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PHOTORESPONSE OF Y-Ba-Cu-O THIN FILMS ON THE μs TIME SCALE - EVIDENCE FOR LOCALISED STATES NEAR E_F

J. Demsar[1], M. Zavrtanik[1], B. Podobnik[1], V.I. Dediu[2] and D. Mihailovic[1]

[1]*Jozef Stefan Institute, Jamova 39, 1001 Ljubljana, Slovenia*

[2]*HTS Laboratory, ICTP, PO Box 586, 34100 Trieste, Italy*

ABSTRACT:

We report a new feature in the photoresponse signal of current biased YBCO microstructures on the very long, μs timescales. The negative voltage transient spreading to beyond 30 μs after excitation by much shorter laser pulses has been observed and detailed and careful analysis show conclusively that it cannot be explained by any kind of direct bolometric mechanism. We therefore propose a non-bolometric kinetic inductance mechanism to be the candidate for the origin of this response, where the relaxation of the photoexcited quasiparticles through *localized states near* E_F takes place. This mechanism is entirely consistent with our recent observations using femtosecond time-resolved spectroscopy.

1. INTRODUCTION

In the last few years several authors[1] have been investigating photoresponse of HTSC thin films (thickness from 6 to several hundred nm) by illuminating a current biased microstrip line at temperatures below T_C with short (from 100 fs to ns) laser pulses and measuring voltage transients. The electrical transients were in most cases consisted of two components: *slow*, with a decay time on the nanosecond timescale and *fast* on the picosecond time-scale. *Slow* component was attributed to a bolometric effect where the optical illumination results in simple heating of the film into a resistive region. In this case the electron and phonon subsystems are described by the same temperature shift with respect to the substrate, which is in turn determined by thermal conductivity of the substrate or by the thermal boundary resistance at the film-substrate interface[1]. The *fast* component, with a decay time of the order of the laser pulse (1.5 ps decay time at 100 fs laser pulses has been reported using electro-optic sampling[2]) is on the other hand still under debate and has been interpreted either as a kinetic inductance bolometric effect[2] or as a non-equilibrium response where several mechanisms have been proposed[1], but none widely accepted.

In the present paper we are presenting a new feature in the photoresponse signal on the μs timescale which has come out during our feasibility study of preparing a multichannel microstrip microbolometer[3] on laser patterned YBCO thin films. The negative photoinduced voltage transient due to illumination of the current-biased microbridge by 200 ns laser pulses at a repetition rate of 1 kHz with extremely long decay time of the order of 30 μs was observed. The comparison of the measured signal to the predicted signal by resistive bolometric and bolometric kinetic inductance[2] models has been made showing that the mechanism responsible is non-bolometric in origin, and suggests some very slow quasiparticle recombination kinetics.

2. SAMPLE PREPARATION

In our experiments the YBCO thin films on NdGaO substrates were used, prepared by the channel-spark pulsed electron beam method[4]. A typical substrate size was $(10 \times 5 \times 0.3)\,\text{mm}^3$ with the film thicknesses approximately 150 nm. Typical transition temperatures were around 89 K for the pristine films.

Low resistivity electrical contacts to the film have been made by evaporating approx. 1 μm thick gold pads on the YBCO surface, which were subsequently annealed in oxygen at 500 ^{o}C for half an hour. Following the annealing we have patterned the microbridge (typical 20 μm width and 400 μm length) by using non-invasive laser-patterning technique[3,5]. Microbridge produced in this way showed practically no shift in critical temperature comparing to the original film, narrow transition ($\Delta T \approx 1K$, 10%-90%) and a critical current density of about 2×10^6 A/cm^2 at 77 K.

3. EXPERIMENTAL DETAILS

The typical set-up for the photoresponse measurements is presented in Figure 1. YBCO films were attached to the cold finger of a continuous flow cryostat. Connections from the contact pads on YBCO to the 50 Ω semi-rigid coaxial cable have been made by wire-bonding technique.

The bridge was biased with DC current through the bias tee. The modulated CW Ar-ion laser $(l = 514.5nm)$ was used as a source of 200 ns (FWHM) pulses at 1kHz repetition. The amplified response (amplifier Miteq AM-1309 (55 dB, 10 kHz to 1GHz)) was analyzed using Tektronix TDS 544A digital scope.

4. RESULTS AND DISCUSSION

In the Figure 2 the typical photoresponse signal obtained by illuminating the current biased microbridge with 200 ns laser pulse (laser power density was 220 W/cm^2, repetition 1kHz, the illuminated area ($70mm \times 20mm$) is presented. The temperature was 84.0 K (T_C^* = 87.2 K and ΔT ~2K, at bias current 5 mA which corresponds to the current density 1.3 10^5 A/cm^2).

The rise time of the signal is approx. 300 ns as expected. The signal then falls to zero in ~ 3 μs and is followed by a small amplitude negative signal (approx. 4 % of the positive peak amplitude) until it relaxes to zero within 30 μs. When increasing the temperature or corresponding bias current, some prolongation of the negative signal is observed, however the general shape of the voltage transient does not change significantly. The signal can be observed (I_{BIAS} = const., P_{LASER} = const.) at temperatures from approx. 4 K to approx. 1 K below T_C^* (depending on the I_{BIAS}), the upper temperature being limited by thermal runaway due to heating of the bridge by the bias current.

At this point it is very important to point out that the negative signal present in our photoresponse is not an artifact of our measuring set-up (the frequency response function of our measuring electronics has been measured in detail and taken into consideration), and the response of our experimental set-up to pulses from 200 ns to 10 μs has also been measured by using passive electronics in place of the microbridge, showing no such effect that could put these results into question.

In order to evaluate the results of our measurements, the measured signal has been compared to the expected voltage transient due to resistive bolometric effects and due to bolometric kinetic inductance effect which has been proposed[2] to be present when illuminating the current biased microbridge with picosecond laser pulses. In order to estimate the signal amplitude and timing properties of the bolometric contribution to the signal, we have used a heat transfer model[6] wherein the optical pulse of duration t (FWHM) supplies heat (absorbed optical energy), at rate corresponding to the temporal profile of the laser pulse, to the very thin superconducting bridge lying on a semi-infinite substrate. Thermal boundary resistance between the film and the substrate is neglected in this model, assuming that it is compensated by lateral heat transfer in the substrate and in the film. The change in temperature of the film is described by

$$\Delta T(t) = \frac{F_0(1-R)}{(pKrc)^{1/2}} \times \int_{-\infty}^{t} \frac{\exp(-2(t'/t)^2)}{(t-t')^{1/2}} dt' \quad , \tag{1}$$

where F_0 is the maximum irradiance, R is the reflectivity and K, c and r thermal conductivity, specific heat and density of the substrate respectively (in our calculation the thermal properties of $LaAlO_3$[7] has been used).

Following the time evolution of the temperature change, and on the basis of experimentally determined resistivity vs. bias current (inset to the Figure 2) we could calculate the expected signal due to resistive bolometric response by using

$$U(t) = A \cdot I_B \cdot \Delta R(t) \quad , \tag{2}$$

where A stands for the amplification of the amplifier (in our case 530), I_B is the bias current, and $\Delta R(t)$ is the calculated resistivity change. As can be seen from the Figure 3, the temporal evolution of the expected signal (b) matches the first part of the measured one (d), however at times longer than 0.5 μs the signals are apparently different. Another important feature, that should be taken into consideration is, that the expected amplitude of the resistive bolometric response based on the model combined with the experimental data should be about 20 times larger than observed.

The second possible mechanism that should be taken into consideration is the bolometric kinetic inductance mechanism[2], which could in principle explain the negative signal in the voltage transient. The model, based on the two-fluid model, proposes that in order to sustain the constant supercurrent under light illumination (when the number of super-carriers is decreased) the remaining pairs should be accelerated resulting in an apparent kinetic inductance. During the recombination process the opposite is supposed. The measured voltage signal obtained by this model is written[2] as

$$U(t) = -A \cdot I_{\mathbf{B}} \cdot \frac{l}{wd} \cdot \frac{m_s}{q_s^2} \cdot \frac{1}{n_s^2(t)} \cdot \frac{¶ n_s(t)}{¶ t} \quad , \tag{3}$$

where A is again the amplification rate, I_B the bias current, l, w and d are the length, width and thickness of the illuminated film, m_S and q_S are the mass and charge of the Cooper pair and finally n_s is the density of the supercarriers, that can be calculated by the two-fluid model.

The temporal evolution of the expected signal due to changes in kinetic inductance, where the time evolution of the supercarrier density is governed by temperature changes through $n_s = n_{so} \cdot (1-(T(t)/T_c)^4)$, is presented in Figure 3 (line c). As can be seen, the timing properties of the expected bolometric kinetic inductance response differ significantly from the measured. Also, if we estimate the amplitude of the voltage transient expected, the obtained result (n_{s0} = 7.10^{21} cm^{-3}, m_S and q_S are taken to be the same as for free electrons) is about 1000 times lower than observed. Although the Cooper pair mass could also be substantially higher than we supposed ($m_s = 2\ m_e$) and the presence of striped phases could also significantly increase the expected signal through the decrease in effective width of the microbridge, the shape of the temporal curve clearly rules out this mechanism for the long-lived signal.

As an alternative approach, when the existence of localized states near E_F is considered[8] the physical picture is completely altered. First the electronic and phonon temperatures are not the same (non-bolometric mechanism) and clearly the electronic temperature can be substantially higher than expected[9]. This would explain the decrease in temperature rise compared to the model (if we assume that first part of the photoresponse signal is predominantly due to resistive bolometric mechanism). The existence of the localized states also explains the presence of the long-lived negative signal due to a non-bolometric kinetic inductance effect, whose amplitude could also be significantly increased by the existance of localized states.

5.CONCLUSION

The presence of a new non-trivial long-lived response in the transient photoresponse measurements presented here suggests that our understanding of the transport properties of HTS materials may be significantly improved by consideration of the contribution to the transport properties of localized states, whose existence in *the normal and superconducting* state of HTS materials now appears additionally confirmed.[8]

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FIGURE CAPTIONS

Figure 1: Schematic of the photoresponse measurement circuit.

Figure 2: The observed photoresponse signal compared to the (dashed) 200 ns laser pulse (note break in ordinate scale). Inset: Resistivity vs. temperature for the 20 mm microbridge (T_{c0}= 89 K) biased at 0.1mA, 2 mA, 5mA and 7mA.

Figure 3: The measured photoresponse (d) compared to the modeled resistive bolometric (b) and bolometric kinetic inductive (c) photoresponse, where (a) is the normalized temperature rise by the heat transfer model[6] (note break in ordinate scale). Inset: blow up the fast component.

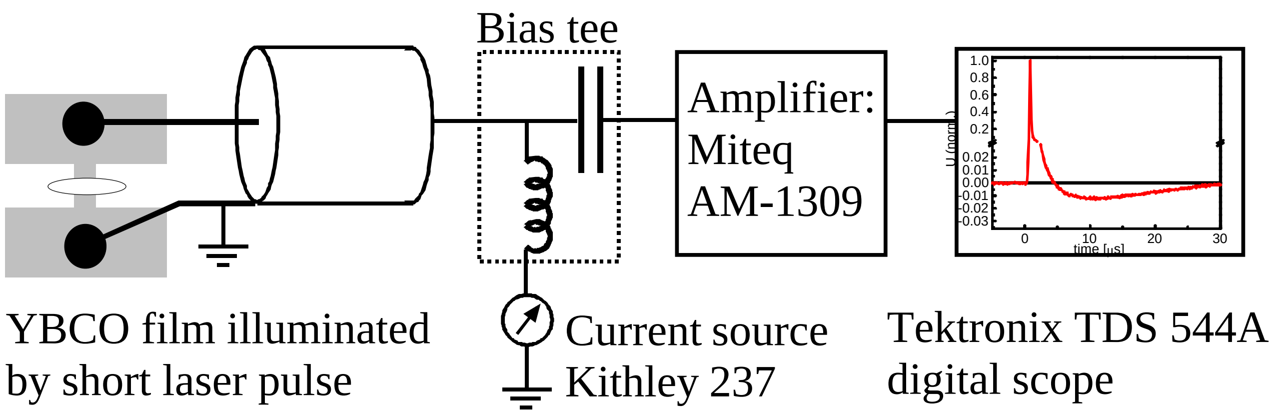

Bias tee
Amplifier:
Miteq
AM-1309
YBCO film illuminated
by short laser pulse
Current source
Kithley 237
Tektronix TDS 544A
digital scope

Figure 1

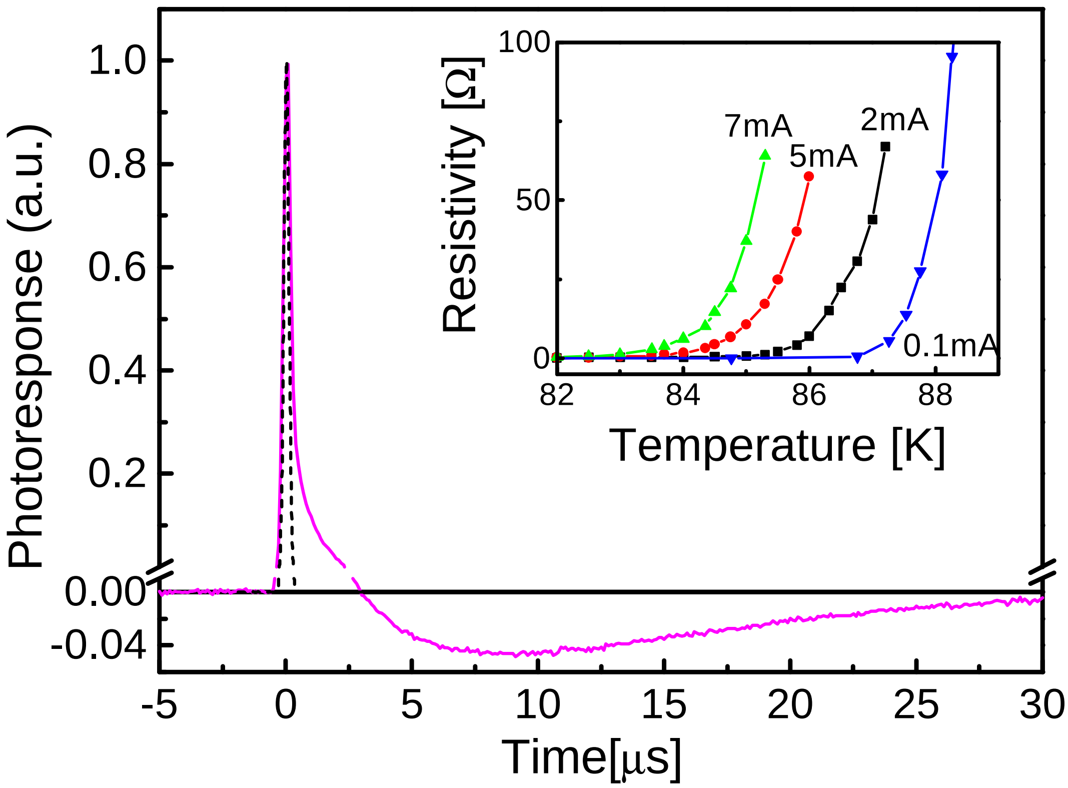
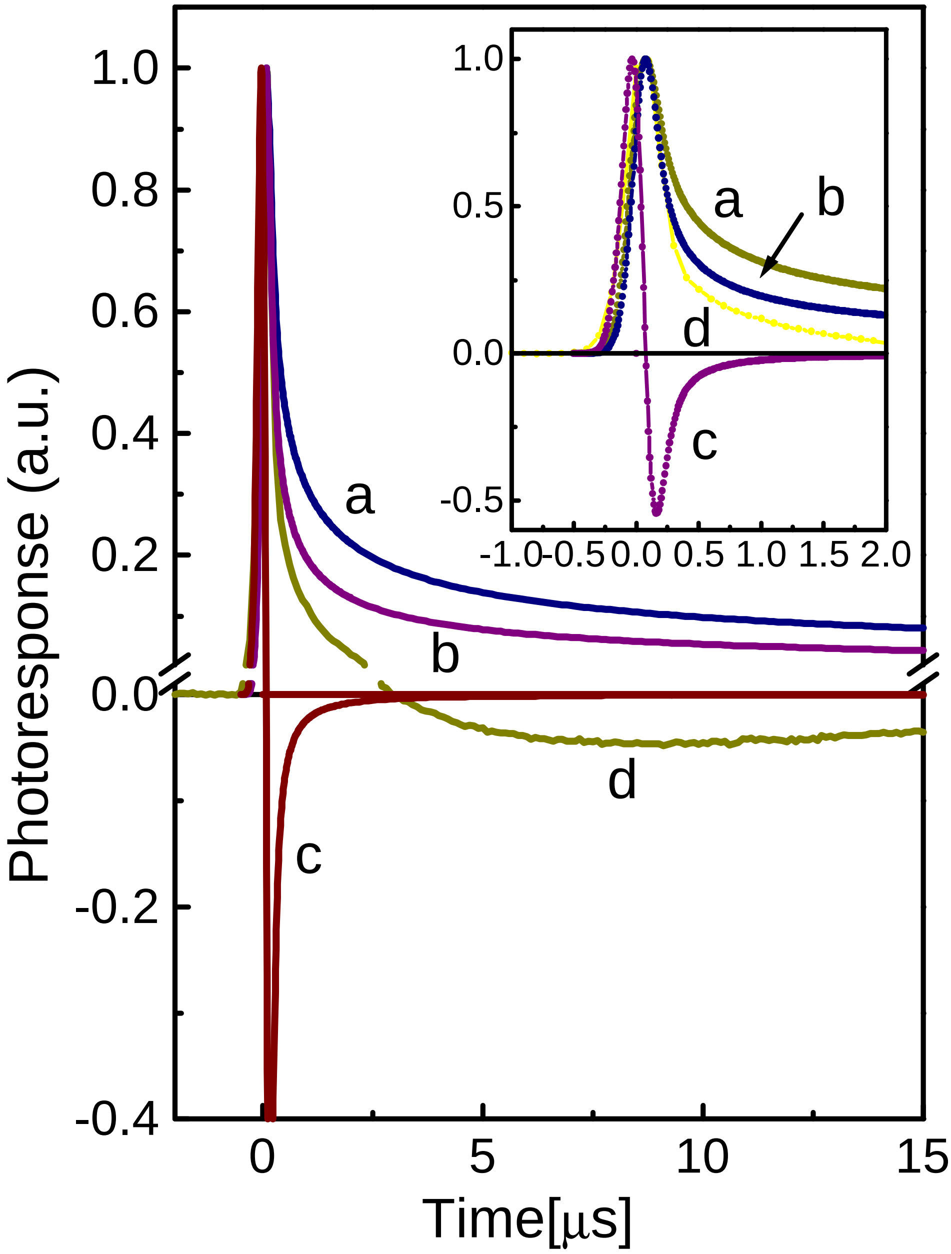

Photoresponse (a.u.)
1.0
0.8
0.6
0.4
0.2
0.00
-0.04
-5
0
5
10
15
20
25
30
Time[μs]
Resistivity [Ω]
100
50
0
7mA
5mA
2mA
0.1mA
82
84
86
88
Temperature [K]

Figure 2



1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Photoresponse (a.u.)
0
5
10
15
Time[μs]
a
b
c
d
1.0
0.5
0.0
-0.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
a
b
c
d

Figure 3

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