Influence of disorder on superconductivity in Bi$_2$Sr$_2$CaCu$_2$O$_x$ 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$_2$Sr$_2$CaCu$_2$O$_x$ 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$_2$Sr$_2$CaCu$_2$O$_x$ is not determined only by the carrier concentration. To characterize the superconductivity of Bi$_2$Sr$_2$CaCu$_2$O$_x$, 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$_2$Sr$_2$CaCu$_2$O$_x$; 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 $N_s(E, \mathbf{r})$ in the atomic length scale. This method has been successfully applied to the observation of $N_s(E, \mathbf{r})$ in conventional superconductors and high temperature superconductors. Recently, in the high temperature superconductor Bi$_2$Sr$_2$CaCu$_2$O$_x$, it was reported that the superconducting energy gap $2\Delta_p$ (peak-to-peak value in $N_s(E, \mathbf{r})$) varies spatially in the length scale of a few nanometers \cite{1} \cite{2}. Pan et al. \cite{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. \cite{2} suggest that underdoped Bi$_2$Sr$_2$CaCu$_2$O$_x$ is a granular superconductor where the superconducting domains ($2\Delta_p < 100\text{meV}$) with the size ~3nm are located in an electronically distinct background ($2\Delta_p > 100\text{meV}$). Both of the results show that the microscopic inhomogeneity exists in Bi$_2$Sr$_2$CaCu$_2$O$_x$. The origin of inhomogeneity is still not clear. We have also observed the spatial variation of $2\Delta_p$ in Bi$_2$Sr$_2$CaCu$_2$O$_x$. To clarify the origin of the inhomogeneity, our results are reported and discussed.

We have measured $N_s(E, \mathbf{r})$’s at 6K in ST in Bi$_2$Sr$_2$CaCu$_2$O$_x$ by STS. The I-V characteristics were measured at 64x64 points in 70x70nm regions of a cleaved surface (c-plane) and $N_s(E, \mathbf{r})$’s were obtained by numerical differentiation. The single crystal sample of Bi$_2$Sr$_2$CaCu$_2$O$_x$ 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 $N_s(E, \mathbf{r})$ measured by STS on various regions (70nmx70nm) 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...
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$_2$Sr$_2$CaCu$_2$O$_x$. 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 $\sim3$nm. (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.

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$_2$Sr$_2$CaCu$_2$O$_x$. They will be very different in region (I) and (II) with the equal carrier concentration. This means that the superconducting properties in Bi$_2$Sr$_2$CaCu$_2$O$_x$ 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

[3] The details will be described elsewhere.