Spatial correlation between impurity states and energy gap distribution in Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Zn$_x$)$_2$O$_{8+\delta}$ (x = 0.02)

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Abstract. We have performed scanning tunneling spectroscopy (STS) measurements on slightly over doped Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Zn$_x$)$_2$O$_{8+\delta}$ (x = 0.02) to investigate spatial correlation between the impurity states and the local gap value. In addition to several impurity states, the spatial variation of energy gap has been observed. The gap values are spatially distributed from 20 meV to 55 meV with the length scale of about 5 nm. The impurity states appear only in the regions whose gap values are less than 50 meV. Furthermore, the number of Zn impurity states estimated from STS results is slightly less than that of doped Zn atoms estimated by inductively-coupled-plasma-mass-spectroscopy. Our results insist that there exist the impurity sites without the resonant states and those impurities are located on the region with the gap value of more than 50 meV.

1. Introduction

Scanning tunneling spectroscopy (STS) technique allows us to measure local electronic density of states (LDOS) with atomic resolution. This technique has been used to study the interesting phenomena of cuprate superconductors [1]-[4]. In Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Zn-Bi2212), Pan et al. observed the LDOS around the non-magnetic Zn impurity. In the tunneling spectrum at the Zn site, a sharp peak appears at the energy of -1.5 meV [1]. There are several theoretical possibilities to interpret this near-zero-energy-peak (NZEP) [5]-[7]. One of the possibilities is the impurity-scattering resonance scenarios. Kruis et al. insist that pseudogap state rather than superconductivity is necessary to form the NZEP [5]. Another possibility is Andreev resonance scenario. In this scenario, the NZEP appears at a local non-superconducting site surrounded by a superconducting region as the bound state [6].

Another interesting feature observed by the STS technique is the spatial distribution of superconducting gap in Bi2212. The superconducting gap ($\Delta$) varies from 20 meV to 65 meV on a length scale of about 5 nm and the tunneling spectrum changes distinctly in its shape [2]-[4]. Fang et al.[4] and Lang et al.[2] claimed that there exist two distinct phases. One is a relatively small gap region ($\Delta \leq 35$ meV), in which the peak in LDOS at $V = \Delta$ is relatively

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Figure 1. (a) Conductance map at -1.5 mV. The inset shows typical STM image on the cleaved surface of Zn-doped Bi2212. (b) Averaged tunneling spectra. The red and black dots are obtained by averaging over all impurity sites and over all regions, respectively. (c) Gap map on the same field of view of (a). The gap values are shown by the color corresponding to the color in the color scale. (d) Tunneling spectra averaged over the each gap value. The color of each spectrum corresponds to that in (c).

sharp in energy and the peak height is very large. another regions have a larger gap, with $\Delta \geq 50$ meV, and broad and small peaks. They insisted that the small gap regions are identified as the region of good superconductivity, whereas the larger gap regions are like a pseudogap phase which competes with superconductivity. If the larger gap regions are non-superconducting phase, the spatial correlation between the distribution of the larger gap region and the location of the NZEP can be used to confirm whether the superconductivity is crucial or not to form the NZEP. In this study, we have investigated the spatial correlation between the gap distribution and the location of the Zn impurity resonant states in Zn-doped Bi2212.

2. Experimental
The samples used in our experiments are $\text{Bi}_2\text{Sr}_2\text{Ca}(\text{Cu}_{1-x}\text{Zn}_x)_2\text{O}_{8+\delta}$ single crystals grown by the floating zone method. In the crystal growth, we use the polycrystalline rod whose nominal concentration of Zn was about 2%, while the Zn percentage per Cu in the single crystal, verified by inductively coupled plasma mass spectroscopy (ICP-MS), was 0.5%. The Zn concentration in the single crystal is smaller than the nominal Zn concentration in the polycrystalline rod. The superconducting transition temperature ($T_c$) of this single crystal was determined to be 85 K by SQUID magnetization measurement. We use the STM produced by UNISOK for our STM/STS experiments. We cleaved the sample in situ at 20 K in the vacuum about $10^{-7}$ Torr and performed immediately STM/STS measurements after the cleavage. The inset of Fig.1 (a) is a typical topographic image of the sample surface with atomic resolution. This image shows the incommensurate supermodulation with a period of 2.2 nm along the $b$-axis. The STS
Figure 2. Analysis of spatial correlation between the local gap value and Zn resonance. We chose the site where the conductance at -1.5 mV are more than 4 nS in the conductance map of Fig.1 (a) as the resonant site. (a) Location of Zn resonance site (black circles) superimposed on the simultaneously taken the gap map. (b) Histograms of gap value. Gray and red histograms show the percentage of each gap value on the all regions and at the all impurity resonance site, respectively. These histograms are obtain form the STS results in three different regions whose size are 25 nm × 25 nm.

3. Results and Discussions

Figure 1(a) shows the conductance image of 25 nm × 25 nm region at the bias voltage of -1.5 mV. As the local density of states (LDOS) is proportional to the differential conductance, this map shows the LDOS map at the energy of -1.5 meV. In this image, several bright spots can be seen. The tunneling spectrum averaged over all bright spots, as shown in the red dots in Fig.1 (b), has the clear peak near $E_F$. This NZEP structure can be observed in the spectra at all bright site in Fig.1 (a). These peaks in the spectra taken at the bright sites appear at the energy of -1.5 ±0.5 mV and have the height of about 4.5 nS which is about ten times greater than the conductance at -1.5 mV in the dark region. The apparent number density of the bright spots within this area is about 0.35% per Cu atoms which is in the same order as $x = 0.5\%$, which is the doping concentration of Zn in the single crystal estimated by ICP-MS measurements. Since all of these features at the bright spots are theoretically predicted at a single impurity site in $d$-wave superconductors and are very similar to the results reported by Pan et al. [1], it can be considered that the observed spectra at the bright site show the LDOS at the Zn sites.

Figure 1(c) shows a gap map for the same field of view as in Fig. 1(a). The gap value, $\Delta$, defined by the energy at the coherence peak above the Fermi energy, is distributed from 20 to 55 meV, and varies on a length scale of about 5 nm. The averaged spectrum of all regions exhibiting a given local $\Delta$ is shown in Fig. 1(d). This figure indicates that the coherence peaks diminish in strength with increasing $\Delta$. Since this reduction is almost same as the results by other groups [2][4], the region with relatively larger $\Delta$ ($\geq 50$ meV) appears to be like a pseudogap region.

We have investigated the spatial correlation between the locations of the NZEP and gap distribution. Figure 2(a) shows the positions of the NZEP superimposed on the gap map shown in Fig. 1(c). No NZEP are observed in any region where $\Delta \geq 45$ meV. To clarify the correlation between the NZEP and $\Delta$, we plot two histograms of local $\Delta$ at the locations appearing NZEP (red histogram) and all locations (gray histogram) in Fig.2 (b). As shown in red histogram, the local $\Delta$ at the locations of the NZEP is distributed from 20 meV to 45 meV, although those in all region are distributed from 20 to 55 meV. From above analysis, one can confirm that the
NZEP disappear in the region whose $\Delta \geq 45$ meV. Furthermore, in our analysis, the number of the NZEP (0.35% per Cu atom) was slightly less than that of Zn atoms in the single crystal (0.5% per Cu atom). This comparison between the number of the NZEP and that of the Zn atoms means that the site without the NZEP exists, although the Zn impurity located on that site.

Our results imply that the NZEP does not appear at the Zn site in the region with $\Delta \geq 45$ meV. Fang et al.[4] and Lang et al.[2] have suggested that the region with the larger $\Delta$ is like a pseudo gap region which competes with superconductivity. If the region with the $\Delta \geq 45$ meV in our sample is pseudo gap phase, the superconductivity is crucial to form the NZEP around Zn impurity site. Hence, the Andreev resonance scenario in which the superconductivity is crucial to form the NZEP seems to be valid to explain our results. To understand more precisely the origin of the NZEP, further investigations such as the doping and the temperature dependence of the NZEP should be necessary.

4. Summary

We have performed STS measurements on slightly over doped $\text{Bi}_2\text{Sr}_2\text{Ca(Cu}_{1-x}\text{Zn}_x)\text{O}_8^{+\delta}(x = 0.02)$ to investigate spatial correlation between the location of the impurity states and the inhomogeneous gap($\Delta$) distribution. The impurity states at the energy of -1.5 meV appear in the region with the relatively smaller gap value (20 meV $\leq \Delta \leq 45$ meV), although the $\Delta$ is distributed from 20 meV to 55 meV in all region. Furthermore, the number of the impurity states estimated from STS results is slightly less than the number of the Zn atoms estimated by Inductively-coupled-plasma-mass-spectroscopy. Our results and analysis show that there exist the impurity sites without the resonance states, although those impurities are located on the region with $\Delta \geq 50$ meV.

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6. References

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