Picosecond Response of Optically Driven Y-Ba-Cu-O Microbridge and Josephson-Junction Integrated Structures

Photoexcitation studies of superconductors have been a subject of intense investigation for the last 20 years. Early experiments were performed on metallic superconductors using nanosecond and picosecond pulses and were concentrated on the dynamics of the photon-induced, superconducting-to-normal transition.[1,2] The discovery of high-temperature superconductors (HTS) prompted a new series of transient photoexcitation experiments. Experiments with optical-pulse-driven current-biased samples and direct measurements of the resulting voltage transient provide the most direct information on nonequilibrium processes in HTS. These experiments are also most relevant when evaluating the potential of HTS materials for fast photodetector applications. Recently, we have observed the single-picosecond electrical response of a current-biased $YBa_2Cu_3O_{7-x}$ (YBCO) microbridge exposed to femtosecond optical pulses.[3–6] The experiments were conducted in the temperature range from 4.2 K to 80 K, using our subpicosecond electro-optic (EO) sampling system.[4] The two mechanisms responsible for the picosecond response of the YBCO microbridge have been identified: nonequilibrium kinetic inductance and hot-electron heating.[7] The corresponding electrical transient was either a 2-ps-wide oscillation for the kinetic inductance response, or a single-picosecond spike for electron heating in the resistive state.[6]

Picosecond-impulse excitation of Josephson junctions has been extensively studied theoretically.[8–10] The simulations showed that a junction response is delayed with respect to the excitation impulse by a turn-on delay time τ_D, which depends on both the junction bias and the critical current I_c overdrive (I_c is defined as the maximum superconducting current that can flow through a Josephson junction). The rise time τ_R of the junction switching transient was also calculated and found to depend on the amount of the I_c overdrive, as well as on the product of the junction's normal resistance × the junction's capacitance ($R_N C_J$). In the case of the single-flux-quantum (SFQ) pulse generation by resistively shunted junctions (RSJ), the generated pulse has been predicted to have an amplitude equal to $2I_cR_N$ and a width corresponding to $\Phi_0/2I_cR_N$,[11] where $\Phi_0 = 2.07$ mV•ps.

In this article, we report our studies on the picosecond photoresponse of a current-biased YBCO microbridge coupled to a bicrystal YBCO Josephson junction. Femtosecond optical pulses were used to excite the microbridge in the resistive state[5] and to generate a series of picosecond-duration electrical transient pulses. These transients were in turn applied to switch the grain-boundary Josephson junction. The junction response was superimposed on the large feedthrough signal, but the junction signal could be identified due to its dependence on the bias current.

Sample Fabrication and Experimental Setup

The test structures, consisting of coplanar strip (CPS) transmission lines, were fabricated on (100) MgO bicrystal substrates, using a standard laser ablation technique and ion-beam etching.[12] YBCO films 50 to 100 nm thick were deposited at the substrate temperature 800°C and at the ambient oxygen pressure of 0.35 mbar. The deposition was followed by an annealing cycle in pure oxygen. Next, a 50-nm-thick gold layer was sputtered *in situ* on top of YBCO thin film at room temperature at an argon pressure of 0.05 mbar. The test structures were prepared in a two-step process. First, they were photolithographically defined and then etched with a low-current-density (1 mA/cm^2) ion argon beam. In the second step, the Au layer was removed from the top of the junction and bridge areas, using the same low-intensity ion etching. As a result, eight 8-mm-long CPS lines, containing 10-μm × 5-μm bridges and 5-μm-wide bicrystal Josephson junctions, were fabricated on each substrate. The 8-mm length of CPS was chosen to restrict the end-of-line reflections, assuring a 50-ps-long reflection-free measurement time-window. The schematic of our CPS line and the measurement configuration are shown in Fig. 77.39. We note that the test structure is not a Josephson-junction transmission line,[11] but rather a high characteristic impedance (80 Ω) CPS line with the junction electrodes representing high inductance. This type of experimental configuration was chosen for practical fabrication considerations and will be improved in future designs.

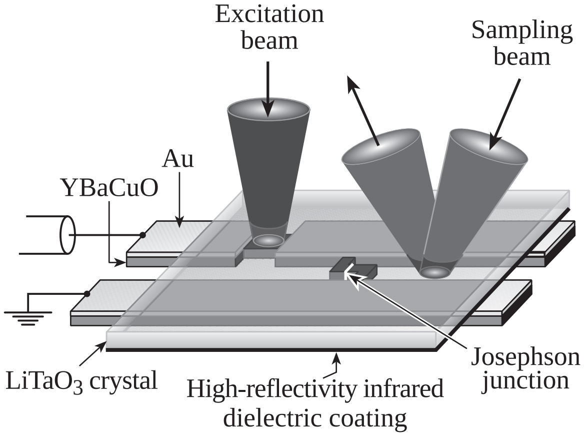

Figure 77.39
Experimental setup of CPS line and measurement configuration.

Our optical system for the femtosecond pulse excitation and EO sampling detection is described in detail in Ref. 4. Briefly, a mode-locked Ti:sapphire laser, operating at a repetition rate of 76 MHz, was used to generate 100-fs pulses at a wavelength of 800 nm. To perform EO characterization, the laser beam was split into two paths: a frequency-doubled ($\lambda = 400$ nm) excitation beam used for inducing the photoresponse signal in the bridge, and an 800-nm sampling beam for monitoring the electric field penetrating an EO ($LiTaO_3$) crystal during the electrical pulse propagation (see Fig. 77.39). The sampling beam was time delayed with respect to the excitation beam by a computer-controlled translation stage, directed between the coplanar lines through the $LiTaO_3$ crystal less than 100 μm away from the bridge, and reflected to the analyzer by a high-reflectivity dielectric coating at the bottom of the $LiTaO_3$ crystal. The sampling beam sensed the instantaneous birefringence introduced in $LiTaO_3$ by the photogenerated transient that propagated in the CPS underneath the crystal. By varying the relative delay between the moment of photoresponse generation (excitation beam) and the signal probing (sampling beam), the whole time-domain waveform could be resolved. From the operational point of view, our EO system can be regarded as a sampling oscilloscope[4] featuring <200-fs time resolution and <150-μV voltage sensitivity, which are well below the characteristics of transients reported here.

The samples were mounted in a continuous-flow helium optical cryostat. All the experiments were carried out in a temperature range from 20 K to 80 K with the temperature control of ±0.2 K. Our test structures were connected to dc current and voltage sources, for biasing and characterizing the *in-situ* current voltage (*I–V*) of the junction and the microbridge, as well as to a 14-GHz-bandwidth oscilloscope for aligning the experiment and monitoring the bolometric response.

Experimental Results

The studied YBCO thin films, junctions, and microbridges exhibited standard, high-quality characteristics. The superconducting transition temperature T_c of as-prepared, 100-nm-thick films was in the 85 K to 87 K range. The *I–V* characteristics of a bicrystal Josephson junction on a MgO substrate showed an RSJ-like behavior with $I_c = 700\ \mu$A and $I_cR_N = 2.5$ mV, and $I_c = 40\ \mu$A and $I_cR_N = 0.1$ mV, at 4.2 K and 77 K, respectively (Fig. 77.40). The microbridge *I–V* curves exhibited a flux-flow transition into a resistive state at $J_c \approx 10^6$ A/cm^2 at 77 K. At higher bias currents, hot-spot formation occurred and the microbridge was driven into a switched (resistive) state. The microbridges were biased with a voltage source to prevent their destruction.[4]

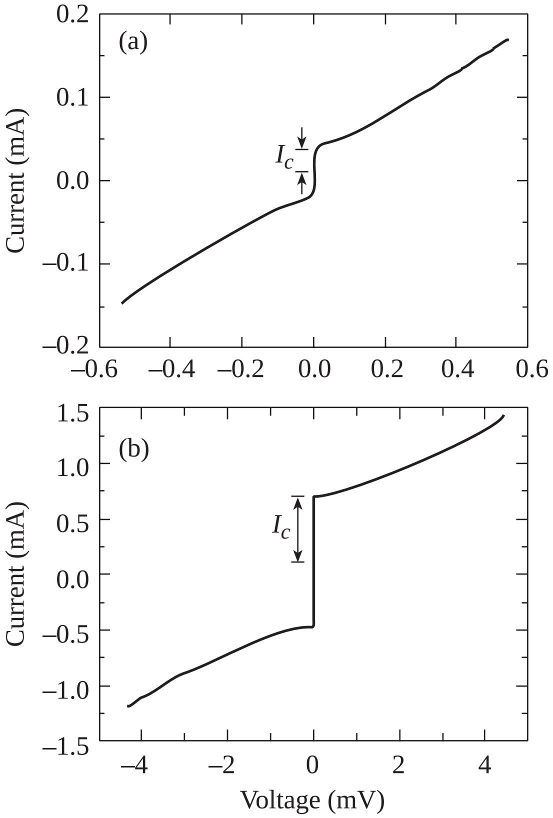

Figure 77.40
Current-voltage characteristics of a bicrystal Josephson junction with $I_c = 40\ \mu$A and $I_c = 700\ \mu$A at 77 K and 4.2 K, respectively.

Figure 77.41 shows the EO sampling measurement of a 2.1-ps-wide electrical transient, typical for the microbridge biased in the resistive state.[5] Pulses of this type were used in all experiments presented in this article. Typically, the pulse amplitude was about 25 mV, which, for the approximately 80-Ω CPS line, corresponded to an ~300-μA current pulse.

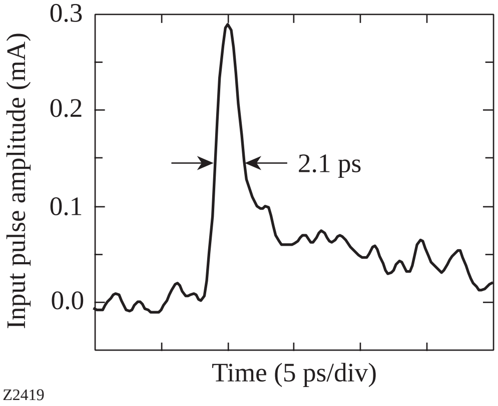

Figure 77.41
Photogenerated electrical transient of the YBCO microbridge.

The pulse from Fig. 77.41 was applied to the junction, and the resulting signal was electro-optically detected approximately 50 μm after the junction (see Fig 77.39). Experiments were performed at 20 K, and the junction I_c was 650 μA (I_cR_N ≈ 2 mV). To elicit a junction response from the measured output, we used the following procedure: We biased our junction in five different points on the *I–V* curve, namely at 0 I_c, ±0.7 I_c, and ±1.5 I_c, and recorded the response. The "+" bias corresponded to the positive amplitude of the input pulse, while in the "–" polarity, the junction was biased in the opposite direction to the excitation pulse. Figure 77.42(a) shows the normalized transient responses from the junction at 0 I_c, +0.7 I_c, and +1.5 I_c. We note that the initial, positive part of each response overlaps, while some differences are visible in the remainder of the pulse. After the initial oscillatory transient, we observe additional oscillations, which are very noisy and, therefore, difficult to analyze. A similar set of responses was collected for the –0.7 I_c, –1.5 I_c, and 0 I_c bias points and is shown in Fig. 77.42(b). All signals presented in Fig. 77.42 look very similar since they are dominated by the inductive response of the junction leads combined with the CPS resistance. Thus, the oscillatory transient with no bias applied to the junction (thin lines in Fig. 77.42) will be referred to as the *feedthrough* in further discussion.

Discussion

We believe that despite the fact that due to the design constraints all the waveforms presented in Fig. 77.42 look very similar and are dominated by the feedthrough signal, they contain information about switching dynamics of the YBCO Josephson junction; thus, we have subtracted the 0 I_c feedthrough signal from each measured waveform (results are shown in Fig. 77.43). For clarity, we separately showed the responses for the ±1.5 I_c biased junction [Fig. 77.43(a)] and for ±0.7 I_c [Fig. 77.43(b)]. In both cases, we overlaid the traces with the 0 I_c signal, which can be regarded as the zero-time reference for the junction response. From Fig. 77.43(a) we observe that when the junction is in the voltage state, the junction response for both bias polarities is positive and consists of an ~1-ps-wide transient with a turn-on delay of 0.7 ps. The response is consistent with our simulations (not shown)

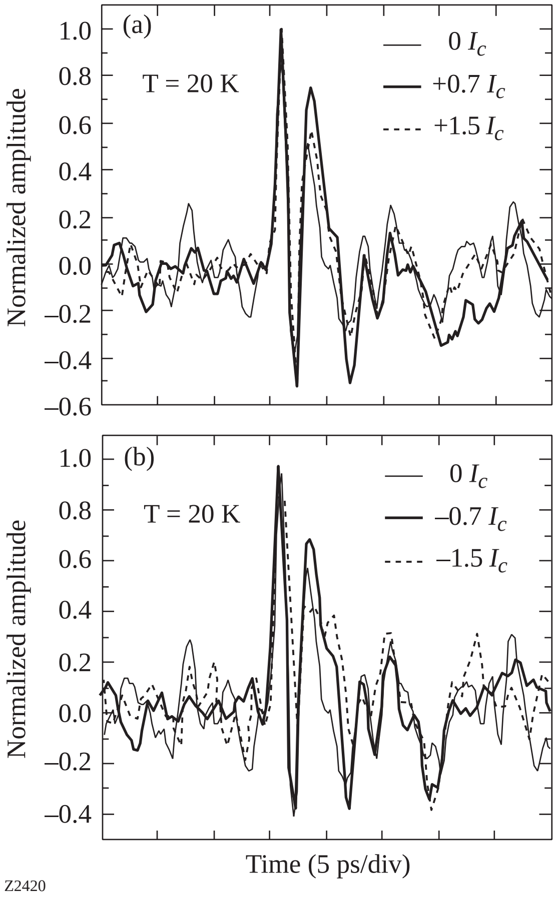

Figure 77.42
The test structure response to the ultrafast input pulse measured for different junction biases on the CPS line 50 μm after the Josephson junction. All signals are normalized to the zero-bias feedthrough signal.

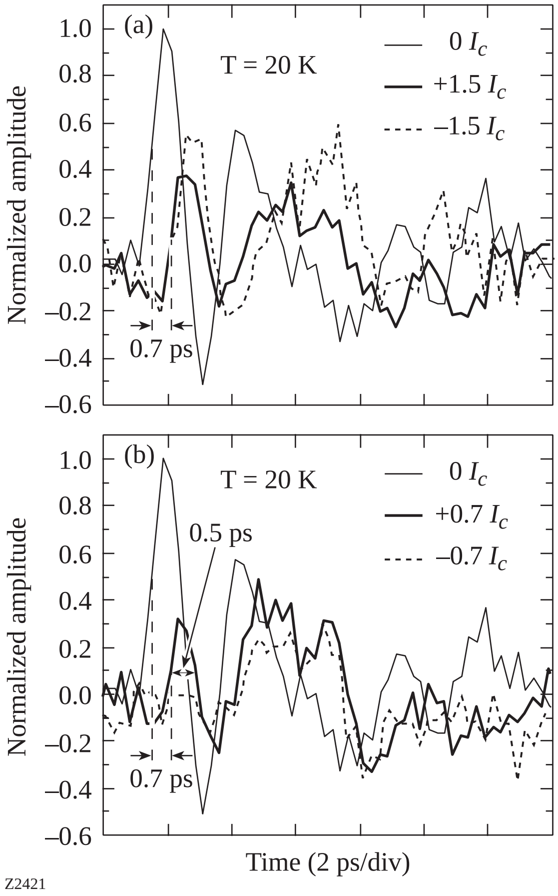

Figure 77.43
Response of the Josephson junction to the 2.1-ps electrical input pulse measured for different junction biases.

that in the voltage state, when junction current is oscillating with the frequency corresponding to the bias voltage, a small (compared to the bias) current-pulse perturbation generates a signal always in the direction of the excitation pulse polarization. In addition, the signal response is delayed with respect to the excitation.

The transients obtained for the junction biased in the superconducting state (±0.7 I_c) are shown in Fig. 77.43(b). When the dc bias polarity is in the same direction (+0.7 I_c) as the 0.46 I_c input-pulse amplitude, the excitation "knocks" the junction out of the zero-voltage state and we observe an SFQ-like, 0.5-ps-wide transient. We note that, at 20 K, $I_cR_N \approx 2$ mV; thus, the SFQ amplitude is expected to be ~ 4 mV, which leads to ~ 0.5-ps SFQ width, in good agreement with our observation. In the case of the negative bias (–0.7 I_c), however, the incoming pulse is unable to switch the junction and no response is detected. The measured τ_D of the +0.7 I_c biased junction is 0.7 ps, the same as for the ±1.5 I_c case. We must finally note that signals observed in Figs. 77.43(a) and 77.43(b) after the initial pulse responses discussed above are associated with the secondary input-pulse reflections and resulting secondary switching of our junction. Their detailed analysis and comparison with numerical circuit simulations will be presented in a later publication.

Conclusion

Picosecond electrical pulses, optically generated in current-biased YBCO microbridges, were used to excite the response of a bicrystal Josephson junction placed in the YBCO superconducting coplanar transmission line. The transients recorded just past the junction contained large feedthrough signals, but the junction response could be separated by subtracting the feedthrough from the signals obtained under different bias conditions. As a result, we were able to observe single-picosecond switching of HTS Josephson junctions, as well as to measure the junction turn-on delay time. Our findings provide confirmation of the potential of YBCO for ultrafast optical and electrical transient detection and processing. In the future, however, a new feedthrough-free test structure representing YBCO Josephson-junction coplanar transmission line is needed. The development of such a circuit is currently underway.

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