Inherent Inhomogeneities in Tunneling Spectra of BSCCO Crystals in the Superconducting State

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Scanning Tunneling Spectroscopy on cleaved BSCCO(2212) single crystals reveal inhomogeneities on length-scales of ∼30 Å. While most of the surface yields spectra consistent with a d-wave superconductor, small regions show a doubly gapped structure with both gaps lacking coherence peaks and the larger gap having a size typical of the respective pseudo-gap for the same sample.

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Tunneling spectroscopy has been an important tool in the study of high-temperature superconductors since their discovery. While in the early days of high-Tc a variety of gap sizes and structures were found and introduced much controversy into the subject, later measurements yielded greater consistency among groups, revealing a more coherent picture of the surface of high-Tc materials as viewed with STM. Among many examples we note that STM studies revealed the nature of the superstructure in BSCCO, the d-wave nature of the gap and its size, the effect of local impurities and the emergence of zero-bias anomalies, and the electronic structure of the core of vortices.

While in general published data concentrates on specific aspects of the properties of the superconductor such as the gap, the pseudo-gap, impurities, etc., very little has been published on the large-scale structure of the electronic state at the surface of high-Tc materials. Judging from photoemission measurements that reveal a \( \vec{k} \)-dependent gap and pseudo-gap, thus asserting that \( \vec{k} \) is a good quantum number, it has been the common belief that the surface is homogeneous with only few scattering centers and that it represents the bulk properties. However, recent measurements by a variety of techniques suggest that superconductivity may not be homogeneous in high-Tc superconductors. In particular, STM measurements of cold-cleaved YBCO have found that the gap along the chains is inhomogeneous and correlates with oxygen vacancies. The issue of homogeneity (either in the static or dynamical sense) is very important in view of recent theoretical developments that find phase separation to be an integral part of the high-Tc scenario.

In this paper we discuss scanning tunneling spectroscopy measurements on the surface of Bi₂Sr₂CaCu₂O₈₋ₓ (BSCCO) single crystals which show that superconductivity in high temperature superconductors is inherently inhomogeneous. This inhomogeneity appears at a scale of a few coherence lengths and is not a consequence of local impurities or strong disorder. We argue that this inhomogeneity is a consequence of electronic phase separation into regions that are proximity-coupled to give a continuous variation of the tunneling spectroscopic features.

The slightly underdoped single crystals of BSCCO used in this study were grown by a directional solidification method and their \( T_c \) of ∼ 80 K was measured by SQUID magnetometry. Crystals were mounted into a UHV-Low-T STM system. The samples are cleaved at room temperature in a vacuum of better than 10⁻⁹ torr.

FIG. 1. Typical topographic scan of a 100 Å x 90 Å area (a). Dotted line marks the location of the spectroscopic scans shown in the lower figure (b). The two bold lines in the scan mark the extreme spectra discussed in the text.
Immediately, they are transferred to the low temperature chamber which houses the STM and presumably reaches much lower base pressure because the walls of this portion of the chamber are held at liquid helium temperature. The base temperature of the microscope is 6 K, however the data shown is this paper were taken at 8 K. Images are taken with a gold tip at a sample bias of -200 mV and a setpoint current of 100 pA. The dI/dV spectra are taken using a lock-in technique with an AC modulation of 1 mV, after fixing the tip location at a height that gives -100 pA current at -200 mV. This setpoint current establishes the relatively arbitrary normalization condition used for the raw data shown in this paper. The quality of the surface and the scanning capability are demonstrated in figure 1a where we show a topographic scan of a 100 Å x 90 Å region. Evident are the atomic resolution and the clarity of the superstructure with average periodicity ∼27 Å. All cleaves which yield images exhibit similar topography.

Figure 1b shows a line of differential conductance spectra taken over a range of 80 Å in the region shown in figure 1a. By fitting the acquired spectra to a d-wave density of states for a maximum gap size ∆ (\(\Delta(\theta) = \Delta \cos(2\theta)\)) with gaussian broadening \(\Gamma\):

\[
\frac{N_S(E)}{N_N} = \int_{-\infty}^{\infty} Re \int_0^{2\pi} \frac{d\theta}{2\pi} \frac{E}{\sqrt{E^2 - \Delta(\theta)^2}} e^{-\frac{(E-U)^2}{2\Gamma^2}} dU,
\]

we find two important results. For most of the spectra this fit yields values of \(\Delta = 42 \pm 2\) mV and \(\Gamma = 4 \pm 2\) mV with residuals approximately the size of the noise. However, there are regions in which the spectra give poor fits to this formula, also yielding unphysically large values of \(\Gamma\) and \(\Delta\). The regions are 20 to 30 Å across, their areal fraction is ∼20%, and they seem to be centered along the superstructure ridges. The size and shape of one of the regions is shown in figure 2a, which maps the gap size (normalized by the 42 mV value found above) as determined by the d-wave fit. This map, like figure 1b, shows that the spectra vary continuously through each region.

This continuous variation suggests two extremal spectra: those from the center of these regions and those far away. These two extreme shapes are shown in figure 3 for positive bias. In particular, the spectrum taken outside the regions are consistent with the density of states of a d-wave superconductor averaged over k-space (as expected for tunneling perpendicular to the Cu-O planes), while the other shows a double gap shape with no coherence peaks. In addition, the shape of the smaller of these two gaps is similar to the shape of the inner part of the superconducting spectra. Figure 2b shows the width at which the conductance reaches twice the zero bias value, normalized by the value of those spectra with the best d-wave fits. This plot uses the same scale as figure 2a in order to emphasize the contrast between them. The only features in figure 2b are consistent with noise. That is, while the behavior at the gap energy is inhomogeneous, at low energies the sample appears to be homogeneous. The fact that the spectra in these regions look like those of the background superconductor at low bias indicates that the node structure exists throughout the sample. Thus, the regions must maintain the d-wave structure despite the apparent suppression of superconductivity. In particular, this rules out these features being caused by impurities. Both theoretical and experimental studies show that potential scatterers yield entirely different behavior, characterized by subgap structure (zero-bias anomalies) and no change in the value of the gap.

Examination of figure 1 and other similar scans shows that the two extreme shapes are separated by a distance of ∼30 Å. For BSSCO this distance is roughly twice the coherence length \(\xi\). This suggests that the smooth variation seen may not be the product of smooth variation in the underlying character of the material, but may instead reflect a breakdown into domains with different character which are then proximity coupled. This proximity coupling would explain why these regions do not break the superconductors d-wave symmetry.
therefore characterized by a gap $\Delta$, associated with pair-to-pair interactions. The superconducting state is thought to be in the clean limit. The superconducting state of the type we are using is believed to represent the gap energy while $\epsilon$ marks the kink energy, related to the size of the “bad” superconductor region (see text).

Although curve (b) in figure 3 has the same shape at low bias as a “good” superconductor, it develops a different gap structure at higher bias. The abrupt change in gap structure is an indication that the spectrum of quasiparticles changes abruptly. HTSC, and in particular BSCCO crystals of the type we are using are believed to be in the clean limit. The superconducting state is therefore characterized by a gap $\Delta$, associated with pairing instability and “pair size” $\xi \sim h v_F/\Delta$. Terminating the gap opening at energies $\epsilon < \Delta$, means a larger length scale $L \sim h v_F/\epsilon$. Since the coherence peaks mark roughly the coherence length, the shoulder in curve (b) indicates a length scale that is roughly twice the coherence length. This is therefore the length at which the system crosses over from the behavior of a pure d-wave superconductor at long length scales to behavior which is more reminiscent of the “insulating” state. The larger gap with no coherence peaks resembles the pseudo-gap.

Summarizing our observations, we find that while the gap changes smoothly between the two extremes presented in figure 3, the system breaks into distinct domains of either “good” or “bad” superconductivity. This observation suggests that the “bad” superconducting regions are a consequence of insulating regions in proximity with the “good” superconductor. Since for high-Tc superconductors the coherence length is so short, proximity implies leakage of the superconducting wavefunction a distance of order $\xi$ into the insulator [22]. Similarly, the superconductor weakens as well over a similar distance close to the boundary. The result is therefore the smoothly modulated behavior shown in figure 2. This follows from a scenario for phase separation where the initial boundaries between adjacent puddles are relatively sharp. Such a situation is most likely a consequence of a proximity to a first order phase transition that is becoming continuous due to disorder [12,17] as was first shown by Imry and Ma [23]. The sharpness of the initial domains is indicated by the relatively sharp kink in the spectrum of the “bad” superconductor as it crosses-over from low energy superconductor-like to high energy pseudo-gap-like behavior.

The above suggestion that the inhomogeneities observed by STM spectroscopy on the surface of BSCCO single crystals are intrinsic and reflect phase separation does not contradict the photoemission results [8-11]. While one might expect that inhomogeneities would destroy the k-dependence observed in photoemission, the type of inhomogeneities seen here would not. The low-k behavior would measure the long-wavelength homogeneity, while, since both the superconducting gap and the pseudo-gap have the same d-wave symmetry, averaging in regions of pseudo-gap would not destroy the symmetry of the gap seen in photoemission. Moreover, the above scenario is also in agreement with recent investigations of vortex structure in High-Tc superconductors. The peculiar result there is the fact that while the zero-field spectroscopy maps show an inhomogeneous pattern, application of a magnetic field results in vortices that are always surrounded by “good” superconductor as judged from the STM spectroscopy [8,12]. Within the framework of our interpretation this implies that vortices will prefer to have their cores reside on “bad” superconducting regions. The surrounding area is then a good superconductor and since the vortex core does not proximity couple to the superconductor, the result is a homogeneous superconductor in the regions surrounding the vortex.

Having argued that the observed inhomogeneities are not the consequence of disorder, we can check this claim by intentionally disordering the surface. Since BSCCO is very sensitive to excessive current density or electric field we locally increased the setpoint current to 500 pA at -200 mV sample bias and scanned the tip over a 140 $\times$ 90 A area. Subsequent topography shows an apparent depression at the center of the “damaged” area because of decreased local density of states. The superstructure and atomic corrugation are no longer visible within this region, indicating strong disorder, though they remain visible over the rest of the sample surface. Figure 4 shows a strip-image of the contour of constant density of states and a line of spectra taken across the “damaged” area. Clearly at about 100 A away from the center of that area a good superconducting gap is obtained indicating only very small influence of the damaged area. As we approach the boundary of the scanned area and continue towards its center the spectra change continuously. In particular, the height of the coherence peak drops continuously to the background conductance level. However, unlike the variations in the spectra shown in figure 1, here the gap size does not change at all as the coherence peaks disappear. Once inside the region, the gap broadens into a pseudo-gap, and then an insulating gap. The last two spectra that are inside the damaged area look very sim-
ilar to those of the pseudo-gap previously observed by tunneling [6] and photoemission [11].

FIG. 4. Spectra taken near the disordered area. The location of each spectra is shown in the topograph (right).

Comparing this area with the region on the native surface, several points are obvious. Both show a continuous decrease in the coherence peak height. Also, both show pseudo-gap features inside the region. However, the pseudo-gap size varies in the intentionally disordered case while it seems to be constant in the other. This is presumably because the disorder, and perhaps doping as well, is varying throughout this region, yielding a varying intrinsic gap size. Secondly, for the native defect, there remains a vestige of the superconducting gap in the pseudo-gapped spectra. This indicates that the smaller size of the native defect allows proximity coupling to the surrounding superconductor. The effect of disorder is therefore different than the intrinsic inhomogeneities observed on the pure surface. When strong enough, the disorder “pins” the insulating phase as is the case in the middle of the damaged area. Again, this implies a “good” superconductor at the periphery of the “bad” superconductor.

In conclusion, we find that the intrinsic surface of BSCCO exhibits inhomogeneities that strongly suppress superconductivity, while maintaining the same low energy structure. These regions show spectra that are reminiscent of the pseudo-gap, but also are proximity coupled to the surrounding superconductor.

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