Resistive Switching Dynamics in Current-Biased Y-Ba-Cu-O Microbridges Excited by Nanosecond Electrical Pulses

The response of a superconductor to the injection of current pulses depends directly on the quasiparticle dynamics[1] since the carriers injected from the external circuit are normal (unpaired) electrons that disturb the quasiparticle–Cooper-pair dynamical equilibrium. Most commonly, a current pulse with an amplitude higher than the sample critical current I_c is used (supercritical perturbation), leading to a collapse of the superconducting state and resulting in the resistive response. This phenomenon was first investigated in metallic superconducting thin films by Pals and Wolter[2] and has been recently observed by Jelila *et al.*[3] in superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) microbridges. In both cases, a resistive (voltage) response induced by the supercritical current was reported to have a certain time delay t_d, defined as the delay between the arrival of the input current pulse and the appearance of the voltage signal. The t_d was directly related to t_D, the time required to achieve collapse of the superconductor order parameter D. Jelila *et al.*[3] successfully interpreted the t_d dependence on the supercritical pulse magnitude, using the theory developed by Tinkham.[1]

The supercritical perturbation in a superconducting bridge can also be achieved by a suitable combination of the excitation-pulse magnitude I_{pulse} and the bias current level I_{dc}. In fact, a two-dimensional space of the supercritical perturbations exists, limited only by the conditions $I_{total} = I_{pulse} + I_{dc} > I_c$ and $I_{dc} < I_c$. Together, the bias current (dc) and the pulsed current (time dependent) represent simultaneous injection of *both* Cooper pairs and quasiparticles into a superconductor, allowing us to study a full range of the quasiparticle–Cooper-pair dynamics from very weak [($I_{pulse} \gtrsim I_c$ and I_{dc} ª 0) or (I_{pulse} ª 0 and $I_{dc} \lesssim I_c$)] to very strong ($I_{pulse} >> I_c$ and $I_{dc} > 0$) perturbations.

The aim of this work is to present our studies on superconducting-to-resistive switching of dc-biased epitaxial YBCO microbridges, subjected to nanosecond electrical pulses in the supercritical perturbation regime. Our studies confirm the existence of a substantial t_d, which depends in a complicated way on both the magnitude of $I_{pulse}(t)$ and the value of I_{dc} biasing the microbridge. Our measurements were interpreted using a modified Geier and Schön (GS) theory,[4] which, contrary to the Tinkham model,[1] allowed for the incorporation of the dc bias of a superconductor and its relation with t_d. We have also demonstrated that for perturbations much longer than the electron–phonon time t_{e-ph}, the dynamics of the current-induced resistive state is limited by the bolometric process and t_D reduces to the phonon escape time t_{es}.

When a long strip of a superconductor is subjected to supercritical perturbation, injected quasiparticles destroy the system equilibrium, resulting in the formation of phase-slip centers, which, in turn, lead to the collapse of D in a characteristic time t_D and the development of a resistive hot spot across the strip's weakest link. At the early, nonequilibrium, or "hot-electron," stage, the quasi-particle relaxation dynamics is governed by inelastic electron–phonon scattering, while the later resistive hot-spot-formation stage is a bolometric process. Thus, t_D should initially follow t_{e-ph} and later be limited by t_{es}. The nonequilibrium process is, of course, measurable only if the width of $I_{pulse}(t)$ is of the order of t_{e-ph} or shorter. The t_d, which determines the appearance of a macroscopic resistive state, is related not only to t_D but also to the sample reduced temperature T/T_c and to the magnitudes of both I_{pulse} and I_{dc} with respect to I_c.

Even though the earlier YBCO experiments by Jelila *et al*.[3] were successfully interpreted using the Tinkham theory,[1] we choose to use the GS theory[4] since it is the only approach that incorporates the dynamics of both Cooper pairs and quasiparticles. The GS model allows the study of the supercurrent-induced response in both the hot-electron and bolometric regimes. It considers a one-dimensional homogeneous superconducting microbridge in which Cooper pairs coexist with quasiparticles. The Cooper-pair dynamics is described by the time-dependent Ginzburg–Landau equation,[5] while the quasiparticle distribution is given by the Boltzmann equation.[6] The main feature in the GS theory is the equation for the conservation of current between the superfluid (Cooper pair) and normal fractions of electrons, and it allowed us to introduce, in a natural way, the bias I_{dc} in addition to the quasiparticle perturbation $I_{pulse}(t)$. In our approach to the GS model,[7] the three aforementioned differential equations are first solved for a constant subcritical current (the dc bias), resulting in equilibrium values for the parameters of the system at a time >> t_{es}. Next, those equilibrium parameters are used as initial conditions to solve the GS equations for I_{total} constituted of the same I_{dc} and a varying transient $I_{pulse}(t)$. The t_d is defined as the time needed by the normal current component to rise to 50% of the total current through the bridge.

Figure 89.36 presents our GS model simulations of t_d dependence on the reduced bias current $i_{dc} = I_{dc}/I_c$ and on the reduced current pulse $i_{pulse} = I_{pulse}/I_c$. The t_d dependence on the supercritical perturbation forms a surface, which exponentially diverges to infinity at the $i_{dc} + i_{pulse} = 1$ boundary and very rapidly drops toward zero at $i_{dc} = 1$. This behavior is expected. In the $i_{dc} + i_{pulse} < 1$ range, the perturbation is subcritical and the bridge always remains in the superconductive state (only the kinetic-inductive response is possible), while for $i_{dc} > 1$, the bridge remains in the resistive state irrespective of the value of the i_{pulse} perturbation. What is unexpected is the nonlinear $t_d(i_{dc})$ dependence for a constant i_{pulse}. From our solution of the GS model, shown in Fig. 89.36, it is obvious that i_{dc} is not just a scaling parameter in the $i_{pulse} > 1 - i_{dc}$ switching criterion. The magnitude of the bridge bias plays the critical role in the switching dynamics not only for $i_{pulse} < 1$ but also for supercritical i_{pulse}'s, as i_{dc} approaches 1. Finally, we mention that the white lines, shown on the t_d surface in Fig. 89.36, correspond to our experiments and will be discussed below.

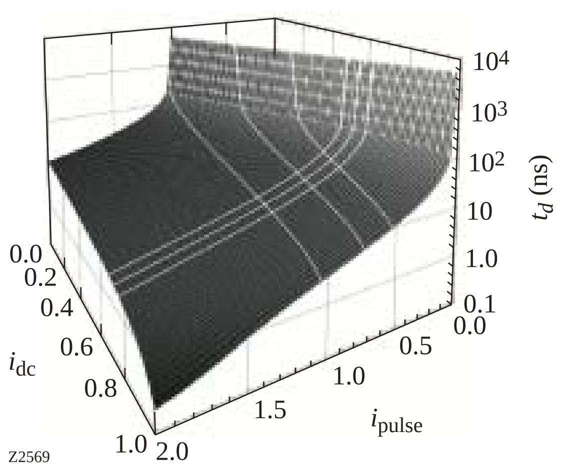

Figure 89.36
The time delay t_d surface as a function of both the reduced bias current i_{dc} and the reduced current pulse i_{pulse}. The t_d dependence on the supercritical perturbation was calculated using a modified GS theory for the parameters ($T/T_c = 0.96$ and $t_D = 17$ ns) directly corresponding to our experimental conditions (white lines).

Our experimental samples consisted of 200-nm-thick epitaxial YBCO films deposited on MgO substrates and patterned into 8-mm-long, 150-μm-wide coplanar strips (CPS's) with a single 25-μm-wide by 50-μm-long microbridge, placed across the CPS. The bridges were characterized by a zero-resistance transition temperature $T_{c0} = 82.5$ K and a critical current density $J_c > 1$ MA/cm^2 at 77 K. For experiments, the samples were mounted on a copper cold finger inside a temperature-controlled nitrogen cryostat. Nanosecond-wide electrical pulses from a commercial current-pulse generator were delivered to the bridge via a high-speed, semirigid coaxial cable wire-bonded directly to the test structure. The dc bias was provided from an independent source and combined with the current pulse through a broadband microwave bias-tee. A 14-GHz-bandwidth sampling oscilloscope was used to monitor the microbridge response. The oscilloscope was connected to the sample via a second semirigid cable wire-bonded to the output contact pads of the CPS.

Figure 89.37 shows a series of waveforms of the time-resolved resistive switching dynamics of our YBCO microbridge subjected to a 20-ns, 130-mA current pulse at different I_{dc} levels. Since the I_c of the microbridge was 125 mA, the I_{pulse} itself was supercritical, which, when superimposed on the dc bias, resulted in I_{total} well above I_c. From the bottom waveform with no biasing to the second waveform from the top with $I_{dc} = 0.76\, I_c$, the resistive response is seen as the onset and growth of the plateau region after the initial kinetic-inductive peak. The time evolution of the voltage response starts with the small inductive peak, as the still-superconducting microbridge appears as an inductive element and differentiates the ~0.5-ns-wide rising edge of the input current pulse.[7] Later, since I_{total} is supercritical, the superconducting state starts to collapse, as discussed earlier, giving rise to the resistive response after the delay time t_d. The top (thick line) waveform in Fig. 89.37 corresponds to $I_{dc} > I_c$ or, alternatively stated, to the YBCO microbridge in the normal state. We note that in this case, the measured output pulse is just the input current pulse, slightly distorted due to resistive loss of the YBCO CPS. A voltage due to the flux-creep effect can be observed before the inductive peak, as the small offset of the waveform, when I_{dc} increases toward I_c. A similar plateau can also be isolated between the inductive and resistive responses, when $t_d > 20$ ns. Plotting the I_{dc}-V curve in both cases permitted us to identify a shift corresponding to I_{pulse} and, therefore, allowed us to compute the actual amplitude of the input pulse across the microbridge.

From a series of data sets analogous to Fig. 89.37, but collected under different experimental conditions, we extracted the t_d values as the time delay between the onset of the inductive peak (instantaneous with the arrival of the input pulse) and the half-point of the rising edge of the resistive region of the voltage response. Our experimental t_d values along with the GS theory are shown in Fig. 89.38. Figure 89.38(a) presents t_d as a function of i_{dc}, for three different values of i_{pulse} = 0.53, 0.74, and 1.04, while Fig. 89.38(b) shows t_d as a function of i_{pulse}, for i_{dc} = 0.68, 0.72, and 0.76, respectively. The GS simulated curves in Fig. 89.38 are the same as the white lines outlined on the t_d surface in Fig. 89.36. The selected levels of supercritical perturbations were $I_{total}/I_c > 1.2$, corresponding to the excitation range where the GS, Tinkham, and Pals and Wolter theories start to disagree.[7] We note that the t_d data points agree very well with the GS theory. The best fit to all our experimental data was obtained for $\tau_D = 17$ ns. This latter value is exactly the same as the τ_{es} for our YBCO-on-MgO films,[8] calculated as $\tau_{es} = (4d)/(K\nu) = 17$ ns, where d = 200 nm is the YBCO film thickness, K = 0.020 is the average phonon transparency of the YBCO/MgO interface,[9] and ν = 2.8 km/s is the velocity of sound in YBCO averaged over the three acoustic modes. Thus, we can conclude that for current excitations that are much longer than $\tau_{e\text{–}ph}$, the resistive transition in YBCO films is governed by the bolometric (equilibrium) process and its time-resolved dynamics is limited by τ_{es}. This latter observation agrees very well with both theoretical[9] and experimental[10] studies of the response of YBCO films exposed to optical perturbations. It is also consistent with earlier pulse perturba-

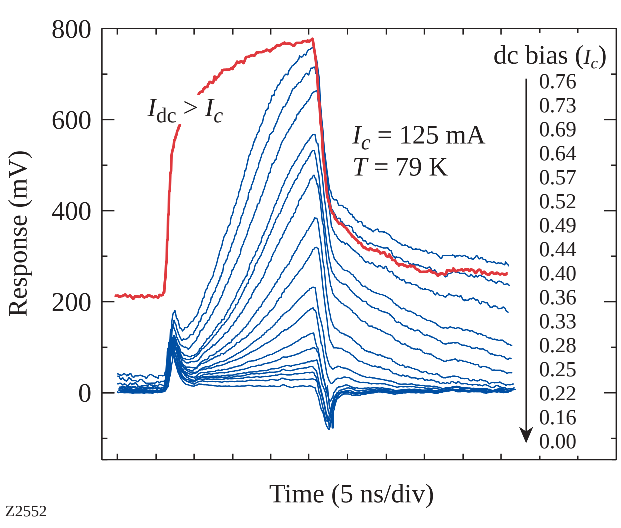

Figure 89.37
Time-resolved YBCO microbridge response to a 20-ns, 130-mA current pulse for the various bridge bias levels at 79 K. T_{c0} = 82.5 K; I_c = 125 mA. For the top (bold) waveform, the bridge was in the normal state ($I_{dc} > I_c$); note the large voltage offset that is representative of the resistive state of the bridge.

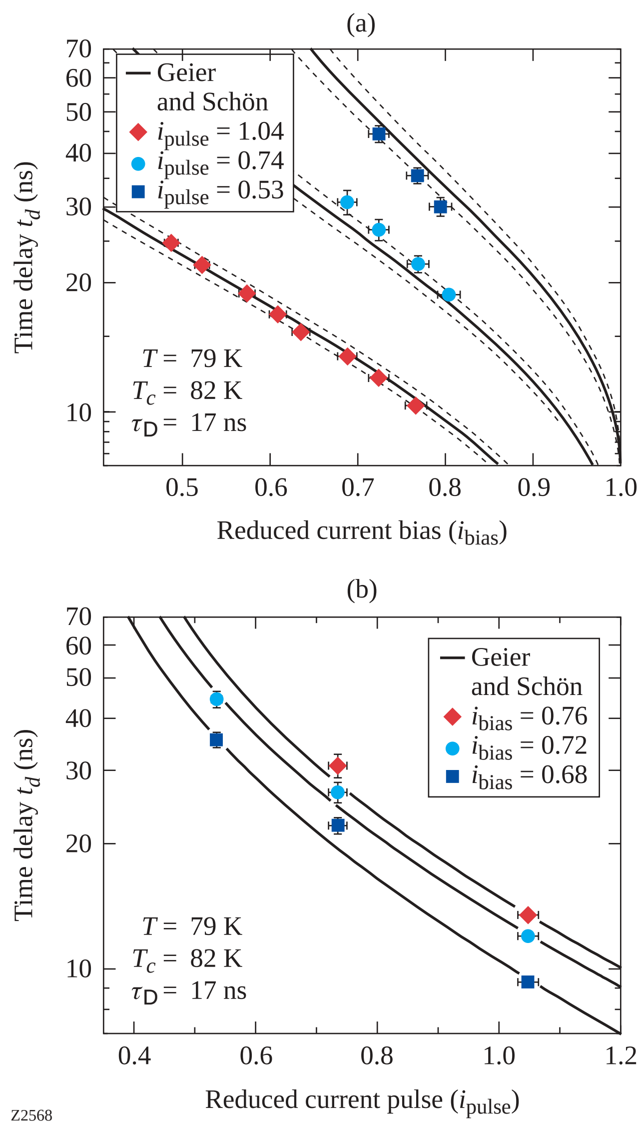

Figure 89.38
The measured t_d as a function of (a) the reduced bias current i_{dc} and (b) the reduced current pulse i_{pulse}. The solid lines represent the GS theory and correspond to the white lines in Fig. 89.36. The dashed lines in (a) define the error range in the amplitude of the current pulse applied the bridge. Note that the t_d scales are logarithmic.

tion experiments, since the literature data[11] seem to show that t_D is proportional to the film thickness and its value is consistent with the experimental determination of t_{es} for YBCO deposited on MgO, which is t_{es} = 0.085 ns/nm.

In conclusion, we have presented a study of dc-biased YBCO microbridges excited by nanosecond-long current pulses, which led to supercritical perturbations and resulted in resistive switching, occurring after a certain delay time t_d. The t_d depends roughly exponentially on both the amplitude of the current pulse and the film dc bias current, in a manner consistent with the GS theory. The duration of the superconducting-to-resistive response is, in our case, governed by the equilibrium dynamics of quasiparticles in the film and is limited by t_{es}, with no need to introduce the special t_D relaxation time. We can also predict that t_d could be shortened by using either thinner YBCO films or better acoustically matched substrates. The resistive response of YBCO bridges exposed to picosecond-long perturbations should be limited by the nonequilibrium $t_{e\text{–}ph}$ interaction time.

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