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Incommensurate, dispersive, density of states modulations in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract

Scanning tunneling spectroscopy of $Bi_2Sr_2CaCu_2O_{8+\delta}$ reveals weak, incommensurate, spatial modulations in the tunneling conductance. When images of these energy-dependent modulations are Fourier analyzed the dispersion of their wave vectors can be determined. Comparison of the dispersions with angle-resolved photoemission indicates that quasiparticle interference, due to elastic scattering between specific regions of the Fermi surface, provides a consistent explanation for the conductance modulations.

Keywords: Quasiparticle interference; Scanning tunneling microscopy; $Bi_2Sr_2CaCu_2O_{8+\delta}$

1. Introduction

The widely accepted model for low-energy physics of the cuprate superconductors relies on the concept of quasiparticles. These quasiparticles are the elementary electronic excitations above the superconducting energy gap which, in $Bi_2Sr_2CaCu_2O_{8+\delta}$, has four nodes [1]. The scattering of these quasiparticles with each other and the crystal determine a great deal of the low-energy physics of these materials. When the scattering occurs between two states it produces oscillations in the norm of a quasiparticle's wave function with wavelength $\lambda = 2\pi/q$, where q is the scattering vector. These oscillations should be observable as spatial modulations in the tunneling conductance detectable by scanning tunneling microscopy [2]. Here we describe the study of these conductance oscillations in $Bi_2Sr_2CaCu_2O_{8+\delta}$.

2. Experimental

We use TSZ grown single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with T_c ranging from 78 K underdoped (UD) to 85 K overdoped (OD). Cleaving the sample in cryogenic ultra-high vacuum reveals the BiO plane. On these surfaces we measure the local differential tunneling conductance ($G = dI/dV$) as a function of position (x, y) with atomic resolution. Because $G \propto$ LDOS(V), where V is the sample bias voltage and LDOS(V) is the local density of states, this results in a two-dimensional map of the LDOS at each energy. Fourier transforms of these LDOS maps reveal $\bar{q}$ with the $\bar{q}$-vectors of the LDOS modulations.

3. Results

Fig. 1 shows a typical FT(LDOS) taken at 16 meV on an UD sample with $T_c = 78$ K. A total of nine features dominate the image. The largest central peak results from short wave vector disorder with $\lambda > 10a_0$ will not

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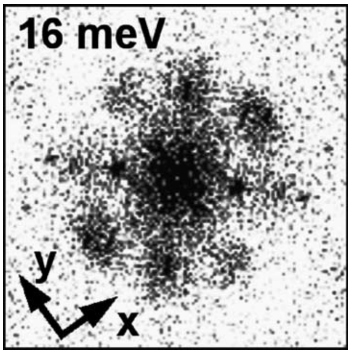

Fig. 1. Typical FT(LDOS) taken at 16 mV on the 78 K UD sample. The Cu–O bond directions are along the *x* and *y* axes. The $(\pi, 0)$ align with these axes while the (π, π) are aligned (45° to them).

be discussed further. Next, one can see four peaks whose $\bar{q}$-vectors are oriented towards the $(\pm\pi, 0)$ or $(0, \pm\pi)$ (i.e. oriented along the *x* and *y* axes with the Cu–O bonds). Finally, an additional four peaks are present in the $(\pm\pi, \pm\pi)$ (45° to the Cu–O direction). At each energy these sets of peaks, along (π, π) or $(\pi, 0)$, are located the same distance from the origin and can be described by two wave vectors: $q_{\pi,\pi}$ and $q_{\pi,0}$ respectively.

The locations of $q_{\pi,\pi}$ and $q_{\pi,0}$ as a function of energy (E) for several different dopings are shown in Fig. 2. The different classes of q's evolve in different characteristic ways. The $q_{\pi,\pi}$ (open symbols) move from high wave vector far from the Fermi energy E_F and move towards lower q at lower energies. The other four points, $q_{\pi,0}$ have a finite wave vector at E_F and disperse inward (shorter q) until they merge with the inhomogeneity peak at higher energy.

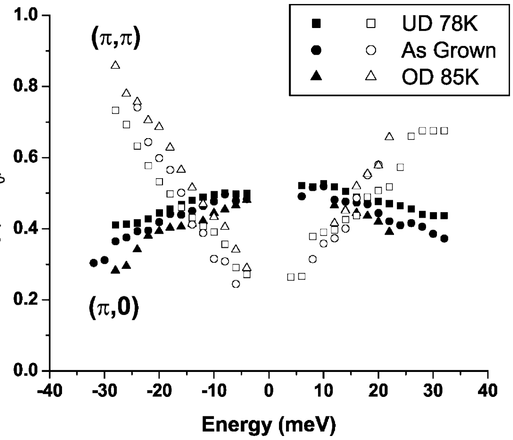

Fig. 2. Dispersion of the discussed modulations for several dopings. Filled symbols are (π, π) and the open ones are $(\pi, 0)$ and $(0, \pi)$. The different shapes correspond to different dopings, for UD, "As Grown", and OD.

To model these phenomena [3] we use the normal state Fermi surface (FS) and the superconducting gap $\Delta(\bar{k})$ as studied by ARPES [1,4–7]. At any energy $(E = eV)$ we expect the eight regions in $\bar{k}$-space above the FS with the lowest energy (i.e. $E = \Delta(\bar{k}_{FS})$ excitations to be the dominate contributors of DOS(E). If we take two q's that connect these "bright-spots" along the $(\pi, 0)$ and (π, π) directions and plot their dispersion we find excellent agreement with these data.

4. Conclusion

We conclude that (1) quasiparticle band-structure effects play the primary role in LDOS modulation effects in $Bi_2Sr_2CaCu_2O_{8+\delta}$, (2) the relationship between the relatively strong "checkerboard" modulations around the vortex core [8] and the modulations in zero-field discussed here and in [9,10] has yet to be determined, and (3) since quasiparticle scattering between high joint-DOS regions of k-space is here shown to be a mechanism for incommensurate, dispersive, spatial modulations of the superconducting electronic structure, renewed exploration of such a scattering-related explanation for other incommensurate magnetic phenomena [11–14] in the cuprates may be appropriate.

Acknowledgements

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