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Simultaneous Quasiparticle and Josephson Tunneling in BSCCO-2212 Break Junctions

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# Simultaneous Quasiparticle and Josephson Tunneling in BSCCO-2212 Break Junctions

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**Abstract**— Tunneling measurements are reported for superconductor-insulator-superconductor (SIS) break junctions on underdoped, optimally-doped, and overdoped single crystals of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (Bi-2212). The junction  $I - V$  characteristics exhibit well-defined quasiparticle current jumps at  $eV = 2\Delta$  as well as hysteretic Josephson currents. The quasiparticle branch has been analyzed in the framework of  $d_{x^2-y^2}$  (*d*-wave) superconductivity and indicates that there is preferential tunneling along the lobe directions of the *d*-wave gap. For overdoped Bi-2212 with  $T_c=62$  K, the Josephson current is measured as a function of junction resistance,  $R_n$ , which varied by two orders of magnitude (1 k $\Omega$  to 100 k $\Omega$ ).  $I_c R_n$  product is proportional to the 0.47 power of  $I_c$  and displays a maximum of 7.0 mV. When the hole doping is decreased from overdoped ( $T_c=62$  K) to the underdoped regime ( $T_c=70$  K), the average  $I_c R_n$  product increases as does the quasiparticle gap. The maximum  $I_c R_n$  is  $\sim 40\%$  of the  $\Delta/e$  at each doping level, with a value as high as 25 mV in underdoped Bi-2212.

## I. INTRODUCTION

The wide energy gap, high critical current density, and high transition temperature are advantages of high  $T_c$  superconductors (HTS) that make them attractive candidates for superconducting electronics.[1] In the past decade, there has been a world-wide effort toward the fabrication of Josephson tunnel junctions, based on HTS. The major difficulty in tunneling junction fabrication is due to the short coherence lengths and anisotropic nature of the superconducting gap in HTS.[2] Two HTS compounds,  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  and  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (Bi-2212) have been extensively studied to produce high-quality thin film planar junctions. Furthermore intrinsic Josephson tunnel junctions have been fabricated in Bi-2212 and  $\text{TlBa}_2\text{CaCu}_2\text{O}_x$  single crystals.[3] These are considered

as *c*-axis tunnel junctions between  $\text{CuO}_2$  planes where other layers act as insulating or semiconducting spacers. Additionally, the anisotropic feature of the HTS cuprates has been used for fabricating grain boundary junctions.[4] Misorientation angle of grains behaves as a barrier because of impedance mismatch. However, grain boundary junctions act as weak links between two superconductors and their properties can be explained by resistive shunted junction model. In our case, superconductor-insulator-superconductor (SIS) tunnel junctions are formed by break junction method on Bi-2212, producing tunneling spectroscopies with clear indication of Josephson and quasiparticle tunnel currents simultaneously. In this paper, we will present the SIS break junction tunneling results on overdoped, optimally-doped, and underdoped Bi-2212 superconductors.

## II. EXPERIMENT

Two sets of single crystal Bi-2212 were obtained to perform break junction tunneling. The first set of samples of Bi-2212 were grown in a 20% oxygen atmosphere by a floating zone technique.[5] The second set were grown by a self flux technique in a strong thermal gradient to stabilize the direction of solidification. Both sets of crystals were well characterized and no significant differences were obtained, in spite of the growth methods that are completely different. Overdoping of single crystal Bi-2212 has been conducted using stainless steel cells sealed with samples immersed in liquid oxygen, as described elsewhere.[6] Underdoped crystals have been obtained by vacuum annealing.[5], [7] The crystals in which tunneling measurements were performed have a  $T_c=62$  K and 82 K for overdoped, 95 K for optimally-doped, and 70 K for underdoped. Tunneling measurements were done with the apparatus described in [8].

SIS break junctions are obtained in an unconventional manner. After the sample is placed in a measurement system and cooled down to 4.2 K, the contact force between the gold tip and sample is adjusted using a differential micrometer. In the ordinary way, a tip pushes onto the surface of the crystal and a superconductor-insulator-normal metal (SIN) junction is formed between the tip and crystal. While the tip is pushed against the crystal, the  $I - V$  curve is continuously monitored until an SIN junction is obtained. Here the insulating barrier is the native surface layer of the crystal. Increasing the force

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of the tip punctures the native layer and establishes an ohmic contact ( $\sim 1$  ohm) between the tip and crystal. For Bi-2212, a piece of the crystal dislodges and mechanically binds to the tip. Relieving pressure separates neighboring Bi-O planes in Bi-2212, because they are weakly bounded when compared to Cu-O and Sr-O layers. Consequently, a SIS tunneling break junction can be formed easily with this HTS cuprate. Furthermore, since this tunnel junction is formed in-situ at 4.2 K and unexposed to air, the barrier interface is clean and impurity free.

### III. RESULTS AND DISCUSSION

A representative  $I - V$  curve of a SIS break junction between two pieces of overdoped Bi-2212 single crystal is shown in Fig. 1. The data is taken at 4.2 K and the junction exhibits sharp current onsets at  $eV \sim \pm 40$  meV which corresponds to  $\pm 2\Delta$  as well as a Josephson current at zero bias. The inset in the Fig. 1 is an expanded subgap region near zero bias to clearly show the switching nature of the underdamped Josephson junction. Notice that the sweep direction is from negative to positive bias. The optimally-doped and underdoped single crystals of Bi-2212 also show same qualitative characteristics.[5], [7]

The tunneling conductance is proportional to the DOS of a superconductor and for a SIS junction, the tunneling conductance can be expressed as [9]

$$\frac{dI}{dV} = c \frac{d}{dV} \int |T|^2 N_s(E) N_s(E+eV) [F(E) - F(E+eV)] dE \quad (1)$$

where  $F(E) = [1 + \exp(E/k_B T)]^{-1}$  is the Fermi function,  $|T|^2$  is the tunneling matrix element,  $E$  is the quasiparticle energy relative to the Fermi level,  $N_s(E)$  is the DOS of the superconductor, and  $c$  is a proportionality constant.  $|T|^2$  is taken as a constant to simplify the calculation which is acceptable near the Fermi level. In this work, the DOS of the superconductor is expressed as

$$N_s(E) = \int d\phi f(\phi) \operatorname{Re} \left\{ \frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta(\phi)^2}} \right\} \quad (2)$$

Here the addition of smearing parameter  $\Gamma$  accounts for lifetime effects. This phenomenological model takes into account two factors. First, results from recent tunneling[10], angle resolved photoemission (ARPES)[11], and tricrystal ring[12] experiments on HTS cuprates suggest a strong case for  $d_{x^2-y^2}$  ( $d$ -wave) pairing symmetry. In our simple model, this is included by using an angular dependent gap function given by  $\Delta(\phi) = \Delta_0 \cos(2\phi)$ [13] where  $\phi$  is the polar angle in  $k$ -space measured with respect to the  $(\pi, 0)$  direction. The resulting DOS shows cusplike feature in the subgap region. However, several tunneling experiments have shown a slight rounding of the subgap region. ARPES results have also suggested that certain particular regions of momentum space are more heavily weighted[11] than others in the contribution to the tunneling current due directly to the band structure. In addition, there may be a certain degree of selectivity in tunneling measurements coming from the tunneling matrix element.[14]

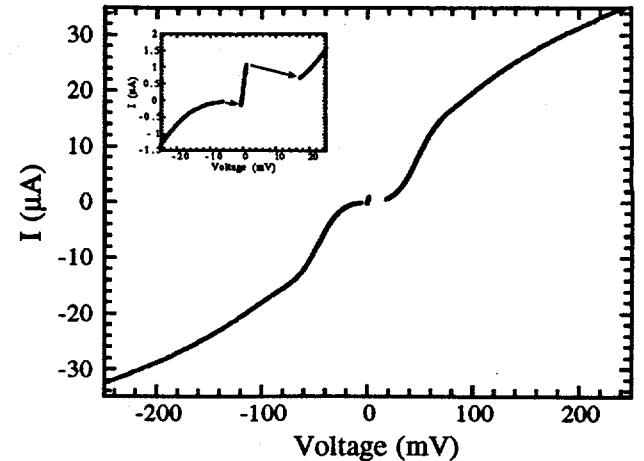


Fig. 1. Current-Voltage characteristics of an overdoped Bi-2212 ( $T_c=62$  K) SIS break junction at 4.2 K. The inset shows the Josephson current in a more sensitive scale.

For these reasons we have included the second factor in our model which is a weighting function  $f(\phi)$  to the DOS model, as is in [10]. Here  $f(\phi) = 1 + \alpha \cos(4\phi)$  where  $\alpha$  is a directionality strength. Although (2) is a phenomenological expression, it will be shown that this weighting function will qualitatively reproduce some of the conductance features observed in the experiment, especially in some SIN junctions. This weighting would also explain the large peak height to background (PHB) ratios observed in SIS junctions as presented in [10].

Fig. 2 shows four representative normalized SIS tunneling conductances for four different doping levels of Bi-2212 (solid lines). Here the Josephson currents have been removed for clarity. The data have been normalized with a third order polynomial. In the figure the dashed lines correspond to numerical fits using our DOS model for  $N_s(E)$  in (1). There is a good agreement with the experimental data in the subgap region. This means that the experimental results are consistent with the  $d$ -wave pairing DOS and the suggestion that there is a preferential tunneling along the lobe directions of Bi-2212. It is also observed that the size of the superconducting gap decreases with increasing oxygen doping. However, above the gap region ( $eV > 2\Delta$ ) there are significant deviations from experimental results. There are dip and hump features outside the gap region that are also observed in SIN tunneling conductances. These features, which have been suggested to be due to strong coupling effects,[5] cannot be reproduced by our simple model. Fig. 2 also shows that quasiparticle PHB ratio increases with increasing oxygen doping. It has been suggested by Halbritter[15] that this may be due to the creation of localized states in the barrier region. However, the presence of localized states should manifest itself as additional peaks in the gap region. SIN and SIS tunneling data on overdoped, optimally-doped, and underdoped Bi-2212 do not show these additional peaks. Furthermore, the gap structure disappears at  $T_c$  pointing to its superconducting origin. This observation seems to rule out resonant tunneling as the source of the change in

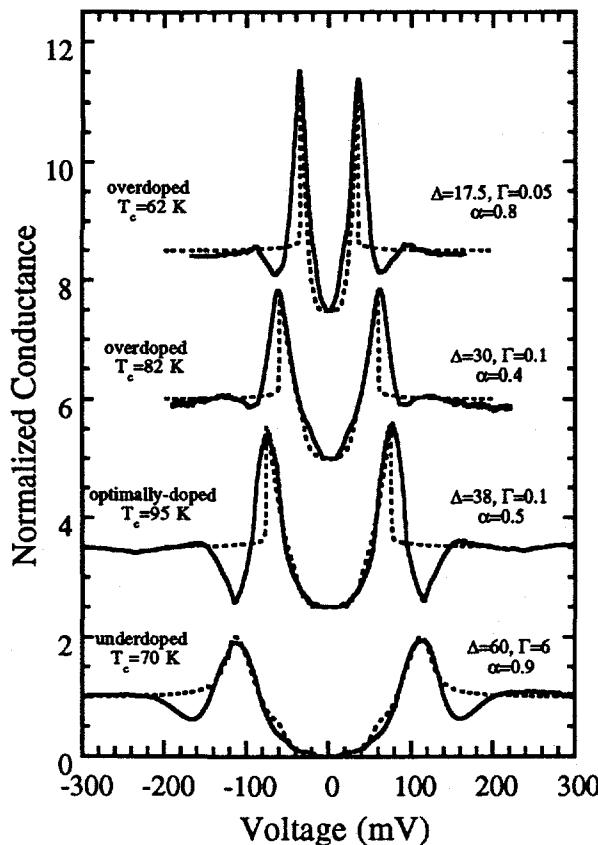


Fig. 2. Normalized conductances of Bi-2212 SIS break junctions for various doping levels. Dashed lines correspond to SIS conductances obtained using the DOS model of (2) with corresponding parameters. For clarity, the data of overdoped ( $T_c=62$  K), overdoped ( $T_c=82$  K) and optimally-doped ( $T_c=95$  K) have been shifted by 7.5, 5, 2.5 units respectively.

PHB ratio with increasing doping. In addition, as clearly seen in Fig. 2, all SIS tunneling conductance show low subgap conductance as well as sharp quasiparticle peaks. These results suggest that Bi-2212 could be one of the appealing candidates for superconducting devices e.g. SIS mixer.[16]

Most of our SIS junctions exhibited a Josephson current. The Ambegaokar-Baratoff (A-B) theory[17] for BCS superconductor predicts the relation

$$I_c R_n = \frac{\pi \Delta(0)}{2e} \quad (3)$$

where  $I_c$  is the Josephson current,  $R_n$  is the resistance of the junction, and  $\Delta(0)$  is the energy gap at 0 K. Table I shows that as  $\Delta(0)$  increases in the underdoped phase, the maximum  $I_c R_n$  increases also. This links the quasiparticle gap to a superconducting energy scale. Furthermore, for overdoped Bi-2212[18] with  $T_c=62$  K, our data show an additional relationship between the Josephson current  $I_c$  and the junction resistance  $R_n$ , where  $R_n$  ranges from 1 k $\Omega$  to 100 k $\Omega$ . There is a scaling behavior that  $I_c R_n$  is proportional to  $(I_c)^p$  where  $p=0.47$  as shown in Fig. 3. This scaling behavior ( $p \sim 0.5$ ) has also been observed in tunneling in the  $a-b$  plane for planar, ramp-edge, bicrystalline grain boundary (GB), biepitaxial GB, and step-edge

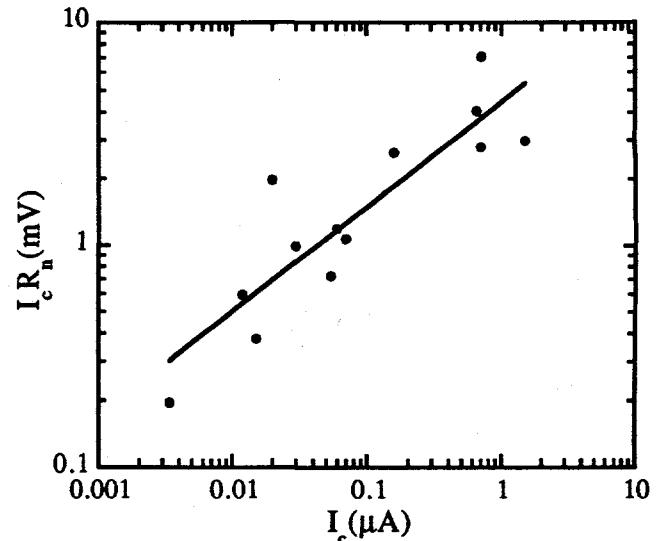


Fig. 3.  $I_c R_n$  versus  $I_c$  for overdoped Bi-2212 with  $T_c=62$  K. The solid line corresponds to a power fit.

TABLE I  
DOPING DEPENDENCE OF  $I_c R_n$  AND ENERGY GAP

	average $I_c R_n$ (mV) (# of Junc.)	Max. $I_c R_n$ (mV)	$\Delta$ (meV)
overdoped ( $T_c=62$ K)	2.4 (10)	7.0	15-20
optimally-doped ( $T_c=92-95$ K)	2.9 (14)	7.8	30-40
underdoped ( $T_c=83$ K)	- (3)	25	44-45
underdoped ( $T_c=74$ K)	- (3)	9.1	53-56
underdoped ( $T_c=70$ K)	- (6)	14.0	55-60

GB junctions.[4] The universality of  $I_c R_n$  vs.  $I_c$  allows us to estimate tunnel junction area in our break junctions, because the areas in grain boundary junctions are known. When we compare Fig. 3 with Fig. 1 of Ref.[4], the results lead to a junction area  $\sim 500$   $\text{\AA}$  on edge.

There is an ongoing debate about the origin of the gap in tunneling measurements of HTS. Are the energy gaps seen in the tunneling data of Fig. 2 superconducting gaps, or are they of other origin? Markiewicz et al. [19] have proposed the idea that the gaps seen in tunneling measurement are charge density wave (CDW) gaps, or a mixed state of superconducting-CDW gap. To address this issue, we note that the Josephson current is observed simultaneously with the gap in the SIS conductance data. As shown in Table I, the average  $I_c R_n$  and the maximum  $I_c R_n$  values increase with increasing gap size. The maximum  $I_c R_n$  value is  $\sim 40\%$  of  $\Delta/e$  at each doping level, with a value as high as 25 mV in underdoped case. The table shows only junctions with smaller than 30 k $\Omega$  junction resistances. The fact that the  $I_c R_n$  values increases with increasing  $\Delta(0)$  presents a strong case that the gaps observed in our tunneling data are superconducting energy gaps.

In summary, we investigated break junction tunneling measurements on Bi-2212 with various doping levels. Simultaneous quasiparticle and Josephson tunneling current

were observed, with  $I_c R_n$  values as high as 25 mV in one of the underdoped samples. It is observed that as the doping level decreases from overdoped to underdoped, the size of the superconducting energy gap increases. Moreover, as the size of the superconducting gap increase, the value of  $I_c R_n$  also increases.

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