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Thermal Model for the Bolometric Response of YBaCuO Films on Polycrystalline YSZ at 10.6 μm Wavelength

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Abstract: Economical bolometers, using YBaCuO thin films sputtered on polycrystalline zirconia substrates, have been fabricated and tested at $\lambda = 10\ \mu\text{m}$ with a cw CO₂ laser. A 2D thermal model for the bolometric response has been developed to include the film to substrate thermal boundary resistance, and take into consideration the various heat flow regimes inside the film and the substrate. This model has been found successful to predict both the amplitude and phase components of the bolometer response with respect to the modulation signal frequency. In particular, the amplitude response, which contains a succession of f^{-1} and $f^{-1/2}$ sections separated by well-identified corner frequencies, could be quantitatively predicted in the 0.5 Hz to 100 kHz experimental frequency range.

1. INTRODUCTION

The discovery of high- T_c superconductors (HTSC) has considerably revived the interest in radiation detectors exploiting various mechanisms, ranging from the transition-edge bolometric principle to non-equilibrium photon effects. One of the earliest applications conceived for HTSC films was in fact the transition-edge bolometer, which detects infrared (IR) light by an induced temperature rise and the associated increase in film resistance. This device is relatively easy to fabricate and presents interesting performances, such as the class of "minibolometers" which has been developed at LGEP [1].

In this paper we shall present results on the elaboration and characterisation of YBaCuO thin films obtained by sputtering on low cost polycrystalline zirconia substrates (PYSZ) (partially stabilised with 3 mol % yttria), and also compare the measured optical response of bolometers at 10.6 μm wavelength with the predictions of a theoretical 2D thermal model introduced in a previous paper [2].

2. EXPERIMENTAL DETAILS

2.1 Sample preparation and characteristics

YBaCuO films were deposited on PYSZ by rf magnetron sputtering in an *on axis* configuration, under an Ar + O₂ + H₂O vapour atmosphere, at 715-725°C substrate temperature; the deposition rate was $\approx 1\ \text{nm/min}$. It was followed by an *in situ* oxygenation phase in pure O₂ atmosphere during cooling down. Four aligned electrical Au contacts were evaporated onto the YBaCuO film and subsequently annealed under flowing oxygen. The geometry of our elementary structures was a $\approx 250\ \text{nm}$ thick YBaCuO film deposited on a $3 \times 10\ \text{mm}^2$ (0.5 mm thick) zirconia slab. As shown by X-ray diffraction, the films were textured with a preferential *c*-axis orientation perpendicular to the substrate surface. Electrical transport measurements led to the typical values. $T_{R=0} \approx 85\ \text{K}$ and J_c (77 K) $\approx 6000\ \text{Acm}^{-2}$, the critical current density being limited by the granular structure of the films [3].

2.2 Experimental set-up

In our experiments, the bolometer was fixed to the cold finger of a liquid helium cryostat, inside a vacuum chamber equipped with a ZnSe optical window. Due to spurious radiations, the temperature

stability was limited to within 0.1 K. We used a laboratory made 10.6 μm wavelength CO_2 laser, delivering a maximum power of $\approx 7 \text{ W cw}$ [4]. The output beam was focused to a spot of diameter $\approx 0.5 \text{ mm}$. The laser output level could be modulated by means of a germanium acousto-optic modulator (IntraAction Corp., model GM403), allowing to chop the power delivered to the sample between 0 and P_0 at a maximum frequency of $\approx 4 \text{ MHz}$.

To detect the resistance change of the bolometer with incoming radiation, we used a four-wire arrangement, with a constant current source (Keithley, model 220) to bias the sample, and a lock-in amplifier (Stanford Research, model SR530) to deliver the amplitude and phase components of the voltage response in the 0.5 Hz to 100 kHz bandwidth. This same amplifier could be operated in a selective voltmeter mode to record the noise voltage spectrum of the sample.

3. RESULTS AND DISCUSSION

3.1 Thermal modelling approach

Thermal modelling is important to understand and predict the dynamic photoresponse (including both amplitude and phase of the detected signal) of superconducting infrared detectors. The model presented here is two-dimensional (2D), based on the experimental "hanging" configuration shown in figure 1 [2] and including the boundary thermal resistance between the film and the substrate. This configuration was devised to improve the detectivity by increasing the thermal contact resistance at the substrate/cold finger interface, following a currently adopted procedure for this family of devices [5].

The superconducting film, of length ℓ in the x direction, of width L in the y direction (perpendicular to the plane of the figure) and of thickness ε , is illuminated by the laser beam of diameter $2a$. The substrate thickness is e and the detected signal voltage contacts (V^+ and V^-) are at the distance λ from the beam axis. Current contacts (I^+ and I^-) allow to inject a bias current I_{dc} .

To solve the problem of finding the temperature distribution in both the film and the substrate, we assume i) the illumination along the Oy axis to be uniform, and ii) the thermodynamic parameters (thermal conductivity, specific heat) to be temperature independent for each medium.

The temperature distribution in the device is a solution of the coupled heat diffusion equations

$$\alpha_F \left(\frac{\partial^2 T_F}{\partial x^2} + \frac{\partial^2 T_F}{\partial z^2} \right) = \frac{\partial T_F}{\partial t}, \quad \forall z \in [-\varepsilon, 0], \quad \forall x \in [-\ell, +\ell], \quad (1)$$

$$\alpha_S \left(\frac{\partial^2 T_S}{\partial x^2} + \frac{\partial^2 T_S}{\partial z^2} \right) = \frac{\partial T_S}{\partial t}, \quad \forall z \in [0, e], \quad \forall x \in [-\ell, +\ell], \quad (2)$$

where α_F and T_F (and α_S , T_S) are the thermal diffusivity and the local temperature of the film (and of the substrate), respectively.

Five boundary conditions to solve Eqs. (1) and (2) have to be written for this problem.

Figure 1: Schematic geometry used in the thermal modelling of the "hanging slab" bolometer configuration.

i) Initial condition for thermal equilibrium at temperature T_0 (cryostat temperature):

$$T_F(x, z) = T_S(x, z) = T_0 . \quad (3i)$$

ii) Strong thermal contact between the substrate and the cryostat:

$$T_F(x = \pm \ell, z) = T_S(x = \pm \ell, z) = T_0 . \quad (3ii)$$

iii) The substrate back side is under vacuum:

$$\left. \frac{\partial T_S}{\partial z} \right|_{z=e} = 0 . \quad (3iii)$$

iv) At the film/substrate interface, the heat flow condition is:

$$-K_S \left. \frac{\partial T_S}{\partial z} \right|_{z=0^+} = -K_F \left. \frac{\partial T_F}{\partial z} \right|_{z=0^-} = h(T_S - T_F) , \quad (3iv)$$

where K_F and K_S are respectively the film and substrate thermal conductivities and h the film to substrate interface thermal conductance.

v) The superconducting film is illuminated on its front side by the time modulated laser beam:

$$-K_F \left. \frac{\partial T_F}{\partial z} \right|_{z=-\varepsilon} = \varphi(t) \psi(x) , \quad \forall x \in [-\ell, +\ell] , \quad \forall t , \quad (3v)$$

where $\varphi(t)$ represents the time dependence of the laser beam intensity and $\psi(x)$ the spatial illumination profile (see figure 2).

To obtain the voltage response of the detector in analytical form, we firstly use the Laplace transforms - with respect to the time variable - of the temperature distributions (Eqs. (1), (2) and (3i) to (3v)) to obtain an analytical solution $T_F(x, z, s)$ [6]. Secondly, we compute the inverse Laplace transform of $T_F(x, z, s)$ by the residue method to obtain $T_F(x, z, t)$. Thirdly, we assume a constant slope $dR/dT \equiv \delta r$ in the whole superconducting transition region of the $R(T)$ law and finally we integrate the fundamental component only (i.e. at frequency f) in $T_F(x, 0, t)$ between the potential contacts, to obtain:

$$V^*(t) = 4 \delta r I_{dc} \frac{\eta P_0}{\ell K_F \pi^2 a} \sum_{k=0}^{\infty} \sin C \left(\frac{(2k+1)\pi a}{2\ell} \right) \sin C \left(\frac{(2k+1)\pi \lambda}{2\ell} \right) \times \\ \text{Re} \left[\frac{\exp(2i\pi f t)}{i} \left(\varepsilon \coth C(\sqrt{v} \varepsilon) - \frac{h}{(K_F v)} \times \right. \right. \\ \left. \left. \frac{1}{\frac{h}{K_F} \varepsilon \sinh C(2\sqrt{v} \varepsilon) + (\sinh(\sqrt{v} \varepsilon))^2 + \frac{h e}{K_S} (\sinh(\sqrt{v} \varepsilon))^2 \coth C(\sqrt{w} e)} \right) \right] , \quad (4)$$

where we have defined:

Figure 2: Sketch of the simplified laser beam modulation waveform (left) and spatial profile (right). The peak power density value can be expressed as $\varphi_0 = \frac{\eta P_0}{\pi a^2}$, where η is the absorption coefficient of the YBaCuO film.

$$v \equiv \frac{2 i \pi f}{\alpha_F} + \left(\frac{(2k+1)\pi}{2\ell} \right)^2 \quad \text{and} \quad w \equiv \frac{2 i \pi f}{\alpha_S} + \left(\frac{(2k+1)\pi}{2\ell} \right)^2, \quad (5)$$

and used $\sin C(u) \equiv \frac{\sin u}{u}$, $\sinh C(u) \equiv \frac{\sinh u}{u}$ and $\coth C(u) \equiv \frac{\cosh u}{u \sinh u}$. As expected, Eq. (4) contains the characteristics of a regular bolometer, i.e. the proportionality of the output signal to i) the slope of the resistive transition δr , ii) the bias current I_{dc} and iii) the effective incident power ηP_0 .

3.2 Thermal modelling: an example

Typical plots of the amplitude and phase variations are represented in figure 3, taking account the numerical data given in table I, which are relative to sample # T77-5 (see next subsection). For the detector studied here, the model gives the following predictions, for increasing frequencies:

i) At very low frequencies, heat mainly leaks along the length of the substrate (x -axis) and, as a rule, the substrate typically behaves as a classical bolometer characterised by a weak thermal coupling. Below the corner frequency, which is $f_{c0} = \alpha_S \pi / 8 \ell^2 \approx 0.03$ Hz for this heat flow process, the amplitude is constant and the phase equals zero. Above f_{c0} , the amplitude is proportional to f^{-1} and the phase decreases towards -90° .

ii) At higher frequencies, the detector response is characteristic of a strong thermal coupling between the YBaCuO film and the thermostat [7]; heat mainly flows through the substrate thickness, along the z -axis. The corner frequency for this process is $f_{c1} = \alpha_S / \pi e^2 \approx 2.7$ Hz. Above this value, the amplitude is proportional to $f^{-1/2}$ and the phase is constant ($\approx -45^\circ$).

iii) Above $f_{ci} \approx 20$ kHz (there is no obvious expression for this frequency), the YBaCuO/substrate interface resistance plays a part in decoupling thermally the YBaCuO film from the substrate. The

Table I: Numerical values used to simulate the "hanging slab" bolometer amplitude and phase responses.

	YBaCuO film [8]	YSZ substrate [9]	Interface
Thickness	$\varepsilon = 250$ nm	$e = 0.05$ cm	-
Length	$\lambda = 0.2$ cm	$\ell = 0.5$ cm	-
Thermal conductivity	$K_F = 0.0265$ Wcm $^{-1}$ K $^{-1}$	$K_S = 0.015$ Wcm $^{-1}$ K $^{-1}$	-
Thermal diffusivity	$\alpha_F = 0.0233$ cm 2 s $^{-1}$	$\alpha_S = 0.021$ cm 2 s $^{-1}$	-
Thermal conductance	-	-	$h = 5$ Wcm $^{-2}$ K $^{-1}$

Figure 3: Theoretical amplitude (left) and phase (right) versus modulation frequency of a slab detector elaborated on 0.5 mm thick (3 mol. % yttria doped) PYSZ substrate (data taken from table I).

amplitude is proportional to f^{-1} and the phase tends again to decrease towards -90° .

iv) Above the highest corner frequency $f_{c2} = \alpha_F/\pi\epsilon^2 \approx 12$ MHz which is a characteristic frequency of the film, the amplitude is proportional to $f^{-1/2}$ and the phase which is constant equals -45° .

3.3. Hanging slab experimental results

We have studied an YBaCuO slab bolometer deposited on a 0.05 cm thick PYSZ substrate in the hanging thermal contact configuration. The working temperature was taken in the middle of the superconductive transition, where the slope dR/dT is maximum. The temperature dependence of the photoresponse for fixed power and bias current is shown in figure 4a and is compared with the derivative dR/dT of the electrical resistance of the YBaCuO film. In figure 4b we have represented the quasi-linear evolution of the detected voltage (for a fixed temperature and optical power) as a function of bias current. We can conclude that this behaviour is bolometric, as also ascertained by an observed quasi-linear dependence as a function of the incident power P_0 in the 0.1 to 15 mW range.

The amplitude and phase responses of the film were also investigated experimentally. The frequency variation of the detected signal, revealed by Bode plots (figure 5) showed a good agreement with the predictions of our theoretical model in the considered frequency range (see figure 3). However, as we were limited by the capabilities of the lock-in amplifier for the lowest (0.5 Hz) and highest (100 kHz) available frequencies, the corner frequencies f_{c0} and f_{c2} could not be observed.

From noise voltage measurements, we determined a noise equivalent power value for this detector $NEP \approx 10^{-9} \text{ WHz}^{-1/2}$ at 10 Hz. Other figures of performance are the device detectivity D^* , (defined as the

Figure 4: Cw infrared response at $10 \mu\text{m}$ wavelength for a slab YBaCuO detector in "hanging" configuration: (a) versus temperature (shown with the slope dR/dT) and (b) versus dc-bias current. (sample #T77-5).

Figure 5: Experimental amplitude (a) and phase (b) versus frequency responses of the "hanging slab" bolometer (#T77-5).

ratio between the square root of the detection area and the NEP) and the thermal time constant τ (defined as the detected signal rise time corresponding to an optical power step input). We found $D^* \approx 10^7$ cm Hz^{1/2} W⁻¹ and $\tau = 9$ ms. These values, although the best reported for granular films, still fall short off state-of-the-art performances obtained for transition-edge bolometric detectors [10].

4. CONCLUDING SUMMARY

We have developed a two-dimensional thermal model where various regimes of heat flow were considered and the contact resistance between the film and the PYSZ substrate taken into account, in order to explain both the experimental amplitude and phase variations of the voltage response. From measured characteristics on an YBaCuO film deposited on a 0.05 cm thick PYSZ substrate, the slope of the amplitude versus frequency voltage response changes, at corner frequencies ≈ 2 Hz and ≈ 20 kHz, from f^{-1} to $f^{-1/2}$ and then to f^{-1} respectively. These results are in good agreement with our 2D thermal model, although more complex device geometries will require subsequent detailed 3D modelling for their optimisation. A further step will be to introduce the penetration depth of the electromagnetic radiation in our model and so study its influence for different film thicknesses.

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