Thermal effects in the flux-creep regime of YBa$_2$Cu$_3$O$_{7-\delta}$ thin film microbridges under high current densities in self field

To cite this article: G Ferro et al 2008 J. Phys.: Conf. Ser. 97 012016

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Thermal Effects In The Flux-creep Regime Of
YBa$_2$Cu$_3$O$_{7−\delta}$ Thin Film Microbridges Under High
Current Densities In Self Field.

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Abstract.
For currents well above the critical current density $J_c$ but below the quenching current density $J^*$ (the current inducing the full transition to the normal state), the electric field vs current density (E-J) curves may be deeply affected by self-heating effects. Until now the influence of these thermal effects on the E-J curves was mainly studied around $J^*$. Here we will first present measurements of the E-J curves in several YBa$_2$Cu$_3$O$_{7−\delta}$ thin film microbridges in the whole range between $J_c$ and $J^*$. Our results confirm that whereas $J_c$ is almost independent on the microbridge width ($w$), $J^*$ and $E^*$ strongly increase when the width decreases. It is also shown that the width dependence on the E-J curves manifests itself already for current densities well below $J^*(w)$. Then by using a finite-element method (FEM), it is shown that the measured E-J curves may be explained, from the dissipation onset ($J_c$) up to the jump itself ($J^*$), in terms of a conventional (smooth) flux-creep plus self-heating effects. An important aspect of our results is that the same flux-creep behaviour in the low dissipation regime allows us to explain the whole E-J curves in film microbridges with different widths.

1. Introduction
Measurements of Current-Voltage Characteristics (CVCs) in thin film superconductivity microbridges with width lower than their thermal diffusion length, $\lambda_{th}$, allow us to probe the relevance of self heating on the quenching to the normal state induced by applied high current densities [1, 2, 3, 4]. By using YBa$_2$Cu$_3$O$_{7−\delta}$ (YBCO) thin films microbridges, this effect was mainly studied around the quenching current density, $J^*$. The central aim of our present work is to study self-heating effects on the whole CVCs (between the critical current, $J_c$, and the quenching current $J^*$) of YBCO thin films measured between 70 K and the critical temperature, $T_c \approx$ 90 K and by applying stepped-ramps currents of 1 ms step duration. In addition to its basic interest [6], these experimental conditions should correspond to the ones of some practical use of cuprate high-Tc superconductors. This is the case, for instance, of fault current limiters operating with the commercial ac currents, i.e., having typical characteristics times around 10 ms [7]. For that we have measured the CVCs of YBCO thin films microbridges of widths 5 $\mu$m $\leq w \leq 100$ $\mu$m and compared our experimental data with simulation results obtained by using a finite element method (FEM).
2. Experimental Details

2.1. Sample preparation
The samples used in this work are epitaxial c-axis oriented YBCO thin films of thickness $d = 120$ nm which were grown onto SrTiO$_3$(100) substrates by pulsed laser ablation. The growth was monitored with a RHEED system [8]. The laser energy used was 70 mJ and the frequency of the laser pulses was 1 Hz. Deposition was done at 780 °C under 0.1 mbar of oxygen pressure for 30 min. After the deposition, the wafers were annealed at 600 °C and postannealed at 450 °C, each annealing process taking 30 min at 600 mbar of oxygen pressure. Several microbridges of widths $w = 2, 5, 10, 20, 50$ and 100 µm and width-to-length ratio 1/10 were patterned on each film by photolithography and etched with Ar ions into a four-probe configuration as can be seen in Fig. 1(a). We show one AFM image of 5 µm patterned microbridge in Fig. 1(b). The contact pads were coated with gold layers, and aluminium wires of 25 µm diameter were soldered achieving contact resistances of typically 100 mΩ.

2.2. Measurement Procedure
The CVCs at different temperatures were measured by using a commercial variable temperature cryostat with a temperature controller achieving a temperature stability better than 50 mK. The current was supplied with a sourcemeter that allows the application of dc currents either continuously or by stepped ramps of about 1 ms of step duration (Fig. 2). Sample Voltage was measured with a data acquisition card. Other experimental details are described elsewhere [1].

2.3. FEM Simulation
Some details of the FEM simulation, a more complete report of which will be published later [5], are as follows. Sample geometry is typically 10-100 µm in width with a length 10 times their width allowing us to use a 2D model. The first step in any FEM procedure is meshing the model. In our case an inhomogeneous meshing is required because the substrates size is around 5 mm width and 1 mm depth. A detail of the implemented meshing is seen in Fig. 3 where we can see, from top to bottom, the film, the interface layer and the substrate. Note that the
Figure 2. A typical stepped current ramp. $V^*$ is the voltage at which the quenching occurs (the corresponding current density is $J^*$).

Figure 3. Typical meshing of a microbridge cross section. We can see the film, the substrate and the interface film-substrate. Note that the meshing is rougher as we go farther from the film. Only half the film (here the right half) is modeled because of the mirror symmetry.

The geometrical model has been halved to save finite elements. The temperature gap at the film-substrate interface was implemented through a very thin layer of vanishing-low heat capacity. The thermal load in the simulations is the Joule’s heat rate produced by a constant current density so that what is calculated is the temperature field as a function of time. The temperature values (averaged over the film’s volume) are converted to electric field values through the assumed background of constant temperature CVCs (see later).

3. Results and Discussion
In Fig. 4 we show the electric field, E, versus the critical current density, J, curve for a 10 $\mu$m and 100 $\mu$m wide microbridges. The symbols represent the measured data at T=78.1 K. The dotted lines represent the function
Figure 4. Experimental (symbols) and simulated curve (solid line) for 10 and 100 µm microbridges at 78.1 K. Note the good agreement between experiment and simulation. Both $J^*$ and $E^*$ decrease with film’s width. The dotted lines are the background heatless CVCs. These background CVCs are, as illustrated, smoothly varying up to the normal state, but their plotting has been pruned for the sake of the clarity.

$$E(J) = E_0 \left( \frac{J}{J_c} - 1 \right)^n,$$

$E_0$, $J_0$ and $n$ being temperature-dependent free parameters determined by fitting the experimental data in the region of low $J$, well below the quench at $J^*$, where self-heating effects are negligible [1, 2]. The solid lines represents the electric field calculated by FEM (using a commercially available package).

As can be seen, our simulation accounts for the whole CVCs from the low current (heatless) range up to the quench. We must note that the simulated curves are just determined by adding to the background curves the self-heating due to the conventional (non-singular) flux creep effects. For that, following an interactive process by using standard FEM, the temperature increase of the system film-substrate due to the dissipated power $J(T)E(T)$ is firstly calculated. Secondly, at this new temperature the power dissipated is again determined by using the corresponding $J$ and $E$ values. Thirdly, the routine is continued in a feedback process [1, 5].

The results of Fig. 5 correspond to a 50 µm microbridge measured at different temperatures (from right to left 74 K, 76.5 K, 78 K, 81.2 K). As can be seen, our model also account for the temperature dependence of the CVC and in particular for both $J^*$ and $E^*$.

4. Conclusions
We have presented CVCs of $c$-axis oriented YBCO superconducting thin film microbridges of different widths. The curves are measured in the temperature range 70 K ≤ $T$ ≤ $T_c$ ≈ 90 K and from the dissipation onset at $J_c$ up to the quenching at $J^*$. By using the finite element method, it was shown that the dependence of the CVCs on both the microbridge width and temperature
Figure 5. Experimental (symbols) and simulated curves (solid line) for a 50 µm microbridge at different temperatures, (from right to left 71.9 K, 73.8 K, 78 K, 82.2 K respectively). The dotted lines are the background heatless CVCs.

may be explained in terms of conventional flux creep plus self heating effects without resorting to any “critical mode” (vortex instabilities, vortex avalanches, etc.)

Acknowledgments
This work has been supported by the Ministerio de Educación y Ciencia of Spain under project MAT 2004-04364 (FEDER), by the Xunta de Galicia under projects PGIDIT04TMT206002PR and 2006/XA049. G. Ferro acknowledges financial support from Spanish Ministerio de Educación y Ciencia through a FPI grant.

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