Self-Heating Effect in Intrinsic Tunneling Spectroscopy of $HgBr_2$ Intercalated $Bi_{2.1}Sr_{1.4}Ca_{1.5}Cu_2O_{8+\delta}$ Single Crystals

C. Kurter, L. Ozyuzer, J. F. Zasadzinski, D. G. Hinks, and K. E. Gray

***Abstract*—We report tunneling results in intrinsic Josephson junction (IJJ) stacks fabricated in the form of square micromesas on $HgBr_2$ intercalated $Bi_{2.1}Sr_{1.4}Ca_{1.5}Cu_2O_{8+\delta}$ (Bi2212) single crystals using photolithography and Ar ion milling techniques. Self-heating is the most common problem encountered in interlayer tunneling and it is likely to reduce the reliability of IJJ data. Although intercalation reduces heating a hundredfold, it still needs to be minimized substantially in order to approach the authentic superconducting energy gap observed by tunneling using more conventional junctions. We report tunneling characteristics of two mesas with the same height but different sizes ($5 \times 5\ \mu m^2$ and $10 \times 10\ \mu m^2$) to show that heating effects are strongly related to IJJ stack size. For the smaller mesa, we observed an energy gap close to that seen in single SIN (S: superconductor, I: insulator, N: normal metal) and SIS break junctions as well as the dip and hump structures at high bias. The subgap data of $5 \times 5\ \mu m^2$ mesa were successfully fit with a momentum averaged d-wave model using convenient parameters. Thus our data is consistent with the predominant pairing symmetry suggested by point contact tunneling, break junction, scanning tunneling microscopy/spectroscopy and angle resolved photoemission measurements in $Bi_2Sr_2CaCu_2O_{8+\delta}$.**

***Index Terms*—High-T_c superconductors, intrinsic Josephson junctions, self-heating, tunneling spectroscopy.**

I. Introduction

BOTH SIN (S: superconductor, I: insulator, N: normal metal) and SIS break junctions created by a gold point contact give consistent and reproducible tunneling results on $Bi_2Sr_2CaCu_2O_{8+\delta}$ [1]–[3]. They show clear spectral features, i.e. quasiparticle peaks at certain voltages proportional to superconducting energy gap and dip/hump features at higher bias, which enable a better understanding of the density of states (DOS) near the Fermi level. These results are consistent with those of other surface probes such as scanning tunneling microscopy/spectroscopy (STM/S) and angle-resolved photoemission (ARPES). Since high temperature superconductors (HTSs) are believed to be natural stacks of intrinsic Josephson junction (IJJ), one may consider interlayer tunneling would give the best results for learning the mechanism in these materials [4]. However, because it has fairly poor thermal conductivity, intrinsic junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$ suffer from self-heating at high bias voltages. In addition, heating is relatively larger for tunneling into an IJJ stack than a conventional superconducting junction on $Bi_2Sr_2CaCu_2O_{8+\delta}$ because of lower specific junction resistance caused by its very thin barrier. As a result of self-heating in intrinsic-junction mesas, some artifacts have been observed in the tunneling characteristics.

The Joule-heating-induced temperature rise in an IJJ stack can be described by a ballistic phonon transport model suggested by Krasnov *et al.* [5];

$$\Delta T_{ball} \propto aP/\kappa_{ab} l_{ph}$$

where $P = JV$ is the generated power per area inside the stack, a is a constant to be determined, κ_{ab} is in-plane thermal conductivity and l_{ph} is phonon mean free path. Because the current is proportional to the junction area and the voltage is proportional to number of IJJs in the stack, N, reducing either of these parameters can help to decrease the amount of heating. Recently, Zhu *et al.* [6] has shown clear and intense improvements in intrinsic tunneling spectra by reducing the mesa area to $0.16\ \mu m^2$.

Several groups have attempted different approaches to the overheating problem. One of the most effective ways has been the short pulse technique in which short-duration current pulses are supplied to the specimen [7], [8]. Severe overheating due to the self-injection of tunneling current was largely suppressed and the pronounced dip/hump structures of conventional tunneling were obtained [9], [10]. Also, in order to quantify self-heating effects on spectra, a special geometry can be fabricated on $Bi_2Sr_2CaCu_2O_{8+\delta}$ utilizing a focused ion beam technique so that the temperature of mesas can be in-situ monitored. In this approach artifacts were subtracted from original data [11], [12].

Intercalation of inert molecules such as $HgBr_2$, HgI_2 or I_2 between the Bi-O layers of $Bi_2Sr_2CaCu_2O_{8+\delta}$ is a promising method for minimizing the heating effect on tunneling spectra. This procedure reduces the interlayer coupling between neighboring CuO_2 planes resulting in increasing the c-axis resistance

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and in turn reducing the current at a given voltage [13]. Insertion of these compounds into host $Bi_2Sr_2CaCu_2O_{8+\delta}$ does not significantly affect the hole carrier concentration in the CuO_2 layers or T_c in spite of large expansion in the unit cell [14]. In this study, we used $HgBr_2$ for intercalation into pristine $Bi_{2.1}Sr_{1.4}Ca_{1.5}Cu_2O_{8+\delta}$ (Bi2212) single crystals. With the suppression of heating by intercalation, we find that the conventional tunneling spectra can be recovered in much larger junctions than were required in non-intercalated Bi2212 [6].

II. Experiment

We grew Bi2212 single crystals with $T_c = 77$ K using a floating zone technique with Ca-rich stoichiometry. The slightly overdoped pristine crystals were annealed with $HgBr_2$ at 230°C for 16 hours in air to get intercalated compounds. After intercalation, the magnetic susceptibility data showed us T_c is only changed slightly by the procedure, to 74 K. For the interlayer tunneling measurements, patterning of the crystal surfaces is essential to reduce the area and stack height. After the deposition of a thin gold film (~40 nm) on freshly cleaved Bi2212 surfaces, an additional heat treatment was done (at 150 °C for 1 hour in flowing air) to reduce the contact resistance. Using photolithography and Ar ion beam etching techniques, small square-mesa arrays with the sizes 5 μm and 10 μm were fabricated on these crystals [15]. In order to get IJJ tunneling characteristics, two contacts were made on two far ends of the crystal by means of silver paint. Our point-contact apparatus was used to make a soft contact onto the top of one of the mesas by a mechanically sharpened hook-shaped soft gold wire of 100 μm diameter. The soft gold finger is flexible enough to make contact without harming or breaking the crystal. The bias current was swept back and forth many times to see the hysteretic quasiparticle branches in I-V curves. All data presented in this paper were taken at 4.2 K.

III. Results

We also obtained numerous spectra by touching the bulk crystal surface with a blunt gold tip of point-contact tunneling (PCT) assembly to create either a single SIN junction or SIS break junction made with larger pressure of the gold probe [16]. Although, IJJs are the perfect models for superconducting tunneling junctions because of their natural formation, most of the time, the information gained from conventionally generated SIS break junctions is more valuable, since their spectra show less heating artifacts owing to relatively larger specific junction resistance [17]. Therefore, firstly we present a representative result of a conventional PCT measurement on $HgBr_2$ intercalated Bi2212 to be able to show a spectrum in which the effect of self-heating is trivial.

Fig. 1 shows the tunneling conductance characteristic of an in-situ formed SIS break junction on an intercalated Bi2212 crystal that is the numerical derivative of I-V data directly obtained from PCT measurement. One can easily see simultaneous quasiparticle and Josephson tunneling, (the latter is the small bump at zero bias). The spectrum exhibits quasiparticle peaks at ±48 mV, which gives direct information about energy gap, 24 meV. The well-defined dip and hump structures are located

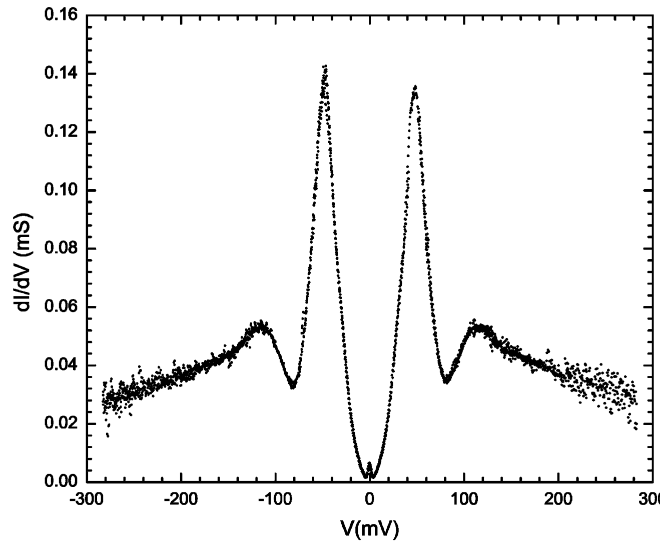

Fig. 1. Representative tunneling conductance of an SIS break junction for $HgBr_2$ intercalated Bi2212 showing well-defined quasiparticle peaks and robust dip/hump structures as well as a little bump indicating Josephson tunneling at 4.2 K.

at ±80 mV and ±115 mV respectively. These indicators imply a small to negligible effect of heating in this junction. The junction resistance of this particular SIS junction of ~ 22 kΩ significantly suppresses the Josephson effects. The generated power on junction can be found approximately $P = 3.5$ μW.

For inter-bilayer tunneling measurements, we fabricated 5×5 μm^2 and 10×10 μm^2 mesas on $HgBr_2$-intercalated Bi2212 to examine the influence of Joule heating on IJJs. Fig. 2(a) and (b) shows the I-V characteristics of two different sized mesas at 4.2 K, belonging to 5×5 μm^2 and 10×10 μm^2 mesas respectively. Both characteristics display hysteretic and multibranched structure in which each branch represents a different IJJ in the stack, and the numbers of quasiparticle branches are 23 and 30 respectively. The shape of the curves, after the knee points which normally correspond to quasiparticle peak positions, follows quite different inclination. Although they are plotted on a different scale for clarity, one can understand the switching currents are dissimilar in magnitude, because of the 4-fold difference between two mesa areas. The 10×10 μm^2 mesa exhibits identical branches in its I-V characteristics, while we can not see the same order in the characteristics of 5×5 μm^2 mesa. The reason could be the roughness on the examined mesa surface due to the improper patterning.

Fig. 3 exhibits dI/dV vs. V for two mesas generated by numerical differentiation of the return branches in the I-V characteristics of Fig. 2. The quasiparticle peak voltage should be divided by the number of the branches in the I-V plot to get the voltage proportional to superconducting energy gap per IJJ. The 10×10 μm^2 mesa has very sharp and narrow peaks at $\pm 2\Delta = 27$ mV per junction that is a characteristic of overheating and rounded subgap region near zero bias that is more reminiscent of s-wave tunneling case. Another striking property related to 10×10 μm^2 mesa is the absence of dip/hump features in the high bias tunneling characteristics that is particular to HTSs. For the 5×5 μm^2 mesa, one can see symmetric

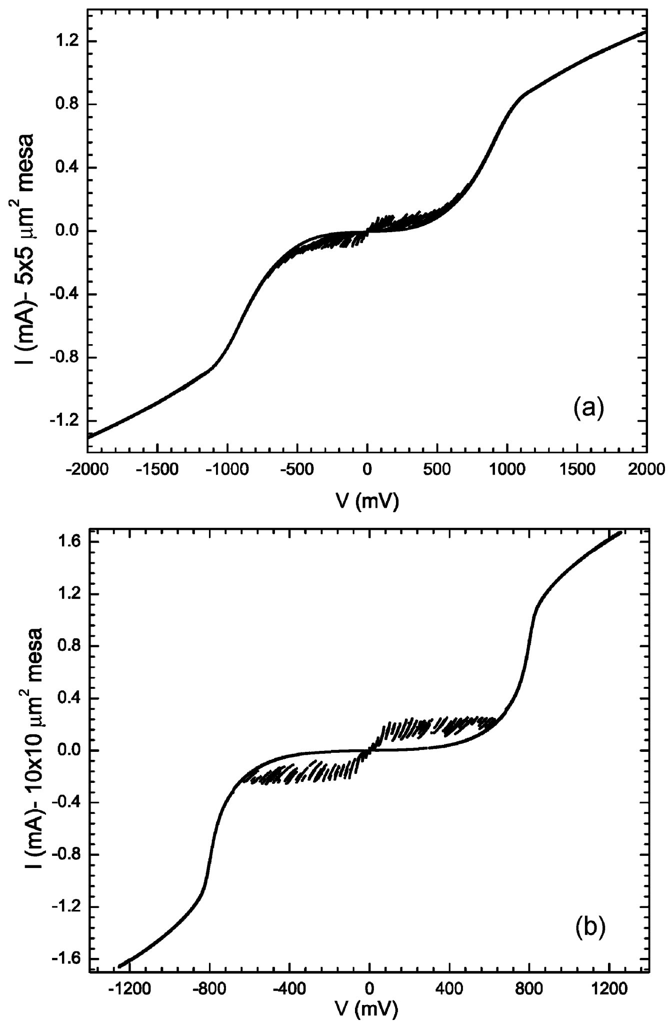

Fig. 2. I-V characteristics of two different sized mesas. (a) $5 \times 5\ \mu\mathrm{m}^2$ and (b) $10 \times 10\ \mu\mathrm{m}^2$, with the same height on $\mathrm{HgBr_2}$ intercalated Bi2212 at 4.2 K. Each branch in the I-V curve points out different IJJ, so the number of IJJs for $5 \times 5\ \mu\mathrm{m}^2$ mesa is 23 while it is 30 for $10 \times 10\ \mu\mathrm{m}^2$ mesa indicating larger heating on it.

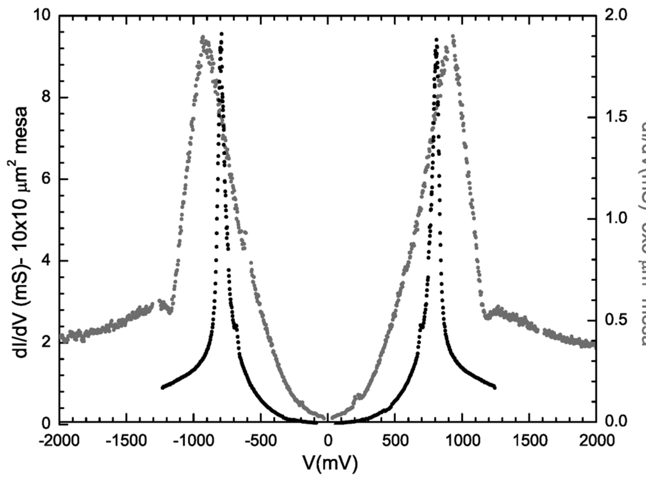

Fig. 3. Comparison of two IJJ tunneling spectra. Gray curve is tunneling conductance of $5 \times 5\ \mu\mathrm{m}^2$ mesa while black one is that of $10 \times 10\ \mu\mathrm{m}^2$ mesa. Data are smoothed numerical derivatives of return branches in I-V characteristics measured at 4.2 K.

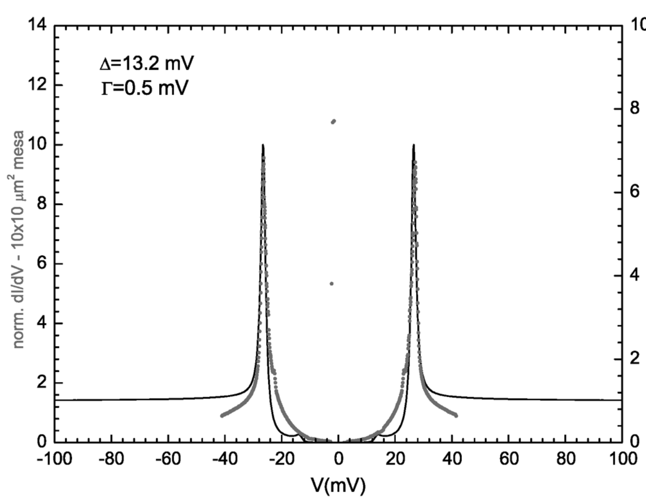

Fig. 4. s-wave model to the normalized data of $10 \times 10\mu\mathrm{m}^2$ mesa using $\Delta = 13.2\ \mathrm{mV}$ and $\Gamma = 0.5\ \mathrm{mV}$ (black curve). It is not possible to fit the data with d-wave model without using large α which makes the tunneling contribution from lobes dominant and leads to s-wave symmetry in DOS.

well-defined quasiparticle peaks at $\pm 2\Delta = 40\ \mathrm{mV}$ which are not so sharp like the peaks caused by overheating, a cusp-like feature intrinsic to d-wave symmetry in the subgap region and evidence of dip/hump features, though they are weak.

Although, both mesas were formed on the same kind of intercalated Bi2212 crystals, the tunneling conductance curves show different features. We tried to fit the experimental data to gain further insight about these peculiarities. Fig. 4 shows an s-wave fit (black, solid curve) to dynamical tunneling conductance of $10 \times 10\ \mu\mathrm{m}^2$ mesa, using the model first proposed by Dynes [18] in which superconducting DOS can be depicted;

$$N_s(E) = Re\left(\frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta^2}}\right), \quad |E| \geq \Delta,$$
$$= 0, \quad |E| < \Delta$$

Here, Γ is a smearing parameter which accounts for lifetime effects and is taken to be 0.5 for this junction. This model is generally called smeared BCS DOS and is in a good agreement with the characteristics of conventional superconductors. Previous tunneling experiments have reproducibly confirmed that Bi2212 has d-wave pairing symmetry [1], [2]. Since the data obtained from $10 \times 10\ \mu\mathrm{m}^2$ mesa have very large peak height to background ratio (PHB), a flat subgap near zero bias and very narrow conductance peaks, there is no way to fit the data unless we use very large α which will be defined later. Using large α calls for dominant preferential tunneling along the antinodes (lobes) which makes the d-wave model look very similar to s-wave tunneling. However, the good compatibility of the data obtained from $10 \times 10\ \mu\mathrm{m}^2$ mesa to s-wave fit may be deceptive and instead we believe the data are due to heating artifacts.

Fig. 5 exhibits a momentum-averaged d-wave fit (black, solid curve) to the data of $5 \times 5\ \mu\mathrm{m}^2$ mesa. The theoretical model,

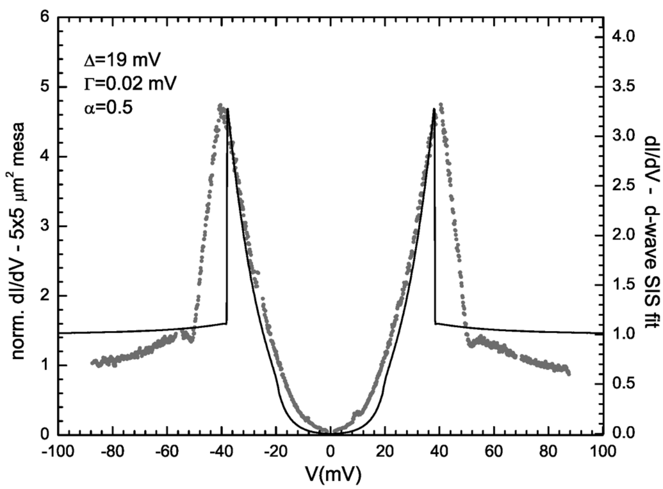

Fig. 5. Momentum-averaged d-wave fit to normalized data of $5 \times 5\ \mu\mathrm{m}^2$ mesa using convenient parameters (black curve). The fit matches with the subgap region of the data perfectly and indicates that heating effect is relatively reduced on spectrum since experimental tunneling conductance is compatible to theoretically suggested d-wave DOS.

suggested by Won and Maki [19] for d-wave superconductors, is given by;

$$N_s(E,k) = Re\left(\frac{E - i\Gamma}{\sqrt{(E-i\Gamma)^2 - \Delta(k)^2}}\right)$$

where $\Delta(\boldsymbol{k}) = \Delta\cos(2\theta)$ is $\boldsymbol{k}$-dependent energy gap. Since PHB of the data obtained from $5 \times 5\ \mu\mathrm{m}^2$ mesa is also very large, we need to include the weighting function $f(\theta)$, such that the superconducting DOS can be written as;

$$N_s(E,\theta) = f(\theta) Re\left(\frac{E - i\Gamma}{\sqrt{(E-i\Gamma)^2 - \Delta(\theta)^2}}\right)$$

where $f(\theta) = 1 + \alpha\cos(4\theta)$, and α weights the tunneling probability toward the $(0,\pi)$ direction. The cusp-like feature near zero bias and broader quasiparticle peaks are intrinsic to $d$wave DOS. Inclusion of the weighting function rounds the subgap region and the conductance peaks. Therefore increasing α gives rise to the directionality and resulting tunneling conductance will look more and more like a BCS DOS. Both spectra show quite high PHB, especially data of $10 \times 10\ \mu\mathrm{m}^2$ mesa, so fits are reliable only in the subgap regions. It means that both data exhibit heating effects, but they are noticeably smaller in the $5 \times 5\ \mu\mathrm{m}^2$ mesa, since experimental data match with d-wave fit and exhibit the dip and hump features at high bias.

In summary, we have obtained conventional point contact and interlayer tunneling characteristics on HgBr_2 intercalated Bi2212 single crystals at 4.2 K. Taking the SIS break junction spectrum as a point of reference in terms of heating because it has relatively larger specific junction resistance, we evaluated the results of IJJ tunneling. We fabricated $5 \times 5\ \mu\mathrm{m}^2$ and $10 \times 10\ \mu\mathrm{m}^2$ sized mesas and concluded that smaller one exhibits less heating effects on spectra by presenting very close superconducting energy gap value to that found from conventional PCT measurements, round quasiparticle peaks, dip/hump structures at high voltage region, and good compatibility to d-wave symmetry.

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