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Fast photoresponse from infrared-laser-induced flux motion in $YBa_2Cu_3O_x$ films

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A fast photosignal has been obtained from epitaxial superconducting $YBa_2Cu_3O_x$ thin films when a small alternating magnetic field was applied in the film plane. No bias current was required to observe this response. Pulsed infrared radiation at a wavelength of 10.6 μm and of 150-ns duration yielded nonlinear signals: the voltage pulses had approximately half the duration of the laser output. Signal polarity was found to depend on the sign of dH/dt. For an applied magnetic field amplitude of 1600 A/m and a frequency of 20 Hz, a maximum signal amplitude of 0.5 mV was observed at 74 K for an absorbed energy of 1 μJ. The response originates from the motion of radiation depinned fluxoids across the plane of the film. These fluxoids are subject to a driving force arising from the flux-line density gradient established in the sample by the alternating magnetic field. The resulting net flux movement generates the photosignal by Faraday's law.

Several experimental techniques have been used to study the dynamics of flux motion in superconducting thin films of high-T_c ceramic material. These include the application of transport currents,[1] alternating magnetic fields,[2] or the establishment of a thermal gradient.[3] In the latter case, a flow of flux parallel to the temperature gradient occurs due to the Nernst effect.[4,5] The temperature difference may be created by a heat source and a cold sink[6] or, for a transient study, by heating one of the film surfaces with pulsed laser radiation. The latter technique has been used to study the temperature dependence of the pinning energies in granular Tl-Ba-Ca-Cu-O films.[7] We attempted to extend this study to epitaxial films of $YBa_2Cu_3O_x$ by reproducing the experimental conditions described in Ref. 7. However, for static magnetic fields up to 4.5×10^4 A/m no Nernst signals could be distinguished from the 5-μV noise.

Remarkably, if a small time-varying magnetic field was applied to the $YBa_2Cu_3O_x$ film (instead of the larger static magnetic field required for the Nernst flux motion) a comparatively strong photoresponse was observed. We found that, in the case of an alternating magnetic field, an amplitude of some A/m ($80 \le H_{ac} \le 4000$ A/m) at a frequency of the order of 10 Hz is all that is required to generate a photosignal; no bias current was applied. We believe this to be the first report of a high-T_c superconducting film's photoresponse that is simulated by a time-varying magnetic field only. Detailed below are the results of studies of the signal dependence on temperature and the observed curtailment of the film output compared with the laser pulse duration. The photoresponse has been found in films from three separate production batches.

Epitaxial $YBa_2Cu_3O_x$ films, 500 nm thick, were deposited on MgO substrates by excimer laser ablation of a sintered superconductor pellet.[8] X-ray diffraction confirmed the epitaxial nature of the films and their c-axis orientation. A stripe (dimensions 4 mm$\times$0.75 mm) was produced by mechanically patterning the film. The sample was attached to the cold finger of a closed cycle refrigerator and electrical contacts were made to a 50-Ω coaxial cable using silver wire and paint. The output signal pulses were amplified with a wide bandwidth high-frequency amplifier and observed with a 50-MHz storage oscilloscope. An electromagnet provided the alternating magnetic field. The experimental geometry was the same as used in previous studies of the Nernst effect:[7] the radiation was normally incident and the magnetic field was applied in the film plane, orthogonal to the longest dimension of the stripe, see inset Fig. 3.

Our radiation source was a Q-switched CO_2 laser, which yielded smooth 350-μJ pulses of about 150-ns duration at a repetition rate of 165 Hz. A pulse profile, obtained with a photon drag detector, is shown in Fig. 1(a). The radiation was focused to a 2-mm spot diameter with a ZnSe lens and entered the refrigerator through a ZnS window. The peak power absorbed during the pulse was calculated as about 100 W, with a total deposited energy of 12 μJ, allowing for optical losses, and assuming a film reflectivity of 0.9.[9] When the film was cooled below T_c ($\approx$84 K) fast electrical pulses were observed, as displayed in Fig. 1(b). Both negative and positive pulses were obtained with the pulse amplitude varying approximately sinusoidally in time at the same frequency as the magnetic field. The signal polarity was determined by the sign of dH/dt. At a frequency of 10 Hz, a maximum sig-

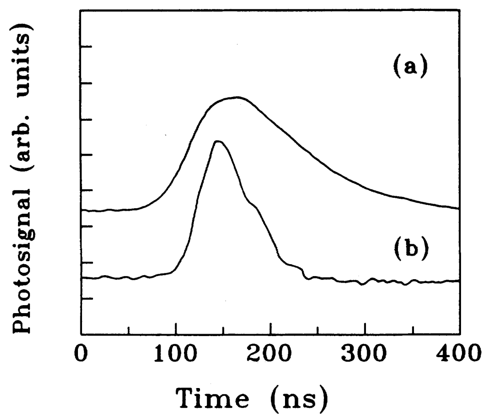

FIG. 1. Comparison of (a) the laser pulse profile and (b) the superconducting film photosignal, showing the curtailment of the photoresponse. The latter pulse was obtained at a temperature of 70 K with an applied magnetic field amplitude of 1600 A/m oscillating at 20 Hz. The peak absorbed power was about 100 W.

nal was found when (dH/dt) was maximum, while at 40 Hz a maximum signal occurred for $(dH/dt)\approx 0$.

It was noticeable that all the voltage pulses had a shorter duration than that of the laser radiation and were temporally coincident with the first part of the laser pulse. Full widths at half maximum heights were 70 and 150 ns, respectively. In order to study this pulse curtailment the laser cavity was slightly misaligned to give the modulated output shown in Fig. 2(a). The corresponding voltage signal is displayed in Fig. 2(b). This response was obtained at a temperature of 70 K, for an applied magnetic field amplitude of 1600 A/m alternating at a frequency of 20 Hz. The reproduction of the laser pulse structure indicates an upper limit for the response time of 20 ns.

We believe that the photosignal arises from flux-line motion, which generates an electric field E by Faraday's law. When the film is placed in an increasing magnetic field, an inhomogeneous distribution of flux lines is found within the sample. The fluxoid density is highest at the

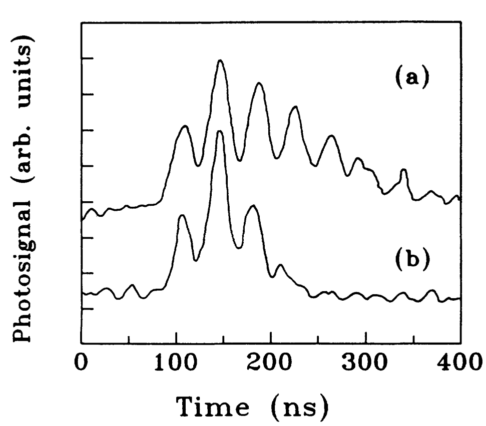

FIG. 2. Response of film (b), under the same field conditions as in Fig. 1, to a modulated laser output (a). The reproduction of the pulse structure indicates a response time of 20 ns or less.

surfaces and decreases toward the film center. This flux-line density gradient exerts a force on the fluxoids, in the same direction as the gradient, i.e., perpendicular to the film surfaces.[10] For flux motion to occur, the magnetic driving force must be larger than the pinning force. If one of the surfaces is heated (through the absorption of laser radiation) the surface fluxoids become thermally depinned and additional flux can enter the film through the heated surface. The resulting net motion of flux lines inward from the irradiated surface generates the photosignal voltage. Therefore, a time-varying magnetic field is required (for observing a photosignal) to reestablish a magnetic flux-line density gradient at the film surfaces in the interval between each laser pulse.

Additionally, the heat propagates diffusively across the film toward the film-substrate boundary. Therefore fluxoids are also depinned in the latter region. These flux lines move in a direction opposite to that of the heat flow and thus tend to cancel the output signal, causing the observed pulse shortening. Calculations of thermal profiles[11,12] have shown that the heated surface is always the warmest region of the film. Therefore, each signal pulse is expected (and observed) to be purely of one polarity. However, the thermal gradient changes with time and becomes negligible for times larger than the characteristic time for heat to diffuse through the film. This characteristic time is given by $t=d^2/D$ where d is the film thickness and D is the thermal diffusion coefficient.[12] For $YBa_2Cu_3O_x$, D can be estimated from bulk sintered pellet data as 1.5×10^{-6} m^2/s.[13] (Heat transfer should be faster in epitaxial films because of the absence of phonon-reflective grain boundaries.) Therefore, using the previous expression, the time taken for the heat to reach the film-substrate interface from the edge of the absorption layer (≈ 100 nm)[9] gives an upper bound of 110 ns. This time is in reasonable agreement with the signal duration. The reproduction of the laser pulse modulation, Fig. 2, may be related to the 100-nm absorption depth. Using the same value of D, the time scale for heat transfer from this layer can be estimated as 7 ns, thus permitting the resolution of a 20-ns pulse structure. With our experimental geometry, the electrical field may be expressed as $E=vB$, where v is the average flux-line velocity normal to the film surface. Taking the peak electrical field of 0.25 V/m, we may estimate a lower bound for the average flux-line velocity at 74 K of the order of 10^2 m/s, assuming $B=\mu_0 H$, where $H=1600$ A/m.

Depinning mechanisms other than thermal activation may also be possible. Radiation-induced currents may directly depin vortices by the Lorentz force. Alternatively, the temperature rise may increase flux penetration through any surface barrier[14] or infrared photons may create fluxoid pairs.[15] However, such mechanisms do not explain satisfactorily our observed pulse curtailment and the requirement of a time-varying magnetic field.

The amplitude of the photoresponse was measured as a function of temperature down to 14 K using smooth laser pulses, as shown in Fig. 1. Results obtained at a magnetic field amplitude of 1600 A/m oscillating at a frequency of 20 Hz are presented in Fig. 3. Also displayed is the resistive transition of the film, obtained for a direct

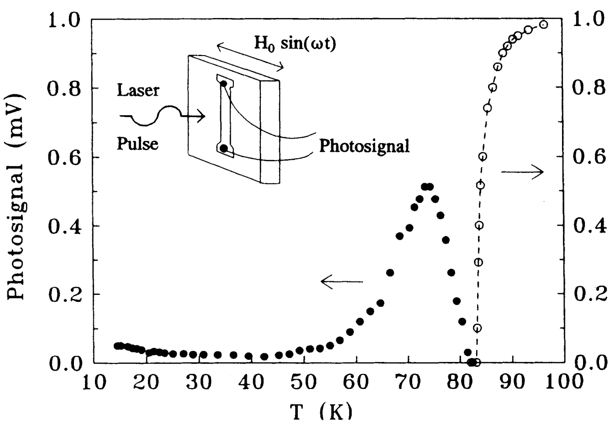

FIG. 3. Temperature dependence of the photosignal amplitude for a peak absorbed power of about 100 W and an applied magnetic field of 1600 A/m at 20 Hz. The superconducting transition is included for comparison. Also shown (inset) is a sketch of the experimental geometry.

current of 100 μA by the four-point technique. The photosignal rises rapidly below T_c, reaching a peak at about 74 K and then decreasing down to 50 K. Below this temperature the magnitude remains approximately constant until around 20 K, where a slight rise occurs. As mentioned above, the magnetic driving force must be larger than the pinning force to be able to move the flux lines across the film thickness. This explains the temperature behavior of the photosignal. The pinning force is larger than the magnetic driving force at low temperatures, thus almost no signal is detected. As the temperature is increased, the pinning force decreases in comparison with the magnetic driving force and the signal increases. Assuming uniform heating of the top half of the film in the 50 ns taken for the signal to reach its maximum, the temperature change in this period (due to the 1-μJ absorbed energy) can be estimated as 1.2 K at 74 K. The reason for the increase in signal below 20 K may be interpreted as due to the larger temperature rise caused by the strongly decreasing film heat capacity.[16]

To summarize, we have found for the first time, that an increase in flux motion in unbiased $YBa_2Cu_3O_x$ superconducting thin films arises from pulsed laser irradiation in a time-varying magnetic field. Such flux movement occurs in a direction normal to the film surface, and thus generates a photosignal across the film width. No corresponding voltage is observed for static magnetic fields up to 4.5×10^4 A/m. It is found that the response occurs on a time scale of 20 ns or less. We interpret the signal to arise from the thermal reduction of the pinning force in comparison with the magnetic driving force. The magnetic field (of the order of 1600 A/m, oscillating at 20 Hz) is required to reestablish the magnetic flux-line density gradient at the film surfaces following each laser pulse. We suggest this novel technique, using suitable short-pulsed laser sources, may be applicable to the time-resolved study of fluxoid dynamics high-T_c thin films, especially at low-applied alternating magnetic fields.

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