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Impurity Effects on the Energy Gap in Fe-doped Bi2212

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Abstract
We performed scanning tunnelling microscopy/spectroscopy (STM/STS) on Fe-doped Bi2212. The Fe substitution for Cu causes a strong spatial inhomogeneity in STS spectra. The energy gap ($\Delta_1 \sim 80mV$) has a sub-gap ($\Delta_2 \sim 70mV$) in some distinct locations on the sample surface. We find that the gap edge peaks are largely depressed and only the sub-gap survives across the region where the spatial modulation of the local density of states is stronger. This indicates, that Δ_1 anti-correlates with Δ_2.

Keywords: Superconductors, Strongly correlated electronic systems, Bi2212, STM/STS

1 Introduction

The influence of impurities on superconductivity is an important characteristic of high-Tc cuprates [1][2]. A slight doping of impurities into the Cu-O plane strongly suppresses the superconductivity [3][4]. In conventional superconductors, it is well-known that magnetic impurities, which break time-reversal symmetry, suppress the superconductivity more strongly than the non-magnetic impurities [5]. However in high-Tc cuprates, the suppression of superconductivity due to magnetic impurities such as Ni is weaker in comparison to non-magnetic impurities such as Zn. It was pointed out that the spin of Ni correlates with the surrounding Cu spins, which causes the pair-breaking effects in Ni-doped samples to be weaker than in Zn-doped samples. These results are supported by STM/STS experiments, which reported that Zn impurities induce a bound (resonant) state near the Fermi level [6]. The energy gap is strongly suppressed at this point, while the Ni impurities induce a resonant state away from the Fermi level, where the energy gap is preserved. Recently, it was reported that the so-called stripe correlation is strongly enhanced in the underdoped regions near doping level p=1/8 in

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Fe-doped LSCO [7], although the effects of impurity on the charge order is not yet fully understood. To understand the relationship between the charge order and the superconductivity, it will be necessary to investigate the impurity effects on both the superconductivity and the charge order in detail. In the present study, we report the results of STM/STS measurements of Fe-free and Fe-doped samples of the overdoped BI2212 to investigate the impurity effects on the energy gap in the superconducting state with the LDoS modulation.

2 Experiments

The STM/STS measurements were performed at 8.5K, using the low temperature STM/STS apparatus of UNISOKU Co. LTD. The single crystals of Fe-free (pure) and the Fe-doped Bi2212 were grown by using the Travelling Solvent Floating Zone (TSFZ) method. Both samples were grown simultaneously under the same conditions. The onset transition temperature (T_c^{onset}) of the pure and the Fe-doped Bi2212, determined by superconducting diamagnetic curves, was estimated to be 82K and 72K, respectively. The Fe concentration, determined by the Curie term of uniform magnetic susceptibility is about 1.7% per Cu atom. We cleaved our crystals in situ in an ultrahigh vacuum just before tip-approach.

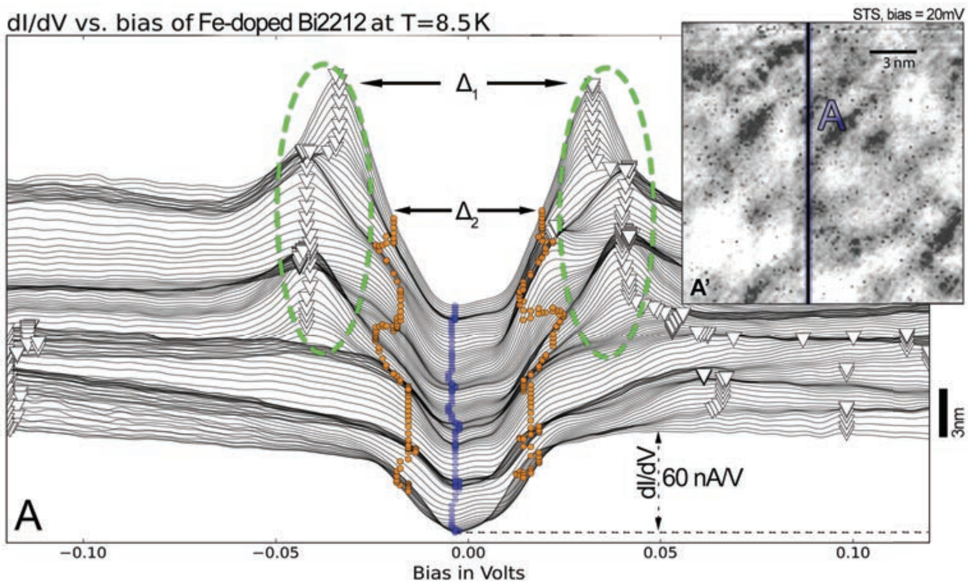

Figure 1: Spatial dependence of the STS spectra for the Fe-doped Bi2212 sample along the blue line shown in the inset image A'. The dashed green ellipses highlight the position of the gap edge peaks and correspond to the dashed green line in Figure 3. The white triangles and the yellow circles represent the gap width Δ_1 and Δ_2. The blue dashed line represents the minimum values. Inset: The LDoS map of Fe-doped Bi2212 at 20 mV.

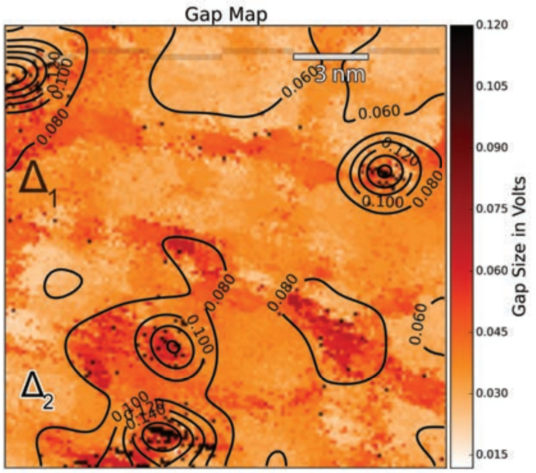

Figure 2: The gap map of overdoped Fe-free Bi2212. The colormap represents the gap size determined from the d^2I/dV^2 extrema (Δ_2). The contour map presents the gap map obtained from the coherence peak bias difference (Δ_1). The contour map representing Δ_1 is in agreement with the the colormap representing Δ_2.

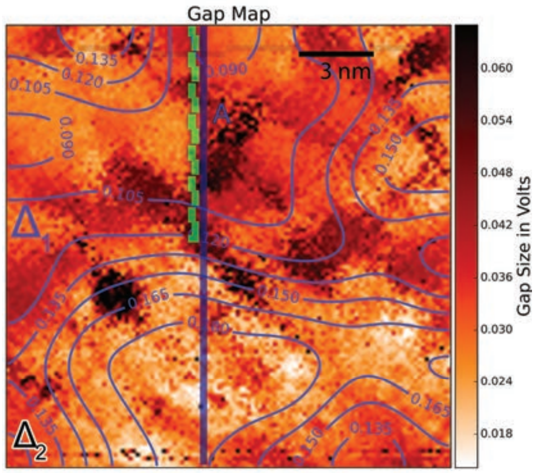

Figure 3: The gap map of Fe-doped Bi2212 was determined from the bias difference between the extremal values of the d^2I/dV^2 map (Δ_2). The gap size values (Δ_2) in the gap map are adjusted to present the true gap size by normalising according to the average gap size Δ_{Fe}. The contour overlay represents Δ_1.
The blue line and green dashed line correspond to the green dashed ellipses and the dI/dV plots in Figure 1 A.

3 Results & Discussion

Figure 1 shows the spatial dependence of the STS spectra for the Fe-doped Bi2212 sample. The appearance of the pure overdoped Bi2212 spectrum is in agreement to previous research [8] and shows no additional features. The averaged spectrum of Fe-free Bi2212 shows a typical d-wave-like V-shaped gap with peaks at the gap edges. The averaged spectrum of Fe-doped Bi2212 shows a zero bias conductance feature. The bottom part of gap rises, resulting in nearly U-shaped gap with the gap minimum slightly shifted. This recovery of the LDoS around E_F is caused by Fe impurities. A similar suppression of the superconducting gap has been found in Zn-Bi2212 and Ni-Bi2212 by A. Mourachkine [9]. The average energy gap size, determined from peak-to-peak energy, is $\Delta_s \sim 73$ mV for Fe-free B2212 and $\Delta_{Fe} \sim 79$ mV for Fe-doped B2212. Figure 1 A' shows the topographic image of dI/dV at +20 mV for Fe-doped Bi2212. The dI/dV image representing the Fe-doped samples shows small defects, which are isotropically distributed over the surface (Fig. 1 A'). The $18nm \times 18nm$ large scan contains about 50 defects, which were extracted by subtracting the background and selecting outliers with $dI/dV > 2\sigma$ (σ: standard deviation). The density of the defects is consistent with the measured Fe content of about 1.7% per Cu atom. The LDoS modulation with $Q \sim 0.2$ was observed in Fe-doped samples, as well as Fe-free samples (Fig. 1 A'). In the present study, the direct correlation between the defect's position and the LDoS modulation pattern is not clear. It could be ascribed to the relatively high density of defects, leading to averaging the effect of each defect. The influence of Fe impurities on the sample was further analysed by inspecting the dI/dV spectra and determining the energy gap size Δ for each pixel position. Because, we can find slight shoulders, in other words, the sub-gap structure inside the gap of Δ_1 at some positions (Fig. 1). The gap size was determined using two different methods. One is the conventional method, which is to locate the maximum dI/dV value on both sides of the bias spectrum (Δ_1). In the other one, to determine the size of the sub-gap inside Δ_1, we focus on the extreme values of the derivative of the dI/dV spectra and define the sub-gap size Δ_2 as their bias difference. The Δ_2 corresponds to the size of sub-gap if it exists. If dI/dV shows a single gap, Δ_2 corresponds simply to the spacing between the steepest part in dI/dV curve and Δ_2 should be scaled to Δ_1. The Gap maps of Δ_2 for Fe-free and Fe-doped Bi2212 are presented in Figures 2 and 3. In these gap maps of Δ_2, the contour maps for Δ_1 are superimposed. The gap size Δ_1 and Δ_2 for Fe-free sample show similar spatial dependence (Fig. 2). This indicates, that the locations of the steepest part between the gap edge peaks and the location of the actual peaks is shifting similarly, consisting with the single gap for the Fe-free overdoped sample. The gap map of Fe-doped Bi2212 shows a different pattern (Fig. 3). The upper part of the gap map (near and around the dashed green line) in Figure 3 looks similar to the gap map in Figure 2; the gap size Δ_1 and Δ_2 show similar spatial dependence. In the lower part of Figure 3, the contour map of Δ_1 takes large values but the colormap of Δ_2 takes smaller than average values. In those areas there is an inverse correlation between Δ_1 and Δ_2. In Figure 1, the STS spectra at the positions where the contour map of Δ_1 takes large values corresponds to those of the lower part where the gap edge peaks have disappeared completely. Interestingly, in the lower part of the LDoS maps, the modulation tends to be stronger (Fig 1 A'). In Fe-doped samples, the superconductivity effect seems to break down on larger spots where the LDoS modulation is stronger.

4 Conclusion

In Fe-doped Bi2212, Fe sites can be detected as defects in the LDoS image. However the direct correlation between the Fe locations and the LDoS modulation is not clear. The Fe impurities cause a strong spatial inhomogeneity in the STS spectra. The STS spectra of Fe-doped Bi2212 show a U-shaped gap (Δ_1) with a sub-gap structure (Δ_2) and a finite DOS around E_F. The gap edge peak around $E = \Delta_1/2$ in Fe-doped samples are strongly depressed and only the sub-gap of ($\sim \Delta_2$) survives over the region where the LDoS modulation tends to be stronger.

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