

# Fast bolometric response by high $T_c$ detectors measured with subnanosecond synchrotron radiation

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We have measured a fast response by thin-film  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  detectors to pulsed, broadband, infrared radiation. Synchrotron light from an electron storage ring was used as the infrared source, providing subnanosecond pulses from far infrared through visible. Pulse responsivities as high as  $10^6$  V/J and as fast as 4 ns have been observed. For film thicknesses in the range 400–3200 Å, the detector response follows the film absorptivity while the speed varies inversely with thickness, suggesting a bolometric mechanism. Calculations based on such a model are in accord with the data. We find no evidence for any nonbolometric components in the response.

Thin films made from ordinary superconductors have been used for some time as highly sensitive infrared (IR) bolometer detectors,<sup>1–3</sup> exploiting the large change in electrical resistance for small temperature changes near  $T_c$ . An analysis of high  $T_c$  superconductors as bolometric detectors<sup>4</sup> suggests that these materials could be used to make sensitive IR detectors. Like most bolometers, these devices generally have a slow response, on the order of milliseconds. Granular superconductors can also detect IR by a nonbolometric mechanism, related to the weak (Josephson) superconductive coupling between grains.<sup>5,6</sup> Josephson detectors can be extremely fast, although usually limited to far IR and millimeter wavelengths.

The first films of oxide superconductors were granular, and initial studies revealed a fast response with an unusual temperature dependence<sup>7–10</sup> leading to the conclusion that the response was not entirely bolometric. Investigations<sup>11–17</sup> using more homogeneous (epitaxial) films have also revealed a fast response (on the order of nanoseconds), but the existence of a nonbolometric component is still under debate.<sup>11,12</sup> In this work, we have studied the response of epitaxial high  $T_c$  films to infrared radiation. Our goals were to obtain quantitative results for the speed and responsivity of several different films, and determine the mechanism for any fast response. Previous studies of epitaxial films utilized visible or near-IR lasers. Because the wavelength (or photon energy) dependence is often sensitive to the response mechanism, we used pulsed synchrotron light from an electron storage ring. This source produces a continuum of frequencies from far IR up into the visible and has other advantages for investigations

of small detectors, such as high brightness, low noise, and a well-defined spectral output.

The detectors were thin films of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  deposited by pulsed laser ablation onto MgO or  $\text{LaAlO}_3$  substrates.<sup>18</sup> As sketched in the inset to Fig. 1, the films, with thicknesses between 400 and 3200 Å, were patterned into four separate bridges of equal length but differing widths, extending from an outer silver pad to a central silver stripe. The width of the stripe, in combination with the 1-mm-thick MgO substrate and a ground plane, produce a microstrip-type stripline with impedance near 50 Ω. This arrangement provides simple access to four different bridges, though only in a two-probe configuration.

The samples were cemented to a copper plate which was bolted to the cold tip of a continuous flow refrigerator. The central silver stripe was attached to a 50 Ω coaxial cable with a stripline launcher. A given bridge was chosen for study by grounding the appropriate outer silver contact pad. All connections were made with silver paint. A dc tee enabled us to bias the sample and recover electrical signal pulses through the same cable. The ac arm of the tee was connected to a 26 dB gain rf amplifier (0.1–1300 MHz) and digitizing oscilloscope (1 GHz bandwidth, <350 ps rise time).

We utilized infrared synchrotron radiation from beamline U4-IR of the National Synchrotron Light Source (NSLS) VUV ring<sup>19</sup> for our studies. Although this synchrotron emits radiation into the soft x-ray region, the mirror and window optics of the IR beamline limit the radiation to wavelengths greater than 500 nm (frequencies below  $20\,000\text{ cm}^{-1}$ ). In this range the power per unit bandwidth,  $dP/d\nu$ , follows  $\nu^{1/3}$  and falls off much more slowly than a blackbody toward low frequencies. Bandpass filters allowed far IR, mid IR, near IR, or visible light to be selected. An off-axis ellipsoidal mirror reduces the  $0.5 \times 3\text{ mm}$   $f/10$  source to an estimated  $200 \times 600\text{ }\mu\text{m}$   $f/2$  spot at

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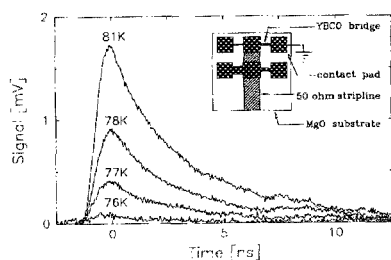


FIG. 1. Photoresponse of a 480 Å  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  film on MgO at several temperatures. The inset shows a drawing of the device. Only one of the four bridges was connected to ground at any one time.

the sample.<sup>20</sup> Because the electrons in the storage ring travel in bunches, the light is pulsed. The pulses are approximately Gaussian in shape, just under 1 ns in duration, and separated by up to 170 ns. The peak power (full spectral band) is about 2.5 W, and the maximum fluence is about  $5 \mu\text{W}/\text{cm}^2$  per pulse.

Figure 1 shows the time-dependent response of a 480 Å film to a pulse of radiation at several temperatures. The initial rise equals the duration of the infrared pulse; once the pulse ends, the response decays as the detector cools to its operating point. In this case the decay time is of the order of 4 ns. As the temperature falls below 82 K (the temperature where  $dR/dT$  is maximum), the magnitude of the response drops, but the decay time remains unchanged. In general, thicker films had larger time constants, with a time constant of 22 ns for a 1680 Å film and 50 ns for a 3200 Å film.

Figure 2 shows the temperature dependence of  $dR/dT$ , the pulsed response, and the chopped response. The maximum value for  $dR/dT$  is about 20 Ω/K for both films. The agreement among fast response, slow response, and  $dR/dT$  provides immediate evidence that, despite the high speed, the fast response is bolometric in origin. We also find that the response is linear in incident intensity and bias current (until bias current heating substantially alters  $dR/dT$ ). The 100- and 200- $\mu\text{m}$ -wide bridges (most closely matched to the incident light spot size) yielded comparable response, with the 500- and 50- $\mu\text{m}$ -wide bridges being less sensitive. At 5 mA bias, the 480-Å-thick, 200- $\mu\text{m}$ -wide bridge has a responsivity (to near IR light) of about

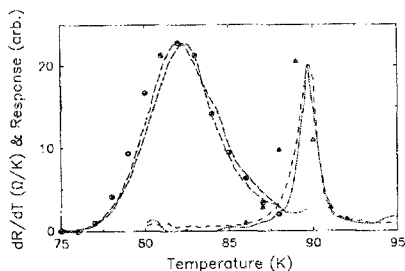


FIG. 2. Comparison of the "fast" photoresponse (points), "slow" photoresponse (dot-dashed lines), and  $dR/dT$  (dashed lines) for two  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  films on MgO: 480 Å (dots) and 1560 Å (triangles).

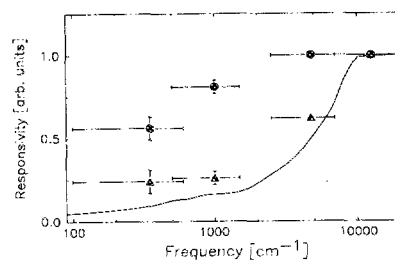


FIG. 3. Relative response of 480 Å (dots) and 1560 Å (triangles) films at far IR, mid IR, near IR, and visible wavelengths. The absorption of a thick film is shown as the solid line.

$1 \times 10^6 \text{ V/J}$  in pulsed mode, corresponding to 1 mV/W for a 1 ns pulse. At 100 Hz—chopped—the responsivity is 18 mV/W.

In Fig. 3 we show the spectral response for both the 480 and 1560 Å films, along with the measured infrared absorption  $A$  (where  $A = 1 - \mathcal{R}$  with  $\mathcal{R}$  the reflectance) for a thick film.<sup>21</sup> The overall spectral response is consistent with the absorption when one allows for the lower reflectivity of thin films in the far IR. The time constant for a given film was the same for all spectral ranges.

Our results—in particular the good agreement between the pulsed response, chopped response, and  $dR/dT$ —indicate a bolometric mechanism. In the following, we estimate the response of our detectors as bolometers and determine the effective thermal conductance between the films and the bath. A bolometer has a responsivity (in V/W) of<sup>22</sup>

$$S = \frac{A(\nu)I}{G(1 + i\omega\tau)} \frac{dR}{dT}, \quad (1)$$

where  $A(\nu)$  is the emissivity (absorptivity) at IR frequency  $\nu$ ,  $I$  the bias current,  $dR/dT$  the slope of resistance versus temperature,  $G$  the thermal conductance,  $\omega$  the chopping frequency, and  $\tau = C/G$  is the thermal time constant with  $C$  the bolometer heat capacity. The scaling of  $\tau$  with film thickness suggests that  $C$  is the heat capacity of the film itself, and the most likely mechanism has the film changing its temperature relative to the substrate with a thermal impedance between. Since the fast response is measured in the high-frequency ( $\omega\tau > 1$ ) limit, the thermal conductance drops out of Eq. (1), which becomes

$$S \approx \frac{A(\nu)I}{\omega C} \frac{dR}{dT},$$

(ignoring the 90° phase lag). Using  $c = 0.9 \text{ J/cm}^3 \text{ K}$  for the specific heat of a high  $T_c$  superconductor,<sup>23</sup> we obtain  $C = 5.2 \times 10^{-9} \text{ J/K}$  for the heat capacity of a film with an area of  $200 \times 600 \mu\text{m}$  and a thickness of 480 Å. The other parameters are  $I = 5 \text{ mA}$ ,  $dR/dT = 23 \text{ Ω/K}$ ,  $\omega = 3.3 \times 10^9 \text{ s}^{-1}$ , and  $A \approx 20\%$ . From this we predict a responsivity  $S = 1.4 \text{ mV/W}$  which compares favorably with the observed responsivity of 1.0 mV/W.

From the measured time constant ( $\tau = 4 \text{ ns}$ ) we next determine the thermal conductance between film and substrate to be 1.3 W/K. Finally, in the low-frequency limit

we expect  $S=19$  mV/W, which agrees well with the observed chopped response of 18 mV/W. The details of the thermal impedance between film and substrate are unclear. If we assume a 100-Å-thick layer of disordered material, we obtain a thermal conductivity of 0.1 W/m K, which is an order of magnitude or more smaller than the thermal conductivity of either  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (along the  $c$  axis)<sup>24</sup> or  $\text{MgO}$ .<sup>25</sup> This comparison suggests that the heat transfer in these detectors is dominated by the thermal impedance mismatch between the high  $T_c$  film and its  $\text{MgO}$  substrate.

In conclusion, high  $T_c$  films can function as fast detectors of light from far IR through the visible. Responsivities above  $10^6$  V/J combined with response times of 4 ns have been achieved, and room exists for substantial improvements. The response speed compares favorably with other broadband devices (e.g., pyroelectric detectors).<sup>26</sup> At the fluences used here (under  $5 \mu\text{W}/\text{cm}^2$  per pulse) we observe no evidence for a nonbolometric component in the response. A bolometer model, in which the film heats relative to the substrate, is in quantitative agreement with the experimental results.

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