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Columnar defect-induced strain and superconductivity in $Bi_2Sr_2CaCu_2O_x$ observed by LT-STS/STM

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Abstract

Superconductivity and crystalline structure around columnar defects in $Bi_2Sr_2CaCu_2O_x$ have been studied by low temperature scanning tunneling spectroscopy and microscopy (LT-STS/STM) and transmission electron microscopy (TEM). Columnar defects have been generated by irradiation with 3.5 GeV $^{135}Xe^{31+}$ ions, 3.8 GeV $^{181}Ta^{37+}$ ions and 3.1 GeV $^{209}Bi^{37+}$ ions and the columnar defects-induced strain has been observed by TEM and LT-STM. The magnitude of the strain has been estimated to be 0.1–0.01% in the region of 6 nm from a columnar defect. The strain induced by a columnar defect does not bring about a remarkable change in the superconductivity in $Bi_2Sr_2CaCu_2O_x$.

Keywords: Scanning tunneling spectroscopies; Scanning tunneling microscopy; Superconductivity

The properties of high temperature copper-oxide superconductors (HTSC) are sensitive to a change of the interatomic distance. The superconducting transition temperature (T_c) can be raised by applying high pressure. Hydrostatic pressure of 31 GPa brought about the increase of T_c in $HgBa_2Ca_2Cu_3O_8$ from 133 to 164 K [1], which is the record of the highest T_c among superconductors. Recently, a uniaxial strain on HTSC has attracted attention. The $La_{1.9}Sr_{0.1}CuO_4$, whose T_c is about 25 K, has been found to exhibit an increase of T_c up to 49 K, which is 100% increase, when the thin film is epitaxially grown on $LaSrAlO_4$ substrate [2]. Due to a mismatch of lattice parameters the lattice is compressed by an amount of 0.6% in the CuO_2 plane (*ab*-plane). In HTSC the derivative of T_c with respect to the uniaxial pressure parallel to the *ab*-plane has the opposite sign to that perpendicular to the *ab*-plane. Under hydrostatic pressure a large increase of T_c cannot be expected.

In HTSC the irradiation with high energy heavy ions generates columnar defects which are amorphous regions along the ion tracks and have a diameter of several nanometers [3]. A columnar defect induces strain in the surrounding crystalline region because the volume of the amorphous region is locally increased. This strain can be regarded as the uniaxial strain. A compressive strain is induced to a lattice in the radial direction around a columnar defect and a tensile strain in the tangential direction. Zhu et al. have observed

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the strain around columnar defects in $YBa_2Cu_3O_{7-\delta}$ by dark field image of transmission electron microscopy (TEM) [4] and their analysis of TEM image showed that the magnitude of strain amounts to 2% at the interface of a columnar defect and the matrix region [5]. This value of strain is comparable to the one in $La_{1.9}Sr_{0.1}CuO_4$ with epitaxial compression [2] and it is expected that superconductivity might be changed around a columnar defect. We have irradiated $Bi_2Sr_2CaCu_2O_x$ single crystals with 3.5 GeV $^{135}Xe^{31+}$ ions, 3.8 GeV $^{181}Ta^{37+}$ ions and 3.1 GeV $^{209}Bi^{37+}$ ions at RIKEN Ring Cyclotron and studied the generated columnar defects by low temperature scanning tunneling spectroscopy and microscopy (LT-STS/STM) and TEM. A columnar defect can be observed as an amorphous region on the TEM. From TEM studies of columnar defects we have found that each ion produces a single columnar defect since the density of columnar defect in $Bi_2Sr_2CaCu_2O_x$ coincides with the one calculated from the dose of heavy ions. The sizes of columnar defects are 5.8 ± 1.4 nm in diameter for Xe-irradiated samples, 8.3 ± 0.7 nm for Ta-irradiated samples and 10.8 ± 0.9 nm for Bi-irradiated samples. The diameter of the columnar defects increases with the increase of the mass of the heavy ion. The strain around a columnar defect can be detected by the careful observation of TEM. Fig. 1 shows a dark field [0 2 0] image of $Bi_2Sr_2CaCu_2O_x$ which was irradiated by 3.5 GeV $^{135}Xe^{31+}$ ions. This image is viewed along the ion track. The lobe-shaped contrast is observed along the line of [0 2 0] direction around columnar defects. This contrast represents a strain of the crystal around columnar defects. The contrast disappears in the direction perpendicular to the diffraction vector, because the displacement field of the strain radiates from the defect. We have succeeded in observing the strain around columnar defects by LT-STM and measured the local density of states of superconducting quasi-particles, $N_S(E, \mathbf{r})$, around them by LT-STS.

The STM/STS measurements were performed with our laboratory-made STM which is able to be operated at temperatures down to 2.2 K and in magnetic fields up to 14.5 T. $Bi_2Sr_2CaCu_2O_x$ single crystals with a superconducting transition temperature $T_c \approx 86$ K were grown by using the traveling solvent floating-zone method. For the measurement of STM/STS we have prepared very clean surfaces of $Bi_2Sr_2CaCu_2O_x$ by cleaving the sample at liquid helium temperature [6].

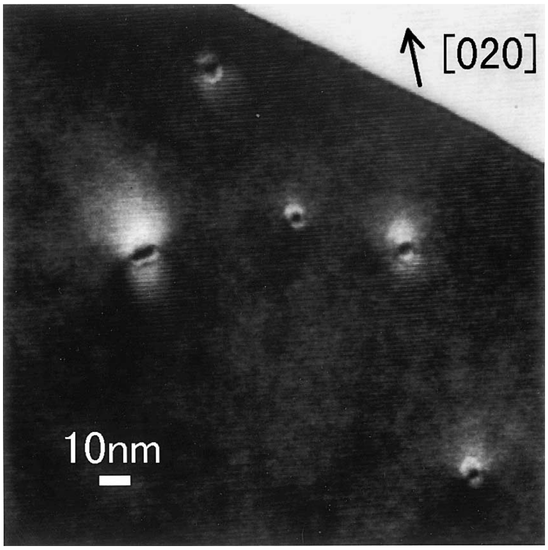

Fig. 1. TEM image with a diffraction vector [0 2 0] of $Bi_2Sr_2CaCu_2O_x$. Columnar defects were generated by irradiation of 3.5 GeV $^{135}Xe^{31+}$ ions and this image was viewed along the ion track. Strain contrast surrounding columnar defects is visible along the [0 2 0] direction.

The samples were irradiated along two directions; perpendicular to the *ab*-plane or [0 0 1] direction and almost parallel to the *ab*-plane or [1 0 0] direction. In our previous report of STS measurements on $Bi_2Sr_2CaCu_2O_x$ with columnar defects, we have investigated the sample which is irradiated with ions perpendicular to the *ab*-plane and discussed the orbital symmetry of Cooper pairing [7]. Here we mainly report the study of the sample of parallel irradiation by 3.8 GeV $^{181}Ta^{37+}$ ion and discuss how a columnar defect-induced strain affects the superconductivity.

Fig. 2 shows an STM image of a columnar defect which is seen as a black region and an elongated shape. This image was acquired in the constant current mode of STM on the *ab*-plane surface of cleaved $Bi_2Sr_2CaCu_2O_x$ and the vertical motions of an STM tip are imaged. The electronic states of a columnar defect were found to be insulating, because a columnar defect is imaged as a

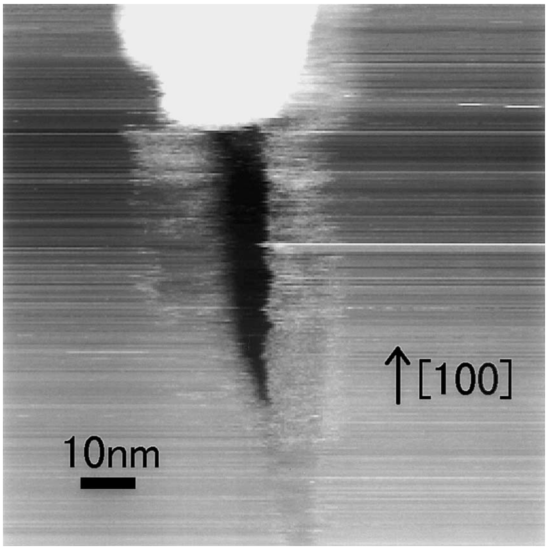

Fig. 2. Constant-current STM image of a columnar defect in $Bi_2Sr_2CaCu_2O_x$ obtained at 4.2 K with tunneling current of 0.2 nA and bias voltage of 0.5 V. The columnar defect was generated by irradiation of 3.8 GeV $^{181}Ta^{37+}$ ion injected with the angle 5° against *ab*-plane and along the [1 0 0] direction. The black color of the columnar defect means that a columnar defect is insulating.

region where an STM tip approaches the surface. In the STM observation the columnar defect is to be observed as an ellipsoid with the long axis along ion track, because the intersection of a column appears as an ellipsoid on the cleaved plane. Thus, the width of the black region in this image corresponds to the diameter of the columnar defect. The obtained value of 8 nm is consistent with the one observed by TEM. From the shape of the columnar defect in the STM image, we are able to estimate the injection angle of the heavy ions from the ratio of the width to the length of the defect; the ratio is about 1:10 and the injection angle is estimated to be about $\sin^{-1}(1/10) \sim 5°$.

A constant current STM image on the *ab*-plane where a columnar defect runs beneath is shown in Fig. 3(a). The white region runs along the [1 0 0] direction in the middle part of the image. The superstructure of the $Bi_2Sr_2CaCu_2O_x$ is also seen as a modulation with about 25 Å cycle along the [0 1 0] direction. The depth of the columnar defect was estimated to be about 6 nm from the distance from the columnar defect imaged at the surface and the injection angle of heavy ions. As described below, the STS results taken along the line in Fig. 3(a) show that the white region is not caused by the change of the electronic states of the surface but by the geometrical protrusion due to the columnar defect.

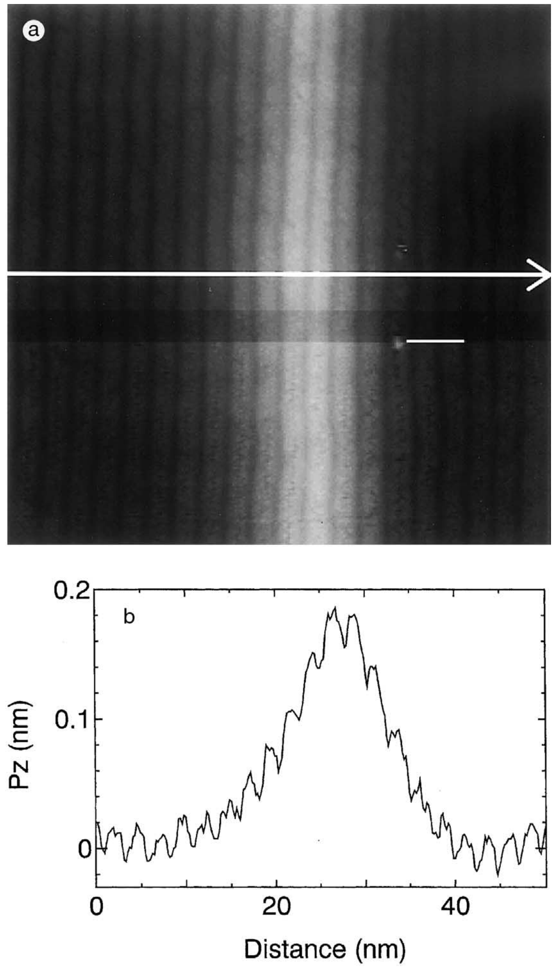

Fig. 3. (a) Constant-current STM topographic image (50 × 50 nm^2) of *ab*-plane of $Bi_2Sr_2CaCu_2O_x$ (4.2 K, 0.2 nA, 0.5 V). A columnar defect runs along the [1 0 0] direction 6 nm beneath the surface. (b) Perpendicular motion of the tip, P_Z, along the line in image (a).

We measured current–voltage (*I–V*) characteristics at 64 points every 0.78 nm spacing and calculated differential conductance spectra $dI/dV(V)$ numerically. The results are shown in Fig. 4. All

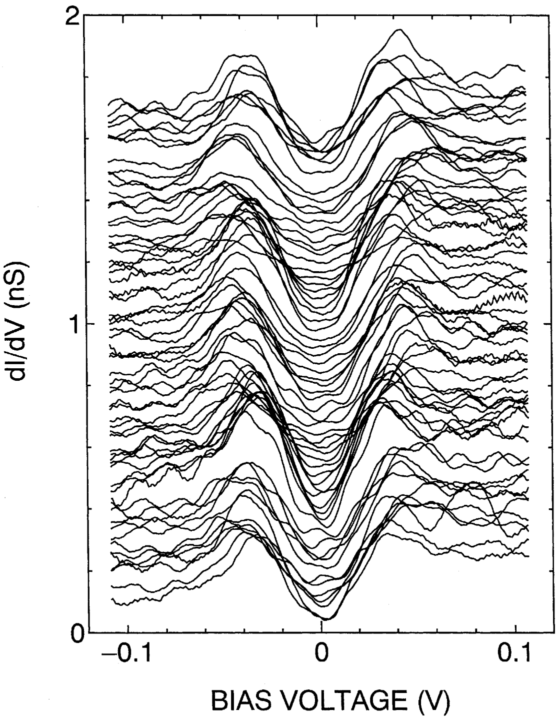

Fig. 4. Differential conductance spectra taken at 64 points along the line in Fig. 3(a). Each spectrum is shifted vertically every 0.025 ns.

measured spectra exhibit a superconducting energy gap with a metallic background. This shape corresponds to the one observed on the *ab*-plane of unirradiated $Bi_2Sr_2CaCu_2O_x$ [6,8]. Since the electronic states in this place are metallic everywhere, the distance between the STM tip and surface is constant. Therefore, the white region in the STM image indicates that the surface rises geometrically and this is the image of the strain observed by STM.

As seen in the profile of the STM image in Fig. 3(b), the swell of the surface is about a few tenths of nanometer high and 20 nm wide. The height of the swell decreases gradually as the position is away from the columnar defect, while the width of the swell is almost the same. From the profile of the STM we can make a rough estimation of the tensile strain on the *ab*-plane. In the region where a columnar defect runs beneath, atoms are pushed up and the distance between atoms expands in the *ab*-plane. The slope at the steepest position is about 1°, so that the expansion or tensile strain is calculated as 0.02% from $1/\cos 1° = 1.0002$. It would be reasonable to think that the strain is largest at the top of the swell. We have estimated the tensile strain in this region to be 0.1–0.01%.

The superconductivity around the columnar defect is considered from the STS data in Fig. 4. On the s-wave superconductors with a Cooper pairing of weak coupling, T_cs are proportional to the values of the superconducting gap, Δ; $2\Delta/k_BT_c = 3.53$. In the present $Bi_2Sr_2CaCu_2O_x$ with $T_c = 86$ K, the value of peak voltage in a tunneling spectrum, Δ_p, has been measured and $2\Delta_p/k_BT_c$ is 8–11 for $T_c = 86$ K [6]. At the present the relation between Δ_p and T_c has not been clearly understood. If Δ_p is proportional to T_c in HTSC, T_c will be locally changed around the columnar defect and the change of Δ_p will be observed. Fig. 5 shows the position dependence of Δ_p along the line in Fig. 2(a) which is obtained from tunneling spectra in Fig. 4. The value of Δ_p fluctuates between 30 and 50 mV probably due to oxygen vacancies with a length scale of several nanometers which corresponds to the superconducting coherence length ξ. Δ_p does not show an additional change in the region where the surface rises; the change of Δ_p in Fig. 5 does not correlate with the swell of the surface. It can be said that in $Bi_2Sr_2CaCu_2O_x$ the strain of the order of 0.1–0.01% does not bring

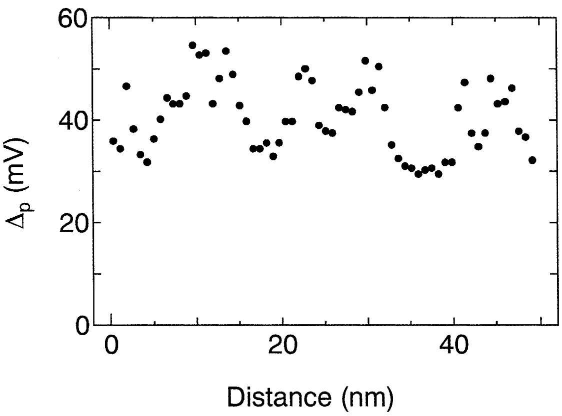

Fig. 5. Position dependence of peak voltage at the superconducting gap, Δ_p, in tunneling spectra in Fig. 4. Average of the peak voltages above and below the Fermi energy is plotted.

about a remarkable change in superconductivity within error. The local fluctuation of Δ_p due to inhomogeneities of the sample dominated over the influence of local strain in Δ_p.

In case of the columnar defect running perpendicular to the *ab*-plane, the compressive strain on the *ab*-plane is induced around it. We have measured $N_S(E, \mathbf{r})$ around a columnar defect and found the change of $N_S(E, \mathbf{r})$ in the region about 5 nm around it [7]; $N_S(E, \mathbf{r})$ exhibits the increase at $E = 0$ meV and the decrease at $E \sim \Delta_p$ at [1 1 0] and $[\overline{1}\,1\,0]$ directions in CuO_2 plane. However, Δ_p does not show a significant change around the columnar defect and the superconductivity is not changed appreciably by the compressive strain induced by the columnar defect. The change of $N_S(E, \mathbf{r})$ has been considered as the boundary effects of $d_{x^2-y^2}$-wave superconductors [9].

In summary we have studied strains and superconductivity around columnar defects by LT-STM/STS and TEM. On the sample irradiated with heavy ions almost parallel to the *ab*-plane, we have observed a swell of the surface by LT-STM which comes from a strain due to a columnar defect running beneath the surface. From the STM image we have estimated the tensile strain in the *ab*-plane as 0.1–0.01%. From the studies of LT-STS around columnar defects, we have found that the columnar defect-induced strain does not so much affect the value of superconducting gap, whether it is tensile or compressive.

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