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

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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.

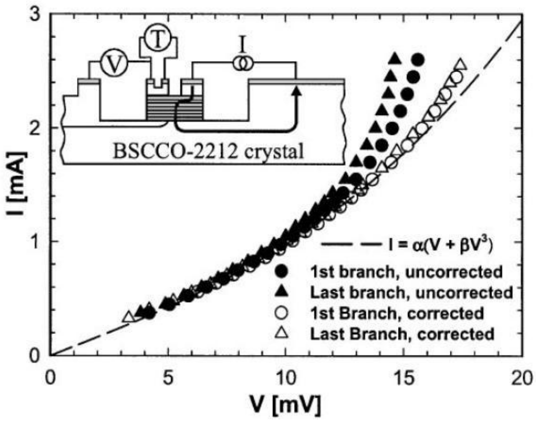
Mesa structures typically 30 x 30 μm^2 x 15-30 nm were lithographically patterned [1] on as-grown and oxygen annealed 2212-BSCCO single crystals of various doping grown using a thermal gradient method [2].

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].



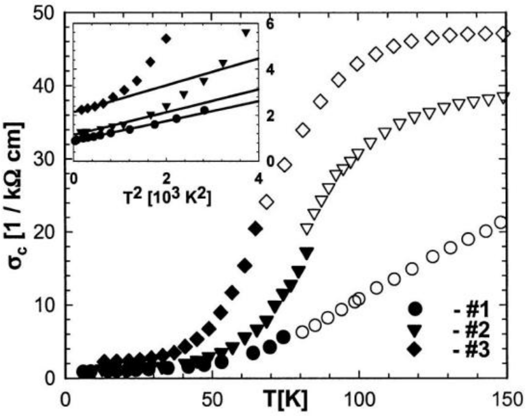


Fig. 1 (left). *I-V* characteristics of 1st and 11th (scaled by 1/11) phase-slip branches for sample 2 at 24 K, before and after correction for sample heating. Note that the temperature-corrected data lie on the same line.

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

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

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.

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