Spatial Correlation between the LDOS Modulation and Electronic Inhomogeneity in Bi$_{2}$Sr$_{2-x}$La$_{x}$CuO$_{6+\delta}$

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Abstract. Low-temperature scanning tunneling microscopy has been performed on underdoped Bi$_{2}$Sr$_{1.4}$La$_{0.6}$CuO$_{6+\delta}$ ($T_c \sim 29$ K) at 4.2 K to observe the non-dispersive spatial modulation of local density of states (LDOS). The LDOS modulation is along the Cu–O–Cu directions and its period is about $4\alpha_0$, though the period is slightly distributed over the surface. The correlation between the modulation period and the nanoscale electronic inhomogeneity, which is represented by the spatial variation of the low-energy integrated LDOS (ILDOS), was analyzed. The result exhibits clear tendency of that the period in the low-ILDOS region is slightly shorter than that in the high-ILDOS region.

1. Introduction

Recently scanning tunneling microscope (STM) has been extensively used to investigate the local density of states (LDOS) at nanometer scale in cuprate high-$T_c$ superconductors. Several spatial variations of LDOS intrinsically exist in the cuprate have been revealed by the STM studies. One is the electronic inhomogeneity, which is the nanoscale spatial variation of both the gap magnitude and the low-energy (below the gap energy) integrated LDOS (ILDOS) [1–5]. The origin of the inhomogeneity is unclear to date, however, the dopant ions probably play a key role in the doped cuprates [6]. Another is the two-dimensional periodic modulation of LDOS. There are two types of the LDOS modulation—energy dispersive modulation and non-dispersive one. The former is well explained by the quasiparticle interference [7], and the latter is thought to be due to a charge order [8–12].

Our previous STM study on the optimally doped Bi$_2$Sr$_{2-x}$La$_x$CuO$_{6+\delta}$ (La-Bi2201) revealed the existence of LDOS modulation, which is along the Cu–O–Cu bonding directions and has a period of about $5\alpha_0$ [11], where $\alpha_0$ is the Cu–O–Cu distance. The observed LDOS modulation is non-dispersive within our experimental accuracy. To search for the origin of the modulation, recently we have investigated the doping dependence of the LDOS modulation [13]. We found that as decreasing hole concentration from optimum doping, the modulation period decreases ($\sim 4\alpha_0$ in underdoped regime) while the direction is kept constant.

Here we present the STM observation of the LDOS modulation in underdoped La-Bi2201. We have found that the modulation period was spatially distributed over the surface and correlates with the low-energy ILDOS; the period in the low-ILDOS region is slightly shorter than that in the high-ILDOS region. This means that the LDOS modulation is affected by the inhomogeneous local electronic states.
Figure 1. (a) Typical low-bias constant current image (45 × 45 nm², V = 45 mV, I = 15 pA) exhibiting the two-dimensional LDOS modulation along the Cu–O–Cu bonding directions. The inset shows spatially averaged tunneling spectrum, which has a broad gap with ∼ 100 meV and pronounced bias asymmetry typical for the underdoped cuprates. (b) Fourier transform of (a) showing the peaks corresponding to the atomic sites (labeled A), the b-axis supermodulation (labeled S), and the LDOS modulation (labeled M). Here, the axes in q-space (qx and qy) are taken along the Cu–O–Cu bonding directions. (c) Low-pass filtered image of (a). The cutoff wave number is ∼ 0.06 × (2π/a₀). (d) Binarized image of (c). The scan area is divided into two regions: high-ILDOS (white) region A and low-ILDOS (black) region B.

2. Experimental
An underdoped La-Bi2201 (x = 0.6) single crystal was grown by using floating zone technique. The crystal was cut into small pieces (∼ 1 × 1 × 0.05 mm³) and then annealed in air at 750°C for 24 hours to increase oxygen homogeneity. The onset temperature of the superconducting transition observed by magnetization measurements was 29 K. The STM measurements were performed by a laboratory-build low-temperature STM at 4.2 K. The sample mounted in the STM was cleaved in situ at 4.2 K prior to the measurements.

3. Results and Discussion
Figure 1a shows a characteristic constant current image of ab (BiO) plane taken at the sample bias voltage V = 45 mV. The scan area of 45 × 45 nm² was taken to satisfy the requirements of both the real space atomic resolution and the sufficient q-space resolution of ∼ 0.01 × (2π/a₀). The image shows the well-known structure of the surface Bi atoms and the b-axis supermodulation.

In addition to the crystalline structure, Fig. 1a reveals spatial variations of the ILDOS, because the tunneling current is proportional to both the tip-surface distance and ILDOS from 0(≡ E_F) to eV. As mentioned earlier, below the gap energy, the low-energy LDOS in La-Bi2201 shows two kinds of spatial variation: the two-dimensional periodic modulation and the inhomogeneous variation at nanoscale [11]. As shown in the inset of Fig. 1a, the spatially averaged gap value of this sample is about 100 meV. Thus, the bias voltage of 45 mV is sufficiently below the gap energy. As a result, both the LDOS modulation and the inhomogeneous background are simultaneously observed in the low-bias image superimposed over the surface structures.

To investigate the periodicity of the LDOS modulation, Fourier transform of Fig. 1a is shown in Fig. 1b. The Fourier peaks correspond to the modulation appear around the origin...
with four-fold symmetry (labeled M), and the Fourier components in the vicinity of the origin represent the inhomogeneous background. The peaks M appear at \( \sim (\pm 2\pi/4a_0, 0), (0, \pm 2\pi/4a_0) \), indicating that the LDOS modulates along the Cu–O–Cu directions with a periodicity of about \( 4a_0 \). However, the period of the modulation seems to be slightly distributed over the surface, resulting in the broad feature of the Fourier peaks.

Looking closely the low-bias STM image, we have noticed that the modulation period correlates with the nanoscale inhomogeneity; the period in the dark (low-ILDOS) region seems to be shorter than that in the bright (high-ILDOS) region. To check whether such a correlation really exists, masked Fourier analysis was performed. First, to extract the spatial pattern of the electronic inhomogeneity, the original image (Fig. 1a) was low-pass filtered to smooth out features smaller than about 6 nm (Fig. 1c). Next, to create the masks corresponding to the high- and low-ILDOS regions, the low-pass filtered image was binarized as shown in Fig. 1d; the regions A and B correspond to the high- and low-ILDOS regions, respectively. Finally, the regions A and B were Fourier transformed separately. The results of the masked Fourier transforms are shown in Fig. 2. The peak M in the original image is located at \( |q| \sim 0.22–0.25 \ (2\pi/a_0) \) corresponding to the periodicity of \( \sim 4.0–4.5a_0 \). The masked Fourier analysis illuminates the difference of the modulation period in the regions A and B. In region A, the peak appears at \( |q| \sim 0.22(2\pi/a_0) \), and in region B, it appears at \( |q| \sim 0.25(2\pi/a_0) \). We have investigated several other scan areas, and the results exhibit clear tendency of that the period in the low-ILDOS region is shorter than that in the high-ILDOS region. This indicates that there certainly exists correlation between the modulation period and the inhomogeneity.

In the previous study, we have investigated the doping dependence of the period of the LDOS modulation in La-Bi2201 [11, 13]. It was found that the spatially averaged period is about \( 5.5a_0 \) in the optimum doping \( (x = 0.4) \) and is shortened with decreasing hole concentration; it is about \( 4.2a_0 \) in the underdoped regime \( (x = 0.6) \) and reaches \( \sim 3.6a_0 \) in the strongly underdoped (non-superconducting) sample with \( x = 1.0 \). In the present study, we found that the modulation period spatially correlates with the low-energy ILDOS. It is known that the electronic inhomogeneity is manifested by the spatial variation of both the low-energy ILDOS
and the gap magnitude; these quantities well correlate with each other—as the gap magnitude increases, the low-energy ILDOS is suppressed [1]. Therefore, we can interpret our results as the spatial correlation between the modulation period and the local gap magnitude, i.e., the modulation in the region exhibiting large gap has shorter period than that in the region with small gap. Furthermore, when the doping level decreases, the average gap magnitude increases. Hence, by using the gap magnitude as a parameter, both the spatial and doping variations of the modulation period can be described; there is a negative correlation between the modulation period and the gap magnitude (the larger gap corresponds to the shorter period). Note that we do not mention that the two phenomena, the LDOS modulation and the energy gap, are directly associated—they are probably connected indirectly. Our result suggests that the LDOS modulation is also affected by the mechanism that causes the nanoscale electronic inhomogeneity and the doping evolution of the gap magnitude.

4. Conclusion

The LDOS modulation in underdoped La-Bi2201 ($x = 0.6$, $T_c \sim 29$ K) was observed by low-temperature STM at 4.2 K. The modulation is along the Cu-O-Cu directions and the period is about $4a_0$. We found that the modulation period was slightly distributed over the surface. It was evidenced from the masked Fourier analysis that the period correlates with the nanoscale inhomogeneity; the period in the low-ILDOS region tends to be shorter ($\sim 4.0a_0$) than that in the high-ILDOS region ($\sim 4.5a_0$). Since the ILDOS is associated with the local gap magnitude, this result can be interpreted as the correlation between the LDOS modulation and the gap magnitude. As a result, both the spatial and doping variations of the modulation period agree with each other in terms of the gap magnitude. It seems that the LDOS modulation is also affected by the mechanism that causes the nanoscale electronic inhomogeneity and the increase of gap magnitude with underdoping. The origin of the LDOS modulation, such as the charge order and/or the quasiparticle interference, is still unclear. We believe that the observed correlation between the LDOS modulation and the electronic inhomogeneity is informative for considering the origin.

References

[1] Pan S H, O’Neal J P, Badzey R L, Chamon C, Ding H, Engelbrecht J R, Wang Z, Eisaki H, Uchida S, Gupta A K, Nq K W, Hudson E W, Lang K M and Davis J C 2001 Nature (London) 413 282
[2] Alldredge J W, Lee J, McElroy K, Wang M, Fujita K, Kohsaka Y, Taylor C, Eisaki H, Uchida S, Hirschfeld P J and Davis J C 2008 Nature Phys. 4 319
[3] Sugimoto A, Kashiwaya S, Eisaki H, Kashiwaya H, Tsuchiura H, Tanaka Y, Fujita K and Uchida S 2006 Phys. Rev. B 74 094503
[4] Kato T, Okitsu S and Sakata H 2005 Phys. Rev. B 72 144518
[5] Kato T, Maruyama T, Okitsu S and Sakata H 2008 J. Phys. Soc. Jpn. 77 054710
[6] McElroy K, Lee J, Slezak J A, Lee D H, Eisaki H, Uchida S and Davis J C 2005 Science 309 1048
[7] McElroy K, Simmons R W, Hoffman J E, Lee D H, Orenstein J, Eisaki H, Uchida S and Davis J C 2003 Nature (London) 422 592
[8] Hanaguri T, Lupien C, Kohsaka Y, Lee D H, Azuma M, Takano M, Takagi H and Davis J C 2004 Nature (London) 430 1001
[9] Vershinin M, Misra S, Ono S, Abe Y, Ando Y and Yazdani A 2004 Science 303 1995
[10] Momono N, Hashimoto A, Kobatake Y, Oda M and Ido M 2005 J. Phys. Soc. Jpn. 74 2400
[11] Machida T, Kamijo Y, Harada K, Noguchi T, Saito R, Kato T and Sakata H 2006 J. Phys. Soc. Jpn. 75 083708
[12] Saito R, Tsuji N, Noguchi T, Machida T, Kato T and Sakata H 2008 Physica C 468 876
[13] Machida T, Kato T, Kamijo Y, Miyashita R, Sakuyama T, Harada K, Saito R, Noguchi T and Sakata H in preparation.