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Two sizes of superconducting gaps on an under-doped $Bi_{2.1}Sr_{1.9}Ca_2Cu_3O_{10+\delta}$ with $T_C \sim 101$ K by tunneling spectroscopy

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Abstract

We measured tunneling conductances on an under-doped trilayer cuprate $Bi_{2.1}Sr_{1.9}Ca_2Cu_3O_{10+\delta}$ (Bi2223) with $T_C \sim 101$ K by a point contact method, which has three CuO_2 planes in a unit cell. The tunneling conductances on Bi2223 exhibited two sizes of gaps originated from outer and inner CuO_2 plane (OP and IP). The estimated size of superconducting gap from OP Δ_{OP} is 34 ± 6 meV, and the Δ_{IP} from IP is 51 ± 5 meV, respectively. We also observed tunneling conductances which simultaneously displayed two superconducting peaks of OP and IP. Moreover, we propose the model of two superconductor-insulator-normal metal junctions which exhibit two sizes gaps of OP and IP.

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Keywords: UD-Bi2223; Tunneling spectroscopy; Multi-layer cuprates; Two-gaps

1. Introduction

Multilayer cuprates with $n \geq 3$ (n: number of CuO_2 planes in a unit cell) have two kinds of crystallographycally inequivarent CuO_2 planes (an inner plane (IP) with four-fold oxygen coordination and outer planes (OP) with five-fold oxygen coordination). The investigations for multilayer cuprates have been extensively performed by nuclear magnetic resonance (NMR). On NMR studies, the each hole concentration for OP and IP was estimated from the Knight shift, and it is now clear that the hole concentration in OP is always higher than that in IP [1]. According to tunneling studies on $Bi_2Sr_2Ca_{n-1}Cu_nO_y$ with n=1 and 2, the magnitude of the superconducting gap Δ decreases with increasing the hole concentration [2,3], and this behavior would be universal for all hole-doped cuprates. Combining

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these reports, on spectroscopic studies of multilayer cuprates with $n \geq 3$, we expect to observe the two sizes of gaps originated from OP and IP. However, there is no report that successfully observed these two-kinds of gaps in the previous studies on Bi2223 using STM/STS [4-6]. Moreover, most of angle resolved photoemission spectroscopy (ARPES) experiments on Bi2223, also report single size of gap [7-10]. On the other hand, our previous tunneling conductances using the point contact technique on various multilayer cuprates with $n \geq 3$ exhibited two sizes of gaps [11-14]. Here, we performed the point contact tunneling measurement on Bi2223 to observe two sizes of gaps with OP and IP. In this paper, we report the first observation of the two sizes of gaps on Bi2223 by the point contact tunneling spectroscopy. Furthermore, we discuss why we successfully observed both OP- and IP-gaps on Bi2223 by the point contact tunneling.

2. Experimental details

A Bi2223 single crystal was prepared by a floating zone (FZ) method. The growth rate was ~~of~~ 0.03 mm/h with a steep temperature gradient. The growth atmosphere was Air flow. The T_C for the as-grown sample was 108 K, which was determined by dc-resistivity measurements. To obtain an under-doped sample, the sample was annealed at 600°C for 50 h in 0.1% O_2 flow [15]. As shown in Fig.1a, the X-ray diffraction pattern shows the only sharp Bi2223 peaks, no impurity phases were observed. The magnetic susceptibility measurement shows single step at 101 K, showing no secondary phases such as Bi2212 and Bi2201, where the T_C was determined as 101 K (see Fig.1b). The SIN tunneling junctions were prepared by a point contact tunneling using an Au-tip along *c*-axis. The d*I*/d*V*s were measured by the ac lock-in technique at 4.2 K. The junction area between an Au-tip and a sample was less than ϕ 200 μm. 62 junctions are formed from one sample.

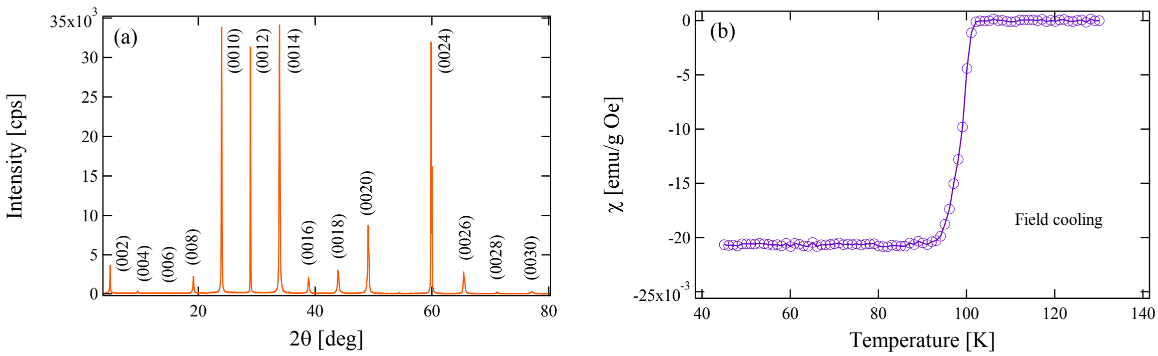

Figure.1 Sample property on UD-Bi2223. (a) X-ray diffraction measurement. (b) Magnetic susceptibility measurement. The T_C was determined as 101 K

3. Results and discussion

Figure 2a shows typical tunneling conductances on the under-doped Bi2223 (UD-Bi2223). The general features of tunneling conductances on the UD-Bi2223 are almost the same as that of bilayer cuprates, Bi2212 and $TlBa_2CaCu_2O_{6.5+\delta}$ [2,16]. That is, as shown in Fig. 2a, the spectra display not only the peak-dip-hump structures but also the *d*-wave like sub-gap shape. Based on our tunneling results, we notice that the observed peak position of peaks spread from 29 mV to 56 mV. However, if we plot the histogram on gap sizes V_p, as shown in Fig. 2b, one may notice that the statistical distribution of the V_p consists of two-peaks (in the case of the histogram on the V_p for Tl1212, the statistical distribution of the V_p had the only single peak [16]), suggesting the existence of two-kinds of gaps. Here, V_p value was the peak voltage of d*I*/d*V* - *V* curve. The red and blue solid lines in Fig. 2b are the Gaussian fitting. The distribution of V_p exhibits expressly two separated distribution. The estimated smaller gap Δ_S/e and larger gap Δ_L/e from V_p are 34 ± 6 mV and 51 ± 5 mV, respectively. These gaps with two different sizes arise from two kinds of the crystallographycally inequivarent CuO_2 planes as previously reported in Ref. [11-14]. Because multilayer cuprates, such a Bi2223, have two kinds of CuO_2 planes which have different the hole concentrations [1]. The hole concentration of OP is higher than that of IP. According to the doping dependence on sizes of V_p for Bi2212, the magnitude of V_p increases as the hole concentration increases [2,3], this doping dependence on V_p are generically common feature for all hole-doped cuprates. Thus, Δ_S and Δ_L assigned to Δ_{OP} and Δ_{IP}, respectively, where the Δ_{OP} (Δ_{IP}) means the superconducting gaps at OP (IP). In addition, our result consists with the observation of the two Fermi surfaces by ARPES experiments for Bi2223 [17].

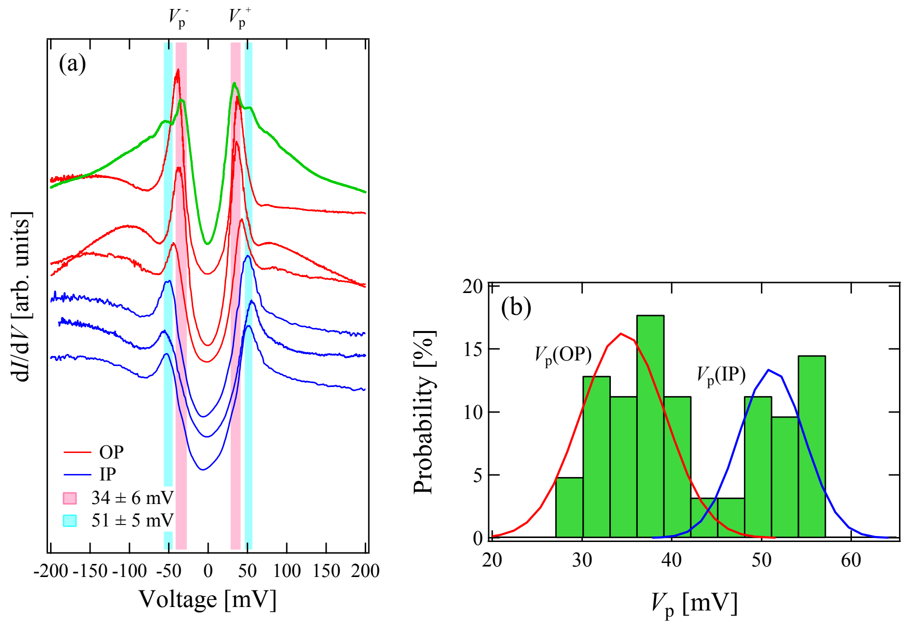

Figure.2 Tunneling results measured at 4.2 K on Bi2223 with $T_C \sim 101$ K. (a) Typical tunneling spectra from OP (reds) and IP (blues). Multi gap spectrum (green) (b) Histogram of V_p estimated from peak to peak on tunneling conductances (= $(V_p^+ - V_p^-)/2$) on Bi2223. Red and blue lines are the Gaussian fitting of congregation from gap sizes on OP and IP of CuO_2 plane, respectively. The V_p of OP and IP estimated from the Gaussian distribution are 34 ± 6 mV (pink hatching region in Fig.2a) and 51 ± 5 mV (light blue hatching region in Fig.2a), respectively. 62 junctions are formed from one sample of the UD-Bi2223.

Next, we discuss why we could observe the two-kinds of gaps (Δ_{OP} and Δ_{IP}) for Bi2223 using the point contact method. One of the explanations would be due to contact surface as shown in Fig. 3. In the case of Fig. 3a, tunneling conductance would display the density of states from the OP. BiO and SrO layers would perform as the tunneling barriers when the Au-tip contact to the surface of BiO layer. Considering outer CuO_2 plane as a superconductor, an SIN tunneling junction would be formed. On the other hand, when the IP's tunneling conductance was observed, we expect the configuration as shown in Fig. 3b. In the configuration of Fig. 3b, the outer CuO_2 plane would not behave as a superconductor owing to deficient carrier when an Au-tip scratched or dug the surface BiO and SrO layer. An Au-tip contact to directly the outer CuO_2 plane, and the outer CuO_2 plane and Ca layer would behave as the tunneling barrier. Therefore, one might observe the tunneling conductance from the IP. Moreover, we sometimes observed the multi gap spectra on Bi2223 as shown in Fig.2a (green line). This observation of the tunneling conductance simultaneously displayed two peaks, certainly indicated the existence of two gaps (Δ_{OP} and Δ_{IP}), not but due to inhomogeneous distribution of gap.

In summary, we performed the point contact tunneling measurement on the under-doped Bi2223. On the point contact tunneling spectroscopy on Bi2223, we firstly observed two sizes of the superconducting gap in Bi2223 because of distribution between CuO_2 planes (OP and IP). The estimated Δ_{OP} and Δ_{IP} are 34 ± 6 meV and 51 ± 5 meV, respectively.

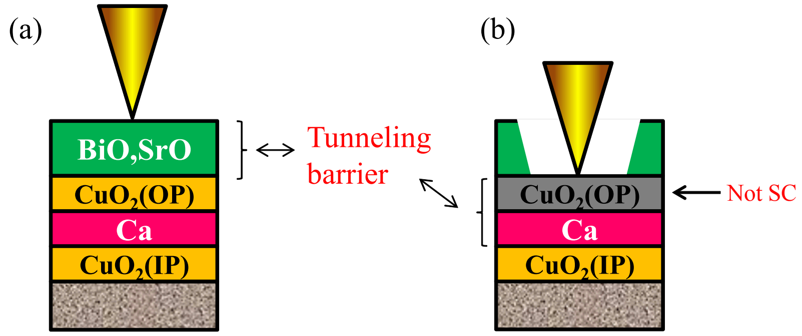

Figure.3 Schematic SIN point contact tunneling junction. (a) Structure of SIN junction when the OP's tunneling coductances. (b) Structure of SIN junction when the IP's tunneling coductances.

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