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STM Studies on Electronic Charge Order in the PG State of Bi2212

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Abstract

Using scanning tunneling microscopy (STM), we confirmed a nondispersive $\sim 4a_0 \times 4a_0$ electronic charge order, whose characteristic energy is the pseudogap (PG), in the PG state of Bi2212 above T_c .

Key words: STM/STS; Bi₂Sr₂CaCu₂O₈; pseudogap; electronic charge order

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1. Introduction

In high- T_c cuprates, the origin of PG and its relation to the superconductivity remain under debate. It has been widely thought that a hidden order dominates the PG state above T_c . Recently, in the PG state of Bi₂Sr₂CaCu₂O_{8+ δ} (Bi2212), Vershinin *et al.* [1] found a charge order in a two-dimensional (2-d) map of energy-resolved STS conductance, which is proportional to the local density of states (LDOS) at a quasiparticle energy. The charge order is oriented along the Cu-O directions; its period, $\sim 5a_0$ (a_0 : lattice constant), is independent of energy, which is called “nondispersive”. Interestingly, it becomes evident in LDOS maps at low energies within the PG, suggesting that the nondispersive charge order may be a hidden order in the PG state above T_c .

However, no other groups reported such a charge order above T_c . In this study, therefore, we performed STM experiments above T_c on slightly UD Bi2212 to confirm the nondispersive charge order in the PG state. STM imaging provides a 2-d map reflecting the integration of LDOS from the Fermi level E_F to $E_F + eV_s$ (V_s : bias voltage), and can also

be expected to detect the nondispersive charge order clearly because its period is energy-independent.

2. Experimental

Single crystals of Bi2212 were grown by TSFZ method. The hole doping level p and T_c are ~ 0.14 and 81 K, respectively. To obtain clean surfaces which are indispensable for STM experiments, the samples were cleaved in ultrahigh vacuum better than 10^{-9} torr before being inserted in situ into an STM head whose temperature is 5 K. STM experiments in the PG state were performed after finishing those at $T \ll T_c$ and warming the sample gradually up to a temperature, 85 K, above T_c .

3. Results and discussion

Figure 1 (a) shows an STM image, measured in the constant-height mode at a bias voltage of $V_s = 40$ mV and $T = 85$ K. As has already been discussed in Refs. [2] and [3], in STM experiments on Bi2212 cleaved surfaces, where the top atomic plane closest to the STM tip is the semiconducting Bi-O plane with an energy gap E_g of the order of 100 meV, the second the insulating Sr-O plane and the third the

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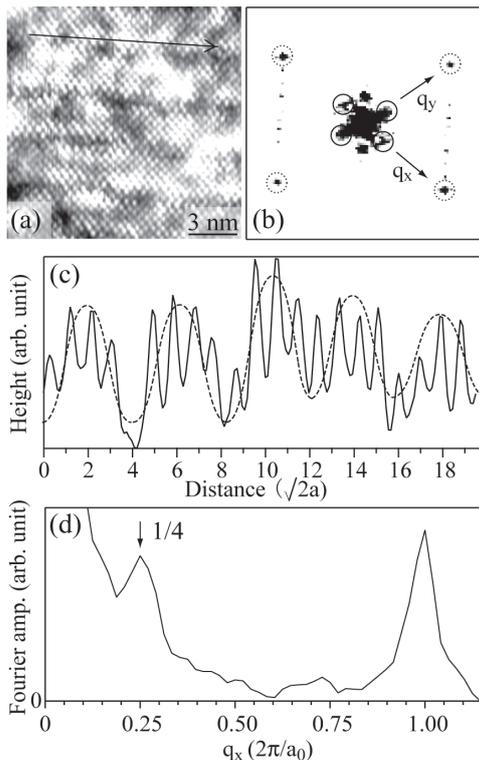


Fig. 1. (a) STM image in the PG state of Bi2212, measured at $V_s = 40$ mV and 85 K. (b) Fourier map of the image. (c) Line profile taken along the solid line with an arrow on the image. The dashed line is a guide to the eye. (d) Line cut taken along the q_x direction on the Fourier map.

metallic or superconducting (SC) Cu-O plane, we can image the Cu-O plane at $V_s < E_g/e \sim 100$ mV, because the Bi-O and Sr-O planes have no electronic states in the energy range from E_F to $E_F + eV_s$, contributing to tunneling. Indeed, a 1-d superstructure with periodic missing atom rows, which is a characteristic feature of the Bi-O plane, is rather weak in the STM image observed at $V_s = 40$ mV, suggesting that the low-bias image reflects the Cu-O plane dominantly. Interestingly, a 2-d charge order can be seen clearly, especially for an upper part of the STM image, in addition to distinguished bright dots, corresponding to Cu-sites. The 2-d charge order is oriented along the Cu-O directions, tilted by 45° from the very weak 1-d superstructure.

Shown in Fig. 1 (c) is the line profile along a trace at 45° from the Cu-O direction or the orientation of the 2-d charge order, indicated by the solid line with an arrow in the STM image (Fig. 1 (a)). In this line profile, the period can be estimated to be about $4a_0$ along the Cu-O directions, where a_0 is the lattice constant or the nearest neighbor Cu-Cu distance. The Fourier transform of the STM image is

also useful to determine the period of the 2-d charge order. The Fourier map is shown in Fig. 1 (b), where four spots surrounded by dotted circles correspond to the Bragg reflections and four broad spots surrounded by solid circles near the origin are due to the periodic charge order. The intense peak in the line cut (Fig. 1 (d)) taken along the q_x direction on the Fourier map (one of the Cu-O directions in the real space) appears at $\sim 2\pi/4a_0$, indicating that the period along the Cu-O direction is $\sim 4a_0$. A similar intense spot is also observed at $\sim 2\pi/4a_0$ along the q_y direction in the Fourier map (the other Cu-O direction in the real space). These results indicate that the period of the 2-d charge order in the PG state above T_c is $\sim 4a_0 \times 4a_0$. Furthermore, it has been found from the V_s dependence of Fourier spots corresponding to the charge order that the period is independent of energy and the intensity becomes evident at low energies within the PG. Thus, we have confirmed the nondispersive $\sim 4a_0 \times 4a_0$ charge order whose characteristic energy is the PG above T_c , although the period obtained in the present STM experiments is slightly smaller than that reported by Vershinin *et al.* [1].

However, we obtained the result that there also exist many Bi2212 samples in which the charge order is unclear even though they exhibit similar PG behavior above T_c . Recently, a similar charge order, whose amplitude is strongly sample-dependent, has been found in the SC state [3–5]. More interestingly, in samples which exhibit strong $\sim 4a_0 \times 4a_0$ charge orders at $T \ll T_c$, the spatial dependence of energy gap structure is very inhomogeneous in nanometer scale, and vice versa. Whether such a correlation between the electronic charge order and the gap inhomogeneity also holds in the PG state will be of great interest for the understanding of its origin.

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