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BCS-like Gap Structure of $HgBa_2CuO_{4+\delta}$ Tunnel Junctions*

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***Abstract*—We report point-contact tunneling into polycrystalline $HgBa_2CuO_{4+\delta}$ superconductors with a T_c onset of 97 K using a superconducting Nb counterelectrode. These SIS' tunnel junctions are of unusually high quality for cuprate superconductors, exhibiting low and flat sub-gap conductances and sharp conductance peaks as expected from a BCS density of states. These features are obtained reproducibly and are consistent with earlier published SIN results using a Au counterelectrode. Use of experimental data to simulate the performance of a quasiparticle mixer indicates that $HgBa_2CuO_{4+\delta}$ may be suitable for use in low noise heterodyne receivers operating at a few *THz*.**

I. INTRODUCTION

Low sub-gap conductance and sharp gap-edge structure are required for superconductor-insulator-superconductor (SIS) and superconductor-insulator-nomal metal (SIN) tunnel junction devices such as mixers [1]. Such tunneling characteristics result from the BCS quasiparticle density of states found in conventional superconductors. The tunneling characteristics of high T_c cuprates have in general been non-ideal [2], displaying strong sub-gap conductances which monotonically increase about the minimum value at zero-bias. In general, mechanical point-contact junctions display the optimum characteristics that can be obtained on high-temperature superconductors (HTS) with a native surface tunnel barrier [3]. In this paper, we report point-contact tunneling into two polycrystalline $HgBa_2CuO_{4+\delta}$ (Hg-1201) samples with a T_c onset of 97 K using a superconducting Nb counterelectrode. These SIS' tunneling junctions exhibit the low, flat sub-gap conductances and sharp conductance peaks as expected from a BCS density of states. These features are obtained reproducibly and are consistent with earlier published results with SIN junctions [4].

The data were fit by introducing a small smearing parameter Γ into the BCS expression. The ratio Γ/Δ was typically 5% - 7%, making this the lowest reproducible value found on any HTS cuprate. Typical gap parameter values were Δ = 13-16 meV but one junction had Δ = 24 meV. Experimental data along with the Tucker theory [5] of quantum mixing were used to simulate the performance of a heterodyne photon detector [6]. It is demonstrated that noise temperature approaching the quantum limit are possible for SIS and SIN quasiparticle mixers in the range of 1-4 THz. Thus Hg-1201 may be suitable for use in low noise heterodyne receivers operating at a few THz.

II. EXPERIMENT

Samples of Hg-1201 were synthesized from stoichiometric mixtures of HgO and Ba_2CuO_3, as described elsewhere [7], and then annealed at 300 °C in oxygen. X-ray diffraction studies confirmed all samples to be single phase without any detectable impurities. ac susceptibility was measured in a 1 G, 100 Hz field using a Lake Shore Cryotronic susceptometer. Susceptibility of a bulk sample exhibits a sharp transition with an onset T_c of 97 K and a full shielding fraction, consistent with the isolated grains of the polycrystalline material being uniform and fully superconducting.

All low-temperature measurements were done with the apparatus cooled by exchange gas to liquid ^{4}He. We waited about 5 h after transferring liquid ^{4}He for thermal stability so that stable junctions could be maintained. Raising the temperature above 4.2 K with a heater was possible, but resulted in much poorer stability of the tunneling contact. An insulating surface prevented vacuum tunneling and the blunt Nb tip was used mechanically to cleave and/or scrape the HTS surfaces at low temperature, leaving a thin, native-barrier for elastic tunneling [8]. The resistance of the resulting junctions could be varied by adjusting the force of the tip on the sample. The current-voltage characteristic I (V) was monitored while the tip was maneuvered to obtain an acceptable junction. First derivative data dI/dV were obtained using a Kelvin bridge with the usual lock-in techniques.

III. RESULTS AND DISCUSSION

Typical experimental conductances (σ_s = dI/dV) obtained on two Hg-1201 samples are shown in Figs. 1(a)-1(c). For all such stable junctions, the high voltage (background) conductance usually increases with voltage and can be

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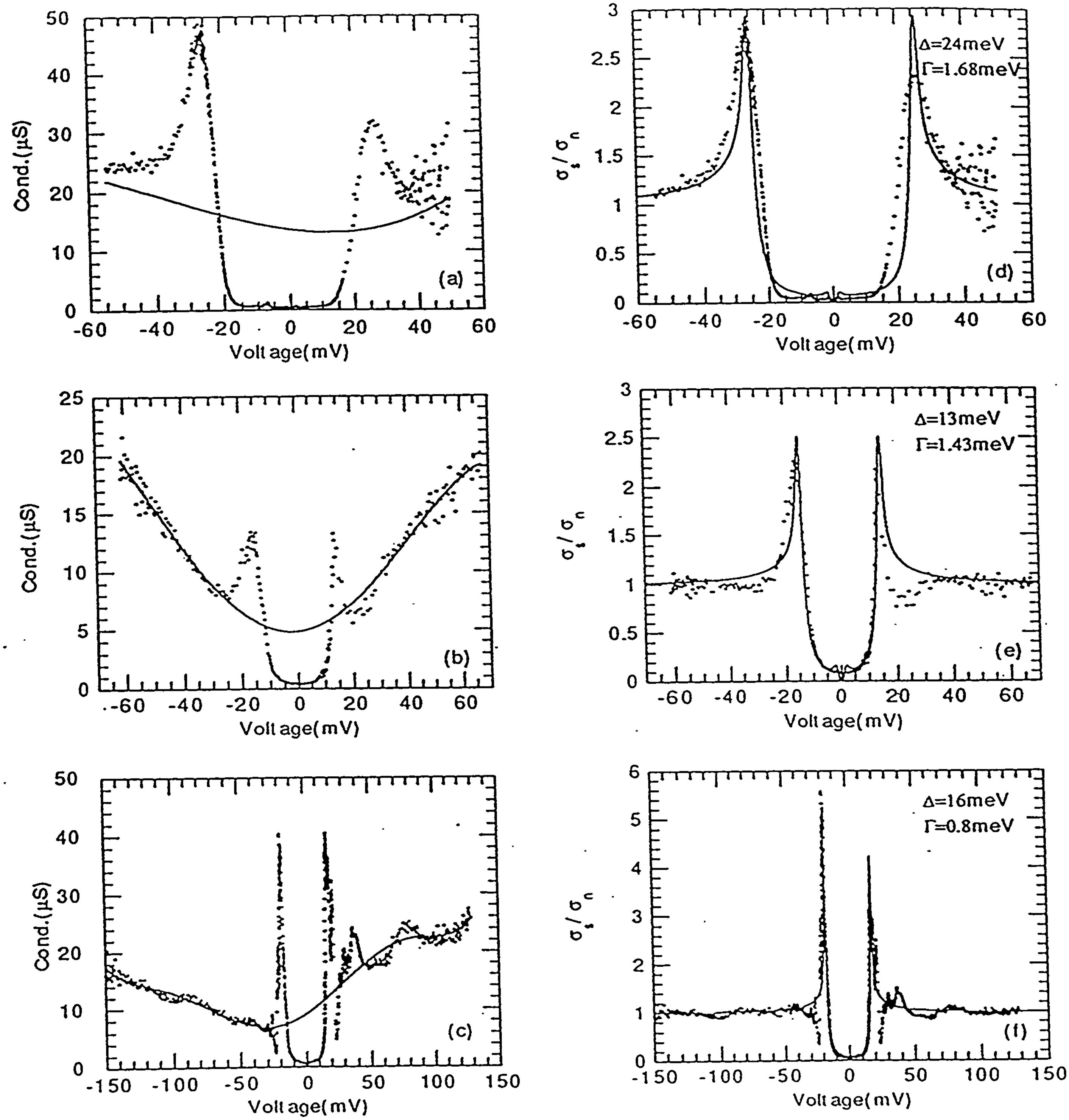

Fig. 1. (a)-(c): Experimental conductances (dots) with the fitted normal state conductances (solid lines) for junctions No.1, No.2 of sample A and junction No.1 of sample B, respectively. (d)-(f): The dots are the corresponding normalized conductances, while the solid lines are the smeared BCS fits including thermal smearing. All tunneling curves here were measured at T = 4.2 K.

attributed to ordinary tunnel barrier transmission [9]. Compared to point-contact tunneling in HTS single crystals [2], the Hg-1201 data exhibit larger noise levels at above-gap voltages. This may be due to the weakly coupled grains [10] of the polycrystalline samples which would have microshorts or Josephson contacts with low critical currents. Here in all plots, positive voltage means that the Nb tip is at a positive voltage relative to the Hg-1201 sample.

In order to proceed, the conductances need to be normalized (i.e., divided by the normal-state value, σ_n). Direct measurements of σ_n can be made at $T > T_c$, but for HTS this is difficult due to the different thermal expansions in the tip assembly materials. However, σ_s is expected to approximate σ_n at high voltages, so we use the high-voltage data to generate a 4th-order polynomial as an estimate of σ_n [solid lines in Figs. 1(a)-1(c)]. The smooth curve of σ_n ensures that no additional structure is introduced by this procedure.

When σ_s is normalized by σ_n, estimated in this way, we arrive at the normalized conductances [dots in Figs. 1(d)-1(f)], which can be compared to theory. Usually, HTS tunneling results are compared to the smeared BCS density of states, first proposed by Dynes *et al.* [11] in which

$$N_s(E) = \mathrm{Re}\{(E-i\Gamma)/[(E-i\Gamma)^2-\Delta^2]^{1/2}\}, \quad (1)$$

where Γ is a smearing parameter to account for lifetime effects, such as inelastic scattering. It should be emphasized that the choice of (1) to account for broadening is mainly one of convenience and while the value of Γ may not have any intrinsic, physical meaning for HTS, it nevertheless is a useful way to compare junctions. The normalized conductance is then given by [9]

$$\sigma_s/\sigma_n = \frac{d}{dV}\int_{-\infty}^{\infty} N_1(E)N_2(E+eV)[f(E)-f(E+eV)]\,dE, \quad (2)$$

where $N_1(E)$ and $N_2(E)$ are the quasiparticle density of states for the two electrodes and $f(E)$ is the Fermi function which accounts for thermal smearing. The Nb gap is assumed to be the bulk value, $\Delta = 1.5$ meV and a small value of $\Gamma/\Delta = 1\%$ is assumed to account for weak quasiparticle damping that occurs at finite temperatures in conventional, strong-coupled superconductors [11]. The fits using (2), shown as solid lines in Figs. 1(d)-1(f), provide values of Δ and Γ for Hg-1201. All tunneling curves here were measured at $T \sim 4.2$ K. There is good agreement with the weakly-smeared BCS model, especially in the magnitude of the conductance peaks and the sub-gap conductance values. Sub-gap conductances in Figs. 1(d) and 1(f) are very low and flat, resulting in ratios Γ/Δ = 5%-7%, the lowest reproducible values found on any cuprate. The small absolute values of Γ (0.8-1.7 meV) means that thermal smearing ($k_BT = 0.36$ meV) cannot be ignored in the analysis. In previous tunneling studies [2] on other cuprate HTS with SIN junctions, the normalized conductance was fit to (1) directly because Γ was much larger than k_BT.

The non-zero Γ values and the large gap voltages (13-24 meV) of Hg-1201 compared to the Nb energy gap result in a missing gap difference ($\Delta_2 - \Delta_1$) feature. Our fitting of the data indicated that the difference feature lies on the sharply rising part of the conductance and can be easily washed out by smearing of any kind. The junction shown in Fig. 1(f) is particularly noteworthy as it displays the highest conductance peaks ever observed for a HTS. It is fit with $\Delta = 16$ meV and $\Gamma = 0.8$ meV. The ratio $\Gamma/\Delta = 5\%$ is slightly improved over values obtained from SIN data [4] on Hg-1201. The dip in conductance just above the peak [see Fig. 1(f)] is evidence of a proximity effect, as is often found [8] in junctions using natural oxides of Nb.

Typical energy gaps were Δ = 13-16 meV, in excellent agreement with previous SIN results [4], but one junction had $\Delta = 24$ meV. The origin of the spread in Δ is unknown, but this could be an indication that there is a variation in T_c along the surface of the sample which possibly results from variations in oxygen content of $HgBa_2CuO_{4+\delta}$. Scanning electron microscopy showed that grain sizes of Hg-1201 surface can be as large as ~ 20 μm, while the radius of the Nb tip is below 1 μm. Thus it is quite possible that we are probing local properties of individual grains with different δ values and hence different T_c.

A final point to be made is that the fit curves of Figs. 1(d)-1(f) display a weak feature near the Nb gap which arises from the finite density of states at $E = 0$ in (1) when $\Gamma > 0$. The fact that the experimental data display a much weaker Nb gap structure (if any) and lower conductance values suggests that (1) may not be the correct way to account for the weak broadening observed in the tunneling data. The sub-gap conductance indicates that Γ is closer to zero, whereas the conductance peaks are broader than the fit. These two facts suggest that the true origin of broadening may be that a small distribution of gap values is being probed. We have not pursued this approach for data analysis as it would not change the basic conclusion which is that the tunneling data are BCS-like.

The low sub-gap conductances and sharp conductance peaks indicate that Hg-1201 has potential as a sensitive photon detector. The large energy gaps are ideal for exploring the THz frequency regime. It should also be noted that since $k_BT << \Delta$ even at 12 K, thermal smearing of junction characteristics is small and operating at a temperature accessible with close-cycle refrigeration can be expected. To test these ideas, experimental data along with the Tucker theory [5] of quantum mixing were used [6] to simulate the performance of a heterodyne receiver based on Hg-1201. We have combined the fully general, three-port Tucker model, both single and double side band regimes (SSB and DSB) with a numerical optimization routine to predict the gain and noise of the HTS mixer. At a given mixer operating temperature (T_{OP}), our model allows us to find the values of source, image and load impedances, bias voltage, operating frequency (f) and local oscillator voltage (V_{LO}) that either maximize the conversion efficiency (1/L) or minimize the mixer noise temperature (T_M). Details of the modelling study are given in [6]. The results summarized in Table I are for minimum SSB values of T_M. In the case of T_{OP} = 4.2 K, experimentally determined values Δ = 20 meV and Γ = 0.07 Δ were used. At higher temperatures (T_{OP} > 4.2 K), Δ and Γ values were appropriately adjusted [6]. It is demonstrated that mixer noise temperatures approaching the quantum limit are possible for SIS and SIN quasiparticle mixers in the range of 1-4 THz.

TABLE I

MODELING OF HG-1201 BASED QUASIPARTICLE MIXERS

Junction Type	T_{OP} (K)	f (THz)	T_M (K)	1/L	V_{LO}/Δ
SIN	4.2	0.81	62	0.29	2
	12	0.96	90	0.24	2
	12	1.02	67	0.29	8
	30	1.28	604	0.07	9
SIS	12	1.83	99	0.29	2
	12	4.00	95	0.09	2
	30	2.20	397	0.10	4

In summary, the SIS' tunneling data of Hg-1201 showed the lowest and flattest sub-gap conductances and highest conductance peaks of all cuprates. Energy gap parameters are determined and consistent with earlier published SIN data. Modeling studies [6] indicate that mixer noise temperatures approaching the quantum limit are possible for SIS and SIN quasiparticle mixers based on Hg-1201 in the THz regime.

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