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Gap distributions and spatial variation of electronic states in superconducting and pseudogap states of $Bi_2Sr_2Ca_2CuO_{8+\delta}$ ☆

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Abstract

High-resolution scanning tunneling microscopy has been used to study the tunneling density of states in lightly underdoped samples of the high-T_c superconductor $Bi_2Sr_2Ca_2CuO_{8+\delta}$ in both the superconducting and pseudogap states. We demonstrate that the tunneling gaps observed in these two states have identical spatial distributions and correlation lengths. This observation suggests that the two gaps, and hence the two phenomena, cannot have a competing origin. In addition, we present measurements that show that in contrast to the superconducting state, in which low energy quasi-particles are homogenous in real space, the states near the Fermi level are spatially inhomogeneous in the pseudogap state. The variation of the low-energy electronic states is spatially correlated with local changes in the pseudogap.

Keywords: Superconductivity; High T_c; Tunneling; STM

1. Introduction

The nature of the electronic states in the high-temperature cuprate superconductors is one of the major unresolved questions in all of physics. Despite 20 years of intensive research, there is still no consensus on the nature of the electronic states created by hole-doping the cuprates. While the superconductor state is best described by a *d*-wave paired BCS-type model, questions such as the mechanics of pairing, the high-temperature normal phases, and the precise nature of the superconducting transition in these compounds – are all still intensely debated. The properties of the underdoped hole-doped cuprates, which show a pseudogap in their single particle excitation spectrum at temperatures above T_c, have been particularly puzzling. Understanding the pseudogap state has been the focus of much attention because many believe it will provide clues for unveiling the mechanism of superconductivity in the cuprates. Views vary as to whether superconducting fluctuations [1], some form of competing order [2–4], or some other non-Fermi liquid behavior is responsible for this unusual state of the cuprates. Some experiments [5,6] suggest that at least some region of the cuprate phase diagram above T_c is dominated by superconducting fluctuations. Other experiments, such as scattering studies [7,8], angle-resolved photoemission (ARPES) studies [9], or scanning tunneling microscopy (STM) measurements [10,11], highlight the importance of the ordering of spins, charges, or circulating currents for underdoped cuprates and their possible connection to the physics of the pseudogap.

The STM can provide a real space view of the electronic states in a cuprate, and, hence, can offer important clues on the nature of the pseudogap and its connection to superconductivity in the cuprates. Previously, we have used STM measurements to study periodic modulation of the electronic states in the pseudogap state of $Bi_2Sr_2Ca_2CuO_{8+\delta}$ single crystals [10]. In this present work, we focus on the spatial variation of electronic state measured in the pseudogap state at temperatures above T_c and contrast these measurements to those in the superconducting state.

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It has been well established that the $Bi_2Sr_2Ca_2CuO_{8+\delta}$ system shows gaps in the superconducting state that can vary by as much as a factor of two on the nanometer scale. It has also been shown that despite such intense electronic variation, the low energy quasi-particles are spatially homogenous [12,13]. However, to date, it is unclear how such real space variations of the electronic states are modified when the temperature is raised above T_c into the pseudogap state. Such information can determine if superconductivity and the pseudogap are due to competing or similar origins.

We present experimental results demonstrating that the spatial characteristics of the superconducting gap are identical to those of the pseudogap state in underdoped $Bi_2Sr_2Ca_2CuO_{8+\delta}$. This strong similarity between the two gaps suggests that the pseudogap measured at high temperatures (in the range of 10–20 K) above T_c is in fact related to pairing. In addition to these measurements, we contrast the response of the low-energy excitations to gap variation above and below T_c. In contrast to the superconducting state, the low-energy quasi-particles in the pseudogap state scatter strongly from gap inhomogeneity. This strong scattering provides a real-space view of why the mean-free path is strongly suppressed above the superconducting transition temperature [14,15].

2. Experiments

The measurements were performed using a home-built ultra-high-vacuum (UHV) STM capable of high-resolution imaging and spectroscopy measurements over a wide range of temperatures (8–300 K). These measurements are particularly challenging, as they require the STM to have high stability in the temperature range where thermal expansion of most materials is large. The samples used for the current work were lightly underdoped $Bi_2Sr_2Ca_2CuO_{8+\delta}$ single crystals, grown using the floating-zone technique, with a T_c of 93 K. Some of the data presented here was obtained from samples with a 0.3% Ni concentration and $T_c = 87$ K; however, the observations described here were identical for samples with and without Ni. To perform STM measurements, the single crystal samples were cleaved in situ in UHV at room temperature before being inserted into the low temperature stage of the microscope. We use Pt/Ir tips that have been calibrated on clean metal surfaces prior to each experiment. Typical STM imaging of the cleaved surface at 100 K, shown in Fig. 1a, displays features consistent with those previously measured at low temperatures. The topographs show an atomic corrugation consistent with the Bi lattice, along with the superlattice distortion characteristic of this material system. Spectroscopic measurements, performed using standard AC lock-in measurements of the differential conductance (dI/dV), confirm that the samples are underdoped as the superconducting gap is replaced by the pseudogap on increasing temperature above T_c. Fig. 1b shows typical spectra obtained in the superconducting and pseudogap state on the same sample.

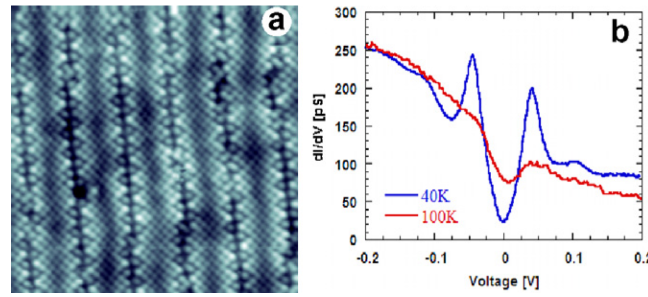

Fig. 1. (a) Topograph of $Bi_2Sr_2CaCu_2O_{8+\delta}$. (b) Typical spectra taken in the superconducting (blue) and pseudogap (red) state. The junction is maintained at −200 mV and 40 pA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The evolution of the spectra with temperature in Fig. 1b is consistent with previous reports on similar $Bi_2Sr_2Ca_2CuO_{8+\delta}$ samples [16]; however, we focus our attention on the spatial dependence of the spectra at different temperatures, which have not been previously characterized.

We measured the variation of the electronic states by performing spatially resolved tunneling spectra over large areas of the sample surface. Fig. 2a and b shows examples of STM spectra obtained along a line of 250 Å, measured at every Å, in the superconducting and pseudogap states, respectively. The observed variation of the spectra in the superconducting state is very similar to that previously reported by other groups [12,13]. The gap value and the local density of states (LDOS) at energies close to the gap fluctuate strongly on the nanometer scale. The data in Fig. 2b show that many of these characteristics are also shared by the spatially resolved spectra measured in the pseudogap state – i.e., a distribution of pseudogaps exists in the sample.

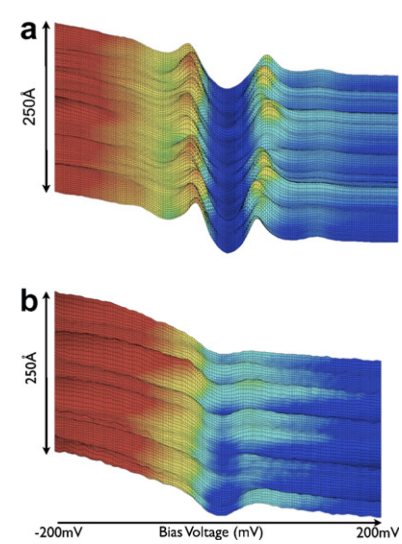

Fig. 2. Spatial variation of the spectra taken along a line in the (a) superconducting (40 K) and (b) pseudogap (100 K) state. The was set at −200 mV and 40 pA.