Spin Polarized Current Injection Through $HgBr_2$ Intercalated Bi2212 Intrinsic Josephson Junctions

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

***Abstract*—To investigate the effect of polarized current on tunneling characteristics of intrinsic Josephson junctions (IJJs), spin-polarized and spin-degenerate current have been injected through the c-axis of $HgBr_2$ intercalated $Bi_{2.1}Sr_{1.5}Ca_{1.4}Cu_2O_{8+\delta}$ (Bi2212) single crystals on which $10 \times 10\ \mu m^2$ mesas have been fabricated. These two spin conditions are achieved by depositing either Au (15 nm)/Co (80 nm)/Au (156 nm) multilayers or single Au film on $HgBr_2$ intercalated Bi2212 with $T_c = 74$ K followed by photolithography and Ar ion beam etching. The I–V characteristics have been measured with and without a magnetic field parallel to c-axis at 4.2 K. A fine, soft Au wire is used to make a gentle mechanical contact on the top of a particular mesa in the array. Tunneling conductance characteristics were obtained and the magnetic field dependence of sumgap voltage peaks was investigated. These peaks do not change in position with increasing magnetic field for both contact configurations. In addition, the temperature dependence of tunneling characteristics of the IJJs are obtained and existence of pseudogap feature is observed above T_c for $HgBr_2$ intercalated Bi2212.**

***Index Terms*—High-T_c superconductors, intrinsic Josephson junctions, pseudogap, spin polarized current, tunneling spectroscopy.**

I. Introduction

INJECTION of spin polarized current through the high temperature superconductors (HTSs) is an effective way to examine their coupling mechanism [1]. There are many studies which intended to apply spin-polarized current in a HTS [2]–[7]. These experiments include: deposition of a magnetic material on the surface of a superconductor and driving the spin polarized current through the ferromagnetic layer while investigating the superconducting properties, such as critical current, critical temperature and vortex lattice [6], [7]. However, there are only a couple of works in which spin polarized current is driven along the c-axis of a superconductor [4], [5] so that injected current tunnels between the CuO_2 layers in HTS. The novelty of this approach is utilizing the interlayer tunneling, first observed by Kleiner *et al.* [8], of spin polarized quasiparticles between intrinsic Josephson junctions (IJJs), which can reveal the distinct properties of HTS. On the other hand, it is now well understood that intrinsic tunneling spectroscopy based on IJJ measurements suffers from heating and artifacts, which are likely to be seen in I–V characteristics [9]–[13]. Thus, the results obtained from the measurements with the application of spin-polarized current may not be reliable unless the serious repercussions of heating and nonequilibrium on IJJs are understood.

Point-contact tunneling (PCT), break junction and scanning tunneling microscopy/spectroscopy (STM/S) studies directly found the magnitude of energy gap and high bias spectral features such as dip and hump for $Bi_2Sr_2CaCu_2O_{8+\delta}$ over a wide doping range [14]–[16] that are tied to the mechanism of superconductivity [17], [18]. The tunneling characteristics of a Josephson junction fabricated from conventional superconductors do not show any robust feature at elevated bias values, which gives no clue on the state of junction, i.e. one cannot estimate whether it is in superconducting or normal state. The fine structure of phonon modes can be seen in tunneling conductance of conventional junctions, however these features correspond to only 1% change of the background tunneling conductance. In our recent study [19], we have shown that dip and hump should exist in HTS superconducting density of states, if the tunneling spectrum is not affected by heating effect severely. Recently, some research groups have used short pulse current technique to minimize the Joule heating on IJJ stacks [20] as well as very small area junctions (below 1 μm^2) [13]. Using each technique, I–V and tunneling conductance characteristics of IJJs on Bi2212 have exhibited similar spectral features close to that obtained from PCT, break junction, STM/S and angle-resolved photoemission.

In this study, we have used $HgBr_2$-intercalated $Bi_{2.1}Sr_{1.5}Ca_{1.4}Cu_2O_{8+\delta}$ (Bi2212) in which the c-axis lattice constant is 2.1 nm, i.e., 0.6 nm larger than nonintercalated Bi2212. The c-axis resistivity at room temperature is above 600 Ωcm after intercalation which is at least 60 times larger than that of pristine crystals. The intercalation of $HgBr_2$ into neighboring BiO layers in Bi2212 decreases the coupling between CuO_2 planes resulting in a reduction of critical current. Since the generated power is smaller after intercalation, the increment of the local temperature will be lower. We use the Co layer to inject a spin-polarized current along the c-axis of $HgBr_2$ intercalated Bi2212 and examine its effect of polarization of quasiparticles while minimizing the effects of heating.

II. Experiment

Single crystals of Ca-rich Bi2212 were grown by a floating zone technique. The small flakes were intercalated with $HgBr_2$ and show bulk T_c of 74 K on magnetization measurements.

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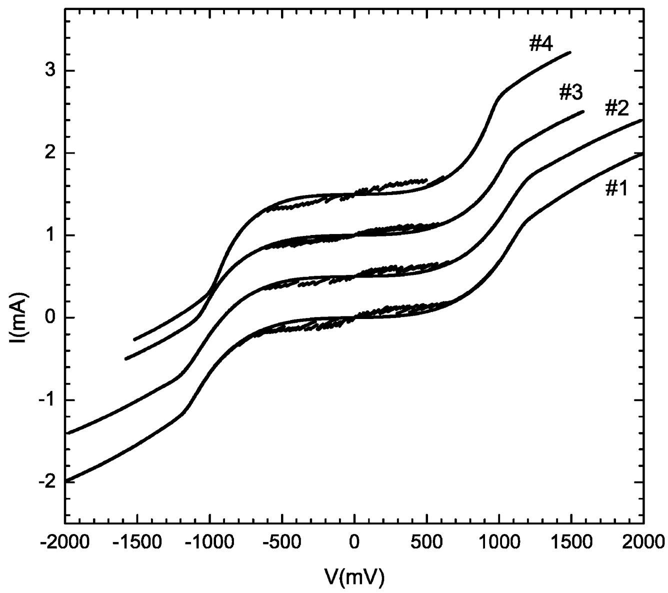

Fig. 1. Current–voltage characteristics of intrinsic Josephson junctions at 4.2 K. The current is swept up and down many times to obtain branches.

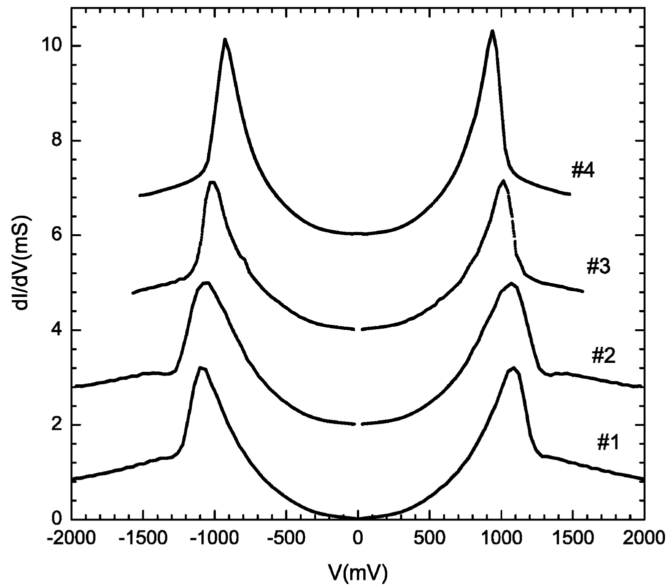

Fig. 2. Tunneling conductance of mesas given in Fig. 1. Only return branches of data are demonstrated for clarity. Since all mesas are in same array, we obtained similar peak positions and tunneling conductances. Note that mesa #4 exhibits relatively larger peak height to background ratio.

Two sets of samples were prepared; in one set, freshly cleaved $\mathrm{HgBr_2}$ intercalated Bi2212 crystals have had a simple Au film deposited on top of the crystal while the other set has a ferromagnetic multilayer ($\mathrm{Au} = 15\ \mathrm{nm/Co} = 80\ \mathrm{nm/Au} = 156\ \mathrm{nm}$). In each case, a $10 \times 10\ \mu\mathrm{m}^2$ mesa structure was fabricated using photolithography and Ar ion beam etching [21]. Mesa heights were measured by atomic force microscopy using tapping mode to find the number of junctions in the mesa and that is confirmed from the number of quasiparticle branches in tunneling characteristics. A three-probe measurement technique was used; two contacts were taken from the corners of the crystal and the other one was from top of the mesa by point contact of a hook-shaped thin gold wire. The dI/dV-V data were obtained by numerical differentiation of the smoothed I–V characteristics. Temperature dependent data were measured from 4.2 K up to a temperature at which the Au tip moved off the mesa due to thermal expansion. In addition, a magnetic field was applied along the c-axis of the crystal for comparison of characteristics with and without magnetic field.

Cobalt was used to inject polarized quasiparticles into $\mathrm{HgBr_2}$ intercalated Bi2212. The magnetization of our sputtered Co films showed saturation around 50 G which is comparable to the epitaxially grown Co films. A thin Au buffer layer was used between Co and $\mathrm{HgBr_2}$ intercalated Bi2212 with the thickness of 15 nm to prevent the possible chemical reactions between ferromagnetic layer and the bulk crystal. Note that the spin diffusion length in Au is reported to be 63 nm [22], so most of the spins travel through Au buffer layer to the intercalated Bi2212 crystal without loosing their polarization. The top of the Co film is covered with a thick Au layer to prevent oxidation.

III. Results

Fig. 1 shows the I–V characteristics of four different mesas on the same array at 4.2 K. Multiple Josephson branches and hysteretic behavior are observed for all of the IJJ stacks. Mesas #2, 3, and 4 are shifted 0.5 mA from each other for clarity. All four junctions show almost similar switching current behavior in both magnitude and separation between quasiparticle branches, which is an indication of homogeneous intercalation of the crystals. The I–V curves exhibit approximately 24 branches, which enables us to find the number of IJJ in the stack. The Josephson current near zero bias cannot be seen presumably due to the contact resistance between Au film and $\mathrm{HgBr_2}$ intercalated Bi2212. It is also possible that self-field of the Co layer might suppress Cooper pair tunneling. There is no backbending in the I–V curves, which is usually observed in the measurements of non-intercalated Bi2212 with similar sized-mesas. This is a clear manifestation that the mesas fabricated on intercalated Bi2212 are comparatively less affected by heating as seen previously [23]. In the I–V curves of mesa #1 and #2, there is a trace of dip and hump features at high bias which can be more clearly seen in dI/dV-V. Mesa #4 exhibits a slightly different tendency in its I–V curve, showing higher conductance at high bias.

Fig. 2 shows the dI/dV-V characteristics (shifted 2 mS from each other) of the same mesas given in Fig. 1. Here, we have presented only the smoothed numerical derivatives of the return branches in I–V characteristics because our main interest is the sumgap voltages and characteristic features at high bias. Especially the data of mesa #1 and #2 are consistent with break junction experiments on $\mathrm{HgBr_2}$ intercalated Bi2212 in terms of exhibiting dip and hump features around ± 1300 mV, yet they are relatively much weaker. Break junction tunneling conductance data show more robust dip and hump structures [15]. The small intensity of these features in shape indicates that there is still some heating in the mesas. On the other hand, the local temperature is certainly below T_c, because the occurrence of such dip/hump structure is a property of the superconducting state. Mesa #4 shows more rounded behavior in the subgap region near zero bias and higher peak height to background ratio. This is usually a consequence of greater heating, but its origin is

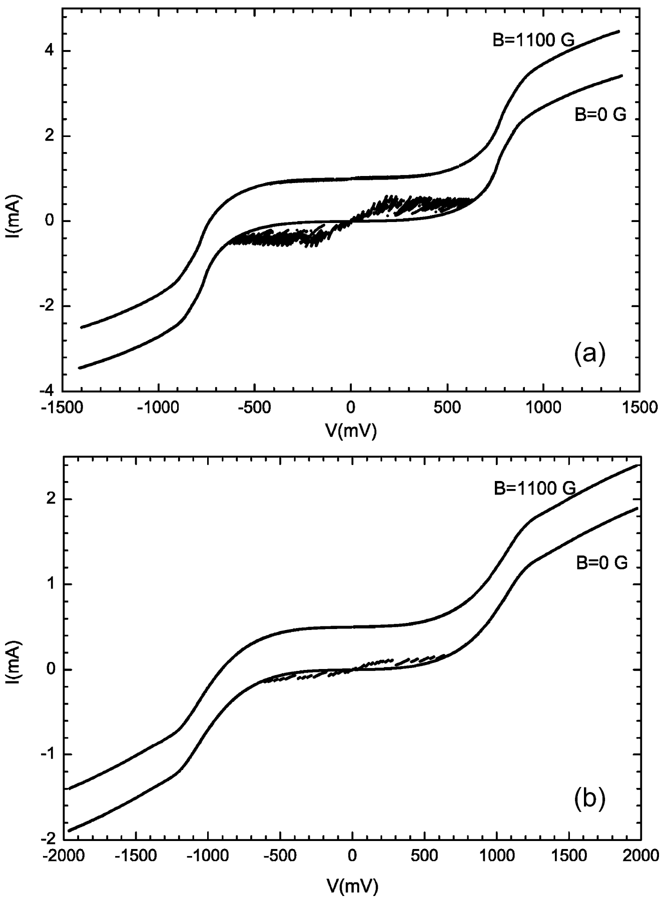

Fig. 3. Current–voltage characteristics of 10×10 $\mu\mathrm{m}^2$ mesa under $\mathrm{B} = 0$ and $\mathrm{B} = 1100$ G for spin degenerate current (a), spin polarized current (b) at 4.2 K. Note that $\mathrm{B} = 1100$ G data are shifted for clarity in both figures.

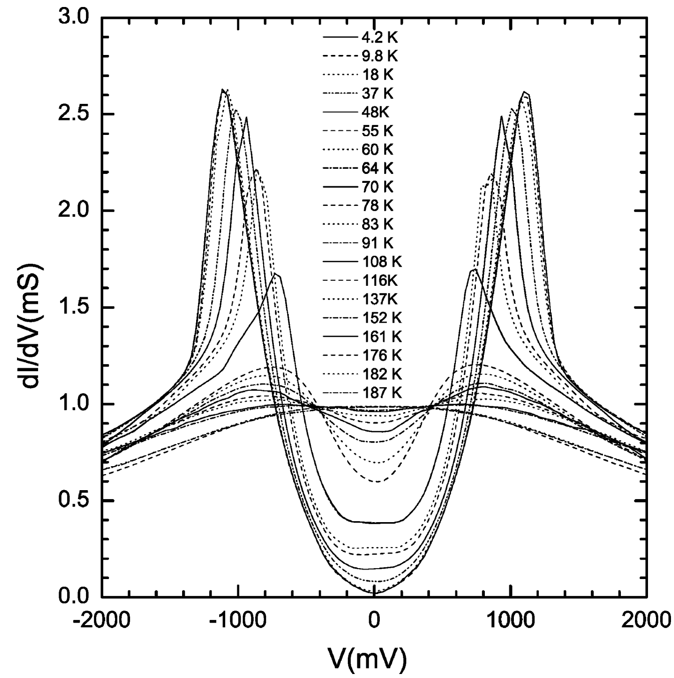

Fig. 4. Temperature dependence of tunneling conductance for mesa #1. Pseudogap can be seen above T_c, but at higher temperature, it disappears, and a dome around the Fermi level is left.

unknown. Since all mesas are very close to each other, within a 300×300 $\mu\mathrm{m}^2$ area, we do not expect to have large height differences after ion milling. Therefore, we can count the quasiparticle branches of a representative I–V curve obtained from any mesa on the array to find the number of IJJs. Since sumgap peaks are around ± 1100 mV, we can calculate the magnitude of energy gap by dividing this value by IJJ number, to get $2\Delta = 46$ mV that is close to the energy gap found from PCT and break junction experiments on the same intercalated material [24].

The amount of the polarization in current depends on the Co thin film. Since Co does not have a single domain in our thin films, applied magnetic field can help increasing the polarization of the current. The I–V characteristics of 10×10 $\mu\mathrm{m}^2$ mesas under magnetic field is given in Fig. 3(a) and (b) at 4.2 K. Here, we have I–V of spin degenerate current in Fig. 3(a) with and without magnetic field of $\mathrm{B} = 1100$ G. While there are hysteretic quasiparticle branches at $\mathrm{B} = 0$ G, they diminish with increasing field. However, the return branches exactly match with each other for both cases. The I–V characteristics are given in Fig. 3(b) for a spin-polarized current with and without field. The disappearance of hysteretic quasiparticle branches can be seen with increasing magnetic field. We have not observed any change of sumgap peaks in locations for the return branches as was seen by Bang *et al.* [5]. The most important difference in our study is our use of intercalated crystals. Thus the influence of heating might be the reason for alteration of the sumgap peak positions with magnetic field in the previous study. Also, the decrease in I_c is observed with spin-polarized current by Lee *et al.* [7] in the same way as we see in Fig. 3, i.e. spin-polarized quasiparticles decrease the magnitude of the switching current.

We have taken the temperature dependence of tunneling characteristics belonging to mesa #1, 2 and 3. In Fig. 4, such dI/dV-V data of the return branches are given for mesa #1. Again here, the tunneling conductances come from smoothed numerical derivatives of I–V and then the dI/dV are smoothed again. The sumgap peaks, V_p's move toward to origin with increasing temperature and the zero-bias conductances increase gradually. Just above T_c up to $\mathrm{T} = 180$ K, a depression around zero bias implies a pseudogap. Higher temperatures suppress the pseudogap and leave the background as a dome around The Fermi level. In Fig. 5, the evolution of sumgap peak positions with temperature is given, and V_p normally follows BCS behavior for SIS junctions. With increasing temperature, the superconducting gap vanishes at T_c and is replaced with pseudogap at higher temperatures. Above T_c, V_p increases, which is misleading. Large scattering above T_c can explain this anomaly and the fits with large smearing parameter can clearly show the pseudogap closes.

In summary, we have investigated IJJ characteristics obtained by spin polarized current injection. It is reproducibly observed that there is no influence of polarized current on sumgap peaks of HgBr_2 intercalated Bi2212. Spin polarized current generates less heating than spin degenerate current even for 10×10 $\mu\mathrm{m}^2$ mesas; we can see dip/hump features in their spectra. Temperature evolution of IJJs shows a pseudogap above T_c for spin polarized current configuration as we observed from the measurements performed with spin degenerate configuration.

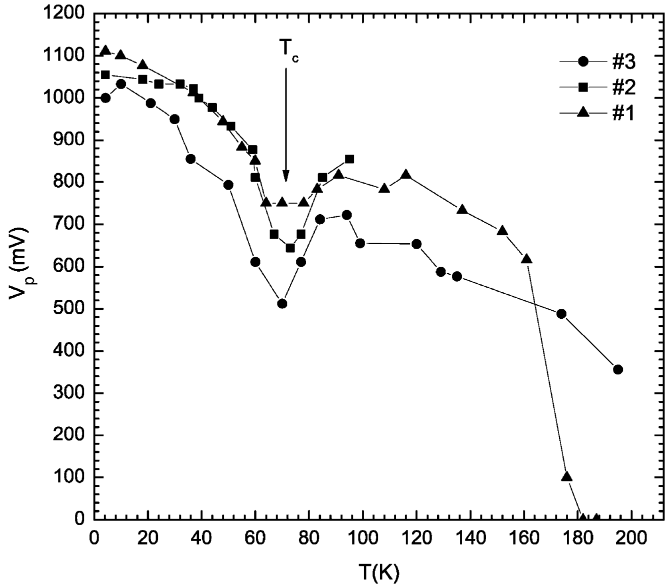

Fig. 5. Temperature dependence of peak voltage for mesa #1, 2, and 3. The arrow indicates bulk T_c of the crystal. While in conventional superconductors the energy gap closes at T_c, $HgBr_2$ intercalated Bi2212 has a pseudogap above T_c, as seen in optimally and underdoped Bi2212.

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