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DISCLAIMER

STM investigation of the superconducting state of BSCCO 2212 and borocarbide materials

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We present spectroscopic Scanning Tunneling Microscope (STM) measurements performed at 4.2 K on BSCCO 2212 single crystals and Y, Lu and Er based borocarbide compounds. The conductance versus voltage spectra on BSCCO 2212 reveal a reproducible dip feature near $e|V| = 2\Delta$, for both voltage polarities pointing to a strong coupling origin of the feature. The conductance spectra obtained on YNi_2B_2C thin films and $LuNi_2B_2C$ single crystals are similar and correspond to a BCS ratio of 3.2 indicating weak coupling superconductivity in these compounds. On Er Ni_2B_2C single crystals, the conductance spectra show a pronounced broadening compared to the spectra obtained on $LuNi_2B_2C$ and YNi_2B_2C, which is attributed to the pair-breaking effect due to the Er magnetic ions.

1. INTRODUCTION

Various tunneling techniques can be used to investigate the gap and low energy quasiparticle excitations near the Fermi level (E_F) of superconducting materials including planar junctions, step-edge junctions, grain-boundary junctions, squeezable junctions, break junctions, point-contact junctions, and scanning tunneling microscope (STM) vacuum junctions [1–5]. Among these, STM is most informative as it provides local spectroscopic information with the possibility of changing the position of the tunnel junction over the sample surface, and gives the ability to vary the tunneling resistance in a controllable way within the same experiment.

There have been numerous SIN tunneling studies of BSCCO 2212 [1,6] which displayed an anomalous spectral feature or "dip" at a voltage V approximately twice that of the conductance peak occurring at $e|V| = \Delta$. This dip is analogous to that observed in ARPES spectra [7,8] which has recently been attributed to coupling of quasiparticles to collective excitations centered near the (π,π) point of the Brillouin zone [9–11]. Here we report on new STM spectroscopic studies of high quality BSCCO 2212 single crystals. We present highly reproducible results obtained with an STM at 4.2 K on both nearly optimally doped and overdoped crystals. We focus the discussion on the dip feature which shows up for both polarities in the conductance curves measured on these crystals.

The borocarbides studied here belong to a recently discovered class of superconductors with tetragonal crystal structure having the chemical formula RNi_2B_2C where R is a rare earth (R=Lu, Y, Tm, Er, Ho, or Dy) [12]. These superconductors are interesting for their high critical temperature ($T_c \approx 16$ K in the Lu compound), their layered crystal structure which is unique among intermetallics, and the strong interplay between superconductivity and magnetism [13]. The magnetic borocarbides exhibit both antiferromagnetism and superconductivity, with Néel temperatures higher (R=Dy) or lower (R= Er, Ho, Tm) than their superconducting transition temperatures. Several tunneling measurements of the gap have been performed by point-contact tunneling on polycrystals and single crystals, and by break-junctions [2–4]. The gap values determined by these methods vary widely depending on the type of measurements and, in some cases on the location in the sample. We present new STM measurements of the tunneling conductance of Y, Lu, and Er borocarbides, obtained in the vacuum tunneling regime. For Y and Lu, the gap values vary remarkably little with either location on the sample or the value of the tunneling resistance, and give strong evidence for weak coupling superconductivity. For Er borocarbide, the tunneling spectra do not follow the conventional BCS form, possibly due to strong magnetic pair breaking from the local moment.

2. Tunneling spectroscopy on BSCCO

The STM measurements on BSCCO were performed with a home built low temperature STM operating in a helium exchange gas at 4.2 K. The STM is analogous to that presented in ref.[14]. To obtain clean atomically flat surfaces the samples, mounted in front of a Pt-Ir tip, were cleaved under helium atmosphere just before cooling down the STM. We investigated a 92 K sample (slightly overdoped) and a 72 K sample (overdoped) grown by the floating-zone method [15]. The differential conductance dI/dV vs.V curves were recorded using standard lock-in techniques with a small ac modulation of 2 mV superimposed on a slowly varying bias voltage applied to the sample. Vacuum tunneling conditions were verified by checking the reproducibility of the spectra recorded at various tunneling resistances ranging from 1 GΩ to 5 GΩ. Figure 1 shows a series of typical raw dI/dV vs.V NIS (normal metal-insulator-superconductor) spectra (raw data) recorded at various locations on both samples. All the spectra consistently show the same features: a very low zero bias conductance of the order of a few percent of the average background conductance, a sharp peaked structure at V_{peak}, and a dip and a hump at $V \approx 2V_{peak}$ and $V \approx 3V_{peak}$ respectively. These features are superimposed on an asymmetrical background consistent with other STM measurements on BSCCO [16]. The important novelty in these spectra is that the dip structure (followed by a hump) already formerly reported to be present at negative bias [1] is also observed symmetrically at positive bias in the best resolved spectra. This rules out explanations which relate the dip to a band structure effect such as a van Hove singularity just below the Fermi level. It strongly suggests instead that the dip is the signature of a boson mode which plays the role of phonons in conventional strongly coupled superconductors [9,10]. It is well-known that such phonon-like boson modes result in a shortening of the quasi particle lifetime and appears as ad-

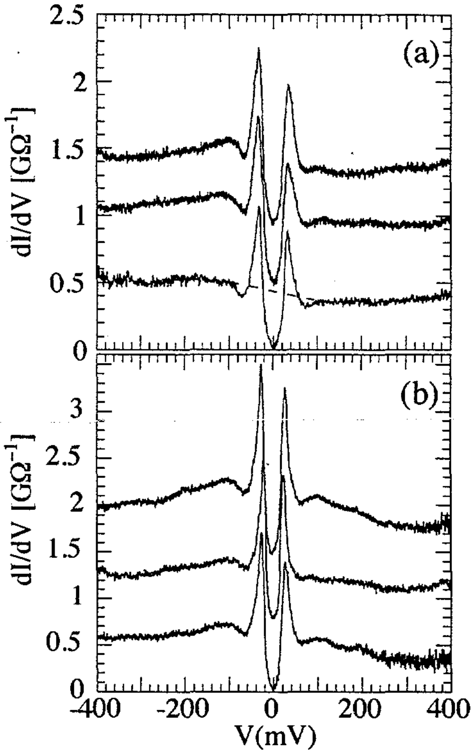

Figure 1. Typical conductance spectra recorded at 4.2 K at various location on a 92 K (a), and on a 72 K (b) BSCCO 2212 overdoped single crystal. The dashed line represents the typical polynomial background used for the normalization of the curves.

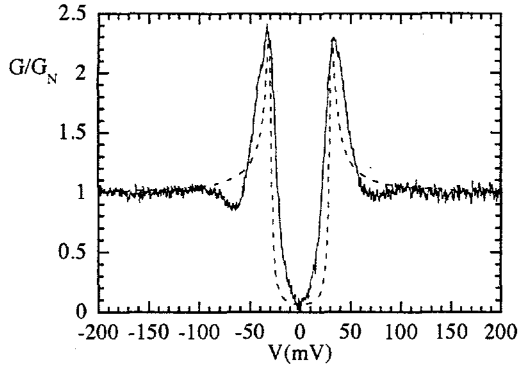

Figure 2. Typical normalized conductance spectrum recorded at 4.2 K on a 92 K BSCCO 2212 single crystal (solid line) compared to a calculated conductance spectrum (dashed line) using a smeared BCS density of states for which $\Delta = 30$ meV and $\Gamma = 2$ meV.

ditional structures symmetrically for both polarities in tunneling spectra [17].

For quantitative analysis we normalize the spectra by a smoothly varying polynomial fit which obeys charge conservation. An example of such a fit is shown as the dashed line in the lower curve of Figure 1a. A typical normalized conductance curve is shown in Figure 2. To estimate the gap value we fit the data with a broadened BCS-like density of states including a smearing parameter Γ [18] which leads to a value $\Delta \approx$ 28-32 meV for the 92 K sample and $\Delta \approx$ 20-24 meV the 72 K sample. This corresponds to BCS ratios of $2\Delta/kT_c \approx$ 7.1-8.0 and 6.4-7.5 respectively. The relatively large dispersion of the gap values found in the STM data is likely due to local variations in the oxygen concentration at the sample surface. Around zero bias all the conductance curves exhibit the same behavior which can be satisfactorily fitted by a second order polynomial over a range extending between $\pm 2\Delta/3$ regardless of the position of the tip over the sample surface. The observed parabolic behavior matches neither the flat behavior expected for an s-wave superconductor, nor the linear behavior expected for a d-wave superconductor. In a d-wave scenario, this could be explained by an anisotropic injection of the tunneling electrons preferentially near the $(\pi,0)$ and $(0,\pi)$ point of the Fermi surface where the gap is expected to have a large non zero value [19,20]. This would also explain the similarity between tunneling spectra and angular resolved photoemission data in which the dip structure is only found near the $(\pi,0)$ and $(0,\pi)$ points.

3. Tunneling spectroscopy on borocarbides

Using the same technique as for BSCCO we have investigated YNi_2B_2C thin films, and $LuNi_2B_2C$ and Er Ni_2B_2C single crystals at 4.2 K. The YNi_2B_2C thin films, grown by magnetron sputtering in a UHV system [21], have T_c = 15.1 K close to the bulk value of 15.7 K. The $LuNi_2B_2C$ and $ErNi_2B_2C$ single crystals were grown by a high temperature Ni_2B flux method using high purity elements [22]. T_c in these crystals is 15.8 K and 10.5 K for $LuNi_2B_2C$ and $ErNi_2B_2C$ respectively.

Figure 3 represents typical normalized conductance spectra obtained on the three borocarbide samples. The data were highly reproducible for changes of both the tunneling resistance and the position of the tip on the sample surface. The conductance curves found in the two non-magnetic compounds, $LuNi_2B_2C$ and YNi_2B_2C, show a peaked structure for both voltage polarities. A fit of these curves with a smeared BCS density of states (dashed curves) provides an estimate of the gap of 2.1 meV and 2.2 meV for YNi_2B_2C and $LuNi_2B_2C$ respectively. This corresponds to a BCS ratio $2\Delta/kT_c = 3.2 \pm 0.1$ in both cases and clearly indicates the weak coupling BCS nature of the superconductivity in these compounds. The good reproducibility of the spectra as a function of location in the $LuNi_2B_2C$ single crystal makes possible direct imaging of the Abrikosov vortex lattice in this compound [23]. Remarkably , $LuNi_2B_2C$ displays a square Abrikosov lattice at sufficiently high fields. The square symmetry can be explained phenomenologically in a Ginzburg-Landau theory which accounts for the fourfold symmetry along the tetragonal axis of the crystal lattice

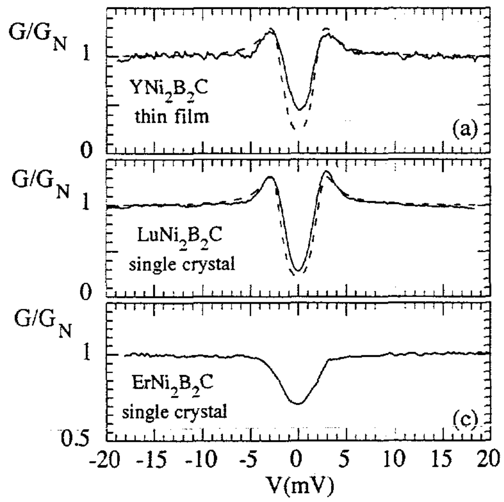

Figure 3. Typical normalized conductance spectra (solid curves) recorded at 4.2 K on a YNi_2B_2C thin film (a), a Lu Ni_2B_2C single crystal (b), and a $ErNi_2B_2C$ single crystal. The dashed curves are calculated with a smeared BSC density of states.

[23]. The STM tunneling results obtained on $ErNi_2B_2C$ single crystals (Figure 3 c) are very different from those obtained on the Lu and Y borocarbides since no peaks in the conductance curves are present. Although a fit to the theory is not possible, the effect can be qualitatively explained in terms of the strong pair-breaking induced by the Er magnetic ions.

4. Conclusions

We use STM conductance spectra to investigate the nature of superconductivity in two classes of materials: the high temperature superconductor BSCCO 2212 and the intermetallic borocarbide compounds RNi_2B_2C. In BSCCO 2212 at nearly optimal doping and at overdoping the BCS ratios imply strong coupling superconductivity, and we find an anomalous dip and hump strucuture in the conductance curves which appears for both polarities of the tunneling voltage. In both BSCCO samples, the anomalous dip appears at twice the gap energy, even though the gap energy itself changes by 40 %. These characteristics rule out explanations based on band structure effects like van Hove singularities and strongly suggest the presence of boson modes coupling to the superconducting electrons. In the Y and Lu borocarbides we find tunneling spectra and BCS ratios consistent with conventional weak coupling superconductivity. Er borocarbide displays prominently broadened tunneling spectra which are inconsistent with the BCS form, possibly due to strong pair breaking effects arising from the local Er moment.

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