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ORIGINAL PAPER

The $I_C R_N$ Value in Intrinsic Josephson Tunnel Junctions in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) Mesas

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Abstract The *c*-axis current-voltage $I(V)$ characteristics have been obtained on a set of mesas of varying height sculpted on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) crystals intercalated with HgB_2. The intercalation, along with the small number of junctions in the mesa, $N = 6$–30, minimizes the degree of self-heating, leading to a consistent Josephson critical current, I_C, among junctions in the mesa. The Bi2212 crystals with a bulk $T_C = 74$ K are overdoped and display negligible pseudogap effects allowing an accurate measure of the normal state resistance, R_N. These properties make the mesas nearly ideal for the determination of the Josephson $I_C R_N$ product. We find $I_C R_N$ values consistently $\sim 30\%$ of the quasiparticle gap parameter, Δ/e, which was measured independently using a mechanical contact, break junction technique. The latter was necessitated by higher bias heating effects in the mesas which prevented direct measurements of the superconducting gap. These values are among the highest reported and may represent the maximum intrinsic value for $I_C R_N$. The results indicate that the c-axis transport is a mixture of coherent and incoherent tunneling.

Keywords Josephson tunneling · $I_C R_N$ product · Bi2212 mesas

1 Introduction

Conventional, low temperature superconductors display an important relationship between the maximum Josephson (or pair) current, I_C, in a superconductor-insulator-superconductor (SIS) tunnel junction and the zero-temperature gap parameter, Δ, relevant for single particle excitations. The relationship, established on theoretical grounds by Ambegaokar and Baratoff [1] (AB), is given by the equation, $I_C R_N = \pi/2(\Delta/e)$ when the superconducting electrodes are identical s-wave superconductors. Here, R_N is the normal state resistance of the SIS junction, defined explicitly to be the value at zero bias, but generally assumed to be constant over the range of voltages from 0 to just beyond $2\Delta/e$. An important assumption of the AB theory is that the tunneling matrix element, $T_{k,k'}$, is independent of quasiparticle momenta, k, k' and is therefore purely incoherent. The AB relationship has been verified experimentally for a number of conventional superconductors and the value of $I_C R_N$ has become of critical importance in a number of superconducting electronic devices. For example, the operating speed of a single-flux-quantum (SFQ) device if found to be inversely proportional to $I_C R_N$ (see for example [2]).

Surprisingly, after more than 20 years of active investigation, the relationship between $I_C R_N$ and Δ has not been established for the high temperature superconductor (HTS) cuprates [2]. What is often found, especially with in-plane (e.g., grain boundary) junctions, is that $I_C R_N$ is significantly smaller than the AB result, typically less than 10% of Δ [3]. This is not surprising given the *d*-wave symmetry of the pairing gap in HTS along with the rather complicated transport processes [3]. A better choice for a more

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fundamental understanding of $I_C R_N$ may lie in c-axis junctions of Bi2212 where ordinary, single-step, elastic tunneling has generally been observed. Somewhat larger values of $I_C R_N$ are found for such junctions. A study of 13 c-axis break junctions [4] on overdoped Bi2212 showed that I_C was proportional to R_N^{-1} over two decades suggesting that $I_C R_N = \alpha\Delta/e$ with a scale factor $\alpha \sim 0.14$ on average. In a few studies, $I_C R_N$ values as high as 40–50% of Δ/e have been found [4, 5], but in each case there is uncertainty in the measurements of R_N and Δ. For example, self-heating in Bi2212 mesas can lead to values of R_N that are too high and Δ that are too low, both effects leading to α values that are artificially large.

On the theoretical side, a lot of effort has been directed toward understanding the nature of c-axis transport, in particular the role of coherent vs. incoherent tunneling between Cu–O bilayers in Bi2212 [6]. Using the AB assumption of purely incoherent tunneling along the c-axis leads to zero Josephson current to leading order for a d-wave superconductor. This is due to the π phase difference between adjacent lobes of the d-wave gap parameter. The other extreme of purely coherent tunneling between d-wave superconductors would provide the maximum value of I_C in an SIS junction but it leads to peculiar single-particle tunneling conductances, including linear dI/dV at subgap bias voltages [7, 8] that are not observed.

The primary goal of the present study is to evaluate α as accurately as possible in Bi2212 so that c-axis transport can be better understood. We take advantage of some high quality intrinsic Josephson junction (IJJ) data on mesas that are nearly idealized for the determination of $I_C R_N$. Those effects that can lead to incorrect values of R_N and Δ have been minimized. We utilize intercalated Bi2212 crystals which increases the specific junction resistance by a factor of 10–30 over pristine samples, thereby reducing the heating power for a given bias voltage. These Bi2212 crystals are Ca rich providing a stable, overdoped hole concentration and nearly nonexistent pseudogap effects in the c-axis, zero bias mesa resistance, R_C, allowing an accurate value of R_N to be obtained. As will be shown, these mesas typically display relatively large, highly reproducible Josephson I_C values. Finally, and most importantly, independent measurements of the quasiparticle gap parameter have been obtained from single junction methods using a mechanical contact tunneling (MCT) apparatus. We find a reproducible value of $\Delta = 24$ meV for these crystals, consistent with other studies of overdoped Bi2212 [9]. This gap parameter cannot be obtained directly from the mesa conductances as there is always some self-heating at these bias voltages. The value of α is consistently found to be about 30% of Δ/e, which is among the highest values reported. It is suggested that this may be close to the maximum intrinsic value and it indicates that c-axis transport is a mixture of coherent and incoherent tunneling.

2 Experiment and Results

Single crystals of Ca-rich $\mathrm{Bi_{2.1}Sr_{1.4}Ca_{1.5}Cu_2O_{8+\delta}}$, were grown by a floating zone technique. Intercalation of $\mathrm{HgBr_2}$ occurred upon heating these crystals in air with excess $\mathrm{HgBr_2}$ gas at 230 °C for 16 hours and X-ray diffraction confirmed the c-axis lattice constant increased from 15.31 Å to 21.51 Å. The intercalated crystals exhibited $T_C \sim 74$ K from magnetization and $\Delta \sim 24$ meV from MCT, indicating they are overdoped [9]. Intercalation of $\mathrm{HgBr_2}$ between the BiO layers reduces the specific dissipation at fixed voltage by thickening the $\mathrm{Bi_2Sr_2O_4}$ tunnel barrier to obtain more than an order-of-magnitude decrease in the c-axis conductance. We can fine tune self-heating by a single control parameter, the stack height, since total heating power is proportional to N for a constant mesa area. Here $N =$ number of junctions in the mesa.

Intercalated crystals were cleaved, sputter coated with gold, and Ar-ion beam etched into arrays of 10×10 μm^2 mesas using photolithography. Our MCT apparatus [10] is also used to contact the gold film atop the mesa with a soft, 100 μm-diameter gold wire that is bent in a hook-shape to minimize the contact force and any potential damage to the mesa. This wire is sharpened to a diameter of 5–10 μm at the end touching the mesa and invariably the tip contacted a single mesa of the array. A total of five IJJ mesas from three different crystals are examined here with N from 6 through 30. The multiple-sweep $I(V)$ in Fig. 1 shows the Josephson current and the number of quasiparticle branches corresponding to the number, N. As is evident, a reproducible Josephson critical current $I_C \sim 0.3$ mA is found for the majority of SIS junctions within a given mesa as well as for the IJJ on other mesas formed on the same crystal.

Single-junction methods were employed for comparison with the IJJ spectra. Both superconductor–insulator–normal metal junctions (SIN) and SIS break junctions were obtained on an intercalated crystal by MCT using a much thicker gold wire with a blunt tip. After collecting SIN data, a hard contact is used to microcleave the underlying crystal leaving a chip of intercalated Bi2212 on the Au tip for subsequent SIS junctions [9, 11], as shown in Fig. 2. Since heating is virtually eliminated for MCT, these data provide the equilibrium properties for interpreting the Bi2212 mesa data. The SIS break junction conductance in Fig. 2 displays the characteristic dip/hump features which are found in most tunneling studies of Bi2212 [9, 11]. Within the inset of Fig. 2 is shown the fit [4] to the normalized conductance using a BCS d-wave gap function, $\Delta(\phi) = \Delta\cos(2\phi)$, and this leads to $\Delta = 24$ meV a value reproduced in SIN junctions as well.

One of the most important and striking results is that the gap-like features shown in Fig. 1, i.e., the upturn in I(V) in Fig. 1a and the conductance peaks of Fig. 1b, are not the superconducting gap. This is more clearly shown in Fig. 3 where the conductance dI/dV vs. V per junction is shown

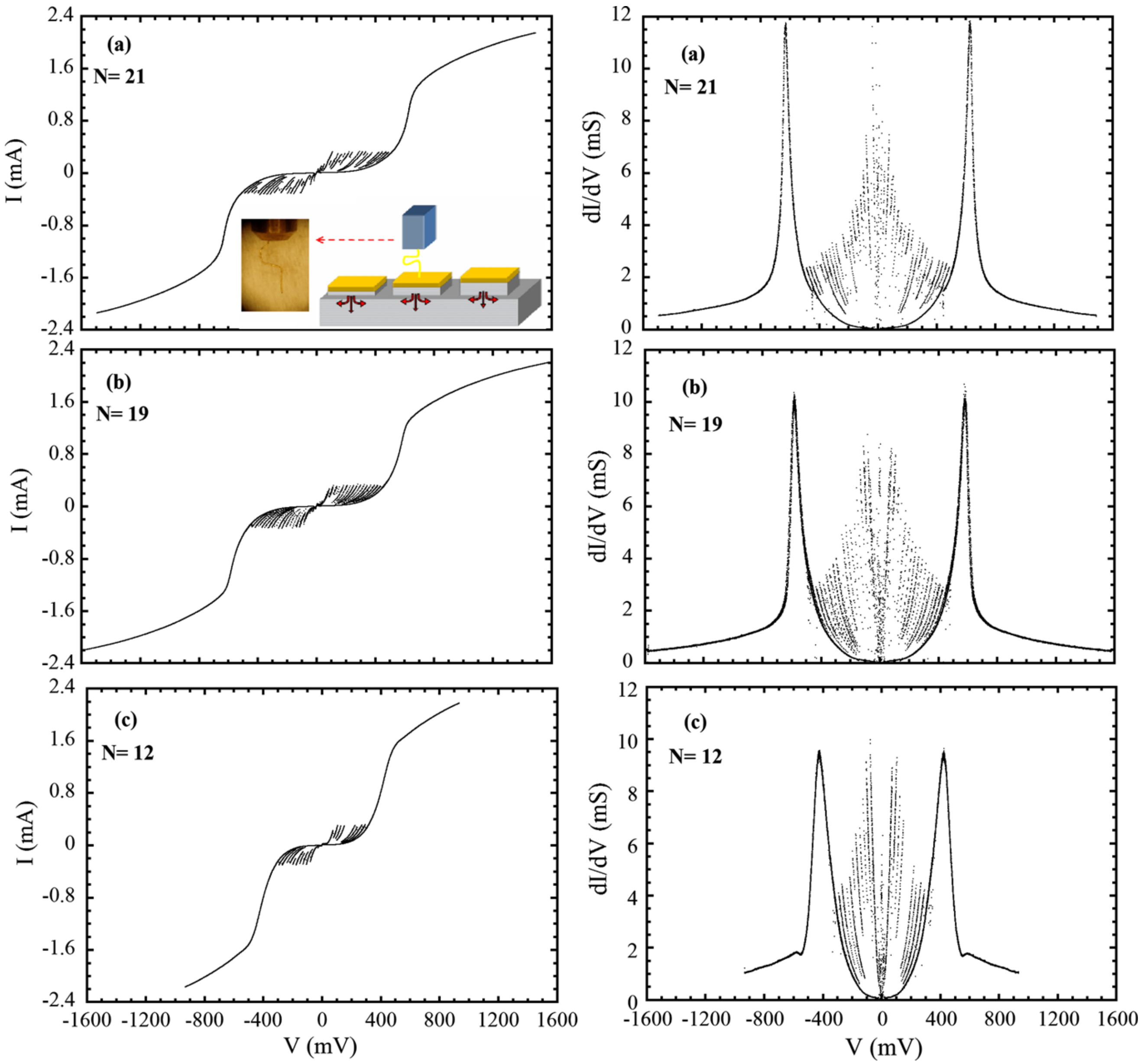

Fig. 1 Current voltage $I(V)$ and dynamic conductance dI/dV vs. V along the c-axis for 3 mesas ($10 \times 10\ \mu m^2$) fabricated on the same Bi2212 crystal. The number of SIS junctions $N = 21$, 19, 12 for (**a**), (**b**), (**c**), respectively. The drawing shows the method of contact to the individual mesas which utilizes a fine gold wire attached to the same tip assembly used for MCT junctions

for the five mesas along with the SIS break junction result. In the absence of heating, such spectra should lie on top of each other. Instead, it is seen that the smallest mesa ($N = 6$) most closely resembles the break junction result, including a dip/hump feature, but as N increases the conductance peak voltage decreases and abruptly sharpens. Data which display the sharp peaks do not show the dip/hump feature. Clearly, the data for $N > 10$ do not represent equilibrium measurements of the superconducting gap. We have shown that such sharp peaks are due to strong self- heating and represent the transition of the mesa into the normal state [12].

Turning now to the determination of R_N we note that there is curvature in the $I(V)$ data of Fig. 1a for voltages above the gap-like feature which eliminates any extrapolation procedure to determine R_N as is done conventional SIS junctions. This is again a self- heating effect and is linked to the strong T dependence of the c-axis resistance $R_c(T)$ measured at zero bias. An example of $R_c(T)$ per junction for the $N = 19$ mesa is shown in the inset of Fig. 3. For temperatures above T_C, there is a linear increase in $R_c(T)$ with increasing T. Below T_C, there again is an increase in $R_c(T)$ with decreasing T which is due to the opening of

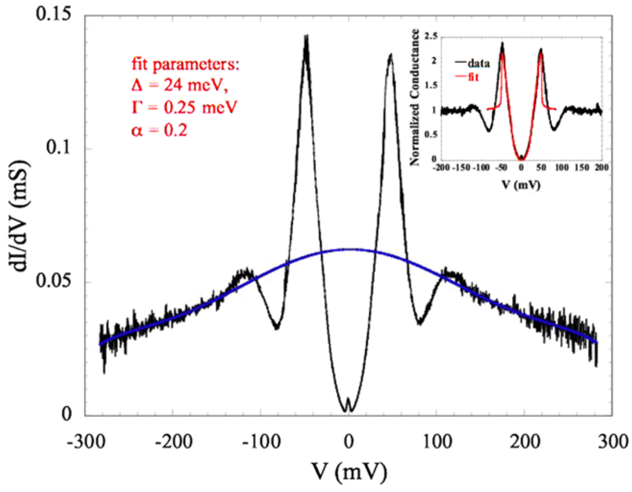

Fig. 2 (Color online) SIS break junction formed by MCT on one of the Bi2212 crystals used for mesa fabrication. *Blue curve* is the estimated normal state conductance. *Inset* shows the normalized conductance along with a BCS d-wave fit (*red*) which leads to $\Delta = 24$ meV

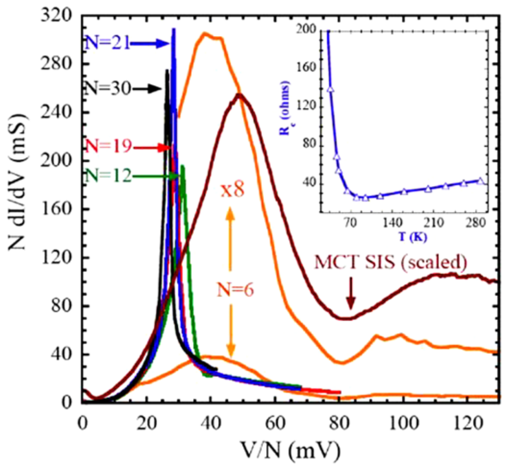

Fig. 3 Conductances (dI/dV vs. V) per junction for the five mesas compared with the SIS break junction from Fig. 2. Only the $N = 6$ mesa shows features comparable to the break junction. Inset shows the zero bias $R_c(T)$ per junction for the $N = 19$ mesa

the superconducting gap. Just above T_C, there is a weak upturn in $R_c(T)$ due to weak superconducting fluctuations (or pseudogap), but it is clear that one can estimate the value of R_N at $T = 0$ from the minimum of $R_c(T)$ which is 26 Ω. Similar values of R_N are found in each of the mesas of this study. We thus obtain $I_C R_N = (0.3\text{ mA})\ (26\ \Omega) = 7.8$ mV for this mesa. Using the measured $\Delta = 24$ meV from the MCT junctions, we find $\alpha = 0.33$ which should be compared to the AB result $\alpha = \pi/2$ for s-wave superconductors. Similar values are found for all 3 junctions in Fig. 1. The $N = 6$ and $N = 30$ mesas have slightly smaller values.

3 Summary and Conclusion

We have fabricated IJJ mesas which are nearly idealized for the determination of the $I_C R_N$ product for c-axis junctions. By comparison to MCT junctions, it was shown that the superconducting gap $\Delta = 24$ meV cannot be found directly in the mesa conductances due to self-heating. Only the $N = 6$ mesa has the characteristic, broader conductance peak and dip/hump feature found in the MCT SIS junction. Similarly, self-heating makes the determination of R_N not straightforward. We utilize the zero bias $R_c(T)$ to estimate R_N where values of 25–30 Ω per junction are found for the five intercalated mesas. The resulting $I_C R_N$ is in the range 30–35% of Δ/e, which is among the highest reproducible values found in IJJ mesas and might be the intrinsic limit for overdoped Bi2212. This value, along with the nonlinear shapes of the IJJ conductances near zero bias, rules out the extremes of purely incoherent or purely coherent tunneling between d-wave superconductors. The c-axis transport therefore appears to be some type of mixture of coherent and incoherent tunneling.

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