# Influence of disorder on superconductivity in $Bi_2Sr_2CaCu_2O_x$ studied by low temperature scanning tunneling spectroscopy

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**Abstract**

The spatial distributions of superconducting energy gap $2\Delta_p$ have been measured at 6K in underdoped $Bi_2Sr_2CaCu_2O_x$ by scanning tunneling spectroscopy. The $2\Delta_p$ has been found to vary in the length scale of about 3nm. In different regions of the cleaved surface, the average values of $2\Delta_p$ are equal to each other, while the variances are different. This means that the superconducting properties in $Bi_2Sr_2CaCu_2O_x$ is not determined only by the carrier concentration. To characterize the superconductivity of $Bi_2Sr_2CaCu_2O_x$, it is necessary to introduce a new parameter of microscopic degree of disorder, which is defined as a ratio of the variance to the average for the distribution of $2\Delta_p$.

*Key words:* superconductivity; $Bi_2Sr_2CaCu_2O_x$; STM/STS;

To investigate the superconducting quasiparticle density of states is important to understand the properties of a superconductor. Scanning tunneling spectroscopy (STS) is able to measure the local density of states $N_s(E,\boldsymbol{r})$ in the atomic length scale. This method has been successfully applied to the observation of $N_s(E,\boldsymbol{r})$ in conventional superconductors and high temperature superconductors. Recently, in the high temperature superconductor $Bi_2Sr_2CaCu_2O_x$, it was reported that the superconducting energy gap $2\Delta_p$ (peak-to-peak value in $N_s(E,\boldsymbol{r})$) varies spatially in the length scale of a few nanometers [1] [2]. Pan *et al.* [1] suggest that the carrier concentration varies spatially in this length scale owing to the unscreened electrostatic potential from the excess oxygen atoms. Lang *et al.* [2] suggest that underdoped $Bi_2Sr_2CaCu_2O_x$ is a granular superconductor where the superconducting domains ($2\Delta_p$ <100meV) with the size ∼3nm are located in an electronically distinct background ($2\Delta_p$ >100meV). Both of the results show that the microscopic inhomogeneity exists in $Bi_2Sr_2CaCu_2O_x$. The origin of inhomogeneity is still not clear. We have also observed the spatial variation of $2\Delta_p$ in $Bi_2Sr_2CaCu_2O_x$. To clarify the origin of the inhomogeneity, our results are reported and discussed.

We have measured $N_s(E,\boldsymbol{r})$'s at 6K in 8T in $Bi_2Sr_2CaCu_2O_x$ by STS. The I-V characteristics were measured at 64×64 points in 70×70nm regions of a cleaved surface ($c$-plane) and $N_s(E,\boldsymbol{r})$'s were obtained by numerical differentiation. The single crystal sample of $Bi_2Sr_2CaCu_2O_x$ was grown by the traveling solvent floating zone method. It is underdoped and the $T_c$ is 83K. The as-grown single crystals were used for the experiment. The spatial distributions of $2\Delta_p$ were obtained from $N_s(E,\boldsymbol{r})$ measured by STS on various regions (70nm×70nm) of the surface cleaved at 4.2K. The typical examples of $2\Delta_p$ maps in two different regions are shown in Figs.1 (a) and (b). They are shown

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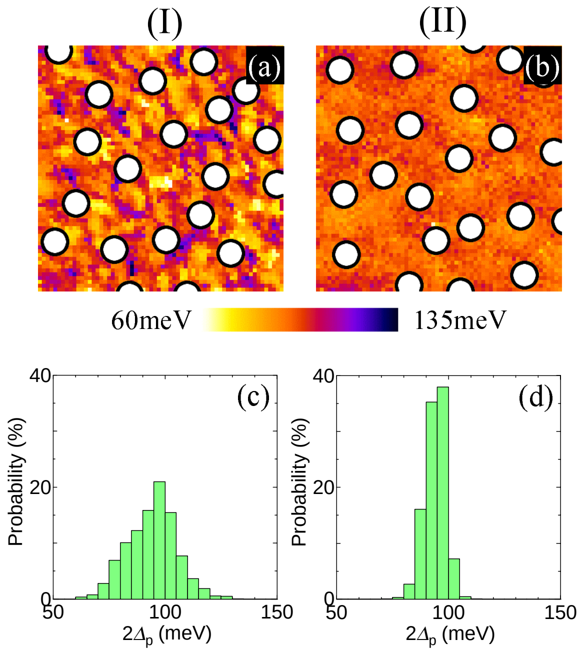


Fig. 1. (a)(b): The spatial distributions of superconducting energy gap $2\Delta_p$ have been measured at 6K in 8T in different 70nm×70nm regions in underdoped $Bi_2Sr_2CaCu_2O_x$. Both of the images are shown in the identical color scale. The vortex cores are masked by white circles. The $2\Delta_p$ in both of the regions vary spatially in the length scale of ∼3nm. (c)(d): The histograms (c) and (d) have been calculated for the distributions of $2\Delta_p$ in region (I) and (II). The $2\Delta_p$ in region (I) is more widely distributed than that in region (II); the variances in region (I) and (II) are 10.9meV and 4.4meV. On the other hand, the average value of $2\Delta_p$ in region (I) is equal to that in region (II); the averages in region (I) and (II) are 94.2meV and 93.9meV.

in the identical color scale. We have successfully imaged the vortex cores by mapping the $N_s(\pm 9\text{meV}, \boldsymbol{r})$ [3]. In Figs.1 (a) and (b), the vortex cores are masked by white circles, since the coherent peaks are suppressed there. The $2\Delta_p$ in both of the regions vary spatially in the length scale of ∼3nm. The presence of different degrees of disorderness has been observed by STS. The histograms for the distributions in region (I) and (II) are shown in Figs.1 (c) and (d). The $2\Delta_p$ in region (I) is more widely distributed than that in region (II); the variance is 10.9meV in region (I) and 4.4meV in region (II). On the other hand, the average values of $2\Delta_p$ are equal to each other; the average is 94.2meV in region (I) and 93.9meV in region (II). It has been reported [4] [5] that the $2\Delta_p$ changes, depending on the carrier concentration of the sample. The equal average values of $2\Delta_p$ in region (I) and (II) mean that the average carrier concentration in region (I) and (II) are the same. From the STM measurements, the topographic images in region (I) and (II) were found not to be remarkably different.

There are two possible explanations for the inhomogeneity of $2\Delta_p$. One is the electronic phase separation into regions with different carrier concentrations The other is disorder which may bring about the spatial inhomogeneity of superconductivity in the length scale of superconducting coherent length. In region (I) and (II) with the equal average carrier concentration, the variances of $2\Delta_p$ have been found to be very different from each other. This can not be explained in terms of the phase separation. Therefore, we can conclude that a microscopic disorder of which we do not know the origin will cause inhomogeneity of superconductivity in the sample. The microscopic disorder is measured only by STS, because other physical measurable quantities are spatial average in some meaning.

The microscopic degree of disorder will affect the superconducting properties in $Bi_2Sr_2CaCu_2O_x$. They will be very different in region (I) and (II) with the equal carrier concentration. This means that the superconducting properties in $Bi_2Sr_2CaCu_2O_x$ is not determined only by the carrier concentration. We need to introduce a new parameter of microscopic degree of disorder; this parameter is defined as a ratio of the variance to the average for the distribution of $2\Delta_p$. The values are 0.115 in region (I) and 0.047 in region (II). We have evaluated microscopic degree of disorder numerically for the first time. The superconducting properties of high-$T_c$ copper oxide superconductors thus far measured should be reconsidered and classified in terms of the microscopic degree of disorder proposed here.

## References

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