Interlayer tunnelling in $Bi_2Sr_2CaCu_2O_{8+d}$ single crystals

P.J. Thomas, J.C. Fenton, G. Yang, C.E. Gough
Superconductivity Research Group, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

This article was published as Physica B 280 (2000) 245
http://dx.doi.org/10.1016/S0921-4526(99)01646-4

We present measurements of the intrinsic quasi-particle conductivity along the c-axis of 2212-BSCCO single-crystal mesa structures in the superconducting and normal states. Direct measurement of the mesa temperature enables corrections to be made for self-heating and permits the acquisition of reliable *I-V* characteristics over a wide range of temperatures and voltages. Unlike a conventional superconductor, there is no evidence for any change in the quasiparticle conductivity at T_c, consistent with precursor pairing of electrons in the normal state. At low temperatures the initial low-voltage linear conductivity exhibits a T^2 dependence, approaching a limiting value at zero temperature.

Keywords: *c*-axis transport; Intrinsic Josephson effects; Bi-2212; Out-of-plane conductivity

The *c*-axis, interlayer quasi-particle DC conductivity has been measured in the normal and superconducting states using small mesas lithographically patterned on the surface of a number of single crystals of 2212-BSCCO with a range of doping. Here we concentrate on the limiting behaviour of the interlayer conductivity at low temperatures and its temperature dependence on passing through T_c.

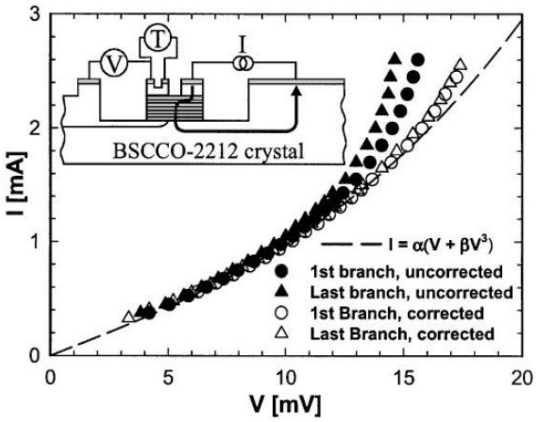
Mesa structures typically 30 x 30 μm^2 x 15-30 nm were lithographically patterned [1] on as-grown and oxygen annealed 2212-BSCCO single crystals of various doping grown using a thermal gradient method [2].

Below T_c, the voltage-dependent conductivity was measured in zero magnetic field by biasing junctions in the resistive phase-slip state. A novel three-contact sample geometry was employed, allowing four-probe measurements to be performed whilst simultaneously monitoring the mesa temperature via the temperature-dependent contact resistance (see inset to Fig. 1). The normal state, low-bias (~1 μA) conductivity was measured down to ~50 K in a field of 6.6 T, overlapping in temperature with zero field measurements in the superconducting state.

Very similar multi-branched *I-V* characteristics were observed to those reported elsewhere [3]. The temperature-corrected *I-V* curves are well described by a tunnel current given by

$$I=\alpha(V+\beta V^3) \quad (1)$$

(see dashed line in Fig. 1). The intrinsic linear conductance, a, is inconsistent with models involving incoherent interlayer tunnelling between layers with a $d(x^2+y^2)$ order parameter symmetry and isotropic scattering around the 2D Fermi surface, as proposed previously [4].



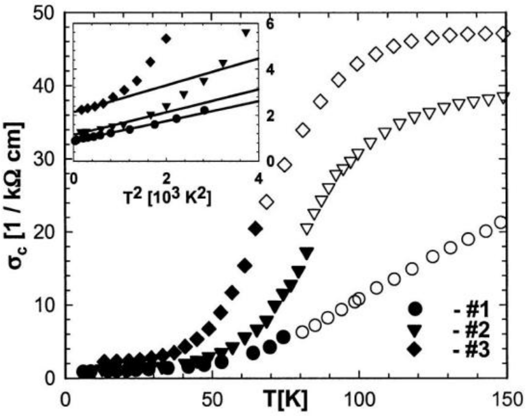


Fig. 1 (left). *I-V* characteristics of 1st and 11th (scaled by 1/11) phase-slip branches for sample 2 at 24 K, before and after correction for sample heating. Note that the temperature-corrected data lie on the same line.

Fig. 2 (right). Quasiparticle conductivity plotted for three samples spanning optimal doping ((#1) T_c =75±3.5 K, (#2) T_c = 87±0.9 K, (#3) T_c=86±0.5 K). Open symbols: normal state. Solid symbols: from fits to I-V curves below Tc. Inset shows low-temperature behaviour.

The derived linear component of the conductivity, σ_c, is plotted as a function of temperature in Fig. 2 in addition to the associated normal state conductivity. At low temperatures, the conductivity is given by

$$\sigma_c(T) = \text{const}(1+\gamma T^2), \quad (2)$$

consistent with impurity-assisted interlayer hopping (see e.g. Ref. [5]), approaching a doping-dependent limiting value at T=0 which is in good agreement with other measurements [6]. When corrected for heating, $\sigma_c(T)$ for samples #1 and #2 (underdoped) exhibit a T^2 dependence over a larger temperature range (up to ~45 K) than previously reported, whilst sample #3 (overdoped) shows a T^2 variation below ~20 K. σ_c is continuous at T_c, with no evidence for the discontinuity in slope expected from any model involving the onset of pairing at T_c. Because it is continuous on passing through T_c, changes in conductivity above T_c are unlikely to be associated with superconducting fluctuations. For all samples, $\sigma_c(T)$ decreases monotonically from temperatures well above T_c, consistent with the onset of a pseudo-gap, possibly due to precursor pairing in the normal state.

Latyshev et al. [6] predict a universal relationship between β (1) and γ (2). Within experimental error, the ratio γ/β for all of our samples is consistent with their model, which assumes coherent interlayer transport between low-lying impurity induced states localised in the d-wave gap nodes.

Acknowledgements

This work is supported by EPSRC. We would like to thank A. Schofield for helpful discussions. We are grateful to P. Andrews and G. Walsh for technical support.

References

[1] A. Yurgens et al., Inst. Phys. Conf. Ser. 148 (1995) 1423.
[2] G. Yang et al., IEEE Trans. Appl. Supercond. 3 (1995) 1663.
[3] R. Kleiner et al., Phys. Rev. Lett. 68 (1992) 2394.
[4] M. Suzuki, K. Tanabe, Jpn. J. Appl. Phys. 4B (Part 2) (1996) L482.
[5] T. Xiang, J.M. Wheatley, Phys. Rev. Lett. 77 (1996) 4632.
[6] Yu.I. Latyshev et al., Phys. Rev. Lett. 82 (1999) 5345.