Electronic Raman Scattering in Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Abstract. The Raman scattering spectra of optimally doped Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Zn$_x$)$_2$O$_{8+\delta}$ (x=0 and x=0.01) have been measured below and above the superconducting transition temperature $T_c$. In $B_{1g}$ Raman spectrum, a broad pair-breaking peak is observed at $T_b\ll T_c$ for x=0.01 as well as for Zn free Bi2212. The peak energy of the $B_{1g}$ spectrum for x=0.01 (~350 cm$^{-1}$) is much smaller than that of the Zn-free sample (~510 cm$^{-1}$), suggesting that the (effective) superconducting gap is largely suppressed by 1% Zn-doping.

1. Introduction

In the high $T_c$ superconductors (HTSC), the energy gap in the normal state, the so-called pseudogap, has intensively been studied as functions of temperature and momentum. The pseudogap develops below a temperature $T^*$ ($>T_c$) around the Fermi surface near ($\pi$, 0) and (0, $\pi$), which is called as antinodal region [1]. At $T<T_c$, the superconducting gap develops at the ungapped parts of the Fermi surface near ($\pi/2$, $\pi/2$), which is called as nodal region. It was reported from angle-resolved photoemission spectroscopy (ARPES) and scanning tunneling microscopy/spectroscopy (STM/STS) that the pseudogap evolves into the superconducting gap continuously with decreasing temperature, suggesting a close relation between the pseudogap and the superconducting gap [1, 2].

Recently it was reported from electronic Raman spectroscopy (ERS), ARPES and STM/STS that the gap magnitude at $T_b<<T_c$ shows a different doping dependence between node and antinode; the gap magnitude monotonically increases around antinodes with decreasing doping level, while it decreases or remains nearly constant around nodes [3-5]. This suggests that the pseudogap, developing around the antinodal region, is irrelevant to the superconducting gap around the nodal region. Very recently, in YBa$_2$Cu$_{3}$O$_{7-\delta}$ (Y123), the difference of the gap nature between around node and antinode was investigated by ERS from viewpoints of impurity effects [6, 7]. The gap around node at $T_b<<T_c$ is completely suppressed by substitution of a small amount of Zn for Cu, while the gap around antinode at $T_b<<T_c$ is not suppressed at all although the gap is largely smeared. This result also suggests that the gap nature is different between node and antinode, although these impurity effects on the energy gap are still controversial [8].

In Y123, ARPES and STS measurements are very difficult because of surface sensitivity. In Bi-based cuprates such as Bi2212, many ARPES and STS experiments have so far been performed, which facilitates comparison of results between different experiments. In the present study, we investigated the impurity effects on the energy gap at $T_b<<T_c$ by Raman spectroscopy on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$.
with optimal doping level. In Raman scattering measurement on HTSC, $B_{1g}$ and $B_{2g}$ spectra mainly reflect the electronic states at the Fermi surface around antinodal and nodal regions, respectively. We present the $B_{1g}$ and $B_{2g}$ electronic Raman spectra below $T_c$ in Zn-doped Bi2212.

2. Experimental

Single crystals of Zn free and Zn-doped Bi2212 were prepared using traveling solvent floating zone method and flux method [9]. The Zn free Bi2212 crystals prepared by the two methods show almost the same $T_c$-value (~91K), where $T_c$ was determined by diamagnetic transition curves. This $T_c$-value of Zn free Bi2212 crystals guarantees that the crystals are optimal doping. To dope Zn at the Cu site in a desired amount, we adopted the flux method in the present study. The Zn-doped Bi2212 sample shows $T_c$$\sim$78 K. The experimental conditions of the crystal growth in the flux method and post annealing were the same between Zn free and Zn-doped Bi2212 samples. Then one can expect that doping level $p$ of Zn-doped samples is almost the same as that of Zn free samples because the substitution of Zn for Cu does not change hole doping level. The Zn concentration (~1%) was examined by Electron Probe Micro-Analysis (EPMA) experiments. The reduction of $T_c$ by Zn impurity, $\Delta T_c$, is ~13 K/Zn%, which is consistent with results already reported [10].

The Raman measurements were performed on cleaved surfaces in a quasibackscattering geometry using triple spectrometer equipped with a charge-coupled device detector. The 514.5 nm line of an Ar$^+$ ion laser with an incident intensity of ~10W/cm$^2$ was used as excitation source. The laser heating effect was estimated to be less than ~10K. Raman spectra were measured in $XY$ ($B_{2g}$) and $X'Y'$ ($B_{1g}$) polarizations, where $X$ and $Y$ are parallel to the Cu-O bonds and $X'$ and $Y'$ are at 45 degrees from Cu-O bonds. In the present Raman experiments, we could not exclude the effects of elastic scatterings in the very low energy region below ~200 cm$^{-1}$. Then we show the Raman spectra above ~200 cm$^{-1}$.

Figure 1. $B_{1g}$ Raman spectra in Zn free Bi2212 with optimal doping at 90 K ($T$$\sim$$T_c$) and 7 K ($T$$<<$$T_c$).

3. Results and discussion

Figure 1 represents the $B_{1g}$ Raman spectra at $T$=90 K ($T$$\sim$$T_c$) and 7 K ($T$$<<$$T_c$) for Zn free Bi2212 sample with optimal doping level $p_{opt}$. In the $B_{1g}$ spectrum at 7K, we observe a broad hump, which is due to the superconductivity and referred to as pair-breaking peak. The peak energy corresponds to the gap magnitude 2$\Delta$. To focus on the pair-breaking peak, we extracted the change of the Raman spectrum induced by the superconductivity; that is, we subtracted the $B_{1g}$ spectrum at 90 K from that at 7 K. Here we used the original Raman spectrum for the subtraction, not the Raman susceptibility corrected by $n(\omega, T)+1$, where $n(\omega, T)$ is the Bose factor. This is because the difference between them is too small at $E$$>$$\sim$200 cm$^{-1}$ in the present temperature range to affect the determination of the peak energy. Shown in Fig. 2(a) is the obtained difference spectrum in $B_{1g}$ channel. The $B_{1g}$ difference spectrum for Zn free Bi2212 shows a broad peak around $E_g$$\sim$510 cm$^{-1}$. The peak energy provides gap magnitude
at the Fermi surface close to antinode because $B_{1g}$ spectrum mainly probes the electronic states on the Fermi surface at antinode. Figure 2(b) exhibits Raman difference spectrum in the $B_{2g}$ channel, which was obtained by subtracting the $B_{2g}$ spectrum at 100 K ($>T_c$) from that at 10 K ($<<T_c$). The $B_{2g}$ difference spectrum shows a broad peak around $E_g \approx 400$ cm$^{-1}$, which is lower than that of the $B_{1g}$ difference spectrum. These gap magnitudes around antinode and node are consistent with other experimental results such as ARPES, tunneling spectroscopy and neutron experiments, and fall on the $E_{pg}$-$p$ and $E_{sc}$-$p$ curves reported [5].

Figure 3(a) shows $B_{1g}$ Raman difference spectrum for 1% Zn-doped Bi2212 with $p-p_{opt}$, which is difference between $B_{1g}$ spectra at 80 K ($\sim T_c$) and at 7 K ($<<T_c$). The $B_{1g}$ difference spectrum for the Zn-doped sample shows a pair-breaking peak around $E_g \approx 350$ cm$^{-1}$, meaning that the gap magnitude around antinode is $\sim 350$ cm$^{-1}$. This value is much lower than that of the Zn free sample. The ratio of the gap magnitude, $E_g(x=0.01)/E_{g0} \approx 0.7$, is smaller than that of $T_c$, $T_c(x=0.01)/T_{c0} \approx 0.86$. This large suppression of the gap around antinode is inconsistent with the recent result reported in Y123, in which the $B_{1g}$ pair-breaking peak in the Zn-doped Y123 does not change in position [6, 7]. Figure 3(b) exhibits $B_{2g}$ Raman difference spectrum for 1% Zn-doped Bi2212 with $p-p_{opt}$, which is difference between at 80 K ($\sim T_c$) and at 7 K ($<<T_c$). One can not find a pair-breaking peak at least above 200 cm$^{-1}$, indicating that the energy gap around node is reduced below 200 cm$^{-1}$ by Zn doping. This result on the $B_{2g}$ difference spectra is consistent with that reported in Y123 [7].

On the basis of a pair-breaking model for a $d$-wave superconductor in the unitary limit, it was reported that the relative anisotropy of the pair-breaking peak energies in the $B_{1g}$ and $B_{2g}$ spectra is robust for impurity doping [11]. As mentioned above, the ratio of the $B_{1g}$ pair-breaking peak energy between the Zn free and Zn-doped samples is $\sim 0.7$. If we simply assume this ratio to be available to the gap around node, the $B_{2g}$ pair-breaking peak is expected to appear around $\sim 280$ cm$^{-1}$. Unfortunately, it is not clear whether or not the $B_{2g}$ pair-breaking peak exists there in the present study. It should be noted that the theoretical model is based on the assumption that a $d$-wave superconducting gap develops over the entire Fermi surface, including both antinodal and nodal regions and the gap is homogeneously suppressed in real space. These are incompatible with the recent results of ARPES and STM/STS [1, 3, 12].

Figure 2. Raman difference spectra for $B_{1g}$ and $B_{2g}$ channels in Zn free Bi2212.
Recently, it was reported from tunneling experiments, specific heat measurements, ARPES and ERS that the energy scale in determining $T_c$ in HTSC is not the maximal gap at the Fermi surface around antinode but an effective superconducting gap on the so-called Fermi arc [1-3, 13, 14]. In addition, ARPES recently reported that the Fermi arc length for optimally doped sample is close to the full length of the Fermi surface [3, 14]. Hence we can conclude that the present $B_{1g}$ and $B_{2g}$ difference spectra for optimal doping will probe the electronic states at the Fermi arc and the effective superconducting gap over the Fermi arc will be suppressed by Zn-doping.

4. Conclusion
We have presented the impurity effects on the electronic Raman spectra in Zn-doped Bi2212. The gap magnitudes at the Fermi surface around both antinode and node are largely suppressed by 1% Zn-doping, suggesting that the effective superconducting gap, detected in both $B_{1g}$ and $B_{2g}$ spectra, is suppressed by Zn doping. More detailed experiments will be needed to fully understand the impurity effects on HTSC.

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