Device-Quality Tunnel Junctions on the High Tc Superconductor $HgBa_2CuO_{4+\delta}$*

John Zasadzinski

Science and Technology Center for Superconductivity
and
Physics Department
Illinois Institute of Technology, Chicago, Illinois 60616

Jun Chen, P. Romano,‡ K.E. Gray, J.L. Wagner, and D.G. Hinks

Materials Science Division
Argonne National Laboratory, Argonne, Illinois 60439

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‡Present address: Universita' di Salerno, Salerno, Italy.

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ABSTRACT

SIN and SIS tunnel junction devices (e.g. photon detectors, logic elements) require quasiparticle characteristics that exhibit sharp current onsets at the gap voltage and very low sub-gap conductances. Progress is reported on the development of such junctions on High T_c cuprates using mechanical point contacts. In general, these contacts display the optimum characteristics that can be obtained from HTS native-surface tunnel barriers. Most cuprates display a sub-gap conductance which monotonically increases with voltage about the minimum value at zero bias.. However, tunneling data of unusually high quality have been obtained for the recently discovered Hg-based cuprate, $HgBa_2CuO_4$ (T_c=96K). SIS' tunneling data using a Nb tip are presented which exhibit very low and flat sub-gap conductances and sharp conductance peaks as expected from a BCS density of states. These results are slightly improved over earlier published results with SIN junctions. Use of the experimental data to simulate the performance of a quasiparticle mixer demonstrates that noise temperatures approaching the quantum limit are possible for SIS and SIN mixers in the range 1-5 THz.

† Present Address: Universita' di Salerno, Salerno, Italy

I. Introduction

The non-linear current-voltage (I-V) characteristics in superconducting-insulator-superconducting (SIS) and superconductor-insulator-normal metal (SIN) quasiparticle tunnel junctions can be used for a variety of device applications. [1] One particular application that seems suited to high Tc superconductors (HTS) is that of a quasiparticle mixer for sensitive photon detection in frequency range of 1-5 THz. It is demonstrated here that the recently discovered cuprate, $HgBa_2CuO_4$ (Tc=95 K) is a very promising material for such a device. The performance of SIS quasiparticle mixers employing conventional, low-T_c superconductors has surpassed that of other techniques for heterodyne detection over a broad range of the mm and sub-mm electromagnetic spectrum. [2-4] Most SIS junctions are Nb based with an upper limit frequency (for mixer gain) given by $2\Delta/h$=700 GHz and are operated at or below 4.2 K. [5,6] Recent attempts to operate such junctions as high as 840 GHz have met with some success. [7] 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 = 80 K-120 K and with energy gaps 2Δ= 30 meV-60 meV offer the possiblity of meeting these requirements, at least in principle.

For most superconducting devices, including mixers, SIS junctions must exhibit quasiparticle (single-electron) characteristics of 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 high-quality junctions with a normal metal counterelectrode (SIN). SIN junctions eliminate unwanted Josephson effects as well in devices which utilize only the quasiparticle currents. Despite a world-wide effort over the past seven years, device-quality SIS or SIN thin film junctions have not been obtained using HTS cuprates. Consequently, there has been little discussion in the literature about HTS quasiparticle junctions as mixers and instead, other devices such as microbolometers have been proposed for THz detection.[8] 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. [9] The ubiquitous, non-ideal features of cuprate junctions has led to speculation that they arise from a novel pairing state such as d-wave. [10]

We report here progress made in the development of SIN and SIS junctions on cuprate and superconductors using a mechanical, point-contact tunneling approach. The term "point contact" is somewhat of a misnomer in that the contact area can be large compared to atomic dimensions. Barrier height analysis of such junctions on Nb using a Au tip indicated a contact diameter of ~2400 Å. [11] 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. The PCT method has generally provided the best quasiparticle junction characterisitics of most HTS materials. [9] For example, ideal, BCS quasiparticle characteristics were first discovered on $Ba_{1-x}K_xBiO_3$ (BKBO) using PCT. [12] Eight different HTS compounds have been examined by this technique but here we focus on the recently discovered, Hg-based compound $HgBa_2CuO_4$ (Hg-1201).

2. EXPERIMENTAL RESULTS

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 [9] and the results are highly reproducible. In Fig. 1 we compare the SIS characteristics of BSCCO (Tc=96 K) and $Nd_{1.85}Ce_{0.15}CuO_4$ (NCCO) (Tc=22 K), [9] along with a BKBO/Nb SIS' junction, [12] 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 different 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 $V\sim3\Delta/e$ for both cuprates and in the case of BSCCO this feature is similar to that found in photoemission experiments. [10] The sharp dip found in the BKBO/Nb junction is a common proximity effect found on air exposed Nb surfaces. [12]

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 recently discovered Hg-based cuprate $HgBa_2CuO_4$ (Hg-1201)by PCT. The samples are polycrystalline with an inductive Tc~95 K. Synthesis methods have been described elsewhere. [13] 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. The data can be fit using a modified BCS density of states [14] which includes a quasiparticle damping term, Γ, so that

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

Note that when Γ=0, eq. 1 reduces to the BCS expression. For the SIN junctions on Hg 1201 the ratio Γ/Δ is ~6-8% making this the lowest value of all cuprates. [13] 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. 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.

Even more striking results are obtained in SIS' junctions using a superconducting Nb tip. Fig. 3 shows the tunneling conductances of three point contact junctions obtained at different locations of a Hg 1201 polycrystalline sample. In each case, a well-defined energy gap is observed and the tunneling data exhibit a low and flat sub-gap conductance. The magnitude of the gap (corresponding to $\Delta_{Nb}+ \Delta_{Hg}$) varies from approximately 12 meV for the lowest conductance junction to 25 meV for the highest conductance junction. One possible explanation for the different gaps is that the higher conductance junction was obtained after the tip scraped the surface, leading to a thinner tunnel barrier and allowing a region of the sample to be probed that had not been exposed to laboratory air. Other possible explanations include surface inhomogeneity (although bulk homogeneity is excellent) or gap anisotropy. The latter explanation relies on the tunneling tip to probe a specific location in k-space, a situation that in not easy to imagine on these polycrystalline samples with rough surfaces.

The junction with the largest gap in Fig. 3 has been normalized and fit in Fig. 4 using eq. 1 and the expression,

$$I(V) = \int N_1(E)N_2(E-eV)[f(E)-f(E-eV)]dE \qquad (2)$$

where $N_1(E)$ and $N_2(E)$ are the densities of states for the two electrodes and f(E) is the Fermi function which accounts for temperature effects. The Nb gap is assumed to be the bulk value, $\Delta = 1.5$ meV and a small value of $\Gamma = 0.01\Delta$ is assumed to account for weak quasiparticle damping that occurs at finite temperatures in conventional, strong-coupled superconductors. [14] The fit parameters for the Hg 1201 are $\Delta = 24$ meV ($2\Delta/kTc = 5.86$) and $\Gamma/\Delta = 7\%$, the latter value being consistent with the SIN data. Fig. 4 shows that there is good agreement between the fit and the data, especially in the magnitudes of the conductance peaks and the sub-gap conductance values.

Another SIS' junction, obtained with a different Hg 1201 sample, is shown in Fig. 5. The normalized conductance is noteworthy for the height of the conductance peaks which are the largest values ever observed for any cuprate tunnel junction. The fit parameters for the Hg 1201 are $\Delta = 16$ meV and $\Gamma = 0.8$ meV. The value of Γ is comparable to thermal smearing ($kT = 0.36$ meV) and the ratio $\Gamma/\Delta = 5\%$, the lowest value observed to date. These data strongly suggest that Hg 1201 has a fully gapped Fermi surface, exhibiting a nearly BCS density of states. There seems to be no evidence for the lines of nodes associated with a d-wave pairing state, which would show up as a linearly increasing conductance about zero bias. [10] Rather, a low and flat conductance is found.

The large conductance peaks of Fig. 5 correspond to a sharp current onset in the I-V characteristics at the sum gap voltage. Such characteristics are exactly what is needed for quantum mixing [3] and the large gap voltages of these junctions (typically 16-24 mV) are ideal for exploring the THz frequency regime. With this in mind, we used the experimentally obtained I-V characteristics for both SIN and SIS' junctions along with the Tucker theory [3] to simulate the performance of a heterodyne detector operating at THz frequencies. The details of this modelling study are reported elsewhere in this conference proceedings. [15] The principal results are that noise temperatures approaching the quantum limit ($h\nu/k_B$) are found for the SIN mixer at 4.2 K in the range 1-5 THz. This is important for device development because thin film, trilayer SIN junctions should be much easier to fabricate than all-high-Tc SIS junctions. The modelling study also shows that if SIS junctions could be obtained with Hg 1201 for both electrodes, then the mixer would exhibit quantum limited noise performance in the same frequency range when operated at 12 K, a temperature easily accessible with closed cycle refrigeration.

In summary, SIN and SIS' tunnel junctions of device quality have been obtained on Hg 1201 polycrystalline samples using a mechanical, point contact approach. These results are in stark contrast to the best quasiparticle tunneling data found on the other HTS cuprates, which typically display significant sub-gap conductance. Modelling studies which incorporate the experimental data indicate that Hg 1201 is an ideal candidate material for development of a low noise, heterodyne photon detector operating at a few THz.

Acknowledgements

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Figure Captions

Figure 1. Comparison of SIS tunneling conductances at 4.2 K for 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. SIS' tunneling conductances (dots) for three junctions obtained obtained at different locations on the same polycrystalline Hg 1201 sample. The counterelectrode is a superconducting Nb tip. Solid lines are smooth curves through the data.

Figure 4. Normalized SIS' tunneling conductance (dots) for the junction in Fig. 3 with the largest gap. The fit (solid line) uses the formula for SIS' conductance (eq. 2) along with the smeared BCS density of states (eq. 1). The Δ and Γ parameters for the Hg 1201 are shown in the figure.

Figure 5. Normalized SIS' tunneling conductance (dots) obtained on a different Hg 1201 sample from that of Figs. 3 and 4, again using a Nb tip. The fit (solid line) uses the formula for SIS' conductance (eq. 2) along with the smeared BCS density of states (eq. 1). The fit parameters for this Hg 1201 junction are Δ=16 meV and Γ/Δ=0.05, the latter value being the lowest observed to date.

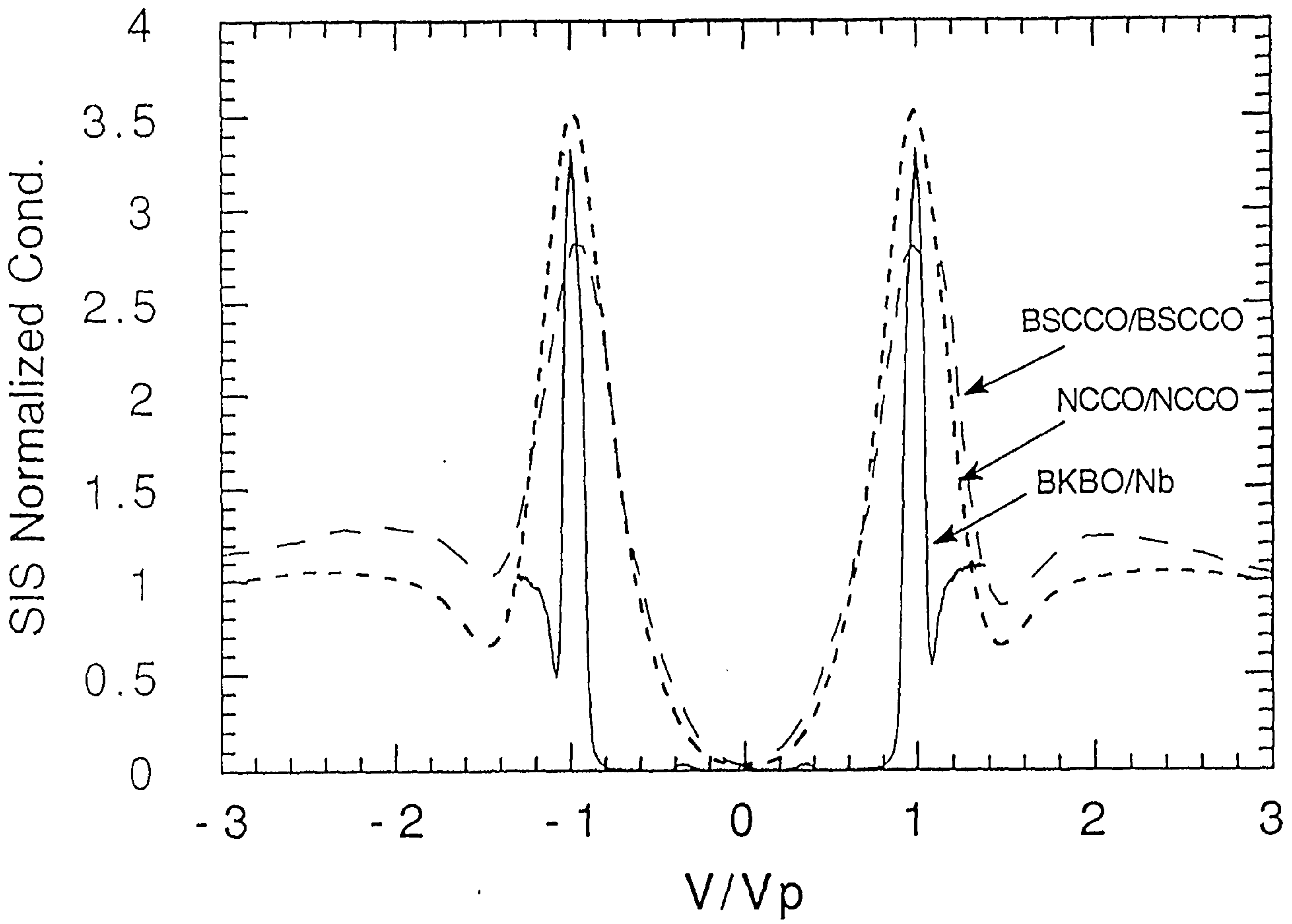
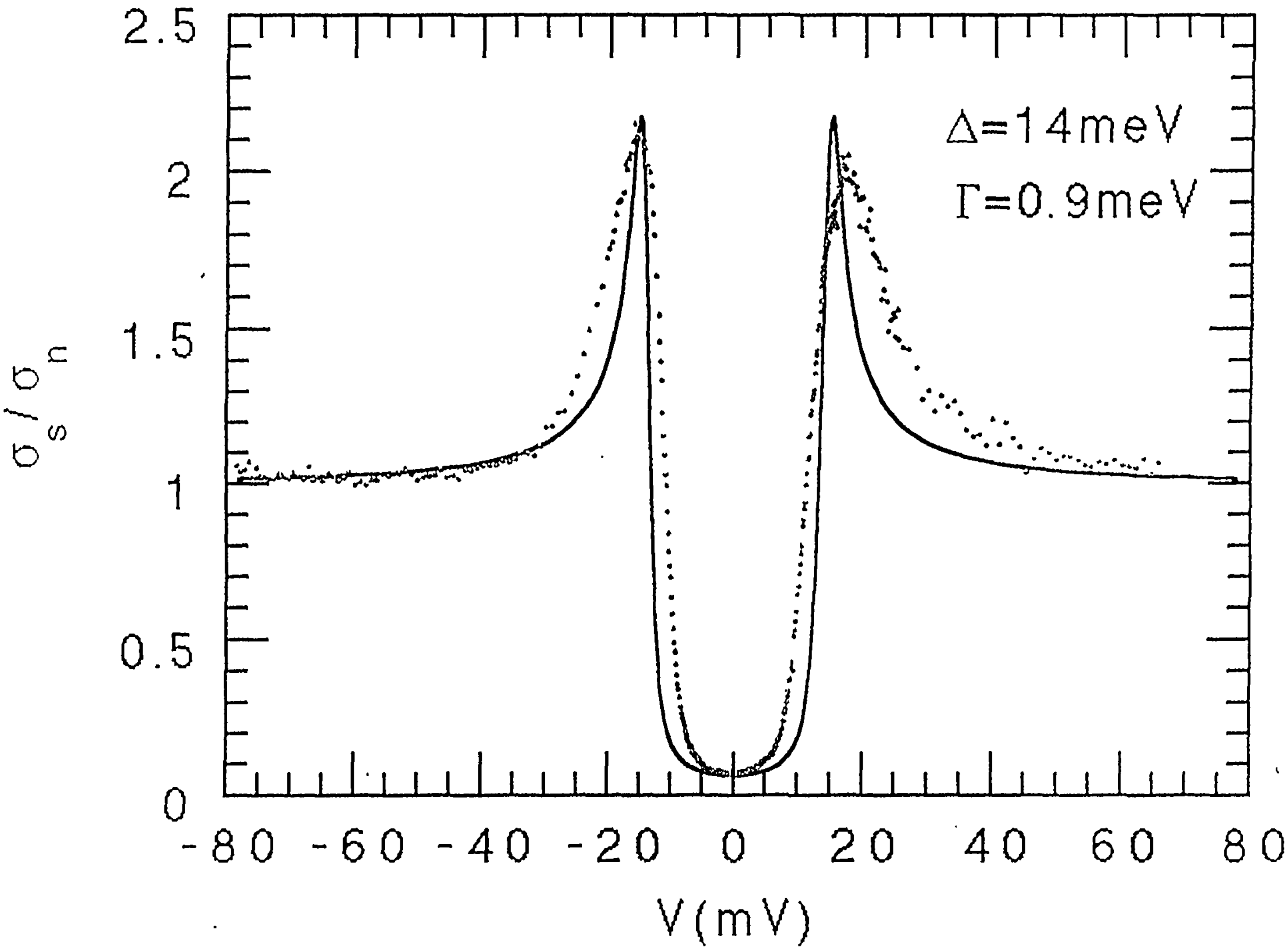
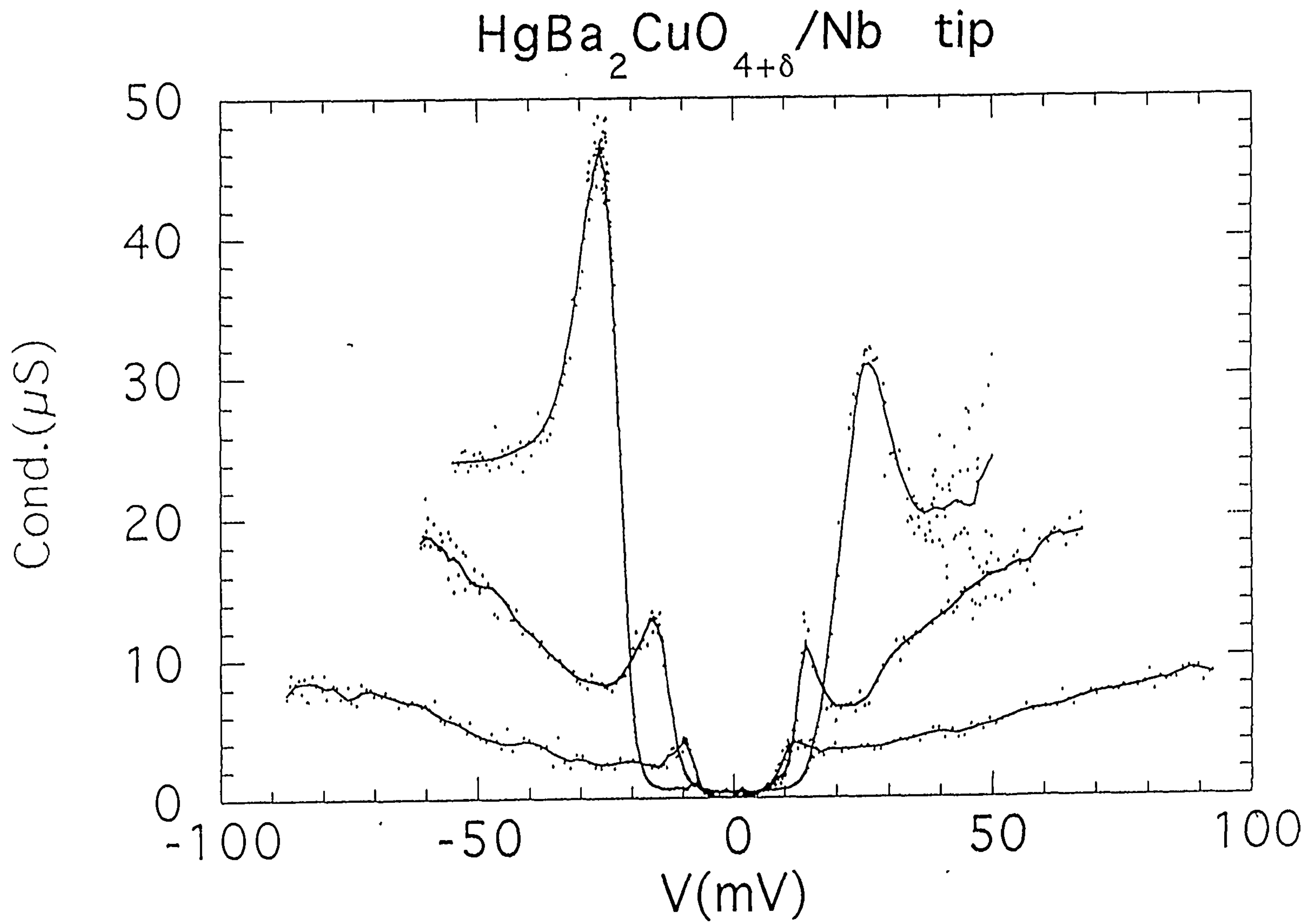
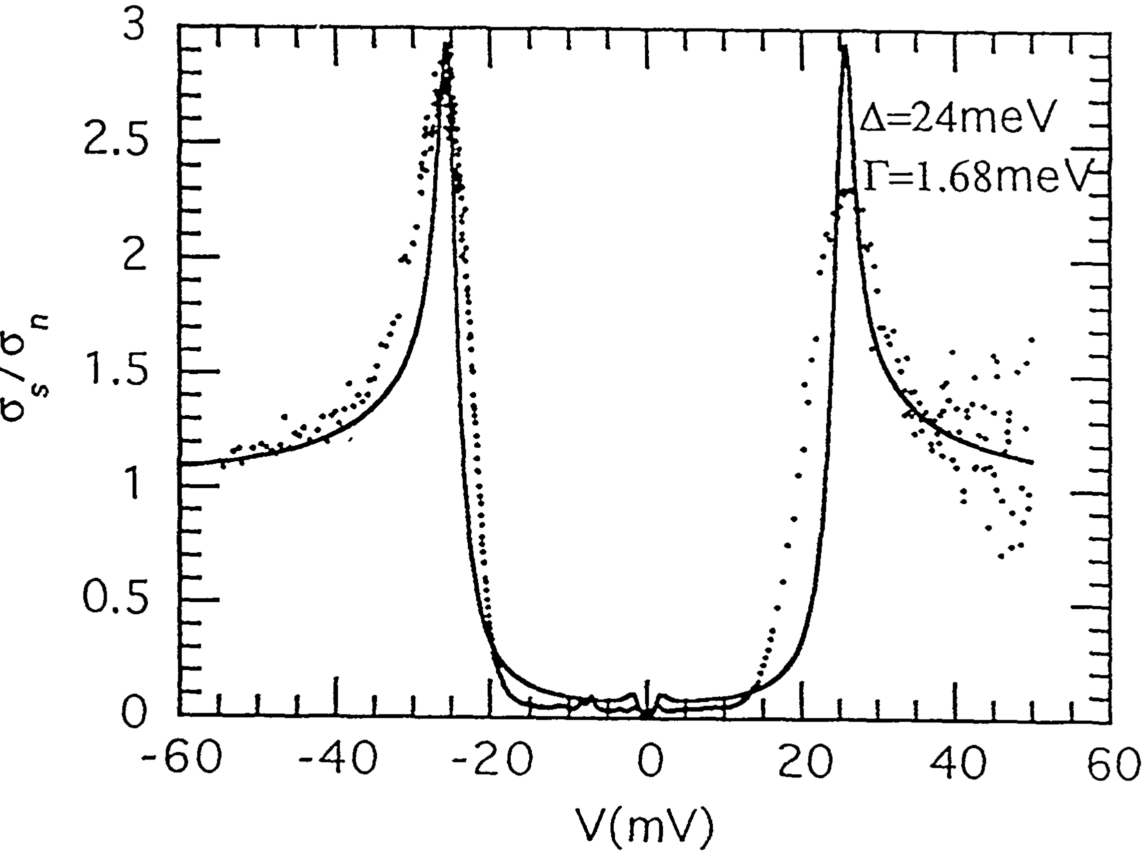

SIS Normalized Cond.
0
0.5
1
1.5
2
2.5
3
3.5
4
-3
-2
-1
0
1
2
3
V/Vp
BSCCO/BSCCO
NCCO/NCCO
BKBO/Nb

Fig 1



F. 2


HgBa$_2$CuO$_{4+\delta}$/Nb tip
Cond.(μS)
50
40
30
20
10
0
-100
-50
0
50
100
V(mV)



Δ=24meV
Γ=1.68meV
σ_s/σ_n
V(mV)

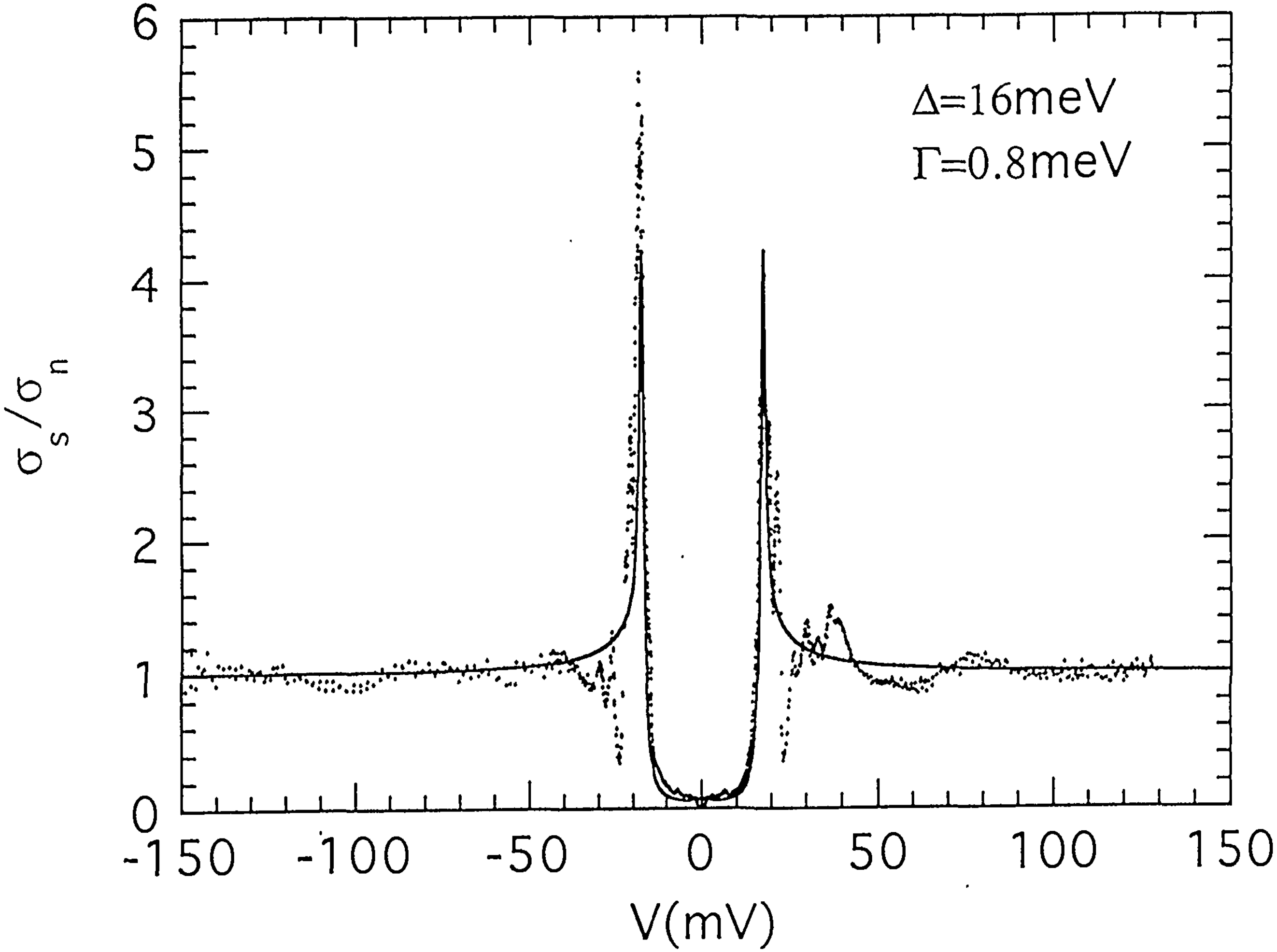


Fig. 5