SWITCHING NOISE IN $\text{YBa}_2\text{Cu}_3\text{O}_x$ "MACROBRIDGES"*

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Abstract

We have observed intermittent switching in the voltage-current characteristics (VIC) of thin film bridges of $\text{YBa}_2\text{Cu}_3\text{O}_x$. At a fixed bias point there are multiple metastable voltage states with lifetimes which depend on the bias current and applied magnetic field. The microbridges are made of thin ($<500\text{nm}$), polycrystalline films of $\text{YBa}_2\text{Cu}_3\text{O}_x$ which are patterned by liftoff into structures with dimensions ranging from less than $1\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$. Details of the fabrication process and the measurements are presented. The results are discussed in the context of fluctuations in the effective resistance of the bridge due to motion of trapped flux.

Motivation

Applications for high transition temperature superconductors depend on understanding and improving the critical current of wires or thin films. Additionally, the transition out of the zero-voltage state is rich in complex and poorly understood physics. We have studied the low voltage behavior of constrictions in thin films of $\text{YBa}_2\text{Cu}_3\text{O}_x$ in an attempt to understand the dynamics of current transport in a high T_c material. An equally important goal of these experiments is to understand the intra-film Josephson effects which have been observed. If grain boundaries are behaving as Josephson weak links, then the fewer the grain boundaries in the sample, the simpler the system.

We fabricated several "macrobridge" samples from thin films of $\text{YBa}_2\text{Cu}_3\text{O}_x$. The term macrobridge is used to avoid confusion with the commonly used term "microbridge." A Josephson weak link can be made by constricting a superconducting film to dimensions smaller than the coherence length; this is the usual definition of a microbridge. The bridge dimensions we fabricated ranged in width from $1\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$ and in length from $0.75\text{ }\mu\text{m}$ to 2 mm . Even the smallest of our samples was many orders of magnitude larger than the expected coherence length of $\text{YBa}_2\text{Cu}_3\text{O}_x$, at most a few nanometers².

We recorded the voltage and differential resistance of each bridge as a function of bias current and of temperature. The measurements were carried out in a small ($0 - 0.05\text{ mT}$), variable magnetic field. As expected the critical currents of the bridges increased with decreasing temperature. They were very sensitive to even this low level of applied field, and an even more unexpected behavior manifested itself.

Extremely noisy sections of the VIC appeared at temperatures which varied from sample to sample but which were always

Fig. 1. The V-I characteristic of B4 ($4\text{ }\mu\text{m}$ bridge) at 24 K . Three time series of the fluctuating voltage are shown below the VIC for three values of bias current, beginning at the arrow and increasing (negative) by $1\text{ }\mu\text{A}$.

well below T_c . Figure 1 shows a VIC for one of the $4\text{ }\mu\text{m}$ wide bridges at 24 K . Below the VIC we plot three different time series of the voltage at three different (constant) bias currents in the noisy region indicated by the arrow. As is immediately obvious from the voltage-time plots, the noise is due to intermittent switching of the bridge voltage between two (or in some cases, three) metastable values. The switching rates and average lifetimes depended on bias current and temperature. It was later observed that the switching rate was strongly dependent on the applied magnetic field.

This behavior has important implications for low-noise (i.e. SQUID) applications of high- T_c thin films. It may also be useful in interpreting, or even evaluating, the material properties which affect the critical current of a high T_c thin film. We address these points at the end of this paper, when we discuss possible interpretations of the phenomenon and model systems which may eventually explain the data. First, we give a brief overview of the fabrication techniques. We then present the electrical measurements we have made to date, and conclude with the above-mentioned discussion of models and interpretations.

Fabrication

The films used in these samples were deposited at AT&T by co-evaporation using the technique described in Reference 1. The Y, Cu and BaF_2 are evaporated simultaneously onto a room temperature substrate which is usually coated with a photoresist mask. The substrate material used for all of the

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samples discussed here was $< 100 >$ yttria-stabilized cubic zirconia. Oxygen is injected into the vacuum system in the vicinity of the substrate. The pressure at the bottom of the evaporation chamber is 3×10^{-3} Pa; it is considerably higher at the sample. Oxygen incorporated into the film during deposition results in smoother post-annealed films.

BaF_2 is used as the source of barium in the films because elemental barium is a highly reactive material which is difficult to evaporate and quickly forms BaO and BaCO_3 when exposed to air. This reactivity also makes thin films containing Ba unstable during processing. BaF_2 does not decompose when evaporated from a tungsten boat, thus molecular BaF_2 is incorporated into the co-evaporated film. The thin films are tolerant of exposure to moisture, air, positive photoresist, developer, and common solvents.

After deposition, the photoresist masked film is lifted off in acetone, leaving the desired pattern in the smooth, as-yet insulating film. Pattern features with $1 \mu\text{m}$ dimensions have been made using standard positive photoresist techniques. Furnace annealing is then required to form the superconducting phase and to incorporate additional oxygen into the film. A typical annealing cycle is 2.5 h at 850°C in flowing oxygen which has been bubbled through water, followed by a slow ramp to 500°C , and an additional 2 h at 500°C in flowing oxygen. The role of the water vapor is to react away the fluorine in the film, reducing the annealing time and temperature requirements.

Two completed bridges are shown in Figure 2. We will present data taken on 4 bridge structures, three from sample chip 3 and the fourth on sample 2. The bridge number we use for reference is followed by its approximate dimensions (length by width): B1 - $1.5 \mu\text{m} \times 1.5 \mu\text{m}$, B2 - $4 \mu\text{m} \times 4 \mu\text{m}$, B3 - $0.1 \text{ mm} \times 2 \text{ mm}$, and B4 - $4 \mu\text{m} \times 4 \mu\text{m}$ from sample 2.

Electrical Measurements

The experimental arrangement is shown schematically in Figure 3. The test probe dips into a magnetically shielded He storage dewar. Our sample holder is a copper block with the sample, spring-loaded gold pins for contact, a carbon-glass resistance thermometer, and a heater resistor. A small copper coil, for applying an external magnetic field, surrounds the sample

Fig. 2. Optical micrographs of two bridges on the same substrate (sample number 2): a. $1.5 \mu\text{m}$ bridge, 200 nm thick $\text{YBa}_2\text{Cu}_3\text{O}_x$. b. B4, the $4 \mu\text{m}$ bridge.

Fig. 3. Block diagram of the measurement apparatus.

and the holder is inserted into an immersible magnetic shield. The sample leads are rf-filtered at room temperature and are shielded from the temperature control leads. The room temperature electronics are battery powered through the first stage of amplification. We can monitor $V - I$, $dV/dI - I$, and V vs. time at temperatures ranging from 120 K to 4 K, with 0.05 K stability over much of that range.

We first characterize the samples by looking at the resistive transition in the $100 \mu\text{m}$ wide strip using an ac excitation current of $5 \mu\text{A}$ rms. The measurements reported here were taken on samples with transition midpoints greater than 88 K and zero resistance (less than $10^{-5} \Omega$) at T greater than 85 K.

The differential resistance characteristics (R_{DI}) of B3, B1, and B2 are strikingly different, as seen in Figure 4. The characteristic of B3 appears to be that of a wide strip of conventional type II superconductor, with a current dependent resistance attributable to flux flow³. The critical current density of the $100 \mu\text{m}$ strip B3 is plotted in Figure 5 as a function of temperature.

Fig. 4. Differential resistance, dV/dI , of: a. B3 at 45 K, b. B2 at 40 K, and c. B1 at 42 K.

The 1.5 and $4 \mu\text{m}$ bridges (B1 and B2) appear to be quite different. The critical current of B1 was very low ($\sim 1 \mu\text{A}$ at 10 K), and the dV/dI was featureless at low voltage, although intriguing gap-like structure could be easily seen at higher voltage (10 - 40 mV). The behavior of B2 was the most interesting one for the purposes of this discussion. The evolution of its R_{DI} as the

Fig. 5. Critical current density for B3 (100 μm wide strip) using a resistance limit of 1 m Ω corresponding to a resistivity criterion of approximately $10^{-9}\Omega\text{-cm}$. The first peak in the differential resistance of Figure 6 is plotted on the same scale.

temperature decreased is shown in Figure 6. The noisy regions of the characteristic can be seen to grow and then shrink with decreasing temperature. At lower temperature the VIC becomes hysteretic at the current where the noise was last seen. In fact, the noise does not go away, instead its lifetime grows enormously with only a small change in temperature. This may be an indication of a thermally activated process with $\omega \propto \exp(-U_P/k_B T)$ where ω is the frequency of switching and U_P is the activation energy or barrier height. It is important to note that there are in fact at least two frequencies involved which correspond to switching in one direction or the other. A plot of voltage vs. time reveals that the lifetimes of the two states can be radically different.

The switching behavior we observed is shown in voltage-time plots in Figure 1 and Figure 7. The data of Figure 1 were taken on a strip-chart recorder and those of Figure 7 were obtained using a digital oscilloscope. The transition time between states was always less than 5 μs , the bandwidth limit of the amplifiers on the digital oscilloscope. There are two distinct modes of switching: where the lifetimes are similar (either long or short) and where they are very different. We occasionally see more than two states, but rarely more than three. Above 20 K, the amplitudes of the voltage swings are approximately 10 – 50 μV . Below that temperature there are very few observable switching events unless a small magnetic field, less than 0.01 mT, is turned on.

These effects are reproducible over thermal cycling of one sample, and appear in all of the patterned samples (grown on cubic zirconia) which we have studied. The smallest single bridge studied was 0.75 μm long by 3 μm wide, on sample 1; it showed pronounced switching, just as did B2 and B4, the 4 μm bridges on sample 2 and sample 3.

Summary and Discussion

Let us now summarize some of the experimental observations and place them in the context of the behavior of conventional superconductors. We have observed phase slip or weak link behavior⁴ in small bridges which are still much larger than the coherence lengths. This suggests that the activity is taking place on an even smaller length scale, perhaps that of the grain

Fig. 6. A family of R_{DIC} for B2 as the temperature decreases. Note the onset of a noisy region at 50 K (arrow) and its virtual disappearance at 38 K.

boundary thickness. The observed bistability, or telegraph noise, is temperature, bias current, and magnetic field dependent. The very rapid change of switching rate with very small fields and small changes in bias current suggests that the noise may be due to the motion of vortices in and out of pinning sites. This is consistent with the apparent onset of switching at intermediate temperatures (30 – 50 K) and the rapid decrease in switching rate at lower temperatures. A possible scenario for the noise is as follows. Above a temperature of order U_P/k_B , the activation energy of a pinning site, vortices will move relatively freely, giving rise to flux flow resistance and additional random noise. When the temperature drops below this level, the probability of trapping increases and the pinning and unpinning become experimentally observable. Thus the temperature dependence of the switching rate and the apparent onset temperature provide clues to the noise mechanism. The voltage difference between states provides further information. The voltage swing could arise via the motion of a vortex across the bridge. It is also possible that the voltage arises because the trapped flux modulates the critical current of an internal weak link. As Figure 7 shows, we see both rapid pulses and slow switching in the same bridge, with roughly the same voltage amplitude. It is possible that one is an effect of vortex velocity while the other is due to the static presence or absence of a vortex.

A detailed analysis of the noise is now underway. This paper has presented the essentials of the experimental data, and suggested possible interpretations. The emphasis for the future is to accumulate statistics on the switching lifetimes. If the process is thermally activated then we may be able to extract the activation energy and compare it with predictions of flux creep theories. We are also exploring the material dependence of the switching noise. We will compare these results with measurements on thin films grown on single crystal SrTiO_3 . Films we

Fig. 7. Time series of noise in B2: a. and b. for identical bias conditions at 47 K, c. at 45 K. The vertical scale has an arbitrary zero because of

have made on SrTiO_3 (both at NBS and AT&T) show much higher critical current densities and far fewer grain boundary effects¹. It may someday be possible to correlate some of the microscopic effects with larger scale phenomena such as critical current.

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