Nonequilibrium kinetic inductive response of Y–Ba–Cu–O photodetectors

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Abstract. We present a comprehensive study of the light-induced transient nonequilibrium kinetic inductive response of high-quality, epitaxial Y–Ba–Cu–O (YBCO) thin films. The test structures consisted of 20–30 µm wide coplanar strip (CPS) transmission lines with 7–10 µm separation, patterned in 100 nm thick YBCO films grown on MgO and LaAlO₃ substrates. Each CPS structure contained a 5 µm wide, 7–10 µm long microbridge. The photoresponse of the microbridge, biased far below the film critical current and temperature, and excited by 100 fs laser pulses, was measured using a cryogenic subpicosecond electro-optic sampling system. The physical origin of the photoresponse is attributed to the nonequilibrium quasiparticle generation and recombination effect and fitted with the Rothwarf–Taylor model. Our measurements show 1.9 ps wide bipolar waveforms for the LaAlO₃-based samples and 2.2 ps wide waveforms for the MgO-based samples. We regard the measured microbridge response times and the corresponding material time constants to be the intrinsic dynamics of YBCO. Our results show that the quasiparticle recombination time is very weakly temperature dependent and there is no phonon-trapping effect in YBCO. The picosecond response of YBCO makes it a suitable material for THz digital and communication applications.

1. Introduction

Photoexcitation studies of thin-film, high-\(T_c\) superconductors have attracted considerable attention because of their promising application as fast, broadband photodetectors and mixers. To this end, epitaxial Y–Ba–Cu–O (YBCO) has received most of the attention. Early experiments have demonstrated the photoresponse of YBCO microbridges, biased in the superconducting state at temperatures well below \(T_c\), to be as fast as 1.5 ps (Hegmann et al 1995). Recently, with an improved experimental test structure, we observed intrinsic photoresponse of the YBCO microbridge (Lindgren et al 1999). The physical origin of the photoresponse was attributed to the nonequilibrium quasiparticle (QP) generation and recombination effect. Although these experiments show YBCO to be a viable material for high-speed photodetectors with intrinsic bit rates exceeding 300 Gbits s\(^{-1}\), there are still ongoing experiments to fully understand the physics of nonequilibrium processes in high-\(T_c\) superconductors.

We present here further studies of the light-induced transient nonequilibrium kinetic inductive response of high-quality, epitaxial YBCO thin films.

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2. Experiment

The test structures consisted of coplanar strips (CPSs) patterned in 100 nm thick YBCO thin films grown on MgO and LaAlO₃. The structures on MgO consisted of 8 mm long, 20 µm wide lines with a 10 µm wide gap. Each CPS structure contained a 5 µm wide and 10 µm long microbridge. On the LaAlO₃ substrate, the lines were 4 mm long and 30 µm wide with a 7 µm separation, and each structure had a 5 µm wide and 7 µm long microbridge. The microbridges were characterized by a zero-resistance transition temperature \(T_{c,0} > 88\) K and critical current density \(J_c > 1\) MA cm\(^{-2}\) at 77 K. To study the nonequilibrium kinetic photoresponse, the bridge was biased in the superconducting state at varying values below the critical current \(I_c\) and at different temperatures below \(T_c\).

Measurements were acquired using a cryogenic electro-optic (EO) sampling system that is capable of measuring ultrafast electrical transients with a temporal resolution of 200 fs and a voltage sensitivity of 150 µV (Lindgren et al 1996). The test structure being measured was covered with an LiTaO₃ crystal to facilitate EO measurements and then mounted on a copper block heat exchanger inside a continuous-flow helium cryostat. One end of the CPS was wire bonded to a 50 Ω semirigid coaxial cable, while the
other end was grounded. This arrangement allowed us to directly observe the switched-state photoresponse on a 20 GHz sampling oscilloscope, which helped us to optimize the EO measurements. Additional wiring to the CPSs provided a means to obtain current–voltage characteristics of the microbridge at the different measuring temperatures (Lindgren et al 1996, 1999).

Optical pulses (100 fs wide and 790 nm wavelength) provided by a Ti:sapphire laser at a 76 MHz repetition rate were split into two beams. One beam was frequency doubled to 395 nm and focused to a 10 μm spot to excite the microbridge. By calculating the amount of light absorbed in our optical beam path, we estimated that the typical power actually delivered to the microbridge was only 60 μW, which was the equivalent of 1 μJ cm⁻², and induced a permanent heating of the bridge area of less than 0.3 K (Hegmann et al 1995). The second (sampling) beam travelled through a computer-controlled delay path before being focused to a 10 μm spot at the high reflectivity coated backside of the LiTaO₃ crystal. The sampling beam sensed the birefringence change in the LiTaO₃ crystal induced by the transient electric field of the microbridge photoresponse. Varying the relative delay between the sampling and the excitation beams, we were able to resolve the time evolution of the photoresponse voltage signal. It is important to note that the 200 fs time resolution of our EO sampler is well below the temporal characteristics of the transients reported here.

3. Results and discussion

3.1. Nonequilibrium kinetic inductance mechanism

According to the nonequilibrium kinetic model (Bluzer 1991, Hegmann and Preston 1993), a photoinduced change in the Cooper-pair density gives rise to a voltage transient

\[ V = I \left( L_{\text{kin}} / \omega d \right) \tau_B \]  

(1)

where \( I \) is the bias current. The kinetic inductance \( L_{\text{kin}} \) is related to the superfluid fraction of electrons in a superconductor \( f_{sc} \) by

\[ L_{\text{kin}} = \frac{1}{\epsilon_0 \alpha_p} \frac{1}{wd} f_{sc} \]  

(2)

where \( \epsilon_0 \) is the vacuum permittivity, \( \alpha_p = 1.67 \times 10^{15} \) s⁻¹ is the plasma frequency of YBCO, and \( I, w, d \) are the bridge length, width and film thickness, respectively.

To analyse the nonequilibrium response of superconductors, one can use the Rothwarf–Taylor (R–T) equations (Rothwarf and Taylor 1967). The nonlinear equations represent the interplay between the nonequilibrium QPs and phonons with an energy greater than or equal to twice the superconducting gap (called 2Δ phonons):

\[ \frac{dN_{QP}}{dt} = I_{QP} - R N_{QP}^2 + \frac{2}{\tau_B} N_{u} \]  

(3)

\[ \frac{dN_u}{dt} = I_u + \frac{1}{2} R N_{QP}^2 - \frac{1}{\tau_B} N_u - \frac{1}{\tau_{es}} (N_u - N_{u,T}) \]  

(4)

where \( N_{QP}, N_u \) and \( N_{u,T} \) are the numbers per unit volume of QPs, 2Δ phonons and thermal equilibrium phonons respectively. \( I_{QP} \) and \( I_u \) are the external generation rates for the QPs (optical pulse) and 2Δ phonons, respectively, \( R \) is the recombination rate for the QPs into Cooper pairs and \( \tau_B \) and \( \tau_{es} \) are the phonon pair-breaking and the phonon escape times, respectively. To solve the R–T rate equations, we keep in mind that they are best suited to describe conditions in the superconductor far below \( T_c \) and for weak to moderate external perturbations. We then introduce the QP recombination time

\[ \tau_R = \frac{2}{R N_{QP}^2} \]  

(5)

where \( N_{QP} \) is the thermal equilibrium value of \( N_{QP} \).

Normalized rate equations can then be obtained by dividing equations (3) and (4) by \( N_{QP} \) and \( N_u \), respectively. (Tonouchi et al 1996). We also ignore \( I_u \) and treat the normalized \( I_{QP} \) as the Gaussian excitation function

\[ I_{QP}(t) = A \exp(-t^2/\tau_f^2) \]  

(6)

where \( A \) is the optical intensity parameter and \( \tau_f \) is the time constant parameter that describes the thermalization time of the optical energy within the QPs in the YBCO. The relevant parameters to be extracted are \( \tau_B, \tau_R \) and \( \tau_{es} \), by directly comparing the numerical solution of equation (1) with the experimental data.

3.2. Measurements

Figure 1 shows typical nonequilibrium kinetic inductive photoresponses of YBCO microbridges measured with our EO sampler. The full-curve waveform is from a structure fabricated on LaAlO₃ and the broken curve is from a structure on MgO substrate. In both traces, the microbridge was biased at 0.8Ic at a temperature of 60 K and 70 K for the LaAlO₃ and MgO substrate samples, respectively. The LaAlO₃-based sample shows a 1.9 ps wide bipolar photoresponse, while a 2.2 ps wide bipolar response was measured for the MgO-based sample.

The main, bipolar feature of the waveform is characteristic for the nonequilibrium kinetic inductive...
response (Bluzer 1991), with the positive part representing the Cooper-pair-breaking process and the negative part corresponding to pair recombination. We note that for all our waveforms the bipolar feature is followed by subsequent oscillations.

For a more qualitative comparison, the photoresponse from the YBCO-on-LaAlO$_3$ sample in figure 1 is shown with its R–T model fit in figure 2 and the photoresponse of the MgO-based sample is shown with its R–T model fit in figure 3. We note that the R–T model replicates the main oscillation of the photoresponse but fails to explain the post-oscillation overshoot and subsequent ringing. The extracted values of $\tau_B = 1$ ps and $\tau_R = 0.55$ ps in figure 2 show the intrinsic ultrafast temporal dynamics of high-quality epitaxial YBCO. Figure 2 clearly indicates that there are no phonon-trapping effects in YBCO. For the YBCO-on-MgO sample in figure 3, the R–T-fitted $\tau_B = 2$ ps and $\tau_R = 5.2$ ps. The longer values for $\tau_B$ and $\tau_R$ are, in our view, substrate related, but are, apparently, due to differences in YBCO growth conditions. We emphasize that the value of $\tau_{es} > 100$ ps shows that the phonon escape time to both substrates is a very slow process relative to the much faster $\tau_B$ and $\tau_R$ and hence has a negligible effect on the nonequilibrium kinetic inductive process.

Table 1 shows the extracted time constant parameters $\tau_B$ and $\tau_R$ at different temperatures for the LaAlO$_3$-based sample. The pair-breaking time remained fixed at 1 ps, but the pair-recombination times show a decreasing trend as the temperature is lowered. This is in direct contrast to what is expected since equation (5) states that $\tau_R$ is inversely related to $N_{QPT}$, and $N_{QPT}$ is well known from BCS theory to exponentially decrease with decreasing temperature. A better understanding of QP–phonon interaction in the photoresponse of YBCO would shed more light in this area, as well as better describing the observed post-pulse overshoot and subsequent ringing.

During the experiment, the photoresponses of both substrate samples were measured while varying the bias current, in one case, and varying the optical excitation power in another. The photoresponse amplitude was observed to scale linearly with the bias current, which is consistent with equation (1). The photoresponse amplitude also showed a direct relation to the optical excitation power, consistent with the R–T equations.

4. Conclusion

We report time-resolved photoresponse measurements of high-quality epitaxial YBCO thin films on LaAlO$_3$ and MgO substrates that were biased in the superconducting state at temperatures below $T_c$. The origin of the photoresponse is attributed to the nonequilibrium kinetic inductance mechanism due to the QP recombination process and mathematically described by the R–T equations. The solutions to the R–T equations provided an adequate fit to our measured data by revealing intrinsic values of Cooper-pair-breaking and recombination times in YBCO (see table 1). The R–T model, however, failed to explain the observed post-pulse overshoot and revealed an unexpected trend of decreasing $\tau_R$ with decreasing temperature. More theoretical work is needed to this end.

Our measurements and the extracted time constants show that YBCO is a viable material for high-speed photodetectors and is suitable for THz digital and communication applications.

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