Fast flux motion in $YBa_2Cu_3O_x$ films in an ac magnetic field activated by laser heating

T. Puig
Institute für Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany and Grup d'Electromagnetisme, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

P. G. Huggard
Institute für Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany

M. Pont
Grup d'Electromagnetisme, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

Gi. Schneider
Department of Pure and Applied Physics, Trinity College, Dublin 2, Ireland

J. S. Muñoz
Grup d'Electromagnetisme, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

W. Prettl
Institute für Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany
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Infrared pulsed laser irradiation has been used to generate a fast photosignal from epitaxial $YBa_2Cu_3O_x$ superconducting films when a small alternating magnetic field is applied in the film plane. No bias current was applied, and no signals were observable in static magnetic fields. The photosignals, 40 ns in duration and tenths of a millivolt in amplitude, are obtained below T_c, with alternating magnetic fields up to 3200 A/m oscillating from 20 to 150 Hz. The laser pulses had a duration of 80 ns, with an absorbed fluence of 1 mJ/cm^2 at a wavelength of 10.6 μm. The signal is interpreted in terms of flux motion thermally activated by the laser heating. The magnetic force due to the alternating magnetic field exceeds the pinning force following the absorption of the radiation and generates the fast flux motion observed. The signal dependencies on temperature, magnetic-field amplitude, and absorbed fluence, as well as ac-susceptibility measurements, confirm this explanation. It is shown that this thermally activated motion, generated at $j \sim j_c$, is faster than an Anderson-Kim creep. We propose that a thermally activated flux-avalanche model based on the self-organized-criticality theory may describe the photosignal observed.

INTRODUCTION

It is well known that high-T_c superconductors present weak pinning potentials as a consequence of their high transition temperatures, short coherence length, and large anisotropy.[1] These weak pinning potentials result in a high degree of magnetic flux-line mobility, which has been studied by many different experimental techniques such as ac susceptibility,[2] vibrating reed,[3,4] dc resistivity,[5,6] microwave absorption,[7] remanent magnetization,[8] and decoration experiments.[9] The high mobility of the flux lines has introduced new phenomena in the field of flux motion (i.e., the appearance of an irreversibility line, the broadening of the resistive transition, and nonlogarithmic magnetic relaxation), which have been analyzed with the newly developed models: thermally activated flux flow (TAFF),[10] collective creep,[11] vortex glass,[12] and thermally activated flux avalanche.[13–15] The TAFF model, valid for $j \ll j_c$, considers the flux-line motion to be governed by a diffusionlike equation; the flux-line lattice is in a "liquid state." A glass-transition temperature, above which fluctuations cause the flux-line system to disorder into a fluid phase and below which crystal lattice imperfections destroy the long-range order, is predicted by the vortex-glass model. In this model, the presence of a current density below the vortex-glass transition induces thermally activated vortex loops which lead to nonlinear dissipation. In the collective-creep model the spatial correlation between the flux lines is taken into account, predicting that the volume of the flux-line bundle thermally activated depends on j and becomes infinitely large for j tending to zero. Recently a "thermally activated flux-avalanche" model based on the self-organized-criticality theory[16–18] has been developed. This model not only considers the spatial correlation of the flux-line hopping process but also the temporal correlation, which is important at $j \sim j_c$.

We have investigated the motion of flux in $YBa_2Cu_3O_x$ films under a different set of conditions and we propose that the thermally activated flux-avalanche model may explain the results. We have applied alternating magnetic fields up to 3200 A/m, parallel to the ab film plane at frequencies from 20 to 150 Hz, 15 K below T_c. At the same time we have irradiated the film with 80-ns laser pulses at a wavelength of 10.6 μm, in the direction parallel to the c axis. Upon this laser heating, 40-ns voltage pulses are measured across the film in the direction perpendicular to both the applied magnetic field and the laser radiation. With static magnetic fields no photoresponse is observed.

Many authors have observed photoresponses from high-T_c superconducting films when radiation was incident on the sample. These experiments can be classified mainly into two groups: current-biased and non-current-biased experiments. In the current-biased experiments, bolometric effects[19,20] and fast nonbolometric responses attributed to generation and decay of quasiparticles by irradiation,[21,22] to optical depairing of vortex pairs,[23] or to Josephson-junction detection in granular films[24] have been reported. In non-current-biased experiments, photovoltaic signals due to film heating over T_c,[25,26] and Nernst voltages[27] have been reported. However, none of the above can explain our requirement of a time-varying magnetic field in a non-current-biased film to observe a photosignal. We recently reported the observation of this induced voltage upon irradiation of a $YBa_2Cu_3O_x$ film in an alternating magnetic field.[28] In this paper, we present clear evidence that the photosignal is due to flux motion thermally activated by the laser heating, where the magnetic force is the driving force of this fast motion. Further, we confirm the photosignal-pulse curtailment in comparison with the laser pulse and the temperature dependence observed in the previous paper. The signal phase dependence on the alternating magnetic field is clarified and it is shown that a time-varying magnetic field is required to generate the signal. From the laser-intensity measurements and calculations based on a one-dimensional model for heat diffusion, we show that the signal is thermally activated with pinning energies of the order of 6 meV, that a thermal force is not the driving force, and that flux motion opposite to the direction of the heat flow is possible. The signal dependence on the magnetic-field amplitude and ac-susceptibility measurements performed on the same sample further confirm that the magnetic force drives the flux motion. It is shown that other than a pure Anderson-Kim thermal depinning is necessary to explain the flux motion, and a thermally activated flux-avalanche model is proposed instead.

EXPERIMENTAL

Epitaxial $YBa_2Cu_3O_x$ films, 500 nm thick, deposited on MgO by the laser-ablation technique,[29] and c-axis oriented were measured after mechanically patterning a stripe of dimensions 5×0.8 mm^2. The resistive transition temperature was 81 K. The sample was attached to the copper block of a He-flow cryostat with silver paint, and electrical contacts were made with thin copper wire and silver paint to a 50-Ω coaxial cable. The contacts were shielded to prevent them from irradiation. The output voltage was amplified with a wide-bandwidth high-frequency amplifier and observed with a 500-MHz LeCroy oscilloscope.

An alternating magnetic field of amplitudes up to 3200 A/m and frequencies from 20 to 150 Hz was generated with a pair of Helmholtz coils. A small pickup coil was attached next to the sample to determine the instantaneous magnetic field in the sample region.

A CO_2 transversely-excited atmospheric pressure (TEA) pulsed laser, $\lambda = 10.6$ μm, was used as a radiation source, yielding 80-ns smooth pulses and pulse energies of 150 mJ. Several CaF_2 and MgF_2 plates were used as attenuators to vary the absorbed fluence between 0.4 and 14 mJ/cm^2 assuming a film reflectivity of 0.9 (Ref. 30). The radiation was incident parallel to the film c axis, i.e., normal to the film surface, and the magnetic field was parallel to the ab film plane and orthogonal to the longest dimension of the stripe. This gave rise to fast voltage pulses across the stripe of tenths of a millivolt. The inset in Fig. 1 shows a sketch of the experimental geometry.

In order to detect the phase difference between the signal and the alternating magnetic field, the laser output pulses were synchronized with the alternating magnetic field; i.e., we used the sinusoidal magnetic field to generate a pulse (at a fixed point of the cycle) that triggered the laser. Any delay between the trigger signal and the laser pulse was eliminated by observing the voltages from the pickup coil and the laser pulse simultaneously. In this way, the magnetic field at the sample region was obtained from the pickup coil voltage at each laser shot. All the measurements were performed with a repetition rate close to 0.5 Hz. As the laser firing point could be moved through the cycle it was possible for the laser pulses to be scanned through the whole sinusoidal magnetic field. Since the signal pulses were obtained at the same instantaneous magnetic-field value, it was possible to average the signal pulses obtained after each laser shot and thus to decrease the noise to 20 μV.

Additionally, the ac susceptibility of the same film was measured with a Lake Shore 7000 ac susceptometer in alternating magnetic fields up to 800 A/m at 111 Hz at

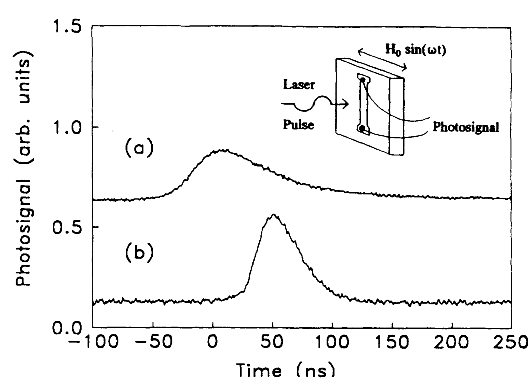

FIG. 1. (a) Laser pulse and (b) resulting film photoresponse. The measurement was carried out at 61 K for an alternating magnetic field of 3200 A/m oscillating at 33 Hz and for an absorbed fluence of 1 mJ/cm^2. The time zero is referred to the oscilloscope trigger point. Also shown is a sketch of the experimental geometry.

temperatures from 4.2 to 90 K. The alternating magnetic field was applied parallel to the *ab* film plane to reproduce the experimental conditions of the photosignal measurements. However, this geometry, in conjunction with the small sample volume, increased the experimental difficulties since the signals measured were of the same order of magntitude as the equipment sensitivity. Thus, the temperature was stabilized and every point was measured ten times to obtain an average. The averaged data presented here have been corrected for demagnetizing effects.

RESULTS

Figure 1(b) shows the photosignal obtained upon the absorption of the laser pulse [shown in Fig. 1(a)] when an alternating magnetic field of 3200 A/m oscillating at 33 Hz is applied parallel to the film plane at a temperature of 61 K. Note that 80-ns full width at half maximum (FWHM) laser pulses give rise to only 40-ns signal voltage pulses. This characteristic curtailment suggests that the signal arises from a nonthermal mechanism, since it has been shown that the thermal diffusion of fluxons caused by a thermal gradient (i.e., the Nernst effect)[27] gives rise to pulses of microsecond duration. However, the temperature dependence of the signal height, as discussed in Ref. 28, shows that this signal is related to dissipation in the superconducting state and thus also to flux motion dissipation. As the temperature is increased, the signal peak value increases up to a maximum which drops again to zero at T_c. For the sample presented here, with an absorbed fluence of 1 mJ/cm^2 and a magnetic field of 2840 A/m oscillating at 33 Hz, a maximum signal of 0.4 mV was observed at 65 K.

On the other hand, this photosignal is not observable when the alternating magnetic field is substituted by a static magnetic field as high as 2×10^5 A/m. However, an alternating magnetic field of 500 A/m oscillating at 25 Hz is sufficient to observe it. We have already reported[28] the appearance of this signal with a 2-Hz oscillating magnetic field. To analyze this point, a static magnetic field of 6400 A/m was applied to a zero-field-cooled sample and immediately afterward two laser pulses were sent to the sample 2 s apart. With the first shot a signal was observed, but no signal could be seen with the second laser pulse. Then, we reduced the static magnetic field to zero and sent another two laser pulses also 2 s apart. Only with the first shot was a signal observed, although with inverse polarity, indicating therefore that what is essential is the presence of a flux-line density gradient in the film.

Figure 2 shows the signal peak dependence within a period of the alternating magnetic field for five different magnetic-field frequencies, a magnetic-field amplitude of 1440 A/m, and an absorbed fluence of 1 mJ/cm^2 at 65 K, normalized to the maximum value. The continuous line corresponds to the normalized magnetic-field time derivative, directly measured with the pickup coil attached next to the sample. From these data, it can be inferred that the signal always follows the dependence dH/dt in the measured frequency range. In our previous work, we did not take into account a frequency-dependent phase shift

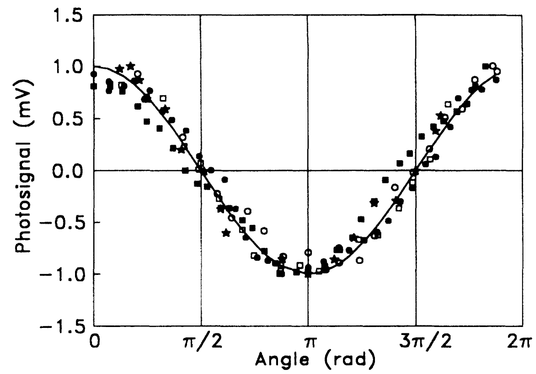

FIG. 2. Signal peak dependence within a period of the alternating magnetic field oscillating at (★) 25, (□) 48, (●) 71, (○) 106, and (■) 139 Hz, normalized to the maximum value. The measurement was performed at 65 K for an absorbed fluence of 1 mJ/cm^2 and an alternating magnetic field of 1440 A/m. The solid line shows the time dependence of the magnetic-field derivative directly measured with the pickup coil.

introduced by the metallic cryostat. Thus, the maximum signal occurs at the point in the cycle where the applied magnetic field is zero, while zero signal is obtained when the applied magnetic field is at its maximum. For this reason all the results presented below were obtained at $(dH/dt)_{max}$.

At this stage, the above results would seem to suggest that the magnetic flux-line density gradient established in the sample due to the alternating magnetic field applied was responsible for the signal. Therefore, we studied the signal dependence on the magnetic-field amplitude and frequency.

No signal dependence on the magnetic-field frequency in the range from 20 to 150 Hz was observable. These results were obtained at a magnetic-field amplitude of 960 A/m, at an absorbed fluence of 1 mJ/cm^2, and at an initial temperature of 65 K.

Figure 3 shows that at low magnetic fields the signal has a linear dependence on the magnetic-field amplitude. At higher fields, a deviation from this linearity tending to saturation is observed. These measurements were performed at 33 Hz for an absorbed fluence of 1 mJ/cm^2 at

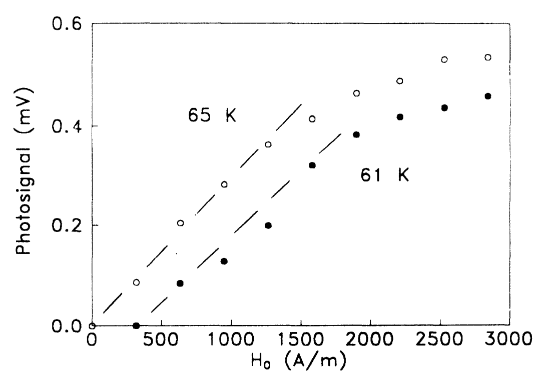

FIG. 3. Photosignal dependence on the magnetic-field amplitude at a frequency of 33 Hz and temperatures of 61 and 65 K. The absorbed fluence was 1 mJ/cm^2.

four different temperatures (56, 61, 65, and 74 K). The signal peak dependence on the magnetic-field amplitude for 61 and 65 K is shown in Fig. 3. Note that the deviation from linearity appears at lower magnetic-field amplitude at 65 K than at 61 K, and that for the lower temperature a minimum magnetic field, H_{ac}^{min}, of 300 A/m is required before any photosignal is observable.

In Fig. 4 we have plotted the magnetic field where the deviation from linearity starts, H_{ac}^{sat}, and the values of H_{ac}^{min} versus the temperature of the measurement. Note that both fields decrease as the measuring temperature is increased.

Finally, we present the results obtained when the signal was measured as a function of the laser intensity. Absorbed fluences varied from 0.4 to 14 mJ/cm^2 for an alternating magnetic field of 2840 A/m oscillating at 33 Hz at 65 K. Several interesting features observed in these measurements have allowed us to find an explanation of the effect, as reported in the discussion.

Figure 5 shows the signal peak dependence on the absorbed fluence in a log-log plot. The nonlinear dependence of the photosignal on fluence confirms that the signal is not proportional to the maximum thermal gradient established in the sample by the laser heating and, therefore, a thermal force alone cannot explain the results. We also observe a delay between the start of the laser and the photosignal pulses that depends on the laser intensity. Figure 6 shows that this delay decreases with increasing absorbed fluence. The experimental conditions were the same as given for Fig. 5. Furthermore, the signal pulse changes in shape and duration as the fluence is increased. This is shown in Fig. 7, where several photosignal pulses, obtained at different fluences for the same experimental conditions as Fig. 5, are presented. In this figure $t=0$ refers to the oscilloscope trigger point and $t=-45$ ns indicates the laser pulse start. Notice that at low fluences only a single peak is observed, while as the fluence is increased a second peak starts appearing on the right shoulder of the main peak. In addition the pulse duration is very much reduced for absorbed fluences above 2 mJ/cm^2.

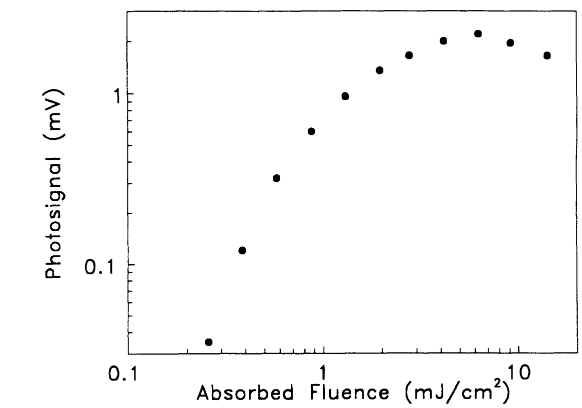

FIG. 5. Photosignal dependence on the absorbed fluence at 65 K for an alternating magnetic field of 2840 A/m at 33 Hz.

To understand this signal it was very important to know the sample magnetization state before each laser pulse energy was absorbed. We measured the real and the imaginary components of the ac susceptibility as a function of the temperature for alternating magnetic fields of 2, 8, 80, 100, 200, and 800 A/m at 111 Hz parallel to the *ab* film plane. Figure 8 shows the results at fields of 2, 200, and 800 A/m as representative data. Note that the imaginary component has been multiplied by a factor of 5. For an alternating magnetic field of 2 A/m and at very low temperatures, an almost complete shielding is observed followed by a very broad transition to the normal state as the temperature is increased. The superconducting onset temperature is at 79 K. When the alternating magnetic field is increased to 800 A/m the sample is not completely diamagnetic at 5 K. In the imaginary component a peak for ac magnetic fields above 100 A/m is observed. This peak, which is due to the hysteretic losses in the material and indicates the tempera-

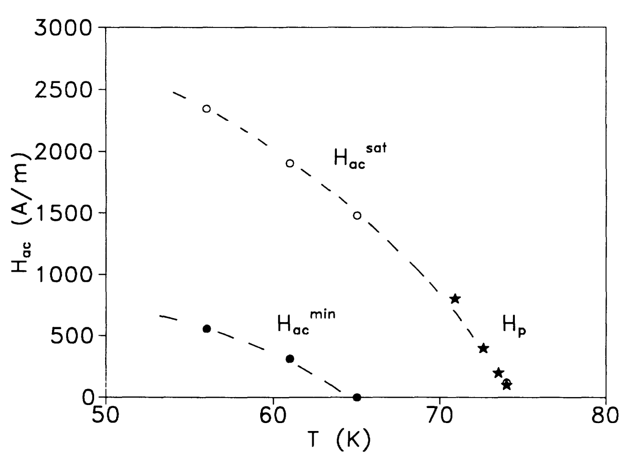

FIG. 4. Magnetic-field amplitude where the photosignal saturates, H_{ac}^{sat}, and minimum magnetic-field amplitude required to observe it, H_{ac}^{min}, as functions of temperature. The magnetic-field frequency was 33 Hz with an absorbed fluence of 1 mJ/cm^2. Also shown is the full penetration field, H_p, obtained from the peak of the imaginary component of the ac susceptibility versus the measuring temperature.

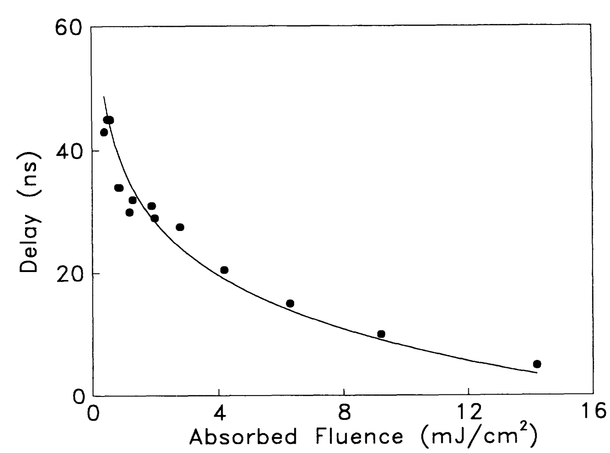

FIG. 6. Delay between the start of the laser and the signal pulses as a function of the absorbed fluence. The measurement was taken at 65 K for an alternating magnetic field of 2840 A/m at 33 Hz. The line shows the simulated delay obtained by the one-dimensional model for heat diffusion.

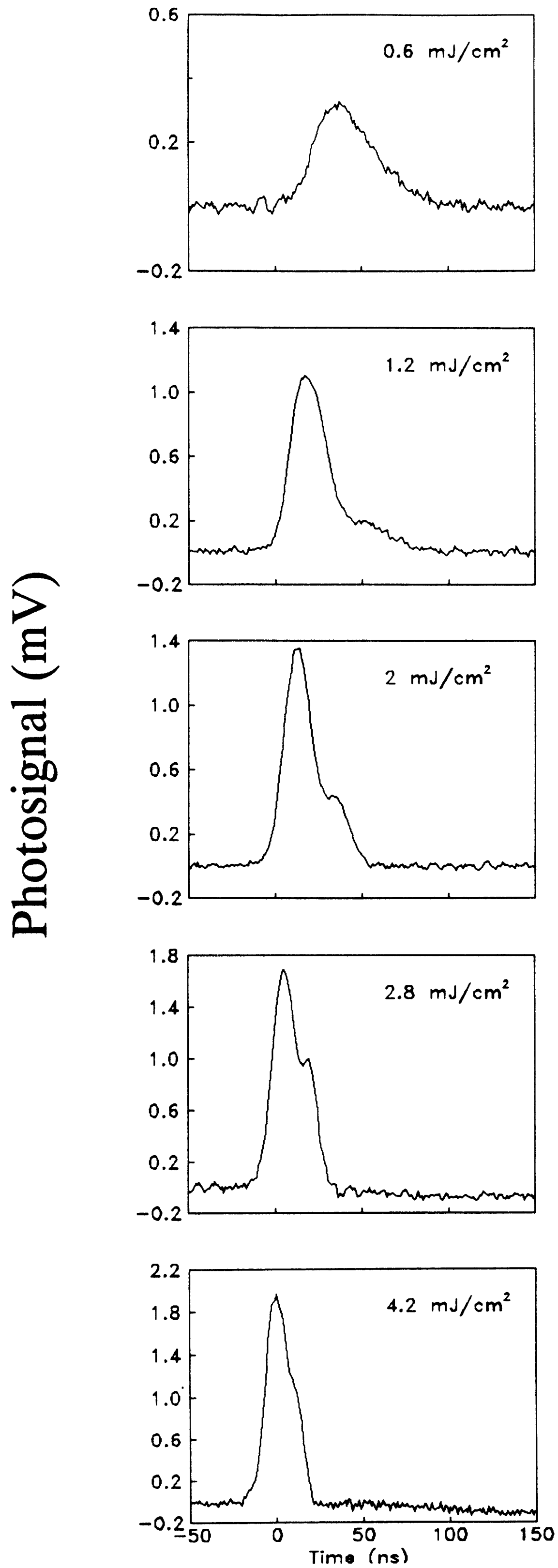

FIG. 7. Photosignal pulses obtained at different absorbed fluences for an alternating magnetic field of 2840 A/m oscillating at 33 Hz and a film temperature of 65 K. The time zero refers to the oscilloscope trigger point.

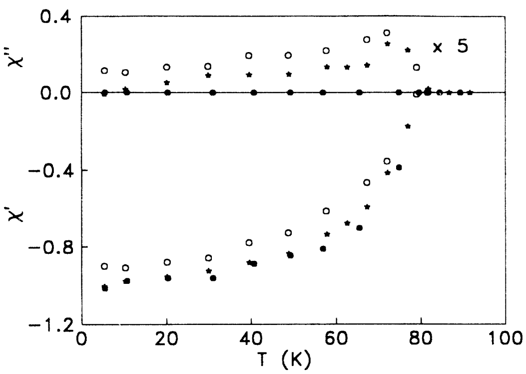

FIG. 8. Real and imaginary components of the ac susceptibility for an alternating magnetic field of (●) 2, (★) 200, and (○) 800 A/m oscillating at 111 Hz parallel to the *ab* film plane. Note that the imaginary component of the susceptibility has been multiplied by 5.

ture where the magnetic field reaches the center of the sample, decreases to lower temperatures as the magnetic field is increased. From these data we can assume that above 55 K, which is in the temperature region where the photosignal measurements have been carried out, the sample is in the critical state before the radiation is absorbed.

DISCUSSION

When an alternating magnetic field H ($H > H_{c1}$) is applied to a superconducting film, a critical state given by the condition $F_m = F_p$ is established in the sample, where F_m is the magnetic-force density given by

$$\mathbf{F}_m = (\nabla \times \mathbf{H}) \times \mathbf{B} , \tag{1}$$

and F_p is the pinning-force density. This condition defines a critical magnetic-flux gradient and gives the magnetic-field penetration into the sample as the alternating magnetic field oscillates.

When the laser radiation is absorbed by the sample, the critical-state condition satisfied just before the laser pulse was absorbed is no longer fulfilled since F_p is thermally reduced. Thus, F_m exceeds F_p and a fast flux motion is observed. This motion is therefore activated by the laser radiation. A preferential direction for flux motion is established by the asymmetrical heating and a net electric field E_f is induced by this fast motion, and is given by

$$\mathbf{E}_f = -\mathbf{v} \times \mathbf{B} , \tag{2}$$

where v is the average flux-line velocity of the flux motion and B the macroscopic magnetic induction. From Eq. (2) we can estimate a lower bound for the average flux-line velocity of our film, assuming $B = \mu_0 H$. At 65 K, for an applied field $H = 3200$ A/m and a measured electric field $E = V/l \sim 0.1$ V/m (V being the measured signal peak voltage and l the length of the stripe), we calculate an average flux-line velocity of the order of 10^2 m/s, consistent with our previous results.[28]

Every time the alternating magnetic field is swept up or down and before a laser pulse is absorbed, a flux-line density gradient due to the critical-state condition is established in the sample. This is the reason for the appearance of a magnetic force F_m, which acts as the driving force of the flux motion. When a laser pulse is absorbed, the sample is heated, the motion activated, and the flux-line density gradient is weakened. Immediately afterwards, the film starts cooling down, this time with a magnetic field applied (a field-cooled process), but no gradient is created during this process. This is because the whole film only needs a time of the order of microseconds to return to the temperature of the substrate.[31] The magnetic fields we have applied had a minimum period of 7 ms and therefore can be considered constant during this cooling period. As the film is field cooled, some fluxons will be trapped, but in any case the flux-line distribution will be far away from a gradient and thus the magnetic force will be zero. Therefore, we need a magnetic-field variation between two laser shots creating a flux gradient in order for a photosignal to be observable.

The ac-susceptibility measurements have confirmed that the film is in the critical state at the temperature and magnetic fields where the photoresponse was measured. This means that in the penetrated region a current density circulates which is equal to the critical current density j_c defined by the critical flux gradient

$$j_c = \frac{1}{\mu_0} \frac{dB}{dx} , \tag{3}$$

where dB/dx is the macroscopic flux-line density gradient in one dimension. As the magnetic-field amplitude increases, the region circulated by j_c (i.e., the volume of the sample that contributes to the photosignal) increases, and thus the photosignal increases as shown in Fig. 3. Maximum signal should be obtained at $H = H_p$ where the flux-line density gradient reaches the center of the film. This is confirmed in Fig. 4 where the $H_{\rm ac}^{\rm sat}$ values are presented together with the H_p values obtained from the peak of the imaginary component of the ac susceptibility. Note that although we could not measure the ac susceptibility at higher ac fields, the values of H_p determined from the ac-susceptibility results are in reasonable agreement with those of $H_{\rm ac}^{\rm sat}$. If the magnetic field is increased above H_p more fluxons penetrate the sample, but since the film is already fully penetrated, we always have the contribution of the whole sample and the signal saturates. The critical current density, J_c, can be estimated from these values of $H_{\rm ac}^{\rm sat}$ using Bean's model

$$J_c = \frac{H_p}{d/2} , \tag{4}$$

where d is the film thickness. At 65 K, where $H_{\rm ac}^{\rm sat} = 1480$ A/m, we obtain a value for the critical current density of approximately 600 A/cm^2. This value is not very high for an $YBa_2Cu_3O_x$ film. However, it is in reasonable agreement with the T_c depression observed in this film and its ac susceptibility.

Figure 5 has shown that the signal is not linear in fluence as it should be if it was proportional to the maximum thermal gradient established in the sample. In addition, the signal pulse drops to zero before this maximum thermal gradient is achieved, confirming that a thermal force given by

$$\mathbf{F}_{\rm th} = s \nabla T , \tag{5}$$

where s is the flux-line entropy density, cannot be the driving force for the flux motion. Therefore, the magnetic force is assumed to be the driving force.

A one-dimensional model for heat diffusion applied to our data[32] has been used to calculate the temperature profiles as a function of time for different film depths and laser fluences. From these data, we have determined the temperature at the free surface of the film when the signal pulse starts to rise, for the different measured fluences. We have obtained a constant value equal to 71 ± 1 K, indicating that for each fluence the flux motion is not activated until the film free surface is heated to 71 K. This explains the delay shown in Fig. 6, where the line simulates the results obtained by the one-dimensional model for heat diffusion. From this temperature an activation energy for the fast flux motion in the sample at 65 K for an alternating magnetic field of 2840 A/m oscillating at 33 Hz can be determined as $K_B T$ with $T = 7$ K: the value obtained is 6 meV.

To explain the differences observed in the shape and duration of the signal pulses of Fig. 7, we need to come back to the critical-state model. First, it should be noticed that these results were obtained at 65 K for an alternating magnetic field of 2840 A/m, which is approximately $2H_p$, and that all these measurements were performed at the point in the cycle where the applied magnetic field is zero corresponding to the critical-state profile shown in Fig. 9(a). Upon absorption of the laser radiation by the film free surface (i.e., the left side of the critical-state profile in Fig. 9), the heat diffuses towards the film-substrate interface. However, when the initial part of the laser pulse is absorbed, only the first part of the film is affected by its heat, the pinning potentials decrease there, and F_m exceeds F_p. A flux motion is generated following the magnetic gradient but in the opposite direction to the heat flow, and thus fluxons move out

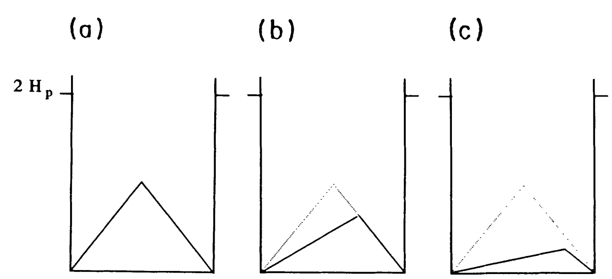

FIG. 9. Critical-state profile for an ac magnetic-field amplitude of $2H_p$ at $H = 0$, (a) before the radiation is absorbed, (b) when the film free surface has reached the activation temperature and flux motion is activated opposite to the direction of the heat flow, and (c) when the activation temperature has reached the negative slope of the flux-line density gradient and flux motion is activated in both directions. The dotted line shows the situation before the laser radiation was absorbed.

from the sample and the positive slope of the critical-state profile j_c decreases as shown in Fig. 9(b). Later on, when the activation temperature (71 K) reaches the negative slope of the critical-state profile, flux motion is activated in the direction of the heat flow as indicated in Fig. 9(c). These fluxons move toward the film-substrate interface, generating a voltage signal of opposite sign to the one generated by the fluxons moving towards the free surface of the film. However, since the surface is always the warmest region of the film,[33] there is always a net flux motion in the direction opposite to the heat flow and a sign reversal of the signal pulse is not observed.

This explains the two peaks appearing in the photoresponses shown in Fig. 7 for absorbed fluences above 2 mJ/cm^2. The photosignal pulse is the summation of two voltage signal pulses of opposite sign. The negative one, generated by the flux lines moving towards the film-substrate interface, arises at later times and is always smaller than the positive one obtained from the flux moving toward the free surface of the film. Furthermore, the second peak approaches the first one as the fluence is further increased, since the motion towards the film-substrate interface is activated at earlier times. At these high fluences, above 2 mJ/cm^2, it is observed that the pulse duration is very much reduced (a 40% reduction of the pulse duration is obtained at 2 mJ/cm^2 in comparison with the 1 mJ/cm^2 pulse). Calculations of the diffusion of heat with time indicate that for fluences above 2 mJ/cm^2 the signal ends when the whole sample is driven to the normal state. At low fluences, below 1 mJ/cm^2, the fluxons move out of the film from the film free surface before the activation temperature reaches the negative edge of the flux-line density gradient. Thus, pulses are observed with a signal peak that end when the flux has completely relaxed out of the sample.

From the photosignal pulses we can estimate the relaxation rate of the phenomenon by dividing the film thickness by the pulse duration. In particular, if we take the signal pulse obtained for 1.3 mJ/cm^2 for the same conditions as Fig. 7, a relaxation rate of 20 m/s is obtained. Notice that this relaxation rate is larger than the 25×10^{-2} m/s given in the literature[34] for typical magnetic relaxation experiments in $YBa_2Cu_3O_x$. Therefore, a model describing this motion must include the observation that the movement, which is initially thermally activated and obtained at large driving forces, is very fast. The collective-creep model,[11] where flux motion is spatially correlated, could be suitable; however, at such large forces, this spatial correlation is lost and the motion is characterized by an Anderson-Kim creep model.[35,36] The large relaxation rates obtained suggest that the observed flux motion must be explained by other than a pure Anderson-Kim creep depinning.

We propose that a flux-avalanche process is likely to occur at this large driving force due to the high magnetic pressure, and that it may explain the fast signal observed. Recently, the self-organized-criticality theory, which is a temporally and spatially correlated model that describes the avalanche effect in a sandpile, has been used to explain the depinning of magnetic-flux lines in the critical state. In the self-organized-criticality model the motion is not necessarily thermally activated, as external mechanical vibrations can also initiate the movement. However, since in the high-T_c superconductors thermal effects are so important, Tang and Bak[17] proposed the combination of thermally activated and avalanche flux motions, resulting in the thermally activated flux-avalanche model. This model assumes that the depinning process is initially thermally activated while the subsequent hopping process of depinned flux lines is exclusively governed by spatially and temporally correlated avalanches of flux lines. The avalanche effect is important near the critical state as a result of high magnetic pressure. This model has been used by Wang and Shi[13,14] to explain their nonlogarithmic magnetic relaxation at $j\sim j_c$ in high-T_c superconductors.

We believe that this motion may be a plausible candidate to explain our experimental results. On one hand, we have shown that the motion is thermally activated and generated at large driving forces. On the other, we need a model able to explain flux motion at large relaxation rates, larger than an Anderson-Kim creep, and an avalanche motion may be able to do it.

In order to confirm that our results may be explained by this thermally activated flux-avalanche model, we must consider the correlation between the average flux-line velocity defined by Eq. (2) and the time-dependent velocity derived from this model

$$v=\omega_0 s_c\left[1-\frac{j}{j_c}\right]^{-\alpha}\exp\left[-\frac{U_0}{kT}\left[1-\frac{j}{j_c}\right]^{\beta}\right], \qquad (6)$$

where ω_0 is an attempt frequency, s_c a characteristic avalanche length, j_c the critical current density, and j the actual current density. U_0 is a characteristic energy and α and β are a critical and a constant exponent respectively. In this equation, thermal and avalanche effects are considered. At low driving forces, the thermal effects are important, while as j increases the avalanche motion starts playing a role. Notice that, in our case, U_0, j, and j_c depend on the film temperature, which strongly depends on depth and time after the laser pulse absorption.

CONCLUSIONS

We have shown that a fast flux motion can be generated in an unbiased $YBa_2Cu_3O_x$ thin film if a time-varying magnetic field is applied parallel to the *ab* film plane and infrared pulsed laser radiation is used to heat the film free surface. We have seen that a thermal force cannot explain the results and instead a magnetic force is considered to drive the flux motion. The critical-state condition established in the film due to the alternating magnetic field is no longer fulfilled upon absorption of the radiation. The pinning force is thermally reduced and the magnetic force generates the flux motion. Pinning energies of the order of 6 meV are thus obtained.

It has been shown that initially the flux motion is only activated in one direction. However, flux motion is activated in the opposite direction when the activation temperature reaches the point where the flux-line density gradient changes its sign. This latter motion is never as important as the flux motion at the film free surface, since the film free surface is always the warmest region of the film. Therefore, it is not possible to obtain a sign reversal of a signal pulse.

We have shown that the flux motion observed is much faster than a pure Anderson-Kim creep. We propose to explain it by a thermally activated flux-avalanche model valid at $j \sim j_c$ in which the flux-line motion is spatially and temporally correlated.

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