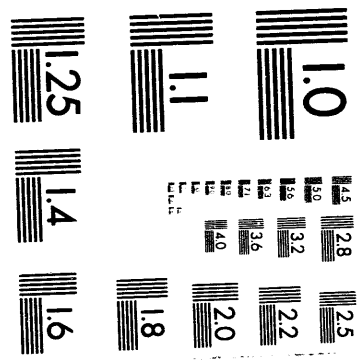
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Manuscript

February 1994

Conf-940132--2

High T_c Superconductor Tunnel Junctions for Photon Detectors*

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Proceedings of the International Conference on Millimeter and Submillimeter Waves and Applications (SPIE 1994), January 10-14, 1994, San Diego, CA

jmc

*Work supported by the U.S. Department of Energy, Division of Basic Energy Sciences-Materials Sciences under contract #W-31-109-ENG-38 (KEG), and by the NSF Office of Science and Technology Centers under contract #DMR 91-20000 (JZ, JC).

High T_c superconductor tunnel junctions for photon detectors

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ABSTRACT

SIN and SIS quasiparticle tunnel junctions on high T_c superconductors (HTS) offer the possibility of low-noise, heterodyne, photon detection in the THz regime. We report progress on the development of such junctions using mechanical point contacts. In general, these contacts display the optimum characteristics that can be obtained from HTS native-surface tunnel barriers. The bismuthate, $Ba_{1-x}K_xBiO_3$, (T_c=25K) displays ideal , BCS, quasiparticle characteristics at T=4.2 K however, at temperatures $T \sim T_c/2$ there is evidence of strong quasiparticle damping which may inhibit device performance. The cuprates typically display non-ideal quasiparticle characteristics including large sub-gap conductances. Recent data for the new Hg-based cuprates (T_c=96K) are promising in that they exhibit very low and flat sub-gap conductances as expected from a BCS density of states. Proximity effect tunnel junctions on $Bi_2Sr_2CaCu_2O_8$/Au bilayers have been studied using an In tip. An induced energy gap has been consistently observed in the Au layer and the data can be understood using the McMillan model. A few junctions show much improved sub-gap characteristics compared to ones made directly on the BSCCO surface and indicate that this approach may be suitable for mixer development.

1. INTRODUCTION

The non-linear current-voltage (I-V) characteristics in superconducting-insulator-superconducting (SIS) junctions can be used for mixing in a heterodyne receiver.[1] The performance of SIS quasiparticle mixers has surpassed that of other techniques for heterodyne detection over a broad range of the mm and sub-mm electromagnetic spectrum.[2] SIS mixers employing conventional, low-T_c superconductors have exhibited quantum noise limited temperatures, T_M=hν/k up to 100 GHz and have been successfully operated up to 500 GHz in waveguide receivers.[3] Most SIS junctions are Nb based with an upper limit frequency given by $2\Delta/\hbar$=700 GHz and are operated at or below 4.2 K. There is a need for low-noise heterodyne receivers in the regime up to a few THz and it would be desireable to operate at temperatures accessible with closed-cycle refrigerators (~12 K). High temperature superconducting (HTS) oxides with T_c = 25 K-100 K and with energy gaps 2Δ= 8 meV-60 meV offer the possiblity of meeting these requirements, at least in principle. However, there has been little discussion in the literature about HTS quasiparticle junctions as mixers and other devices such as microbolometers have been proposed for THz detection.[4]

For use as a mixer, SIS junctions must exhibit low sub-gap conductance and a sharp current rise at the gap voltage, $2\Delta/e$. It should also be noted that since $kT \ll \Delta$ (even at 12 K) in those HTS with Δ>15 meV, thermal smearing of junction characteristics is small and strong non-linearities can be expected in junctions with a normal metal counterelectrode (SIN). SIN junctions eliminate problems with Josephson effects as well. Despite a world-wide effort over the past seven years, mixer-quality SIS or SIN thin film junctions have not been obtained using HTS cuprates. It is not understood why SIS quasiparticle junctions on HTS cuprates are so difficult to obtain but a general consensus is that superconductivity in the Cu-O layers is very sensitive to structural disorder arising from defects, oxygen vacancies, or strains. Chemical or structural transformations at the interface of HTS cuprates with an insulating tunnel barrier can therefore lead to non-superconducting , non-metallic or magnetic layers and this, coupled with the short coherence lengths, leads to degraded tunneling performance. The problem is exacerbated by the hostile processing environment for thin film deposition, i.e., high temperature and high oxygen pressure. Mechanical methods such as break junctions and point-contact tunneling (PCT) junctions have provided the highest quality SIS and SIN characteristics on cuprate superconductors such as BSCCO and Nd-Ce-Cu-O (NCCO), but these are still not ideal. The ubiquitous non-ideal features of cuprate junctions has led to speculation that they arise from a novel pairing state such as d-wave.

We report here progress made in the development of SIN and SIS junctions on cuprate and bismuthate superconductors using a mechanical, point-contact approach. This mechanical method has proven to be a reliable and versatile tool for making many quasiparticle junctions on a given sample. The tip can be used to scrape, clean and in some cases cleave the HTS surfaces at low temperatures, leaving a thin, native-barrier for elastic tunneling. This point contact method has generally provided the best quasiparticle junction characterisitics of most HTS materials and also has preceded the development of thin-film junctions.[5] For example, ideal, BCS quasiparticle characteristics were first discovered on $Ba_{1-x}K_xBiO_3$ (BKBO) using PCT[6] and this result, in part, has stimulated the development of all-thin-film, SIS junctions.[7,8] Also, the method has allowed a thorough examination of proximity effect tunneling in BSCCO/Au bilayers with the discovery that improved junction characteristics can be obtained. Eight different HTS compounds have been examined by this technique but here we focus on BKBO, BSCCO and the recently discovered, Hg-based compound $HgBa_2CuO_4$ (Hg-1201).

2. EXPERIMENTAL RESULTS

2.1 Bismuthates

The most promising candidate for SIS mixers is $Ba_{1-x}K_xBiO_3$ (BKBO) which has been shown to display ideal, BCS quasiparticle characteristics[6] at 4.2K. High quality thin film, SIN and SIS junctions have been obtained on planar trilayer structures[7] and with films grown on bicrystal substrates[8], although reproducibility seems to be a problem. A great deal of junction research has already been reported on this compound and so here we focus only on the junction behavior at T>4.2 K. Although the maximum bulk T_c is 30K, thin films of BKBO typically have T_c~20-25K.[7,8] SIS mixer detectors using commercial, closed-cycle refrigerators will have an operating temperature of ~12K and it is important to determine the device characteristics of BKBO at these elevated temperatures. Our PCT measurements on BKBO indicate anomalously large quasiparticle damping rates, Γ, at these operating temperatures. Quasiparticle damping can be included in the density of states in the following way:

$$N(E) = \mathrm{Re}\, E\text{-}i\Gamma / ((E\text{-}i\Gamma)^2\text{-}\Delta^2)^{1/2} \qquad (1)$$

Γ is essentially zero in BKBO at 4.2K and in this case, eq. 1 reduces to the BCS expression. A quantitative study of the temperature dependence of Γ has been made using an STM in the point-contact mode[9] and this work has shown that the damping rate increases with temperature as $\sim T^3$ so that at T=12K, Γ~1 meV, which is approximately 25% of Δ. Such large damping rates smear out the nonlinearity of the I-V characteristics at V=2Δ/e and can be expected to diminish device performance. These results are consistent with other tunneling geometries which utilize the native barrier of BKBO, including trilayer[7] and grain boundary type junctions.[8] The origin of the large damping rate as T increases is not yet understood, but it may be intrinsic to electron-phonon coupled superconductors with high frequency phonon modes.

2.2 Cuprates

The SIS quasiparticle characteristics for $Bi_2Sr_2CaCu_2O_8$ (BSCCO) (T_c=86-96 K) have been measured by a variety of tunneling methods[5] and the results are highly reproducible. In Fig. 1 we compare the SIS characteristics[5] of BSCCO (Tc=96 K) and $Nd_{1.85}Ce_{0.15}CuO_4$ (NCCO) (Tc=22 K), along with a BKBO/Nb SIS' junction,[6] all of the data being obtained by mechanical junctions. The BSCCO and NCCO data are representative of the very best quasiparticle data found on any HTS cuprates. To compare these junctions, which have widely varying gap values, we have normalized the voltage axis by the voltage of the conductance peak, V_p. For symmetric SIS junctions V_p is close to 2Δ, even in the presence of smearing from non-zero temperature or quasiparticle lifetime effects. For the BKBO/Nb junction V_p is the sum gap (~6 meV). The characteristics of the cuprates BSCCO and NCCO are quite similar and include a monotonically increasing conductance about the minimum, zero-bias value, in contrast to the low and flat conductance of the the BKBO/Nb junction. Also, there is a strong dip feature at V~3Δ/e for both cuprates and in the case of BSCCO this feature is similar to that found in photoemission experiments. The sharp dip found in the BKBO/Nb junction is a common proximity effect found on air exposed Nb surfaces.

The principal question is whether the non-ideal features of the cuprates are intrinsic, i.e., due to the quasiparticle density of states, or are the result of a surface problem arising from disorder, decomposition, proximity effects etc. What is unusual about the BSCCO and NCCO data is the remarkable similarity in shape of the conductances despite the widely different Tc values. This seems to imply that intrinsic properties are being probed and it has been suggested that the tunneling results on cuprates are indicative of a d-wave pairing state.[10] If so, then this would be deleterious for potential mixers since the d-wave state has lines of gap nodes which lead to "states in the gap" or intrinsic sub-gap conductance.

Figure 2 shows SIN data on the newly discovered Hg-based cuprate $HgBa_2CuO_4$ (Hg-1201)by PCT.[11] The data follow the general trend of the best curves seen in cuprate superconductors, but these show significantly lower and flatter sub-gap conductances and they can be reproducibly obtained. Fitting the data to eq. 1 (solid line of Fig. 1) the ratio Γ/Δ is ~6-8% making this the lowest value of all cuprates. These results are more suggestive of a well-developed energy gap over the entire Fermi surface in contrast to the gap nodes found in d-wave models. These characteristics, which have been obtained on bulk, polycrystalline samples are thus much more promising for SIN or SIS junction development. The additional broadening seen in the conductance peaks suggests a small distribution of gap values is being probed. This inhomogeneity is not reflected in the bulk susceptibility of the material, where a sharp superconducting transition is observed, and is likely due to exposure of the sample to atmosphere.

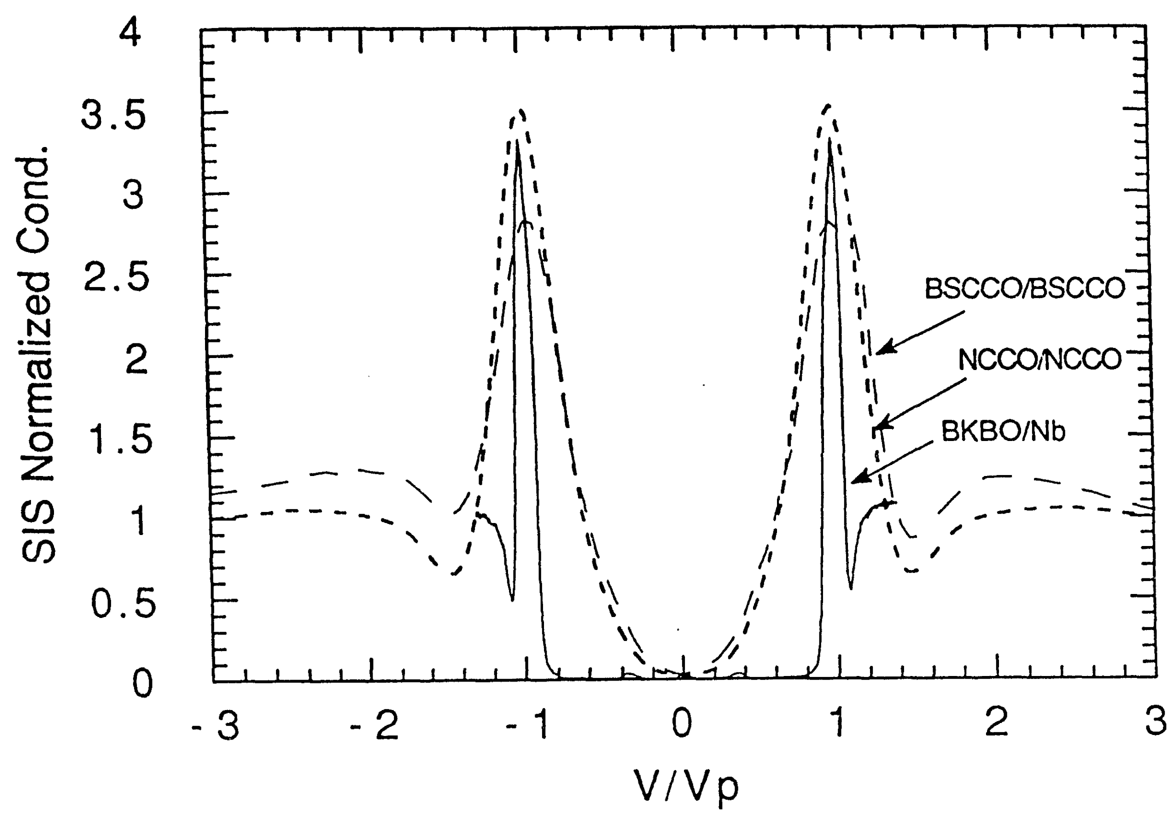

Figure 1. Comparison of SIS tunneling conductances at 4.2 K for the a BKBO/Nb junction and the cuprate junctions BSCCO/BSCCO and NCCO/NCCO. All data are from mechanical contacts. The NCCO SIS curve has been generated from SIN data obtained with a Au tip.

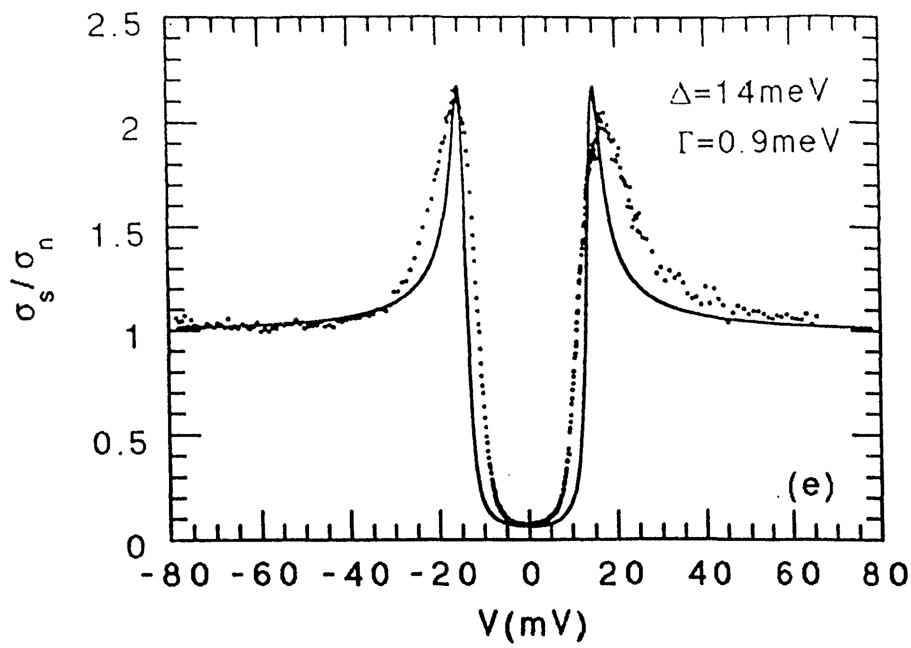

Figure 2. Normalized SIN tunneling conductance (dots) for Hg-1201 polycrystalline sample obtained with a Au tip. The fit (solid line) is obtained using eq. 1 of the text and Δ=14 meV and Γ=0.9 meV.

Figure 3 shows the I-V characteristics of the Hg-1201 junction and the classical current responsivity, R=S/2, where $S=(d^2I/V^2)/(dI/dV)$ is the curvature parameter. The R value is one figure of merit which can be applied to quasiparticle junctions to examine their suitability as mixers. The maximum value of R is approximately 300 V^{-1}, which is respectable for an SIN junction at 4.2 K, but is about 8 times smaller than found in Pb-alloy SIS junctions[1] where quantum limited noise performance is observed.

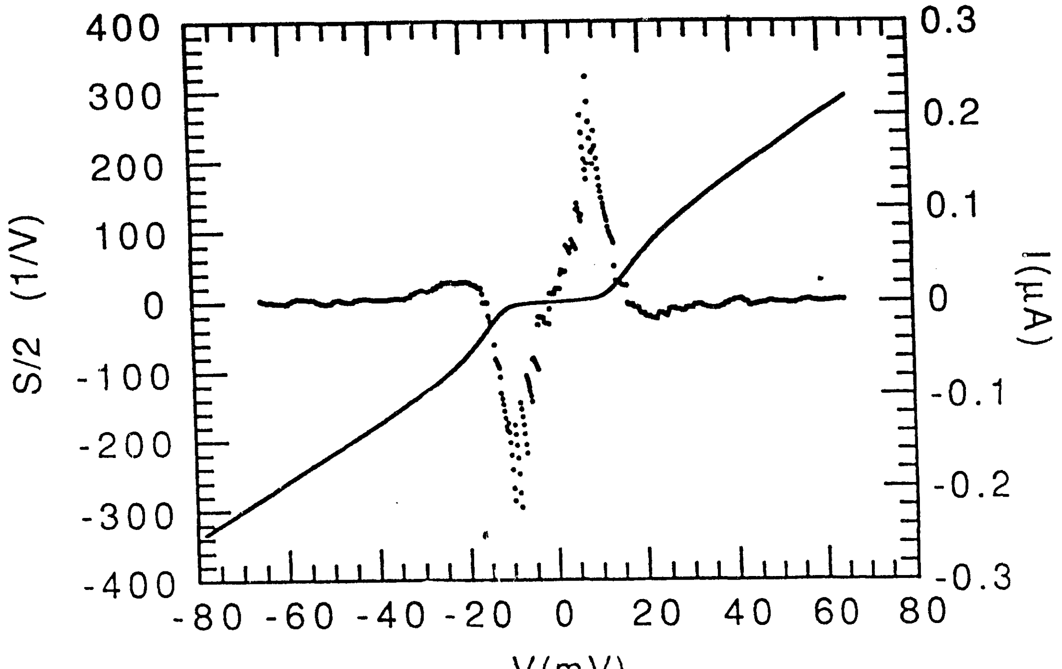

Figure 3 I-V characteristic (solid line, right side scale) of the Hg-1201 junction shown in Fig. 3. The dotted curve (left scale) is the classical responsivity, S/2, determined from the measured dI/dV.

The voltage width of the current rise at $V=\Delta/e$ in Fig. 3 is larger than the photon energy at 1 THz ($h\nu$=4.1 meV). Thus this junction would be expected to display only weak quantum effects and the Tucker model[2] could be expected to provide reasonable estimates of the gain and mixer noise of such a junction.[12] While the results of such an analysis would likely indicate a less-than-ideal mixer element, it would provide a basis for comparison with existing or proposed detectors in the THz range. Most importantly, the Hg-1201 results suggest that more ideal features can be obtained with improvements in sample and surface quality as might be achieved in single crystals or in dense, highly oriented films.

2.3 Proximity Effect Junctions

The idea of using the proximity effect to fabricate tunnel junctions is not new and is currently used in all Nb-based junction devices.[13,14] In 1979 it was demonstrated that high quality quasiparticle tunnel junctions could be made on Nb and V by using a thin (20-200 Å) overlayer of Al.[15] The junctions were of the form SNIC where S was Nb or V, the normal (N) layer was Al, the insulator (I) was Al oxide and C was a convenient counterelectrode such as Indium. Here the Al layer prevented any exposure of the underlying superconductor to oxygen which would degrade the surface, and at the same time the Al oxide was well-known to provide high quality, self-limiting tunnel barriers. In 1983 the technique was extended to all-Nb junctions[16] which displayed Josephson currents and low sub-gap conductances. Present Nb mixer technology incorporates junctions which are not truly SIS, but rather SNIS or SNINS, where the normal, N layer is a thin Al film and the insulator, I, is Al oxide.

Considering the importance of proximity effect junctions in current SIS mixer detectors, it becomes essential to understand the nature of the proximity effect in HTS. HTS cuprates are not conventional metals in that they are quasi two-dimensional systems with strong in-plane electron correlations. Also, neither the pairing mechanism nor the symmetry of the superconducting state is understood. We have used point contact tunneling to study junctions of the form SNIC where the SN bilayer was BSCCO/Au and the counterelectrode was an Indium tip. The barrier is In oxide. Single crystals of BSCCO were cleaved in 10^{-7} torr with an immediate deposition of 200-600 Å of Au. Previous studies of BSCCO/Au bilayers by photoemission[17] showed no evidence of a proximity induced gap in the Au. Our data consistently showed a gap parameter which decreased in a monotonic fashion from ~15 meV to ~5 meV for 200 Å and 600 Å Au layers respectively. Representative conductance curves are shown in Fig. 5.

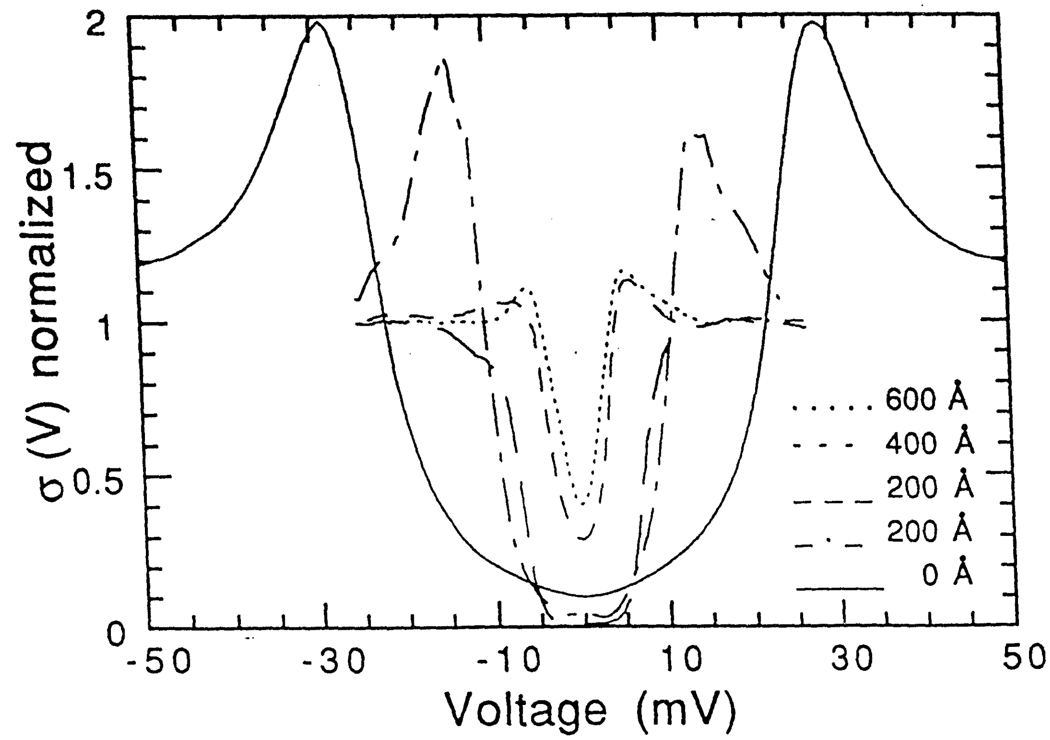

Figure 4. Representative SNIC junction tunneling conductances of BSCCO/Au bilayers using an In tip. Au thicknesses are indicated in the legend.

The dependence of the energy gap with Au thickness can be fit using the McMillan model[18] of the proximity effect. Several junctions with 200 Å Au layers showed very low sub-gap conductances, improved over junctions formed directly on the BSCCO surface as can be seen in Fig. 3. Reasonable quantitative agreement with the McMillan model has been found in detailed fits of three representative junctions. One example is shown in Fig. 4 for a 200 Å gold thickness. The fit used a value of Δ_S=22.5 meV for the underlying BSCCO film which was the same value used to fit the gap vs. Au thickness dependence. The fit required additional smearing which was accomplished by using a temperature T=17 K instead of the measured value of 4.2 K. The physical origin of the additional smearing is unknown. The junction displays a large gap, reasonably sharp conductance peaks and a low, flat conductance near zero bias. These features together represent a significant improvement over SIN junctions formed directly on the BSCCO surface and suggest that the proximity effect approach may be suitable to improve the quality of SIN and SIS junctions for mixer development.

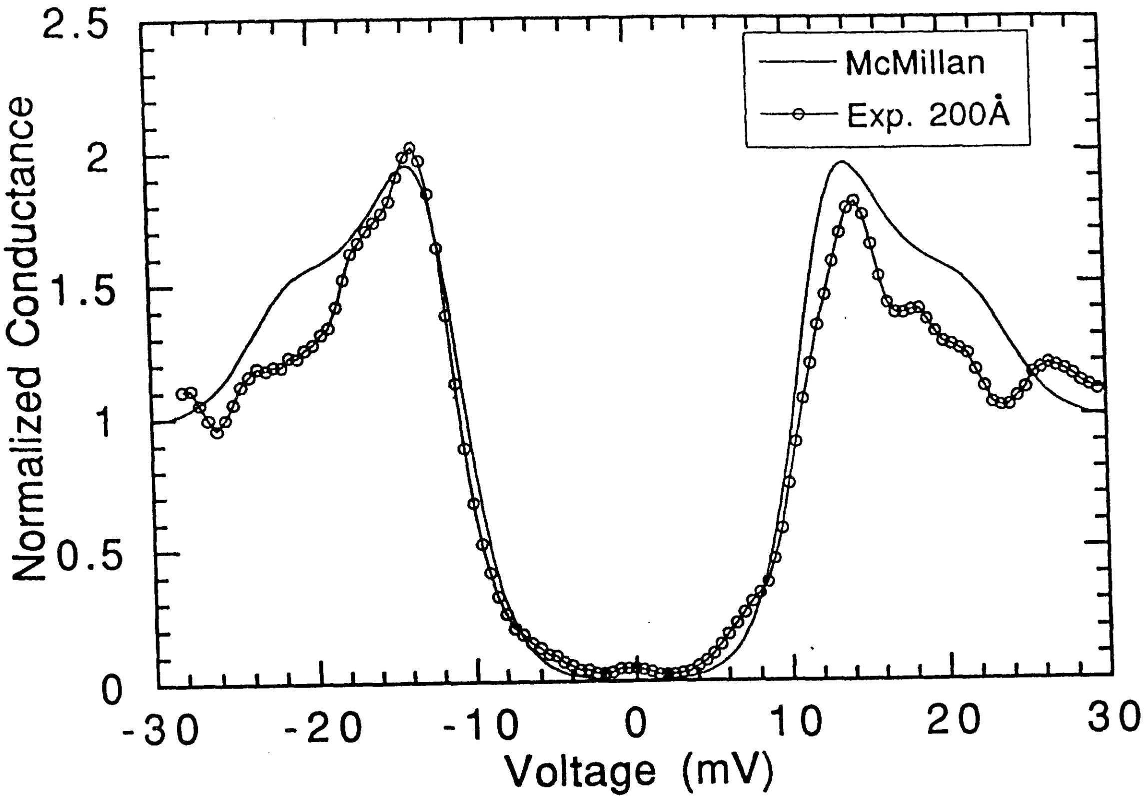

Figure 5. Experimental normalized conductance (open circles) for a proximity effect junction on a BSCCO/Au bilayer with nominal Au thickness of 200 Å. The theoretical fit (solid line) is from the McMillan model using parameters: Δ_S= 22.5 meV, Γ_N=21 meV and T=17 K.

These proximity effect results have been independently confirmed using a low temperature STM[19] and vacuum tunneling. The proximity induced gap in the Au layer can be found at many locations on the surface and this indicates that the effect is not necessarily confined to specific regions, e.g. near cleavage steps for example. However, it should be noted that the very best junctions (as in Fig. 5) represent a small percentage of the total junctions measured. This may indicate that there is a wide variation in Au thickness or NS coupling at the BSCCO/Au interface. More study is needed.

All-thin-film bilayers of BSCCO/Au were studied using laser ablation. The Au was deposited in-situ after cool-down of the BSCCO film. In some cases, very high quality junctions were obtained as shown in Fig. 6 for a junctions with Au thickness ~400 Å. The tunneling conductance could be fit using BCS density of states and thermal smearing. Note the observation (and fitting) of the difference peak structure (Δ_1-Δ_2) in Fig. 6, however the BSCCO gap was quite small (~1meV). The small gap appears to be due to a combination of proximity effect and low value of BSCCO T_c~30K. We suspect that the actual BSCCO composition is 2201 which is often an impurity phase in 2212 films.

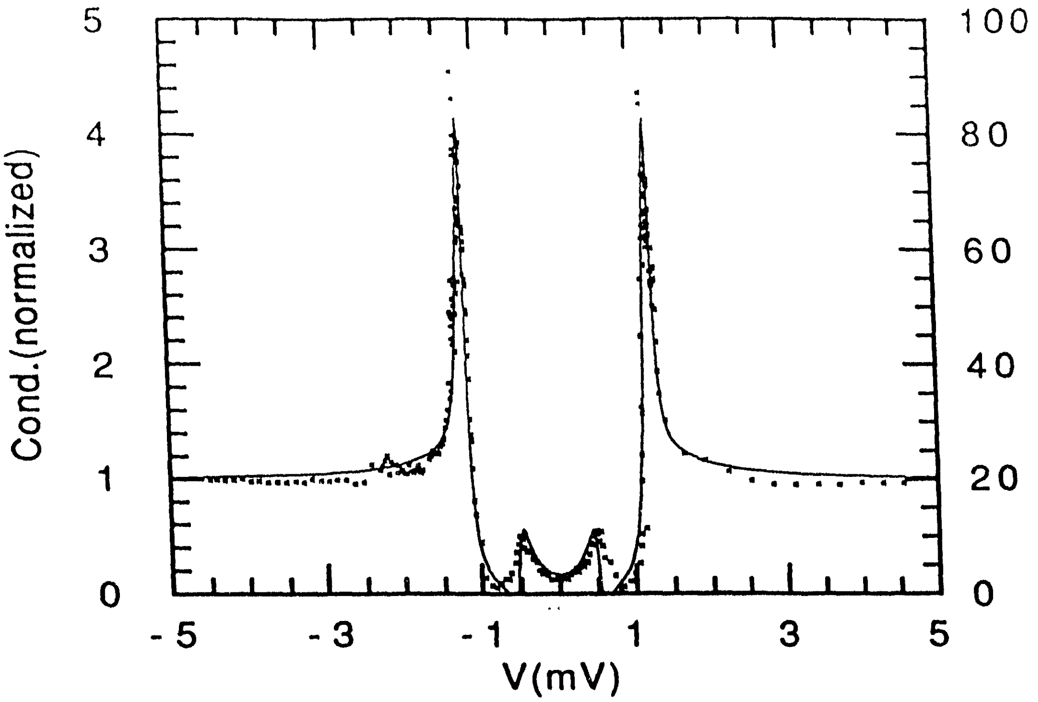

Figure 6. Tunneling conductance (dots) for a BSCCO/Au thin film bilayer with Au thickness=400 Å. Solid line is a fit using BCS gaps, Δ_1=0.9 meV and Δ_2=0.35 meV.

3. CONCLUSIONS

There has been significant improvement in the quality of SIN and SIS quasiparticle junctions on HTS materials in the past few years. All-thin-film SIS junctions of BKBO now exist which display sharp I-V characteristics at 4.2 K. These films typically have Tc values in the range of 20-25 K and 2Δ~7 meV, suitable for photon detection at 1 THz. Operation of BKBO junctions at 12 K in closed-cycle refrigerators may be problematic due to an anomalously large quasiparticle damping rate that seems to be intrinsic to all native-oxide junctions at these temperatures. This damping rate smears out the nonlinearity of the I-V characteristic and will likely diminish device performance.

SIN tunneling results on Hg-1201 polycrystalline samples (Tc=96 K) appear BCS-like and may dispel any concerns that the non-ideal characteristics commonly found in cuprate junctions are intrinsic. Further improvements in junction quality are expected for single crystals and thin films.

A proximity effect induced gap has consistently been observed by PCT in BSCCO/Au bilayers formed on cleaved single crystals . This result has been confirmed by vacuum tunneling with an STM and is in contrast to earlier photoemission results. In a few cases with nominal Au thickness of 200Å, the junction characteristics have improved over contacts made directly to the BSCCO surface. The main improvement is the appearance of a low, flat conductance near zero bias. We have also observed a few high quality junctions on all-thin-film BSCCO/Au bilayers, but the gap features are quite small and may be due to a 2201 impurity phase. It thus appears that a proximity effect approach may lead to better quasiparticle junctions as is the case with all Nb-based mixers, where Al proximity layers are used. Au is likely to be incompatible with HTS thin film processing so that junctions of the form SNIS would be very difficult to fabricate. However, proximity effect SIN junctions could be made of the form SNIN' where N' is a convenient metallic electrode. An advantage of SIN junctions is the absence of Josephson noise. A suitable barrier layer would need to be deposited on the Au surface. A future approach might be to incorporate the proximity effect method with Hg-1201 films.

4. ACKNOWLEDGEMENTS

We acknowledge the assistance at Argonne of Qiang Huang and Paola Romano for tunneling measurements, John Wagner for bulk sample preparation , R. T. Kampwirth and C. Romeo for thin film bilayers; also, M. Romalis, IIT for data analysis. This work is partially supported by the U.S. Department of Energy, Division of Basic Energy Sciences-Materials Sciences (KEG), under contract No. W-31-109-ENG-38 and the National Science Foundation, Office of Science and Technology Centers (JZ, JC and QH), under contract No. DMR 91-20000.

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