The scanning tunneling spectroscopy (STS) technique based on scanning tunneling microscope (STM) enables us to measure local electronic density of states (LDOS) in atomic scale. So far, there have been a lot of important studies to investigate the key mechanism of high temperature superconductors at atomic scale. The origin of the near-zero-energy peak (NZEP) is usually considered as the impurity-scattering resonant state because Zn-impurity has a strong scattering potential.

Salkola and co-workers considered quasiparticle scattering from a repulsive $\delta$-potential impurity using the $T$-matrix approach and derived the resonant state within this area is about 0.2% which is in the same order. In this work, we report on the temperature dependence of NZEP in Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals grown by the floating zone method (the superconducting transition temperature $T_c = 89$ K, nominal $x = 0.6\%$). They are cleaved at 100 K below $1 \times 10^{-7}$ Pa and then cooled to 30 mK. The data were taken during subsequent warming up to 52 K. We used an electrochemically etched tungsten wire for STM tips. The STS measurements were performed by lock-in technique with a modulation amplitude of 0.50 mV and a frequency of 411.7 or 511.7 Hz. It takes typically 24 hours to obtain an STS image of 128×128 pixels. It was crucial to keep the temperature variations within $\pm 1\%$ at $T \geq 20$ K to avoid unexpected tip crushes and thermal drifts of the STS data.

In Fig.1(a)-(d), we show the STS data of the cleaved surface of Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ obtained at $T = 30$ mK. Figure 1(a) shows a topographic image. The inset is a magnified topographic image but on a different surface of Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212). On the Cu-O plane, they observed a tunnel spectrum with a sharp peak at the energy ($-1.5$ meV) slightly below the Fermi level ($E_F$) and cross-shaped fourfold quasiparticle spatial distributions. The origin of the NZEP is still a matter of debate. To test these scenarios, measuring the temperature evolution of the NZEP should be one of the key experiments. If the Kondo resonance scenario is correct, the peak weight of the NZEP will increase at $T < T_K$. The value of $T_K$ is estimated about 15 K from the measured peak energy of $-1.5$ meV. In this paper, we report on the temperature dependence of NZEP in Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals grown by the floating zone method (the superconducting transition temperature $T_c = 89$ K, nominal $x = 0.6\%$). They are cleaved at 100 K below $1 \times 10^{-7}$ Pa and then cooled to 30 mK. The data were taken during subsequent warming up to 52 K. We used an electrochemically etched tungsten wire for STM tips. The STS measurements were performed by lock-in technique with a modulation amplitude of 0.50 mV and a frequency of 411.7 or 511.7 Hz. It takes typically 24 hours to obtain an STS image of 128×128 pixels. It was crucial to keep the temperature variations within $\pm 1\%$ at $T \geq 20$ K to avoid unexpected tip crushes and thermal drifts of the STS data.
The NZEP smears out, of Fig. 2(a) is different from that of Fig. 1(b). Note that the scan area increasing peak height, and increasing peak width with increasing temperature up to 52 K. The peak energy is decreasing peak height, and increasing peak width with increasing temperature up to 52 K. The peak energy is determined as $-0.8 \pm 2.4$ meV at all the temperatures we studied. It scatters fairly largely impurity to impurity presumably due to different scattering potentials. It is difficult to determine the peak height precisely since we averaged the spectra over $6-18$ positions around the impurity although it is very sensitive to the exact tip location with respect to the impurity site. These curves are not obtained on the same Zn impurity atom. Nevertheless, we emphasize that the NZEPs certainly exist even at high temperatures. The decrease of the NZEP height with increasing temperature seems to be well explained by the thermal broadening effect as seen in Fig. 3(a). Here the dashed lines are calculated spectra based on the 1.8-K data taking account of the thermal broadening effect in the Fermi distribution function.

Figure 3(b) shows the temperature dependence of full-width at half maximum of NZEP (d). The peak width is insensitive to the averaging around the same impurity. The increase of $d$ at higher temperatures above 20 K shows the thermal broadening effect since the dashed line $(d(mV)=5.0+1.2k_BT)$ represents the experimental data fairly well. The intrinsic width $(d_0=5.0 \text{ mV})$ below 2 K is similar to that obtained by Pan et al. [4].

We carried out STS measurement in a magnetic field of 6 T at $T=2$ K. We observed the similar width $(\sim 6 \text{ mV})$ of NZEP to that obtained in zero field. Pan et al. also reported no significant field dependence of $d_0$ between 0 and 7 T [24]. The Zeeman splitting energy should be about 0.4 meV at $B=6$ T [25]. This is hard to be detected in our measurement since it is much smaller than $d_0$. We also note that the field of 6 T is too low to break up the Kondo singlet [26].

Let us now discuss the origin of the NZEP. At first, according to the Kondo resonance scenario, it is predicted that the broadened Kondo peak still survives almost up to $T_s$ in spite of $T_K < T_s$ [27]. The temperature dependence of the peak weight becomes weaker above $T_K$. Thus, only the existence of the NZEP at $T > T_K$ does not mean straightforwardly the relevance of the Kondo resonance scenario. Next, let us consider the impurity-scattering resonance scenario further from the viewpoint whether superconductivity is crucial or not. According to the calculation by Kruis et al. [12] and Balatsky et al. [12], superconductivity is unnecessary to form the
impurity-induced resonant state. Thus, they claim that the NZEP will be observed even in the pseudo-gap region ($T > T_c$). On the other hand, there are arguments that the Andreev resonance in unconventional superconductor is the origin of the NZEP. The quasiparticle scattering with sign change of the pair potential results in the resonant state $28, 22, 30$. This is observed in the tunnel junction experiments, for example, by Iguchi et al. $31$. The multiple Andreev scattering around a surface impurity will form the NZEP. Future STS experiments for the pseudo-gap phase in the under-doped regime would discriminate these two possibilities.

In summary, we measured the temperature dependence of near-zero-energy peak (NZEP) in Zn-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$. The NZEPs are clearly observed up to 52 K with thermal broadening. This result provides an important hint to understand the origin of the NZEP.

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