Analysis of the nonequilibrium photoresponse of superconducting films to pulsed radiation by use of a two-temperature model

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Photoresponse of a superconducting film in the resistive state to pulsed radiation has been studied in the framework of a model assuming that two different effective temperatures can be assigned to the quasiparticle and phonon nonequilibrium distributions. The coupled electron-phonon-substrate system is described by a system of time-dependent energy-balance differential equations for effective temperatures. An analytical solution of the system is given and calculated voltage transients are compared with experimental photoresponse signals taking into account the radiation pulse shape and the time resolution of the readout electronics. It is supposed that a resistive state (vortices, fluxons, network of intergrain junctions, hot spots, phase slip centers) provides an ultrafast connection between electron temperature changes and changes of the film resistance and thus plays a minor role in the temporal evolution of the response. In accordance with experimental observations a two-component response was revealed from simulations. The slower component corresponds to a bolometric mechanism while the fast component is connected with the relaxation of the electron temperature. Calculated photoresponse transients are presented for different ratios of the electron and phonon specific heat, radiation pulse durations and fluences, and frequency band passes of registration electronics. From the amplitude of the bolometric component we determine the radiation energy absorbed in a film. This enables us to reveal an intrinsic electron-phonon scattering time even if it is much shorter than the time resolution of readout electronics. We analyze experimental voltage transients for NbN, $YBa_2Cu_3O_7$, and $TlBa_2Ca_2Cu_3O_9$ superconducting films and find the electron-phonon interaction times at the transition temperatures of 17, 2.5, and 1.8 ps, respectively. The values are in reasonable agreement with data of other experiments.

I. INTRODUCTION

Since the experiment by Testardi[1] the radiation-induced nonequilibrium state of superconducting films has been studied intensively. Numerous investigations of the photoresponse of superconducting films to either periodic or pulsed radiation has been partially motivated by the practical request for fast and sensitive detectors. On the other hand, the experiments offered give the possibility to determine relaxation times of quasiparticles and phonons. Activity in this field has been renewed a few years ago by the discovery of high-temperature superconductivity (HTSC). It was suggested that HTSC materials should have a relatively strong electron-phonon interaction.[2,3] This caused a competition aimed to the experimental observation of the shortest response time. Although a response time of ≈ 15 ps has been demonstrated experimentally[4–6] the explanation of the nature of such a fast response remains controversial.

Basically three different mechanisms of the response have been proposed. These are the Josephson effect at intergrain weak links, the bolometric effect limited by phonon escape from the illuminated area of a film, and a quasiparticle-nonequilibrium mechanism determined by radiation-induced nonequilibrium distributions of quasiparticles. Depending on the thickness and geometry of a film the decay time of the bolometric response may vary from milliseconds to several hundred picoseconds. The other two mechanisms may provide response times in the picosecond time regime. The model which will be discussed further is not applicable to the response determined by the Josephson effect. The latter thus remains out of the scope of this article.

For there is no uniform relation between the change of quasiparticle distribution and the change of the film resistance, the magnitude of the response depends on the state of the film, whether it is in resistive or supercurrent carrying state. The resistance of the film in the resistive state may be connected with magnetic vortices freely moving in a viscous manner under the influence of the Lorentz force. At a fixed biasing current a resistance charge may result from the change of either the vortex concentration or the effective viscosity. Additional free vortices may appear due to radiation induced depinning of vortices[7,8] or unbinding of vortex-antivortex pairs.[9] Film granularity may also contribute[10] to the resistance. Intergrain contacts presumably have smaller critical currents than the grains. At any bias some contacts are in the normal state and do not carry a supercurrent. An increase of the number of contacts in the normal state truncates the superconducting path along the film and increases the resistance. The critical current of a contact depends on the values of energy gap in the contacting grains. Absorbed radiation depresses the energy gap and may result in a drop of the critical current below the biasing current. The contact then switches into the normal state and contributes to the resistance change. Besides granularity the resistive state may be connected with

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macroscopic nonuniformity. When the biasing current increases normal regions appears at "weak" points where critical parameters (e.g., transition temperature or critical current) are smaller than in the remaining part of the film. Absorbed radiation produces a resistance change due to either diffusive motion of the normal/superconducting boundaries[11] or increasing of the electric-field penetration depth.[12]

In the superconducting state of a film at temperatures $T < T_c$ electric current is carried by Cooper pairs with a finite inertia. From the macroscopic point of view this state can be equivalently described by the kinetic inductance which is inversely proportional to the density of Cooper pairs. Radiation quanta can break Cooper pairs, which results in a change of the kinetic inductance of the film. At constant bias current the change of kinetic inductance produces a voltage transient across the film which contributes to the photoresponse.[13,14]

Besides the mechanism of the photoresponse there has been little consensus regarding processes which limit the speed of the response. The response time may be the time inherent to the resistive state itself, e.g., the time free vortices need to recombine into pairs or to cross the film in the direction perpendicular to the biasing current.[9,15] On the other hand, the response time can correspond to the quasiparticle relaxation time.[16–18] This would be the case if the decay of the resistance change occurs with the same speed as the thermalization of quasiparticles, or faster.

In this paper we present an analysis based on the assumption that for the resistive state of a film the characteristic time of the reestablishment of the resistance is shorter or equal to the relaxation time of the nonequilibrium quasiparticle distribution. Accordingly, the response time of the film in the resistive state should be the quasiparticle relaxation time. The resistive state of the film then only plays the role of an ultrafast transformer of a change of the quasiparticle distribution function into a change of the film resistance.

Theoretically, nonequilibrium distributions of phonons and quasiparticles can be described by a system of time-dependent coupled kinetic equations.[19] Various simplified models derived for different limiting cases are in practical use. The Rothwarf-Taylor equations[20] are valid for temperatures $T \ll T_c$ where quasiparticle energies are much smaller than the superconducting energy gap Δ. In this case all quasiparticles may be considered to have the same energy and their total number is an appropriate parameter. At $T \approx T_c$ the energy spectrum of quasiparticles cannot be neglected. In this situation an effective temperature may be introduced as a parameter describing the quasiparticle distribution. Assigning another effective temperature to phonons it is possible to describe a nonequilibrium state by a system of coupled time-dependent energy-balance equations.[21,22] This two-temperature model has been successfully used to analyze quantitatively the photoresponse of superconducting films in the resistive state to periodic optical[21,23] or microwave[22,24] radiation as well as results of pump-probe experiments at room temperature.[25] The model has also been applied for a qualitative description of the response to radiation pulses.[26] A quantitative analysis of the pulsed photoresponse can be carried out only if the bandwidth of the read-out electronics is taken into account and if the radiation energy absorbed in the film is known.[27,28] We meet both requirements by introducing the transient characteristic of the measuring circuit into our calculations and by exploiting the bolometric component of the response as a measure of the absorbed energy. This enables us to use the quasiparticle relaxation time as the only adjustable parameter to fit model calculation to experimental photoresponse transients.

The paper is organized as follows. The two-temperature model is briefly reviewed in Sec. II. An analytical solution of the system of time-dependent energy-balance equations for electron and phonon effective temperatures is derived taking into account the radiation pulse shape. The shape of the superconducting transition curve and the frequency band pass of the readout electronics are taken into account in calculations of signal transients. In Sec. III results of calculations are presented for different electron and phonon specific heats and electron-phonon interaction times. We will show how the radiation pulse shape and the electronics transient characteristic influence the photoresponse signal. In Sec. IV experimental results are compared with the model calculations and electron-phonon interaction times are estimated for different materials. The influence of the nature of a resistive state on the shape and decay time of the photoresponse signal is also discussed in this section. Section V summarizes our results.

II. FORMULATIONS

The use of different effective temperatures to characterize nonequilibrium distributions of electrons and phonons was shown to be a good approximation for both the resistive and the normal state of superconducting films.[21,22,25,29,30] The model supposes a very short quasiparticle thermalization time. Fast thermalization may occur at high energies via both electron-electron interaction and electron scattering by optical phonons and at low energies mainly via electron-electron scattering.[31–33] For phonons a single-temperature approximation remains reasonable for a relatively weak coupling between phonons and the substrate.[21] The establishment of a nonequilibrium phonon temperature then occurs via electron-phonon and phonon-phonon interaction. The latter channel is most likely dominating for high-temperature superconductors due to the strong phonon anharmonicity[34] inherent to these materials.

Let us now consider a superconducting film carrying a constant current and driven in the resistive state at the temperature T close to the transition temperature. Under this condition the energy gap is small compared to $k_B T$ and the quasiparticle energy spectrum is close to that of electrons in a normal metal. Consequently, the inelastic scattering of quasiparticles as well as their recombination into Cooper paris can be described by the electron-phonon interaction time.[35] We suppose that the film is uniformly illuminated by radiation pulses and that the biasing current is uniformly distributed over the film

cross section. We also neglect Joule heating by the biasing current and consider only small deviations from equilibrium. This enables us to use the linearized form of the general equations[36] for the effective temperature of electrons (T_e) and phonons (T_p).

The time-dependent effective temperatures T_e and T_p are obtained as a solution of coupled linear heat-balance equations written for the unit volume of the film:[21,26]

$$\begin{aligned} c_e\frac{dT_e}{dt} &= -\frac{c_e}{\tau_{e-p}}(T_e-T_p)+P(t) , \\ c_p\frac{dT_p}{dt} &= \frac{c_e}{\tau_{e-p}}(T_e-T_p)-\frac{c_p}{\tau_{es}}(T_p-T_0) , \end{aligned} \tag{1}$$

where c_e and c_p are the electron and phonon specific heat, respectively, T_0 is the substrate temperature, τ_{e-p} is an average electron-phonon interaction time, τ_{es} is the time of phonon escape from the film into the substrate, and $P(t)$ is the time-dependent power of radiation absorbed in the unit volume of the film.

Strictly speaking, instead of τ_{e-p} [Eqs. (1)] one should use the electron temperature relaxation time τ_T which is an average[22] of the energy-dependent electron-phonon scattering time $\tau_{e-p}(\varepsilon)$ over the quasiparticle distribution function f_ε

$$\tau_T^{-1}=\int \tau_{e-p}^{-1}(\varepsilon)\frac{\delta(\varepsilon f_\varepsilon)}{\delta T_e}N_\varepsilon d\varepsilon \left[\int \frac{\delta(\varepsilon f_\varepsilon)}{\delta T_e}N_\varepsilon d\varepsilon\right]^{-1} , \tag{2}$$

where ε is the electron energy and N_ε the electron density of states. It was shown[22] that for a normal metal τ_{e-p} and τ_T differ by a factor of ~ 1.5. Supposing that this is also valid for a superconducting film in the resistive state at $T\approx T_c$ we will use in our discussion τ_{e-p}.

An analytical solution of the system (1) exists when the function $P(t)$ is a combination of polynomial and exponential functions. It is clear from the physical point of view that, to the extent the radiation fluence per pulse is constant and the pulse duration is less than τ_{e-p}, neither the magnitude nor the decay time of the effective temperature change depend on the shape of the radiation pulse. Therefore we chose for $P(t)$ a form providing the simplest analytical solution of Eqs. (1)

$$P(t)=\eta E n^3(2d\tau_0)^{-1}\xi^2\exp(-n\xi) , \tag{3}$$

where $n=3.4, \xi=t/\tau_0$ is the dimensionless time, τ_0 is the full width of the pulse at half maximum, η is the absorptivity of the film, E is the radiation fluence per pulse, and d is the film thickness. The general solution for the dimensionless deviation of the effective temperature from the equilibrium value is

$$\begin{aligned} \frac{T_e-T_0}{T_0} &= \frac{D}{\alpha_2-\alpha_1}[A_1 v_1\exp(\alpha_1\xi)-A_2 v_2\exp(\alpha_2\xi)] , \\ \frac{T_p-T_0}{T_0} &= \Gamma_2\frac{D}{\alpha_2-\alpha_1}[v_1\exp(\alpha_1\xi)-v_2\exp(\alpha_2\xi)] , \end{aligned} \tag{4}$$

where

$$\begin{aligned} v_{1,2} &= \frac{[\beta_{1,2}^2\xi^2+2\beta_{1,2}\xi+2]\exp(-\beta_{1,2}\xi)-2}{\beta_{1,2}^3} , \\ \beta_{1,2} &= \alpha_{1,2}+n , \\ A_{1,2} &= \alpha_{1,2}+\Gamma_2+\Gamma_3 , \\ D &= \eta E n^3(2dT_0c_e)^{-1} , \end{aligned} \tag{5}$$

and the characteristic dimensionless decay parameters are

$$\begin{aligned} \alpha_{1,2} &= \frac{1}{2}[-(\Gamma_1+\Gamma_2+\Gamma_3)\pm\sqrt{(\Gamma_1+\Gamma_2+\Gamma_3^2)-4\Gamma_1\Gamma_3}] , \\ \Gamma_1 &= \tau_0/\tau_{e-p} , \\ \Gamma_2 &= \Gamma_1(c_e/c_p) , \\ \Gamma_3 &= \tau_0/\tau_{es} . \end{aligned} \tag{6}$$

Assuming that in the resistive state the dependence of the film resistance on the electron temperature $R(T_e)$ is the same as the dependence of the film resistance on the ambient temperature $R(T)$, the former can be approximated by the expression

$$R(T_e)=R_n\left[1+\exp\left[-4\frac{T_e-T_c}{\Delta T_c}\right]\right]^{-1} , \tag{7}$$

where R_n is the experimentally found resistance of the film in the normal state at $T\geq T_c$ and ΔT_c is the width of the superconducting transition measured with the biasing current. The transition temperature is determined here as the temperature where $R=R_n/2$. The voltage transient across the film can be written as

$$V(\xi)=I[R(T_e)-R(T_0)] , \tag{8}$$

where I is the biasing current.

Supposing the film impedance to be real and equal to $R(T_e)$, the impedance mismatch between the film and the signal readout line can be taken into account by the expression

$$V_{in}(\xi)=V(\xi)R_0/[R(T_e)+R_0] , \tag{9}$$

where R_0 is the wave resistance of the readout line and $V_{in}(\xi)$ is the voltage transient at the input of the registration electronics. We simulate the influence of the limited frequency band pass of the registration electronics making use of the Duhamel integral method.[37] The output voltage transient is determined by

$$V_{out}(\xi)=\int_0^\xi \dot{V}_{in}(\tau)h(\xi-\tau)d\tau , \tag{10}$$

where $h(\xi)$ is the transient characteristic of the read-out system. This function represents the voltage response of electronics to a vertical voltage step with unit height. The transient characteristic is the Fourier transform of the frequency band-pass characteristic. To approximate $h(\xi)$ we use a form suitable for conventional electronics[38]

$$h(\xi)=\left[1-\exp\left[-\frac{\xi\tau_0 f_H}{0.35}\right]\right]\exp\left[-\frac{\xi\tau_0 f_L}{0.35}\right], \tag{11}$$

$$\frac{0.35}{f_H}=\sqrt{\sum_i (0.35/F_i)^2};\quad \frac{f_L}{0.35}=\sqrt{\sum_i (f_i/0.35)^2},$$

where F_i and f_i are the upper and lower band pass frequencies of different components (e.g., cables, amplifiers, oscilloscope) constituting the registration read-out system.

III. RESULTS

To demonstrate the results of calculations we choose parameters (Table I) typical for $YBa_2Cu_3O_7$ films. The value of the electron specific heat $c_e \approx 0.022$ J cm^{-3}K^{-1} at $T=80$ K has been reported by several groups.[18,29] The phonon escape time $\tau_{es}=3.6$ ns corresponds to a film with the thickness 40 nm on a MgO substrate.[39] For a laser fluence $E<1$ μJ cm^{-2} these parameters lead to a maximum electron temperature change ΔT_e of about 10 K which does not run out of the interval of superconducting fluctuations and is still small compared to the ambient temperature. Thus we are in the linear regime of the electron temperature relaxation. The results obtained under these conditions are shown in Figs. 1–6 for different values of the specific-heat ratio c_p/c_e, laser pulse duration and fluence, and the upper band-pass frequency.

Examples of the electron (solid lines) and phonon (dashed lines) temperature transients are shown in Fig. 1 for $\tau_{e-p}=3.5$ ps, $E=1$ μJ cm^{-2}, $c_p/c_e=40$, and a pulse duration $\tau_0=0.5$ ps and $\tau_0=25$ ps (inset). The equilibrium temperature T_0 is taken as zero level. Basically, there are two components of the electron temperature transient. The slower component corresponds to the cooling of the film via phonon escape to the substrate with the characteristic time τ_{es}. Depending on the radiation pulse duration, the decay of the fast component reflects either the establishment of an equilibrium between electrons and phonons with the characteristic time $\tau_{e-p} \gg \tau_0$ (ballistic regime) or, for $\tau_0 \gg \tau_{e-p}$, it is a measure of the difference between electron and phonon temperatures in the quasistationary regime. In the latter case the fast component reproduces the radiation pulse shape.

Unless another value is specified, signal transients in Figs. 2–5 are calculated with $E=100$ nJ cm^{-2}. This results in the maximum change of the film resistance small compared to the wave resistance of the readout transmission line and enables us to neglect impedance mismatch

TABLE I. Parameters used in model simulation.

Film thickness	$d=40$ nm
Electron specific heat	$c_e=0.022$ J cm^{-3} K^{-1}
Transition temperature	$T_c=80$ K
Transition width	$\Delta T_c=2$ K
Operation temperature	$T_0=80$ K
Phonon escape time	$\tau_{es}=3.6$ ns
Biasing current	$I=0.3$ mA
Normal-state resistance at T_c	$R_n=100\Omega$

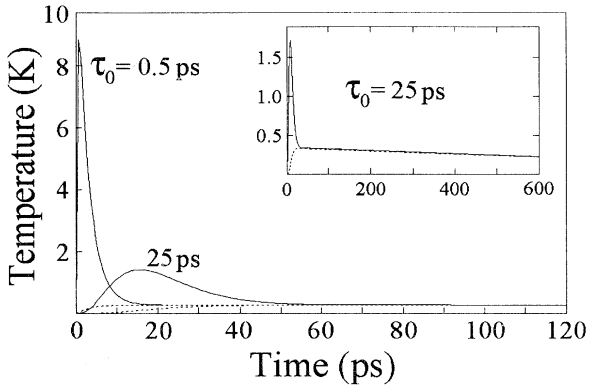

FIG. 1. Calculated and temporal evolution of the effective electron temperature (solid lines) and effective phonon temperature (dashed lines) for two different values of the laser pulse duration τ_0. The equilibrium temperature is chosen as zero level. The inset shows temperature transients for $\tau_0=25$ ps in a larger time scale.

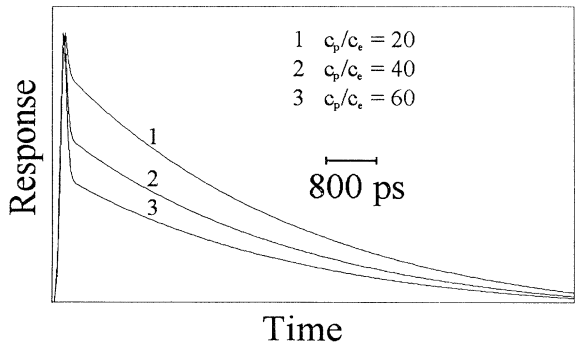

FIG. 2. Variation of the signal transients with the change of the c_p/c_e ratio.

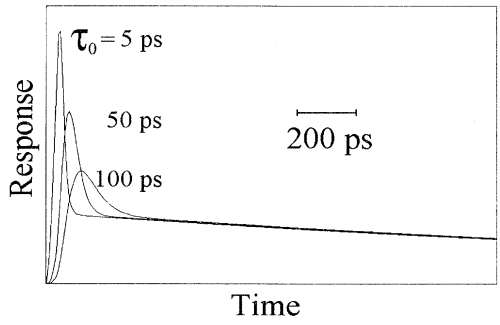

FIG. 3. Signal transients for the electronics transient time $\tau_a=35$ ps and different durations of the laser pulse τ_0.

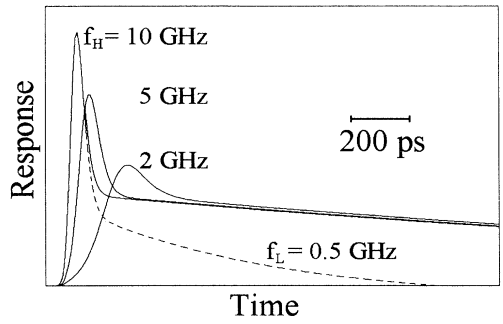

FIG. 4. Influence of the electronics frequency band pass on the signal transients. Solid curves are calculated for $f_L = 0.01$ GHz, values of f_H are indicated at each curve. The dashed curve is obtained for $f_L = 0.5$ GHz and $f_H = 10$ GHz.

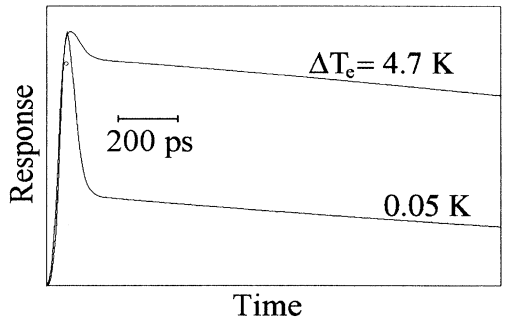

FIG. 6. Signal transients for two different fluences $E = 100$ nJ cm^{-2} (lower curve) and $E = 1$ μJ cm^{-2} (upper curve). The maximum change of the electron temperature is indicated at each curve.

(see discussion below). The variation of the signal transient with the ratio c_p/c_e is illustrated in Fig. 2 for $\tau_0 = 40$ ps, $\tau_{e-p} = 3.5$ ps, and a finite frequency band pass of electronics ($f_L = 10$ MHz, $f_H = 3.5$ GHz). The major features of the electron temperature transients shown in Fig. 1 are clearly reproduced in signal transients. The increase of the phonon specific heat makes the fast component of the response more pronounced although its width is limited by electronics.

Figure 3 demonstrates the effect of the laser pulse duration on the width of the fast component for $f_H = 10$ GHz at fixed fluence. Until the laser pulse duration is smaller than the electronics transient time $\tau_a = 0.35/f_H = 35$ ps the duration of the fast component is limited by electronics. For $\tau_a < \tau_0$ the fast component follows the laser pulse. When τ_0 increases, the amplitude of the fast component decreases which is caused by both the transition from the ballistic to the quasistationary regime of the quasiparticle thermalization and the decrease of the maximum radiation power.

The importance of an adequate registration electronics for pulse measurements is seen in Fig. 4 which demonstrates the influence of the time resolution of the electronics on the measured signal. Signal transients are calculated for $\tau_0 = 25$ ps. Decreasing of the upper band-pass frequency smears out the fast component (solid lines), while the increase of the lower band-pass frequency leads to the distortion of the slow component and may even result in a negative transient.

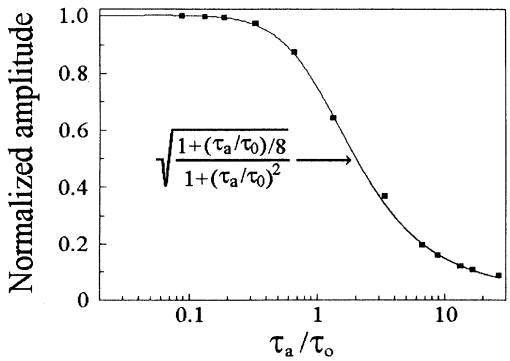

FIG. 5. Normalized amplitude of the fast component of the signal as a function of the time resolution of the readout electronics. The amplitude of the fast component at $\tau_a/\tau_0 \ll 1$ is taken as unity. The solid line shows the analytical fit.

The decrease of the normalized amplitude of the fast component with the increase of the ratio τ_a/τ_0 is illustrated in Fig. 5 for $\tau_0 \gg \tau_{e-p}$. The solid line shows an analytical fit with the expression

$$[1+\tau_a/(8\tau_0)]^{1/2}[1+(\tau_a/\tau_0)^2]^{-1/2} .$$

This formula is helpful for practical estimates of how readout electronics reduces the amplitude of the photoresponse.

The maximum change of the electron temperature ΔT_e increases linearly with the laser fluence as long as $\Delta T_e \ll T_0$. The change of the film resistance is proportional to ΔT_e to the extent the $R(T_e)$ dependence can be approximated by a straight line. This is valid for the middle part of the transition, at the upper part of the transition curve even small changes of the electron temperature are not reproduced linearly by the resistance change. For $\Delta T_e \approx \Delta T_c$, independently on the operation temperature, voltage transient across the sample is distorted due to nonlinearity of the $R(T_e)$ curve. The impedance mismatch between the film and the readout line influences the signal shape [Eq. (9)] if the maximum resistance change ΔR is comparable with or larger than $R_0 + R(T_0)$.

The effect of both the impedance mismatch and the nonlinearity of the $R(T_e)$ dependence on the response signal is seen in Fig. 6 where signal transients are shown for two different fluences. For the smaller fluence the conditions $\Delta T_e \ll \Delta T_c$ and $\Delta R \ll R_0 + R(T_0)$ are both fulfilled. For the higher fluence [$\Delta T_c \sim \Delta T_c$ and $\Delta R \approx R_0 + R(T_0)$] the fast component of the response becomes less pronounced.

IV. COMPARISON WITH EXPERIMENT

The proper interpretation of experimental data in the framework of the two-temperature model requires two essential parameters. These are the radiation energy absorbed in the film and the electron-phonon interaction time. Both parameters can be determined from experimental results. To obtain the radiation energy absorbed in a film we use the bolometric component of the response signal. For HTSC films which are not extremely thin the phonon escape time is long compared to the electron-phonon interaction time and, for short laser pulses, also to the pulse duration.[39] Consequently, within the time scale of the fast component, phonons play the role of a heat sink with a large heat capacity ($c_p \gg c_e$). Therefore, after the quasistationary equilibrium between quasiparticles and phonons has been established, the change of phonon temperature is a measure of the radiation energy absorbed in the film. This situation enables us to fit independently the slow component of the experimental signal transient with the absorbed energy as a parameter. With the best fit value of the absorbed energy one can determine the absorption coefficient using the experimental value of the fluence. In the next step we fit the whole experimental signal transient revealing the value of the electron-phonon interaction time.

Figures 7(a) and 7(b) show experimental response signals from Refs. 29 and 4, respectively, together with calculated transients. In both cases similar $YBa_2Cu_3O_7$ films were studied while laser pulse duration and temporal resolution of electronics were $\tau_0=0.3$ ps, $f_H=23$ GHz (Ref. 4) and $\tau_0=40$ ps, $f_H=3.5$ GHz (Ref. 29). For model calculations we used the phonon specific heat[14,27] $c_p=0.9\ \mathrm{J\,cm^{-3}\,K^{-1}}$ and experimental data from Refs. 29 and 4 (parameters used are listed in Table II). From the best fit indicted by the dashed line we concluded $\eta=0.2, \tau_{e-p}=3.5$ ps [Fig. 7(a)] and $\eta=0.5, \tau_{e-p}=1.5$ ps [Fig. 7(b)]. We note here that model simulations of experimental results obtained in different conditions for similar films reveal close values of η and τ_{e-p}. The electron-phonon interaction time derived from the fitting procedure is also close to $\tau_{e-p}\approx 2.0$ ps concluded from the study of submillimeter photoresponse of $YBa_2Cu_3O_7$ films.[16,40]

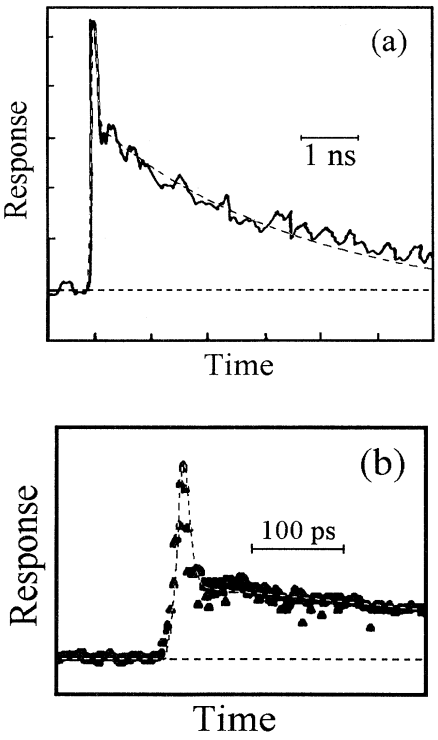

FIG. 7. The best fit (dashed lines) of the model calculations to the photoresponse signals of $YBa_2Cu_3O_7$ films from Ref. 29(a) and Ref. 4(b). Horizontal dashed line shows zero level.

The signal transient[30] for a $TlBa_2Ca_2Cu_2O_9$ film and the calculated wave form (dashed line) providing the best fit are shown in Fig. 8. The parameters (Table II) used in calculation were taken from Ref. 30. From the fitting procedure we obtained $\tau_{e-p}=1.8$ ps at 65 K which is, to our knowledge, the first estimate of the electron-phonon interaction time in $TlBa_2Ca_2Cu_3O_9$ compound.

For NbN films at a temperature near 10 K the electron-phonon interaction time is of the order of ten picosecond[41] which is comparable with the phonon escape time for films thinner than 100 Å. The phonon and electron specific heats are also comparable at $T=10$ K. Both facts make the calculated transients less sensitive to variations of τ_{e-p}. The electron-phonon interaction time for NbN was estimated[41] from results of pulse measurements with $\tau_0\approx 10$ ps which is close to the electron-phonon interaction time in NbN. To realize better accuracy, we measured the response of a 200 Å thick NbN film with 80 fs pulses of a titanium-sapphire laser (wavelength 0.85 μm). Signal transients were monitored with a 541208 Hewlett Packard sampling oscilloscope; the upper frequency of the registration band pass was ≈ 9 GHz. Figure 9 shows the response signal of the film measured at $T=8.1$ K. The rise time of the signal is limited by electronics (transient time $\tau_0=39$ ps). The fast component of the signal is weakly pronounced most likely due to the small ratio c_p/c_e.

Since we did not know about experimental data for the phonon specific heat of NbN films, we made an estimate of c_p using the Debye model. The transition temperature, the Debye temperature Θ_D, and the Sommerfeld constant γ of NbN depend on the nitrogen-to-niobium ratio x. Generally,[42] γ and Θ_D tend to increase with the decrease of x while T_c peaks at $x\approx 0.94$ reaching a value of ~ 17 K. For films similar to that we study in the present article $\gamma=1.85\times 10^{-4}\ \mathrm{J\,cm^{-3}\,K^{-2}}$ has been reported.[43] This results in $c_e=2.3\times 10^{-3}\ \mathrm{J\,cm^{-3}\,K^{-1}}$ at $T=8$ K. Referring to $\gamma(x)$ and $\Theta_D(x)$ dependencies[42] we assume for our film a Debye temperature of 250 K. At $T=8$ K this gives $c_p=(12\pi^4/5)nk_B(T/\Theta_D)^3=5.0\times 10^{-3}\ \mathrm{J\,cm^{-3}\,K^{-1}}$ ($n=4.8\times 10^{22}\ \mathrm{cm^{-3}}$ is the atom density of NbN). Other parameters used in model calculations are taken from the experiment (see Table II). From the best fit indicated by the solid line in Fig. 9 we concluded $\eta=0.44$ and

TABLE II. Parameters used for fitting model calculations to experimental data.

	$YBa_2Cu_3O_7$ Ref. 4	$YBa_2Cu_3O_7$ Ref. 29	$TlBa_2Ca_2Cu_3O_9$ Ref. 30	NbN
Film thickness, d (nm)	40	45	400	20
Electron specific heat, c_e ($J\,cm^{-3}K^{-1}$)	0.022	0.022	2.3×10^{-3}	1.3×10^{-3}
Phonon specific heat, c_p ($J\,cm^{-3}K^{-1}$)	0.9	0.9	0.22	5.0×10^{-3}
Operation temperature, T_0 (K)	85	77	65	8.1
Transition temperature, T_c (K)	85	75	63	8.2
Transition width, ΔT_c (K)	3	4	5	0.25
Phonon escape time, τ_{es} (ns)	2.0	3.9	8.2	0.16
Biasing current, I (mA)	22	0.4	15	0.2
Normal state resistance at T_c, R_n (Ω)	50	100	100	2600
Radiation fluence, E ($\mu J\,cm^{-2}$)	4.4	8	12	2×10^{-4}
Laser pulse duration, τ_0 (ps)	0.3	40	40	0.1
Lower bandpass frequency, f_L (GHz)	0.01	0.01	0.01	0.1
Upper bandpass frequency, f_H (GHz)	23	3.5	1.6	9.0

$\tau_{e-p}=17$ ps. The best fit value of the absorption coefficient reasonably agrees with $\eta=0.46$ calculated for an optically thin metal film by the formula[24] $\eta=(4R_\square/Z_0)/(1+2R_\square/Z_0)^2$ where $Z_0=377\Omega$ is the impedance of free space and $R_\square=360\,\Omega$ is the sheet resistance of our film in the normal state. The value of the electron-phonon interaction time revealed from the fitting procedure ($\tau_{e-p}=17$ ps) is very close to $\tau_{e-p}=19$ ps concluded from modulation measurements with millimeter wavelength radiation.[43]

We now discuss how the nature of the resistive state may restrict the validity of the two-temperature model. The resistive state of a current carrying HTSC film may be related to magnetic vortices moving perpendicular to the biasing current. In a model considering unipolar vortices partially localized at pinning centers[7,44] the resistance of a film is inverse proportional to the effective viscosity of flux-flow and proportional to the density of free vortices which is determined by the temperature-dependent activation energy. Since no direct interaction mechanism between photons and vortices is known, it is reasonable to suppose that radiation influences the vortex dynamics via the nonequilibrium quasiparticle distribution. The effective viscosity of flux flow, the vortex density, and the activation energy are temperature dependent. Therefore, the increase of the effective electron temperature gives rise to a change of the film resistance. The relaxation of the resistance change may be determined by the flux-flow relaxation[45] or by the rebinding of vortices at pinning centers.[26] The maximum value of the characteristic rebinding time is the time a vortex travels from one side of the film to the other. At $T\approx T_c$ for a film width of 10 μm the traveling time is ~100 ps.[9] This is much longer than the intrinsic response time concluded from pulse measurements. The rebinding time obviously drops down with the increase of the pinning center density and may become shorter than few picoseconds for granular films or for films with a high density of defects.[26] On the other hand, it was shown[45] that in the dirty limit the flux-flow relaxation time is of the order of the inelastic carrier scattering time. In the clean limit (e.g., for $YBa_2Cu_3O_7$) the nature of the energy dissipation by moving vortices may differ from that in the dirty limit. Nevertheless, it seems to be unlikely that the flux-flow relaxation time in the clean limit increases up to several picoseconds.

In the Kosterlitz-Thouless model[46,47] the film resistance is also proportional to the density of free vortices which, in its turn, is determined by the temperature-

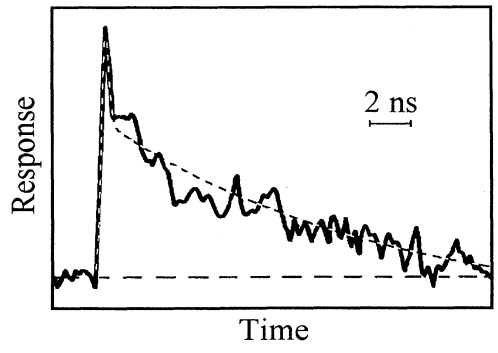

FIG. 8. Photoresponse signal of a $TlBa_2Ca_2Cu_3O_9$ film from Ref. 30 and the best model fit (dashed line). Horizontal dashed line shows zero level.

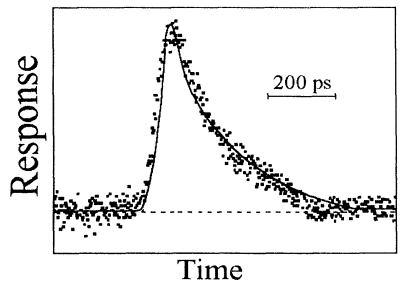

FIG. 9. Photoresponse signal of a NbN film and the best model fit (solid line). Dashed line shows zero level.

dependent binding energy of a vortex-antivortex pair. The recombination of free vortices with different polarities into pairs provides the effective mechanism of the resistance decay. The characteristic time of this process is[15]

$$\tau_r = \frac{\varphi_0^2}{8\pi c^2 R_\square(T) k_B T} , \tag{12}$$

where φ_0 is the magnetic flux quantum and $R_\square$ is the sheet resistance of the film. For $R_\square = 100\,\Omega$ at $T = 80$ K we find $\tau_r \approx 10^{-12}$ s. At lower temperatures, when the film resistance drops to zero, recombination of vortices may contribute to the intrinsic response time.

The resistance in the resistive state of a granular film may be caused by motion of Josephson vortices or hypervortices.[48] Such a film can be thought of as a granular Josephson medium consisting of superconducting particles (grains) connected by Josephson junctions. Vortices in this medium have no normal core. Their effective size is of the order of the grain size or larger. Vortices move in a viscous manner driven by a force which is proportional to the local current density. The motion of vortices is not affected by pinning centers. Therefore the effective time of the resistance decay is the time a vortex takes to cross the film[48]

$$t_\kappa = \frac{\pi \kappa e W^2}{4\hbar I_c} , \tag{13}$$

where κ is the effective viscosity, W the film width, and $I_c \propto W^{1/2}$ the current at which vortices begin to penetrate into the film. An estimate of t_κ can be obtained using the viscosity of Abrikosov vortices in the Stefan-Bardeen model.[49] For $\kappa = 6.4\times10^{-12}\gamma T_c \approx 4.6\times10^{-10}$ J s cm^{-2} and typical values[48] $W = 2\times10^{-4}$ cm, $d = 3\times10^{-5}$ cm, and $I_c = 4\times10^{-4}$ A, we obtain $t_\kappa \approx 10^2$ s. This time obviously has nothing to do with picosecond transients. Also we would like to emphasize that Eq. (15) leads to the dependence $t_\kappa \propto W^{3/2}$ which has not been observed experimentally.

In narrow granular films with the width of the order of the characteristic grain size the resistivity may arise from intergrain contacts having smaller critical currents than the biasing current.[10] As the contact critical current decreases with the decrease of the energy gap in granules forming the contact, the response of such a system is proportional to the electron temperature change in granules. The contact resistance switches from zero to the normal-state value within the time carriers need to be converted from pairs into quasiparticles. The conversion time, $\sim h/\Delta$, is always much shorter than the electron-phonon interaction time. Therefore, the latter determines the speed of photoresponse.

The resistance state of quasi-one-dimensional epitaxial films was related to phase-slip centers.[50] The resistance contributed by one center is determined by the electric-field penetration depth and by the normal-state resistance of the film. The electric-field penetration depth corresponds to the decay length of the charge imbalance between electronlike and holelike quasiparticles which is temperature dependant via the superconducting energy gap. Consequently, the rate of the resistance change is governed by the energy-gap relaxation time. This point of view is also applicable to the resistive state resulting from macroscopic normal regions pinned at geometric nonuniformities.

Referring to different types of the resistive state which were discussed above, we conclude that the resistive state may most likely be considered as a noninertial transducer of the electron temperature change to the change of the film resistance. In other words, $\Delta R = (\delta R/\delta T_e)\Delta T_e$, where $\delta R/\delta T_e$ is equal to the temperature derivative of the film resistance $\delta R/\delta T$, which can be obtained from the experiment.

Although the two-temperature model provides a rather good description of the experimental results one of the assumptions we made may not be valid for $YBa_2Cu_3O_7$ films. It was supposed that the establishment of the electron temperature occurs during a time small compared to τ_{e-p} and that within this time almost no energy is transferred from electrons to phonons. However, nonequilibrium electrons may transfer energy to optical phonons which in turn decay into acoustic phonons. Evidence of such a mechanism has been concluded from the experimental observation of the anharmonic broadening of optical-phonon lines.[34] For optical-phonon modes strongly coupled with electrons the time τ_{p-p}, in which optical phonons decay into acoustic phonons, varies[32] from approximately 4 to 7 ps at $T = 90$ K. With the use of the detailed balance condition $\tau_{p-e} = \tau_{e-p} c_p/c_e$ (τ_{p-e} is the phonon-electron interaction time) the portion of the absorbed radiation energy, which is transferred to phonons until the electron temperature is established, can be estimated as $\tau_{p-p}/\tau_{p-e} = (\tau_{p-p} c_e)/(\tau_{e-p} c_p)$. As the single-particle electron-phonon interaction time decreases with the increase of the energy of an electron this portion is larger when electrons are excited by radiation quanta to higher energies. Consequently, the portion of the absorbed energy, which is retained in the electron subsystem and which gives rise to the electron temperature, decreases with the increase of radiation frequency. This conclusion corresponds to the experimental observation[27,51] of a spectral dependence of the nonequilibrium photoresponse. The magnitude of the nonequilibrium component of the response to visible light pulses was found to be two to three times smaller than predicted by the electron heating model.[22,24] Our model simulations show that an increase of τ_{e-p} decreases the ratio of amplitudes of the fast and slow component. Therefore the use of the two-temperature model to describe the photoresponse to visible light pulses leads to an overestimate of the electron-phonon interaction time which may be approximately twice shorter than the best-fit value.

V. SUMMARY

We have applied the two-temperature model for interpretation of the results of pulses photoresponse measurements carried out in the resistive state of both high-T_c and conventional superconducting films. We have shown that the observed slow component of the response is determined by the phonon escape from the film. The fast

component is consistent with the electron temperature relaxation with a decay time corresponding to the electron-phonon interaction time. The resistive state provides a fast connection between the electron temperature and the film resistance and does not influence the characteristic response time.

Taking into account the frequency band pass of registration electronics and using the magnitude of the bolometric component of the photoresponse as a measure of absorbed radiation power, we estimated the electron-phonon interaction time by a fitting procedure where τ_{e-p} was the only adjustable parameter. This method provides reasonable results even if the transient time of the registration electronics is longer than the intrinsic response time of a superconducting film. We found the electron-phonon interaction time at the transition temperature 1.8 ps, 1.5–3.5 ps, and 17 ps for $TlBa_2Ca_2Cu_3O_9$ ($T_c \approx 70$ K), $YBa_2Cu_3O_7$ ($T_c \approx 80$ K), and NbN films ($T_c \approx 8$ K), respectively, which is in agreement with the results obtained from modulation experiments with millimeter radiation. An interpretation of the pulse photoresponse data obtained in the superconducting state would require us to take into account the kinetic inductance contribution to the voltage transient.

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