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Modelization and experiments on high T_c superconducting bolometers in the 10-90 K range of temperature

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Abstract. — As previously reported, the critical current I_c dependence *versus* optical power P in the mW range at 780 nm, with P focused on microbridges of YBCO thin films, can be calculated using simple assumptions on heat production in the superconducting film and heat conduction to the substrate. For the model was only valid on a limited range of temperature T where the thermal boundary resistance R_{bd} lying at the film-substrate interface could be taken as a constant $R_0 = 10^{-3}$ K cm²/W, we present a full model obtained by integration of the coupled Fourier equations of the temperature in the superconducting anisotropic YBCO film and in its substrate. We show that the thermal boundary resistance modeled as $R_{bd}(T) = B/T^3 + R_0$, with B/T^3 given by the acoustic mismatch model, is still limiting the heat transfer from the film to the substrate at least down to 10 K. As a consequence, the simple model that uses only $R_{bd}(T)$ and dI_c/dT is still useful and allows realistic evaluations of the current sensitivity $S_1(P, T)$ to the applied power P on the temperature range 10-90 K. Calculated $S_1(p, T)$ in the 0.1-1 A/W range agree well with those measured on YBCO/MgO or YBCO/SrTiO₃ devices.

1. Introduction.

As shown in [1], the full interpretation of light interaction with high T_c superconducting thin films is still an open problem. These authors have identified the important thermal process that occurs at the film substrate interface and which leads to thermal energy transport across the boundary in nanoseconds. This work [1] was very useful to enforce the hypothesis of the bolometric response on this time scale at the transition temperature T_c of the film, namely : YBa₂Cu₃O₇. The search of non bolometric components of the response below T_c can in principle be done *via* the current voltage (I - V) characteristic of microbridges and their sensitivities to light focused upon them provided that the bolometric component is removed. In [2] we suggested the use of the critical current (I_c) *versus* temperature (T) dependence as the thermometer needed to evaluate the temperature rise of the device exposed to light. The model

valid down to 60 K, showed no evidence of non bolometric response. We now present the results of a more detailed study, valid down to 10 K, which leads to correct estimations of bolometric effects on critical current of superconducting microbridges. Section 2 of the paper reports on sample preparation and experiments. Section 3 is devoted to the modelization of bolometric effects in the film. It includes calculations on the electric field in the $\text{YBa}_2\text{Cu}_3\text{O}_7$ film, on the associated heat production and of the temperature profile *via* numerical integration of the Fourier equations (anisotropic case) from which the modified critical current value is deduced. Finally, in section 4, we discuss the results and their implications in the observation of non bolometric effects *via* that experimental technic.

2. Sample preparation and experiments.

We have tested thin films of $\text{YBa}_2\text{Cu}_3\text{O}_7$ deposited by laser ablation on (100) MgO with a thickness of 200 nm and a high quality $\text{YBa}_2\text{Cu}_3\text{O}_7$ epitaxial layer which has been synthesised by thermal decomposition (830°) of tetramethylheptanedionates of yttrium, barium and copper in the presence of oxygen. The MOCVD equipment has been fully described [3] elsewhere. Argon is used as a carrier gas and the partial pressures of the different precursors are monitored *via* a careful control of the sources temperatures. The growth time was 10 min leading to a deposited thickness of 40 nm — as measured by alpha step — on a 1 cm^2 single crystal of SrTiO_3 cut along the (100) plane. During deposition, total and oxygen pressures are kept at constant values of 5 and 2 Torr respectively. After growth is completed, the layer is cooled down for about 20 min under 760 Torr of oxygen. The crystallographic orientation of the film has been checked by X-ray diffraction. A $\theta/2\theta$ scan showed a strong *c*-axis orientation as evidenced by the absence of any other diffraction lines apart from the 001 ones. Pole figures recorded [4] on samples grown in similar conditions showed a very good in-plane orientation. The thin films were patterned in microbridges or meanders a few μm in width using standard photolithographic technics. Contacts were taken on sputtered gold and the samples were placed on a cold finger in a windowed cryostat. The light source is a laser diode at 790 nm with a very low astigmatism ; it can be focused on microbridges (11 μm FWHM) and the spot positioning is monitored by a CCD camera mounted on binocular lenses. The total magnification is up to 2 100 with a sample to front lenses distance of 7 cm. The laser diode can be modulated at frequencies up to 200 MHz allowing the measurement of cut off frequencies. During a run of experiments, we record the critical current dependences *versus* temperature, the current sensitivity $S_1(V, P)$ as a function of applied optical power P and voltage bias V , and the cut off frequencies. Note that the measurement of S_1 is done using a low noise voltage regulation that was described in [2, 5]. This technic differs from usual practice where the devices, biased with a dc current I_b , have voltage responsivities which are strongly dependent of I_b below T_c . The measured results are reported in figure 1a and figure 1b and give critical current densities and current sensitivities as function of the temperature.

3. Model.

We first calculate the electric field distribution inside the system vacuo- $\text{YBa}_2\text{Cu}_3\text{O}_7$ substrate and its associated heat production. The values reported in [6] related to the refractive indices of the film and substrate allowed the calculation of the incident and reflected waves of electric field E^+ and E^- using the standard Maxwell theory for, at optical frequencies, the YBCO layer may be considered as a simple conductor. The electromagnetic waves that propagate along the z axis are limited to a circular Gaussian spot and, within the restriction of a normal incidence, a cylindrical coordinate system may be used. The origin is chosen at the vacuo- $\text{YBa}_2\text{Cu}_3\text{O}_7$ interface, $r = 0$ at the spot center and the z axis is directed from the top layer to the substrate. The system is invariant by rotation around z axis. The production of heat per unit of volume in

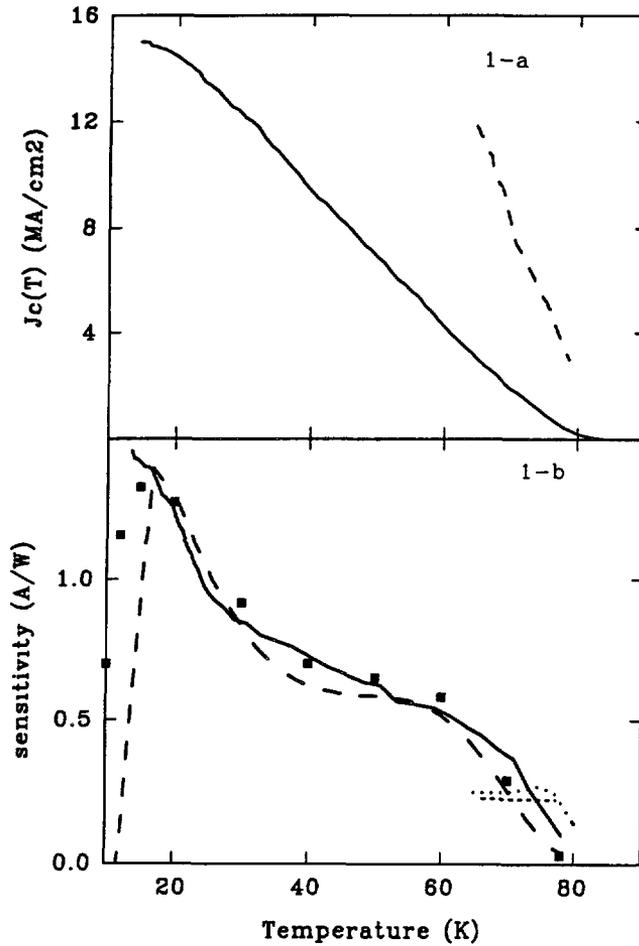


Fig. 1. — a) (—) Critical current density $J_c(T)$ of a $0.1 \times 7 \times 15 \mu\text{m}^3$ YBCO/MGO microbridge (a). (---) Critical current density $J_c(T)$ of a $0.04 \times 25 \times 100 \mu\text{m}^3$ YBCO/SrTiO₃ microbridge (b). b) (—) Microbridge (a) response. (-----) Microbridge (b) response. (■) Calculated response using the full model. (....) Calculated response using the simplified process of [2].

YBa₂Cu₃O₇ can therefore be expressed as :

$$q(r, z) = \frac{1}{2} \sigma |E^+(0, z) + E^-(0, z)|^2 \exp\left[-\frac{\pi}{4} \left[\frac{r}{r_0}\right]^2\right], \tag{1}$$

where σ is the real part of the complex conductivity found in [7], $E^+(0, z)$ and $E^-(0, z)$ are the amplitudes of the electric field waves at $r = 0$, and r_0 is the radius at half maximum of the spot. Once the calculation was done, we checked the total absorbed power was just the incident power minus the reflected and transmitted power. The Fourier equations of the system, after reduction of the cylindrical symmetry, then write :

$$\rho_f c_f \frac{\partial T_f}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r k_{ab} \frac{\partial T_f}{\partial r} \right) + \frac{\partial}{\partial z} \left(k_c \frac{\partial T_f}{\partial z} \right) + q(r, z, t) \quad 0 < z < d \tag{2a}$$

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r k_s \frac{\partial T_s}{\partial r} \right) + \frac{\partial}{\partial z} \left(k_s \frac{\partial T_s}{\partial z} \right) \quad d < z < z_1. \tag{2b}$$

The subscripts *f* and *s* refers to the film and substrate respectively ; ρ , c , k refer to the volumic mass, the specific heat and the thermal conductivity respectively, d is the film thickness and z_1 is the substrate one. Further, the subscripts *ab* and *c* in (2a) are associated to the $\text{YBa}_2\text{Cu}_3\text{O}_7$ anisotropy in the *ab* plane and along axis *c*. A good discussion of boundary conditions needed to find a solution to these equations was given for the one dimensional case, in reference [6] and we retain the following conditions.

Firstly, the thermal emission at the film surface may be neglected, as well as the heat flux entering the back of the film. Secondly, the substrate may be seen as a semi infinite medium. The temperature discontinuity at the film substrate interface is related to the heat flux through the thermal boundary resistance $R_{bd} = B/T^3 + R_0$. Here, we have assumed that R_{bd} is the simple sum of its high temperature limit and its low temperature limit in the acoustic mismatch model. From [1], we retain $R_0 = 10^{-3} \text{ K cm}^2/\text{W}$ and $B = 17 \text{ K}^4 \text{ cm}^2/\text{W}$. The equations depicting the boundary conditions are the following :

$$\left. \begin{aligned} \frac{\partial T}{\partial z}(z=0) = 0 \quad \frac{\partial T}{\partial r}(r=0) = 0 \quad \frac{\partial T_s}{\partial r}(r=0) = 0 \\ -k \frac{\partial T}{\partial z}(z=d) = -k_s \frac{\partial T_s}{\partial z}(z=d) = \frac{T(d) - T_s(d)}{R_{bd}} \\ T_s(z=z_1) = T_0 \quad T(r=r_1) = T_s(r=r_1) = T_0 \end{aligned} \right\} \quad (3)$$

with $r_1 \gg r_0$ and T_0 the thermostat temperature. The whole system of equations has been solved in the $(0, z, r)$ plane using a finite differences relaxation method. Numerical values of constants ρ , c , k at each thermostat temperature can be found in the litterature and are collected in [8]. The result is a matrix $[T_{ij}]$ of the temperatures at each point of a network covering the film and the substrate. A set of isotherm curves obtained by the method is drawn in figure 2. It clearly shows that the film temperature drops to the thermostat one in less than $2 r_0$ while the substrate temperature stays very close to the heat sink temperature. From the matrix $[T_{ij}]$, the critical current of the microbridge under light was also evaluated using the critical

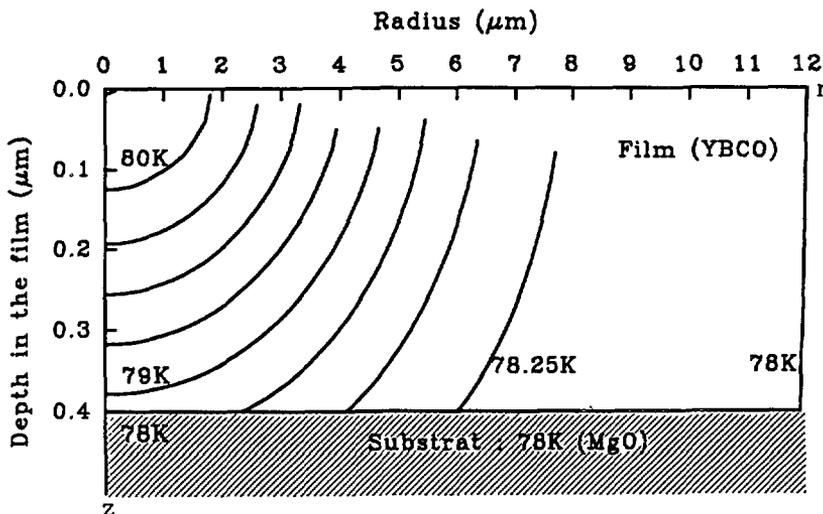


Fig. 2. — Example of isotherm curves in a YBCO film with a thickness of $0.4 \mu\text{m}$. The applied Gaussian spot has a power of 1 mW . its radius r_0 is $4.4 \mu\text{m}$. Spacing of isotherms is 0.25 K .

current density *versus* temperature dependence. The results are reported in figures 1a and 1b. It shows that the agreement between the numerical calculations and measured data is quite good. The most important result deals with the comparison between the spot size and the hot spot size in the film : as shown in the figure 3, the temperature profile follows within 1 μ the optical one in the ideal case of a rectangular optical spot. This result remains true on the whole temperature range considered. It follows that the simplified method described in [2] holds at these temperatures if the above expression of $R_{bd}(T)$ is then adopted. Results of such calculations are shown in figure 2b which agree well with experimental data.

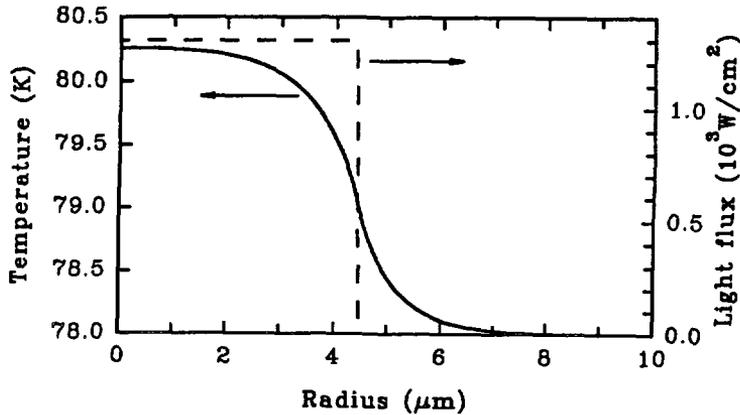


Fig. 3. — Calculated temperature distribution at the surface of a 0.4 μm thick YBCO film when receiving a power of 1 mW in a circular spot and with a uniform power flux.

4. Discussion.

The last result is important because it allows easy estimations of bolometric effects at all temperatures provided the critical current I_c *versus* temperature dependence is known. Elsewhere, the low temperature part would produce no bolometric response for the $I_c(T)$ derivative is zero so that the measure of the I_c variations under light irradiation, would lead to interesting informations on non-bolometric effects without using ultrashort light pulses. However this has never been observed since in low quality films the $I_c(T)$ derivative never goes to zero while in good quality films the critical current is so high that the measurements are unpractical. Another important point is that the method would allow the estimation of bolometric response of Josephson junctions and these experiments are under way.

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