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Temperature dependence of the $YBa_2Cu_3O_7$ energy gap in differently oriented tunnel junctions

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Abstract. We have applied the break-junction technique to highly biepitaxial *c*-axis oriented $YBa_2Cu_3O_7$ thin films with T_C (ρ=0) = 91 K. Mechanically adjustable junctions with a good stability and tunneling current favored along the *ab*-planes have been realized. The conductance characteristics of these junctions show the presence of gap related maxima that move towards zero bias for increasing temperatures. Considering the misorientation angle $\alpha \approx 45° \pm 5°$ of the junction, a maximum gap value at the Fermi level $\Delta_0 \approx 22$ meV is inferred at $T = 13$ K. The temperature dependence of the gap related structures, shows a quasilinear behavior for $T > 0.4\ T_C$ similar to that observed in *c*-axis oriented, S-I-N type $YBa_2Cu_3O_7$ planar junctions.

PACS. 74.50.+r Proximity effects, weak links, tunneling phenomena, and Josephson effects – 74.72.Bk Y-based cuprates – 74.76.Bz High-T_c films

1 Introduction

Since the discovery of the high T_C superconductors (HTS), a growing number of tunneling experiments and theoretical calculations have suggested that cuprates exhibit an unconventional pairing state: a state with an order parameter that in the momentum space has a different symmetry from that of the isotropic, *s*-wave Cooper pair state describing the low-temperature superconductors. The majority of the reports, including SQUID interferometer, corner Josephson junction and grain boundary flux quantization measurements, indicate a predominant $d_{x^2-y^2}$ wave symmetry [1,2] corresponding to an energy gap with functional form in the *k*-space $\Delta(\mathrm{k}) = \Delta_0[\cos(k_x\mathrm{a}) - \cos(k_y\mathrm{b})]$, where Δ_0 is the maximum gap value and a, b are the *in*-plane lattice constants. For such a symmetry, there is a π-phase shift of the superconducting order parameter (OP) for orthogonal directions in the *k*-space which results in a positive and negative sign of the pair potential along those directions. Indeed, for a pure symmetry, nodes of the pair potential exist along the [110] directions in the CuO_2 planes. Quasiparticles at the surface/interface experience a different OP before and after the scattering process and subsequently midgap bound states arise at the Fermi surface [3–6]. These states have been observed as zero bias conductance peak (ZBCP) in the conductance spectra of different HTS/I/Normal tunnel structures [7–10]. Another consequence of the unconventional symmetry of the OP is that, in the tunneling characteristics of junctions that show well developed ZBCP, the gap related structures (GRS), that is the conductance maxima at $V \neq 0$, completely disappear or are highly suppressed and shifted towards lower energies, depending on the misorientation angle of the interface with respect to the crystal axes [5].

Experimentally, a remarkable variety of tunneling spectra has been reported both for S-I-N and S-I-S junctions, generally deviating from the ideal BCS behavior and indicating different values of the energy gaps [11,12]. Spectral anomalies such as suppressed or enhanced gap related structures, quasilinear conductance backgrounds, zero bias conductance peak, and asymmetry complicate even more the analysis and introduce uncertainty in the determination of the value of the energy gap and its temperature dependence. As discussed before, there are some intrinsic reasons responsible for the uncertainty of this scenario. In addition to this, the experimental work on HTS is complicated by the difficulty of realizing high quality tunnel junctions. Indeed, due to the short and anisotropic coherence length ξ and to the easy oxygen desorption, surfaces often do not represent the bulk properties of these materials. Moreover, HTS have complex lattice structures and need crucial deposition conditions that make difficult to grow multilayers with sharp interfaces preserving epitaxiality through the whole sandwich. In this respect, few and contradictory quasiparticle tunneling results are reported in the literature [13–15] for all-high T_C tunnel junctions. To avoid these problems in order to study the

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temperature behavior of the $YBa_2Cu_3O_7$ superconducting energy gap, we have used the break junction technique that provides clean and unaffected interfaces obtained by fracturing a thin strip sample in liquid helium just before the measurements. In this paper, we first show that the produced junctions are stable in temperature and mechanically tunable (by means of a micrometric screw). Then, we report the *ab*-plane tunneling characteristics, from which we deduce the temperature dependence of the GRS. The data are compared with those obtained in high quality, *c*-axis oriented YBCO/Pb planar junctions. There are two main advantages in using a S-I-S configuration for this analysis: first, the break-junction tunneling spectra do not have the bias polarity sensitivity of the S-I-N junctions being symmetric with respect to the Fermi level; second, the temperature behavior of the conductance maxima directly reproduce the $\Delta(T)$ variation, and no deconvolution procedures have to be applied to the data.

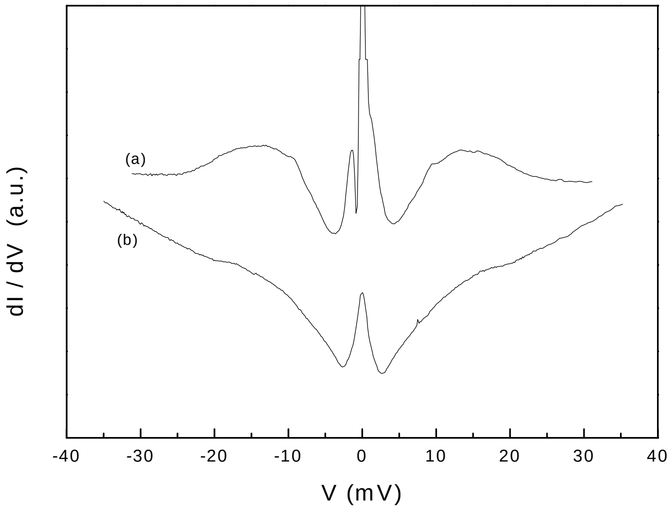

Fig. 1. Tunneling spectra measured on the same $YBa_2Cu_3O_7$ break-junction by changing the distance d between the fractured electrodes.

2 Tunneling measurements

The tunnel junctions were produced by applying the break-junction technique to highly biepitaxial *c*-axis oriented $YBa_2Cu_3O_7$ thin films (thickness $\sim$ 200 nm), d.c. sputtered on (001) $SrTiO_3$ substrates [16]. The standard four probe resistivity measurements showed good metallic behavior in the normal state with sharp superconducting transition $\Delta T_C \le 0.5$ K and T_C (ρ=0) $\ge$ 91 K. The structural characterization of the films was performed by means of X-ray diffraction analysis. Only (00ℓ) peaks were observed, indicating a strong *c*-axis orientation with a FWHM of the (005) peak of 0.08°. Moreover, the ϕ-scan analysis of the (103) planes showed that the $YBa_2Cu_3O_7$ films were bi-epitaxial along the CuO_2 planes [17]. A photolithographic process was used to reduce the films into strips 100 μm wide. Four in-line Ag contacts were thermally evaporated for current and voltage contacts and gold leads were attached by indium soldering. The samples were fixed to a bending plate by epoxy glue at two separate points and then the whole sample was covered by epoxy resin. To obtain a planar fracture we scratched a straight groove in the central part of the substrate to favour a localized fracture. After curing and bending, the epoxy cover cracks along the desirable line and the sample is divided in two electrodes separated by a helium barrier. We always measured the resistive transition of the $YBa_2Cu_3O_7$ films before breaking them at low temperatures to verify the quality of the films after the fabrication treatments. By this technique, tunable resistance junctions with current favoured along *ab*-planes have been realized. A micrometric screw allowed us, after breaking, to readjust the junction resistance by varying the gap space between the two electrodes. The reduction factor $\delta l/\delta d$, where δl is the shift of the micrometric screw and δd is the distance between the electrodes, is about $10^3 \div 10^4$ for our inset [18]. So, considering that one can estimate screw movements of about 1 μm, we can vary the distance between the electrodes d by steps of the order of few angstrom. It is worth to notice that the material elongated on both sides of the fracture can experience some lattice distortion locally reducing the transition temperature. However, after breaking, the movements piloted by the screw, do not further stress the lattice because of the separation between the electrodes. An additional advantage of the break-junction technique is the possibility of changing the barrier thickness during the measurements, so that the weak link regime and the quasiparticle tunneling regime can be investigated on the same sample [17,19]. In Figure 1 we report two different conductance spectra measured on the same optimally doped $YBa_2Cu_3O_{7-\delta}$ junction at T = 5 K. Curve (a), corresponding to the lowest normal resistance, was obtained with the smallest distance between the electrodes. We observe the presence of a narrow Josephson related peak and of a ZBCP. By increasing the distance, curve (b), the Josephson current is suppressed while the ZBCP is still observed. In both cases, the GRS are recognizable, suggesting a good mechanical stability of the system that preserves the junction geometry.

For the majority of our junctions we have obtained a good barrier stability with temperature. As an example, the temperature dependence of the normal state resistance R_N (V = 100 mV) is reported in Figure 2, for the same sample of Figure 1 in a different electrode configuration. A variation of about 15% in the temperature range between 4.2 K and 100 K is observed, that is not relevant when studying the temperature dependence of the GRS. This is the upper limit in our junctions for resistance changes with temperature. In Figure 3 we report the tunneling conductance data (dI/dV *vs.* V) for the same barrier configuration of curve (a) in Figure 1, measured in the temperature range between 4.2 K and 100 K.

At low temperatures, these spectra show coexistence of three different features. Conductance maxima at V = $\pm$16 mV, and a huge, narrow zero bias peak superimposed to a wider, $\pm$5 mV, structure can be observed. The last

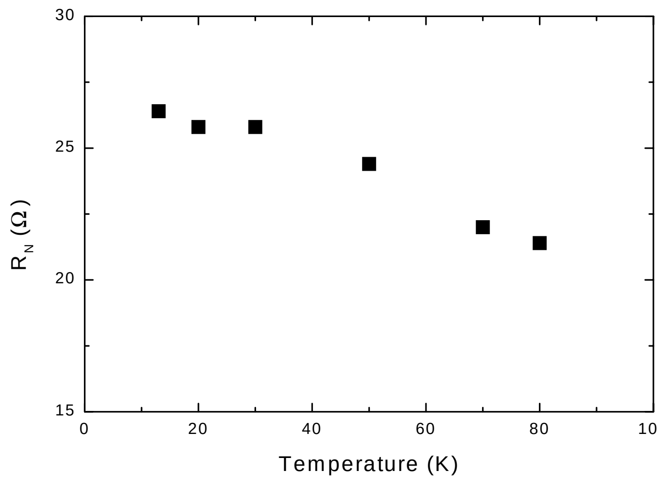

Fig. 2. Temperature dependence of the normal-state resistance R_N ($V = 100$ mV) for a different configuration of the $YBa_2Cu_3O_7$ break-junction.

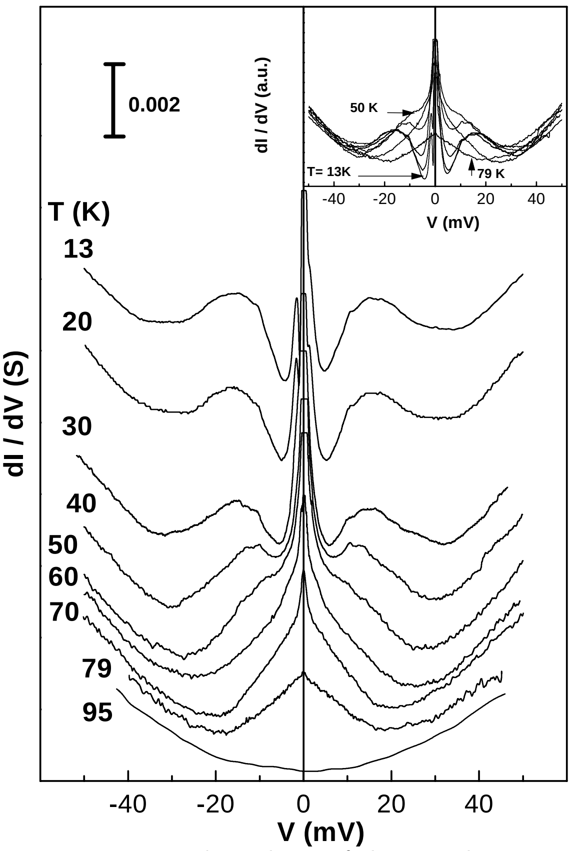

Fig. 3. Temperature dependence of the tunneling spectra in the (a) configuration of Figure 1. The curves have been successively shifted for clarity. The inset shows the high stability of the background conductance.

features have been related to the Josephson effect and to the formation of Andreev bound states at the Fermi level, respectively. Physical reasons and behavior of the two overlapped zero bias structures have been discussed elsewhere [20]. Here we focus our attention on the temperature behavior of the gap related structures observed at $V \neq 0$. As already mentioned, there is a strong dependence of the quasiparticle conductance spectra on the misorientation angle a between the normal to the interface and the crystalline axes [16,21,22]. For a pure $d_{x^2-y^2}$-wave symmetry, the measured value of the energy gap is related to its maximum value at the Fermi level by the expression $\Delta = \Delta_0 \cos[2(\vartheta - \alpha)]$, where θ is the angle of incidence for a quasiparticle approaching the junction [22]. The structural characterization of the $YBa_2Cu_3O_7$ films allowed us to determine the lateral lattice alignment in order to quantify the *in*-plane misorientation α of the junctions [24]. However, after breaking, we could only estimate the "average misorientation angle" since, due to the microscopic faceting of the fracture, different orientations can be present at junction interface. So, from the measured $\Delta = \pm 16$ meV, estimating $\alpha \approx 45^o \pm 5^o$, we have obtained $\Delta_0 \approx 22$ meV for the $YBa_2Cu_3O_7$ compound at $T = 13$ K. As expected, the voltage positions of the conductance maxima in Figure 3 shift to lower energies for increasing temperatures. However, quantitative evaluation can be only made up to 60 K. At least two reasons can be responsible for the reported effect. Indeed, when not completely developed GRS are observed, thermal smearing severely obscures the presence of conductance features at high temperatures ($k_B T \approx 5$ meV at $T = 60$ K). Second, during the fracturing process, lattice distortions can be produced at the interfaces, locally reducing the critical temperature of the $YBa_2Cu_3O_7$ compound. Taking into account that the Josephson effect, the narrow peak in Figure 3, is observed up to $T = 70$ K, we have considered this temperature as lower limit for the junction T_C^J.

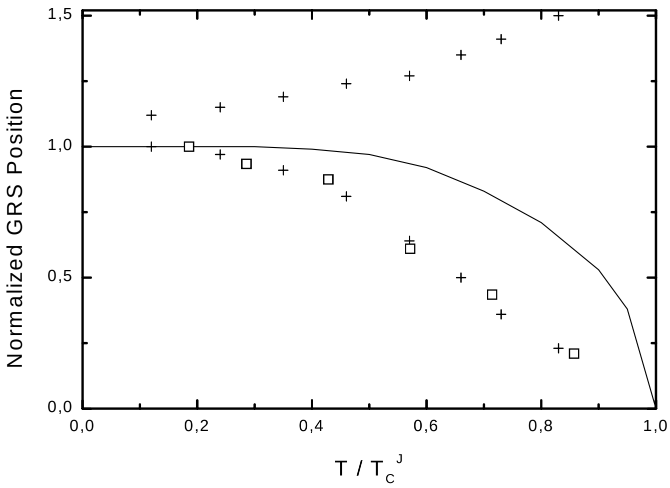

Fig. 4. Normalized temperature dependence of the GRS of Figure 3 (open squares) Upper crosses indicate the voltage position of the conductance maxima for a *c*-axis oriented $YBa_2Cu_3O_7$/Pb planar-junction, while lower crosses refer to the deconvoluted data [24]. Continuous line shows the BCS theoretical behavior.

In Figure 4, we report the normalized temperature dependence of the GRS (open squares) for the same junction. We observe that, in comparison with the BCS behavior (full line), the superconducting gap closes more rapidly towards the junction T_C^J. For comparison, in the figure, upper and lower crosses refer respectively to the measured and the deconvoluted data obtained in c-axis oriented, S-I-N type $YBa_2Cu_3O_7$ junctions [23,24]. The fact that different tunneling configurations, with different orientations of the $YBa_2Cu_3O_7$ films and single crystals show a quasilinear temperature behavior of the GRS for $T > 0.4\ T_C^J$, highly supports the hypothesis that we are measuring an intrinsic property of this compound.

3 Conclusions

In summary, by means of tunable break-junctions, we have measured the *ab*-plane tunneling spectra of the $YBa_2Cu_3O_7$ compound close to the gap-node direction [110], in a temperature range up to 100 K. By considering a *d*-wave pairing symmetry, we have estimated that at $T = 13$ K the maximum value of the superconducting energy gap at the Fermi level is $\Delta_0 \approx 22$ meV. For increasing temperatures, a quasilinear dependence of the GRS has been measured similar to that previously reported for c-axis oriented $YBa_2Cu_3O_7$ planar junctions.

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