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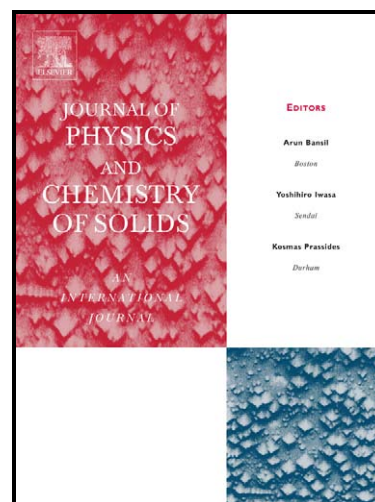
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Thermal behaviour of high-temperature superconducting fault current limiters: Application to *microlimiters*.

J. A. Lorenzo-Fernández^{1,2}, M. R. Osorio¹, J. A. Veira¹, M. J. Tello², F. Vidal¹

¹*LBTS, Departamento de Física da Materia Condensada, Universidade de Santiago de Compostela, E15782, Spain*

²*Departamento de Física de la Materia Condensada, Facultad de Ciencia y Tecnología, Universidad del País Vasco, Bilbao E48080, Spain*

Abstract

Fault current limiters are one of the most promising applications of high-temperature superconductors. Two important and interrelated aspects of these devices are their thermal behaviour and their refrigeration. Here we will present some results of our recent researches about this topic concerning the possibility of using superconducting thin-film microbridges as very efficient microlimiters intended to operate at very low powers as could be superconducting microelectronics applications (SQUID based electronics, infrared detectors, etc.).

Key words: Fault current limiters, microlimiters, thin films, refrigeration.

PACS: 85.25.-j, 74.72.-h, 74.78.-Bz

Superconducting fault current limiters (SFCL) based on high temperature superconductors (HTSC) of different types, inductive, resistive or hybrid (i.e. inductive-resistive), have been extensively studied [1, 2, 3, 4, 5, 6, 7]. The refrigeration and thermal behaviour of the superconducting elements are aspects of crucial importance for the overall performance of these devices. Thin film samples present several advantages to be used in current limiting applications [4, 8, 9]. We have studied the use of this kind of samples in two up to now nearly unexplored configurations. One is a hybrid limiting device based on meandered HTSC thin-films refrigerated by using a thermoacoustic refrigerator [10], and the other a resistive FCL based on “thermally small” superconducting microbridges [9] intended to operate at very low powers (SQUID based electronics, infrared detectors,

etc.). In this work we will summarize some of our recent results on this last issue.

In figure 1 we show a typical electric field versus current density ($E - J$) curve, corresponding to one of the microbridges (denoted BS7) used in our experiments. This microbridge, whose length, width and thickness are, respectively, 385 μm , 28 μm and 300 nm, and with $T_c = 88.6$ K, has been grown on a sapphire substrate. The two characteristic current densities are indicated in this figure: The critical, J_c , at which dissipation first appears, and the so-called supercritical, J^* , at which the microbridge is triggered into highly dissipative states. Let us note here that we have chosen for our studies microbridges of these dimensions to guarantee a good thermal behaviour before, during and after the current fault, as we will see below. In addition, the widths of our microbridges are well above the threshold at which J^* is sample-width dependent [11]. The strong increase of E for current densities around J^* make this type of

Email address: felix.vidal@usc.es (F. Vidal¹)

samples very useful for FCL. However, the current is effectively limited only for electric fields or, equivalently, applied voltages well above that at which the limiter is triggered from normal operation (sample in the superconducting state) to current fault mode. In addition, once J^* is attained, a thermal runaway [12, 13] can be provoked which causes the reduction of the circulating current well below the nominal value (i.e., the current in normal operation without a fault) or very important damage on the microbridge (that can be even burnt out).

The superconducting microbridge exchanges heat mainly with its substrate, because at the operation temperatures, around 90 K, the heat transfer coefficient between YBCO films, for instance, and their substrate is $h_{bs} \approx 10^3 \text{ Wcm}^{-2}\text{K}$, whereas through liquid nitrogen or between the substrate and the copper holder they are 1000 times less [9, 14, 15]. Hence, the conditions for a good refrigeration and, therefore, an optimal operation of the limiting device, depend very much on the relative dimensions of the microbridge and their substrate. The optimal refrigeration should allow us to operate with the minimum microbridge temperature increment relative to that of the bath, ΔT_b . If the Biot number [9, 16] of both the microbridge and its substrate are $Bi \ll 1$ and, simultaneously, the thermal diffusion length, L_{th} , is longer than the corresponding thickness, ΔT_b may be crudely approached by

$$\Delta T_b = e_b J E \left(\frac{1}{h_{bs}} + \frac{A_b}{A_s} \frac{1}{h_{sr}} \right), \quad (1)$$

where e_b is the microbridge thickness, A_b and A_s are the surface areas of the superconductor bridge and, respectively, its substrate. As $h_{bs} \gg h_{sr}$, ΔT_b will directly depend on A_b/A_s , the condition of “thermal smallness” being,

$$\frac{A_b}{A_s} < \frac{h_{sr}}{h_{bs}}, \quad (2)$$

under which ΔT_b approaches its “intrinsic” value, which is the temperature increase just associated with the effective thermal resistance of the interface bridge-substrate. For our microbridges similar to BS7 and under faults with characteristic times above 10

ms (of the order of commercial ac current periods), the conditions, $Bi \ll 1$ and $L_{th} > e$ fully apply. In addition, as $A_b/A_s \approx 4 \times 10^{-4}$ whereas $h_{sr}/h_{bs} \approx 10^{-3}$, this microbridge is “thermally small”. One may use equation 1 to estimate ΔT_b when the microbridge is in stationary conditions under currents just below J^* . From figure 1, the power density involved is around $5 \times 10^6 \text{ W/cm}^3$ which leads, by also using the appropriate parameter values¹, to $\Delta T_b \approx 0.1 \text{ K}$. Even for faults involving powers ten times higher than those considered above, ΔT_b will remain below 1 K. One may also use equation 1 to roughly estimate that if the superconducting bridge had A_b/A_s one thousand times larger, as it is the case of those currently proposed for high power applications [1, 17], ΔT_b would take values at least two orders of magnitude higher. To confirm these values at a quantitative level, ΔT_b has been calculated by using a finite element method similar to the one described in [13]. Under the same conditions as above, for the BS7 microbridge we found again $\Delta T_b \approx 0.1 \text{ K}$.

In the case of SrTiO_3 substrates, which have relatively poor thermal conductivities, the condition $Bi \ll 1$ does not apply anymore. Therefore, a term proportional to $1/k_s$ (i.e. to the thermal conductivity of the substrate) must be added in equation 1. For microbridges under the same conditions as before, this leads to $\Delta T_b \approx 2 \text{ K}$, a value that is confirmed by using the finite element method commented above. Let us stress, finally, that for a bridge on sapphire but having a surface relative to that of its substrate one thousand times larger, the finite element method yields $\Delta T_b \approx 50 \text{ K}$.

To probe a microlimiter with low thermal dimensions, we have implemented the electrical circuit schematized in the inset of figure 1, with the microbridge BS7 as R_b connected in series to the variable load resistance R_L , this last one representing the impedance of the circuit to be protected. The measurements were made in a cryostat with the sam-

¹The substrate thermal conductivities (K_s) and heat capacities (C_s) are of the order of 10 W/cm K and 0.6 J/cm³ K for sapphire, and 0.2 W/cm K and 1 J/cm³ K for SrTiO_3 , whereas for YBCO bridges $K_b \approx 0.05 \text{ W/cm K}$ and $C_b \approx 0.7 \text{ J/cm}^3 \text{ K}$. See, e. g., Refs. [14, 15, 16].

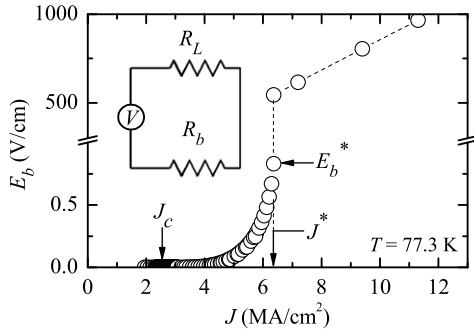


Figure 1: A typical $E - J$ curve obtained at $T = 77.3$ K in one of the microbridges used in our experiments (BS7). The inset shows a schematic diagram of the circuit used to probe how the microbridge acts as a FCL, protecting the load resistance, R_L , from a voltage fault. Figure from Ref. [9].

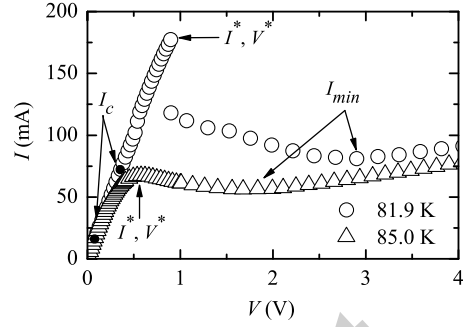


Figure 2: Two $I - V$ curves, showing their strong bath temperature dependence, of the $R_L - R_b$ circuit schematized in the inset of figure 2. In these examples R_b is the microbridge BS7 and $R_L = 4.9 \Omega$. Figure from Ref. [9].

ple submerged in a forced flow of helium gas. The temperature of the copper holder of the microlimiter was measured with a platinum thermometer and regulated with an electronic system which ensures a temperature stabilization better than 0.05 K. Two examples of the $I - V$ curves obtained in this $R_L - R_b$ circuit (with $R_L = 4.9 \Omega$, this value taking already into account the resistance of the circuit electrical wires, of the order of 1.9Ω) by using the electronic system described elsewhere [11, 12] are shown in figure 2. In these curves the voltage was imposed and acquired during pulses of 1 s, a time much longer than the one needed by the microlimiter to reach the stationary state. The bath temperatures were 81.9 K (circles) and 85.0 K (triangles). As below V^* the flux-flow resistance of the microbridge remains much lower than R_L , both curves are almost linear up to V^* . Together with the low heating estimated above, this quasi-ohmic behavior is crucial to allow the microlimiter to work just below V^* under stationary conditions and without disturbing the circuit to be protected.

The results presented in figure 2 also illustrate two other central aspects of the microbridges when working as FCL. Note first that, once the source voltage overcomes V^* , the current in the circuit varies quite slowly even up to voltage faults as important as four

times V^* , the current taking a minimum value, I_{min} , at some (temperature-dependent) voltage. Moreover, the sharp drop at V^* of the current is also temperature dependent, being almost absent in the curve at 85.0 K. Both aspects are related and may be explained in terms of the approaches based on the propagation of self-heating hot spots [18, 19, 20]: Above V^* part of the microbridge becomes normal and then, as the total voltage of the circuit is fixed, the resistance increase originates a current decrease up to the minimum current, I_{min} , capable of sustaining the normal zone. If the fault voltage increases, the hotspot length will grow accordingly, keeping the current roughly constant. At a quantitative level, both aspects may be easily explained by just taking into account the reduced temperature (T/T_c) dependence of I^* and I_{min} ,

$$I(T) = I(0) \left(1 - \frac{T}{T_c}\right)^n, \quad (3)$$

with $n = 3/2$ for I^* [11, 12] and $1/2$ for I_{min} [18, 19, 20]. Therefore, if the reduced temperature increases both the discontinuity at V^* and the ratio I^*/I_{min} will decrease, in agreement with the results of figure 2. The “optimal” reduced temperature for the microlimiter operation, T_{op}/T_c , will be then given by the condition $I^*(T_{op}) = I_{min}(T_{op})$. By using equa-

tion 3, this leads to,

$$\frac{T_{op}}{T_c} = 1 - \frac{I_{min}(0)}{I^*(0)}. \quad (4)$$

At T_{op} the current limited during the voltage fault will be roughly equal to the nominal one. As $I_{min}(0) < I^*(0)$, T_{op} will be near, but below enough, T_c to make $I^*(T_{op})$ adequate for the practical operation of the microlimiter under such an optimal temperature.

The above results, experimentally confirmed with our studies [9], allow us to “thermally tune” a superconducting microlimiter for an optimal protection. The results summarized in figure 3 were measured by using a circuit similar to that of the inset of figure 1. In these examples, R_S is again the BS7 microbridge and $R_L = 51.2 \Omega$ (taking into account the resistance of the circuit electrical wires). For the curve measured at 83.0 K, the applied voltage was 5.8 V before (t_1) and after (t_2) a fault regime of 9.5 V. For the curve at 85.0 K, which is near T_{op} , these values were 3.5 V and 7.5 V, respectively. As expected, the protection is excellent, whereas there is an overprotection when working well below T_{op} . In both cases the recovery after the fault is achieved under current. This is another considerable practical advantage when compared to the superconducting limiters used in high power applications [1, 17]. These results suggest that optimal current limitation in superconducting electronics could be accomplished by the own conductive pathways after a proper design (e. g. by decreasing the width of the pathway at well refrigerated selected locations), thus improving compactness.

We have summarized some of our works on the thermal behaviour and the refrigeration of fault current microlimiters based on HTSC thin-film microbridges. Our results indicate that by using the appropriate substrates and the right ratio microbridge-to-substrate area it is possible to operate in a regime where a relative small fault provokes their transition to highly dissipative states that strongly increase the limitation efficiency. This opens then a promising application of these *microlimiters* in microelectronics based on HTSC materials.

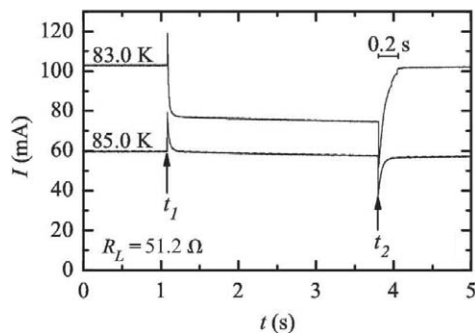


Figure 3: Two examples of the time evolution of the current measured in presence of voltage faults between t_1 and t_2 . Figure from Ref. [9].

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