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Studies of boundary effects and symmetry of Cooper pairing in $Bi_2Sr_2CaCu_2O_x$ by LT-STS

Nobuhiko Nishida[a,*], Shin-ichi Kaneko[a], Hideaki Sakata[a], Hisayoshi Kajiwara[a], Masashige Matsumoto[b], Takashi Mochiku[c], Kazuto Hirata[c], Tadashi Kambara[d]

[a]*Department of Physics, Tokyo Institute of Technology, 2-12-1 Ohokayama, Meguro-ku, Tokyo 152-8551, Japan*
[b]*Department of Physics, Faculty of Science, Shizuoka University, 836 Oya, Shizuoka 422, Japan*
[c]*National Reseach Institute of Metals, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan*
[d]*The Institute of Physical and Chemical Reseach, Wako, Saitama 351-0198, Japan*

Abstract

The local density of states of quasi-particles, $N(E,r)$, around columnar defects generated by bombardment of high-energy heavy ions parallel to the c-axis in $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) and 2H-$NbSe_2$ has been studied by scannning tunneling spectroscopy at 4.2 K and compared. The regions of columnar defects have been found to be insulating and circular superconductor–insulator boundaries have been studied. In Bi-2212 the $N(E,r)$ has exhibited the increase at $E=0$ meV and the decrease at $E\sim 35$ meV at [1 1 0] and [$\bar{1}$ 1 0] directions in CuO_2 square network and seems to show the pattern with four-fold symmetry, while in 2H -$NbSe_2$ such things have not been observed. This is new evidence of the presence of $d_{x^2-y^2}$ component in the order parameter of Bi-2212.

Keywords: Boundary effects; Columnar defects; d-wave superconductivity; Bi-2212; STM/STS

To determine the symmetry of the order parameter in high-T_c copper-oxide superconductors is important to understand the superconducting mechanism. When the Cooper pair has the internal degree of freedom such as the p- or d-wave orbital symmetry, the superconductivity is much affected by boundaries or impurities. It has been pointed out that in the $d_{x^2-y^2}$ superconductors the Cooper pairs are destroyed due to the interference effect near [1 1 0] and [$\bar{1}$ 1 0] direction boundary surfaces of the CuO_2 network and zero-energy states are formed, while at [1 0 0] or [0 1 0] direction surface boundary the superconductivity is intact [1,2]. In s-wave superconductors such boundary effects will not occur. Thus, from studies of the boundary effects we can determine the symmetry of the order parameter in HTSC. We have calculated [3] the $N(E,r)$ near a circular insulator-superconductor boundary in $d_{x^2-y^2}$ superconductors, assuming specular reflections at the boundary; the $N(E,r)$ has a zero-bias peak near [1 1 0] and [$\bar{1}$ 1 0] directions boundaries and shows a four-fold symmetric pattern around the circle. Scanning tunneling spectroscopy is able to measure the $N(E,r)$ in atomic spatial resolution through measurements of differential tunneling conductances.

We have measured the $N(E,r)$ on the c-plane surfaces of Bi-2212 and 2H-$NbSe_2$ cleaved at 4.2 K in zero magnetic field around columnar defects of about 4 nm diameter, generated by high-energy heavy ions of 3.5 GeV $^{136}Xe^{+35}$ and 3.8 GeV $^{181}Ta^{+37}$ from RIKEN Ring Cyclotron implanted perpendicular to the c-plane. A single crystal of Bi-2212 was grown by the traveling solvent floating–zone method. It is slightly over-doped and T_c is 86 K. The I–V characteristics were measured at 64×64 points in 50×50 nm area and the $N(E,r)$'s are obtained by the numerical differentiation. The experimental procedures are the same as we reported before in STS of Bi-2212 [4]. The columnar defect region has been found to be insulating by STS. In Figs. 1 and 2, the $N(E=0,r)$ are shown around a columnar defect in

* Corresponding author. Fax: + 81-3-3483-6670.
E-mail address: nishida@ltp.phys.titech.ac.jp (N. Nishida)

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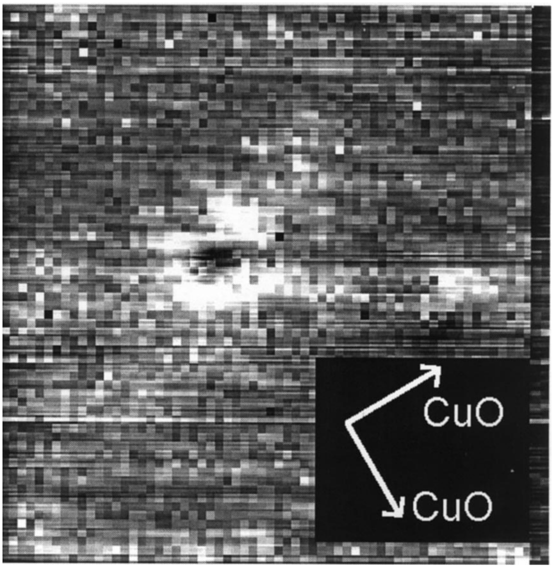

Fig. 1. The $N(E=0,r)$ on the c-plane surface of Bi-2212 at 4.2 K are shown in 50 nm × 50 nm. The increase are shown in [1 1 0] and [$\bar{1}$ 1 0] directions around the columnar defect. The white region at the right of the columnar defect extending in the x-direction is considered not to be intrinsic; the columnar defect region is highly insulating and the STM probe scanned from left to right sometimes damaged the surface in the right region of a columnar defect.

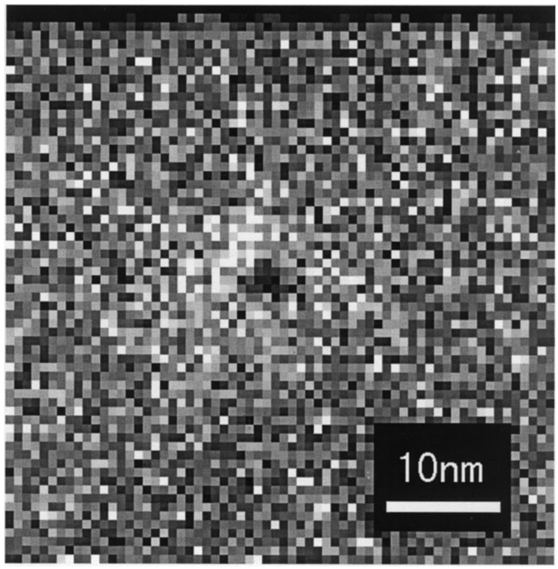

Fig. 2. The $N(E=0,r)$ on the c-plane surface of 2H-$NbSe_2$ at 4.2 K. The anomalous increase observed in Bi-2212 has not been observed in 2H-$NbSe_2$.

Bi-2212 and 2H-$NbSe_2$. In Bi-2212, the increases of $N(E=0,r)$ and the decrease of $N(E=35\,\text{meV},\ r)$ have been observed in the [1 1 0] and [$\bar{1}$ 1 0] directions in the region of about 5 nm from the columnar defect edge and seemed to exhibit a four-fold symmetry pattern, while in 2H-$NbSe_2$ such anomalies have not been detected. The increase of $N(E=0,r)$ near a columnar defect becomes almost double, compared with those at positions far enough from the columnar defect, though the theoretical calculation predicts a steeper increase [3], taking into account that the boundary will not be perfectly specular, the discrepancy from the theoretical calculation will be acceptable. From the fact that the $N(E,r)$ shows a pattern of four-fold symmetry around a columnar defect and that the anomalies have not been observed in s-wave superconductor 2H-$NbSe_2$, we have concluded that in Bi-2212 the order parameter has the $d_{x^2-y^2}$ component, though there remains the possibility of a mixing of s-wave component near a boundary. The details will be published elsewhere.

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