Abstract

We have demonstrated proximity effect coupling between a high transition temperature superconductor and a normal metal. In a device with a 1 µ long gap in a YBa$_2$Cu$_3$O$_7$ film spanned by a Au shunt we have observed a dc supercurrent and the ac Josephson effect under microwave irradiation from 2GHz to 15GHz. Preliminary work has also begun with Ag shunts. These high quality S-N interfaces should be applicable both to probing the superconducting state in oxide superconductors and to building high $\tau_C$ electronic devices.

I. Introduction

In conventional superconductors, thin film structures containing tunnel junctions or weak-link microbridges have been a rich field of study for both fundamental research and device applications. In the new high transition temperature superconductors, like YBa$_2$Cu$_3$O$_7$, material problems have made the realization of such structures more difficult than in materials like Pb, Sn, In, or Nb. Initial studies of junctions between YBa$_2$Cu$_3$O$_7$ and a low temperature superconductor, Pb, are beginning to yield fundamental information on energy gap structures. JUNCTIONS between two high temperature superconductors, though, are much more difficult. First, YBa$_2$Cu$_3$O$_7$ and its relatives react strongly with dielectrics during the heat treatment necessary to form the superconducting phase, and destroy thin tunneling barriers. Second, the superconducting coherence length ranges from less than a nanometer to a few nanometers, depending on orientation of the film. This short coherence length means that any junction device must have interfaces that are perfect on the scale of a few lattice spacings, difficult in this reactive material. Some success has been obtained using natural defects, like grain boundaries, as barriers, or forming mechanical "break junctions". While these techniques have formed quantum interference devices that operate at temperatures near 77 K, there is little control over the nature of the junction and the technique is difficult to extend to many applications. In addition, such devices have a high level of 1/f noise from electron trapping at grain boundaries that makes them difficult to use for many applications. These limitations have hampered fundamental research into the nature of these materials and limited the range of possible technological applications of thin films to passive devices like high-speed transmission lines interconnecting conventional semiconductor circuits and interconnects. D. Schwartz, P.M. Mankiewich, R.E. Howard, L.D. Jackel, B.L. Straughn, E.G. Burkhardt, A.H. Dayem AT&T Bell Laboratories Holmdel, NJ 07733, USA.

THE OBSERVATION OF THE AC JOSEPHSON EFFECT IN A YBa$_2$Cu$_3$O$_7$/Au/YBa$_2$Cu$_3$O$_7$ JUNCTION


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superconducting films made with BaF₂ show that the film is chemically uniform up to the surface. This is essential if one is to make good SNS devices which depend heavily on the interface quality between the superconductor and normal metal.

III. Weak Link Fabrication

Fabrication of the S-N-S bridge structure requires three lithographic steps to define the superconducting banks and the bridging normal metal film. Since the films are deposited on a room temperature substrate and the pre-annealed films made with BaF₂ are chemically robust, it is possible to fabricate overlapping layers of material using lift-off. This has enabled us to combine optical lithography with e-beam lithography and have the pre-annealed film survive the rigors of the combined chemical treatments.

The first step in the process was to photolithographically define a coarse superconducting lead pattern on the surface of the SrTiO₃. A film was deposited on the resist pattern and after removing the substrate from the evaporator was placed in acetone for liftoff of the resist and the unwanted film. The film was not annealed at this point but was further coated with a resist (PMMA) for definition of the small gap (about 1 μm) by electron beam lithography. Another superconducting film is then deposited that overlaps the original lead pattern. After liftoff of the PMMA, the two banks are separated by a gap 1 μm long. At this point the sample was annealed using the technique described above and the small area where the two layers overlap became uniform throughout its thickness with no evidence of an interface between the layers. At this point, the film was mounted in a cryostat with spring loaded electrical contacts and the transition temperature and resistivity was measured.

The final fabrication step was to coat the superconductor with PMMA, and use e-beam lithography to write a 10 μm by 10 μm square centered on the gap between the two banks. A gold film was then evaporated to a thickness of 0.24 μm and the resist lifted off in acetone to form the normal metal bridge between the superconducting banks.

At this point the SNS junction had a room temperature resistance of several thousand ohms that increased with decreasing temperature. Since the superconductor is known to react in air to form oxides and carbonates, the characteristics were probably dominated by the interfacial resistance from these layers. In order to decrease this excess resistance, the device was annealed for 10 sec. at 750 °C in oxygen. After annealing, the resistance at room temperature was about 100 Ω. This value was consistent with the resistance expected from the YBa₂Cu₃O₇ banks alone. At 77 K when the banks are superconducting, the resistance of the bridge was about 0.3 ohms. No change in the superconducting properties of YBa₂Cu₃O₇ thin film was observed after this high temperature treatment.

For comparison, a similar gold film was deposited on both a SrTiO₃ substrate and on an unpatterned superconducting film. Before heat treatment, the resistivity of the gold was about 6 μΩ-cm on the SrTiO₃ and slightly higher on the YBa₂Cu₃O₇ film. After heat treatment, these values changed by less than 10%, indicating that there is minimum interaction between the materials.

From studies on other bridge structures, it is clear that the key to this technology is careful control of the interface quality and the annealing schedule. For example, on a 1 μm long Ag bridge, the low temperature resistance of the bridge could be changed dramatically and reversibly by changing the heating and cooling rates as well as the peak annealing temperature. This is consistent with changing the oxygen stoichiometry of the interface between the superconductor and the Ag. Since the coherence length in the superconductor is only a few lattice constants long, this interface chemistry must be carefully controlled. Simple behavior with the resistance decreasing smoothly with increasing annealing time and temperature could be obtained with a carefully prepared sample.

IV. Electrical Characteristics

Electrical measurements were made in a low noise, magnetically shielded, variable temperature cryostat. Leads for four-terminal measurements were attached using either spring-loaded contacts or silver paste. Microwave irradiation was provided by placing an antenna in the base of the cryostat near the sample.

Since the intrinsic weak-link behavior of some thin films is well documented, we characterized our material by studying the behavior of superconducting constrictions down to 1 μm square. Bridges made from films on SrTiO₃ were irradiated with microwaves (2 to 15 GHz) and showed no response even at temperatures close to their transition temperature, which was the same as that of the unpatterned film. This indicated that the transport characteristics were not dominated by intrinsic weak links in the film.

The films on ZrO₂ substrates, though, are qualitatively different from those on SrTiO₃. Since there is no epitaxy of the superconductor on this substrate, the films are granular with much lower current density, typically 1A/cm² at 77 K. As a result, large-area films of this material show a strong response to microwave irradiation. This is a strong indication of inhomogeneity and Josephson coupling between the grains. Since an ideal microbridge depends upon having a well-defined weak link between two strong superconductors, the films on SrTiO₃ were used for the S-N-S devices.

Electrical characteristics of the bridge were measured as a function of temperature and microwave irradiation. The maximum current at 4.2 K for the S-N-S bridge was about 12 μA, giving an Iₜ R product of 36 μV in a bridge slightly less than 1 μm long. The ac Josephson was also studied using microwave irradiation. Figure 2 shows the differential resistance, dV/dI, as a function of voltage at 4 K when the sample was irradiated with 10 GHz microwaves. There are distinct minima in differential resistance at the expected interval of about 2μV/GeVHZ. This response, with the appropriately scaled voltage response was observed for microwaves over the frequency range of 2 to 15 GHz. Above 16 K, the R=0 state disappeared because of thermal noise, but microwave response persisted to even higher temperatures.

V. Discussion

From the measurement of the gold film evaporated on SrTiO₃ and on a large-area YBa₂Cu₃O₇ film, we estimate that the low temperature resistivity of the bridge is about 1-2 μΩ-cm at low temperature. Using the standard expression for the normal state coherence length, ξ₀, at 4.2 K we estimate ξ₀ = 0.07 μm. In the dirty limit approximation in a long bridge, this would give an Iₜ R product of about 5 μV. This assumes a BCS value for the gap, which should be accurate to within a factor of two depending upon orientation. Considering the strong dependence of Iₜ R on ξ₀, and the uncertainty in the parameters of the bridge, this is in excellent agreement with experiment.
The measurements are not completely consistent with a simple S-N-S structure. A gold film with resistivity of 2 μΩ-cm, which is consistent with the observed I-R product, would give a bridge resistance of only about 15 mΩ, not 330 mΩ. The most simple model accounting for the extra resistance is to make the reasonable assumption of a barrier at the Au/superconductor interface. A related situation has been seen in Nb/Cu microbridges15 and a similar theoretical framework should be able to describe our devices.

Finally, since the I-R product is at least as large as would be expected from the properties of the normal metal, the superconducting properties of these S-N-S junctions can be expected to improve dramatically as the length of the bridge is reduced. Considering the morphology of the superconductor and the patterning accuracy available, dimensions down to or even below 0.1 μm are possible. At this size, the devices should operate at 77 K or above and provide a new probe into the physics of the material as well as the possibility of high temperature electronics.

Figure 1. Micrograph of a completed junction. The lithographic length of the junction, as defined by the length of the YBCO is 1μ.

Figure 2. The differential resistance of the bridge shown in Fig. 1 at 4.2 K in the presence of 10GHz microwave radiation.

REFERENCES