Photoresponse of inhomogeneous high-T_c superconducting films and the memory effect

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(Submitted 18 November 1992)
Zh. Eksp. Teor. Fiz. **103**, 2072–2101 (June 1993)

A theoretical model is proposed for the nonequilibrium resistive state of thin inhomogeneous superconducting films in the presence of time-dependent external electromagnetic radiation. It is shown that long-lived nonequilibrium states and a memory effect, manifested experimentally as temporal dispersion (dependence of the magnitude of the photoresponse not only on the amplitude of the electromagnetic radiation acting on the film at a given moment in time but also on preceding changes in the amplitude of the electromagnetic radiation and arising due to pinning of the magnetic field) of the photoresponse can occur and the conditions under which they exist are determined. A classification is given for possible types of photoresponses that can be observed in different structures of inhomogeneous high-T_c superconducting films. It is shown that the existence of the memory effect is determined by the variance of the energy distribution of weak links. The computational results obtained with the help of the proposed model are in good agreement with the experimental data.

An important problem arising in the study of the properties of superconducting materials, including also high-T_c superconductors, is the problem of studying nonequilibrium states. Nonequilibrium states are of interest from different standpoints: From the theoretical standpoint it is of interest to determine the physical mechanisms responsible for the departure from equilibrium as well as to investigate the different characteristics of a superconductor and from the standpoint of applications it is important to determine the possibility of utilizing various nonequilibrium effects and mechanisms in different electronic devices which already exist or can be produced on the basis of the high-T_c superconductors. In this paper we discuss a range of physical phenomena associated with the nonbolometric (nonthermal) response, which we observed experimentally in superconducting films, to laser radiation. We examine the existing theoretical models of the appearance of nonbolometric photoresponse in high-T_c superconducting films as well as the necessity for modifying the models in order to take into account new experimental data obtained at the Institute of Applied Physics of the Russian Academy of Sciences.[1]

INTRODUCTION

Several mechanisms for the nonbolometric (not associated with the heating of the crystal lattice) photoresponse in superconductors are now known. New experimental data,[1] which we discuss below, show that in high-T_c superconducting films different mechanisms for departure from equilibrium can be manifested simultaneously. We now consider the familiar mechanisms of nonequilibrium and resistivity in superconducting films.

1. Laser induction of nonequilibrium resistive states in superconducting films was first observed in low-T_c superconductors. Thus the nonbolometric response of thin films of the low-T_c superconductor Pb was observed in one of the first experimental works on this subject.[2] The existence of the response was ascribed to the breaking of Cooper pairs by the action of laser radiation and to the formation of nonequilibrium quasiparticle distributions (see also Refs. 3 and 4). The concept of nonequilibrium quasiparticles was further theoretically elaborated in Refs. 5–7, and it was employed, taking into account the nonequilibrium nature of the phonon system as well,[8,9] for interpreting the properties of low-T_c superconducting films (see, for example, Ref. 10).

Analysis of the experimental data for spatially inhomogeneous high-T_c superconducting films[4] showed that in such films optical suppression (of the type described in Ref. 5) of superconductivity can occur only in spatial regions where the order parameter is locally depressed. For this reason, if we consider a multidimensional film (as in Ref. 4), then at temperatures below the point at which the equilibrium resistance vanishes and for not too intense laser radiation (such that not all channels for superconducting current flow between contacts are destroyed) these models of nonequilibrium quasiparticles and phonons cannot explain the appearance of a nonequilibrium resistive state. In a multidimensional sample with local suppression of superconductivity in some spatial regions the superconducting current can bypass these regions and flow along the remaining flow paths. This latter possibility is very important in the study of the nonbolometric response of high-T_c superconducting films, since, as is well known, the temperature range of the nonbolometric response extends below the point at which the resistance of the film vanishes.[3,4,11,12]

2. Another mechanism for the appearance of the resistive photoresponse in superconducting films is photofluxon detection, proposed in Refs. 13–15. This theory is based on the existence of magnetic vortices, carrying magnetic flux

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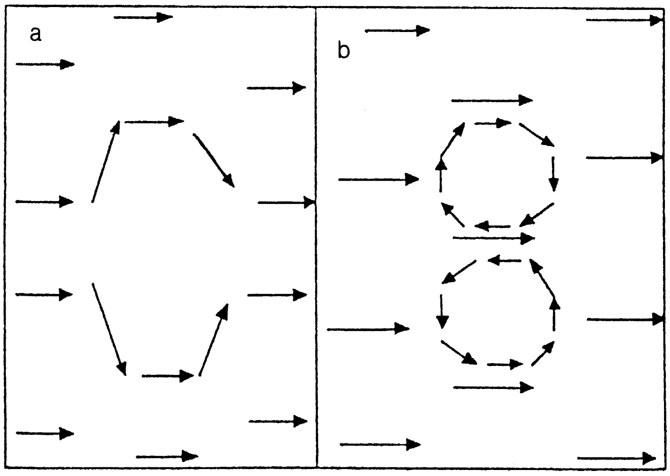

FIG. 1. Taken from Refs. 13–15—photofluxon detection model. Current distribution near a fluxon pair created as a result of the formation of a nonequilibrium "warm hole" in the superconducting film. a) Current flowing around the region where superconductivity is suppressed on scales of the order of the size of the vortex core due to the absorption of a photon. b) Pair of vortices oriented so that the external transport current prevents annihilation of the vortices. The current configurations (a) and (b) are equivalent.

$\phi_0=h/2e$, in the superconductors. The appearance of an electric field and dissipation, which are caused by the motion of the magnetic vortices, is a familiar effect (see, for example, Ref. 16). A vortex moving with velocity $\mathbf{v}$ in a superconductor induces an electric field[16]

$$\mathbf{E}=\frac{1}{c}[\mathbf{B}\mathbf{v}], \tag{1}$$

where c is the velocity of light and $\mathbf{B}$ is the magnetic induction (for vortices having the same polarity $B=n\phi_0$, where n is the concentration of vortices). It is this electric field $\mathbf{E}$ that is responsible for the resistive response of the system.

In the theory of Refs. 13–15 it is assumed that, by analogy to the mechanism of detection of photoconductivity in semiconductors, a vortex-antivortex pair, i.e., close fluxons of opposite "polarity" (see Fig. 1b), can arise when a photon interacts with a thin superconducting film in an external magnetic field. Due to the Lorentz force the transport current acts on these vortices, canceling their mutual attraction, and pushing them to opposite edges of the film. This results in unsteadiness, i.e., transport of a quantum of flux ϕ_0 through the film, which corresponds to the appearance of a voltage jump. In this model the vortex pair arises due to the creation of a "normal core" on scales of the order of the superconducting coherence length. This is made possible by thermal fluctuations or absorption of a photon. In this case it can be assumed that, as a result, two overlapping vortices of opposite polarity occur. If these vortices are separated, circulating currents appear and these vortices can be stable (see Fig. 1). An expression for the energy of such a vortex pair is given in Refs. 13–15. This energy is equal in order of magnitude to the condensation energy in two vortex cores. The transport current J required in order to balance the attraction of two vortices in a pair is approximately equal to the critical Ginzburg–Landau current in the superconductor. This situation is the two-dimensional generalization of phase-slip centers in one-dimensional superconducting microstrip.[17,18] The photofluxon detection model[13–15] agrees well with the experimentally observed properties of films of the low-T_c superconductor NbN. However, it neglects the existence of a pinning potential for magnetic vortices. This circumstance can markedly alter the behavior of the vortices, which is especially important for high-T_c superconducting films in which the pinning potential is quite high.

3. The Anderson–Kim model[16,19] of the resistive state and different modifications of this model provides a good description of the nonequilibrium properties of high-T_c superconducting films. In these models it is assumed that the resistive state of a superconductor arises due to hopping of magnetic vortices between neighboring pinning centers. Since hops of vortices occur due to activation the pinning potential barrier, the resistivity of the superconductor is described by the formula

$$\rho=\rho_{\text{flow}}\exp(-U/T), \tag{2}$$

where for a quasiequilibrium state it can be assumed[16] that $\rho_{\text{flow}}\approx\rho_n B/H_{c2}$, where ρ_n is the resistivity in the normal state, B is the magnetic induction of the vortices (average macroscopic field obtained by averaging over all vortices), H_{c2} is the critical field, U is the pinning potential, and T is the temperature. The idea of using such models for describing resistive states of superconducting films is based on the fact that external perturbations can decrease the pinning potential and this results in a sharp increase of the resistance.

Zeldov *et al.*[20,21] were among the first to associate the appearance of the nonbolometric photoresponse of high-T_c superconducting films with photoactivated flux creep. Different modifications of the Anderson–Kim model[19] are now successfully employed for describing the nonequilibrium properties of high-T_c superconducting films. Different approximations are employed for both the pinning potential U and the pre-exponential factor ρ_{flow} (see, for example, Refs. 3, 12, and 22–24). Flux creep has been studied as a function of the magnetic field and temperature (see, for example, Ref. 22) as well as the transport current and the spatially nonuniform distributions of the pinning potential.[24]

We call attention here to a circumstance that will be required below. The formula (2) contains two factors, the preexponential factor ρ_{flow} and the exponential factor $\exp(-U/T)$. As a result of this, the system can exhibit qualitatively different behavior depending on the value of U/T. Thus for $U/T\gg1$ the nonequilibrium response is determined by the magnitude and the distribution of the pinning potential of the vortices (virtually all vortices are pinned). In the opposite case $U/T\ll1$ the behavior of the system is determined by the preexponential factor and virtually nothing depends on U.

This completes our review of the models of different mechanisms of nonequilibrium and resistive states in superconducting films. We now present new experimental

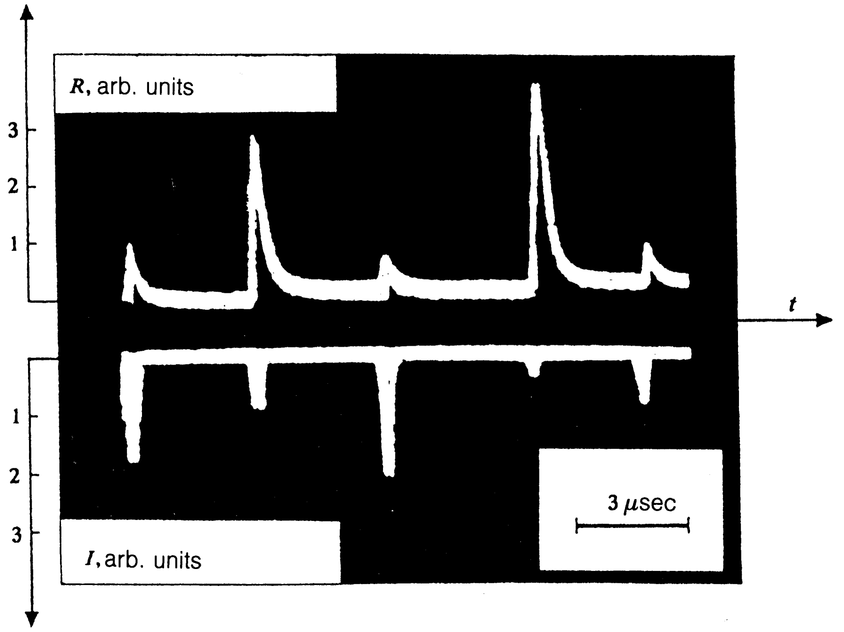

FIG. 2. Oscillograms (taken from Refs. 1 and 25) of the laser pulses $I(t)$ and the photoresponses $R(t)$ to them. It is evident from the figure that in this case a memory effect occurs in the system—the amplitude R_i of the photoresponse pulse is correlated with the amplitude of the preceding (in time) I_{i-1} laser pulse.

facts[1,25] and discuss a theoretical model for describing the resistive state and the nonbolometric response of thin high-T_c superconducting films.

RESISTIVE PHOTORESPONSE OF HIGH-T_c SUPERCONDUCTING FILMS AND THE MEMORY EFFECT

A new effect associated with the nonbolometric response of a thin high-T_c superconducting film to irradiation by a sequence of Nd:YAG laser pulses ($\lambda = 1.06$ μm) of different amplitude was first observed at the Institute of Applied Physics of the Russian Academy of Sciences.[1,25] A weak transport current $j \ll j_c$, where j_c is the critical current for a given film, was passed along a film and the nonequilibrium resistive response was recorded with the help of the standard procedure. The experimental apparatus and the parameters of the $YBa_2Cu_3O_{7-x}$ superconducting films are described in detail in Refs. 1, 4, and 25. We note only that the temperature memory effect discussed below existed in the range where the nonbolometric photoresponse of the superconducting film to the laser radiation was observed.

The experiments showed that different photoresponses of the system are possible. In one possible case the amplitude of the photoresponse pulse is proportional to the amplitude of the laser pulse acting on the film at the same moment in time. But cases of the type displayed in Fig. 2, taken from Refs. 1 and 25, are also possible. In these cases the correlation between the amplitude of the photoresponse pulse is correlated with the amplitude of the preceding (in time) laser pulse, i.e., a memory effect is observed: The high-T_c superconducting film stores information about the amplitude of the first laser pulse. The second laser pulse "read outs" this information. This is manifested as the appearance of a photoresponse pulse whose amplitude is proportional to the amplitude of the first laser pulse. At the same time, information about the amplitude of the second laser pulse was recorded in the film. The third laser pulse reads out this information and recorded information about its own amplitude, and so on (see Fig. 2). We note that this experiment was performed without an external magnetic field. In this case the magnetic field existed only in the form of the field generated by the transport current.

In our theoretical model, which makes it possible to interpret this memory effect, we assume that in order to explain the observed effect the spatially nonuniform structure of $YBa_2Cu_3O_{7-x}$ films must be taken into account, just as for other high-T_c superconductors (see, for example, Refs. 26–28) A high-T_c superconducting film consists of crystallites (granules) and the space between the granules. In the granules the superconducting order parameter Δ is much greater than its value in the intergranular space. A fragment of such a film is illustrated schematically in Fig. 3.

It is obvious that flow of the transport current along the film and the strength of the critical current in the film are associated with the superconducting current paths along channels of strong superconductivity (in the intergranular space the order parameter Δ either can be completely destroyed ($\Delta = 0$) or quite easily suppressed by the current or other external perturbations). The current-flow channels are also illustrated schematically in Fig. 3. It is clear that in this situation the simple mechanism for the appearance of resistivity due to excess quasiparticles,[5–7] which destroy superconductivity primarily in regions of weak superconductivity, cannot lead to the appearance of the resistive state in the film as a whole. In the two-dimensional film under consideration, these regions of locally suppressed superconducting order parameter will be shunted by superconducting paths—the superconducting current will by-pass these regions. We associate the existence of the memory effect with the appearance and pinning of magnetic vortices in regions of weak superconductivity. It is the photoactivated creep[20,21] of these vortices that leads to the appearance of the resistive photoresponse. We

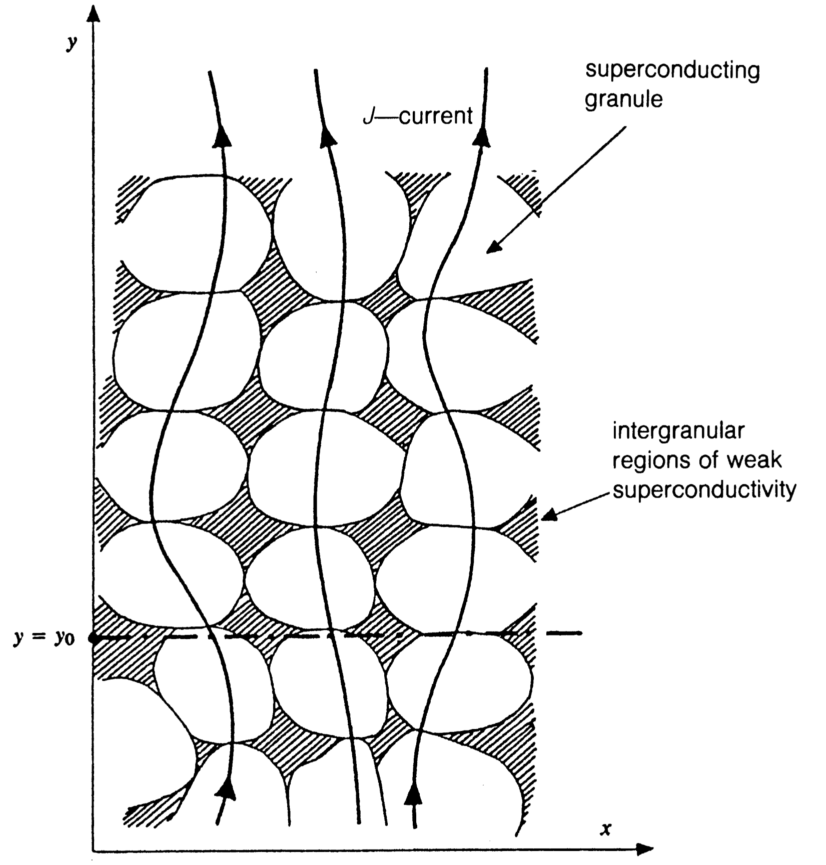

FIG. 3. Schematic representation of the spatial structure of an inhomogeneous high-T_c superconducting film and transport current channels. The inhomogeneous superconducting film consists of granules—regions of "strong" superconductivity. The spaces between the granules are regions with low values of the order parameter, i.e., regions of "weak" superconductivity.

must show, first, how a single laser pulse can read out information about the preceding laser pulse and record new information and, second, what the recording mechanism is.

The possibilities for describing this memory effect are contained in Eq. (2). As we have already mentioned, they arise due to the presence of two factors, the exponential factor and the preexponential factor ρ_{flow}. In the case when the pinning potential is sufficiently strong and the laser pulse does not significantly suppress the pinning potential, the exponential dependence predominates in Eq. (2). In this case the amplitude of the photoresponse should be correlated with the instantaneous (and not the preceding) laser pulse and there is no memory effect. The existence of a memory effect can be associated only with the effect of the preexponential factor, which, as noted in Ref. 24, can be significant if the laser radiation strongly suppresses the pinning potential ($U \to 0$). The preexponential factor in Eq. (2) is $\rho_{\text{flow}} \sim B \simeq n\phi_0$, where n is the number of pinned magnetic vortices per unit area of the film. Thus we arrive at the conclusion that the laser pulses not only photoactivate the magnetic vortices but they also change the density n of pinned vortices.

LASER "RECORDING" OF MAGNETIC VORTICES

We now consider the scheme, displayed in Fig. 3, of a spatially nonuniform high-T_c superconducting film. Laser radiation acting on such a film suppresses the order parameter Δ in the hatched regions where the superconductivity is weak due to absorption of the laser radiation and appearance of excess quasiparticles (see Ref. 5). Since the medium is nonuniform, the order parameter Δ is suppressed in different degrees in different regions (Δ may be suppressed in some regions, where it is small, and not suppressed in other regions). Spatial redistribution of the current will then occur—the transport current will bypass regions where the order parameter is suppressed. The difference between the situation here and that in Refs. 13, 14, and 15 is that the order parameter is suppressed locally not on scales of the order of the correlation length ξ but rather on scales of the intergranular regions, which can significantly exceed the scale ξ. After the laser pulse ends and the initial value of the order parameter is restored, the magnetic field in the quadrupole magnetic structure formed (depending on the spatial scales and the energy gain) can separate into pairs of Abrikosov vortices or the magnetic field can have the structure of Josephson vortices in a randomly nonuniform medium. In the presence of strong pinning these magnetic structures are found to be pinned after the laser pulse ends.

With the help of a simple two-dimensional model we now illustrate how the magnetic field of the transport current in the form of quadrupole magnetic structures penetrates into the region of photosuppressed superconductivity. For this we consider some transverse cross section $y = y_0$ of a high-T_c superconducting film (see Fig. 3). In this section the order parameter Δ is photosuppressed in some regions, and current does not flow there. In addition, according to the conditions of the experiment the total current flowing through the section is constant ($j = \text{const}$),

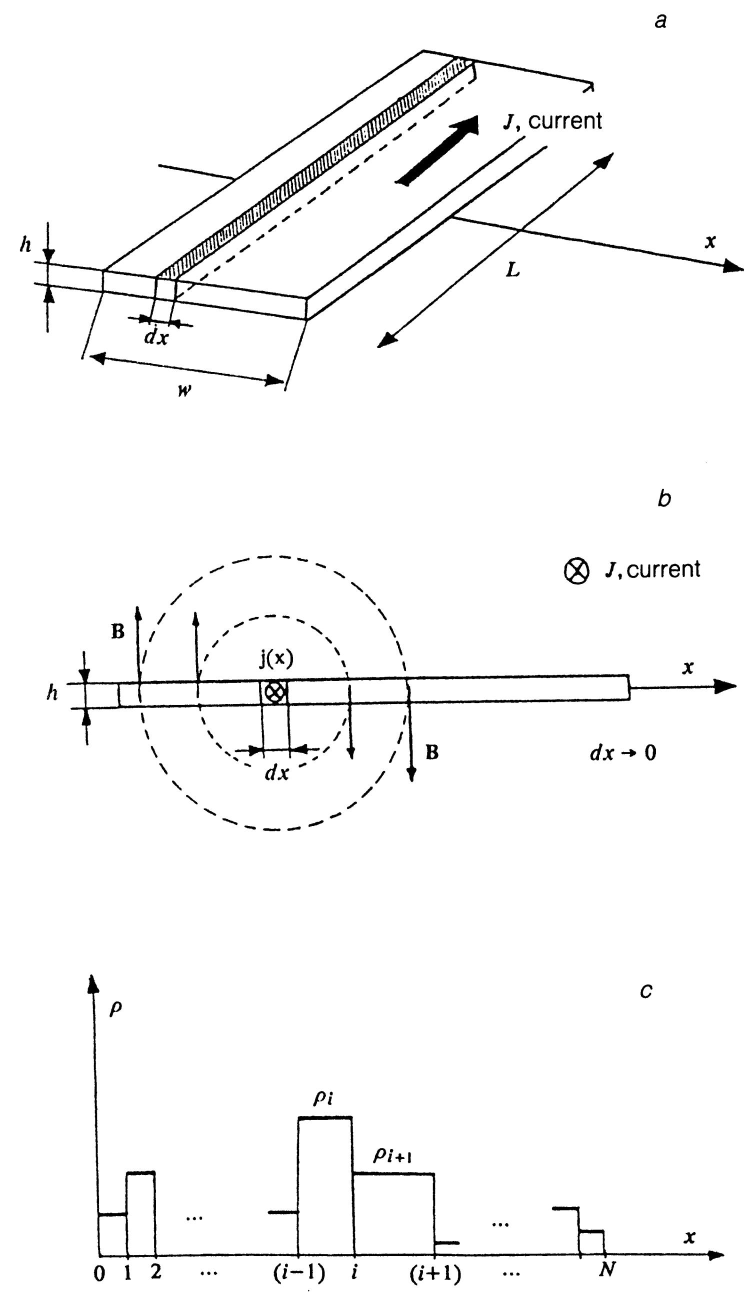

FIG. 4. Illustration for the derivation of Eqs. (6) and (7)—induction of the magnetic field of the transport current in a metallic film with spatially nonuniform resistivity distribution $\rho(x)$. a) Geometry of the problem, b) transverse cross section of the thin film shown in Fig. 4a. The magnetic induction **B** in the plane of the thin film has only two directions—up and down; c)—diagram of the piecewise-constant resistivity distribution of the film.

and it does not depend on the amplitude of the laser radiation. On this basis, we now consider the following model of the transverse section of a thin high-T_c superconducting film. We assume that nothing changes in the direction of the current (along the y axis in Fig. 3), i.e., in this approximation the spatial nonuniformity of the film has the form of stripes oriented parallel to the y axis. As the second simplifying assumption we assume that the current density in regions where current does flow does not depend on the coordinate x, and in the "destroyed" regions the current is equal to zero (the total current satisfies $j=\text{const}$ irrespective of the number and volume of destroyed regions). In other words, we neglect the superconducting screening current and we show that in this case the edges of the "holes" are the most important characteristic. This formulation of the problem is shown schematically in Fig. 4a. Assume that the resistivity of the film is a function of x: $\rho=\rho(x)$. Then the resistance of a separate longitudinal film element of width dx is given by the formula

$$Z(x)=\rho(x)\,\frac{L}{hdx}=\frac{L\rho(x)}{hdx},$$

where L and h are the length and thickness of the film. It is assumed that the film is thin—nothing changes over the thickness of the film. For resistances (elementary channels of width dx) connected in parallel, the conductances $Z^{-1}(x)$ are summed. For this reason, the total resistance R of the film between the contacts is given by

$$R^{-1}=\int\frac{hdx}{L\rho(x)}=\frac{h}{L}\int\frac{dx}{\rho(x)},\tag{3}$$

where the integration extends over the entire width of the film. The lines of force of the magnetic field generated by the elementary current are shown schematically in Fig. 4b. In order to find the intensity of this magnetic field, the elementary current flowing parallel to an element dx must be calculated. For a fixed total current $\mathscr{J}$, the voltage on the film can be written, using Eq. (3), as

$$V=\mathscr{J}R=\frac{\mathscr{J}L}{h}\Big/\int\frac{dx}{\rho(x)}.$$

Then the current flowing along an element of width dx is

$$j(x)dx=\frac{V}{Z(x)}=\frac{\mathscr{J}dx}{\rho(x)}\Big/\int\frac{dy}{\rho(y)},$$

where $j(x)$ is the linear current density (per unit length along the x axis). The partial magnetic field generated at the point x by an elementary current located at the point x' is given by the formula

$$dH(x)=\frac{2}{c}\frac{j(x')dx'}{x-x'} \tag{4}$$

(the direction of the current here is chosen in the manner shown in Fig. 4a). The magnetic field of the elementary currents generated in the plane of the film by the elementary currents can have only two orientations as shown in Fig. 4b: upward (positive) and downward (negative). For this reason, in order to find the total magnetic field at the point x the elementary fields (4) must be summed:

$$H(x)=\frac{2}{c}\int\frac{j(x')dx'}{x-x'}, \tag{5}$$

where the logarithmic singularity obtained by integrating must be cut off on a scale of the order of the thickness h of the film. These singularities arise because the thin-film approximation has been used.

We use the strong-pinning model and assume that after the laser pulse ends the magnetic induction of the vortices is determined by Eq. (5), i.e., by the magnetic field which was formed in the film when the film was in the resistive state. Introducing the dimensionless magnetic field (normalized to the quantity $H_0=2\mathscr{J}/cw$, where w is the width of the film) and the dimensionless coordinates (normalized to the quantity w) we finally obtain the following formula for the dimensionless magnetic field (and the induction B) in the film (see also Fig. 4):

$$B(x)=\left\{\int_{x_0}^{x_n}\frac{dy}{(y-x)\rho(y)}\right\}\Big/\left\{\int_{x_0}^{x_n}\frac{dy}{\rho(y)}\right\}, \tag{6}$$

where x_0 and x_n are the coordinates of the left- and right-hand edges of the film (here it can be assumed that the coordinate x is normalized to an arbitrary quantity—this results only in renormalization of the dimensional field H_0); see Fig. 4.

In order to simplify the calculations we consider a model with piecewise-constant resistivity (see Fig. 4c) and we assume that the points x_i, $i=\overline{0,...,N}$, are the boundaries of the regions. Then the integrals in Eq. (6) are easy to calculate. It is only necessary to bear in mind that when calculating the integral in the numerator the divergence must be cut off at a value of order h. Introducing the conductances $s_i=1/\rho_i$ of the layers, we obtain finally

$$B(x)=\left\{\sum_{i=1}^{N}s_i\ln\left(\frac{|x_i-x|+h}{|x_{i-1}-x|+h}\right)\right\}\Big/\left\{\sum_{i=1}^{N}s_i(x_i-x_{i-1})\right\}, \tag{7}$$

where it should be noted that the values of x in the formula (7) are not limited by the width of the film. Outside the film this formula describes the field not too far away, as long as the field decays logarithmically. With the help of the formula (7), which, in contrast to Eq. (6), no longer contains any singularities because the finite thickness h of the film is taken into account, it is easy to obtain the field distribution for arbitrary resistivity profiles $\rho_i=\rho_i(x)$. Modeling of a situation with regions where superconductivity is destroyed corresponds to the fact that some s_i are zero (current does not flow in these regions).

Consider a film in which the spatial distribution $\Delta(x)$ of the superconducting gap is nonuniform, for example, of the form shown at the bottom of Fig. 5. In this figure the cases corresponding to different laser radiation intensities and therefore different "degrees of destruction" of Δ as well as the values of Δ corresponding to these cases are designated by the numbers 1–3. Current does not flow through a destroyed region (the total current remains constant). The cases a–c in Fig. 5 correspond to different configurations of the magnetic field, obtained with the help of Eq. (7). In the calculations it was assumed that if superconductivity is not destroyed in some region i and current flows through this region, then $s_i=1$. In regions where Δ is destroyed there is no current flow and $s_i=0$. The case a in Fig. 5 corresponds (Fig. 5d) either to zero or low light intensity, such that superconductivity is not destroyed in the film and current flows through the entire section of the film.

In Figs. 5a–c the sections (hatched regions) through which an electric current flows are shown schematically below the field profiles. The "holes" are regions where the laser light destroys superconductivity and through which no current flows. The laser intensity increases from a to c: $I_a<I_b<I_c$. Thus under the action of the laser pulse resistance appears in different sections of the cross section of the superconducting film for different reasons. In regions of weak superconductivity, where the light is strong enough to suppress the order parameter, current flow ceases and a "hole," into which the magnetic field penetrates, appears. The resistance of the other sections through which the entire current flows is associated with the motion of vortices. It is evident from Fig. 5 that the formation of a "hole," along which electric current does not flow, in the film results in the formation at this location of a quadrupole magnetic structure or, by analogy to Refs. 13–15, a pair of vortices of opposite polarity (see also Fig. 1). In addition, the more holes formed in the film, the narrower the area of the section through which current flows (see Fig. 5) and the larger the quadrupole magnetic moment of the film are.

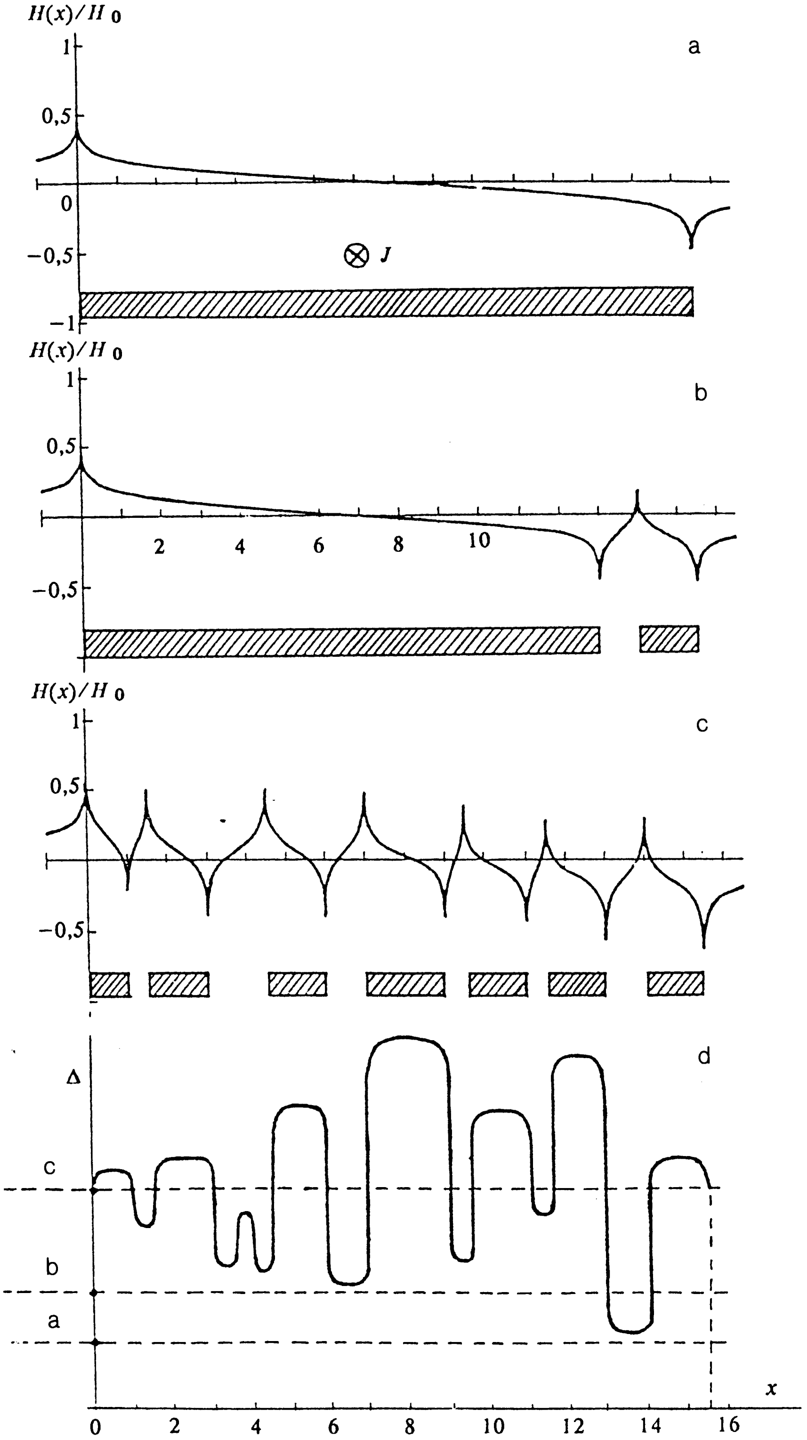

FIG. 5. Distribution of the magnetic field of the transport current in a thin film with "holes". The distribution was calculated with the help of Eq. (7). The cases *a–c* correspond to different laser radiation intensities: $I_a<I_b<I_c$. The transverse section of the film is shown schematically beneath the magnetic-field distributions in the cases *a–c*: The hatched regions are the parts of the film section which carries the transport current. The discontinuities in the film are regions where superconductivity is suppressed by the laser radiation. The transport current does not flow in these sections. It is assumed that the total current through the transverse section of the film in cases *a—c* is constant; *d*—the conventional order parameter profile for these two cases. The superconducting gap width Δ is plotted along the ordinate; the gap can be suppressed by laser radiation in the cases *a—c*, respectively.

Laser radiation interacting with a superconducting film changes the order parameter Δ, as a result of which currents flowing along the film are redistributed, which in turn changes the magnetic field. For this reason, the relaxation of the magnetic field always lags somewhat behind the change in the order parameter ($\tau_\Delta<\tau_H$, where τ_Δ and τ_H are the relaxation times of the order parameter and magnetic field, respectively). As a result, after the laser pulse ends there is not enough time for the quadrupole structures formed to relax and these structures are pinned. The specific structure of the magnetic field pinned in a superconductor is thus not too important. The different types of magnetic vortex structures are distinguished only by the specific expression used for the pinning potential.

The mechanism which activates creep of Abrikosov magnetic vortices is quite well known [see Eq. (2)].[3,16,19,22,24] This mechanism presupposes[16] that vortices are pinned on some inhomogeneities, which produce a potential barrier to the motion of the vortices. The rate of hopping of vortices through the pinning barriers is given by the formula

$$\nu=\nu_0\exp(-U/T), \tag{8}$$

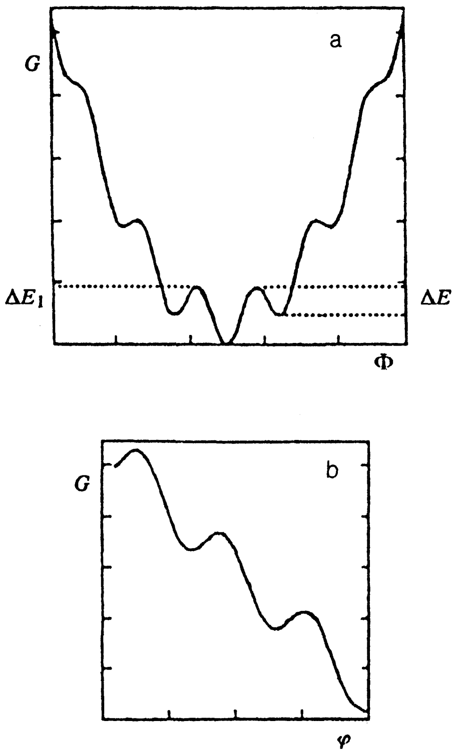

FIG. 6. Taken from Ref. 29—the energy potential G for a Josephson structure versus a) the magnetic flux Φ and b) the gauge-invariant phase difference φ. The barriers of the potential G correspond to the pinning potential barriers for Josephson vortices. Two neighboring local minima of the potential G correspond to energy states differing by an elementary flux quantum and the phase difference $\delta\varphi=2\pi$.

where the pinning potential U is given by different models (see, for example, Refs. 3, 16, 22, and 24).

Pinning, a pinning potential, and flux creep also exist for Josephson vortices.[29–31] Thus pinning and creep of magnetic vortices in a Josephson medium were studied in detail in Ref. 29. It was shown that in a Josephson medium[29] a) the normal (nonsuperconducting) regions, surrounded by superconducting loops (closed Josephson structures) play the role of pinning centers; b) the pinning potential barriers are determined by the barriers between metastable states, which are associated with the Josephson structure; and, c) the current flowing in the structure lifts the degeneracy of the states of the Josephson structure and lowers the pinning barriers.

Figure 6 displays schematically the energy potential G (taken from Ref. 29) of a Josephson structure as a function of a) the magnetic flux Φ and (b) the gauge-invariant phase difference φ (see Ref. 29). For pinning of Abrikosov vortices similar dependences exist in the coordinate space (see, for example, Ref. 16). This analogy is associated with the fact that for a Josephson structure the transition between neighboring minima of G corresponds to a change in phase by 2π and therefore entry of a quantum of flux into a current-carrying loop. Thus a transition to a neighboring local minimum of G as a function of φ corresponds to a displacement of a quantum of flux in real space (as in the case of Abrikosov vortices). In Ref. 29 it was also found that the relaxation of the magnetic induction B in a Josephson network of finite size R is determined by the equation

$$\frac{dB}{dt}=-\frac{\phi_0}{\tau_0 Rd}\exp(-\Delta E/T),$$

where d is the size of the current-carrying loops, ΔE is the pinning potential (see Fig. 6), and T is the temperature. Thus the effects of pinning and creep are similar for Abrikosov and Josephson vortices. Only the specific formulas for the pinning potential are different. Thus we shall not be concerned below with the specific type of magnetic vortices which are pinned and move in the high-T_c superconducting film.

Finally, we obtain the following qualitative picture of the resistive state induced by laser radiation in a high-T_c superconducting film with a spatially nonuniform structure of the type shown in Fig. 3. The laser pulse suppresses superconductivity in the hatched regions of weak superconductivity, the number of regions destroyed increasing with the pulse amplitude I. Current starts to bypass regions where the order parameter is destroyed. As a result, quadrupole magnetic structures form at these locations, the number of such structures increasing with the number of destroyed regions. At the end of the laser pulse, when the order parameter Δ relaxes to its initial profile, the magnetic structures are pinned in the form of vortices of opposite polarity. It is clear from what we have said that (if the superconducting regions spread as a function of Δ) the concentration of pinned vortices at the end of the $(i-1)$st pulse is all the higher the greater the amplitude I_{i-1} of this pulse is. This can be expressed qualitatively in the form (see also Ref. 25).

$$B_{i-1}\approx\phi_0 n_{i-1}=B(I_{i-1})\approx B_0+\alpha I_{i-1}+\cdots. \tag{9}$$

The next ith laser pulse decreases the pinning potential of the barriers and leads to photoactivated creep. Generalizing the resistivity formula (2), we can express the amplitude of the resistive response at the ith laser pulse as follows:

$$\rho_i=\rho_{i-1}^{\text{flow}}\exp(-U(I_i)/T_i), \tag{10}$$

where $\rho_{i-1}^{\text{flow}}\approx\rho_n B_{i-1}/H_{c2}$ and B_{i-1} is determined by the formula (9). The appearance of a resistive photoresponse of the form (10) is associated with the fact that as the pinning potential decreases, the pinned vortices start to move across the current-flow channels due to their interaction with one another and with the transport current. It is known that the interaction potential of the vortices in a thin film is a logarithmic function of the distance between them. In addition, there are many magnetic vortices and their polarity alternates (upwards–downwards). Under these conditions the main direction of motion of the magnetic vortices is determined by their interaction with the transport current. For this reason, it is understandable that the appearance of resistance of the film as a whole is connected with the motion of magnetic vortices, such that the vortices move toward one another, crossing the current-flow channels. We note that magnetic vortices can annihilate one another as a result of their motion through a re-

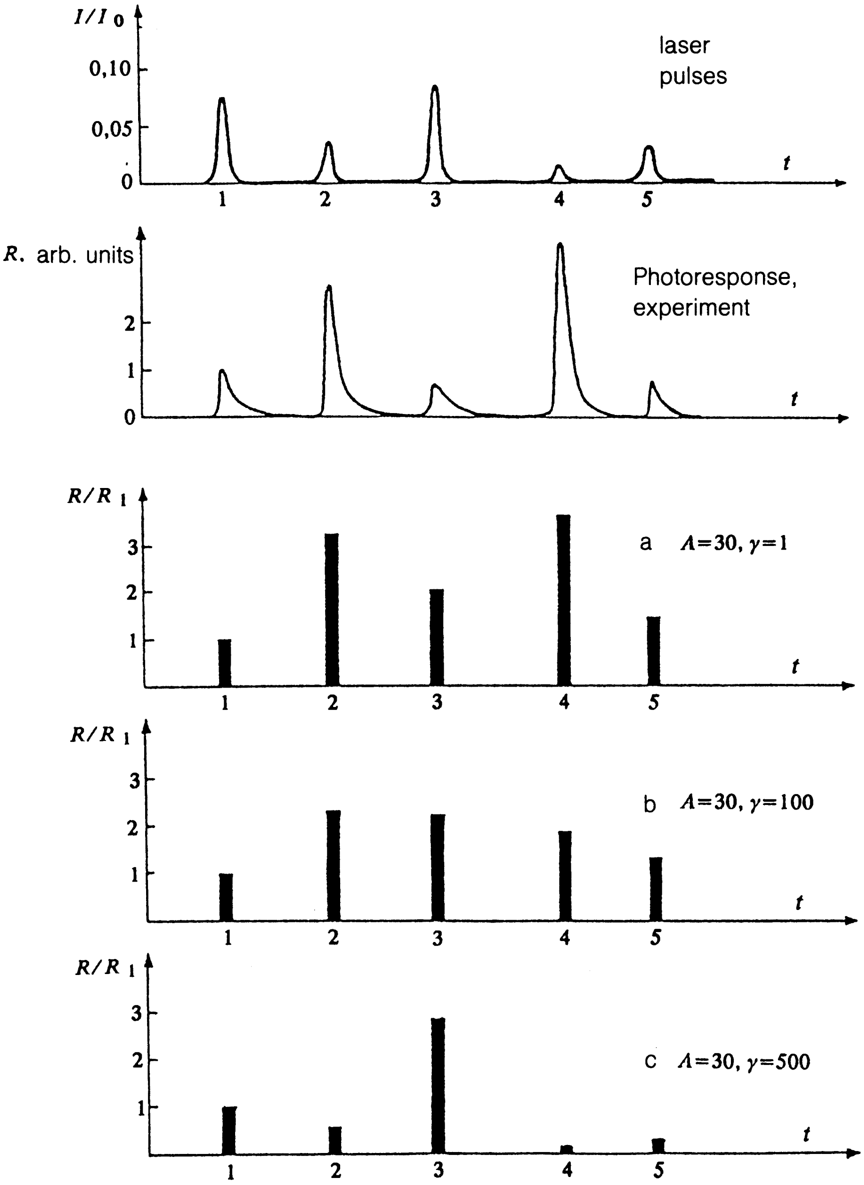

FIG. 7. Experimental realizations of a sequence of laser pulses and the photoresponses to them (see also Fig. 2). a, b, c) Results of numerical computation, performed with Eq. (11), of the amplitudes of the photoresponse pulses for different values of the parameters and a prescribed sequence of laser pulse amplitudes, as shown at the top of the figure. The case a) corresponds to the presence of a memory effect.

gion of weak superconductivity (though the Lorentz force—the current-vortex interaction force—impedes such motion). But if such hops do occur, they do not significantly affect the resistance of the film, since comparatively little current flows through regions of weak superconductivity (and no current flows at all through regions where superconductivity is completely suppressed).

Using a simple thermodynamic estimate (see, for example, Ref. 16) and estimates of the effective temperature from the condition of energy balance, Genkin *et al.*[25] derived the following formula for the dimensionless amplitude of the response of the film to the *i*th laser pulse:

$$R_i \simeq (1+AI_{i-1})\exp\{-\gamma(1-t_0(1+I_i))^2\}, \qquad (11)$$

where $\gamma=pL^3H_c^2(0)/8\pi T_0$, $t_0=T_0/T_c$, and A is a dimensionless constant, which depends on the structure of the film. Figure 7 shows a sequence of laser pulses corresponding to the experimental realization (see Fig. 2), and a sequence of photoresponses R_i, calculated using the formula (11) for different values of the parameters. For small values of γ (for example, in regions of weak superconductivity) the given amplitudes of the laser pulses are sufficient to decrease the pinning potential significantly. In this case $\exp\{...\}\sim 1$, and the preexponential factor plays the main role in Eq. (11). In this case, as shown in Fig. 7a, the amplitude of the photoresponse is correlated with the amplitude of the preceding laser pulse, i.e., the observed memory effect also occurs. Figure 7b is an intermediate case, while Fig. 7c ($\gamma=500$) is close, with respect to the parameter, to the case of a single crystal. In the latter case the exponential behavior in Eq. (11) is significant and there is no memory effect.

We now give a dynamical description of the memory effect, and we propose a model which describes the time dependence of the quantities of interest to us.

DYNAMICAL MODEL OF THE MEMORY EFFECT

We now consider the spatially nonuniform structure, shown in Fig. 3, of a high-T_c superconducting film. We

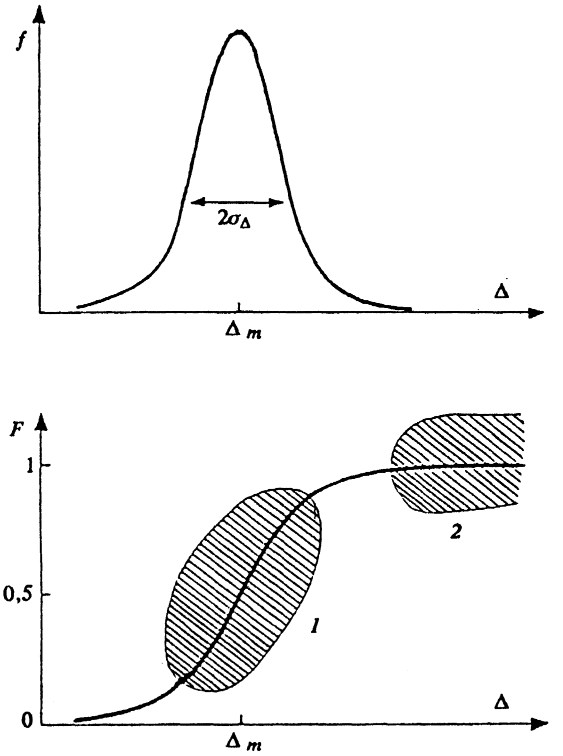

FIG. 8. Schematic diagram of the distribution function (F) and density (f) of weak links as a function of energy. Δ—energy gap (energy of a weak link); Δ_m—mathematical expectation (average value of Δ); and, σ_Δ—spread in the distribution. Two regions are marked in the plot of $F(\Delta)$: *1*) region of rapid growth of F (this region is determined by the spread σ_Δ) and *2*) region of saturation of $F(\Delta)$.

assume that the regions of weak superconductivity can be very diverse and that the order parameter and the pinning potential are random quantities having a distribution of the type displayed in Fig. 8. The channels through which the current J flows are also random, and they are thus, in principle, identical.[1)] For this reason, the total electrical resistance of the film is of order

$$R_{\text{total}} \sim R_1/N,$$

where R_1 is the resistance of a single channel and N is the number of current channels. In addition, during the action of the laser radiation both R_1 and N are functions of the laser radiation intensity. But for not too high laser radiation intensities the number of these main channels of current flow does not change too much with increasing radiation intensity. We assume that the number N of main current-flow channels is fixed and that the transport current flows mainly through some transverse sections of the film ($N \approx$const). The appearance of resistance R_1 in a single flow channel is, however, associated with the motion of magnetic vortices forming "along the edges" of the channel. The total resistance of a single channel is then simply the sum of the resistances of separate sections of the channel (conductors connected in series). The total resistance R_1 of a single channel will therefore be proportional to the total number n of magnetic vortices, depinned in accordance with the activation law (8).

Hence we write the equation determining the time dependence of the total concentration of vortices pinned in a high-T_c superconducting film, taking into account the increase in the number of vortices due to destruction of weak links by the laser radiation and penetration of the magnetic field of the current into these regions and taking into account also the relaxation of the concentration of vortices due to depinning. We propose the following equation for describing the dynamical properties of the system under consideration:

$$\frac{dn}{dt} = S(I(t)) - \frac{n(t)}{\tau} \exp\left\{-\frac{U(I(t))}{T}\right\}, \tag{12}$$

where $n(t)$ is the concentration of pinned magnetic structures, S is the laser-intensity-dependent source of pinned vortices, τ is the characteristic relaxation time, and U is the pinning potential. The equation (12) is an equation for the concentration of pinned vortices along the edges of a single (any) current channel. For the equation written in this form we neglect the spatial dependence of the pinning potential and the source of vortices, making the assumption that there exist weak links with distribution function $F(\Delta)$ of the type shown in Fig. 8, i.e., in Eq. (12) $U(I)$ is the average pinning potential. This local model has the advantage that the description of the system is simple—all properties are described with the help of a single equation.

The last term in Eq. (12) describes relaxation to a nonmagnetized (vortex-free) state in accordance with the flux-creep theory[19–24] or, in other words, read-out of pinned vortices. Following Ref. 16 we write the resistance of the current channel in the form

$$\rho \approx \rho_n \frac{n(t)\phi_0}{H_{c2}} \exp\left\{\frac{-U(I(t))}{T}\right\}, \tag{13}$$

where ρ_n is the resistance in the normal state, H_{c2} is the critical field, and $T \sim T_0$ is the lattice temperature.

In this case only the following properties of the pinning potential U are important for us. In the absence of laser radiation ($I=0$) U is a finite quantity and we have $U/T_0 \gg 1$ (see also Refs. 20–22), so that activation of vortices from pinning centers is exponentially small. When the light intensity is high, however, due to the increase in the effective temperature of the system we have $U \to 0$ (in the resistive normal state, when $\rho = \rho_n$, there are no vortices in the superconductor). For definiteness we employ below the expression for the pinning potential for Abrikosov vortices[16]

$$U \sim H_c^2 \xi^3 \sim (1-t^2)^2 (1-t)^{-3/2} \equiv (1+t)^2 (1-t)^{-1/2}, \tag{14}$$

where H_c is the thermodynamic field, ξ is the coherence length, and $t = T/T_c$. The main difficulty in Eq. (12) is writing an expression for the source $S(I(t))$. In writing down the source function S we follow our previous qualitative considerations about the laser-induced penetration of a magnetic field into the sample and pinning of magnetic vortices. We write the laser radiation intensity as a sequence of Gaussian pulses:

$$I(t)=\sum_i I_i(t)=\sum_i a_i \exp\left\{-\frac{(t-t_i)^2}{2\sigma_i^2}\right\}, \tag{15}$$

where a_i is the amplitude of the ith pulse (at the time t_i) and $2\sigma_i$ is the characteristic width of the ith pulse.

We now consider a single pulse from the sequence (15). When the ith laser pulse arrives, the intensity of the radiation at first increases, reaches a maximum a_i, and then decreases to zero. Our source has the specific feature that on the leading edge, when the intensity of the light is increasing, the superconducting order parameter and the pinning potential can only decrease. In this case pinning of vortices does not arise, so that we have $S_i(t)=0$ if $dI_i/dt \geqslant 0$ holds, where S_i is the source function during the ith pulse. Consider a not too narrow pulse of width τ_p such that

$$\tau_p \gg \tau_\varepsilon, \tag{16}$$

where τ_p is the duration of the pulse and τ_ε is the characteristic relaxation time of the pinning potential (and order parameter), equal in order of magnitude to the energy relaxation time of the quasiparticles.[4-6] The approximation (16) makes it possible to assume that the pinning potential follows virtually instantaneously the change in the intensity of the laser radiation. It is thus obvious that the fastest vortex pinning process should coincide with the highest rate of change of $I_i(t)$. Thus it can be assumed that

$$S_i \sim \frac{1}{2}\left\{\left|\frac{dI_i}{dt}\right|-\frac{dI_i}{dt}\right\},$$

i.e., S_i is proportional to the derivative of the intensity of the radiation on the trailing edge of the pulse. In addition, as the radiation intensity increases, the number of destroyed weak links and therefore the number of vortices formed increase. The simplest assumption in this case could be that the number of destroyed regions is proportional to their energy distribution function $F(\Delta)$, taken at the point where the energy scale of the radiation pulse determining the destruction scale a_i (the maximum Δ destroyed by the light is determined from the condition $\Delta \approx a_i$) is equal to the corresponding value of Δ. Then

$$F(a_i)=\int_0^{\Delta=a_i} f(\Delta)d\Delta, \tag{17}$$

where $f(\Delta)$ is the energy distribution function of the weak links. Thus

$$S_i \sim \frac{F(a_i)}{2}\left\{\left|\frac{dI_i}{dt}\right|-\frac{dI_i}{dt}\right\}. \tag{18}$$

But it is obvious that a rapid change (decrease) in the laser pulse intensity, as given by the term enclosed in braces in Eq. (18), is insufficient for pinning of vortices. Pinning (and depinning) of vortices is a probabalistic process. For this reason it is necessary to take into account in the formula for S_i the probability that the vortices formed will be pinned. It is only in this case that the concentration of pinned vortices will increase. Physically, this means that in order for magnetic vortices to be pinned as the light intensity decreases, the pinning potential must be sufficiently high. This can be taken into account mathematically by introducing a factor representing the pinning probability

$$q_i=\{1-\exp[-U(I_i)/T_0]\}. \tag{19}$$

In Eq. (19) with $U=0$, $q_i=0$—there is no pinning; in the case of strong pinning, when $U/T_0 \gg 1$, $q_i=1$, i.e., the pinning probability is one.

We note that when the ith pulse acts the amplitude of all other pulses in the sum (15) is exponentially small. Finally, introducing the normalization constant $\alpha=\text{const}$, we obtain the following formula for the source S of pinned vortices in Eq. (12)

$$S(t)\approx\alpha\left\{1-\exp\left[-\frac{U(t)}{T_0}\right]\right\} \times\sum_i \frac{F(a_i)}{2}\left\{\left|\frac{dI_i}{dt}\right|-\frac{dI_i}{dt}\right\}. \tag{20}$$

The form of the distribution function $F(a_i)$ is not known exactly. But, in order to establish criteria for the existence of the memory effect it is of interest to study the dependence of the type of photoresponse on the magnitude of the moments of the distribution function. It will be shown below that the behavior of the system (form of the photoresponses) can be substantially different in the cases of "narrow" and "wide" spreads in the energy distribution $F(\Delta)$ of the weak links. The terms "narrow" and "wide" are introduced here for the magnitude of the spread of the distribution $F(\Delta)$ with respect to the spread of the distribution of a different random quantity—the energy scale of the amplitude of the laser pulses. Thus, in the case of a wide (in the sense indicated above) spread of the distribution $F(\Delta)$ a large amplitude of a laser pulse corresponds to a large number of destroyed weak links, which does not happen when $F(\Delta)$ has a narrow spread. We consider two limiting cases: 1) the case of wide spread of the energy distribution function $F(\Delta)$ of weak links (actually this is the case when the region *1* in Fig. 8 corresponds to different a_i; the larger a_i, the larger the number of destroyed weak links is); for simplicity we assume

$$F(a_i)\approx c_1a_i+c_2a_i^2+c_3a_i^3+\ldots\approx c_1a_i. \tag{21}$$

[It is obvious that $c_0=0$, since for $a_i=0$ there should be no destroyed links: $F(0)=0$]; 2) the case of narrow spread of the distribution function (see Fig. 8), i.e., for arbitrary a_i all $F(a_i)=\text{const}$ (this is actually the region *2* in Fig. 8). The latter case corresponds to high laser pulse amplitude. It is found that in all regions of weak links superconductivity is destroyed and the concentration of vortices pinned by the ith pulse does not depend on the pulse amplitude.

In further calculations we employ for the pinning potential a relation of the type (14), and the relation between the effective temperature T and the intensity of the laser radiation can be estimated from an energy balance condition of the form

$$\sigma_\omega E_\omega^2=N(T)\frac{T-T_0}{\tau_\varepsilon(T)}, \tag{22}$$

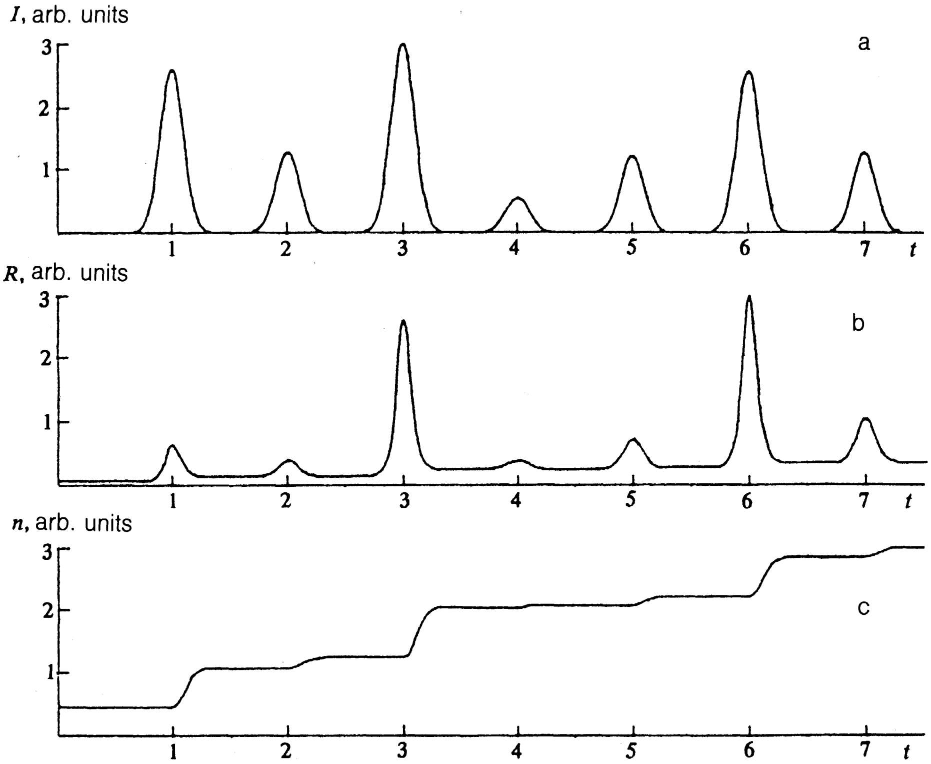

FIG. 9. $I(t)$ is the sequence of laser pulses which is given by Eq. (15); $R(t)$ is the photoresponse nonequilibrium resistance of the film) to this sequence of laser pulses; $n(t)$ is the time dependence of the concentration of pinned vortices—obtained by integrating Eq. (12) numerically with a fixed source of laser pulses for the case of low laser pulse amplitudes $I(t)$ (the energy scale of the amplitude of the laser pulses is much smaller than the pinning potential barriers). In this case there is no memory effect—the amplitudes of the photoresponse pulses are correlated with the amplitudes of the laser pulses acting on the film at the same moment in time. In this case (low amplitudes of laser pulses) the result is virtually independent of the spread in the energy distribution function of the weak links. In Eq. (12) $\tau=0.1$; the parameters of the pinning potential [see Eq. (11)] are $\gamma=10$ and $t_0=0.9$.

where σ_ω is the dissipative part of the conductivity at the frequency of the laser radiation, $N(T)$ is the quasiparticle concentration, $\tau_\varepsilon(T)$ is the energy relaxation time, and T_0 is the lattice temperature of the sample. For the case of the standard isotropic model of a superconductor the formula (22) gives the following relation between the laser radiation intensity I and the temperature T:[4]

$$I/I_0=(T/T_0)^4(T/T_0-1),$$

$$I_0\approx\frac{\ln 2}{2\pi}\frac{cT_c^2}{e^2L_D^2}(1+\omega^2\tau^2),$$

where c is the velocity of light, T_c is the superconducting transition temperature, L_D is the diffusion length, and τ is the momentum relaxation time of the quasiparticles.

NUMERICAL SOLUTIONS OF THE DYNAMICAL EQUATION

In this section we present the results of solving numerically the dynamical equation (12) with the source (20) of pinned vortices. The dependence of the pinning potential on the laser source is determined using Eq. (15). Standard numerical methods were used to solve Eq. (12).

The figures presented below—the results of numerical computation—were constructed as follows. Each figure consists of three plots arranged next to one another. Time, measured in this case in units of the time interval between the laser pulses, is plotted along the abscissa. The sequence of laser pulses $I(t)$ (source of laser radiation), determined by the formula (15), is shown at the top (a). The pulse amplitude and width (as well as the separation of the pulses) were given. The intensity $I(t)$ (as also the other amplitudes—photoresponse and vortex concentration) are plotted here in arbitrary units (on a the scale that is everywhere linear). Arbitrary units are used because it is difficult to choose the absolute normalization *a priori*—it depends on the absorption coefficient for electromagnetic radiation in the inhomogeneous medium we are studying, on the profiles $T_c(\mathbf{r})$ and $U(\mathbf{r})$, and other quantities. For this reason, we do not consider absolute scales (in the calculation the absolute or dimensional scale of the intensities can be changed). We are interested in the relative magnitude of the responses of the system. We have chosen a sequence in which the relative magnitudes of the amplitudes of the first five pulses are virtually identical to the amplitudes on the experimental oscillogram shown in Refs. 1 and 25. The resistive responses are shown in the center plot (b)—the resistance of the film calculated from the formula (13) for such a source $I(t)$ by solving Eq. (12) for $n(t)$ for this source. The solution itself of Eq. (12)—the time dependence of the concentration $n(t)$ of pinned vortices—is shown in the plot (c) at the bottom of the figure. The ratio of the energy scales of the laser intensity and the pinning potential can be easily understood from the behavior of the concentration in all plots: A decrease of the concentration is associated with a significant decrease of the pinning barrier U.

Figure 9 displays a limiting case corresponding to small laser pulse amplitudes for which a significant decrease of the pinning barrier U is impossible. In this case U/T is not small, and we have a strong exponential dependence on the strength $I(t)$ of the laser source. Because the efflux term in Eq. (12) is exponentially small the pinned vortices are practically not read out (the influx term S is significantly larger), and $n(t)$ must increase with

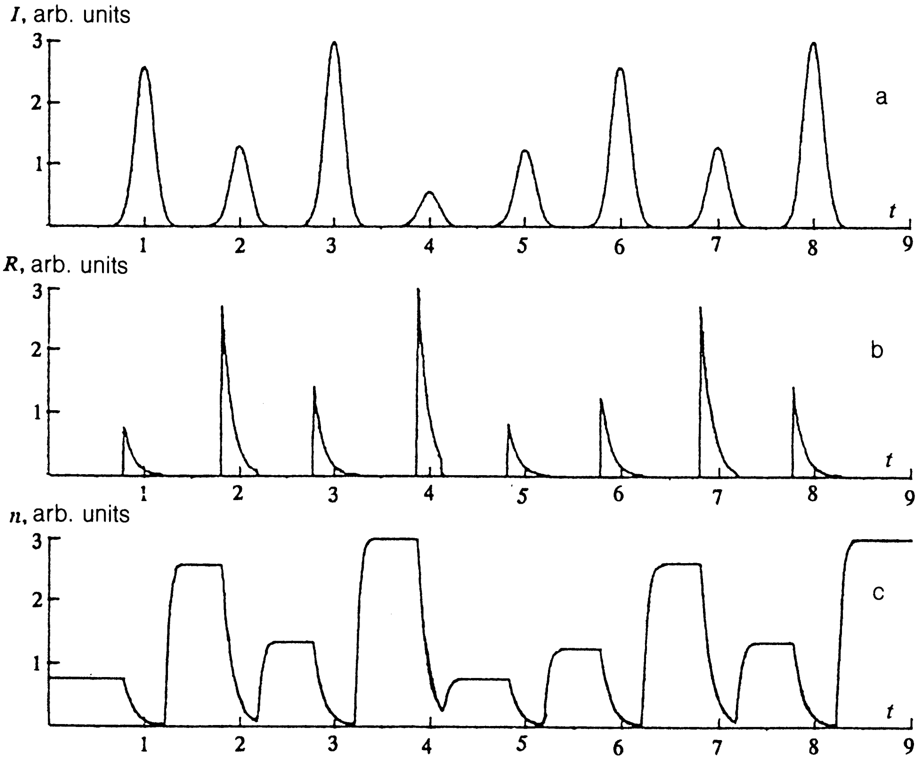

FIG. 10. Similar to Fig. 9 but for the case when a memory effect does occur. The case of large spread in the energy distribution function of weak links $F(a_i) \sim a_i$ (see text); the absolute magnitude of the amplitudes of the laser pulses is chosen to be much greater than in Fig. 9 and it is high enough for the pinning barrier to decrease significantly (during the action of the pulse $n(t)$ drops almost to zero).

time. Since pinned vortices accumulate with time, the photoresponse acquires a pedestal which increases in time. One can see from Fig. 9 that in this case the amplitudes of the photoresponses are correlated with the amplitudes of the laser pulses, acting at the same moment in time, i.e., there is no memory effect. The solution $n(t)$ and the form $R(t)$ of the resistive responses obtained in this case are qualitatively independent of the form of the energy distribution function $F(\Delta)$ of the weak links. Plots similar to those in Fig. 9 are obtained for both wide spreading $F(a_i) \sim a_i$ [see Eq. (20)] and narrow spreading $F(a_i) = \text{const}\ (a_i)$, i.e., for low amplitude $I(t)$ there is no memory effect, irrespective of the film structure. We note that the increase in $n(t)$ shown in Fig. 9 in reality does not extend to infinity. An infinite number of vortices cannot be recorded in a finite sample. But this saturation of the source of pinned vortices is not taken into account in Eq. (12). Taking this saturation into account will not change anything fundamentally. It will merely lead to the fact that at some point the concentration $n(t)$ will stop increasing and will reach a stationary level.

Figures 10 and 11 correspond to high laser intensity (with respect to the energy scale of the pinning potential). Here the amplitude of the pulses is such that each laser pulse significantly decreases the pinning potential, and almost all pinned magnetic structures are read out [$n(t)$ decreases almost to zero].

The case of photoresponse represented in Fig. 10 corresponds to wide spreading of the energy distribution function of the weak links [see Eq. (21)]. The amplitude of the photoresponse pulse is correlated with the amplitude of the preceding laser pulse—a memory effect occurs. This case corresponds completely to our quasistatic model of the memory effect given by Eq. (10): Up to the moment of arrival of the ith laser pulse the concentration $n(t)$ of vortices is proportional to the amplitude of the $(i-1)$st pulse. The sequence of photoresponse amplitudes in this case seemingly repeats the sequence of laser pulse amplitudes, but with a shift by one pulse. The reason for this is that the amplitude of the photoresponse in this case is proportional to the concentration of magnetic vortices, pinned in the sample up to the time that the next laser pulse arrives.

This circumstance is seen clearly in the bottom figure—the time dependence $n(t)$. The photoresponse pulses have the following form: With the arrival of a laser pulse, when the light intensity becomes quite high, and the pinning potential decreases, the resistance of the film increases sharply—"read-out" of the pinned vortices starts [the concentration $n(t)$ starts to decrease]. In this case the relaxation time τ in Eq. (12) is chosen to be of the order of the pulse width τ_p. The relation between τ and τ_p is not too important. It is only obvious that for $\tau \gg \tau_p$ ($\tau > \tau_p$) complete read-out of all pinned vortices by each pulse will not occur. Under these conditions vortices will accumulate in the system. On the trailing edge of a laser pulse, when the radiation intensity decreases, the order parameter in the inhomogeneous superconductor and the pinning potential both relax. When the pinning potential has relaxed significantly and becomes large enough, pinning of the magnetic structures formed starts. This is manifested as an increase in $n(t)$ on the "tail" of the laser pulse.

We note that our photoresponses are shifted somewhat in time with respect to the laser pulses relative to the oscillogram shown in Fig. 2. This shift is a consequence of our simplified model—we assume that the pinning potential is the same everywhere in the film, i.e., we neglected

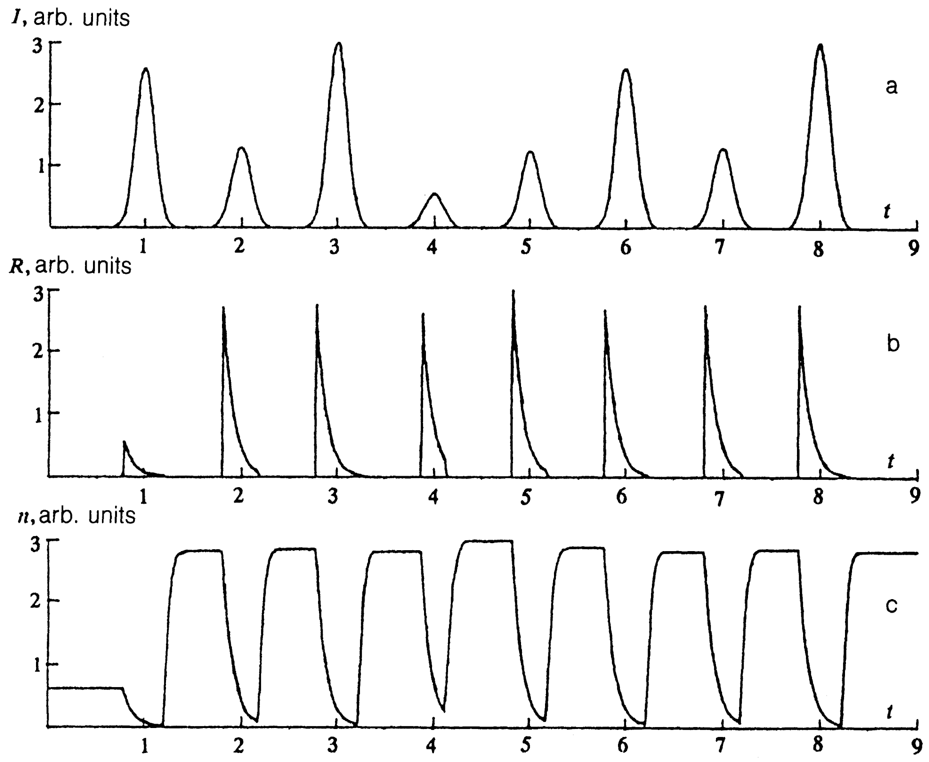

FIG. 11. Similar to Fig. 10, but for the case of small spread (see text) of the energy distribution function of weak links $F(a_i)=\text{const}$. In this case each laser pulse "breaks through" all weak links and the amplitudes of the photoresponse pulses are virtually independent of the amplitudes of the laser pulses—there is no memory effect.

the spatial dependence $U(\mathbf{r})$. In reality there is some spread in the values of U (in the randomly inhomogeneous film U is also a random quantity). There exist spatial regions with both weak and strong pinning. It is obvious that when the spread in the values of U is taken into account, the rate of growth of the photoresponse pulses (leading edge) should be lower than in our model. For a nonuniform distribution of U, the number of regions where depinning of magnetic vortices occurs increases as $I(t)$ increases. In our model, however, depinning of the magnetic field occurs immediately throughout the entire film, as soon as the average pinning potential, which is prescribed, decreases sufficiently. Thus when the spread in the random quantity U a function of the depth is taken into account, the maximum of the resistive response pulse should almost coincide with the maximum of the laser pulse. But, qualitatively, our simplified model describes completely the memory effect which we are studying. This effect occurs in high-T_c superconducting films thanks to the presence in such films of a quite deep pinning potential for magnetic vortices. As one can see from the plots of $n(t)$, it is because of the strong pinning that the concentration of pinned vortices remains virtually unchanged in the time interval between two laser pulses.

In the case of a narrow spread in the energy distribution of weak links, however, when $F(a_i)\simeq\text{const}$, i.e., when the number of destroyed weak links does not depend on the amplitude of the laser pulse, the photoresponse amplitudes are virtually constant when the amplitude of the laser pulses is large. This is illustrated in Fig. 11. In this case the system does not exhibit a memory effect. We note that in all cases the initial condition $n(0)$ in the system in practice influences only the magnitude of the first photoresponse pulse. Thus for $n(0)=0$ the amplitude of the first photoresponse pulse is zero.

The case illustrated in Fig. 12, when the spread in the energy distribution of the weak links is wide and $F(a_i)\sim a_i$ holds is also of interest. But the average amplitude of the laser pulses, with respect to the depth of the pinning potential, is chosen to be intermediate between the cases of Figs. 10 and 11 and the case of Fig. 9, namely, $\langle a_i\rangle\sim U$, and as a result the relation between the photoresponse amplitude and the laser amplitude is more complicated. In this case not only the energy spread of the weak links but also the spread of another random quantity—the amplitude of the laser pulses—become significant. In the activational formula for creep of magnetic vortices both the exponential and preexponential factors become important. In the case when the sample is irradiated by light pulses with amplitude sufficient for the pinning barrier to decrease significantly, the memory effect is observed when $F(\Delta)$ has a wide spread [see, for example, pulses 1, 2, 3, 6, 7, and 8—after each pulse $n(t)$ relaxes practically to zero]. But if the pulse amplitude is too low (pulse 4), the barrier U cannot decrease significantly, there is no virtually no readout of vortices, and the photoresponse is very weak. Thus Fig. 12 demonstrates a complicated correlation between the amplitudes of the photoresponse and laser pulses: The memory effect is sometimes present (when the amplitude of the laser pulses is large) and sometimes absent (when a laser pulse of low amplitude arrives).

The proposed dynamical model, which takes into account the energy distribution of weak links in a high-T_c superconducting film, enabled us to classify different possible cases which can occur in an experiment. By observing different experimental realizations of sequences of photo-

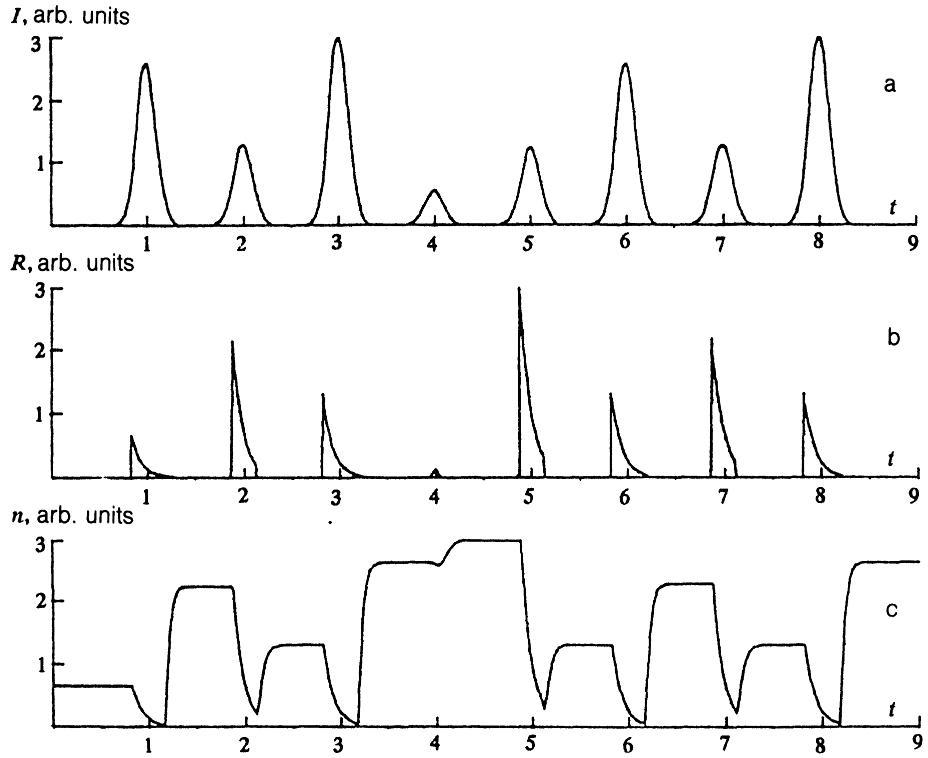

FIG. 12. Similar to Fig. 10, but for the case of somewhat lower absolute values of the laser pulse amplitudes. The case demonstrating the dependence of the photoresponse amplitudes not only on the spread in the energy distribution function $F(\Delta)$ of the weak links but also on the dispersion of another random quantity—the amplitude of the laser pulses: it is evident from the figure that the amplitude of pulse 4 is too low for the pinning potential barrier to decrease significantly.

response and laser pulses and by varying the amplitude of the laser pulses it is possible to get an idea (by analyzing plots of the type shown in Figs. 9–12) of the magnitude of the pinning potential in a high-T_c superconducting film and of the spread of the energy distribution of the weak links. The memory effect under discussion can thus be employed for diagnostics of high-T_c superconducting films.

DISCUSSION

Our spatially "averaged" dynamical model of the memory effect provides a good qualitative description of the experimental data. The behavior of the system under consideration depends on the ratios of three energy scales:[2)] the laser radiation intensity, the superconducting gap width Δ,[3)] and the pinning potential. If the radiation is weak, the resistive response is determined by the exponential probability of depinning of magnetic vortices. In this case the system does not exhibit memory—the photoresponse pulse amplitude is correlated with the amplitude of the laser pulse acting on the system at the same moment in time. If, however, the amplitude of the laser radiation is high enough to induce complete depinning of all magnetic vortices, the amplitude of the photoresponse will be determined by the number of vortices that were "stored" in the film. In order for the resistive photoresponse of the system to be correlated with the preceding laser pulse, the number of stored magnetic vortices must increase with the amplitude of the laser pulse. This is possible only in the case when there is a spread of the energy of weak links in the film—the higher the pulse amplitude, the more weak links are destroyed by the pulse.

For high radiation intensity the memory effect should not be observed either because superconductivity is destroyed in all weak links and the spread of the energy distribution of the weak links has been exceeded or because for such intensities the threshold of superconducting current flow in the film has been crossed. The latter case is the situation when for intense laser radiation no continuous paths for the superconducting current to flow between contacts remain in the superconducting film. In this case the nonequilibrium resistive state of the superconductor can be determined not by the motion of magnetic structures (as a whole) but rather by the relative length of the path along which the normal (nonsuperconducting) current flows or, equivalently, by the penetration of the electric field into the superconductor, which occurs in accordance with a model of the type considered in Ref. 4. In this case, the higher the amplitude of the laser pulse, the larger the region of optically suppressed superconductivity, the greater the effective penetration depth of the electric field into the superconductor, and therefore the higher the resistance of the film. Thus in the case when the spread of the energy distribution of the weak links in the film is wide, the memory effect under discussion can occur only for laser radiation intensity within some range $I_{\min} < I < I_{\max}$. The narrower the spread of the energy distribution of the weak links, the narrower this region is. The lower limit $I_{\min}$ is determined by the pinning of vortices: For $I < I_{\min}$ virtually all vortices are pinned. The upper limit $I_{\max}$ is determined by the spread of this distribution and (or) destruction of the threshold for superconducting current flow in the film.

It follows from the picture described here that the memory effect discussed above can be a very precise tool for diagnostics of high-T_c superconducting films. In addition, it can be used to investigate how the fundamental characteristics of superconducting films, such as the pinning potential and the current-flow threshold, depend on the external parameters. Indeed, the lower limit I_{min} of the laser intensity is related to the average pinning potential $\langle U \rangle$. The pinning potential, however, in turn depends on the external magnetic field, the transport current, and the film structure. Thus, by determining the limiting intensities (I_{min} and I_{max}) and by studying their dependence on the conditions of film growth and film structure, we can judge the quality of the film, the pinning potential, the current-flow threshold, and the spread in the energy distribution of the weak links, as well as the dependence of these quantities on the external parameters. Elaboration of these theoretical ideas will make it possible to study the distribution function of these random quantities when treating spatially nonuniform distributions $U(\mathbf{r})$ and $\Delta(\mathbf{r})$.

CONCLUSIONS

We have described the memory effect and the behavior of the resistive photoresponse of high-T_c superconducting films as a function of the pinning potential U, the nonuniform profile of the superconducting gap Δ, and the laser radiation intensity I. The entire description was based on Eq. (12). In conclusion, we discuss the general physical meaning of this equation.

In our case Eq. (12) was written for the concentration of pinned magnetic vortices. This is a simple balance equation. It contains the influx term S—the increase in concentration n due to laser action—and a relaxational term. The memory effect in this case is characterized by the fact that the inhomogeneity of the medium is taken into account in S: The stronger the laser radiation, the greater the changes occurring in the medium (volume of destruction). The relaxational term, however, is characterized by exponential dependence on the pinning potential $\sim\exp(-U/T)$. For the system studied there exists a set of local energy minima, and depending on the magnitude of the external perturbation the system can occupy these different energy states, which are metastable but can be quite long-lived.

In our case the different energy states of the system are states without magnetic quadrupoles (or vortices) or states with one or more pinned quadrupoles. Thus the energy dependence of the thermodynamic potential G as a function of the magnetic field, flux, transport current, and other external actions (parameters) is similar to that shown in Figs. 6a and b of Ref. 29. These metastable energy states relax as a result of activation of elementary excitations (in this case pinned vortices) through the potential barrier U, so that the film resistance is described by Eq. (13). The concentration n of vortices (or the magnetic induction of the system $B\sim n\phi_0$) in the pre-exponential factor in Eq. (13) is nothing more than a function of the energy state of the system between pulses ($n\sim B\sim\langle\varepsilon\rangle^{1/2}$, where $\langle\varepsilon\rangle$ is the average energy, since $B^2/8\pi$ is the energy density). It is obvious that the system can exhibit memory only if these metastable (in the absence of electromagnetic radiation) states are long-lived, and this is determined by the height of the pinning potential barrier.

Actually, the memory effect discussed in this paper can be a particular manifestation of a wider class of hysteresis effects. We note that the fact that n is the concentration of pinned vortices does not appear explicitly anywhere in the arguments presented here. For this reason, this method of description and the mechanisms discussed could also pertain to other physical systems. The only requirement is that the systems must have a wide spectrum of metastable energy states, separated by potential barriers, and that their lifetimes in these metastable states be sufficiently long. Hysteresis effects can also occur under these conditions. Here $n(t)$ must be interpreted as the concentration of the corresponding long-lived elementary excitations in such systems. The general dynamics of such excitations and photoresponses of the system can be similar to that considered in this paper.

An example of such systems is spin glasses, which have a wide spectrum of metastable energy states which lie above the ground state and are separated by potential barriers.[33] It is thus possible that spin glasses could also exhibit memory effects of the type considered here. This is also indicated by the well-known approach for describing the magnetic properties of high-T_c superconducting materials with the help of the spin-glass model (Hamiltonian).[34] This model is an alternative to the model of magnetic-flux creep.[19–25] Although the relation between these two approaches is still not entirely clear,[29] there are grounds for believing that since these models describe the same object (high-T_c superconductors), they could be equivalent from the viewpoint which we discussed here (the existence of a wide spectrum of metastable energy states of the system which are separated by potential barriers). In this sense, the nonequilibrium properties of spin glasses and inhomogeneous superconductors with pinning of magnetic vortices could be equivalent.

In conclusion we take this opportunity to thank A. A. Andronov and Yu. N. Nozdrin for helpful discussions of the results.

[1)] It is assumed that the most diverse in homogeneities occur in the path of the current flowing in each channel. For this reason the currents in these channels are, on the average, subject to identical conditions.

[2)] Here it is assumed that the relaxation times of the order parameter and quasiparticle energy are much shorter than the laser pulse widths and that relaxation is almost instantaneous.

[3)] For low laser radiation intensities the superconducting gap Δ may not be destroyed, just as, for example, laser intensity $I > I_0$, where I_0 is some threshold, is necessary in order to destroy Δ via the coherence instability.[5]

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Translated by M. E. Alferieff