection [10], penetration depth [11], specific heat [12] and recent Raman experiments [13] of cuprates suggest a rather different behavior from the one-gap picture. To address this issue, we measured doping and temperature dependence of ARPES spectra of underdoped cuprates and found the evidence of two distinct energy gaps in different momentum spaces. Our

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results have been published in a pair of recent papers [1,2]. Some of the results were presented at the LEHTSC2007 conference and are reproduced below. Also, in this write up, we do not differentiate the semantic difference an energy scale and an energy gap, our current goal is to establish the basic experimental phenomenology.

2. Experimental

We address this problem by careful examinations of both doping and temperature dependence of the gapping behaviour at different sections of the underlying Fermi surface in momentum space. The distinct doping dependence of the energy gaps is difficult to discern near optimal doping but becomes obvious in deeply underdoped samples. For this reason, experiments on deeply underdoped samples are crucial. The distinct temperature dependence, especially the behaviour of the superconducting gap opening at Tc around the nodal region, is easier to address using samples near optimal doping since the larger superconducting gap size permits more accurate measurements at given resolutions. High quality single crystals of deeply underdoped $Bi_2Sr_2(Ca,Y)Cu_2O_8$ and slightly underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ were grown by the travelling solvent floating-zone method. Although the nominal concentration of Y in the $Bi_2Sr_2(Ca,Y)Cu_2O_8$ crystal is 0.2, it varies from piece to piece as well as Tc. Magnetization measurements via SQUID were performed to determine Tc of each piece of sample. Then, samples with Tc = 30, 40, 50 K were selected for ARPES measurements. These samples were used to investigate the doping dependence of the gap [1]. On the other hand, a number of samples near optimal doping with Tc ranging from underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ with Tc of 75K to overdoped sample with Tc of 86K were used to investigate the temperature dependence of the gap [2].

All ARPES spectra were taken at beamline 5-4 of the Stanford Synchrotron Radiation Laboratory (SSRL). Incident photon energy of 19 eV with total energy resolution of 14 meV, and photon energy of 22.7 eV with energy resolution of 5 meV as well as photon energy of 7 eV with 3 meV energy resolution were used for $Bi_2Sr_2(Ca,Y)Cu_2O_8$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples, respectively. We stress that the quality of the data as well as the superior energy resolution were critical factors allowing us to draw the conclusions in our study. For example, our sample and experimental geometry permit the observation of sharp quasiparticle peak near the nodal region for underdoped samples with Tc as low as 30K, something never seen before. These are also the factors contributing to the difference between our work and another paper that suggests the presence of a single gap [14].

3. Results and Discussion

In this short write-up, we will not repeat all the works we published already [1,2], instead we show two examples that give the spirit of our findings.

We first highlight the doping dependence of the energy gaps in deeply underdoped regime [1]. The ARPES measurements on heavily underdoped $Bi_2Sr_2(Ca,Y)Cu_2O_8$ samples (Tc = 50, 40, 30 K) reveal an existence of a sharp coherence peak near the nodal region, which gradually loses spectral weight and gets broader moving toward the antinodal region. In the antinodal region, the peak disappears and only a broad hump in the spectra can be observed. Follow the convention of the field, we contrast the gap on the Fermi arc around the node [15,16,17,18] with the gap at the antinode. Here, we operationally define the Fermi arc as the region where one can see a peak in the spectrum. Figure 1 (a) and (b) reproduces symmetrized spectra of deeply underdoped samples at intermediate region, which is within the Fermi arc region, and the antinodal region, respectively. On the one hand, as indicated by the shaded area in Figure 1 (b), spectra at antinode show a larger gap with less doping, which is consistent with previous ARPES results [6, 7,19,20] . One the other hand, the gap in the spectra within the Fermi arc surprisingly exhibits an opposite trend with doping.

For a more comprehensive view of the trend, we plotted the peak position at several different momentum positions within the Fermi arc and at the antinode in Fig. 1(c). Apparently, the doping dependence of the energy gap along the Fermi arc differs from that in the antinodal region. We also note that the gap within the Fermi arc region, determined by the peak position of the Fermi function divided spectra, was consistent with a $d_{x^2-y^2}$ form, whereas the hump position deviated from $d_{x^2-y^2}$

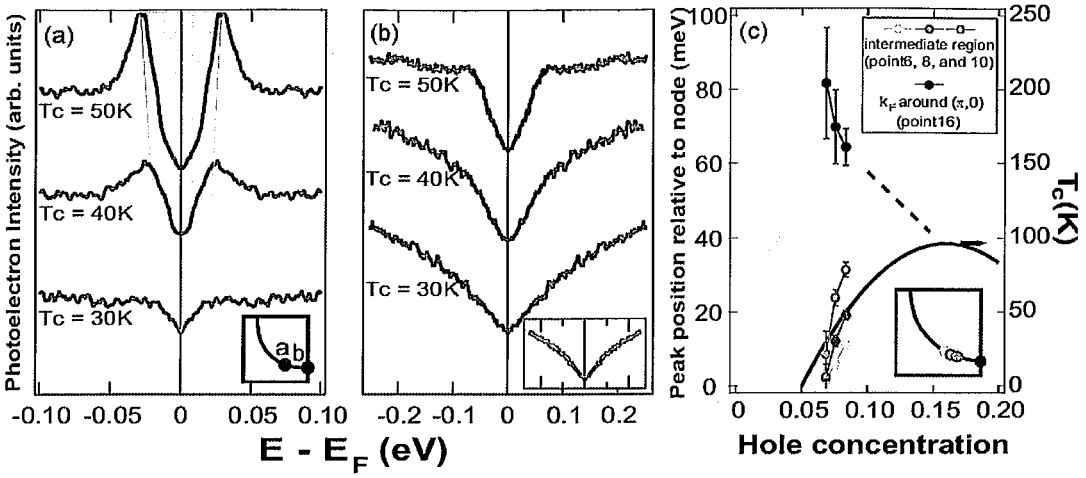

Figure 1. Doping dependence of the symmetrized spectra in (a) the intermediate region and (b) the antinodal region. Their corresponding locations on the FS are shown in the inset in (a). The shaded area denotes the region inside the gap determined by the peak positions of the EDCs. For the antinodal spectra, the position of the hump, which is determined from the second derivative of the spectra, is used as the peak position. The inset in (b) shows temperature dependence of the spectra of Tc = 30 K sample taken at 10 K (blue) and 50 K (red) at the antinodal region. (c) Dopoing dependence of energy gaps in the intermediate region and antinodal region.

around the antinodal region.

We now show that there is also a distinct temperature dependence of the gap at different parts of the momentum space, which can be better discerned by ARPES experiments near optimal doping [2]. Figure 2 reproduces temperature dependence of the gap at a position near the nodal region of slightly underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ compounds with Tc = 92 K. The gap collapses at a temperature very close to Tc with a temperature dependence consistent with that predicted by BCS theory (Figure 2(d)). The thermally populated upper Bogoliubov band can also be observed in raw EDCs for temperatures lower than Tc, and disappears at temperatures higher than Tc (Figure 2 (a-b)). This further confirms that the energy gap observed near the nodal region clearly related to the superconducting gap, which closes at temperatures above Tc. On the contrary, there was almost no temperature dependence of the gap magnitude at antinode (not shown, but see reference 2).

It seems impossible to explain our data by a single gap along the Fermi surface. Our data points towards a two-gap picture; The first energy gap opening at Tc in the Fermi arc region is associated with the order parameter of the superconducting states, whereas the pseudogap near the antinodal region represents an energy scale associated with a different mechanism that may or may not be related to superconductivity.

Due to the much smaller near nodal gap, clean temperature dependent results as those shown in Fig. 2 have not been obtained in deeply underdoped samples. However, the general trend is consistent. First, although energy distribution curves (EDCs) in the Fermi arc shows a temperature dependence of spectra across Tc, there was essentially no change in the EDC of the Tc = 30 K sample between the superconducting (T = 10 K) and the normal (T = 50 K) states in the antinodal region as shown in inset in Fig. 1 (b). Those behaviors again suggest that the energy gaps in the Fermi arc region and the antinodal region likely represent two distinct energy gaps arising from different mechanisms. Better experimental conditions are required to really sort out the detailed temperature dependence of the nodal gap.

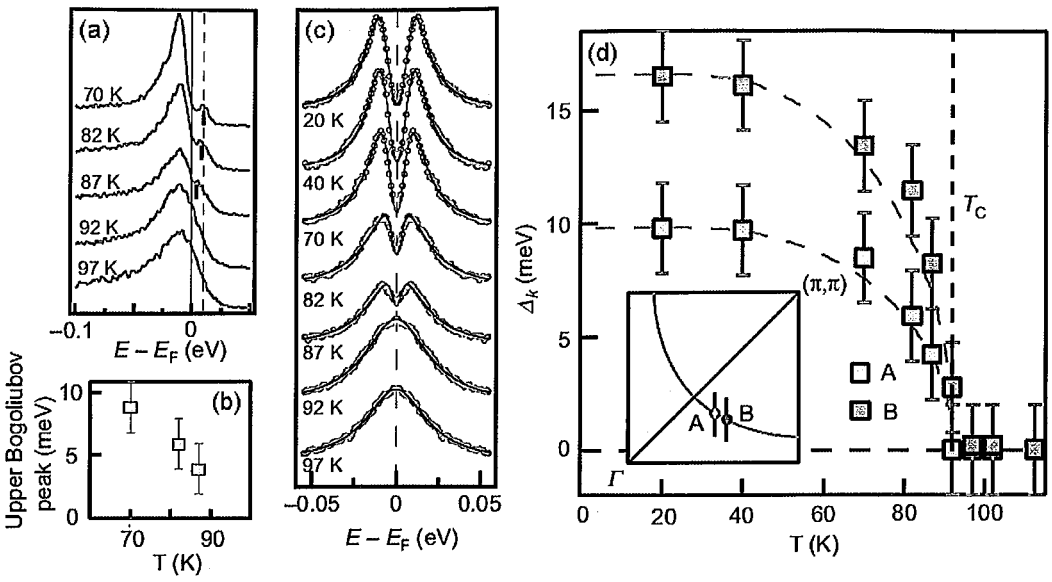

Figure 2. Temperature dependence of (a) EDCs and (c) symmetrized EDCs at point A on FS shown in the inset in (d). Temperature dependence of the peak position of the thermally populated upper Bogoliubov band in (a) is plotted in (b). (d) Temperature dependence of the fitted gap size [21] near the node. The dashed lines show the temperature dependence of the superconducting gap based on weak-coupling BCS theory.

This momentum-space two-gap scenario could resolve contradictory gap measurements by different experimental techniques. We suggest that Andreev reflection [10], penetration depth [11], intrinsic tunneling spectroscopy [22], and femtosecond spectroscopy [23], which suggests the gap closes at Tc, are probably more sensitive to the nodal region or the superconducting condensate directly. On the other hand, the scanning tunneling microscopy (STM) spectrum is more sensitive to the antinodal region, thus, a smooth transition from the pseudogap and superconducting gap was observed. Notably, the issue on the temperature dependence of STM spectra has recently been revisited and the coexistence of two energy gaps in underdoped cuprates has also been suggested [24, 25].

This two-gap scenario has two serious implications, which could be very important for developing a microscopic theory of high Tc superconductivity. First, the pseudogap near the antinodal region in these deeply underdoped samples is unlikely to be a precursor state of the superconducting state, especially in deeply underdoped regime. Second, our data suggest that the weakened superconductivity in the deeply underdoped region arises not only from the loss of phase coherence [26] caused by the decrease in the superfluid density but also a weakening of the pair amplitude. In this case, a mechanism for the superconducting gap reduction could be related to the shrinkage of the coherent Fermi surface with less doping, leading to a smaller phase space for pairing. Although we proposed different mechanisms for two gaps in momentum space, the relationship between the superconducting gap and pseudogap is still not clear. The fact that the gap along Fermi surface showed smooth connection from the superconducting gap to the pseudogap near optimal doping implies an intimate relationship between two gaps. To clarify this problem, further systematic studies on other cuprate families as well as further theoretical studies are strongly desired.

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