Section 2
ADVANCED TECHNOLOGY DEVELOPMENTS

2.A Interaction of Picosecond Optical Pulse with High-Temperature Superconductors

The recently discovered high-temperature, ceramic oxide superconductors present new possibilities for optical detectors and opening switches.[1-5] The viability of these applications depends on the nature of optical interactions and resulting microscopic energy transport within these materials, and how the superconducting electrical properties are thereby affected. Several models have been proposed[6-8] to explain experimental observations on the oxide superconductors, but the full picture remains somewhat murky. The major contention appears to be whether the optical response is predominantly bolometric (i.e., thermal), or alternatively due to some other, perhaps nonequilibrium mechanism.

We have investigated the transient electrical response of $YBa_2Cu_3O_7$ (YBCO) superconducting films irradiated with fast optical pulses from a Nd:YAG laser. The pulses are about 100 ps long, and the temporal resolution of the sampling scope is about 1 ns, fast enough to distinguish thermal and nonthermal processes. We show below that, although the magnitude of the signal corresponds to simple heating, nonequilibrium energy transport must be playing a part in distributing the heat through the thickness of the film.

A parallel motivation for our experiments has been to assess the feasibility of a high-T_c film as the active element in an optically triggered high-current opening switch. In such a switch, a superconducting current shunt is illuminated by a fast optical pulse.

The superconductor is then rapidly converted into a high-resistance (normal) conductor, diverting the current into the desired load. Potential applications include pulsed-power systems[9] and fault-current limiters.[10] Several features of oxide superconductors are attractive for such a device, including low optical reflectivity, large absorption depth, high normal-state resistance, moderate operating temperatures (77°K), and potentially large currents (up to ≈ 10 MA/cm^2). A switch 1 μm thick and 1 cm wide would be able to carry 1 kA. Our measurements reported here indicate that the most important requirement, fast switching (on the nanosecond scale or less), can also be met in these films.

Opening switches are interesting because they can be used in conjunction with inductive electrical storage devices such as superconducting magnets. As shown in Fig. 39.17, the opening switch is placed in series with the inductor and, when the switch opens, the current is diverted to the load. At the present time there are very few fast electronic opening switches. Most electronic switches are closing switches that can only be used with capacitive storage systems. An additional advantage of a superconducting opening switch is that it would not introduce losses in the inductive charging circuit.

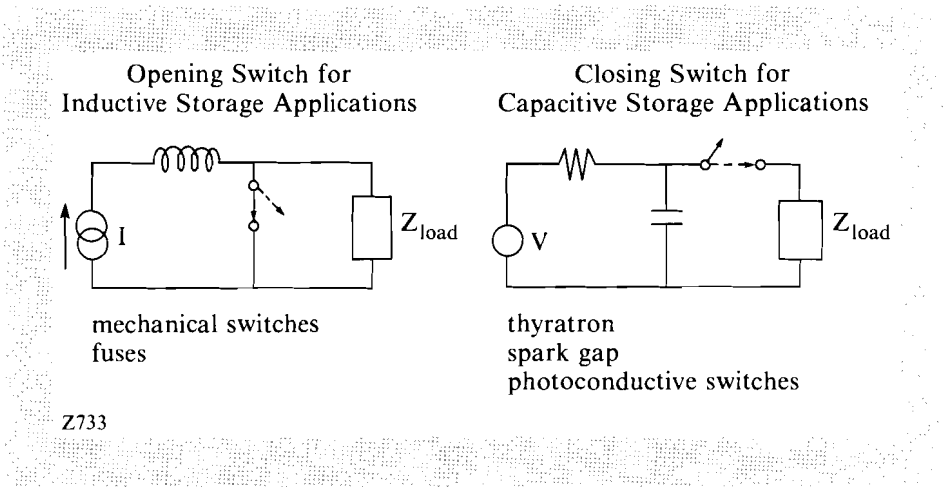

Fig. 39.17
Opening and closing switch configurations.

Sample Preparation

The superconducting films for this study were deposited (by personnel at CVC Products of Rochester, NY) using rf magnetron sputtering from a single stoichiometric $YBa_2Cu_3O_7$ target onto polished yttria-stabilized zirconia single-crystal substrates, yielding films of similar composition.[11] After an *ex-situ* anneal to 850°C followed by a slow cool in oxygen to convert completely to the superconducting state, the films consisted of randomly oriented grains ≈ 1 μm across for a 1-μm-thick film.

In order to carry out quantitative electrical measurements on the films, we have used a scanned focused laser beam to ablate parts of the film and thereby pattern device structures.[12] The laser was the same one used for the laser switching described below: a pulsed Nd:YAG laser with regenerative amplification, with 100-ps pulses at

1.064 μm and a repetition rate of 1 kHz. A single pulse with 10 μJ of energy, focused down to a 20- to 40-μm spot (a fluence of 1 to 10 J/cm^2), could etch through a 1-μm-thick film. By scanning the sample at $\approx$1 mm/s, we could etch line across the film. The samples used for the transient response studies consisted of an *H* structure with a central bridge region 263 μm wide and 2.5 mm long.

Low-resistance contacts (about 1 Ω) were obtained by evaporating 0.2 μm of Ag on top of the YBCO films, and then wire-bonding to the Ag pads. The dc resistive transition of the bridge region of a 0.7-μm-thick film is shown in Fig. 39.18 for two different measuring currents, together with the temperature dependence of the superconducting critical current (defined by a voltage of 1 μV). Note that the normal-state resistance is only weakly dependent on temperature. This sample is not optimized, exhibiting a broadened transition ($R = 0$ only below 60°K) and relatively low critical-current density (<1 kA/cm^2 at low T). Thicker films (>1 μm) generally exhibited much better superconducting performance, as did films prepared on epitaxial substrates or by deposition at higher temperatures. Still, as we indicate below, this nonideal granular film showed a strong optical response over a wide range of temperatures, currents, and laser powers. The data presented in this paper will primarily focus on the film of Fig. 39.18, but data will also be presented on thicker and thinner film as well as films on $SrTiO_3$.

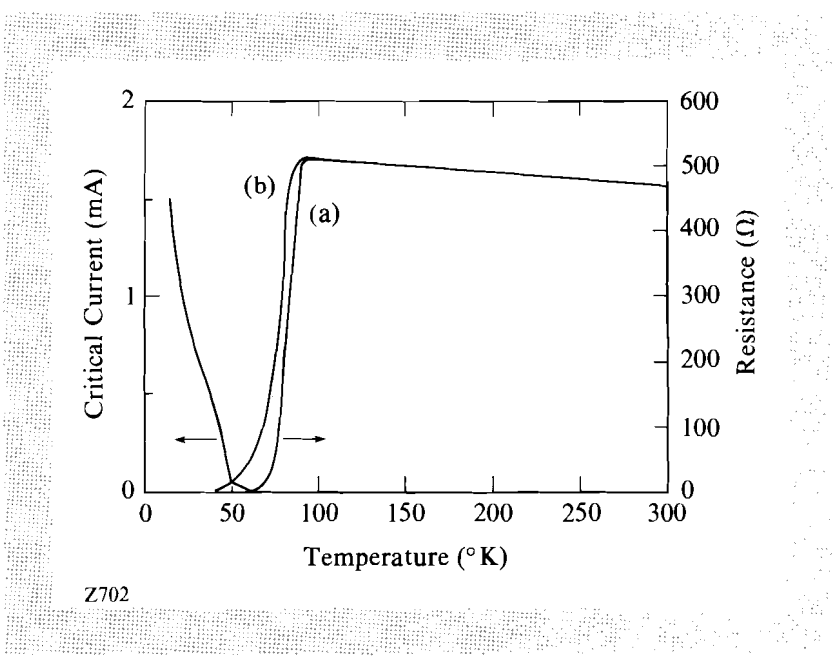

Fig. 39.18
Temperature dependence of dc resistance $R(T)$ for superconducting YBCO film #216 using two measuring currents, (a) $I = 10$ μA and (b) $I = 1$ mA. The dimensions of the region tested were 2 mm long $\times$ 200 μm wide $\times$ 0.7 μm thick. Also plotted is the critical current $I_c(T)$.

Experimental Procedure

For the pulse-excitation measurements (see Fig. 39.19), the sample was mounted in vacuum in a continuous-flow He Dewar, on a stage whose temperature could be controlled from 10°K to 100°K or higher. The switch was illuminated (from the top of the film) through a quartz window with a 3-mm-wide beam from the Nd:YAG infrared laser with

100-ps pulses, each with up to 100 μJ of energy, at a repetition rate of 50 Hz.

The switch was provided with a dc bias (typically 0.1 to 5 mA) across its legs, and the voltage across the two others was connected to a terminated 50-Ω coaxial line, which was measured with either a fast-analog or a digital-sampling oscilloscope. Care was taken to eliminate possible transmission-line reflections in the circuit. Data was recorded with a 200-MHz digital oscilloscope. The rise time was measured with a 350-MHz fast-analog scope.

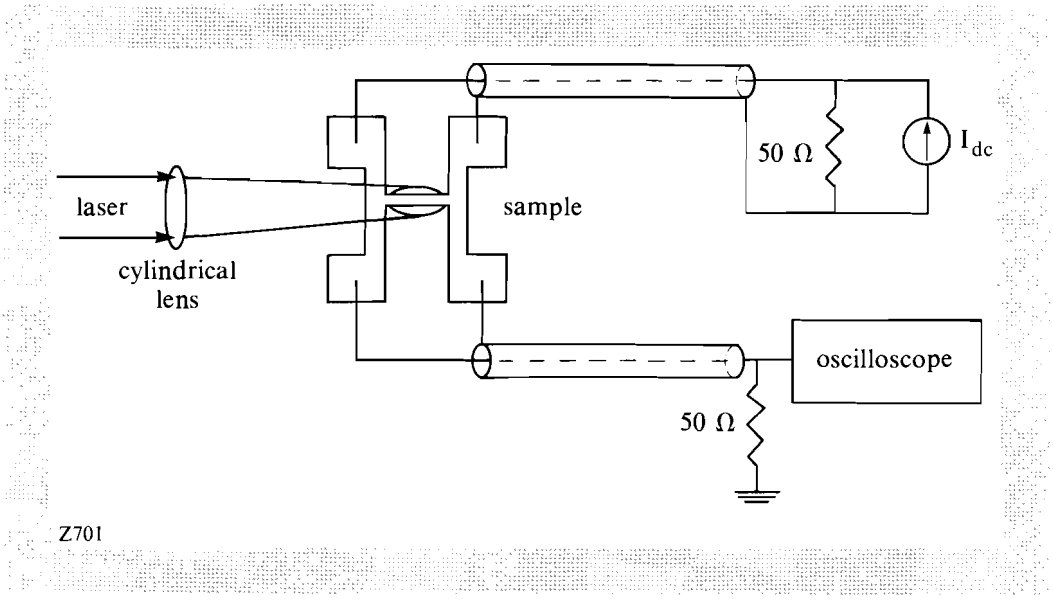

Fig. 39.19
Schematic of the experimental setup for pulsed-laser excitation of superconducting thin-film sample.

An example of the transient response of the sample to a 150-ps laser pulse is shown in Fig. 39.20, on the 10-ns time scale. Since the full normal-state resistance of the switch was about 500 Ω, much greater than the 50-Ω line impedance, a parallel combination of the two was measured. The data were taken for $T = 17°K$, for a current $I = 2$ mA and incident fluences of 0.53, 2.1, and 6.7 mJ/cm^2. The nonzero voltage on the left results from the use of a two-point probe, thus including the contact resistance in the baseline measurement. After illumination the load resistor experiences a sharp rise in voltage in about 2 ns, a slower rise in voltage on the scale of 10 to 100 ns (missing in some cases), and a slow decay back to the background level with a characteristic time of about 1 μs. The fast rise and slow relaxation on these time scales were present for all parameters studied. The measured rise time was limited by dispersion in the measurement circuit.

Results and Discussion

In Fig. 39.21 we plot the magnitude of the fast voltage rise versus the laser fluence, together with results of a simple heating model

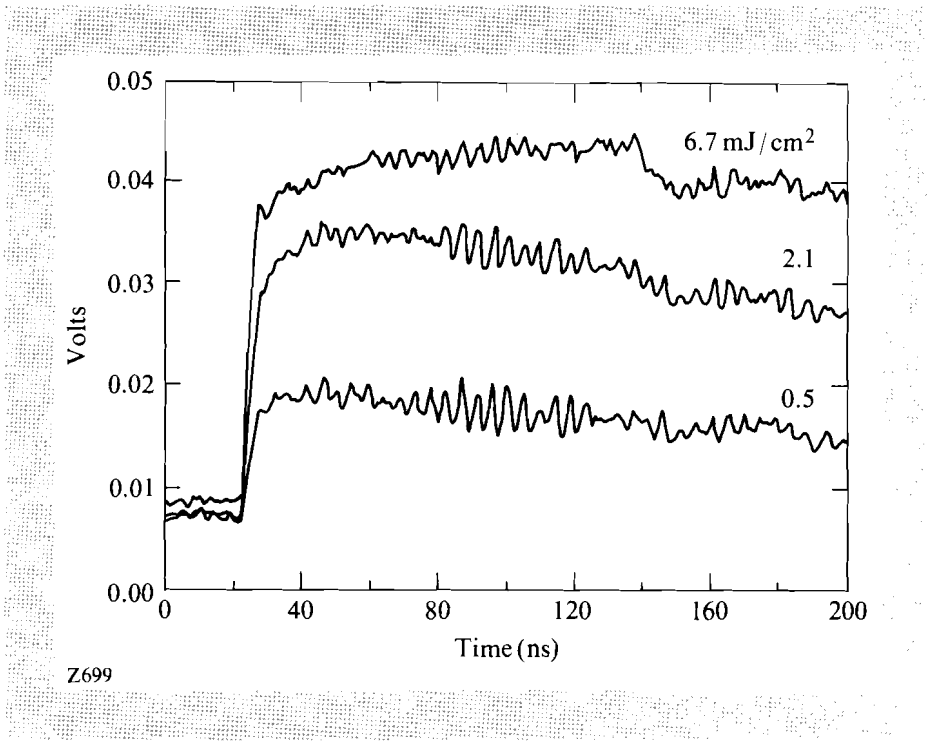

Fig. 39.20
Transient response of sample #216 to a 150-ps optical pulse, for several values of laser fluence, for $T = 17$ °K and $I = 2$ mA. The switching time ≈ 2 ns was identified on a faster analog scope.

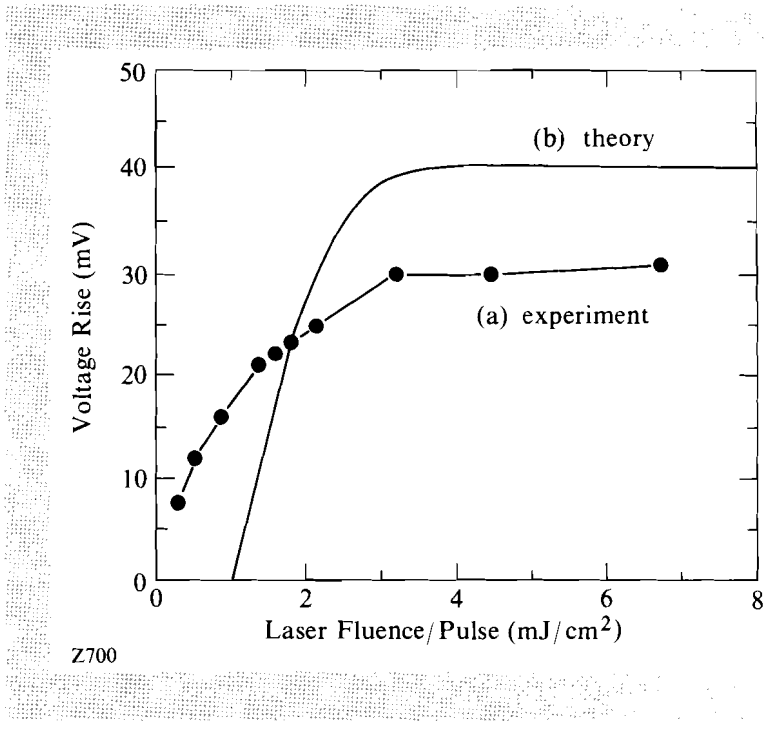

Fig. 39.21
Dependence of the fast transient voltage rise on laser fluence. (a) Experimental measurements, for $T = 17$ °K and $I = 2$ mA. (b) Theoretical results of a simple heating model assuming uniform distribution of energy through the film thickness.

where we assume the optical energy is uniformly distributed throughout the film. The switch was assumed to attain a resistance given by the resistance versus temperature curve in Fig. 39.18. Above a fluence of about 2 mJ/cm^2 per pulse, the voltage saturates, corresponding to switching the full normal-state resistance.

The optical-absorption depth for the YBCO film was measured using a spectrophotometer and found to be about 120 nm, only weakly dependent on wavelength. This is consistent with other reports in the literature.[13] Since the films are much thicker than this, the optical energy is initially deposited almost entirely in the top 200 nm of the film. If the effect of the light was simply to drive the top layer of the superconducting film into the normal state, an initial voltage would fall as soon as the current could divert into a deeper layer of the film that is still superconducting (the films should be superconducting down to the substrate, particularly at low T). This would be the case whether the current was flowing uniformly or was restricted to the surface by superconducting screening. This current redistribution should occur much faster than the equilibrium heat flow (see below). A straightforward application of Maxwell's equations shows that field penetration into a conductor (essentially the ac skin-depth problem) occurs by a diffusive process with a characteristic electromagnetic diffusivity $D_{em} = \rho/\mu_o \approx 10^5$ cm^2/s, where $\rho \approx 1$ mΩ·cm is the normal resistivity of this film. This value corresponds to approximately 1 fs for current to divert around a normal layer $\approx$100 nm thick, much faster than our temporal resolution, and can clearly not account for the 1-μs decay we observe.

Equilibrium thermal transport is governed by the thermal diffusivity $D = K/C$, where K is the thermal conductivity and C the heat capacity (per unit volume). These were not measured for these films, but an upper estimate of K at 25°K (for a single crystal) is of order 0.01 W/cm°K, and that for C at a similar temperature is 0.1 J/cm^3°K.[14] These correspond to $D \approx 0.1$ cm^2/s, or diffusion of 30 nm in 100 ps and 300 nm in 10 ns. Clearly, in less than 2 ns, the heat cannot have spread throughout a 700-nm film. We are therefore forced to conclude that, on the nanosecond time scale, the heat is distributed essentially uniformly throughout a 0.7-μm film.

The estimates made above have been verified by modeling the thermal transport with finite-element code. The energy absorbed per unit length was deduced from the optical-absorption length. The initial temperature distribution was determined by integrating:

$$dE_{\text{absorbed}}(x)/dx = \rho \int_{T_0}^{T_f} C_p(T)dT$$

where $C_p(T) = 0.0028T$–0.04 (J/cm°K) and is determined from a fit to the data in Ref. 14. ρ is the linear mass density and dx is the incremental length, using a thermal conductivity of 5×10^{-3} W/°K cm^2. These values were used to solve the one-dimensional heat equation. Figure 39.22 shows the time evolution of the temperature profile for the case of insulated boundary conditions. This case will underestimate the time necessary for the entire thickness of the material to rise above T_c because it ignores the heat lost to the substrate. This figure shows that the temperature changes very little in 2 ns and takes 50 ns to rise above T_c at the back of the film. The

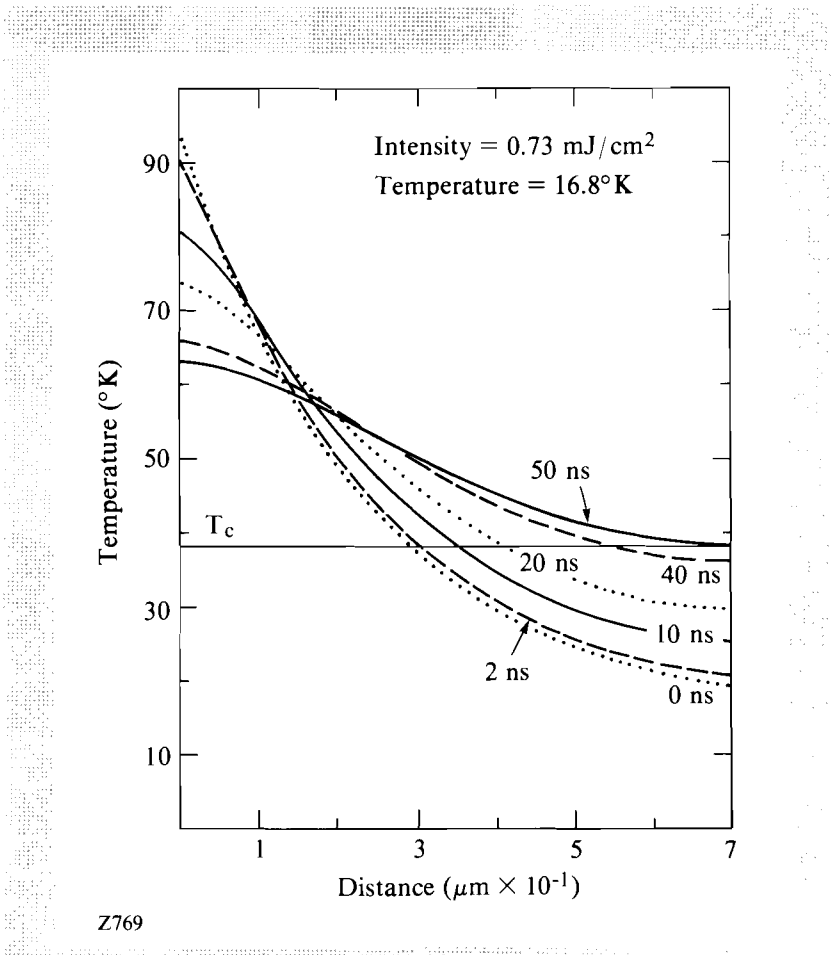

Fig. 39.22
Time evolution of the temperature profile of a 0.7-μm YBCO film.

actual voltage rise time measured for the case illustrated in Fig. 39.22 was less than 2 ns. This was indicative of all the points illustrated in Fig. 39.21 whether or not the optical energy was sufficient to drive the entire film normal at zero time. Clearly thermal transport cannot account for the fast rise times that we observe.

If neither optical absorption nor equilibrium heat flow is capable of distributing this energy, then an alternative nonequilibrium mechanism must be responsible. We suggest that hot-electron transport, which has previously been demonstrated for optically excited metals such as Cu and Au,[15,16] is likely to provide part of the answer. The initial effect of the radiation is to create a number of highly excited electrons and holes in the top 100 nm of the film. These distribute their energy among other highly excited electrons, which spread, either ballistically or diffusively, penetrating into the film. They then thermalize with the lattice (due to the electron-phonon interaction) in a relaxation time that is likely to be a few picoseconds. For an electron diffusivity of order 10^3 cm^2/s, this corresponds to just under 1-μm penetration. Future studies will determine whether these are reasonable estimates, and whether they depend significantly on temperature.

Despite the proposed nonequilibrium energy transport, the voltage rise following the switching appears to be consistent with a bolometric (i.e., thermal) response. This is evident from the dependence of the voltage rise on laser fluence, which we plot in Fig. 39.21 together with the theoretical dependence predicted by a simple heating model. Despite the approximations in the analysis, the experimental and theoretical curves in Fig. 39.21 agree in general magnitude and shape (without any adjustable parameters), and in particular in the fluence (3 mJ/cm^2) at which saturation occurs.

In addition, the rise on the 10-ns scale (see Fig. 39.20) that immediately follows the faster jump is consistent with a redistribution of some heat towards the back of the film, perhaps because the hot-electron penetration depth is comparable to the film thickness. The final slow recovery ≈ 1 μs appears to be due to heat flow out of the film into the substrate. A thinner film should have a much faster cooling time, especially in combination with a well-matched substrate and a transparent top layer to carry away heat, since the thermal-relaxation time goes as the square of the thickness.

Furthermore, we have carried out preliminary measurements on both a thicker and a thinner YBCO film (1.5 μm and 0.2 μm). The general results on these films are also consistent with the above picture of a fast voltage rise on the nanosecond scale, followed by a slow decay that corresponds to thermal conduction out of the film. However, Fig. 39.23 shows data from a YBCO film on $SrTiO_3$. The rise time of the voltage pulse was 20 ns. This is approximately the time of thermal transport. It is unclear whether the physics of the absorption mechanism is different or whether the high dielectric constant of the substrate ($\epsilon \approx 1000$) is influencing the rise time. The film does have higher transition as shown in Fig. 39.24.

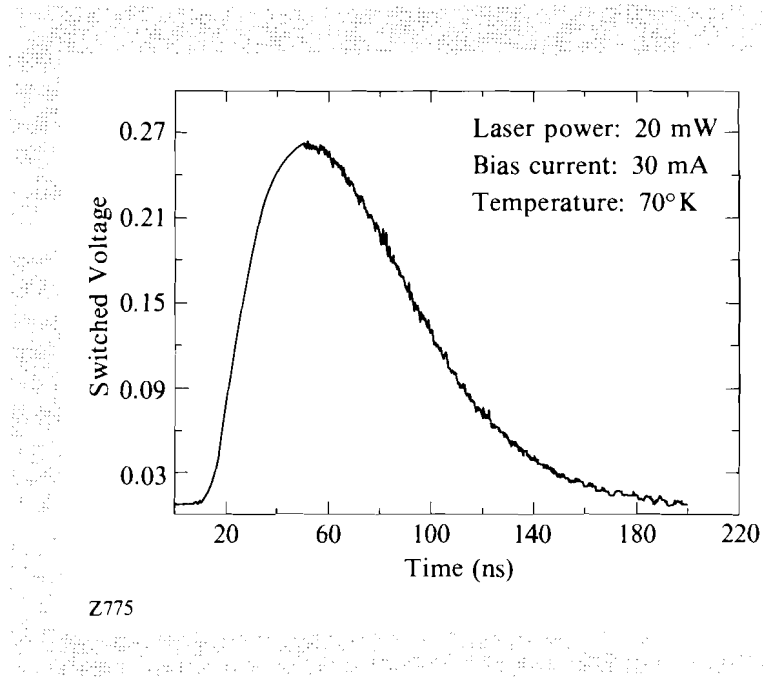

Fig. 39.23
Transient response of YBCO on $SrTiO_3$.

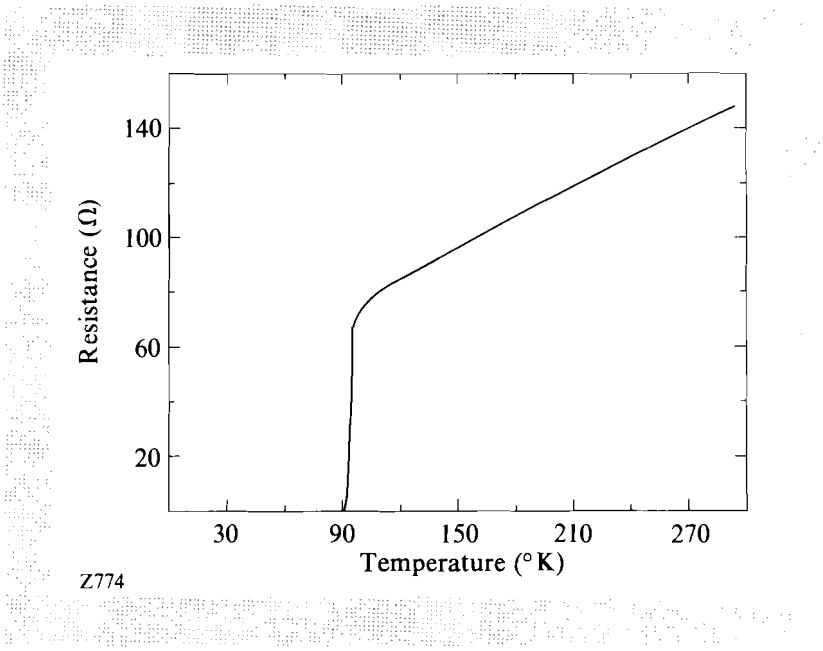

Fig. 39.24
Resistance versus temperature of YBCO on $SrTiO_3$.

We did not concentrate on the low-power limit for this study, so that we have not clearly identified threshold effects. However, extrapolation of our data to zero light intensity indicates the absence of a threshold level that is in marked contradiction to the purely bolometric response. If this is indeed the case, this may indicate a nonequilibrium response where the effect of the light is to break the Cooper pairs rather than heat the lattice.

Although our measurements to date have included only granular films, we would anticipate that epitaxial YBCO films would switch in a similar time. An epitaxial film would have a much larger critical current, so that switching of larger currents (amps instead of milliamps) would become possible, although self-heating would then become relevant.

In summary, we have shown that a 150-ps optical pulse illuminating a high-temperature superconducting film, even one as thick as ≈ 1 μm, can induce a very rapid transition from the superconducting to the normal state, in a time of order 1 ns or less. Switching back to the superconducting state tends to be much slower, of order 1 μs or longer. We can understand this behavior in terms of a model in which the heat is initially deposited in an optical penetration depth ≈ 100 nm at the top of the film, but rapidly spreads (in several ps) via nonequilibrium hot electrons an additional distance of order 1 μm. These then thermalize with the lattice, and for a 150-ps optical pulse, produce an essentially bolometric response on this same time scale. The cool-down process is much slower, however, since it involves equilibrium thermal conductivity (via phonons) out of the film into the substrate.

These characteristics are highly encouraging for potential application to an optically triggered opening switch, particularly if similar results

can be obtained using films with higher critical currents. The existence of this nonequilibrium mechanism suggests that even faster switching, down to the picosecond scale, may be possible for shorter optical pulses. The fact that fast switching occurs in optically thick film means that large currents can be switched on rapid time scales because the film thickness does not limit the switching time.

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