Resistive switching dynamics in current-biased $YBa_2Cu_3O_{7-x}$ microbridges excited by nanosecond electrical pulses

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(Received 18 June 2002; published 3 October 2002)

We report our studies on the time-resolved dynamics of the superconducting-to-resistive transition in dc-biased epitaxial $YBa_2Cu_3O_{7-x}$ (YBCO) microbridges, excited by nanosecond-long current pulses. Our experimental structures consisted of 200-nm-thick epitaxial YBCO films deposited on MgO substrates. They were patterned into a single 25 μm by 50 μm microbridge, embedded in the middle of a coplanar transmission line. The resistive switching was induced by the collaborative effect of both the Cooper-pair bias current and the quasiparticle pulse excitation, which together always exceeded the bridge critical current, forming the supercritical perturbation. The experimental dynamics was analyzed using Geier-Schön (GS) theory, which we modified to include the dc bias. We observed that the resistive state was established after a certain delay time t_d, which, in full agreement with the GS model, depended in a nonlinear way on both the excitation pulse magnitude and the bridge dc bias. For our nanosecond perturbations, the resistive switching dynamics was the bolometric process, limited by the phonon escape time τ_{es}.

DOI: 10.1103/PhysRevB.66.132501 PACS number(s): 74.72.Bk, 74.25.Fy, 74.76.Bz

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 and they disturb the quasiparticle–Cooper-pair dynamical equilibrium. Most commonly, a current pulse with amplitude higher than the sample critical current I_c is used (supercritical perturbation), leading to a collapse of the superconducting state and resulting in a 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 τ_Δ, the time required to achieve collapse of the superconductor order parameter Δ. 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, there exists a two-dimensional space of the supercritical perturbations, 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 $[(I_{pulse} \approx I_c$ and $I_{dc} \approx 0)$ or $(I_{pulse} \approx 0$ and $I_{dc} \approx I_c)]$ to very strong $(I_{pulse} \gg I_c$ and $I_{dc} > 0)$ perturbations.

The aim of this work is to present our studies on superconducting-to-resistive (S-R) 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-Schön (GS) theory,[4] which allowed for the incorporation of the dc bias of a superconductor and its relation with t_d.

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 Δ in a characteristic time τ_Δ and the development of a resistive hotspot across the strip's weakest link. At the early, nonequilibrium, or "hot-electron," stage, the quasiparticle relaxation dynamics is governed by the inelastic electron-phonon relaxation time $\tau_{e\text{-ph}}$, which for YBCO is ~1 ps.[5] The subsequent resistive hotspot-formation stage is a bolometric process, characterized by the phonon escape time τ_{es}, which for YBCO is typically on the order of nanoseconds and, in general form, is given by[6]

$$\tau_{es} = (4d)/(Kv), \quad (1)$$

where d is the YBCO film thickness, K is the average phonon transparency of the YBCO/substrate interface, and $v = 2.8$ km/s is the velocity of sound in YBCO averaged over the three acoustic modes. Thus τ_Δ should initially follow $\tau_{e\text{-ph}}$ and later be limited by τ_{es}. The nonequilibrium process is, of course, measurable only if the width of $I_{pulse}(t)$ is of the order of $\tau_{e\text{-ph}}$ or shorter. The t_d, which determines the appearance of a macroscopic resistive state, besides τ_Δ, is also related 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 Tinkham theory,[1] we choose to use GS theory[4] since it is the only approach that incorporates the dynamics of both Cooper pairs and quasiparticles. The GS model also allows the study of the

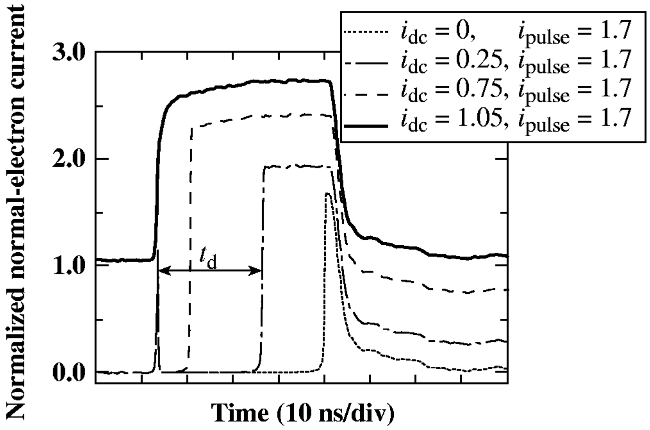

FIG. 1. Normalized normal-electron current vs time, simulated based on the modified GS theory for a YBCO bridge exposed to the supercritical perturbation consisting of a fixed normalized i_{pulse} and four different values of i_{dc} (see legend). The time delay t_d is defined as the time interval between the onset of the inductive response and the 50% point of the S-R transition.

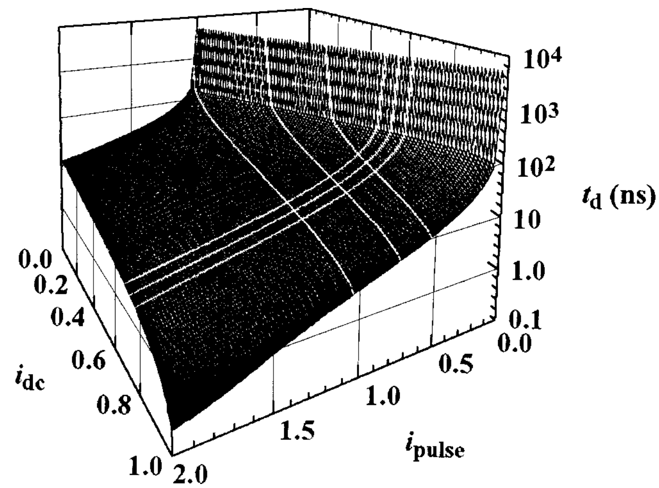

FIG. 2. Time delay t_d surface as a function of both i_{dc} and i_{pulse}. The t_d dependence on the supercritical perturbation was calculated using a modified GS theory for the parameters ($T/T_c=0.96$ and $\tau_\Delta=17$ ns) directly corresponding to our experimental conditions (white lines).

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,[7] while the quasiparticle distribution is given by the Boltzmann equation.[8] The main feature in the GS theory is the conservation of current between the superfluid and normal fractions of electrons. The latter relationship allowed us in a natural way to introduce into the GS model the supercurrent bias I_{dc} in addition to the quasiparticle perturbation $I_{\mathrm{pulse}}(t)$ and calculate time evolution of the normal-electron current component $I_n(t)$ flowing through the bridge as[9]

$$I_n(t)=\frac{1}{1+\dfrac{\pi\Delta_0 fQ}{dQ/dt}[1-2\,f_{\mathrm{FD}}(\Delta)]}I_{\mathrm{total}}(t), \qquad (2)$$

where $f=\Delta/\Delta_0$ and $Q=2\xi(T)mv$ are the main GS variables [$\xi(T)$ is the temperature-dependent coherence length and mv is the momentum the Cooper pair], $\Delta_0=\Delta(T=0)$, and f_{FD} is the Fermi-Dirac distribution function.

In our approach, the GS differential equations (i.e., Ginzburg-Landau and Boltzmann equations) are first solved in a steady state ($t \gg \tau_{\mathrm{es}}$), for a bridge perturbed only by I_{dc}, resulting in equilibrium values for the parameters of the system. Next, those parameters are used as initial conditions to solve again the GS equations for normalized $i_{\mathrm{total}}=I_{\mathrm{total}}/I_c$, constituted of the same $i_{\mathrm{dc}}=I_{\mathrm{dc}}/I_c$ and a time-varying $i_{\mathrm{pulse}}(t)=I_{\mathrm{pulse}}/I_c$, and finally, to compute Eq. (2). Figure 1 presents the normalized transients of the normal-electron current $i_n(t)=I_n/I_c$, calculated using Eq. (2) for four different values of i_{dc} and the constant, supercritical i_{pulse}. The shape of i_{pulse} corresponds to our actual experimental i_{pulse} signal. We note that after the initial spike (injection of normal electrons into a superconducting film), i_n drops to zero and the bridge remains superconducting until the S-R transition that occurs after the delay time t_d. The transition itself is very rapid, since our model takes into account only the intrinsic dynamics of the Δ collapse, without thermal broadening associated with the bridge self-heating. After the transition, i_n simply follows the i_{total} pulse. For $i_{\mathrm{dc}}>1$, the bridge always remains in the normal state, $f=0$, and i_n directly reproduces i_{total}. We note that this case, i_n exhibits a dc offset, which, as expected, is equal to i_{dc}. Figure 1 also demonstrates our way of defining t_d as the time interval needed for the i_n component to reach the 50% point of the S-R transition (in particular, t_d is shown as corresponding to the 50% point of i_n flowing through the bridge, for $i_{dc}=0.25$ and $i_{\mathrm{pulse}}=1.7$).

Using the procedure outlined above, we performed extensive simulations of various conditions leading to the S-R transition and plotted the results in Fig. 2, which presents the t_d dependence on both i_{dc} and i_{pulse}. The t_d dependence on the supercritical perturbation forms a surface, which exponentially diverges to infinity at the $i_{\mathrm{dc}}+i_{\mathrm{pulse}}=1$ boundary and very rapidly drops toward zero at $i_{\mathrm{dc}}=1$. This behavior is expected. In the $i_{\mathrm{dc}}+i_{\mathrm{pulse}}<1$ range, the perturbation is subcritical and the bridge always remains in the superconductive state (only the kinetic-inductive response is possible[5]), while for $i_{\mathrm{dc}}>1$, the bridge remains in the normal state irrespective of the value of the i_{pulse} perturbation. What is unexpected is the nonlinear $t_d(i_{\mathrm{dc}})$ dependence for a constant i_{pulse}. From our solution of the GS model, shown in Figs. 1 and 2, it is obvious that i_{dc} is not just a scaling parameter in the $i_{\mathrm{pulse}}>1-i_{\mathrm{dc}}$ switching criterion. The magnitude of the bridge bias plays the critical role in the switching dynamics not only for $i_{\mathrm{pulse}}<1$, 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. 2, correspond to our experiments that will be discussed below.

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)

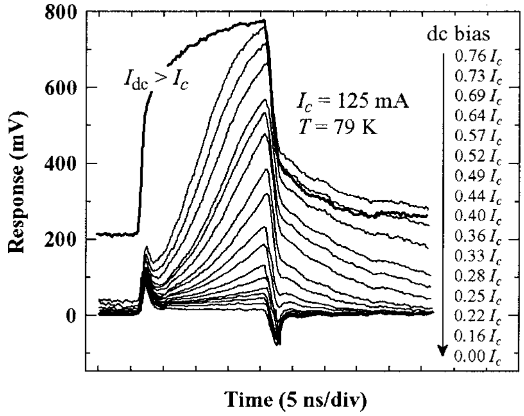

FIG. 3. Time-resolved YBCO microbridge response to a 20-ns, 130-mA current pulse for the various bridge bias levels at 79 K. $T_{c0}=82.5$ K; $I_c=125$ mA. For the top (thick line) wave form, the bridge was in the normal state ($I_{dc}>I_c$); note the large voltage offset that is representative of the normal state of the bridge.

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, transition width 0.5 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 cryostat. Nanosecond-wide electrical pulses from a commercial current-pulse generator were delivered to the bridge via a 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 3 shows a series of wave forms 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. The experimental, time-resolved response is qualitatively very similar to that predicted by GS model and shown in Fig. 1. From the bottom $I_{dc}=0$ wave form to the second wave form from the top with $I_{dc}=0.76 I_c$, the resistive response is seen as the *S-R* transition and the growth of the plateau region after the initial inductive peak. The *S-R* itself is stretched, as the resistive state produces substantial self-heating, but we can still define t_d in the same manner as in Fig. 1. The same self-heating effect is also visible on the post-pulse falling edge of the bridge response, as I_{dc} approached I_c. On the other hand, for $I_{dc} \ll I_c$, we observe a small negative inductive peak at the time moment corresponding to the end of the excitation pulse, suggesting that the bridge in this case remained in the superconductive state or, in other words, that t_d was longer that the 20-ns excitation pulse width. We can also identify the signature of the flux-creep effect, manifesting itself as a small voltage offset, observed before the initial inductive peak, as I_{dc} increased toward I_c. Finally, we note that for $I_{dc}>I_c$, the measured wave form (top thick line in Fig. 3) corresponds to the YBCO microbridge in the normal state. As predicted earlier, the measured output pulse in this case is just the input current pulse (see Fig. 1) multiplied by the bridge normal-state resistance. In the experimental case (Fig. 3), the output signal is slightly distorted due to resistive loss of the YBCO CPS.

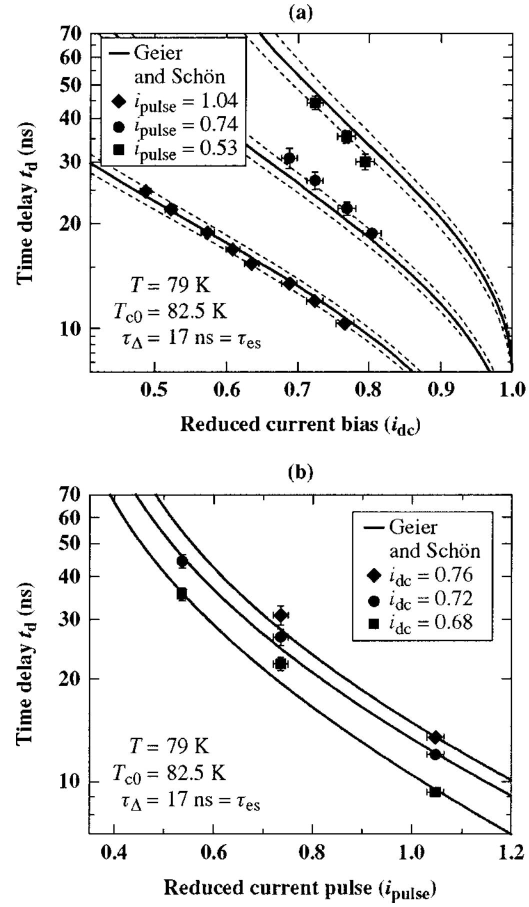

FIG. 4. Measured t_d as a function of i_{dc} (a) and i_{pulse} (b). The solid lines represent the GS theory and correspond to the white lines in Fig. 2. The dashed lines in (a) define the error range in the amplitude of the current pulse applied the bridge. Note that the t_d scales are logarithmic.

From a series of data sets analogous to Fig. 3, but collected under different experimental conditions, we extracted the t_d values as the time delay between the onset of inductive peak (instantaneous with the arrival of the input pulse) and the half-point of the *S-R* region of the voltage response. Our experimental t_d values along with GS theory are shown in Fig. 4. Figure 4(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. 4(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. 4 are the same as the white lines outlined on the t_d surface in Fig. 2. The selected levels of supercritical perturbations were $i_{total} > 1.2$, corresponding to the excitation range where the GS, Tinkham, and Pals-Wolter theories start to disagree.[9] 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 $\tau_\Delta = 17$ ns. This latter value is the same as the $\tau_{es} = 17$ ns for our YBCO-on-MgO films, calculated using Eq. (1) and $d = 200$ nm and $K = 0.020$ for the YBCO/MgO interface.[10] 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[6] and experimental[11] studies of the response of YBCO films exposed to optical perturbations. It is also consistent with earlier pulse perturbation experiments, since the literature data[12] seem to show that τ_Δ is proportional to the film thickness, and is consistent with the experimental determination of τ_{es}/d for YBCO deposited on MgO, which is 0.085 ns/nm.

In conclusion, we have presented a study of dc-biased YBCO microbridges excited by nanosecond-long current pulses, which lead 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 GS theory. The duration of the *S-R* response is, in our case, governed by the equilibrium dynamics of quasiparticles in the film and is limited by τ_{es}, with no need to introduce the special τ_Δ relaxation time. We can 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 $\tau_{e\text{-ph}}$ interaction time.

The authors want to thank Ying Xu for her assistance in experiments and Professor Boris Shapiro, Bar Ilan University, for fruitful discussions. This work was supported by NSF Grant No. DMR-0073366 and Grant No. 2000164 from the U.S.-Israel Binational Science Foundation, Jerusalem, Israel.

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