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$YBa_2Cu_3O_{7-\delta}$-Ag-Al/Al_2O_3/Pb Superconducting Tunnel Junctions

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$YBa_2Cu_3O_{7-\delta}$-Ag-Al/Al_2O_3/Pb superconducting tunnel junctions with high subgap resistance were fabricated using the proximity effect induced superconductivity in the Ag-Al layer by the $YBa_2Cu_3O_{7-\delta}$ film. At low temperatures an energy gap of 9-10 meV is found to be induced in the aluminum layer. At higher voltages ($V \leq 120$ meV) the dynamic conductance dI/dV is proportional to V.

The realization of a useful high-T_c Superconductor-Insulator- Superconductor (S-I-S) tunnel or Josephson junction strongly depends on the quality of the S-I interface, which has to be sharp and free of defects on an atomic scale due to the small coherence length of an oxide superconductor. Despite this problem junction structures have been made by evaporating a classical superconductor, e.g. Pb or Nb, on top of a $YBa_2Cu_3O_{7-\delta}$ film [1,2]. The de-oxygenated top surface layer of the oxide superconductor is then used as a tunnel barrier. These junctions do not show a well defined tunnel gap. Its value is usually obtained from the nonlinear dependence of the tunnel current on voltage.

Here we report on the fabrication and electrical characterization of $YBa_2Cu_3O_{7-\delta}$-Ag-Al/Al_2O_3/Pb tunnel junctions. The thin Ag-Al normal metal bilayer becomes superconducting due to the proximity effect induced by the $YBa_2Cu_3O_{7-\delta}$. In this junction structure we take advantage of both the superconducting contacting capability of Ag on $YBa_2Cu_3O_{7-\delta}$ [3] and of the oxidation properties of Al, which enable the formation of a closed and controlled thin Al_2O_3 barrier layer. The junction's current-voltage (I-V) characteristic does show a pronounced gap at 3.9 K. We obtain a value of $\Delta_{1:2:3} = 9\text{-}10$ meV for the energy gap induced by the superconducting $YBa_2Cu_3O_{7-\delta}$ in the Ag-Al bilayer. This gap decreases with increasing temperature and vanishes at $T \sim 20$ K due to the temperature induced loss of superconducting coherence in the normal metal. At higher voltages ($V \leq 120$ mV) we observe an $I \propto V^2$ dependence at low temperatures, equivalent to a $dI/dV \propto V$ dependence for the dynamic conductance; this is the supposedly characteristic behavior of the normal tunneling density of states of an oxide superconductor [4]. At high temperatures (70-80 K) the dynamic conductance dI/dV becomes nearly constant since the tunnel process just probes the normal excitations of the Ag-Al bilayer as a result of the decreased inelastic scattering length.

Figure 1 presents a schematic diagram of the tunnel junction geometry. A 1 mm wide $YBa_2Cu_3O_{7-\delta}$ strip is sputtered on a (100) $SrTiO_3$ substrate with an Ar pressure of 3×10^{-3} Torr. Superconductivity is obtained after annealing in flowing O_2 at 850° C for 1/2 hour. Then a Ag strip of 20 nm thickness is sputtered after which the sample is heated up to 450° C in flowing O_2 during 1/2 hour to obtain a good superconducting contact between $YBa_2Cu_3O_{7-\delta}$ and Ag [3]. After evaporation of a 30 nm thick Al strip the substrate is completely covered with SiO_2. Using a CF_4/O_2 plasma a 100 μm^2 hole is etched in the quartz layer. After surface cleaning by Ar ion milling and oxidation in an O_2 plasma the

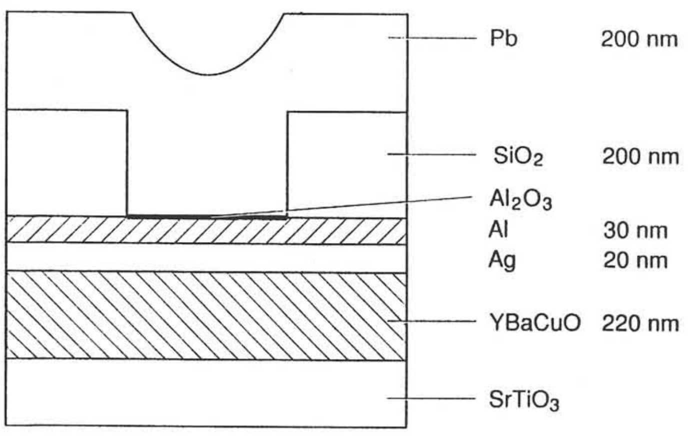

Figure 1 : Schematic diagram of the tunnel junction geometry.

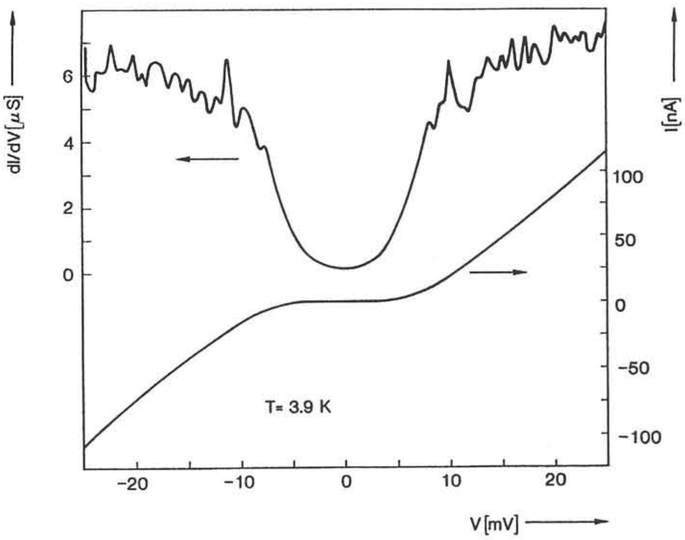

Figure 2 : I-V characteristic (lower curve) and dI/dV-V characteristic (upper curve) for a proximity effect based tunnel junction at 3.9 K.

Al is covered with a closed Al_2O_3 layer. As a final step a crossed Pb strip is evaporated to form the second junction electrode. After contacting the sample with In, it was mounted in a continuous flow cryostat. Electrical measurements were done using a standard four probe technique.

Figure 2 (lower trace) shows the I-V characteristic of a proximity effect based tunnel junction at 3.9 K. The fairly high tunnel resistance (170 kΩ at 20 mV) is indicative for a good quality aluminum oxide layer. We clearly observe a gap characterized by a very high resistance around zero voltage bias. The upper curve of Fig. 2 is the dI/dV-V characteristic obtained by numerical differentiation. The irregular structure in dI/dV at higher voltages is probably due to inelastic tunneling which becomes very pronounced in the numerical derivative. At V=10-11 meV larger peaks appear which presumably are related to the peak in the tunneling density of states (DOS) of the Pb. Indeed for a tunnel junction consisting of two superconducting electrodes with a different gap (in this case $\Delta_{1:2:3}$ and Δ_{Pb}) one would expect the appearance of a peak in the dynamic conductance dI/dV at a voltage $|V| = (\Delta_{1:2:3} + \Delta_{Pb})/e$. Although our data are not perfectly symmetric in voltage we can estimate, taking $\Delta_{Pb} = 1.2$ meV, that $\Delta_{1:2:3} = 9\text{-}10$ meV at this temperature, in good agreement with gap values reported elsewhere [1,2]. Note that $\Delta_{1:2:3}$ is a proximity superconducting gap, induced in the Al by the outdiffusion of superconductive carriers from the $YBa_2Cu_3O_{7-\delta}$ film. The characteristic length over which this diffusion takes place is the normal metal coherence length $\xi_N(T)$; from previous work [3] we found at low temperatures that $\xi_N(T) \simeq (93\ \text{nm})/\sqrt{T}$ for our proximity systems. This dependence leads to the experimentally observed disappearance of the energy gap at about 20 K.

In conclusion we have made $YBa_2Cu_3O_{7-\delta}$-Ag-Al/Al_2O_3/Pb tunnel junctions based on the superconducting proximity effect with very low subgap conductance. The energy gap induced in the Al layer by the $YBa_2Cu_3O_{7-\delta}$ is 9-10 meV. The temperature dependence of the dynamic conductance dI/dV is in agreement with proximity effect theory. At higher voltages $dI/dV \propto V$, typically reflecting the normal tunneling density of states of the oxide superconductor.

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