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TUNNELING SPECTRA AND SUPERCONDUCTING GAP IN $Bi_2Sr_2CaCu_2O_{8+\delta}$ AND $Tl_2Ba_2CuO_{6+\delta}$

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Tunneling spectra are reported for $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) over a wide doping range using superconductor-insulator-superconductor (SIS) break junctions. The energy gap inferred from the tunneling data displays a remarkable monotonic dependence on doping, increasing to very large values in the underdoped region even as T_c decreases. This leads to unphysically large values of the strong coupling ratio (~20). The tunneling spectra are qualitatively similar over the entire doping range even though the gap parameter, Δ, changes from 12 meV to 60 meV. Each spectrum exhibits dip and hump features at high bias with characteristic energies that scale with the superconducting gap. Tunneling spectra of near optimally-doped $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201) also display a weak dip feature in superconductor-insulator-normal metal (SIN) junctions. Generated SIS spectra of Tl-2201 are compared with measured spectra on Bi-2212 and it is concluded that the dip and hump features are generic to high temperature superconductors.

High temperature superconductors (HTSs) exhibit a complex temperature versus hole doping phase diagram which contains novel physics.[1] Furthermore, the phase diagram is generic for all HTSs and is very similar to that found for organic superconductors.[2] This might be an indication that electronic features, such as the pseudogap in the underdoped phase of cuprates, are universal to layered, correlated systems. In this paper we present measurements of the tunneling density of states (DOS) and are particularly focused on high energy features, dip and hump, in the single particle excitation spectrum. $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) is the most studied HTS by surface sensitive probes, because of the clean surfaces which arise after cleaving and the availability of crystals over a wide doping range. Tunneling spectroscopy is one of the direct methods that measures the DOS and energy gap in superconductors. Superconductor-Insulator-Normal metal (SIN) tunneling measurements on optimally-doped Bi-2212 have revealed sharp quasiparticle peaks at $|eV| \sim \Delta$, followed by a dip around 2Δ and a broad hump at higher energies most clearly seen on the occupied side of the DOS.[3,4] Tunneling data on single crystals of $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201) have also exhibited sharp quasiparticle peaks, but a relatively weak dip feature that is sometimes difficult to see at all in the

SIN spectra.[5] The precise determination of the energy gap can be more directly obtained from Superconductor-Insulator-Superconductor (SIS) junctions. Since the resulting tunneling spectrum is the convolution of two superconducting DOS, the quasiparticle peaks exactly occur at $\pm 2\Delta$. Furthermore any fine structure in SIN tunneling spectra is enhanced in the SIS geometry along with a shift in energy by the gap value.

Tunneling measurements are conducted using *Au* tip in a mechanical, electrical and magnetic noise isolated environment.[6] In this study, SIS break junctions of Bi-2212 are obtained by a novel technique that is described elsewhere.[3] SIS break junctions in single crystals of Bi-2212 displayed both quasiparticle and Josephson current simultaneously. However, the techique is not successful for Tl-2201 because of strong bonding between planes. Neverthless, SIS tunneling spectra of Tl-2201 can be generated from a convolution of the SIN tunneling data for a comparison to Bi-2212.

Figure 1(a) shows the doping dependence of Bi-2212 SIS break junction tunneling spectra at 4.2 K. In the figure, each spectrum corresponds to different crystals with different hole concentrations, p, from heavily overdoped T_c=56 K, optimally-doped T_c=95 K, to underdoped T_c=70 K. Each spectrum is normalized by a constant, shifted vertically and Josephson current peak at zero bias deleted for clarity. We note first that the energy gap increases with decreasing doping, even as T_c drops from the optimally-doped value 95 K down to 70 K underdoped. There is thus a clear indication that Δ does not follow T_c. This raises a question of whether the measured gap is fully due to superconductivity or has a contribution from some other effects such as spin density wave or charge density wave.[7] Josephson tunneling addresses this issue, because multiplication of the Josephson current, I_c, and junction resistance, R_n, is expected to be proportional to the superconducting gap. The relation between I_cR_n and Δ has shown that the measured gap is predominantly due to superconductivity.[8] This is also indicated by the consistent shape of the spectra of Fig. 1(a) over the entire doping range. For all doping levels, the dip and hump features are well pronounced and scale with the energy gap. The dip energy, ω_{dip}, is $\sim 3\Delta$ for optimally-doped (consequently 2Δ in the DOS) and underdoped Bi-2212, and approaches 4Δ for heavily overdoped crystals in SIS junctions. There is also a general weakening of the dip strength as doping increases. Angle resolved photoemission spectroscopy also probes single particle excitations, and exhibits spectra around (π,0) direction[9] with similar anomalous dip and hump that is found in tunneling.

Figure 1(b) shows how the measured gap parameter varies with doping in Bi-2212. The solid curve is the mean-field gap prediction for $d_{x^2-y^2}$ superconductors, $2.14kT_c$. The dots are average energy gaps obtained on many different junctions and the hole concentrations are estimated from $T_c/T_{c,max}=1\text{-}82.6(p\text{-}0.16)^2$. The most underdoped sample with T_c=70 K exhibits an energy gap magnitude of nearly 60 meV which leads to a strong-coupling ratio, $2\Delta/kT_c \sim 20$. For the other extreme, a heavily overdoped sample with T_c=56 K, Δ is around 12-15 meV, and this leads

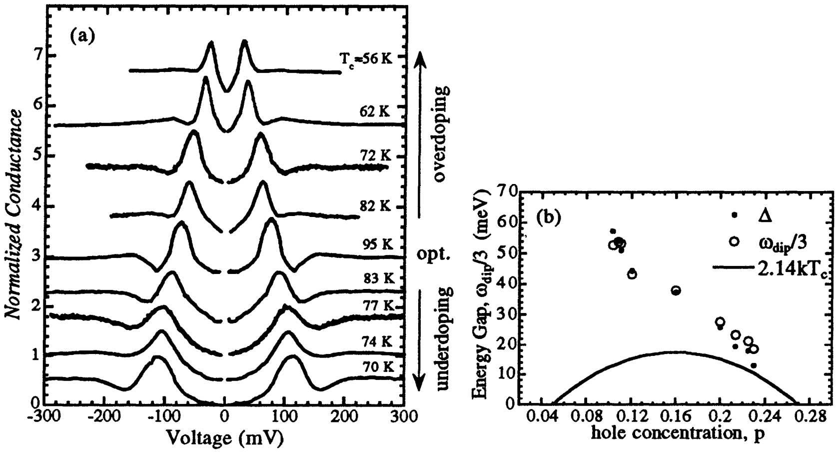

Fig. 1. (a) Doping dependence of SIS break junction tunneling spectra in Bi-2212. (b) Energy gap and $\omega_{dip}/3$ versus hole concentration from SIS break junctions.

to $2\Delta/kT_c{\sim}5$. Note that the magnitude of energy gap approaches the mean field prediction only at the heavily overdoped compounds. To demonstrate the scaling of the dip feature with the energy gap, we also plot $\omega_{dip}/3$, for the SIS junctions. As is seen, ω_{dip} strongly depends on p and scales with Δ, furthermore indicating that the phenomenon responsible for the dip in heavily overdoped phase is the same as in the underdoped phase, and is tied to the superconductivity.

The universal phase diagram of HTSs suggests that the robust dip feature in SIS tunneling spectra of Bi-2212 might be seen in other cuprates as well. Tl-2201 junctions have exhibited the most reproducible tunneling data that are consistent with a $d_{x^2-y^2}$ order parameter.^{5} Since the energy gap magnitude of overdoped Bi-2212 with T_c=62 K is compatible with optimally-doped Tl-2212, we compare them in Fig. 2. We show a set of overdoped Bi-2212 break junctions in Fig. 2(a) which exhibit energy gaps between 15-20 meV. The SIS spectra also display relativily weak dip and hump feature respect to optimally-doped and underdoped Bi-2212 and this is another basis for comparison with Tl-2201. The novel technique mentioned earlier has failed to provide SIS break junctions of Tl-2201, however SIN tunneling data have been used to generate SIS data which is shown in Fig. 2(b). The convolution of SIN data in Tl-2201 produces the dip and hump features that are reasonably consistent with those found on overdoped Bi-2212. However, the locations of the dip features are different. In Tl-2201 the dips are closer to 3Δ whereas for the most overdoped Bi-2212, as mentioned earlier, the dips are closer to 4Δ. This suggests that the strength of the dip may be tied to the magnitude of the gap, but that the location is more closely tied to the hole concentration.

SIS tunneling spectra of Bi-2212 over a wide doping range and generated SIS spectra of optimally-doped Tl-2201 display qualitatively similar features, such as sharp quasiparticle peaks, dip and hump structures. This suggests that these higher energy spectral features are intrinsic to the DOS of HTS. In Bi-2212 the dip scales

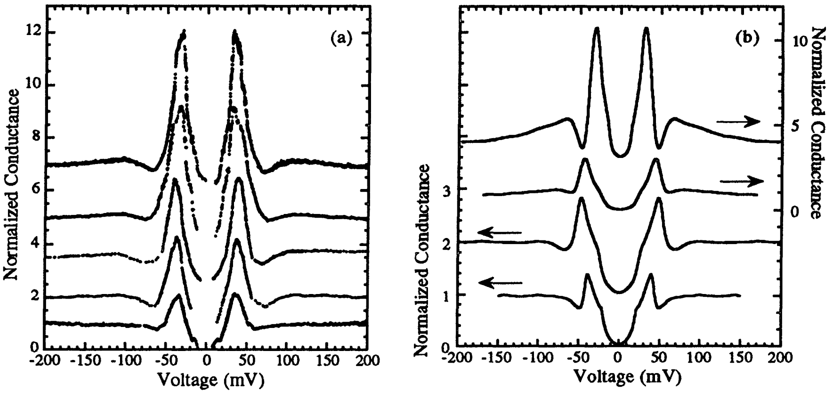

Fig. 2. (a) Tunneling spectra of SIS break junctions in overdoped B-2212 with T_c=62 K. (b) Generated SIS tunneling spectra of optimally-doped Tl-2201 with T_c=86 K.

as approximately 3 times the gap parameter over most of the doping range including the underdoped region. Therefore the difference in energy between the dip and the gap also increases as the doping decreases and this argues against models of the dip that are associated with the collective mode observed in neutron scattering. The doping dependence of the superconducting gap follows that of the pseudogap temperature[10] which suggests that the pseudogap is due to some type of precursor superconductivity.

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