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Electrical response of superconducting $YBa_2Cu_3O_{7-\delta}$ to light

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We have studied the effect of visible and near-infrared light on the electrical properties of superconducting thin films of $YBa_2Cu_3O_{7-\delta}$. The responses we observe can all be explained in terms of light heating the film to a temperature above the superconducting transition. No evidence that the light directly affects superconductivity was found.

Although thin-film superconducting bolometers have been used for years, their extreme cryogenic requirements have restricted their application. With the new, higher temperature superconductors, a large variety of applications are conceivable, especially if photoexcited quasiparticles (QPs) can directly modify the electrical properties before sharing their energy with the other modes (e.g., phonons) in the sample. Such a nonbolometric mechanism could permit high-speed, high-sensitivity infrared detection, as has recently been claimed in Josephson-coupled, granular, thin films of $Ba(Pb_xBi_{1-x})O_3$.[1] A direct effect of electronic excitations on the superconducting properties of $YBa_2Cu_3O_{7-\delta}$ would also be of scientific interest, since it could give important insight into the excitations present in these superconductors. With these ideas in mind, we have examined the electrical response to optical illumination of a wide variety of thin films of $YBa_2Cu_3O_{7-\delta}$, grown by sputtering, evaporation, or chemical precipitation. In contrast to other authors,[1,2] we conclude that all our results, for steady-state and pulsed, visible and near-infrared illumination, are consistent with a bolometric model, in which the illumination affects superconductivity only to the extent that the entire film is heated.

Measurements were made by current-biasing a small area of film, exposing it to light, and monitoring the voltage developed. Since we use a four-probe geometry, the voltage is identically zero in the superconducting state, and any voltage developed must represent a destruction of superconductivity. (This is strictly true only if no light hits the voltage leads directly. For example, we observed thermocouple effects when light was allowed to hit the indium contact pads.)

The absorption of light will always produce a temperature rise determined by the thermal properties of film and surroundings. If the critical current at the new temperature is less than the bias current, a voltage will be observed, equal to that measured in the same film at the same bias current at the higher temperature. Whether this bolometric mechanism is responsible for an observed effect can be determined if one knowns the magnitude of the temperature rise produced by the light.

The simplest method[3] for estimating the temperature rise is to measure the voltage produced by the light at temperatures above the critical temperature T_c. At such temperatures any exotic mechanisms are presumably absent, so only the bolometric effect is present. Dividing the voltage by the temperature coefficient of the normal-state voltage gives the temperature rise. If one is careful to keep the illumination geometry and power level identical, a similar temperture rise will be produced in the illuminated superconductor at a temperature just below T_c. (The lattice thermal properties vary slowly, and the electronic contribution to the thermal properties is a small fractional effect near 100 K.) The assumption of similar thermal properties is only correct for a small range of temperatures around T_c, however, since for large fractional temperature changes significant changes in the thermal conductivity and heat capacity of the film and substrate will occur. Thus this technique can be confidently applied only to films with a sharp transition to fully superconducting behavior. Broader transitions[2] make evaluation of the possible bolometric contribution more difficult.

Figure 1 shows the temperature-dependent optical signal in a sample grown by electron beam evaporation. This sample had zero resistance at 70 K and a critical current density of 10^4 A/cm^2 at 4.2 K. The signal was obtained by

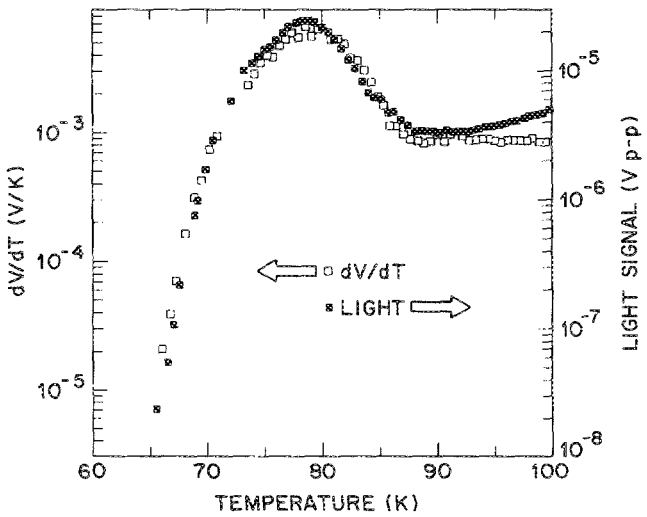

FIG. 1. Comparison of temperature dependence of response to red light ($\lambda = 632.8$ nm) (filled squares) and temperature derivative of measured voltage (open squares) at a constant bias current of 10 mA for an evaporated sample. Except for a gradual change with temperature, the two quantities are proportional, as expected for a bolometric response.

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passing a 10 mA bias current through the sample, illuminating with a 1 mW helium-neon laser chopped at 227 Hz, and synchronously detecting the voltage across the sample. This figure also shows the numerical derivative of a measurement of voltage versus temperature taken with the same bias current. Both the optical response and the temperature coefficient of the voltage show peaks around T_c, with a similar width in both cases. Above T_c, the light-induced voltage reflects only the bolometric effect, so the ratio of the two quantities yields an estimated temperature rise of 0.01 K caused by the illumination. This same temperature rise is fully adequate to explain the more dramatic peak in the response near T_c. Any nonbolometric effect might be expected to become obvious at lower temperatures, after the bolometric effect has disappeared. The close proportionality of the two quantities, even as they decrease dramatically, shows that any such effect is orders of magnitude smaller. A very high quality film, with zero resistance at 92 K and a critical current density of 10^7 A/cm^2 at 4.2 K grown in the same system, also showed a response only in the immediate vicinity of the transition, and of course no long tail at lower temperatures.

The most sensitive probe of small changes in QP density is the tunneling characteristic of a Josephson junction. This effect has been exploited[1] in the use as optical detectors of films of $Ba(Pb_xBi_{1-x})O_3$, whose extremely uniform grain boundaries act as a large network of almost-identical Josephson tunnel junctions. As discussed elsewhere,[4] in an unusual sputtered film of $YBa_2Cu_3O_{7-\delta}$, we have observed features in the electrical characteristics associated with junctions, although the morphology is not nearly as uniform as that of the $Ba(Pb_xBi_{1-x})O_3$ films of Ref. 1. Figure 2(a) shows a portion of the dV/dI vs I characteristic that includes one such feature. This feature has a nonhysteretic current-voltage characteristic; other features showed hysteretic characteristics. Figure 2(b) shows the response to chopped He-Ne light as a function of bias current. The light response peaks at precisely the bias at which the junction switches from low to high voltage.

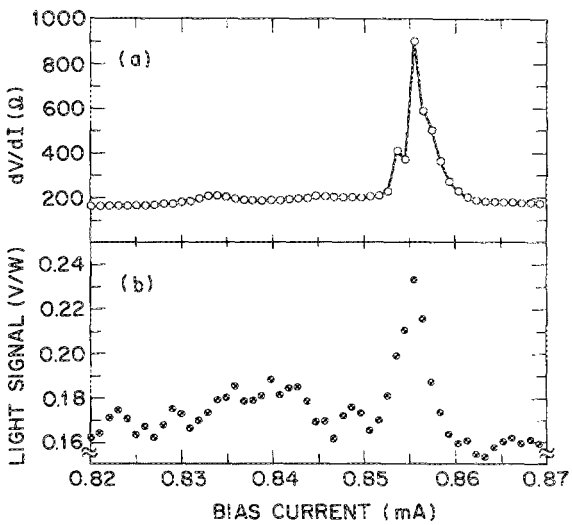

FIG. 2. (a) Differential resistance of a sputtered film, as a function of bias current, showing a large peak corresponding to the critical current of an internal junction. (b) Voltage response to chopped red light has a peak at the same current, reflecting the high sensitivity of the junction critical current to the light. The magnitude of the peak is explained by the known temperature coefficient of the critical current, again consistent with a bolometric mechanism.

Although this response is clearly associated with the junction, its magnitude is still consistent with a bolometric mechanism, in which heating caused by the light reduces the critical current of the junction, causing the junction to switch. If we model the voltage as the sum of a part associated with the junction V_J, and a background part V_B from the rest of the film, (which is still resistive) then the change in the voltage caused by a light power P is

$$\left.\frac{dV}{dP}\right|_I = \left.\frac{d}{dP}\{V_B + V_J[I - I_C(T), T]\}\right|_I$$

$$= \frac{dT}{dP}\left\{\left.\frac{dV_B}{dT}\right|_I - \left.\frac{\partial V_J}{\partial I}\right|_T \frac{dI_C}{dT} + \left.\frac{\partial V_J}{\partial T}\right|_{I-I_C(T)}\right\}. \quad (1)$$

The last term reflects the change in shape of the junction characteristic with T, which is probably small compared to the effect of the change in I_C. By biasing away from the junction, we measured $dV_B/dT|_I \sim 10$ mV/K, so the observed light response of 0.17 V/W implies $dT/dP \sim 17$ K/W. A direct measure of $dI_C/dT \sim -0.02$ mA/K, multiplied by the extra resistance of the junction ($\partial V_J/\partial I|_T \sim 700\ \Omega$) and by 17 K/W predicts a bolometric light response from the junction of 0.24 V/W. The observed peak in the light response is even smaller than predicted: only about 0.06 V/W above the background. Clearly the junction does not show a large nonbolometric response.

Junction critical currents will be reduced by an increased QP density whether the increased density results from simple heating or from a nonbolometric effect. In either case the largest response will be seen for films having junctions with (a) no small resistances shunting the junctions, which would reduce the voltage change when a junction switches to the normal state, and (b) a narrow distribution of critical current densities, so a small increase in QP density will switch many junctions. Therefore, the highly uniform morphology of the $Ba(Pb_xBi_{1-x})O_3$ films described in Ref. 1 are well suited for bolometric detection, as well as for any nonequilibrium mechanism acting via critical current reduction. If the morphology were favorable, the bolometric response of our $YBa_2Cu_3O_{7-\delta}$ films might be improved by several orders of magnitude given optimum film characteristics, without recourse to nonbolometric effects.

To study the time response we used a pulsed YAG laser ($\lambda = 1.064\,\mu$m), with a pulse duration of roughly 10 ns. All the results can be explained in terms of heating, but since the detailed response is not simple, it will be described in some detail. To most clearly distinguish bolometric from other effects we describe experiments on a high quality evaporated sample with a 2 K wide transition, and zero resistance at about 90 K.[5] Above T_c the voltage response should simply reflect the time dependence of the temperature. Figure 3(a) shows that the decay is well described by an inverse square root law,

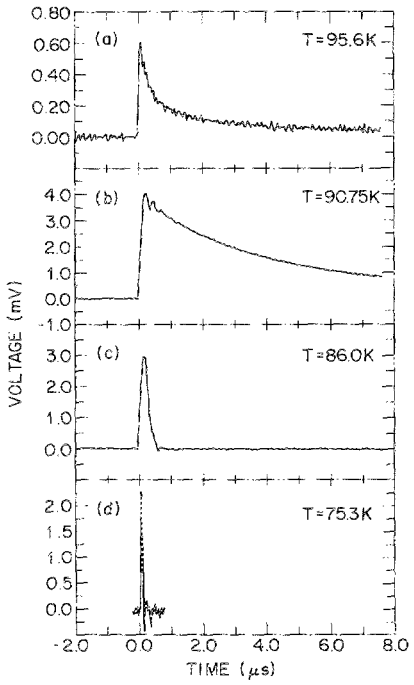

FIG. 3. Temperature dependence of voltage response to pulsed, near-infrared light (duration 10 ns, $\lambda = 1.064$ μm) for a 2800-Å-thick evaporated film biased in 1 mA through a 33-μm-wide bridge. (a) Above T_c, $\delta V \propto t^{-1/2}$, as expected for heat diffusion into a semi-inifinite substrate. (b) for T in the middle of the transition, response is much larger, consistent with the larger temperature coefficient of resistance. Decay is slow, as long as the temperature remains above T_c. (c) For lower starting temperatures, signal is large, but decays abruptly to zero as the temperature falls below T_c. (d) At still lower temperatures, the response is still faster, and may not be resolved. The response disappears rapidly if the light intensity is lowered.

$$T(t) = T_{\rm amb} + \Delta T_0 (t/t_0)^{-1/2}. \qquad (2)$$

Here $T_{\rm amb}$ is the ambient (starting) temperature. ΔT_0 is the maximum temperature rise, achieved at some early time t_0, which can be no shorter than the pulse duration. (If the film response is faster, the observed response will be a convolution with the excitation pulse.) This square root time dependence is expected for thermal diffusion in one dimension, which is reasonable for an illuminated region wide compared to the film thickness.

The response shown in the figure is caused by about 13 μJ of light in an area of order 10^{-3} cm^2. By comparison with Fig. 1, the maximum voltage of 0.6 mV corresponds to a temperature rise of about 20 K, substantially larger than the transition width for this film. However, the pulse response of our electronics (measured by applying a voltage step to the bias leads) is of order 60 ns. Thus the true maximum temperature rise in response to a 10 ns pulse is $\sim\sqrt{60/10}$ larger than that observed, i.e., $\Delta T_0 \sim 50$ K. For the pulse energy shown, one would expect the bolometric response to disappear completely at a temperature $T_c - \Delta T_0$, or ~ 40 K. We actually saw a response only above 55 K, but since changes in thermal properties over this large temperature range are neglected in the simple model, this is reasonably consistent with a bolometric mechanism.

As the temperature is lowered below the $R = 0$ temperature, the pulse still drives the sample normal for the short period during which $T(t) > T_c$. Response times of a few tens of ns are observed when the initial film temperature is near 77 K. The ultimate response depends on how fast heat leaves the film, which is probably the diffusion rate through the film, presumably faster than 1 ns. (Thermal boundary resistances, $\propto T^{-3}$, are negligible at these high temperatures.) However, the utilization of this speed in, for example, communications, is complicated by a highly nonlinear dependence on pulse energy in this high-speed regime. The nonlinearity also causes an interaction between each pulse and any heat remaining in the sample from preceding pulses. We have verified that the nonlinearity is of the form expected from Eq. (2). Thus, even on the time scale of these pulsed experiments (~ 10 ns), all the effects observed are bolometric in origin.

A steady-state QP density larger than that corresponding to the local temperature would require a "bottleneck" in the relaxation process. That is, either the recombination rate of QPs, or the conversion of high-energy phonons (or other excitations created by recombining QPs) to low-energy phonons must be slow compared to the rate at which low-energy phonons (heat) are removed into the substrate. At low densities, optically excited QPs must recombine with rare, thermally excited QPs, which will be slowest at low temperatures. We searched for an optical response at temperatures as low as 1.7 K, but any signal had a pulse area less than 1% of that near T_c.

One would expect that since heat is removed more rapidly from thinner films, they would be more likely to show nonthermal effects, but we saw no effects in films as thin as 2000 Å; perhaps thinner films are necessary. Good quality tunnel junctions, which are directly sensitive to QPs, might make much more quantitative statements about QP dynamics possible.[6] However, the films showing internal Josephson junctions described above showed no effects larger than the heating response.

In summary, we have studied the optical response in films of $YBa_2Cu_3O_{7-\delta}$. Since any nonbolometric response may well depend on film morphology, we surveyed a variety of films, including films with both high and low critical current, films grown by evaporation, sputtering, and chemical precipitation, and films with clear indications of internal Josephson junctions. Everything we have seen is consistent with a bolometric mechanism, in which heating of the film reduces the critical current below the bias current. Our observations do not preclude the possibility of nonbolometric effects in other circumstances, but we expect that such effects will be seen only on very short time scales, in very thin films, and at temperatures much lower than T_c. Nonetheless, the bolometric response can be fast and sensitive, and may be useful for some applications.

We recently learned of independent work[7] which concluded that the effect in epitaxial films was entirely bolometric.

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[1]Y. Enomoto, M. Suzuki, and T. Murakami, Jpn. J. Appl. Phys. **23**, L333 (1984).
[2]M. Leung, P. R. Broussard, J. H. Claassen, M. Osofsky, S. A. Wolf, and U. Strom. Appl. Phys. Lett. **51**, 2046 (1987).
[3]L. Testardi, Phys. Rev. B. **4**, 2189 (1971).
[4]W. S. Brocklesby, Don Monroe, M. Hong, S. H. Liou, J. Kwo, G. J. Fisanick, and P. M. Mankiewich, Phys. Rev. B **38**, 11805 (1988).
[5]A. F. J. Levi, J. M. Vandenberg, C. E. Rice, A. P. Ramirez, K. W. Baldwin, M. Anzlowar, A. E. White, and K. Short, J. Cryst. Growth **91**, 386 (1988).
[6]P. Hu, R. C. Dynes, and V. Narayanamurti, Phys. Rev. Lett. **10**, 2786 (1974).
[7]M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, Appl. Phys. Lett. **53**, 1332 (1988).