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Tunnelling Studies in BiSrCaCuO:Pb Break Junctions

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Abstract: Single-particle tunnelling experiments have been performed on polycrystalline BiSrCaCuO:Pb using break junction configuration in the temperature range $4{\cdot}2\ K \leq T \leq T_c$. A single peak at $V = \pm 60$ mV, ascribed to a gap feature, has been observed in the conductance spectra at 4·2 K from which a ratio of $2\Delta(0)/K_BT_C = 6{\cdot}2\ (\pm 0{\cdot}5)$ is obtained. The temperature dependence of Δ is compared with the BCS theory. Alternative non-BCS mechanisms may also have to be invoked to obtain satisfactory agreement between the measured values and theory. Attempts to fit the experimental data by considering lifetime smearing Dynes model have resulted in $\Delta = 25$ meV and $\Gamma = 4{\cdot}1$ meV.

1 INTRODUCTION

In order to understand the mechanism of superconductivity in High Temperature Superconductors (HTSC) a knowledge of various parameters such as superconducting energy gap, density of states near the Fermi level, the interaction of electrons with phonons and other possible pairing mechanisms, weak link behaviour, etc., is of vital importance. Electron tunnelling spectroscopy is one of the best methods for obtaining such information.[1,2] Surface contamination by non-superconducting interfaces should be eliminated in order to obtain the current–voltage characteristics (*IVC*) with a well-defined gap structure. In the case of HTSC materials it is extremely difficult to fulfil this requirement because these materials possess very short coherence length ξ and mean free path l for the scattering of quasiparticles. Besides planar tunnelling junctions using natural oxide barriers[3] or artificial barriers,[4,5] a number of alternative techniques have been employed such as break junction,[6,7,8] point contact[9,10] and vacuum tunnelling using STM.[11,12] Tunnel junctions based on HTSC materials are discussed in detail in Ref. 13. In the case of break junctions, the above-mentioned problems are overcome to a very great extent by (a) cleaving the material under cryogenic conditions and (b) carrying out measurements *in-situ* in a helium atmosphere. Also this method can be successfully used for HTSC single crystals and whiskers which are usually small in dimensions. In this paper we discuss some results of tunnelling measurements of the energy gap in polycrystalline BiSrCaCuO:Pb samples in the temperature interval $4{\cdot}2\ K \leq T \leq T_c$.

2 EXPERIMENTAL METHODS

High purity polycrystalline $Bi_{1{\cdot}4}Pb_{0{\cdot}6}Sr_2Ca_2Cu_3O_x$ was prepared from mixtures of Bi_2O_3, PbO_2, $SrCO_3$, $CaCO_3$ and CuO in the ratio Bi:Pb:Sr:Ca:Cu = 1·4:0·6:2:2:3. The starting materials were mixed, ground, and reacted at 800°C in air for 24 h, then furnace cooled to room temperature. The reacted materials were reground and pelletised, then sintered in air at 850°C for 96 h followed by cooling to room temperature in the furnace. The stoichiometry of the sample was confirmed by X-ray diffraction (XRD). Figure 1 shows the X-ray diffractogram along with the Miller indices of the prominent reflections. All the peaks could be indexed to the 2223 phase and no traces of other phases were found. The samples were found to be superconducting through dc magnetic susceptibility and electrical resistivity measurements, which indicated a bulk $T_C = 108$ K (Fig. 2).

To produce break junctions, a modified version of the customary breaking method was used.

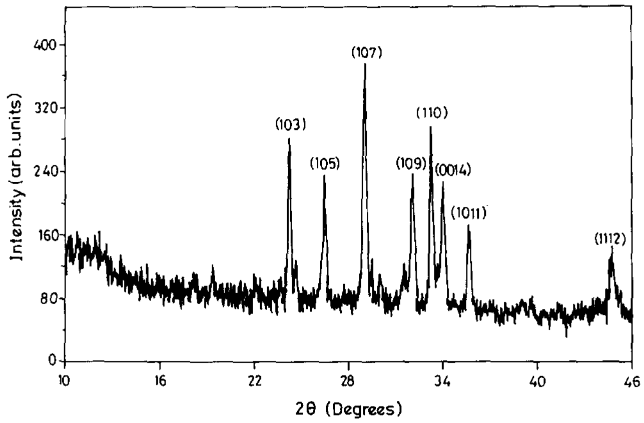

Fig. 1. XRD for $Bi_{1.4}Pb_{0.6}Sr_2Ca_2Cu_3O_x$.

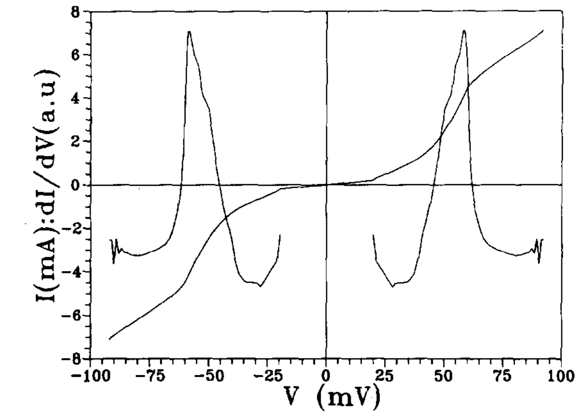

Fig. 3. *I–V* and d*I*/d*V* plots for Bi-2223 break junction measured at 4·2 K.

Rectangular-shaped samples of size 3 × 1·5 × 0·5 mm^3 with saw engravings in the middle were mounted onto a flexible substrate with copper spots for the current and voltage contacts. The samples were fixed to the substrate by liquid indium–gallium alloy which yields a solid bond when the system is cooled down. The substrate was mounted onto a brass spring plate which could be bent by micrometric screws. The breaking of the sample was carried out in a cryostat at liquid helium temperature. The bending of the spring was stopped when the splitting of the sample occurred, i.e. when the resistance abruptly rose. Further small deformations of the spring made it possible to adjust the critical current I_c and resistance R_n of the Josephson junction within reasonable limits. The *IVC* were obtained using a computer-controlled data acquisition system. The conductance was calculated from *IVC* by numerical differentiation.

3 RESULTS AND DISCUSSION

Figure 3 shows the *I–V* and d*I*/d*V* characteristics of a typical BiSrCaCuO:Pb break junction at 4·2 K. These curves are quite reproducible and confirm that the tunnel junctions are of high quality. The existence of Josephson current points out the possibility of a thin barrier in these junctions. Besides Josephson current, a well-pronounced gap-like structure is seen in the symmetric d*I*/d*V* curve with a peak-to-peak separation of $4\Delta = 120$ meV. Hence we obtain $2\Delta/K_BT_C = 6{\cdot}2\ (\pm\ 0{\cdot}5)$. On some *IVC*s, at bias voltages $V \geq 2\Delta/e$, a clearly defined knee structure (local build-up of the excess current) was observed at $T = 4{\cdot}2$ K (Fig. 4). The amplitude of this feature increases with an increase of junction resistance R_n. The appearance of the sharp knee is associated apparently with a proximity effect.[14,15] A similar feature was observed earlier in the case of transition metals and was explained by the formation of SNI structure at the surface.[14] Qualitatively the knee structure in the *IVC* is very similar to the characteristics of the niobium junctions in which the niobium surface is contaminated by oxygen.[16] Theoretical studies of the *IVC* of SNINS structure were performed by Golubov and Kupriyanov.[15] In the present case, since the junction is formed by breaking the sample in a helium atmosphere the possibilities of surface contamination or oxidation are minimal. Hence, the formation of the SNI structure may be due to cleaving the sample at the grain boundaries. As a result, distortion of energy bands and formation of

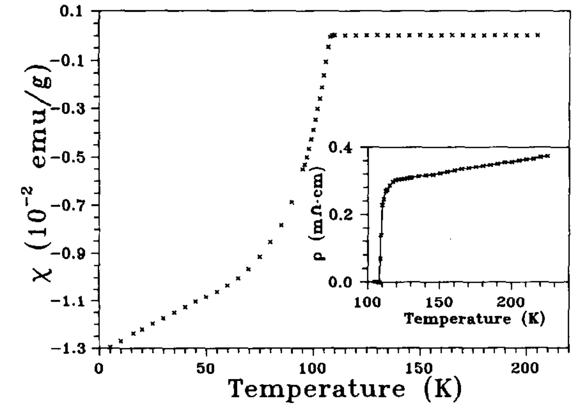

Fig. 2. χ vs *T* plot for Bi-2223. Inset shows the plot of ρ vs *T*.

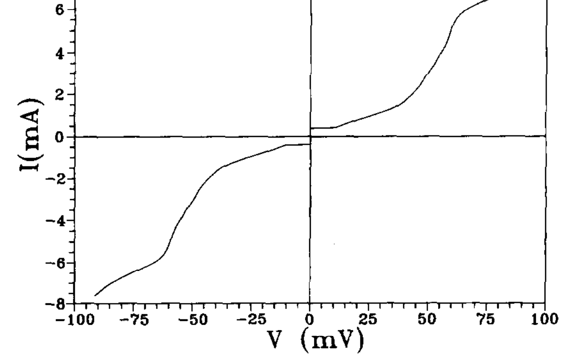

Fig. 4. *IVC* of Bi-2223 junction at 4·2 K exhibiting knee structure.

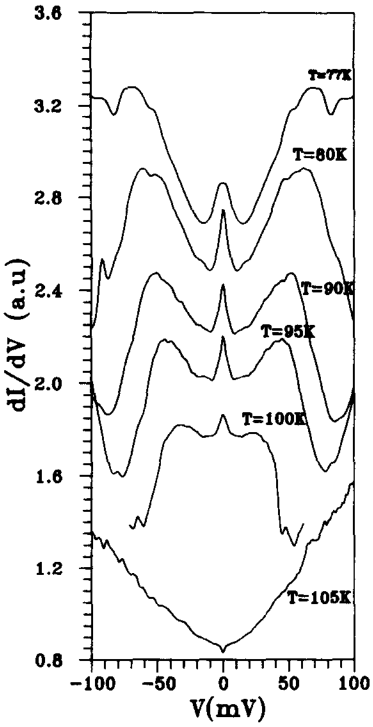

Fig. 5. d*I*/d*V* vs bias voltage at various temperatures.

an SNI structure at the surface takes place, where N is a thin normal metal layer in which superconductivity is absent owing to low concentration of charge carriers.

The d*I*/d*V* characteristics at different temperatures are shown in Fig. 5. The value of the gap parameter was determined from the peak-to-peak distance. With increase in temperature the gap value slowly decreases. The temperature dependence of Δ is compared with that expected from BCS theory (Fig. 6). The solid line in the figure is obtained using Thouless' formula.[17]

$$\frac{\Delta(T)}{\Delta(0)} = \tanh\left[\frac{\Delta(T)\,T_c}{\Delta(0)\,T}\right] \tag{1}$$

BCS-like temperature dependence of the gap parameter has been observed by many authors.[8,18] In some cases, for example in BiSrCaCuO:Pb

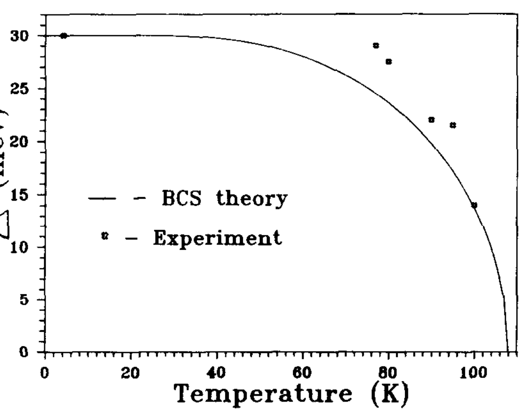

Fig. 6. Variation of Δ with temperature.

phase intergrowth samples, Aminov *et al.*[19] showed a deviation from BCS and explained that it was due to proximity effect.

In the present case, this anomaly may be explained using the gap equation arising from interlayer tunnelling.[20,21] Details are published elsewhere.[22] The gap equation is given by

$$\Delta_k = T_J(k)\frac{\Delta_k}{2E_k}\tanh\frac{\beta E_k}{2} + \sum_q{}' V_{kq}\frac{\Delta_q}{2E_q}\tanh\frac{\beta E_q}{2} \tag{2}$$

Here $T_J(k) = t_\perp^2(k)/t$ is the strength of a momentum-conserving Josephson interaction and $t_\perp(k)$ is the single particle tunnelling matrix element between adjacent Cu–O layers. The presence of an additional intralayer mechanism of the BCS form $V_{kq} = V_{BCS}$ is also assumed. The first term on the right hand side of the above equation leads to a gap which is weakly temperature-dependent.[20] This equation is solved for two limiting cases, $V_{kq} << T_J(k)$ and $T_J(k) << V_{kq}$. When $T_J(k) < V_{kq}$, the temperature dependence of superconducting gap is similar to that of BCS theory, while when $V_{kq} << T_J(k)$ the gap exhibits a steeper decrease with increasing temperature in the vicinity of T_c.

The BCS theory assumes that the quasiparticle lifetime is very large so that the damping effect does not significantly broaden the energy levels of the electron system. When the system is at a temperature near T_c or when it is strongly coupled so that quasiparticle lifetime is largely reduced by the electron–phonon interaction, this assumption is invalid. Dynes *et al.*[23] have obtained the quasiparticle lifetime τ by measuring the corresponding temperature-dependent lifetime broadening of the energy gap edge. They treated this effect by simply adding an imaginary part Γ to the energy variable in the BCS density of states.

$$N_s(E) = Re\left[\frac{(E - i\Gamma)}{\sqrt{(E - i\Gamma)^2 - \Delta^2}}\right] \tag{3}$$

where $\Gamma \approx \hbar/\tau$.

In the case of the symmetrical S-I-S junctions the expression for tunnelling current through the junction is

$$I(V) = \frac{1}{2eR_n}\int_{-\infty}^{\infty}\left(\left(\tanh\left(\frac{E}{2kT}\right) - \tanh\frac{(E + eV)}{2kT}\right)\right)N(E,\Gamma)N(E + eV,\Gamma)\,dE \tag{4}$$

where Δ is the gap parameter, Γ damping factor and R_n is the normal state resistance of the junction. A fairly good fit between experimental and theoretical curves is obtained by varying three parameters:

Δ, Γ and R_n. In our case for T = 4·2 K we have obtained 25 meV and 4·1 meV for Δ and Γ, respectively. For certain junctions, due to the presence of knee structure in the *IV* characteristics, the experimental curve does not agree well with the theory.

In conclusion, tunnelling measurements have been performed on a BiSrCaCuO:Pb superconductor. A gap value of 30 meV is obtained at T = 4·2 K. The temperature dependence of the gap parameter may be accounted for by invoking an interlayer tunnelling mechanism.

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