On the relations among the pseudogap, electronic charge order and Fermi-arc superconductivity in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Abstract. On the basis of STM/STS, break-junction tunneling and electronic Raman scattering experiments on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ reported so far, we suggest that the static, electronic charge order is associated with inhomogeneous electronic states on antinodal parts of the Fermi surface that are outside the Fermi-arc around the node and responsible for the pseudogap, and coexists with the homogeneous superconductivity caused by the pairing of coherent quasiparticles on the Fermi-arc, the so-called “Fermi-arc superconductivity”, in the real space, although the two electronic orders or the corresponding energy gaps compete with each other in the $k$-space.

1. Introduction

One of the striking features in high-$T_c$ cuprates is an unusual electronic state characterized by a gap-like structure around the Fermi level $E_F$, the so-called “pseudogap” (PG), which develops below around temperature $T^*$ in the normal state (Fig. 1). STM/STS and ARPES experiments have revealed that in high-$T_c$ cuprates, the low-temperature ($T< T_c$) energy gap amplitude $\Delta_0$, reflecting the strength of pairing interactions, increases monotonically with the lowering of doping level $\rho$, at least down to a slight underdoping level, although $T_c$ is reduced in the underdoped (UD) region, and PG temperature $T^*$ roughly scales with $\Delta_0$ [1-7]. Furthermore, ARPES experiments also demonstrated that the PG has a d-wave like structure as in the superconducting (SC) state [6, 7]. These findings have prompted many researchers to suppose that the PG may be something related to the high-$T_c$ superconductivity, for example, some kind of precursor of superconductivity. However, in the UD region, where the PG develops markedly, $T_c$ is largely reduced, as seen in the electronic phase diagram (Fig. 1), and an effective SC gap in determining $T_c$ develops on arc-shaped parts of the Fermi surface around the gap node points near ($\pm \pi/2a$, $\pm \pi/2a$), the so-called “Fermi-arc,” resulting from the formation of PGs on parts of the Fermi surface near ($\pm \pi/a$, 0) and (0, $\pm \pi/a$). This fact suggests that the PG formation may be a phenomenon competing with the superconductivity. Thus, we have not succeeded in explaining the relation between the PG and the high-$T_c$ superconductivity consistently, and it is still under debate.

Recently, an electronic charge order (ECO), which is oriented along the two Cu-O bond directions with a period of $\sim 4a \times 4a$ ($a$, the lattice constant or the Cu-O-Cu distance), was discovered in the PG state by STM/STS experiments [8-10]. It has been found that the characteristic energy scale of the ECO is the PG, suggesting that the ECO can be a candidate for the hidden order of the PG state.
Therefore, studies on the ECO are expected to give us important clues to understanding of the origin of the PG and its relation with high-$T_c$ superconductivity.

In this article, on the basis of STM/STS, break-junction tunnelling and electronic Raman scattering experiments on the PG, ECO and effective SC gap in determining $T_c$ that have been performed so far by our group [1, 2, 5, 11-13], we will discuss the role of the Fermi-arc in the SC transition of Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ (Bi2212) and the relations among the PG, ECO and high-$T_c$ superconductivity.

2. Experiments

Single crystals of Bi2212 were grown by the traveling solvent floating zone method. The hole-doping level $p$ ranges from ~0.1 to ~0.22 for the crystals used here. The details of STM/STS, break-junction tunneling and electronic Raman scattering spectroscopy experiments were reported in Refs. 1, 2, 5, 10 and 11.

3. Results and Discussion

3.1. Pseudogap and effective SC gap

Shown in Fig. 1 (the electronic phase diagram as functions of $T$ and $p$) is the $p$ dependence of low-temperature energy gap amplitude $\Delta_0$, which has been obtained so far in STM/STS and break-junction tunneling experiments [1, 2, 5]. One can see that the $\Delta_0$ value roughly follows the $T^*-p$ curve and does not scale with $T_c$. In our previous works, we demonstrated that the product of $p$ and $\Delta_0$, $p\Delta_0$, roughly scaled with $T_c$, at least in the doping range examined ($0.1 < p < 0.22$), as shown in Fig. 1. Interestingly, the PG starts to open at around $T^*$ on the antinode points of the Fermi surface (FS) near $\left(\pm\pi/2a, \pm\pi/2a\right)$ with the lowering of $T$ [14, 15]. However, an ungapped region remains around the node point of the FS even just above $T_c$, leading to the Fermi-arc; thus, the FS can be divided into two parts [14, 15]. These two parts of the FS, inside and outside the Fermi-arc, have been considered to consist of coherent and incoherent electronic states, respectively. Furthermore, electronic Raman scattering experiments demonstrated that, in the spectra

![Figure 1. Schematic electronic phase diagram, $p$ dependences of $\Delta_0$, $p\Delta_0$ ($\Delta_{\text{eff}}$) and $\Delta_c$.](image)

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for $B_{2g}$ symmetry, probing the coherent electronic states around the node points, the energy gap $\Delta_c$ scales with $T_c$ (Fig. 1) [11, 16]. In light of these facts, we have argued that even if incoherent quasiparticles outside the Fermi-arc form pairs in the PG state below $T^*$, they cannot establish long-range phase coherence in collective motion, which will be done by the pairing of coherent quasiparticles on the Fermi-arc, and suggested that the energy gap opening on the Fermi-arc below $T_c$ will be proportional to $p\Delta_0$ in magnitude and function as an effective SC gap in determining $T_c$, as schematically shown in Fig. 2 [12, 13]. Indeed, it has recently been demonstrated by Yoshida et al. in ARPES experiments that the length of the Fermi-arc is roughly proportional to $p$ and the magnitude of the effective SC gap on the Fermi-arc is of the order of $p\Delta_0$ [17]. As the doping level $p$ is lowered, the effective SC gap on the Fermi-arc is reduced through the shrinkage of the Fermi-arc, while the PG on the antinodal FS part is enhanced; thus the two energy gaps compete with each other in the $k$-space.

Figure 2. Schematic illustration of PG and effective SC gap. The PG develops below $T^*$ on the antinodal FS parts near $(\pm \pi/a, 0)$ and $(0, \pm \pi/a)$. On the other hand, the effective SC gap opens below $T_c$ on the Fermi-arc.

Very recently, it has been reported by Tanaka et al. for ARPES experiments that in heavily-UD Bi2212 crystals ($p<~0.08$) whose $T_c$ is largely reduced ($T_c<~60$ K), two kinds of energy gaps, a SC gap on the Fermi-arc and a PG on the antinodal Fermi surface, open in the SC state, and the gap value $\Delta_0$ at the antinode, obtained by extrapolating the SC gap data on the Fermi-arc towards the antinode, decreases with the lowering of $p$ [18]. Employing this ARPES result on the $p$ dependence of $\Delta_0$, the large reduction of $T_c$ in heavily-UD samples is also explained in terms of the scenario that the energy gap opening on the Fermi-arc with a magnitude of order $p\Delta_0$ will function as an effective SC gap in determining $T_c$.

3.2. Coexistence of Fermi-arc superconductivity and electronic charge order in real space: two electronic orders competing in $k$-space

Figure 3 (a) is an example of STM images observed on the Bi2212 cleaved surface at 85 K, higher than $T_c = 81$ K, with a low bias voltage $V_s$ of 30 mV [10]. The cleavage in Bi2212 usually occurs between the semiconducting Bi-O planes, forming a bilayer, with an energy gap $E_g$ of the order of 0.1 eV. In STM experiments on the cleaved surface, the topmost atomic plane closest to the STM tip is the semiconducting Bi-O plane, the second the insulating Sr-O plane, and the third the metallic or SC
Cu-O plane, and the Bi-O and Cu-O planes can be observed selectively, as reported in our previous works; STM images measured at |$V_s$| > $E_g/e \sim 100$ meV reflect the Bi-O plane while STM images measured at |$V_s$| < ~100 meV are the Cu-O plane [19, 20]. Therefore, the low bias ($V_s = 30$ mV) image in Fig. 3 (a) corresponds to the Cu-O plane. One can see in this image that a two-dimensional (2D) electronic charge order (ECO) develops in the PG state above $T_c$. From the Fourier transform (Fig. 3 (b)), furthermore, it is found that the period of the 2D ECO is 4 times the lattice constant, $4a$, along the two Cu-O bond directions, intersecting at right angles; that is, $4a \times 4a$.

Shown in Fig. 3 (c) is the spatial dependence of STS spectra, which was examined along the solid line on the STM image in Fig. 3 (a) [10]. Similar PG structures can be seen in the STS spectra, regardless of position. The spectrum, which tends to increase gradually with the lowering of $V_s$, is largely reduced around $V_s$=0, corresponding to the Fermi level; thus, it exhibits a broad peak around the positive voltage $V_s^p$, while a broad bend appears around $-V_s^p$ in the negative $V_s$ region. We define the energy size of the PG, $\Delta_{PG}$, from the peak position, $V_s^p$; $\Delta_{PG}$=E$_p$. One can see in Fig. 3 (c) that the $\Delta_{PG}$ value is largely modulated or inhomogeneous on the nanometer scale for the present sample, which exhibits strong $4a \times 4a$ ECO. Furthermore, it was found in our recent works that the PG structure was homogeneous in samples with a very weak ECO. To understand such a correlation between the ECO and the gap inhomogeneity, it has been proposed that the ECO is dynamic in itself and, if Bi2212 samples involve strong scattering centers for quasiparticles leading to gap inhomogeneity such as crystallographic imperfections, the scattering centers will function as effective pinning centers for the dynamically fluctuating ECO and make it static [10, 21]. On the basis of this pinning picture, the dynamically fluctuating ECO would be a candidate for the hidden order of the homogeneous PG state and the degree of development of the static ECO can be explained in terms of the density and/or strength of pinning centers.

**Figure 3.** (a) STM image for a UD Bi2212 sample, obtained at 85 K and $V_s$ = 30 mV. (b) Line cuts taken along the $q_x$ and $q_y$ directions on the Fourier map (inset). (c) 2D illustration for the spatial dependence of the STS spectrum, measured along the white line in the image.

From the $V_s$-dependence of the STM image in another Bi2212 sample, it was found that the period of the ECO was energy-independent, i.e. nondispersive, while its amplitude decreased rapidly with increasing energy and became negligibly small above the PG energy, $\Delta_{PG}$ (Fig. 4) This, consistent with the result reported by Vershinin et al. [8], indicates that the characteristic energy of the $4a \times 4a$ ECO in the PG state above $T_c$ is the corresponding energy gap, the PG, as in the SC state below $T_c$ [20]. As mentioned in the previous subsection, the FS is divided into coherent and incoherent parts, inside and outside the Fermi-arc, which are responsible for the SC gap and the PG, respectively. It should be remembered here that the PG is spatially inhomogeneous in samples exhibiting the strong,
pinned ECO, and vice versa. This is naturally understandable, because incoherent electronic states are easily modified by external perturbation, which is due to the randomness associated with pinning potentials for the ECO [22]. Furthermore, since the characteristic energy of the ECO is the PG, incoherent, antinodal quasiparticle or pair states outside the Fermi-arc will also be responsible for the ECO. In fact, as has been demonstrated in low-temperature ($T<T_c$) STM/STS experiments, at low energies around $E_F$, reflecting the quasiparticle states inside the Fermi-arc, the gap structure is characterized by a spatially homogeneous d-wave gap and the ECO tends to fade out, while at high energies around the gap edge, reflecting the quasiparticle states outside the Fermi-arc, the gap structure is strongly inhomogeneous and the ECO becomes marked [10, 21, 22]. It is therefore suggested that if the static ECO is stabilized in the inhomogeneous PG state above $T_c$, it will remain below $T_c$, together with the inhomogeneous gap structure in the antinodal region, and coexist with the homogeneous superconductivity caused by the pairing of coherent quasiparticles on the Fermi-arc, that is, the so-called “Fermi-arc superconductivity” [12, 13], in the real space, although the two electronic orders or the corresponding energy gaps (the effective SC gap and PG) compete with each other in the $k$-space as mentioned in the previous subsection.

4. Summary
On the basis of energy gap data for Bi2212, which have been reported so far for ARPES, STM/STS, break-junction tunnelling and electronic Raman scattering experiments, we have suggested that the effective SC gap in determining $T_c$ opens on the coherent FS parts around the d-wave gap node points.
or the Fermi-arc, while the PG opens on the incoherent FS parts outside the Fermi-arc or the antinodal FS parts, and that both energy gaps compete with each other in the k-space. Furthermore, it has been suggested that the antinodal FS parts will also be responsible for the 2D electronic charge order (ECO). The incoherent, antinodal FS parts seem to be strongly affected by randomness, leading to the inhomogeneous PG state, in which the static ECO is stabilized by the pinning of the dynamically fluctuating one. The static ECO in the inhomogeneous PG state persists to the SC state, and coexists with the homogeneous superconductivity on the Fermi-arc, sharing with the FS. Thus, the present findings will provide a conclusion for the relations among the high-Tc superconductivity, PG and 2D ECO in Bi2212.

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