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Low-energy spectroscopic mapping studies in optimally-doped $Ca_{2-x}Na_xCuO_2Cl_2$

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Abstract

We performed high-resolution scanning tunneling microscopy/spectroscopy on an optimally-doped $Ca_{2-x}Na_xCuO_2Cl_2$ crystal with $T_c \sim 25$ K. The so-called "checkerboard" local-density-of-state modulation previously found in heavily underdoped regime also manifests in the spectroscopic map of the optimally-doped sample. In addition, spatially-inhomogeneous energy gap with peaks at the gap edges is observed below about 10 meV. The gap tends to be buried at elevated temperatures and correlates with the checkerboard modulation. These results suggest that the gap is related to superconductivity which coexists with the checkerboard modulation.

Keywords: STM/STS; Charge order; Superconductivity; Magnetic field effect

1. Introduction

Recent scanning tunneling microscopy/spectroscopy (STM/STS) measurements on high-T_c cuprates have revealed the "checkerboard" (CB) local-density-of-state (LDOS) modulations in the vortex core [1], above T_c [2], and in heavily underdoped regime [3]. The CB modulation is often discussed in terms of the electronic order which competing/coexisting with superconductivity. However, the relation between CB and superconductivity is still unclear. $Ca_{2-x}Na_xCuO_2Cl_2$ is an ideal material for CB research because it shows very clear CB modulation [3]. However, no clear superconducting signal was observed in the LDOS spectrum probably because the available samples were limited in the underdoped regime. Recent progress in sample preparation has allowed us to grow sizable optimally-doped crystals. In this article, we report on results of STM/STS measurements on optimally-doped $Ca_{2-x}Na_xCuO_2Cl_2$ and discuss the possible coexistence of CB and superconductivity.

2. Experimental

Single crystals of optimally-doped $Ca_{2-x}Na_xCuO_2Cl_2$ with $T_c = 25$ K were grown by a flux method under high pressure [4]. STM/STS measurements were performed with a newly-developed ultra-high-vacuum very-low-temperature STM. Sample surface was prepared by *in situ* cleaving along (001) plane. Differential conductance dI/dV spectrum, which is a measure of the LDOS, was taken at every pixel of the topographic STM image to make a spectroscopic map. Measurements were performed in the temperature range between 0.4 K and 20 K.

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3. Results and discussion

Fig. 1 shows a constant-current STM image and a simultaneously acquired dI/dV map taken at energy $E = +25$ meV. In underdoped samples, the CB modulation has been clearly observed around this energy [3]. It is obvious that the CB modulation is also observed in the present optimally-doped sample. Namely, the CB modulation is a robust feature in $Ca_{2-x}Na_xCuO_2Cl_2$.

Typical tunneling spectrum shows V-shaped pseudo-gap, which characterizes the CB state, below $|E| \sim 100$ meV [3]. To look for the spectroscopic evidence of superconductivity, we performed detailed low-energy spectroscopy inside of the pseudo-gap. We found that another gap opens below $|E| \sim 10$ meV. The low-energy gap accompanies coherence-peak-like structures at the gap edges and reminds us of a superconducting gap.

The low-energy gap is spatially-inhomogeneous. To analyze the gap variation, we classify the gap according to its magnitude. As shown in Fig. 2a, smaller gap has sharper gap-edge peak. This behavior is similar to that for the superconducting gap of $Bi_2Sr_2CaCu_2O_8$ [5]. Next we examined the temperature effect. Fig. 2b shows the temperature evolution of the spectrum taken at the position indicated in Fig. 1a. Thin solid line overlaid on the 20 K spectrum denotes the thermally broadened 0.4 K spectrum. It is clear that the observed 20 K spectrum is more broadened than expected. Although we could not go beyond the transition temperature T_c, this result suggests that the gap is closing or buried toward T_c. The same tendency is commonly observed over the field of view.

The observed temperature effect and the similarity between the low-energy gap and the superconducting gap

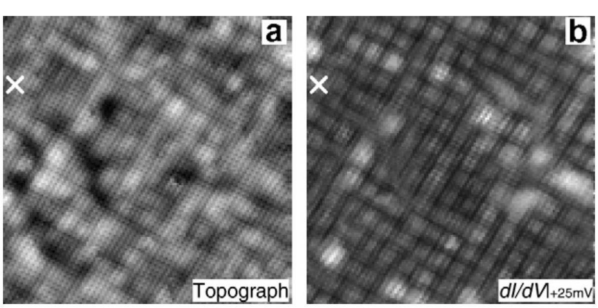

Fig. 1. (a) Constant-current STM topograph and (b) simultaneously acquired dI/dV map at +25 meV. Feedback loop was stabilized at a sample bias voltage/tunneling current of +150 mV/0.1 nA. Scan size: 20 nm × 20 nm. Temperature: 0.4 K. White cross denotes the position where spectra shown in Fig. 2b were taken.

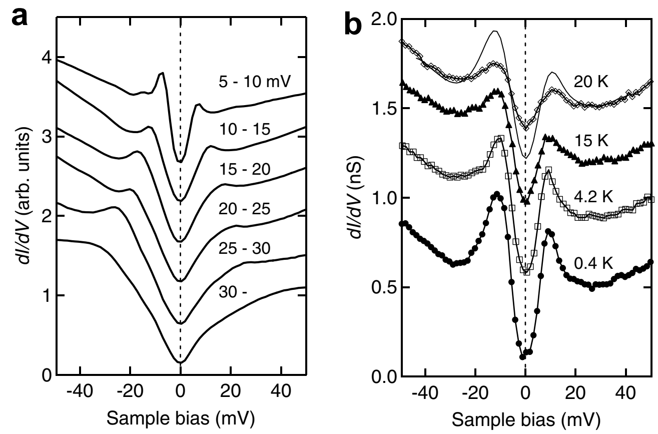

Fig. 2. (a) Average tunneling spectrum associated with each gap magnitude in a given field of view. Each curve is shifted vertically. (b) Temperature dependence of the tunneling spectra taken at the position indicated in Fig. 1. Each curve is shifted vertically.

of $Bi_2Sr_2CaCu_2O_8$ strongly suggest that the low-energy gap in $Ca_{2-x}Na_xCuO_2Cl_2$ is originated from superconductivity. The magnitude of the low-energy gap of $Ca_{2-x}Na_xCuO_2Cl_2$ is about 1/3–1/4 of the superconducting gap of $Bi_2Sr_2CaCu_2O_8$. This is naturally understood by considering the difference in T_c.

Finally, we examined the spatial variation of the low-energy gap. We found that the gap is inhomogeneous but ubiquitous. Namely, superconductivity may coexist with the CB modulation. The gap-edge peak shows a wide variety of shapes. In the field of view shown in Fig. 1, 16% of the spectra show no peak and 49% of the spectra show single-sided peak either in the filled (8%) or empty (41%) states. The position where no peak is observed is always at the dark "perimeter" of the CB plaquette. Such a close correlation between the peak and CB indicates the interplay between superconductivity and the CB modulation.

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