RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 39, NUMBER 13 1 MAY 1989

Nonbolometric optical response of $YBa_2Cu_3O_{7-\delta}$ epitaxial films

E. Zeldov,* N. M. Amer, G. Koren,† and A. Gupta
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598-0218

(Received 9 December 1988; revised manuscript received 10 March 1989)

The optical response of high-quality epitaxial $YBa_2Cu_3O_{7-\delta}$ films on $LaGaO_3$ and $SrTiO_3$ substrates is reported. A careful analysis of the results reveals a strong nonbolometric response at temperatures below the onset of the superconducting transition. This finding is in contrast with recently published reports which attribute the optical response of epitaxial films to a bolometric effect only. We interpret this response as due to *photoenhanced flux creep* in the superconducting films.

Understanding nonequilibrium phenomena in superconductors has been essential to our knowledge of superconductivity and its applications.[1] With the discovery of high-temperature superconductors, the possible application of $YBa_2Cu_3O_{7-\delta}$ films for fast, wide spectral range optical detection was recently reported.[2-4] The previously investigated samples were either granular in structure[2] or epitaxially grown.[4] In the former case the optical response was attributed to photoinduced phase slips across the weak links between the grains of the superconducting material. In the latter case the response was interpreted as a bolometric effect which modulates the sample resistivity due to the radiation heating.[3,4] In this Rapid Communication we present the photoresponse of high-quality epitaxial films. A careful examination of the results shows that, in addition to the bolometric effect, a strong nonbolometric response exists in these epitaxial films.

The $YBa_2Cu_3O_{7-\delta}$ thin films were deposited by laser ablation on (100) $LaGaO_3$ and $SrTiO_3$ substrates as described elsewhere.[5] This deposition method yields high quality, *c*-axis oriented, epitaxial films with sharp superconducting transitions [$T_c(R=0)$ of up to 92 K] and high critical currents.[5] In this study, 0.25–0.6-μm-thick films were patterned using an excimer laser-microscope system to form a microbridge 25–35 μm wide and 100–200 μm long. The samples were placed in a variable-temperature optical cryostat and their transport properties were measured using the four-probe technique. A 2-mW HeNe laser beam (633 nm) was used as the optical excitation source. The beam was focused to about 60-μm diam on the microbridge and was mechanically chopped at a typical frequency of few hundred Hz. The resulting voltage drop at a constant current was monitored with a lock-in amplifier.

Figure 1(a) shows the resistivity versus temperature characteristics of thin $YBa_2Cu_3O_{7-\delta}$ film on $LaGaO_3$ substrate measured at four different currents. As the current is increased, the transition curve broadens towards lower temperatures as typically observed in high-temperature superconductors. Figure 1(b) shows the measured photoresponse as monitored by the lock-in amplifier and normalized by the bias current. The data in Figs. 1(a) and 1(b) were acquired simultaneously as the dc and ac components of the voltage drop in the four-probe configuration. The ac component was small compared to the dc voltage.

The photoresponse shows a sharp maximum in the transition region which may lead to the conclusion that the response is purely bolometric. If this were the case, the induced voltage change ΔV, due to small temperature variation ΔT, will then be given by

$$\Delta V = I \frac{dR}{dT} \Delta T , \qquad (1)$$

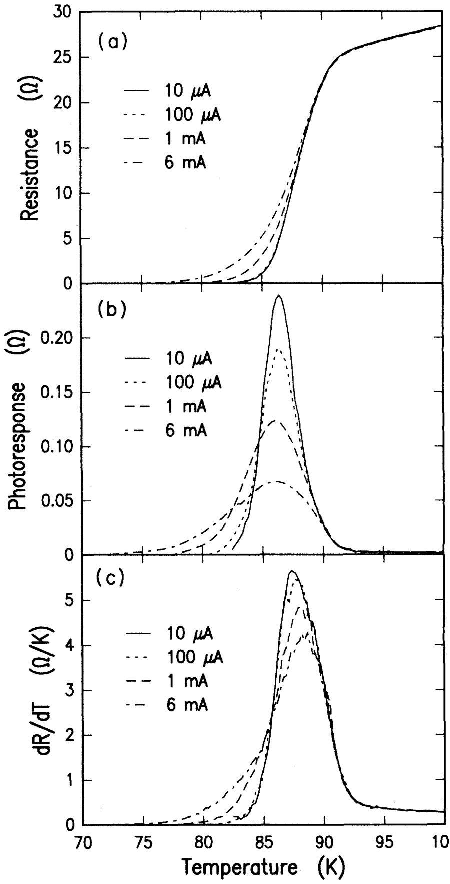

FIG. 1. Temperature dependence of the (a) resistance; (b) photoresponse; and (c) resistance derivative of $YBa_2Cu_3O_{7-\delta}$ film on $LaGaO_3$ substrate at various bias currents.

where I is the bias current and dR/dT is the temperature derivative of the resistance $R(T)$. Since $R(T)$ was measured directly, its derivative was calculated numerically and the result is shown in Fig. 1(c).

A significant difference between the photoresponse [Fig. 1(b)] and the derivative of the resistivity [Fig. 1(c)] is readily observed. First, the photoresponse peaks at lower temperatures compared to the peak in the derivative. At 10-μA bias current, the shift between the two maxima is about 1 K whereas at 6 mA it is 2.5 K. The photoresponse peak shifts slightly to lower temperatures with increasing current, while the peak of the derivative shifts to higher temperatures. In addition, the peak amplitude of the derivative in Fig. 1(c) varies only by about 25% when the bias current is changed from 10 μA to 6 mA whereas the normalized photoresponse varies by a factor of more than 3.5. Finally, the overall shape of the curves in Figs. 1(b) and 1(c), and in particular the broadening with the increased current, are significantly different. While the full width at half maximum of the derivative does not increase significantly with current, the photoresponse shows a peak which is considerably narrower than that of the derivative at 10-μA bias and which becomes much wider at higher biases.

We can now estimate the bolometric component of the photosignal. The resistance characteristics in Fig. 1(a) show a finite slope above the transition onset. Thus, in this region the bolometric signal will be present according to Eq. (1) and there will be no superconductivity-related component. A careful examination of the photoresponse shows that the measured signal accurately follows the derivative of the resistivity above 90 K at all bias currents. Hence, using Eq. (1), we derive the value of 6.3 mK for ΔT, which is the rms variation of the film temperature due to the optical heating. Thus, knowing ΔT and making use of Eq. (1), we can evaluate the bolometric contribution to the measured photosignal assuming a temperature independent ΔT. Figure 2 shows the measured photoresponse and the calculated bolometric component at 1-mA bias. Clearly above 90 K the measured signal is purely bolometric, whereas at lower temperatures the nonbolometric response coexists with the inevitable bolometric signal. However, Fig. 2 shows that the nonbolometric component is much larger than the calculated bolometric contribution.

It may be argued that the observed signal is nevertheless bolometric in nature and that the induced heating ΔT actually varies with temperature and is not constant as assumed above. The following arguments show that this is not the case. At the low chopping frequencies used in the present study ΔT is determined mainly by the thermal properties of the substrate. Measurements of the thermal diffusivity of $LaGaO_3$ do not show, however, any significant variations in the relevant temperature range.[6] Moreover, ΔT above 90 K remains constant and would have to increase sharply below 90 K, by a factor as large as 30, in order to explain the experimental results on a bolometric basis only. To further support our conclusion, the photoresponse was measured with the excitation beam focused about 200 μm away from the microbridge. The scattered light illuminating the bridge in this configuration was considerably smaller, whereas the heating of the film was not changed significantly since the bridge was within the thermal diffusion length of the substrate. As expected, the response was mainly bolometric and closely followed the resistance derivative. Finally, to rule out the possibility that the magnitude of the heating of the illuminated microbridge is changed significantly below the superconducting transition due to some variations in optical or thermal properties of the film or the film-substrate interface, we refer to Fig. 3 which shows the measured photoresponse normalized by the resistance derivative at three bias currents. The result of such normalization is the effective ΔT, which would be the temperature increase of the film if the photoresponse were thermal in nature. Figure 3 shows two features that cannot be explained by thermal arguments. First, the effective ΔT sharply increases below the transition onset by a factor of 30, which is large to be fully accounted for by any changes in thermal properties of the film, substrate, or the interface; and the second is the strong dependence of the ΔT value on the bias current. Since most of the film volume is superconducting even at currents above

FIG. 2. The photoresponse and the resistance derivative multiplied by a $\Delta T = 6.3$ mK. The photoresponse accurately follows the resistance derivative at temperatures above 90.5 K.

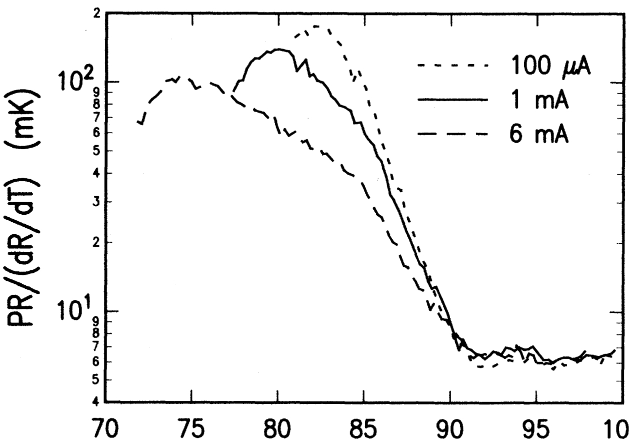

FIG. 3. Photoresponse (PR) normalized by the resistance derivative at various bias currents.

the critical current, the temperature increase of the film would be current independent if the response would only be determined by the thermal properties of the system.

Similar results were obtained for $YBa_2Cu_3O_{7-\delta}$ films on a $SrTiO_3$ substrate. However, the distinction between the photoresponse and the bolometric signal was not as dramatic as that shown in Fig. 2. Two possible reasons for the difference are the following. The measured temperature increase ΔT of the film on $SrTiO_3$ was substantially larger compared to that on $LaGaO_3$. This is probably due to the difference in the thermal properties of the two substrates. The thermal diffusivity of $SrTiO_3$ was indeed found to be smaller than that of $LaGaO_3$ in the relevant temperature range.[6] A larger ΔT causes a larger bolometric signal, while the nonbolometric response should not change under the same illumination conditions. In addition, the sample on the $SrTiO_3$ substrate had a sharper transition, leading again to a larger bolometric contribution.

Finally, we would like to comment on a possible mechanism for the observed nonbolometric response in the $YBa_2Cu_3O_{7-\delta}$ thin films. The superconducting samples were of relatively high epitaxial quality as determined from the transition temperatures, critical currents, and x-ray diffraction measurements.[5] Furthermore, their V-I behavior showed a monotonic increase in dV/dI with current indicating nongranular behavior.[7] Thus, the induced phase slip mechanism in the weak links as proposed by Leung *et al.*[2] for granular films does not apparently apply to our case. On the other hand, there is strong evidence that the critical currents in epitaxial films are limited by flux creep.[7] Since we observe a strong correlation between the transport properties with and without illumination, we suggest that the measured photoresponse is an evidence for *photoenhanced flux creep* in $YBa_2Cu_3O_{7-\delta}$ films. Under thermal equilibrium conditions and above the critical currents, a finite voltage drop is obtained due to thermally activated flux motion.[7-9] We believe that the activation process is enhanced by photon absorption. Such an enhancement could, for example, occur via some vibrational modes which enhance the flux line excitations and thus induce excess flux creep. The details of this possible mechanism must be examined by studying the photoresponse under variable applied magnetic field. Preliminary results from magnetic-field-dependence experiments support such a flux creep related process and will be published separately.

In conclusion, we have shown that, contrary to recently published work, epitaxial $YBa_2Cu_3O_{7-\delta}$ films exhibit a strong nonbolometric optical response which could be attributed to *photoenhanced flux creep.*

E.Z. is grateful to the United States-Israel Educational Foundation and to the Fulbright Program for support.

---

[*] On leave from the Department of Electrical Engineering and Solid State Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel.

[†] Permanent address: Physics Department, Technion-Israel Institute of Technology, Haifa 32000, Israel.

[1] D. N. Langenberg, in *Proceedings of the Fourteenth International Conference on Low Temperature Physics–LT14*, edited by M. Krusius and M. Vuorio (North-Holland, Amsterdam, 1975), Vol. 5, p. 223.

[2] M. Leung, P. R. Broussard, J. H. Claassen, M. Osofsky, S. A. Wolf, and U. Strom, Appl. Phys. Lett. **51**, 2046 (1987).

[3] Y. Enomoto, T. Murakami, and M. Suzuki, Physica C **153–155**, 1592 (1988).

[4] M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, Appl. Phys. Lett. **53**, 1332 (1988).

[5] G. Koren, A. Gupta, E. A. Giess, A. Segmuller, and R. B. Laibowitz, Appl. Phys. Lett. **54**, 1054 (1989).

[6] E. Zeldov and N. M. Amer (unpublished).

[7] J. Mannhart, P. Chaudhari, D. Dimos, C. C. Tsuei, and T. R. McGuire, Phys. Rev. Lett. **61**, 2476 (1988).

[8] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988).

[9] T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. Lett. **61**, 1662 (1988).