Nonequilibrium resistive response and "memory" during optical excitation of $YBa_2Cu_3O_{7-x}$ high-T_c superconducting film

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Experiments on the resistive response $YBa_2Cu_3O_{7-x}$ superconducting films to laser light are reported. It has been found that the film "remembers" information about the incident laser pulse and that this information can be read out by a subsequent laser pulse. An interpretation is offered for the observed effects.

Research on the effect of optical radiation on low-temperature superconductors dates back a fairly long time (see Ref. 1, for example). When the high-T_c superconductors appeared, the corresponding research methods were turned toward these new materials. As in Ref. 1, a resistive response of a nonthermal nature was found.[2]

In this letter we are reporting experiments on the resistive response of a high-T_c $YBa_2Cu_3O_{7-x}$ film to laser light at a wavelength $\lambda = 1.06$ μm during the flow of a direct current with a density of $(1\text{–}5)\times 10^3$ A/cm^2 through the film. This current corresponds to a current density of $(0.06\text{–}0.3)j_c$, where j_c is the critical current density. The experiments were carried out over the temperature range 10–110 K. The experiments were carried out by the four-probe method[1] on bridges of high-T_c films synthesized by laser evaporation at the Institute of Applied Physics, Academy of Sciences of the USSR. The thickness of the bridges was 1000–6000 Å, the width of the bridges was 0.05–0.1 mm, the length of the bridges was 3–8 mm, the critical current density was $j_c \approx 10^5$ A/cm^2, the transition temperature was $T_c \approx 88$ K, and the transition width was $\Delta T_c \approx 2\text{–}3$ K.

Figure 1b shows the shape of the laser pulse applied to the film. Figure 1a shows the shape of the photoresponse of the high-T_c film to this pulse found experimentally (in the form of a voltage that arises across the film), as a function of the time at several temperatures: $T_1 = 110$ K, $T_2 = T_c$, $T_3 = 84$ K, and $T_4 = 77$ K. At $T > T_c$ the relaxation time is $\approx 10^{-4}$ s, indicating that this relaxation is of a thermal nature. As the temperature is lowered, a faster component appears at T_c; the relaxation time for this faster component quickly decreases, reaching[1)] ≈ 10 ns at $T = 50$ K. The relaxation time of the response thus decreases by three or four orders of magnitude over a temperature interval ≈ 40 K. Note the observed delay (on the order of a few nanoseconds) of the response with respect to the laser pulse; this result is evidence that there is a threshold light intensity for this effect.

Figure 2 shows the amplitude of the response versus the temperature. The dashed line is the response calculated from the $R(T)$ dependence and the formula $\Delta U = (dR/dT)\Delta T_H$, where ΔT_H is the heating of the film observed experimentally at

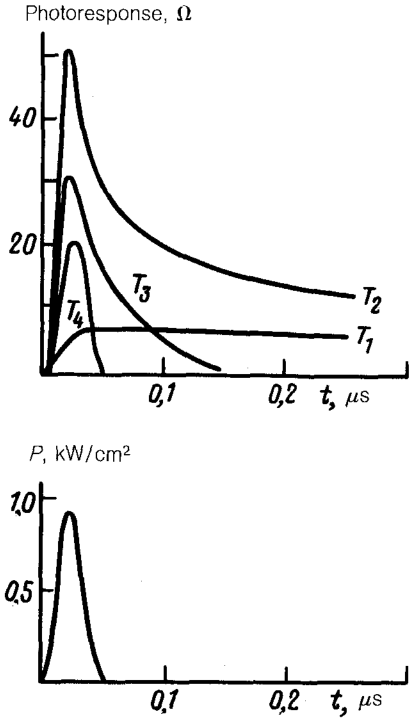

FIG. 1.

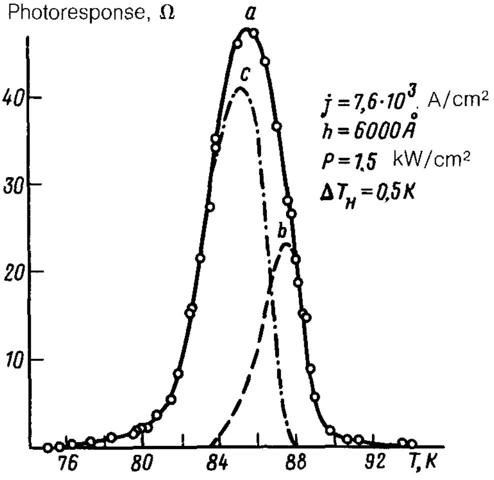

FIG. 2. a—Observed response; b—thermal component of response; c—known thermal component of response.

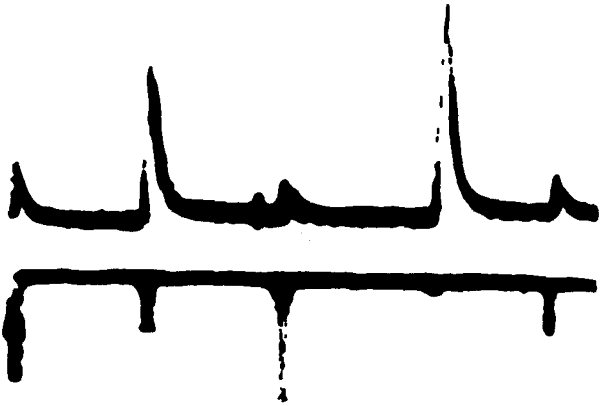

FIG. 3. Oscilloscope traces of the light pulses and of the responses to them. Lower trace—Laser pulses; upper trace—response of the system.

$T = 110$ K. At a light intensity ≈ 1.5 kW/cm^2 we have $\Delta T_H \approx 0.5$ K.

To verify this estimate of the heating of the system, we carried out some further experiments on high-T_c films with a wide superconducting transition ΔT_c. Because of the "low quality" of the films, the films were in a resistive state in the pertinent temperature region, so it was possible to directly measure the heating of the system. On the other hand, the thermal properties of the thin superconducting films, which are determined in this case by the properties of the substrate (Zr_2O, MgO, or $SrTiO_3$), were essentially the same as those of films of "high quality." These experiments verified that our estimate of the heating of the sample was acceptably accurate. As in Ref. 2, the observed maximum amplitude of the response is greater than the amplitude of the thermal response. The maximum in the amplitude of the response is ≈ 2 K lower than the maximum of the derivative dR/dT of the experimental $R(T)$ curve. The fast response is observed at temperatures $T \geqslant 50$ K (in the case of thin films); this results is further evidence that the response is not of a thermal nature.

Exposure of a high-T_c film at $T < T_c$ to laser pulses with a length of 30 ns, a repetition frequency ≈ 3 μs, and various amplitudes revealed a "memory": The magnitude of the response of the film was proportional not to the amplitude of the pulse acting on the system at the given instant but to the amplitude of the preceding pulse (Fig. 3).[2)] The film "remembers" the first pulse. When the second pulse arrives, a response proportional to the amplitude of the first pulse appears; when a third pulse arrives, the response is proportional to the amplitude of the second pulse; and so forth, until the sample is heated to $T \approx T_c$, where the fast response of the system, and also the memory, disappear. This effect persists when the laser pulses are repeated at intervals up to a minute. On the films with a large transition width ΔT_c, there is a decrease in the time over which a laser pulse applied to the film is remembered.

The nonthermal response of a high-T_c superconducting film can be attributed to a deviation from equilibrium caused in the electron, phonon,[2] and magnetic subsystems by the laser light. The deviation from equilibrium is associated with the magnetic field of the current passing through the film. Under specific conditions, the various subsystems may contribute differently, so it is important to take into account the structure of the $YBa_2Cu_3O_{7-x}$ films used in the experiments. The test samples had a crystalline texture with a **c** axis running perpendicular to the plane of the film, with crystallites ~1000 Å in size in the *ab* plane. The film thus constituted a set of regions of "strong superconductivity" (in the crystallites) and "weak superconductivity" (in the volume between crystallites). The optical radiation destroys the superconductivity primarily in the regions of "weak superconductivity," where the superconducting gap Δ is small. We suggest that the observed memory might be due to a penetration of magnetic field into regions of destroyed superconductivity and to a pinning of this field in these regions. A pinning of magnetic field has also been observed experimentally in high-T_c superconducting films by other investigators (Ref. 3, for example).

Over a time on the order of the energy relaxation time of the quasiparticles, τ_ϵ (typical values are $\tau_\epsilon \sim 10^{-12}$ s), the "weak superconductivity" is destroyed, and the magnetic field begins to penetrate into the region of inhomogeneity. The total energy of the magnetic field penetrating into the film is proportional to the volume in which the superconductivity is destroyed, so it is proportional to the amplitude of the laser pulse. When the laser pulse is "turned off," the superconductivity in the inhomogeneities is restored over a time on the order of τ_ϵ, while the magnetic field "does not have time" to escape from the inhomogeneous region.(3) It remains there in the form of a pinned vortex structure. The number of vortices is proportional to the total energy of the magnetic field that has penetrated into the sample. When the next laser pulse arrives, the system exhibits a resistive response because of a motion of these vortices. When the pulse ends, a new portion of magnetic field is pinned at inhomogeneities. We thus have a resistive response of the system which is proportional to the number of magnetic vortices that are pinned in inhomogeneous regions with the help of the preceding laser pulse. We believe that this mechanism is responsible for the memory effect. These effects might find practical application in the development of fast detectors of electromagnetic radiation and in optical data storage.

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(1) On our apparatus it was not possible to measure times shorter than ~7 ns, so the time scales of the fast response might in fact be substantially shorter.

(2) Responses of various magnitudes were observed to laser pulses of the same amplitude. The magnitude of the response was correlated with the amplitude of the previous pulse. This results proves that a correlation of the response with specifically the preceding pulse is being observed in the experiments, rather than an inverse dependence of the response amplitude on the amplitude of the laser pulse.

(3) The time scale over which the magnetic field would be capable of escaping from an inhomogeneous region is determined by the current relaxation time.

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[1]K. V. Mitsen, Trudy FIAN **174**, 124 (1986).
[2]E. Zeldov, N. M. Amer *et al.*, Phys. Rev. B **13**, 9712 (1989).
[3]A. M. Grishin *et al.*, in *Proceedings of the Twenty Sixth All-Union Conference on Low-Temperature Physics,* Vol. 1, Donetsk, 1990, p. 156.

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