

Interlayer Transport of Quasiparticles and Cooper Pairs in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ Superconductors

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We study the c -axis transport of stacked, intrinsic junctions in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystals, fabricated by the double-sided ion beam processing technique from single crystal whiskers. Measurements of the I - V characteristics of these samples allow us to obtain the temperature and voltage dependence of the quasiparticle c -axis conductivity in the superconducting state, the Josephson critical current, and the superconducting gap. We show that the BCS d -wave model in the clean limit for resonant impurity scattering, with a significant contribution from coherent interlayer tunneling, describes satisfactorily the low temperature and low energy c -axis transport of both quasiparticles and Cooper pairs. [S0031-9007(99)09468-5]

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The observation of the pseudogap in the underdoped cuprate superconductors $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4+\delta}$, and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi-2212) is indicative of the breakdown of the Fermi-liquid theory above T_c in these systems [1]. On the other hand, the superconducting state is usually discussed in the BCS d -wave pairing model, which is based on the Fermi-liquid picture. Such an approach may be limited because (i) the properties of the normal state determine the mechanism of superconductivity, and (ii) the ratio $2\Delta_0/T_c$ is well above the BCS ratio for d -wave pairing and is strongly doping dependent. Specifically, the BCS approach may fail in describing the properties of the superconducting state that are directly related to the quasiparticles, while the electrodynamics, based on supercurrents (macroscopic quantum phenomena), is insensitive to the pairing mechanism.

The interlayer currents of both quasiparticles and Cooper pairs may be studied in highly anisotropic Bi-2212 crystals with Josephson interlayer coupling by measuring the I - V characteristic of the c -axis current. Such measurements provide information on the voltage and temperature dependence of the quasiparticle c -axis current, the energy gap, and the Josephson interlayer current. These data allow us to check the validity of the BCS d -wave model and determine the degree of the coherence of the interlayer tunneling. The question of coherence in both the normal and superconducting state is the focus of numerous studies (see, for example, [2–5]). Recently, Tanabe *et al.* [3] and Schlenga *et al.* [4] measured the quasiparticle c -axis transport in the superconducting state of Bi-2212 crystals and concluded that their data support the d -wave pairing scenario. However, their results for the quasiparticle current are insufficient to determine the nature of the interlayer

transport and the effect of intralayer scattering on this transport.

Our measurements of I - V characteristics have been performed on stacked, intrinsic mesa junctions, fabricated from high quality single crystal Bi-2212 whiskers by double-sided focused ion beam (FIB) processing [6]. For the fabrication, we used the conventional FIB machine of Seiko Instruments Corp., SMI 9800 (SP) with Ga^+ -ion beam. The details of the fabrication are described in Ref. [7]. Here, we note only that the method allows us to fabricate the mesa junctions with the in-plane size down to $0.5 \mu\text{m}$ without degradation of T_c . We studied five junctions with in-plane areas ranging from $6 \mu\text{m}^2$ down to $0.3 \mu\text{m}^2$, and a two-dimensional array of 6×6 stacks with area $0.5 \mu\text{m}^2$ each (see Table I). The number of intrinsic junctions, N , in the stack was typically about 50. The four leads were attached outside of the junction area [see Fig. 1(a)]. The contact Au pads were ablated and annealed before the FIB processing to avoid the diffusion of the Ga ions into the junction body. Figures 1(b) and 1(c) show the I - V characteristics of samples No. 2 and No. 4. The fully superconducting overlap geometry of the stack was used to suppress the effects of quasiparticle injection on the tunneling characteristics, usually occurring in junctions of the mesa type with a normal metal top electrode [3,8]. We also substantially reduced the effects of self-heating in our submicron mesa junctions. Self-heating manifests itself in the form of an S-shaped I - V curve near the gap voltage V_g [9]. The measured temperature dependence of the c -axis resistivity of the stacks (at dc currents $\approx 1 \mu\text{A}$) was typical for slightly overdoped Bi-2212 crystals with $T_c \approx 77 \text{ K}$ [2].

The critical current was determined from the I - V characteristics as the current of switching from the

TABLE I. Parameters of the stacked Bi-2212 mesa junctions. Data for samples No. 7 and No. 8 are from Refs. [3,4].

No.	S (μm^2)	N	T_c (K)	J_c (A/cm^2)	V_g/N (mV)	$\sigma_q(0)$ ($\text{k}\Omega\text{cm}$) $^{-1}$	b (meV) $^{-2}$
1	6.0	69	76	600	16	3.0	...
2	2.0	65	76	600	20	2.0	0.014
3	1.5	50	78	400	22	3.7	0.029
4	0.6	34	76	40	50
5	0.3	50	78	23	44	1.7	0.008
6	36×0.5	50	76	72	...	2.5	...
7	400	40	~ 80	250–500	20	1.7	0.012
8	256	1	86	680	22	1.5	...

superconducting to the resistive state, averaged over the stack. The variation of the critical current along the stack is not large (usually within 15%), indicating a good uniformity of our structures. The c -axis critical current density, J_c , for the junctions with in-plane areas $S > 2 \mu\text{m}^2$ was typically $600 \text{ A}/\text{cm}^2$ at $T = 4.2 \text{ K}$ (see Ref. [9]), and is consistent with the data reported by other groups [3]. For bigger stacks, the dependence of J_c on magnetic fields parallel to the layers demonstrates well resolved Fraunhofer diffraction patterns [10], which prove the presence of the intrinsic dc Josephson effect in our stacks. J_c is depressed for submicron junctions (see Table I), presumably due to the Coulomb blockade effect [9].

The superconducting gap voltage of the stack, V_g , was determined from the I - V characteristics as the voltage at the maximum of dI/dV . The gap of the intrinsic junction,

$2\Delta_0 \approx eV_g/N$, reaches values as high as 50 meV (see Table I and Ref. [9]).

The multibranch structure, which is clearly seen in Fig. 1(b), corresponds to subsequent transitions of the intrinsic junctions into the resistive state for increasing voltage [4,11]. At voltages $V > V_g$ all junctions are resistive. In the downsweep of voltage, starting from $V > V_g$, the I - V curve is observed in the all-junctions resistive state. Here, only quasiparticles contribute to the c -axis dc transport. The Ohmic resistance, R_n , at $V > V_g$ is well defined [see Fig. 1(c)]. This resistance is nearly temperature independent (Fig. 2) and corresponds to the conductivity $\sigma_n(V > V_g) \approx 80 (\text{k}\Omega\text{cm})^{-1}$ for energies well above the pseudogap and the superconducting gap.

The I - V curve of the all-junctions resistive state [lower curve in Fig. 1(b)] at low voltages fits the dependence

$$I_q(V) = \sigma_q(0) \frac{S}{s} \left[v + \frac{b}{3} v^3 \right], \quad v = V/N, \quad (1)$$

where $v \leq 10 \text{ mV}$, as seen in Fig. 3, and s is the spacing between intrinsic superconducting layers (15.6 \AA). Values for $\sigma_q(0)$, b , and S are given in Table I. For the quasiparticle differential conductivity, $\sigma_q(v, T) \equiv s^{-1} \partial J_q / \partial v$, at $v \rightarrow 0$ we find for $T \leq T^* \approx 30 \text{ K}$:

$$\sigma_q(T) = \sigma_q(0) (1 + cT^2), \quad (2)$$

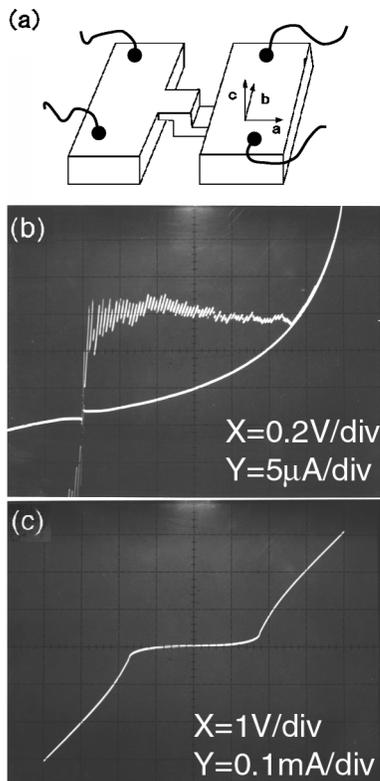


FIG. 1. Schematic view of the setup (a) and the I - V characteristics of the Bi-2212 stacks at $T = 4.2 \text{ K}$; (b) enlarged I - V scale of sample No. 2; (c) extended I - V scale of sample No. 4.

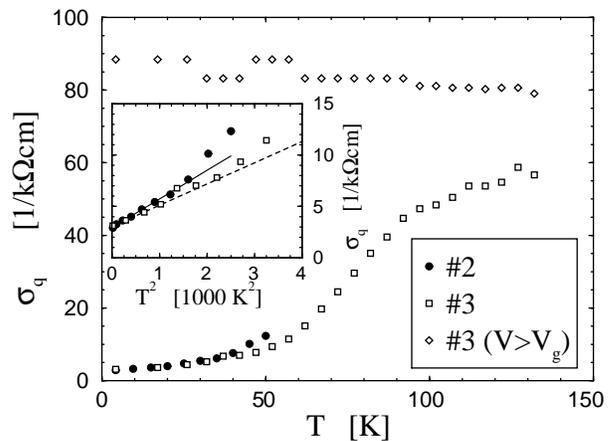


FIG. 2. Quasiparticle dynamic conductivity vs T for voltages $v > V_g/N \approx 2\Delta_0/e$ and $v = V/N \rightarrow 0$, as extracted from the I - V characteristics of samples No. 2 and No. 3. Inset: σ_q vs T^2 at voltage $v \rightarrow 0$. Lines are fits for $T^2 < 1000 \text{ K}^2$.

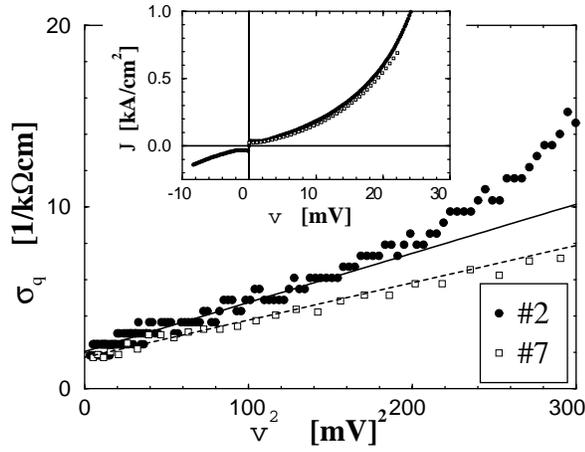


FIG. 3. The quasiparticle differential conductivity vs $v^2 = V^2/N^2$ at $T = 4.2$ K as extracted from the I - V characteristics of sample No. 2 and No. 7 [Fig. 4(c) in Ref. [3]]. Lines are fits for $v < 10$ mV. Inset: Corresponding J - v curves.

with $c \approx 9.6 \times 10^{-4}$ and $6.4 \times 10^{-4} \text{ K}^{-2}$ for samples No. 2 and No. 3 (see inset in Fig. 2). We estimate the accuracy for extracting b and c to be within $\approx 30\%$.

Previously, the quasiparticle conductivity in the superconducting state was obtained from c -axis conductivity measurements in high magnetic fields, which suppress the contribution of Josephson current to the c -axis transport. By this way, in magnetic fields up to 18 T, $\sigma_q(T)$ was obtained at temperatures above 50 K and found to increase with temperature [12]. These results are in quantitative agreement with those shown in Fig. 2. We note that the data for samples No. 7 and No. 8, taken from Refs. [3,4], are also in quantitative agreement with ours, though these samples may be slightly different. The coefficients b , c and $\sigma_q(0)$ were obtained at low voltages ($V < 0.1$ V) and low currents ($I < 1 \mu\text{A}$), to reduce heating effects. Our estimates for these coefficients agree with those obtained with only one junction being resistive [4]. Thus, we think that heating and quasiparticle injection do not strongly affect our estimates for b , c and $\sigma_q(0)$, though they may be partially responsible for the observed scatter in these parameters. Nonequilibrium effects are more important for extracting Δ_0 and $\sigma_q(V > V_g)$, especially for mesas with areas $S > 1 \mu\text{m}^2$. Since our submicron mesas have gap values close to those recently determined by surface tunneling measurements in slightly overdoped Bi-2212 single crystals [13], we conclude that we succeeded in reducing heating effects in these samples significantly.

Our results differ remarkably from the tunneling characteristics of junctions between conventional superconductors in two aspects. First, the value $\sigma_q(T)$ remains nonzero as $T \rightarrow 0$. As was mentioned above, Tanabe and co-workers also observed Ohm's law in the all-junctions resistive state at low temperatures, but considered it as being of extrinsic origin. Second, $J_c(T)$ at $T \rightarrow 0$ is substantially reduced (by a factor ≈ 30) in comparison with the value given by the Ambegaokar-Baratoff relation, $J_c^{(AB)}(0) =$

$\pi\sigma_n\Delta_0/2es$. Instead, we find at $T \rightarrow 0$ for stacks with large areas that the relation,

$$J_c(0) \approx \pi\sigma_q(0)\Delta_0/es, \quad (3)$$

holds. This result is expected when coherent tunneling is dominating the c -axis transport. We obtain the ratios $esJ_c(0)/[\pi\sigma_q(0)\Delta_0] \approx 1.2$ and 1.5 for samples No. 1 and No. 2, respectively, and ≈ 0.74 and 0.8 for samples No. 3 and No. 5, if we take into account that their effective critical current is reduced in comparison with the Josephson critical current, due to the Coulomb blockade, and take a typical $J_c(0) = 600 \text{ A/cm}^2$ as for large area stacks.

We analyze these experimental data in the framework of the BCS d -wave pairing model inside the layers, considering the general form of the tunneling Hamiltonian:

$$\mathcal{H} = \sum_n \int d\mathbf{r} \left[t_n(\mathbf{r})\psi_{n\sigma}^+(\mathbf{r})\psi_{n+1,\sigma}(\mathbf{r}) + \text{H.c.} \right] + \mathcal{H}_{\parallel,n}. \quad (4)$$

Here, $\mathcal{H}_{\parallel,n}$ is the BCS Hamiltonian for d -wave pairing with isotropic intralayer scattering inside layer n , described by the bare scattering rate, ν_0 , of electrons with defects. The superconducting gap is expressed as $\Delta(\varphi) = \Delta_0 \cos 2\varphi$, where φ is the angle of the momentum on the two-dimensional cylindrical Fermi surface. Further, $t_n(\mathbf{r})$ is the random, isotropic interlayer transfer integral which depends on the in-plane coordinate \mathbf{r} due to crystal imperfections. The correlation function $K(\mathbf{r}) = \langle t_n(\mathbf{r})t_n(0) \rangle$ in the Fourier representation is $K(\mathbf{q}) = t_{\perp}^2 [a\delta(\mathbf{q}) + (1-a)g(\mathbf{q})]$, where $at_{\perp}^2 = \langle t(\mathbf{r}) \rangle^2$ and $(1-a)t_{\perp}^2 = \langle t^2(\mathbf{r}) \rangle - \langle t(\mathbf{r}) \rangle^2$. The weight for in-plane momentum conserving (coherent) tunneling is a , while that for incoherent tunneling is $(1-a)$. Incoherent tunneling is described by the normalized function $g(\mathbf{q})$ with the characteristic momentum transfer q_0 . In the following, we will discuss the case of a strongly incoherent part, when $\nu_F q_0$ is of order ϵ_F . For small transfer integral we calculate the quasiparticle interlayer current density, using perturbation theory with respect to $t_n(\mathbf{r})$,

$$J_q(v) = \frac{es}{\pi\hbar} \int_{-\infty}^{+\infty} d\omega \int d\mathbf{k} \int d\mathbf{q} K(\mathbf{q}) \times [f(\omega) - f(\omega + ev)] \times A(\omega + ev, \mathbf{k} + \mathbf{q})A(\omega, \mathbf{k}), \quad (5)$$

where $f(\omega)$ is the Fermi distribution function, and $A(\omega, \mathbf{k})$ is the spectral density of the Green function. Scattering by impurities leads to the formation of gapless states,

$$2\pi A(\omega, \mathbf{k}) \approx \frac{(1 + \xi_{\mathbf{k}}/E_{\mathbf{k}})\gamma}{(\omega' - E_{\mathbf{k}})^2 + \gamma^2} + \frac{(1 - \xi_{\mathbf{k}}/E_{\mathbf{k}})\gamma}{(\omega' + E_{\mathbf{k}})^2 + \gamma^2},$$

at low ω , $E_{\mathbf{k}} \lesssim \gamma$. Here, $E_{\mathbf{k}} = [\xi_{\mathbf{k}}^2 + \Delta^2(\varphi)]^{1/2}$ is the quasiparticle energy and γ is the impurity bandwidth of quasiparticles; $\omega' \sim \omega$ is the impurity renormalized frequency [14–18]. The quasiparticle current at $T, ev \ll$

Δ_0 comes mainly from regions near the gap nodes on the Fermi surface. The angle dependent quasiparticle density is sharply peaked near the nodes at angles $\varphi_g \pm \varphi_0/2$, $\varphi_g = \pm\pi/4, \pm 3\pi/4$, with $\varphi_0 \sim \gamma/\Delta_0$. Impurity scattering results in a nonzero density of states at zero energy, $N(0)\varphi_0$. For the coherent part this leads to a universal quasiparticle interlayer conductivity $\propto aN(0)\varphi_0/\gamma \propto aN(0)/\Delta_0$ at $T \rightarrow 0$. The combined parts of coherent and incoherent conductivities give the following at $\nu \rightarrow 0$:

$$\sigma_q(0) \approx \frac{2e^2 t_{\perp}^2 N(0) s}{\pi \hbar \Delta_0} \left[a + (1-a) C_1 \frac{\gamma}{\epsilon_F} \right], \quad (6)$$

where $N(0)$ is the 2D density of states per spin at the Fermi level. Here and in the following, C_i ($i = 1, 2, 3$) are numerical coefficients of order unity. For the coherent part, this regime is valid at temperatures $T \ll T^*$, where the crossover temperature $T^* \approx \gamma \sim (\hbar\nu_0\Delta_0)^{1/2}$ for strong scattering, and $T^* \approx 4\Delta_0 \exp(-\pi\Delta_0/\nu_0)$ in the limit of weak scattering. Finite T corrections to σ_q at $T \lesssim T^*$ are quadratic in temperature [17]:

$$\frac{\sigma_q(T)}{\sigma_q(0)} \approx 1 + \frac{\pi^2}{18} \left(\frac{T}{\gamma} \right)^2 \left[1 + \frac{(1-a)}{a} \frac{\gamma C_2}{\epsilon_F} \right]. \quad (7)$$

Using the results of Ref. [17], we obtain, at $T \rightarrow 0$ and for voltages $e\nu \lesssim \gamma$ for the coefficient b in Eq. (1),

$$b \approx \frac{1}{8\gamma^2} \left[1 + \frac{(1-a)}{a} \frac{\gamma^2 C_3}{\epsilon_F} \right]. \quad (8)$$

For the critical current density at $T = 0$ and in the clean limit, $\hbar\nu_0 \ll \Delta_0$, we obtain [19]

$$J_c(0) \approx \frac{2et_{\perp}^2 N(0)}{\hbar} \left[a + (1-a) C \frac{\Delta_0}{\epsilon_F} \right], \quad (9)$$

where $C \lesssim 1$ is a numerical coefficient, which depends on the form of the function $g(\mathbf{q})$. We neglected the effect of the pseudogap (if any) on J_c at low T .

We see that the contribution from incoherent tunneling to the quantities $J_c(0)$ and $\sigma_q(0)$, and the parameters c and b , is negligible, if $a \gg C\Delta_0/\epsilon_F$. Assuming that this is the case, we obtain the universal relation (3) and the ratio $c/b = 4\pi^2/9 \approx 4.4$. Our data obey relation (3) as was mentioned above. We obtain $c/b \approx 6.9$ and 2.2 for samples No. 2 and No. 3, respectively. From the value of c we estimate $\gamma \approx 3$ meV. For resonant scattering this estimate agrees well with the crossover temperature $T^* \approx 30$ K, while in the Born limit T^* is much smaller. Thus we discard the Born limit. The value of $\gamma \approx 3$ meV leads to $\hbar\nu_0 \approx 0.4$ meV, confirming our assumption of the clean limit for superconductivity inside the layers.

Thus, we obtain a self-consistent description for our c -axis transport characteristics, i.e., for $\sigma_q(\nu, T)$ and $J_c(0)$ at low temperatures and low voltages, $\max(T, e\nu) \lesssim \gamma$, assuming a significant contribution of coherent tunneling to these quantities, $a > 0.05-0.1$. It is noteworthy that σ_n , as well as $\sigma_q(T, \nu)$ at $T > \gamma$ or $e\nu > \gamma$, are related to the high energy regime and thus remain outside of our description of the c -axis transport.

We conclude that the BCS d -wave pairing model in the clean limit with *resonant* intralayer scattering and significant contribution of *coherent* interlayer tunneling provides a satisfactory and consistent description of the experimental data for the low energy and low temperature interlayer transport in the superconducting state of Bi-2212 crystals for both quasiparticles and Cooper pairs. In spite of the fact that the normal state properties deviate from the Fermi-liquid behavior, we find that our data for interlayer transport are consistent with the interpretation that superconductivity restores the Fermi-liquid behavior of quasiparticles, at least at low temperatures. This is in agreement with the formation of a sharp quasiparticle peak in the density of states in the superconducting state in angle-resolved photoemission spectroscopy measurements [20].

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