Section 2
ADVANCED TECHNOLOGY DEVELOPMENTS

2.A Anomalous Optical Response of Superconducting Films

The effect of optical (both visible and IR) radiation on the electrical properties of high-T_c superconductors (HTS) has been a subject of active research in the recent years. HTS thin films have been used in a number of devices, including broadband optical detectors,[1] fast-switching devices,[2] and superconducting quantum interference devices (SQUID's).[3,4] The HTS films are attractive because they exhibit low reflectivity and a high-absorption coefficient over the visible and near-infrared part of the spectrum.[5] There have been a series of experiments on infrared detection using HTS thin films, following the development of a nonbolometric infrared detector by Enomoto and Murakami using granular $BaPb_{0.7}Bi_{0.3}O_3$ films.[6] Fast nonbolometric switching has been observed in optically thin $YBa_2Cu_3O_{7-x}$ (YBCO) films.[7,8] Subnanosecond switching times have been reported in some cases.[8]

The prime objective of our experiment is to explore the possibility of high-power switching using the optically triggered response in thin epitaxial films. Unlike most other experiments on the photoresponse of HTS thin films, we have used optically thick films (800 nm). The purpose of using thick films is to achieve very high currents. For example, a 1-µm × 1-cm switch would carry 100 A at a current density of 10^6 A/cm^2, and 1 kA at a current density of 10^7 A/cm^2. In our experiment, a current-carrying HTS film was hit with laser pulses and the resulting electrical signal was measured. We have observed two distinct switching components: a fast nonthermal component (~few nanoseconds) followed by a slow thermal one (~100 ns).

Nonbolometric and Bolometric Components in the Photoresponse of the HTS Switch

The films used in our experiments were deposited on polished 1-cm^2 MgO substrates using rf magnetron sputtering.[9] Laser ablation was used to pattern the films into H structures with a central bridge of 2-mm length and width that varied from 100 to 250 µm.[10] This was done by a Nd:YAG laser focused to a 5-µm spot at optimum fluence. The sample was mounted on a gold-coated alumina strip and silver bond pads were evaporated on the sample. A variable dc, constant current source was connected through a 50-Ω coaxial cable to the bond pads on the sample using aluminum wire bonds. The coaxial cables were current-charged transmission lines. The cables were long enough so that no reflections occurred in the time scale of interest. Thus, the influence of the electronic response of the dc current source could be neglected. The other side of the switch was connected to a 50-Ω load across which the voltage was measured. In the superconducting state, the central bridge of the switch acts as a short circuit at the end of the input transmission line and no voltage appears at the load. When the bridge is driven normal, current is diverted to the load and a voltage signal is recorded. The sample was placed inside a cryostat on copper mounts and provided with a temperature sensor. The copper mounts were in contact with the cold finger. A laser beam from a Nd:YAG laser was focused on the bridge using a cylindrical lens to concentrate the energy on the switch. The optical system was chosen to optimize both the intensity and uniformity of illumination at the switch. Energy flux was measured by scanning a razor across the beam. The beam, assumed to be Gaussian, was focused symmetrically on the switch, i.e., the beam axis passed through the center of the switch. The variation of the intensity along the length of the switch was +21% to -34.7% and along the width was +1.5% to -5% about the mean intensities. The fluence was varied, using a wave plate and a polarizer, from 0.5 to 14 mJ/cm^2. The laser had a pulse width of 170 ps with a repetition rate of 1 kHz. The voltage signal was measured with a 350-MHz oscilloscope and recorded later with a computer-interfaced digitizing oscilloscope. A schematic of the experimental setup is shown in Fig. 51.8.

The observed signal clearly exhibited two switching mechanisms (Fig. 51.9). The slower response, which is believed to be bolometric in nature, was preceded by a faster component having a rise time of the order of a few nanoseconds. The slow thermal component had a time lag compared to the optical trigger, which increased with decreasing laser fluence. The dependence of this time lag of the thermal component, called the response time of the switch, on the laser fluence is shown in Fig. 51.10. For the same laser fluence, this time lag was found to decrease with increasing bias current. A simulation of the bolometric response, described in the next section, exhibited similar dependence of the response time on fluence and bias current. The faster component, which is synchronized with the optical trigger in time, is not of a thermal origin. At present, the origin of this nonbolometric signal component is not clearly understood. It is not associated with the energy redistribution in the film since such a mechanism cannot account for a sharp recovery followed by a secondary thermal rise. The fall time of this signal component is 5 to 6 ns. In the time period that the nonbolometric part of the signal exists, the optical energy is mostly confined to the front surface of the film, suggesting that the signal originates at the surface.

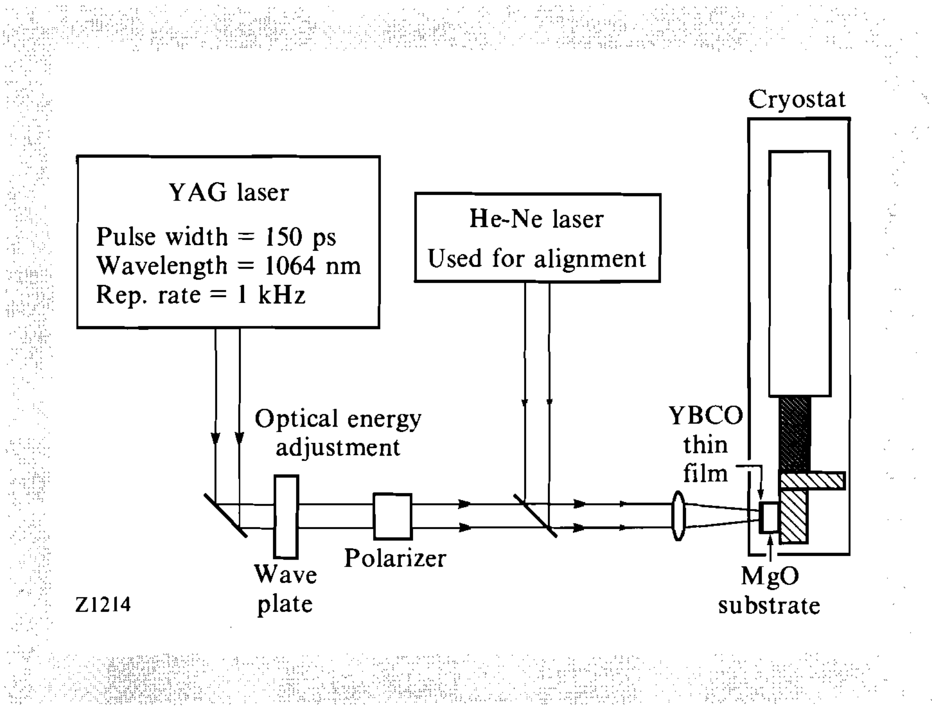

Fig. 51.8
Experimental setup to study the optically triggered switching in HTS thin film.

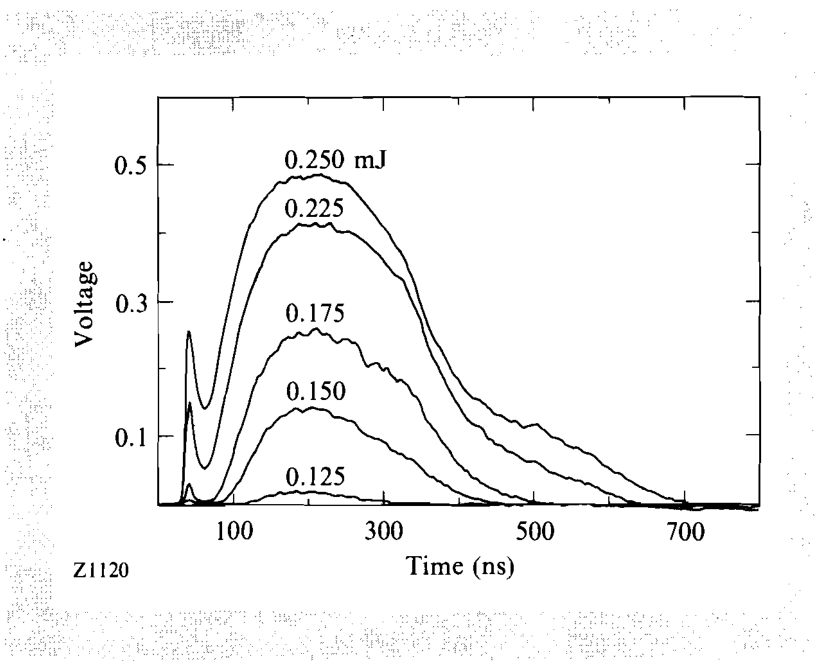

Fig. 51.9
The bolometric and nonbolometric switching components in the photoresponse of YBCO thin film for varying laser fluence. The total optical energy used in each case is shown (about 20% of this energy is absorbed by the switch). The central bridge has dimensions 100 μm × 2 mm. Initial temperature is 70 K and bias current is 30 mA.

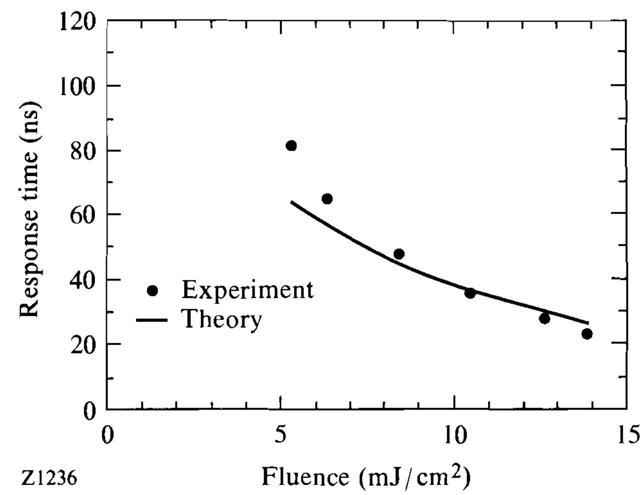

Fig. 51.10
Thermal response time as a function of laser fluence. The theoretical curve is calculated using the peak intensity of the Gaussian energy distribution.

Variation of the initial temperature of the sample permitted the fast signal to be clearly distinguished from the slow one. When the sample is cooled to a temperature just below T_c before hitting it with the laser pulse, the response time of the thermal component is comparable to the width of the fast pulse. This results in a superposed signal that appears to be a single voltage pulse with a sharp initial slope followed by a slow "thermal-like" rise. As the sample is cooled to lower initial temperatures, the thermal pulse starts moving out in time and the overlapping time interval of the two signals becomes smaller. Finally, at low temperatures the two signals are separated in time. Since this temperature is well below T_c (= 84 K), usually less than 60 K, we need a high bias current and/or high laser fluence to perform the switching. At low temperatures the critical current is very high, and a significant amount of optical energy is needed to raise the temperature above the critical temperature.

The peak amplitude of the fast signal decreases with diminishing laser intensity. However, its rise time (~4 ns), fall time (~5 to 6 ns), and response time (time lag relative to the optical trigger) were found to be independent of laser fluence, bias current, and initial temperature. There is a minimum fluence for the fast component to exist for any given temperature and bias current. The thermal component also has a threshold fluence, corresponding to the minimum energy required to raise the temperature of the film above its critical temperature. The threshold fluence for the thermal component is found to be lower than that for the nonthermal component. When the fluence is between these two thresholds, we can observe only the thermal part of the signal.

Modeling and Simulation of the Bolometric Component

We have simulated the thermal response of the laser-irradiated HTS thin-film bridge. The film is divided into 64 slices, each of thickness 125 Å. The substrate is also divided into 2000-Å slices. The continuity equation of heat-flow is applied in one dimension (1-D):

$$\partial / \partial x\left[K(T)\partial T / \partial x\right]=\rho \partial / \partial t\left[c(T)T\right],$$

where K is the thermal conductivity, ρ is the density, and $c(T)$ is the temperature-dependent specific heat.

Thermal conductivity of YBCO film is taken to be 10^{-2} W cm^{-1} K^{-1}. The thermal conductivity of crystalline MgO is given by the formula

$$K_{\mathrm{MgO}} = 21.25–0.1875\ T\ \mathrm{Wcm}^{-1}K^{-1} \qquad (60\ \mathrm{K} < T < 100\ \mathrm{K})$$

in the temperature range of interest. Specific heat of MgO is calculated under the T^3 approximation, with Debye temperature (θ_D) of 946 K:

$$c_{\mathrm{MgO}} = \left(12\pi^4 R / 5\right)\left(T / \theta_D\right)^3 JK^{-1}\mathrm{mol}^{-1} .$$

The specific heat of YBCO was measured by Ref. 11 and fit with a linear function

$$c_{\mathrm{YBCO}} = 2.83 \times 10^{-3} T - 3.97 \times 10^{-2} JK^{-1}\mathrm{gm}^{-1} .$$

The temperature distribution as a function of distance into the sample is computed by solving the heat equation using the method of finite differences. A time-dependent temperature profile is shown in Fig. 51.11 assuming a uniform illumination of the crossbar with the mean intensity of the Gaussian distribution (13.86 mJ/cm^2) and an initial temperature of 70 K.

This temperature distribution is used to compute the critical current in each slice based on the measured dc characteristics of the film. It is assumed that if at a given instant of time there are some slices with temperature below T_c, they will carry supercurrent unless the current density in the slice exceeds the estimated

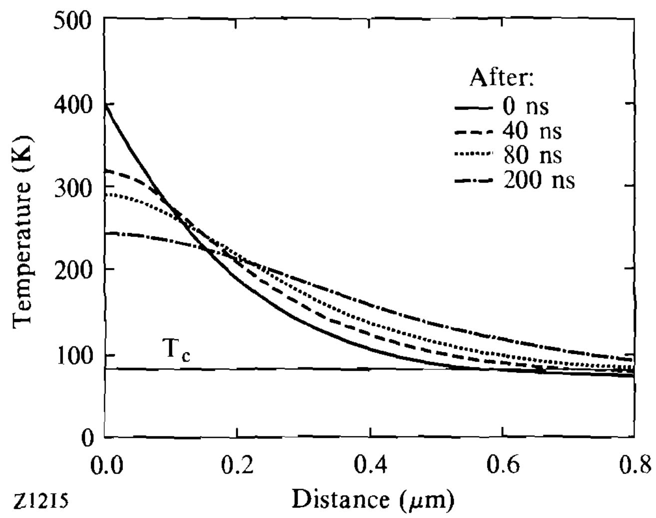

Fig. 51.11
Time variation of the temperature distribution across the thickness of the film.

critical current density. The electrical model is a parallel combination of temperature-dependent linear and nonlinear resistors, one for each slice. If the sum of the critical currents in the slices with $T < T_c$ (I_{sc}) exceeds the applied current (I_0), there is no voltage signal at the output. A slice with temperature above T_c has a normal resistance that varies with temperature. After a period of time, which is called the response time of the switch, I_{sc} becomes less than I_0 and there is a nonzero equivalent resistance in the switch resulting in a voltage signal at the output. This happens because all the slices except a few are above the critical temperature. In this case the output signal is determined by an iterative redistribution of the current between the superconducting and the normal slices. The redistribution is done so that the voltage across all the slices is the same. However, because of the high critical currents of our samples and the small currents we used (<100 mA), this condition ($I_0 > I_{sc}$) was satisfied over a very short period of time. When all slices have $T > T_c$, we have a set of normal resistors in parallel, with resistance varying according to their respective temperatures. In this case, the output voltage can be determined analytically.

Experimentally obtained resistance versus temperature data has been used in this simulation to determine the normal resistance. A set of simulated signals with varying fluence are shown in Fig. 51.12. These correspond to an initial temperature of 70 K and a bias current of 30 mA. The response time of the signal increased as the fluence decreased. The dependence of response time on temperature and the bias current is shown in Fig. 51.13. The response time increases at lower temperatures and lower bias currents.

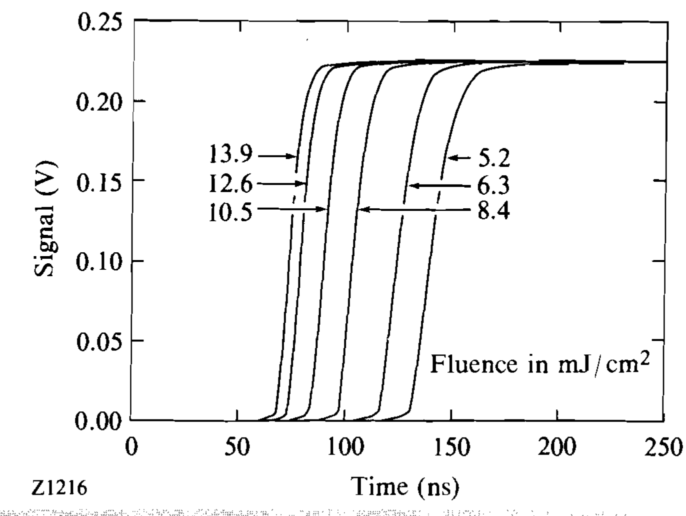

Fig. 51.12
Simulated signals showing increasing response time for decreasing fluence.

In the simulation, uniform illumination across the switch at the mean intensity was assumed. Without this approximation, the simulation would have been extremely complicated involving a solution of 3-D flow in anisotropic YBCO and a spatially varying resistance function. In the experiment the central portion of the switch receives more energy than the peripheral part and is expected to go normal while the edges of the switch are still superconducting. Time required for the temperature to exceed the critical temperature will be less than that calculated with the uniform illumination approximation at the center and more at the edges. This can be thought of as a network of normal and superconducting resistors, which in each layer form a mesh. The resistors representing the hot central part of the switch will offer normal resistance while the peripheral ones will be superconducting. Each node in a layer is connected to the corresponding nodes in the neighboring layers. This 3-D network contains time-varying, nonlinear resistors and the analysis becomes complicated. However, a qualitative assessment of the effect of nonuniform illumination on the signal can be made. It will reduce the response time of the switch (by about 10%), since the central part goes normal before the "uniformly illuminated" film. It will also increase the thermal rise time (by about 25%, including the reduction of the response time) because the edge of the illuminated region goes normal after the central region of the film.

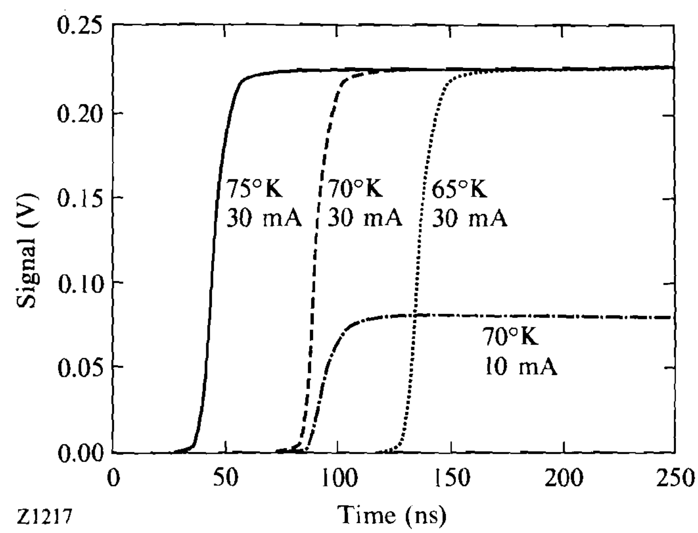

Fig. 51.13
Simulated signals showing that response time increases for lower initial temperatures and lower bias current.

The theoretical curve in Fig. 51.10 is calculated using the peak rather than the mean intensity of the Gaussian distribution. As mentioned above, the peak intensity at the center of the film determines the time at which the sample starts to go normal and, therefore, the response time. The calculated response time is a function of the thermal conductivity of the sample. Values of thermal conductivity higher than the one used in our simulation have been reported.[11] A higher value of thermal conductivity would imply faster heat distribution and shorter response time. The value of thermal conductivity corresponding to our experimental response times lies within the range of reported measured values of thermal conductivity of YBCO films.

Conclusion

A fast, nonbolometric switching component has been observed in optically thick (8000-Å) $YBa_2Cu_3O_{7-x}$ films along with a slow bolometric component.