Quasiparticle spectra and their spatial variation on $YBa_2Cu_3O_y$ by scanning tunneling spectroscopy

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Abstract

We have carried out low temperature scanning tunneling microscopy/spectroscopy (STM/STS) on $YBa_2Cu_3O_y$(YBCO) and succeeded in observing vortices and quasiparticle state inside the vortex core. In this paper, we present experimental details of STS measurement and its results. Samples are chemically etched with 1% Br-ethanol to achieve suitable surface condition for STS study. Observed vortices have differences in its shape but arranges in relatively ordered configuration. The spectra of the vortex core shows localized states at $V_{\mathrm{sample}} \simeq \pm 5$ mV which does not consistent with the core state in pure $d_{x^2-y^2}$ order parameter.

Key words: Scanning tunneling spectroscopy; Quasiparticle density of state; $YBa_2Cu_3O_y$

STM/STS is a powerful tool for detecting local density of state (LDOS) modulation from the perturbation by impurity or external magnetic field. Recently, application of STM/STS to the high temperature superconductor (HTSC), especially to $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212), have achieved much success for unveiling novel properties of HTSC[1–4]. In this study, we treat YBCO which is the major HTSC material but not enough studied by STM/STS. We report on imaging of vortices and observation of quasiparticle density of state around vortex core, which is an important first step to uncover the complex vortex state of HTSC.

YBCO single crystals are grown by self-flux method using Y_2O_3 crucible. Slightly overdoped crystals($T_c \sim$ 90 K, $\Delta T_c \sim 1.5$ K) prepared by annealing in 1 bar oxygen at 450°C are used in this study. The post-annealed samples are chemically etched with 1% Br in ethanol for a minute, then rinsed in ethanol, immediately transferred into the loadlock chamber to be high vacuum condition. Surface prepared with this method is stable and does not degrade by exposing in ultra-high vacuum (UHV) up to room temperature, in contrast to the surface prepared by the cleaving[5,6]. This surface characteristic implies that the topmost layer of the etched sample is neither highly reactive BaO layer nor CuO-chain layer. At present we can't determine the topmost layer because we can't obtain atomic image of the etched surface. We can observe clear step structures which have one unit cell step height and twin boundary which is observed as a straight hollow of less than 1 Å deep. At zero magnetic field, clear superconducting energy gap is observed for entire scan region of over 1 μm square field without any insulating terrace. STS measurements are carried out in UHV condition (10^{-10} Torr) at $T = 4.5$ K in $\mu_0 H = 1$ T (field cooled) applied parallel to the c-axis. Tip used in this study is mechanically sharpened Pt/Ir wire, mounted perpendicularly to the (001) surface of YBCO. Typical tunneling parameters are $I = 0.1$ nA, $V_{\mathrm{sample}} = 0.03$ V. We proceed measurement by dividing measuring field into typically 64×64 or 128×128 regions and taking $I - V$ curve at each point, which takes a time of about 5 and 20 hours, respectively. Differential conductance which is proportional to the LDOS is derived by differ-

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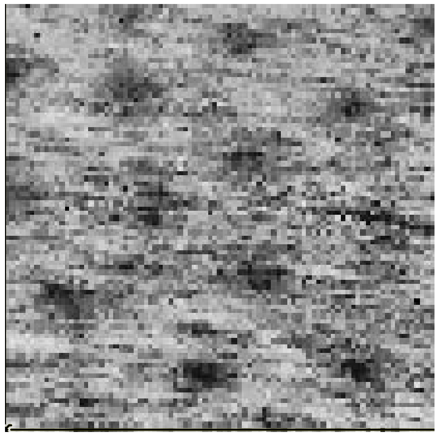

Fig. 1. Spectroscopic image of the vortices at $T = 4.2$ K, $\mu_0 H = 1$ T. The image is obtained as the ratio of the DOS map of $V_{\text{sample}} = 20$ mV to 0 mV, taken on 1500 Å square field of view and not filtered.

entiating the $I - V$ curves.

Figure 1 shows spectroscopic image of vortices which is taken over 1500 Å×1500 Å area. In this figure, the dark regions correspond to the vortex core. Spacing between them is about 500 Å which agrees with the calculated value of $a_{\triangle} = 490$ Å. One can see that vortices show slight difference in its shape, probably due to the influence of impurity and fluctuation. Due to the fluctuation, vortices show tiny motion even in the vortex solid state. But vortices at relatively strong pinning site will be limited its motion to narrower region than the others, result in seemingly smaller vortex core. This is one of some possibilities, of course. There may be other explanation, for example the influence of inhomogeneous superconducting state reported in Bi2212[2]. But this is very delicate problem and beyond the subject of this paper. The vortex core arrangement shows not so disordered as that in Bi2212[4]. According to our study on the vortex phase diagram of untwinned YBCO, vortex state in this temperature and magnetic field region is supposed to be the Bragg glass (vortex lattice) phase which have long range translational order[8]. At present we can't conclude the vortex state as Bragg glass phase and spectroscopy for wider range will be necessary to determine this point.

Figure 2 shows typical spectra obtained inside and outside the vortex core. The spectra outside vortex core show clear superconducting energy gap, in contrast to that inside vortex core which shows quasiparticle bound states at $V_{\text{sample}} \simeq \pm 5$ mV. The split of quasiparticle bound state is not explained with the core state in pure $d_{x^2-y^2}$ order parameter. These feature are quite similar to the results by Maggio-Aprile *et al.*[7]. In this study, we observe another type of spectra inside vortex core region typically represented in the inset of Fig. 2, which shows peak structure at zero sample bias.

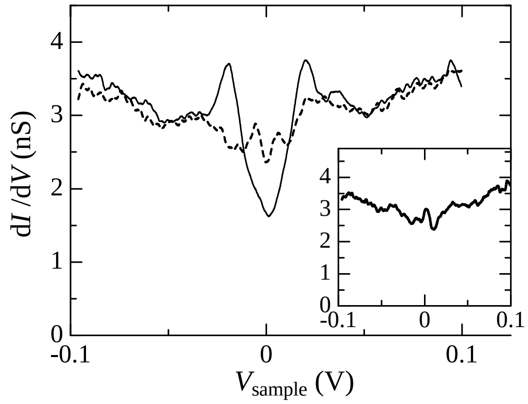

Fig. 2. typical spectra observed inside (dotted line) and outside (solid line) the vortex core. The inset shows third type spectrum at vortex core site.

This third type spectrum is not always observed, which suggests that this spectrum reflects the weak impurity scattering at the impurity or defect site. In that case, it is quite reasonable to observe this at vortex core region because it is well known that impurities and defects in the superconductor easily traps vortices, especially in HTSC.

We have succeeded in imaging vortices at several temperatures up to 80 K, though images become unclear at higher temperatures. This makes it possible that we observe structural changes of the vortex matter system due to the phase transition[8]. The experiments for that are in progress.

In summary, we have carried out STS measurement on YBCO and observed vortices and quasiparticle DOS around vortex core. These results are the important first steps for elucidating the complex features of the vortex state in HTSC

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