STM/STS Study on 4a×4a Electronic Charge Order of Superconducting Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$

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We performed low-bias STM measurements on underdoped Bi2212 crystals, and confirmed that a two-dimensional (2D) superstructure with a periodicity of four lattice constants (4a) is formed within the Cu-O plane at $T < T_c$. This 4a×4a superstructure, oriented along the Cu-O bonding direction, is nondispersive and more intense in lightly doped samples with a zero temperature pseudogap (ZTPG) than in samples with a d-wave gap. The nondispersive 4a×4a superstructure was clearly observed within the ZTPG or d-wave gap, while it tended to fade out outside the gaps. The present results provide a useful test for various models proposed for an electronic order hidden in the underdoped region of high-$T_c$ cuprates.

KEYWORDS: STM/STS, pseudogap, electronic charge ordering, superstructure, cuprate

Recently STM/STS studies on the pseudogap state of Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ (Bi2212) at $T > T_c$ have revealed a nondispersive two-dimensional (2D) superstructure with a periodicity of about four lattice constants (4a) in the Cu-O plane at $T < T_c$. This 4a×4a superstructure, oriented along the Cu-O bonding direction, is nondispersive and more intense in lightly doped samples with a zero temperature pseudogap (ZTPG) than in samples with a d-wave gap. The nondispersive 4a×4a superstructure was clearly observed within the ZTPG or d-wave gap, while it tended to fade out outside the gaps. The present results provide a useful test for various models proposed for an electronic order hidden in the underdoped region of high-$T_c$ cuprates.

In the present study, we performed low-bias STM measurements on underdoped Bi2212 samples, and succeeded in observing an energy-independent 4a×4a electronic superstructure with a substructure having a periodicity of 4a/3 in the low-bias STM images, which is essentially the same as the electronic checkerboard order reported by Howald et al. and Hanaguri et al. in LDOS maps of lightly-doped Bi2212 and Na-CCOC. The present 4a×4a superstructure is accompanied by a d-wave-like gap or ZTPG, and is discussed in terms of a wide variety of unusual electronic orders proposed for the underdoped region of high-$T_c$ cuprates.

The single crystal of Bi2212 in the present study was grown by the traveling solvent floating zone method. We estimated doping level $p$ of the sample from the SC critical temperature $T_c$ determined from the superconducting diamagnetism and the characteristic temperature $T_{max}$ of the normal-state magnetic susceptibility. $T_c$ and $T_{max}$ follow empirical functions of $p$ respectively.

We performed STM/STS experiments at $T \sim 9$ K on two samples A and B cut from the same single crystal with $T_c \sim 72$ K ($p \sim 0.11$). In the present STM/STS experiments, the sample was cleaved after a superconducting state at $T \sim 9$ K just before the approach of the STM tip to the cleaved surface in situ. As is well known, Bi2212 crystals are usually cleaved between neighboring Bi-O layers. The excess oxygen atoms within Bi-O layers, which provide holes into Cu-O planes nearby, will be lost to a high degree during the process of cleaving. However, if the cleaving is carried out at very low temperatures, the reduction of excess oxygen atoms, thus hole carriers, will be suppressed to some extent. After the approach of the STM tip to the cleaved surface, we obtained STM images of 512×512 pixels in the constant height mode under various constant sample biases, $V_s$'s. The differential conductance $dI/dV$ was measured by using a standard lock-in technique with ac bias modulation of 3 mV and a frequency of 4 kHz.

Shown in Fig. 1(a) is a typical STM image measured at $T \sim 9$ K on sample A under a low-bias voltage ($V_s = 30$ mV), which lies within the pairing gap as will be men-
Fig. 1. (a) STM image of sample A at $T \sim 9$ K, showing a $4a \times 4a$ superstructure together with atoms and a 1D superstructure, inherent in the Bi-O plane, perpendicular to the b axis. The image was measured at a sample bias ($V_s$) of 30 mV and initial tunneling current ($I_t$) of 0.3 nA. (b) Profiles along the line at the same position in STM images at various bias voltages (yellow line in the top panel). The line was purposely taken to be perpendicular to axis b, that is, 45 degrees from the orientation of the $4a \times 4a$ superstructure so that the 1D superstructure of the Bi-O plane could not obscure the profile of the $4a \times 4a$ superstructure.

Fig. 2. (a) STM image of sample B at $T \sim 9$ K, measured at $V_s = 10$ mV, $I_t = 0.3$ nA. (b) Line profile of the STM image at $V_s = 10$ mV along the yellow line in the top panel. For comparison, the line profile of sample A at $V_s = 30$ mV (Fig. 1(b)) is also shown (broken line).
consistent with the results of the line profiles of real-space STM images. The 1/4\(\times\)4a superstructure can clearly be observed in STM imaging. This fact implies the possibility that in-gap states, namely the hole pairs, will contribute to the formation of the 4a\(\times\)4a superstructure. In high-\(T_c\) cuprates, the gap size increases with the decrease in the doping level.\(^{14,15}\) Thus, the larger gap size measured on the cleaved surface for sample A than for sample B means that the doping level of the cleaved surface of sample A is lower than that of sample B, though both samples are cut from the same single crystal. The 4a\(\times\)4a superstructure is very intense in sample A and appears throughout the cleaved surface, whereas it is relatively weak in sample B and appears locally over the cleaved surface, as mentioned above. Furthermore, the low-bias STM image previously reported for nearly optimally doped Bi2212 with \(\Delta_0 \approx 35\) meV exhibited no 4a\(\times\)4a superstructure.\(^{13}\) These results indicate that a low hole doping level favors the formation of the 4a\(\times\)4a superstructure. It should be noted here that the cleaved surface of sample A has more missing atom rows within the cleaved Bi-O plane than that of sample B, which can be clearly seen in the high-bias STM images, predominantly reflecting the electronic structure of the Bi-O plane. (The high-bias STM images of the present samples will be published elsewhere.) If the missing atom rows are introduced within the Bi-O plane during the cleaving process, excess oxygen atoms will also be removed around the missing atom rows at the same time, which leads to the reduction of the average hole doping level of the Cu-O plane. Thus the high density of the random missing atom rows in the cleaved surface of sample A may be a possible reason why the average hole doping level is lower in the cleaved surface of sample A than for sample B, though both samples were cut from the same single crystal. The low density of the random missing atom rows in the cleaved surface of sample B can also explain its homogeneous electronic structure, namely the homogeneous pairing gap.

In the present experiments of low-bias STM imaging, namely Cu-O plane selective imaging, on under-doped Bi2212,\(^{13}\) we confirmed that an intense, nondispersive 4a\(\times\)4a superstructure was formed within the Cu-O plane. The 4a\(\times\)4a superstructure has a substructure with a periodicity of 4a/3 and is clearly observed within the pairing energy gap. Such features of the present 4a\(\times\)4a superstructure are in good agreement with those of the 4a\(\times\)4a electronic charge order reported for lightly doped Na-CCOC.\(^{2}\) The intense, nondispersive 4a\(\times\)4a electronic charge order is different in origin from the dispersive 2D modulation caused by quasiparticle scattering interference.\(^{5}\) The present nondispersive electronic charge order is consistent with the findings of Howald.
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et al. in the LDOS maps for the SC state of Bi2212. They claim that the nondispersive superstructure results from the formation of a static stripe order. The present results can be explained in terms of a static stripe order except for the experimental finding for sample B that the paring gap is influenced only slightly even over the region where the dynamical $4a \times 4a$ charge order is locally pinned down. Since the formation of the static stripe order causes the superconductivity to seriously deteriorate, as demonstrated for La$_{2-x}$Ba$_x$CuO$_4$ and La$_{1.6-x}$Nd$_{0.4}$Sr$_x$CuO$_4$ systems where simple 1D strips develop, the paring gap would be seriously influenced over the region where the $4a \times 4a$ electronic charge order is pinned down. The present $4a \times 4a$ electronic charge order, clearly appearing within the pairing gap, is not inconsistent with models for the electronic charge order due to pair density waves, electronic supersolids, or paired-hole Wigner crystallization.

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