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

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We study the c-axis transport of stacked, intrinsic junctions in Bi$_2$Sr$_2$CaCu$_2$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.

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The observation of the pseudogap in the underdoped cuprate superconductors YBa$_2$Cu$_3$O$_{7-\delta}$, La$_{2-x}$Sr$_x$CuO$_{4+\delta}$ and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212) is indicative of the breakdown of the Fermi-liquid theory in these systems [1]. The situation remains unclear in the overdoped regime. 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 (a) the properties of the normal state determine the mechanism of superconductivity, and (b) 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 almost 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 theoretical and experimental studies, see for example [2-4]. Recently, Tanabe et al. [5] 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 high quality, stacked, intrinsic mesa junctions, fabricated from perfect 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 $\mu$m without degradation of $T_c$.

We studied 5 junctions with in-plane areas ranging from 6 $\mu$m$^2$ down to 0.3 $\mu$m$^2$, and the 2D array of 6×6 stacks with area 0.5 $\mu$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. Fig. 1(b) shows the I-V characteristic of sample #2. The fully superconducting overlap geometry of the stack let us avoid the effects of quasiparticle injection on the tunneling characteristics, usually occurring in junctions of the mesa type with a normal metal top electrode [1]. 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 $V_g$ [8]. As a result, for small junctions we found the high quality tunneling characteristics free of the nonequilibrium effects mentioned above [Fig. 1(c)]. The measured temperature dependence of the c-axis resistivity of the stacks (at DC...
currents $\approx 1 \mu A$) was typical for slightly overdoped Bi-2212 crystals with $T_c \approx 77$ K.

The critical current was determined from the I-V characteristics as the current of switching from the 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 $S > 2 \mu m^2$ was typically 600 A/cm$^2$ at $T = 4.2$ K (see Ref. [10]), 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 [11], 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 [10].

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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. [10]. Note that this relation would be exact for a stack of conventional s-wave junctions.

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The multibranched structure, which is clearly seen in Fig. 1(b), corresponds to subsequent transitions of the intrinsic junctions into the resistive state for increasing voltage [13]. At voltages $V > V_g$ all junctions are resistive. In the down-sweep 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, $R_n$, 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 $ (kΩ 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

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

where $v \leq 10 \, \text{mV}$, as seen in Fig. 3, and $s$ is the spacing between intrinsic superconducting layers (15.6 Å). 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 $v \to 0$ we find for $T \leq T^* \approx 30$ K:

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

with $c \approx 9.6 \cdot 10^{-4}$ K$^{-2}$ and $6.4 \cdot 10^{-4}$ K$^{-2}$ for samples #2 and #3, respectively, 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 [13]. These results are in quantitative agreement with those shown in Fig. 2. We note that data for sample #7, taken from Ref. [10], are also in quantitative agreement with ours, though the sample may be slightly different.

FIG. 2. Quasiparticle dynamic conductivity vs. $T$ for voltages $v > V_g/N \approx 2\Delta_0/e$ and $v = V/N \to 0$, as extracted from the I-V characteristics of samples #2 and #3. Inset: $\sigma_q$ vs. $T^2$ at voltage $v \to 0$. Lines are fits for $T^2 < 1000 \, \text{K}^2$

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 $T \to 0$. As was mentioned above, Tanabe and coworkers 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 $T \to 0$ is substantially reduced (by a factor $\approx 30$) 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 $T \to 0$ for stacks with large areas that the relation

$$J_c(0) \approx \frac{\pi \sigma_n(0) \Delta_0}{es}$$

(3)

holds. This result is expected when coherent tunneling is dominating the $c$-axis transport. We obtain the ratios $es J_c(0)/[\pi \sigma_n(0) \Delta_0] \approx 1.2$ and 1.5 for samples #1 and #2, respectively, and $\approx 0.74$ and 0.8 for samples #3 and #5, if we take into account their effective critical current is reduced in comparison with the Josephson critical current, due to the Coulomb blockade, and take a typical $J_c(0) = 600$ A/cm$^2$ as for large area stacks.

![Graph](image)

**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 #2 and #7 (Fig. 4(c) in Ref. [4]). Lines are fits for $v < 10$ mV. Inset: Corresponding $J$-$v$ curves.

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:

$$\mathcal{H} = \sum_n \int d\mathbf{r} [t_n(\mathbf{r}) \psi^+_{n,\sigma}(\mathbf{r}) \psi_{n+1,\sigma}(\mathbf{r}) + h.c.] + \mathcal{H}_{\parallel,n}.$$ (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, $\nu_0$, of electrons with defects. The superconducting gap is expressed as $\Delta(\varphi) = \Delta_0 \cos 2\varphi$, where $\varphi$ 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 $K(q) = t_n^2 [a \delta(q) + (1 - a) g(q)]$, where $a t_n^2 \approx \langle t(\mathbf{r}) \rangle^2$ and $(1 - a) t_n^2 \approx \langle t^2(\mathbf{r}) \rangle - \langle t(\mathbf{r}) \rangle^2$. 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 $g(q)$ with the characteristic momentum transfer $q_0$, e.g., with a Gaussian distribution $g(q) = (\pi/q_0^2) \exp(-q^2/4q_0^2)$. In the following, we will discuss the case of a strongly incoherent part, with $v_F q_0$ of order $\varepsilon_F$. Here $v_F$ and $\varepsilon_F$ are the Fermi velocity and energy, respectively. For small transfer integral we calculate the quasiparticle interlayer current density, using perturbation theory with respect to $t_n(\mathbf{r})$,

$$J_q(v) = \frac{es}{\pi^2 \hbar} \int_{-\infty}^{+\infty} d\omega \int d\mathbf{k} \int d\mathbf{q} \Delta_0 K(q) \times [f(\omega + ev) - f(\omega)] A(\omega + ev, \mathbf{k} + \mathbf{q}) A(\omega, \mathbf{k}),$$ (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, $A(\omega, \mathbf{k}) \approx \gamma/(\omega - E_k^{\pm 2} + \gamma^2)$ at low $\omega$, $E_k^{\pm} \ll \gamma$. Here $E_k = [\xi_k^2 + \Delta^2(\varphi)]^{1/2}$ is the quasiparticle energy and $\gamma$ is the impurity bandwidth of quasiparticles [13–19]. The quasiparticle current at $T, ev \ll \Delta_0$ 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 $\propto a N(0) \varphi_0/2 \gamma \propto a N(0)/\Delta_0$ at $T \to 0$. The combined parts of coherent and incoherent conductivities give at $v \to 0$:

$$\sigma_q(0) \approx \frac{2 e^2}{\pi h} N(0) s \left[ a + (1 - a) C_1 \frac{\gamma}{\varepsilon_F} \right],$$ (6)

where $N(0)$ is the 2D density of states per spin at the Fermi level. Here and in the following $C_i$, ($i = 1, 2, 3$), is a numerical coefficient of order unity. For the coherent part this regime is valid at temperatures $T \ll T^*$, where the crossover temperature $T^* \approx \gamma/(\hbar v_0 \Delta_0)^{1/2}$ 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 $\sigma_q$ at $T \lesssim T^*$ are quadratic in temperature [18]:

$$\sigma_q(T) \approx \sigma_q(0) + \frac{e^2 t_n^2 N(0) \pi s}{6 \hbar \Delta_0} \left( \frac{T}{T^*} \right)^2 \left[ a + (1 - a) C_2 \frac{\gamma}{\varepsilon_F} \right].$$ (7)

Using the results of Ref. [18], we obtain at $T \to 0$ and for voltages $ev \lesssim \gamma$ for the coefficient $b$ in Eq. (8)

$$b \approx \frac{1}{8 \gamma^2} \left[ a + (1 - a) C_3 \frac{\gamma^2}{\Delta_0 \varepsilon_F} \right].$$ (8)
The expression for the interlayer Josephson critical current density, \( J_c \), is similar to Eq. (3), but with the \( A_i \)’s replaced by the anomalous Gorkov functions at \( v = 0 \). For the critical current density at \( T = 0 \) and in the clean limit, \( h\hbar_0 \ll \Delta_0 \), we obtain \(^{20}\)

\[
J_c(0) \approx \frac{2e^2 t_1^2 N(0)}{h} \left[ a + (1 - a) C \frac{\Delta_0}{\epsilon_F} \right],
\]

where \( C \lesssim 1 \) is a numerical coefficient, which depends on the form of the function \( g(q) \). 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 \( a \) and \( b \), is negligible, if \( a > C\Delta_0/\epsilon_F \). Assuming that this is the case, we obtain the universal relation \(^{13}\) and the ratio \( c/b = 2\pi^2/3 \). Our data obey relation \(^{13}\) as was mentioned above. We obtain \( c/b \approx 6.9 \) and 2.2 for samples \#2 and \#3, respectively. These numbers are in agreement with the theoretical prediction within the accuracy of our estimates. From the value of \( c \) we estimate \( \gamma \sim 3 \) meV. For resonant scattering this estimate agrees well with the crossover temperature \( T^* \approx 30 \) K, while in the Born limit \( T^* \) would be very much smaller. Thus we discard the Born limit. The value of \( \gamma \sim 3 \) meV leads to the estimate \( h\hbar_0 \approx 0.4 \) 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 \( \sigma_q(v,T) \) and \( J_c(0) \) at low temperatures and low voltages, \( \max(T,nev) \ll \gamma \), assuming a significant contribution of coherent tunneling to these quantities. Note that the weight for coherent tunneling, \( a \), should be bigger than \( C\Delta_0/\epsilon_F \approx 0.05-0.1 \), but may still be much smaller than unity in our model for the low energy behavior of the \( c \)-axis transport. It is noteworthy that \( \sigma_{\alpha} \), as well as \( \sigma_q(T,v) \) at \( T > \gamma \) or \( ev > \gamma \), 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 ARPES measurements \(^{21}\).

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**TABLE I.** Parameters of the stacked Bi-2212 mesa junctions. Data for sample #7 are from Ref. \(^{4}\).

| No. | \( S \) (\( \mu m^2 \)) | \( N \) | \( T_c \) (K) | \( J_{c} \) (A/cm\(^2\)) | \( V_0/N \) (mV) | \( \sigma_q(0) \) (mV/cm\(^{-1}\)) | \( b \) |
|-----|-----------------|-----|---------|-----------------|---------------|-----------------|-----|
| #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 |

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