Intrinsic picosecond response times of Y–Ba–Cu–O superconducting photodetectors

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We report our femtosecond time-resolved measurements on the photoresponse of an epitaxial YBa2Cu3O7−x (YBCO) thin-film photodetector, patterned into a microbridge geometry. By varying the current–voltage biasing conditions between the superconducting and resistive (hot spot) states, we observed transients that correspond to the nonequilibrium kinetic-inductance and the nonequilibrium electron-heating response mechanisms, respectively. The two-temperature model and the Rothwarf–Taylor theory have been used to simulate the measured wave forms and to extract the temporal parameters. The electron thermalization time and the electron–phonon energy relaxation time were determined by the electron temperature rise and decay times, which were found to be 0.56 and 1.1 ps, respectively, in the resistive state. We have also measured the ratio between the phonon and electron specific heats to be 38, which corresponds to a phonon–electron scattering time of 42 ps. No phonon-trapping effect (typical for low-temperature superconductors) was observed in YBCO, in the superconducting state, so the quasiparticle lifetime was given by the quasiparticle recombination time, estimated from the Rothwarf–Taylor equations to be below 1 ps.

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Photoexcitation studies of superconductors have been a subject of intense investigations for the last 20 years, with the renewed interest due to the discovery of high-temperature superconducting (HTS) materials. The ultrafast photoresponse in YBa2Cu3O7−x (YBCO) was observed in both optoelectronic and infrared mixing experiments. Recently, we have observed the single-piceosecond electrical response of a current-biased YBCO microbridge exposed to femtosecond-pulse optical radiation. The experiments were conducted at liquid nitrogen temperature using a subpicosecond electro-optic (EO) sampling system. They revealed that the kinetic inductance mechanism was responsible for the picosecond response, but the constraints set by the sample geometry prevented us from drawing any conclusions regarding the physics of the nonequilibrium phenomena. Complementary experiments performed by others have revealed the emission of terahertz radiation from current-biased YBCO thin-film microbridges when irradiated with femtosecond optical pulses.

At the theoretical level, the fast photoresponse of HTS materials has been extensively studied, using either the nonequilibrium electron heating or the kinetic inductance models to explain the observed electrical transients. The most complete recent review on photoresponse mechanisms in HTS thin films is presented in Ref. 9.

In the two-temperature (2T) model, the electron and phonon subsystems are assigned temperatures T_e and T_ph, respectively. The balance between the systems is governed by the coupled differential equations:

\[
\frac{dTE_e}{dt} = \frac{\alpha P_{\text{in}}(t)}{V} - \frac{C_e}{\tau_{e-\text{ph}}}(T_e - T_{\text{ph}}),
\]

\[
\frac{dT_{\text{ph}}}{dt} = \frac{C_{\text{ph}}}{\tau_{\text{ph}-e}}(T_e - T_{\text{ph}}) - \frac{C_{\text{ph}}}{\tau_{\text{es}}}(T_{\text{ph}} - T_s),
\]

where \( C_e \) and \( C_{\text{ph}} \) are the electron and phonon specific heats, \( \alpha \) is the radiation absorption coefficient, \( V \) is the volume of the bridge, and \( T_s \) is the sample temperature. \( P_{\text{in}}(t) \) is the incident optical power, in our case modeled as a Gaussian-shaped pulse. The equations also contain the characteristic times \( \tau_{e-\text{ph}} \) for electron–phonon scattering, and \( \tau_{\text{es}} \) for phonon escape to the substrate. We note the energy balance equation \( \tau_{e-\text{ph}} = \tau_{\text{ph}-e}(C_e/C_{\text{ph}}) \), where \( \tau_{\text{ph}-e} \) is phonon-electron scattering time.

In the kinetic inductance model, a photoinduced change in Cooper-pair density gives rise to a voltage transient \( V_{\text{kin}} = I(dL_{\text{kin}}/dt) \), where \( I \) is the bias current and \( L_{\text{kin}} \) is the kinetic inductance. We can assume that in the nonequilibrium case the superfluid fraction is related to the electron temperature according to \( f_{\text{sc}} = 1 - (T_e/T_c)^2 \) and calculate the kinetic inductance as \( L_{\text{kin}} \propto 1/f_{\text{sc}} \).

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To analyze the nonequilibrium kinetic inductive response, one can also use $f_\infty = (N_0 - N_{QP})/N_0$, where $N_0$ and $N_{QP}$ are the numbers per unit volume of all electrons and quasiparticles (QPs) in the superconductor, respectively, derived from the set of rate equations developed by Rothwarf and Taylor (RT). The RT equations are nonlinear and describe the deviation of the system from the equilibrium as the interplay between the QPs and phonons with an energy greater than or equal to twice the superconducting gap. The physical processes that establish nonequilibrium concentration $N_{QP}$ are the same as in the case of global $T_e$.

In this work we report the single-picosecond response of a current-biased YBCO microbridge, fabricated from a very high-quality epitaxial film, and exposed to $<100$ fs optical pulses. We have been able, using our EO experimental setup, to resolve the intrinsic response times involved in the photogenerated signal, and show that the response could be quantitatively described by the 2T or, equivalently, RT model. We believe that our findings provide important information about the physics of energy relaxation processes under nonequilibrium conditions in HTS materials. They also demonstrate the potential of YBCO for ultrafast detection of optical transients.

Our experimental setup has been described in detail in Ref. 11. Briefly, our test structures consisted of a 4-mm-long coplanar waveguide (CPW) transmission line with a 30-μm-wide center line and 7-μm-wide gaps and gold contact pads at both ends. A 5-μm-wide, 7-μm-long microbridge was placed at the center of the CPW. The bridge typically exhibited a zero-resistance temperature $T_{c0} > 89$ K and a critical current density $j_c > 10^6$ A/cm$^2$ at 77 K and was fabricated in a 100-nm-thick YBCO film laser deposited on LaAlO$_3$ substrates, using a wet-etch patterning method. The entire sample was overlaid with an electro-optic LiTaO$_3$ crystal to facilitate EO measurements.

The sample was mounted inside an exchange-gas, liquid-helium optical cryostat. The sample temperature was regulated in the 20–80 K range and stabilized to ±0.2 K by a temperature controller. One end of the CPW was wire bonded to a semirigid 50 Ω coaxial cable, while the other end was grounded. This arrangement allowed us to directly observe the bolometric part of the bridge response on an oscilloscope with the bandwidth of 14 GHz.

A commercial Ti:sapphire laser provided ~100-fs-wide optical pulses (790 nm wavelength) at a 76 MHz repetition rate, that were split into two paths. The first (excitation) beam was frequency doubled in a nonlinear crystal intensity modulated, and focused by a microscope objective to a 10-μm-diam spot to excite the microbridge. By calculating the amount of light absorbed in our optical beam path, we estimated that the power actually delivered to the microbridge was only 60 μW, which was the equivalent to the fluence of 1 μJ/cm$^2$, or approximately $2 \times 10^{13}$ 3 eV photons per cm$^2$, and was low enough to induce below 0.3 K permanent heating of the bridge area. The second (sampling) beam traveled through a computer-controlled delay line and was focused to a 10-μm-diam spot inside LiTaO$_3$ at the gap between the center and ground CPW lines, only ~20 μm from the microbridge. The sampling beam sensed the transient birefringence introduced in the LiTaO$_3$ crystal by the bridge photoresponse electric field, allowing us to resolve the time evolution of the photoresponse voltage signal. From the operational point of view, our EO system can be regarded as a sampling oscilloscope featuring ~200 fs time resolution and ~150 μV voltage sensitivity, which are well below the characteristics of the transients reported here.

Current–voltage characteristics of our microbridges were typical for a superconducting constriction and consisted of two different voltage states—the superconducting/flux–flow state with the zero/low voltage across the bridge and the resistive/switched state where the current is almost constant while the voltage across the bridge increases rapidly. The observed behavior depends on the formation of a hot spot in the bridge region. In the hot spot, the temperature is roughly constant and equal to $T_s^2/T_b$, where $T_b$ is the bath temperature. In our case, the microbridge is fairly small, so the hot spot covers a very large portion (or all) of the bridge, especially at 80 K.

Depending on whether the bridge was biased into the superconducting or resistive state, we observed two differently shaped photoresponse transients. Figure 1 shows a transient (dots) typical for the switched state. The bath temperature was 80 K, leading to the hot-spot temperature $T_s = 94$ K. The photoresponse was simulated by us using the 2T model and the wave form resulting from numerically solving Eq. (1) is shown as a solid line in Fig. 1. In the calculations, we used $C_e = \gamma T_e$, and the values for $\gamma$ and $C_{ph}$ from Ref. 13. The simulated wave form is in units of $T_e$, but it can be easily translated into voltage, which is proportional to $\Delta T_e$, according to $\Delta V = I(dR/dT)\Delta T_e$, where $R$ is the bridge resistance and the derivative should be evaluated at $T_e$. We note that agreement between the experiment and simulations is excellent. The rise time of the transient in Fig. 1 corresponds to $\tau_{ph}$, while the fall time is governed by $\tau_{ph,e}$. In our simulations, we have taken $\tau_{ph}$ into account by assuming that the electron system responds to the incident optical pulse with a broadened Gaussian shape. The input pulse width was adjusted until a least-squares fit to the rising edge of the photoresponse transient was achieved, rendering $\tau_{ph,e} = 0.56$ ps. Similarly, a least-squares fit was applied to the falling edge of the transient, resulting in $\tau_{ph,e} = 1.1$ ps.

FIG. 1. Measured voltage transient (dots) and the fitted nonequilibrium electron temperature (solid line), when the bridge was biased in the resistive hot-spot state. The inset shows the bolometric part of the photoresponse, registered with the help of the 14 GHz-bandwidth oscilloscope.

The photoresponse transient was achieved, rendering $\tau_{ph,e} = 0.56$ ps. Similarly, a least-squares fit was applied to the falling edge of the transient, resulting in $\tau_{ph,e} = 1.1$ ps.
From our simulations, we see that this plateau corresponds to the 0.3 K increase of the phonon (lattice) temperature. The 250 μV high bolometric signal was also directly observed (see inset in Fig. 1) on the fast oscilloscope and exhibited a few-nanosecond fall time, consistent with $\tau_{\text{et}}$. The comparison between the measured nonequilibrium (Fig. 2) and bolometric (inset in Fig. 1) wave forms and the fitted $T_e$ and $T_{\text{ph}}$ allowed us to determine the ratio $C_{\text{ph}}/C_e$ to be 38. The corresponding $\tau_{\text{ph-e}} = 42$ ps.

When the bridge was biased in the superconducting state, we observed a fast, oscillatory transient of the shape shown in Fig. 2. No signal could be seen on the oscilloscope in this case. The main oscillatory feature of the transient is characteristic for the nonequilibrium kinetic inductive response, with the positive part representing the process of breaking Cooper pairs and the negative part corresponding to the pair recombination. The dashed and solid lines in Fig. 2 represent theoretical fits obtained finding $f_{\text{sc}}$ from the 2T model and the RT equations, respectively. We note that both models describe the main features of the transient quite well, but the fit to the negative part of the transient is much better in the case of the RT model. At the same time, neither model can explain the post-pulse overshoot. The trailing oscillations are the new feature and were present in all low-noise traces collected in the superconducting state. The period of these oscillations does not correspond to any sample feature size, as it would if the reflections were the cause; thus, we believe that the oscillations are intrinsic to the YBCO photoresponse in the superconducting state.

We note that the main transient lasts less than 2 ps with the recombination (negative) part essentially as fast as the pair breaking; thus, there is clearly no phonon-trapping effect present in the photoresponse of YBCO. This observation is contrary to the standard response of a low-$T_c$ superconductor, but is in direct agreement with the theoretical prediction that since the $\tau_{\text{ph-e}}$ in YBCO is very long and much longer than phonon–phonon interactions, acoustical phonons do not participate in the secondary Cooper-pair breaking and the experimental QP lifetime is the real QP recombination time $\tau_R$. The above observation is also in good agreement with the fact that QP relaxation in YBCO does not depend on the film thickness and the optically thick films exhibit the single-ps photoresponse.

By using a least-squares fit to the transients shown in Fig. 2, we found $\tau_{\text{et}} = 0.86$ ps, and from the RT model the phonon pair breaking time $\tau_{\text{ph}} = 3.0$ ps and QP recombination rate $R = (2.8 \pm 0.2) \times 10^{-18}$ ps$^{-1}$ cm$^3$, leading to subpicosecond $\tau_R$. We note that $\tau_{\text{et}}$ is considerably longer than $\tau_{\text{et}} = 0.56$ ps found in the resistive state and we have $\tau_R \ll \tau_{\text{ph}}$, which translates in the lack of phonon-trapping effect.

In conclusion, we have found that nonequilibrium conditions govern the behavior of a YBCO microbridge when illuminated by femtosecond laser pulses, producing electrical transients of single-picosecond duration. The 2T model can excellently explain the photoresponse signals originating from biasing the resistive state. The resistance of the bridge increases due to a transient raise of $T_e$, so a bias current produces a voltage spike. The signal was followed by a nanosecond-duration bolometric component, due to the increase of $T_{\text{ph}}$. In the superconducting state, pair breaking and quasiparticle recombination, led to a picosecond change of superfluid density, which in the presence of a bias current gave rise to an oscillatory kinetic-inductive transient. While our measured wave forms can be qualitatively reproduced by both the 2T and RT models, the physical processes responsible for the lack of phonon trapping and the secondary oscillations in the superconducting state clearly require more theoretical understanding.

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