Evidence of a Normal-State Pseudogap in Bulk Superconducting Tunneling Junctions of $YBa_2Cu_3O_{7-\delta}$

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ABSTRACT

Planar contact tunneling experiments have been performed on bulk superconducting tunneling junctions of $YBa_2Cu_3O_{7-\delta}$ in the temperature range 77-295K. A clear depression in the conductance curves measured, attributed to the pseudogap, has been observed in temperatures above Tc (approx. 90K determined from dc resistivity measurements) before disappearing at T*=275K. The width of the pseudogap has been quantitatively measured as Dps, ave = 25.6meV from the differential conductance plots. These results agree with the current understanding of the phenomenology and nature of this pseudogap, namely: (1) the pseudogap value is relatively temperature-independent; (2) the superconducting gap and the pseudogap have the same d-wave nature; and (3) the superconducting gap evolves from the pseudogap.

Keywords: pseudogap, tunneling, $YBa_2Cu_3O_{7-\delta}$

INTRODUCTION

It is now apparent that the electronic properties of high-temperature superconductors are very different from that of conventional superconductors. Various experiments have shown clear differences in the electronic and magnetic properties of both materials. Despite this, a mechanism of superconductivity for these high-temperature cuprates has yet to be arrived at.

Recent measurements on the superconducting energy gap of these materials (Mourachkine, http://xxx.lanl.gov/cond-mat/9903395) may provide the missing clues on the mechanism. Note that the superconducting energy gap defines a range of energy levels that are forbidden to electrons (with all the states below the gap completely filled). In conventional low-temperature (BCS) superconductivity, the presence of this gap signifies the sudden transition at Tc, the superconducting transition temperature. However, underdoped high-temperature superconductors show the onset of a gap far above this transition temperature (Wang, 1999; Chen, 1999; Renner & Fischer, 1995).

It is therefore important to determine if this transition, which begins in the normal state, is connected to the superconducting transition. Understanding this normal-state pseudogap will shed light on the mechanism of high-temperature superconductivity. One central question is the relationship of these properties with those of the superconducting state. The results of experiments studying these relationships may provide the needed hints on which theories of high-temperature superconductivity are correct.

In this paper, we present direct experimental evidence for the existence of this normal-state pseudogap in optimally doped bulk superconducting samples of $YBa_2Cu_3O_{7-\delta}$. Fully de-oxygenated $YBa_2Cu_3O_{7-\delta}$ samples were prepared (with Tc=90K determined through resistivity measurements) from which planar

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contact tunneling experiments have been performed in < 280K. This result agrees with the current understanding of the phenomenology of this pseudogap.

METHODOLOGY

Near single-phase or optimally doped bulk superconducting pellets of $YBa_2Cu_3O_{7-\delta}$ (Y-123) were prepared via the solid state reaction method (Sarmago, 1991). The pellets were cut into 2x20x2mm and 2x10x2mm rods and prepared as a SIS (superconductor -insulator-superconductor) junctions. The junctions were then mounted on an electron tunneling facility for measurement of the characteristic I-V and dI/dV-V curves at different temperatures in the range of 12K-295K. The I-V plots of the prepared junctions have shown the expected nonlinearity observed previously at 77.0K (Guerra et al., 1998). The dI/dV-V plots, on the other hand, show a clear depression at zero bias (attributed to the pseudogap) up to temperatures, Tc < T to room temperature. The details of the procedure for measuring these characteristic curves have been discussed elsewhere (Guerra, 1998). For this investigation, the characteristic dI/dV-V plots of the junctions were obtained at 77K, 90K, 110K, 130K, 150K, 210K, 250K, and 280K during the warm-up of the tunneling facility from 77K to room temperature.

RESULTS AND DISCUSSION

Superconducting electron tunneling was performed on near-single phase bulk superconducting tunneling junctions of Y-123. Fig. 1 (filled and unfilled circles) shows typical differential conductance (dI/dV vs. V) plots obtained for the prepared Y-123 tunneling junctions at 77K and 12K, respectively. The inset shows a typical I-V plot for these junctions obtained at 77K. The conductance plots in this figure has been normalized to the energy scale for comparison with the theoretical calculation at T=0K (Fig. 1 [thin solid line]). Note that both experimental conductance plots clearly define two peaks in their conductance (as predicted by theory). The separation between these two peaks has been shown previously to be equal to the superconducting energy gap of Y-123. Calculating the value of this energy gap yields a value of $2\Delta \approx 25.4$meV. Other important features of this plot are the unequal magnitude of these two peaks and the non-zero conductance at zero bias. The nature and significance of these features has also been discussed in a previous investigation (Guerra, 1998).

Fig. 2 shows the different conductance plots obtained at different temperatures in the temperature range 77K-280K. Each of the plots has been shifted with respect

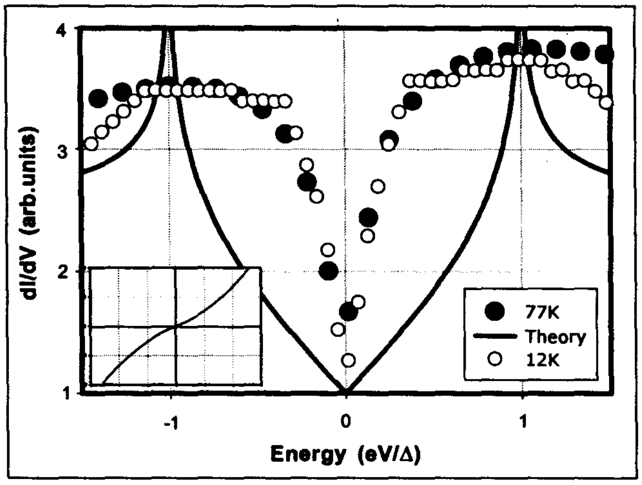

Fig. 1. Typical differential conductance plot obtained for the prepared Y-123 junctions at 77K (filled circles) and 12K (unfilled circles). Note the peak separation, unequal magnitude of the peaks, and the non-zero conductance at zero bias observed in both temperatures. The solid line corresponds to theoretical calculations at T=0K. The inset shows a typical I-V plot obtained from the junctions at 77K.

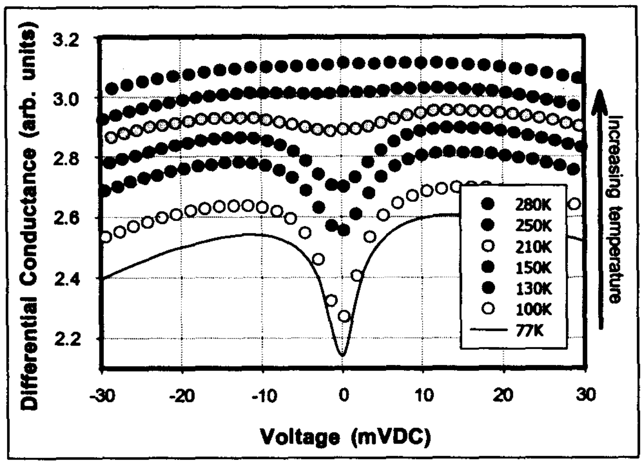

Fig. 2. Differential conductance plots obtained for the prepared Y-123 junctions at different temperatures above 77K. The graphs have been shifted from each other for clarity. Note the persistence of the depression at zero bias (a characteristic of the pseudogap) even at high temperatures.

to each other for better inspection and comparison. Note the persistence of the signature twin peaks and depression at zero bias even in the conductance plots obtained above Tc=90K. These features only disappear in the conductance plot at T=280K. At 77K (i.e., below Tc), the conductance plot corresponds to the superconducting phase of the material. Thus, we can measure the distance between the two peaks in the plot as the superconducting energy gap. However, above Tc, the material is no longer in its superconducting state but, instead, in its normal state. Thus, we can no longer define the peak separation in the plots as a superconducting energy gap. Instead, since the plots are similar, this 'normal-state gap' has been termed as the pseudogap. It is important to point out here that the pseudogap does not refer to the peaks in the normal-state conductance but, instead, to the depression in the normal-state conductance at zero bias. At room temperature, the normal-state conductance is flat and featureless, corresponding to a straight and linear I-V characteristic. Now, if we make a depression in this conductance, say at zero bias, we obtain a conductance similar to what we have obtained experimentally. Thus, we can relate this depression at zero bias to the peaks in the normal-state conductance. The actual mechanism and origin of this pseudogap is unknown at the moment. However, there is some agreement in the community as to its nature and phenomenology (Timusk, http://xxx.lanl.gov/cond-mat/9905219). One of the striking features of Fig. 2 is that the d-wave nature of the superconducting gap is preserved and persists in the transition to the normal state up to some temperature $T^* >$ Tc. A preprint by Mourachkine (1999) has similarly found T*=280K in overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals from tunneling measurements. The pseudogap seems to be related to the superconducting gap in the sense that it evolves smoothly into the superconducting gap and has the same d-wave symmetry.

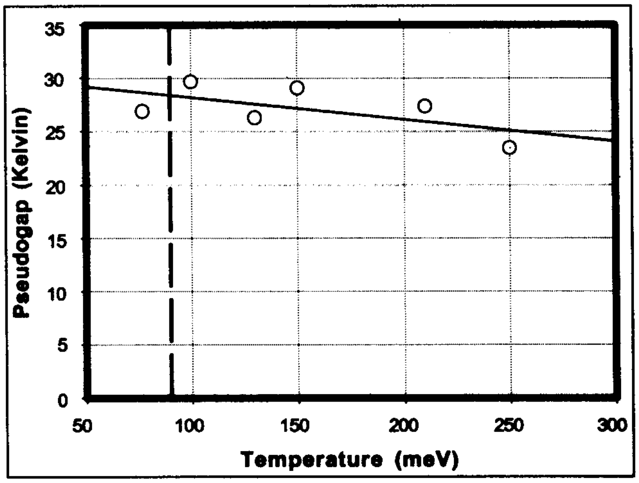

Fig. 3. Temperature dependence of the pseudogap. Note that the energy gap does not go to zero at T_c and that the pseudogap value is temperature independent to a certain degree. The dotted line corresponds to the transition temperature T_c=90K (determined from dc resistivity measurements). The thin solid line corresponds to a first-order linear regression line of the data points in the graph.

Fig. 3 shows the temperature dependence of the magnitude of the pseudogap. The first data point in this plot corresponds to the superconducting energy gap. The dotted line correspond to the transition temperature, Tc. From this figure, we find that unlike a conventional superconducting gap, the magnitude of the pseudogap is temperature independent. Thus, in the case of the cuprates, the gap starts as the pseudogap in the normal state and evolves into the superconducting gap below Tc, i.e., Δ(T) does not go to zero at Tc as predicted by BCS theory of superconductivity.

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