YBa$_2$Cu$_3$O$_{7-\delta}$-Ag-Al/Al$_2$O$_3$/Pb Superconducting Tunnel Junctions

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YBa$_2$Cu$_3$O$_{7-\delta}$-Ag-Al/Al$_2$O$_3$/Pb superconducting tunnel junctions with high subgap resistance were fabricated using the proximity effect induced superconductivity in the Ag-Al layer by the YBa$_2$Cu$_3$O$_y$ 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$_2$Cu$_3$O$_y$ film. 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$_2$Cu$_3$O$_{7-\delta}$-Ag-Al/Al$_2$O$_3$/Pb tunnel junctions. The thin Ag-Al normal metal bilayer becomes superconducting due to the proximity effect induced by the YBa$_2$Cu$_3$O$_y$. In this junction structure we take advantage of both the superconducting contacting capability of Ag on YBa$_2$Cu$_3$O$_y$ and of the oxidation properties of Al, which enable the formation of a closed and controlled thin Al$_2$O$_3$ barrier layer. The junction's current-voltage ($I$-$V$) characteristic does show a pronounced gap at 3.9 K. We obtain a value of $\Delta_{123} = 9-10$ meV for the energy gap induced by the superconducting YBa$_2$Cu$_3$O$_y$ 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 ($V \leq 120$ meV) 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. 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$_2$Cu$_3$O$_y$ strip is sputtered on a (100) SrTiO$_3$ substrate with an Ar pressure of $3 \times 10^{-3}$ 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$_2$Cu$_3$O$_y$ and Ag. 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.
Al is covered with a closed Al₂O₃ 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 Δ₁23 and Δ₁₉) one would expect the appearance of a peak in the dynamic conductance dI/dV at a voltage \[|V| = (Δ₁23 + Δ₁₉)/e\]. Although our data are not perfectly symmetric in voltage we can estimate, taking Δ₁₉ = 1.2 meV, that Δ₁₂₃ = 9-10 meV at this temperature, in good agreement with gap values reported elsewhere.²¹² Note that Δ₁₂₃ is a proximity superconducting gap, induced in the Al by the outdiffusion of superconductive carriers from the YBa₂Cu₃O₇ film. The characteristic length over which this diffusion takes place is the normal metal coherence length \[ξ_n(T)\]; from previous work³ we found at low temperatures that \[ξ_n(T)\approx(93 \text{ nm})/\sqrt{T}\] 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 YBa₂Cu₃O₇-Ag-Al/Al₂O₃/Pb tunnel junctions based on the superconducting proximity effect with very low subgap conductance. The energy gap induced in the Al layer by the YBa₂Cu₃O₇ 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 ∝ V, typically reflecting the normal tunneling density of states of the oxide superconductor.

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References