Electro-Optic Sampling of 1.5-ps Photoresponse Signals from $YBa_2Cu_3O_{7-\delta}$ Thin Films

Studies of the fast photoresponse of high-T_c thin films may reveal important information on scattering mechanisms or nonequilibrium processes in high-T_c materials. Optical pump-probe experiments on $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films have reported picosecond and subpicosecond time constants,[1,2] but the interpretation of the results is still controversial. Photoresponse experiments with current-biased samples may provide more direct information on nonequilibrium processes,[3–8] but the bandwidth of the oscilloscopes used in these experiments is usually the limiting factor in resolving fast voltage transients on the picosecond time scale. Photoresponse signals with widths ranging from 16 to 40 ps have been reported recently using fast oscilloscopes.[5,7,8] Electro-optic sampling,[9] on the other hand, offers improved time resolution in the subpicosecond regime and has been used to study superconducting electronics[10] and the propagation of picosecond pulses on superconducting coplanar transmission lines.[11] Electro-optic sampling has also been used recently to show that laser-induced switching of Pb transmission lines from the superconducting to the normal state occurs within 1 ps.[12]

This article describes experiments that, to the best of our knowledge, are the first to use electro-optic sampling to study the photoresponse of YBCO thin films. We have observed electrical transients as fast as 1.5-ps full-width at half-maximum (FWHM), which are the fastest photoresponse signals reported to date from a YBCO thin film. We have also found that picosecond transients can be seen in optically thick films (>100 nm), despite previous claims that fast transients can be seen only in ultrathin films with thicknesses of the order of 10 nm.

A schematic of the experimental setup is shown in Fig. 63.35. The *c*-axis YBCO films were grown epitaxially by laser ablation on 0.5-mm-thick $LaAlO_3$ substrates. Films with thicknesses of 100 and 200 nm were used. A coplanar transmission line structure[7] was patterned into the films using standard photolithographic techniques and a wet chemical etch. The center line of the coplanar waveguide (CPW) had a width of 130 μm, and the width of the gap to the ground lines was 336 μm. The length of the CPW was about 1.5 mm. A bias current could be applied to one end of the CPW, while the other end was terminated to the ground plane by a narrow bridge with a length of 100 μm. The bridge widths were 7 μm and 17 μm for the 100-nm film, and 10 μm for the 200-nm film.

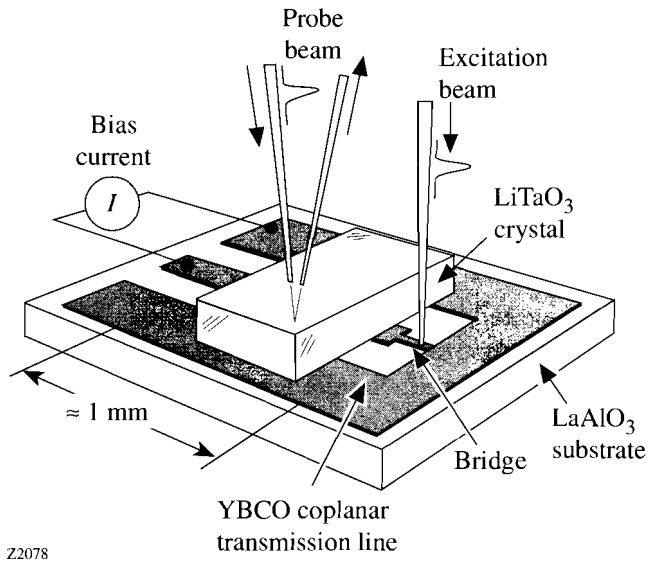

Fig. 63.35
Schematic of the experimental setup.

After processing, the 7-μm bridge of the 100-nm film had a zero-resistance critical temperature T_{c0} of 90.5 K and a transition width of about 0.8 K. The resistivity ρ at 100 K was 144 $\mu\Omega$ cm (R = 205 Ω), and the critical current J_c at 77 K was about 2×10^6 A/cm^2 (I_c = 12 mA) using a 10 μV/cm criterion for the onset of dissipation in the bridge. As described elsewhere,[7] the 10-μm bridge of the 200-nm film had T_{c0} = 89 K, ρ(100 K) = 124 $\mu\Omega$ cm (R = 62 Ω), and $J_c = 1.5 \times 10^6$ A/cm^2 (I_c = 29 mA).

A mode-locked Ti:sapphire laser operating at a repetition rate of 76 MHz was used to generate 150-fs pulses at a wavelength of 790 nm. To perform electro-optic sampling,[10] the pulses were split into two beams: an excitation beam for

inducing a photoreponse signal in the bridge, and a probe beam for monitoring the electric field from the resulting voltage transient in the $LiTaO_3$ crystal. Both beams were focused onto the sample by passing them through the same microscope objective, also used for viewing the illuminated region. The diameter of the spot size on the bridge was about 10 μm. The excitation beam was chopped by an acousto-optic modulator at a frequency of 1 MHz, and a translation stage provided the necessary time delay of the probe beam with respect to the excitation beam. The electric field in the electro-optic crystal was probed close to the edge of the center line of the CPW and about 400 to 500 μm from the position of the microbridge. A reflective dielectric coating on the bottom face of the 1-mm-thick $LiTaO_3$ crystal reflected the probe beam back out through the microscope objective to an analyzer that detected the change in polarization of the probe beam arising from the electric field of the photoresponse signal. Lock-in amplification techniques were then used to extract the electro-optic signal. After 30 averages for each waveform, a voltage resolution of about 0.5 mV for the photoresponse signals could be obtained. Due to large reflections from the end of the short transmission line, time delays beyond 40 to 50 ps could not be studied.

As described elsewhere,[7] the samples were mounted in vacuum on a cold finger cooled with liquid nitrogen. All the experiments discussed here were therefore carried out at a base temperature of 78.6 K, as measured by a temperature diode placed near the sample. It is important to note that increasing the average power P_{av} of the excitation beam raised the average temperature of the film at the laser spot. It was estimated that the average temperature increase of the portion of the bridge illuminated by the beam was about 3 K/mW. Thus, for $P_{av} = 0.4$ mW incident on the bridge, the base temperature would increase to 79.8 K.

Figure 63.36 shows a 1.5-ps-wide voltage transient observed from the 7-μm bridge of the 100-nm film. The slow rise time and the faster fall time of the transient followed by oscillations suggest that the original photoresponse signal generated at the bridge has experienced some dispersion by the time it reaches the sampling point in the electro-optic crystal.[11] The inset of Fig. 63.36 shows a 1.8-ps-wide photoresponse signal from the 10-μm bridge of the 200-nm film. Figure 63.37 shows the dependence of the photoresponse signal on the bias current for the 7-μm bridge of the 100-nm film at a fixed fluence of 15 $\mu J/cm^2$. At high bias currents, as shown in Fig. 63.37(a), there is a fast transient less than 2 ps wide followed by a fast tail with a fall time of about 10 ps. At later

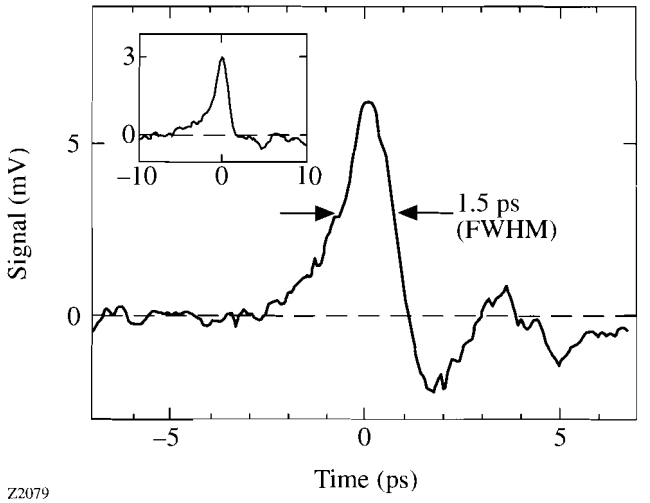

Fig. 63.36
Photoresponse signal from a 7-μm-wide bridge of a 100-nm-thick YBCO film at a bias current of 15 mA and a fluence of 15 $\mu J/cm^2$ ($P_{av} = 0.4$ mW). The full-width at half-maximum (FWHM) of the voltage transient is 1.5 ps. The inset shows a photoresponse signal from a 10-μm-wide bridge of a 200-nm-thick film at the same fluence but at a bias current of 60 mA. The width of the signal in the inset is about 1.8-ps FWHM.

times, a much slower component develops due to a resistive bolometric response of the film.[6,7] As the bias current is decreased, as in Fig. 63.37(b), the amplitude of the fast tail becomes much smaller with respect to that of the initial fast transient, and only a small amount of the resistive component remains. At lower bias currents, the fast tail and resistive component disappear completely, as shown in Fig. 63.37(c) and in the 15-mA case of Fig. 63.36, and only the picosecond transient remains, followed by a negative component in the signal with a decay time of about 15 ps.

We believe that the picosecond photoresponse transient (FWHM < 2 ps) is due to a kinetic inductive response given by $V = I\ dL/dt$, where V is the voltage, I is the bias current, and L is the kinetic inductance of the bridge.[3,5–8] Figure 63.38 confirms the linear behavior of the amplitude of the picosecond photoresponse signal with the bias current, as predicted by a kinetic inductive response. The kinetic inductance of a superconducting bridge is inversely proportional to the superfluid density. In a purely kinetic inductive response, a positive voltage transient represents a net breaking of Cooper pairs, and a negative transient signifies a net recombination of excited quasiparticles back into Cooper pairs.[3] The negative response seen in Fig. 63.37(c) may be evidence for an effective nonequilibrium recombination time of about 15 ps in YBCO. Negative transients with durations of about 30 ps have been

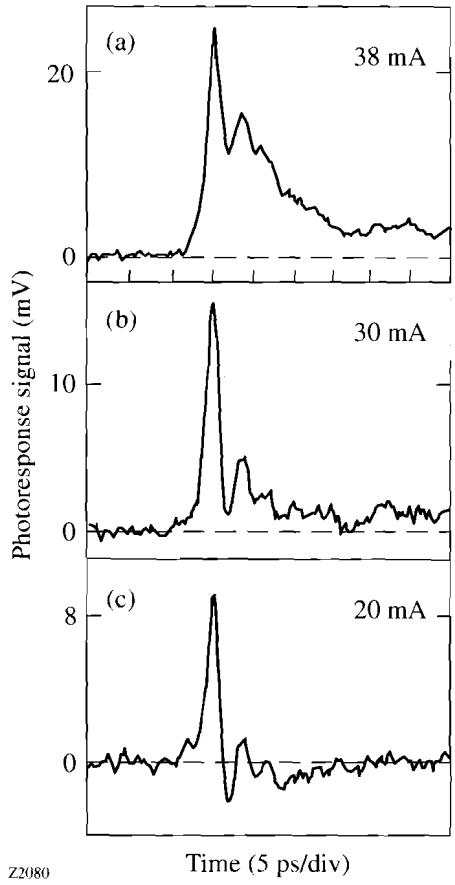

Fig. 63.37
Photoresponse signals from the 7-μm bridge of the 100-nm film for bias currents of (a) 38 mA, (b) 30 mA, and (c) 20 mA. The fluence was 15 μJ/cm^2 (P_{av} = 0.4 mW). Aside from the different bias currents, conditions were identical to those of the 15-mA case of Fig. 63.36. Notice the fast tail at high bias currents in (a) and (b), which then disappears at lower bias currents in (c). Also notice the negative component to the signal in (c).

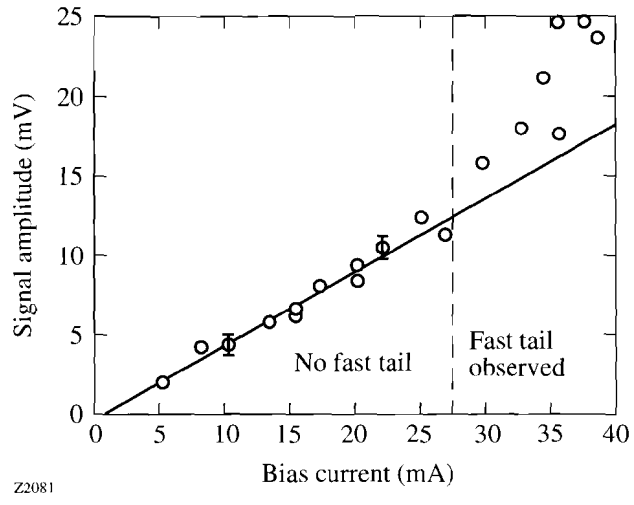

Fig. 63.38
Amplitude of the photoresponse signal (open circles) as a function of bias current for the 7-μm bridge of the 100-nm film at a fluence of 15 μJ/cm^2 (P_{av} = 0.4 mW). Above 28 mA, a fast tail is present, and the amplitude of the signal is not linear with the bias current. Below 28 mA, the fast tail disappears, and the response becomes linear with bias current. The solid line is a least-squares fit to the data below 28 mA. Error bars of ±0.5 mV are shown on two of the data points.

reported recently in photoresponse experiments on YBCO thin films using fast oscilloscopes.[7,8] The area under the negative part of the response in Fig. 63.37(c) is also approximately equal to the area under the faster positive component. This suggests that the positive transient arises mainly from a nonequilibrium (or nonbolometric) kinetic inductive mechanism,[3,5,8] as opposed to a change in the kinetic inductance arising from a purely thermal (or bolometric) response, which would not account for the observed negative transient.[6,7]

A kinetic inductive bolometric model,[6,7] however, predicts a voltage transient with an amplitude of about 30 mV and a width of 0.15-ps FWHM for the conditions given in Fig. 63.37(c). This would give a 3-mV signal after broadening to 1.5-ps FWHM, which is the same order of magnitude as the observed transient of about 9 mV. In a two-temperature nonequilibrium heating model with a ratio of phonon to electronic heat capacities of $C_{ph}/C_e = 40$ and an electron-phonon relaxation time of 1.5 ps,[13] the change in temperature ΔT_e of the electronic system is about 32 K. The electronic temperature would therefore exceed T_c, which might induce a transition in the bridge to the normal state. The resistance of the 7-μm × 100-μm × 100-nm bridge at 110 K is around 220 Ω, or about 22 Ω for a 10-μm section. At a bias current of 20 mA, this would give a voltage transient with an amplitude of 400 mV for a superconducting-to-normal-state transition, which is much larger than the observed signals.

The origin of the fast tail may be due to several mechanisms. At high bias currents (Fig. 63.37) or large fluences (not shown), where the fast tail is seen in the photoresponse signal, the time over which net pair breaking occurs may be extended, which would widen the positive response of the signal. The fast tail may also be due to fast vortex motion across the width of the bridge. Studies of flux-flow transistors have revealed vortex velocities as high as 6×10^7 cm/s.[14] The transit time across a 7-μm-wide bridge would therefore be about 12 ps, which is close to the observed fall time of about 10 ps for the fast tail. Recent studies on switching instabilities in current-biased YBCO thin films have reported lower vortex velocities

of the order of 2×10^5 cm/s,[15] which would not account for a 10-ps duration of the fast tail. Furthermore, the duration of the fast tail did not increase when a wider bridge with a width of 17 μm was used with a 10-μm laser focus. Experiments with larger beam focuses on wider bridges may be necessary to study this effect.

In conclusion, we have observed for the first time photoresponse signals less than 2 ps in duration from YBCO thin films using electro-optic sampling techniques. The picosecond transients were seen in optically thick films and at a repetition rate of 76 MHz. We believe that the fast picosecond response is due to a kinetic inductive mechanism, and that the fast tail may be due to ballistic vortex motion across the bridge. The fast response shown in this work makes YBCO films suitable for high-speed applications, e.g., as photodetectors operating above 100 GHz.

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