Superconducting microlimiters based on YBCO thin-films grown on SrTiO$_3$ substrates

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Abstract. It has been shown recently that superconducting microbridges implemented with YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) thin-films grown on sapphire substrates could be used as very efficient fault current limiters for microelectronic devices with some elements working at temperatures below $T_{cI}$, the superconducting critical temperature, and, simultaneously, under very low power conditions (below 1 W). These so-called microlimiters are then well adapted to important applications of the superconducting microelectronics, as infrared detectors or SQUID based electronics. Here we will present new results obtained by using YBCO microbridges grown on SrTiO$_3$ substrates, which have a thermal conductivity of the order of 50 times lower than the sapphire substrates used in most of our previous work. These new measurements confirm the important role played in the behaviour of microlimiters by the thermal exchanges between the microbridges with their substrates and between these last with their environment. Our present results also show that the temperature for optimal operation of the microlimiter is substrate-dependent.

1. Introduction

In a recent work [1] we have shown that YBCO microbridges may be very efficient fault current limiters to operate at very low power (SQUID based electronics, infrared detectors, etc [2]). This high efficiency relies mainly on the fact that, in normal operation (i.e. for non-fault currents), the superconducting microbridges are in the flux-flow regime at a current close to $I^*$ [3, 4], the current at which the sample enters the normal state. The normal operation in a dissipative state (although relatively low dissipative) demands an adequate refrigeration of the microbridge for the thermal stability of both the microbridge and the circuit to be protected. In addition to the microbridge design, thin film samples refrigeration strongly depends on the thermal characteristics, mainly thermal conductivity, of the used substrates. The aim of this work is to extend our previous studies about YBCO microbridges grown on sapphire to other substrates with different thermal conductivity, in particular to substrates of SrTiO$_3$, which show a thermal conductivity about 50 times lower than that of sapphire [5, 6].
2. Experimental Details

The studied samples were microbridges obtained from thin films of high quality YBa$_2$Cu$_3$O$_{7−δ}$ grown on SrTiO$_3$ or sapphire substrates (square shaped, 5 mm side length, 0.5 - 1 mm thick). They were patterned with lengths in the range 400 - 800 μm, and widths in the range 10 - 30 μm using a standard photolithography technique. The thickness was ~200 nm for the films grown on SrTiO$_3$ and ~300 nm for those grown on sapphire. Their critical temperature, $T_{cl}$, defined as the value at which the derivative of the electrical resistivity versus temperature around the transition is maximum, is about 90 K. The samples were attached to a copper sample holder using a high thermal conductivity grease (Apiezon), and the microbridges were wire bonded to electrical contacts in the sample holder. The sample was submerged in a forced flow of He gas, and the temperature was controlled with a standard temperature controller (Oxford Instruments ITC 503).

The circuit used for the experiments consists of a programmable voltage source and the microbridge and a resistor in series (see inset of figure 1). The resistor $R_L$ represents the device to be protected from current faults.

3. Results and discussion

Figure 1(a) displays the variation of the resistivity versus temperature for the YBCO thin film grown on SrTiO$_3$. It is also indicated the critical temperatures, $T_{c0}$ and $T_{cl}$ (this last one defined by using the temperature derivative of the resistivity). The scheme of the microbridge displays its dimensions. Figure 1(b) shows the $I-V$ curve of a circuit comprising a microlimiter made with one of these microbridges (sample BS4, with $T_{cl} = 90.4$ K, and size $20 \times 800$ μm$^2$) and a resistor $R_L = 33$ Ω. The curve was acquired at a temperature of 0.93 $T_{cl}$. Each point was acquired during a DC voltage pulse of 1 s in duration, and the values of voltage and current in the circuit were measured just before the end of the pulse. This duration was long enough to ensure that the microbridge was thermally stationary when the measurements were triggered. In this figure we indicate the two relevant currents for our purposes: the supercritical current $I^*$ at which at least part of the superconducting microbridge abruptly leaves the flux-flow state and enters the normal state [4, 3], and $I_{min}$, the minimum value of the current capable of sustaining the hotspot that appears for voltages over $V^*$ [7].

For $V < V^*$ the current increases linearly with voltage because the microbridge flux-flow resistance is much lower than $R_L$: the protected device is not perturbed by the presence of the microlimiter, i. e. the $I-V$ characteristic of the circuit behaves exactly as if the microlimiter did not exist. For $V > V^*$ part of the microbridge is in the normal state and its resistance is much higher (normal state resistivity is typically 100-1000 times higher than flux-flow resistivity, see [1]), and current decreases. If the microbridge is designed so that its $I^*$ value is a bit higher than the nominal current of the protected device (i. e., the current during operation without faults) this behaviour may be used to limit fault currents very efficiently.

In figure 1 the microbridge is limiting the current more than it is necessary ($I_{min}$ is much lower than $I^*$), which may prevent the protected device from working. The device would be protected, i. e. faults would not damage it, but the supplied power would be not high enough for its normal functioning. We will say that a microlimiter is capable of optimal limitation if it verifies the condition $I^* \simeq I_{min}$. This feature would be very useful because the device could continue to work even during faults, as if nothing abnormal was happening.

Figure 2a shows the temperature dependence of the current densities $J^*$ and $J_{min}$ of microbridge BS4. The dashed lines are the least square fits to the expression

$$J = J_0 \left(1 - \frac{T}{T_{cl}}\right)^x,$$

with $x = 3/2$ for $J^*$ and $x = 1/2$ for $J_{min}$ (see [7, 8] and [3, 9], respectively), and $J_0$ as a
Figure 1. (a) Resistivity versus temperature for the YBCO thin film grown on SrTiO$_3$. It is indicated the critical temperatures, $T_{c0}$ and $T_{cl}$ (defined by calculating the temperature derivative of the resistivity). The scheme of the microbridge displays its dimensions. (b) $I - V$ curve of the circuit with the microlimiter working at temperature 0.93 $T_{cl}$. Sample used was BS4, grown on SrTiO$_3$. The inset shows the circuit schematically, where $R_L$ is a 33 Ω resistor that represents the device to be protected from faults, and $R_b$ represents the resistance of the microlimiter. The coordinates $I^*$ and $V^*$ correspond to the point at which the transition to the supercritical state occurs. $I_{min}$ is the minimum current capable of sustaining a hotspot in the microbridge.

free parameter. When the temperature is not close to $T_{cl}$ the value of $J^*$ is much higher than $J_{min}$. As said above and shown in figure 1, if the microbridge was used for current limitation at these temperatures the limited current would be much less than the nominal value, being the normal operation of the protected device impossible during fault. This behaviour changes as temperature approaches $T_{cl}$, because the relative difference between $J^*$ and $J_{min}$ decreases. We will call “optimal temperature” $T_{op}$ to the value at which the optimal limitation condition ($J^*(T_{op}) = J_{min}(T_{op})$) is verified [1]. In this way, equation 1 yields

$$\frac{T_{op}}{T_{cl}} = 1 - \frac{J_{0min}}{J_0^*},$$

where $J$ stands for current density.

Figure 2b shows data of $J^*$ and $J_{min}$ for a sample grown on sapphire substrate (sample BS6, with $T_{cl} = 88.9$ K, and size $28 \times 790 \mu m^2$). In general the currents behave like those of the microbridge grown on SrTiO$_3$. In this case it is also found an optimal temperature for which the current limited during the voltage fault will be roughly equal to the nominal one.
Figure 2. a) Values of $J^*$ and $J_{\text{min}}$ versus temperature normalized by the critical value $T_{cl} = 90.4$ K for microbridge BS4, grown on SrTiO$_3$. The dashed lines represent least squares fits to the expression $J = J_0(1 - T/T_{cl})^x$, with $x = 3/2$ for $J^*$ and $x = 1/2$ for $J_{\text{min}}$. Only $J_0$ is let to vary and its value is $J_0 = 174$ MA/cm$^2$ for $J^*$ and $J_0 = 1.9$ MA/cm$^2$ for $I_{\text{min}}$. b) Idem for sample BS6, grown on sapphire. In this case, $T_{cl} = 88.9$ K and the fit parameter is $J_0 = 90.7$ MA/cm$^2$ for $I^*$ and $J_0 = 2.9$ MA/cm$^2$ for $I_{\text{min}}$.

Let us note that the currents corresponding to these samples are around 10 mA for sample BS4 and 50 mA for sample BS6, both being high enough for many practical applications [2].

In figure 3 it is shown the quotient $T_{op}/T_{cl}$ for the whole set of studied microbridges. We observe that for the samples under study $T_{op}$ values for SrTiO$_3$ substrates are higher than when sapphire is used. However, the important point is that a lower optimal temperature would be desirable because it would allow a higher value of the nominal current in normal operation without sacrificing resistance during limitation.

From equation 2 it can be seen that a way to get a lower $T_{op}$ is to increase $J_{0\text{min}}$. This parameter may be expressed as [8]

$$J_{0\text{min}} = \sqrt{\frac{h_{ef} T_{cl}}{\rho N e_m}},$$

where $e_m$ is the thickness of the microbridge, $T_{cl}$ is its superconducting critical temperature and $\rho_N$ is the normal state resistivity. $h_{ef}$ is the effective heat transfer coefficient between the microbridge and the environment. Therefore, a possible way to increase $J_{0\text{min}}$ is, for instance, to augment $h_{ef}$. In a rough approach, $h_{ef}$ can be expressed as

$$\frac{1}{h_{ef}} = \frac{1}{h_{m-s}} + S_m R_{ts} + \frac{S_m}{h_{s-Cu} S_s},$$

where $m$ stands for microbridge, $s$ for sapphire, $C$ for copper, and $u$ for vacuum.
where $S_m$ and $S_s$ are, respectively, the surfaces of the microbridge and the substrate through which the thermal exchange takes place, $R_{ts}$ is the thermal resistance of the substrate, and $h_{m-s}$ and $h_{s-Cu}$ are the heat transfer coefficient between microbridge and substrate and between substrate and the copper holder. The typical value of these coefficients are $h_{m-s} \sim 1000 \text{ W cm}^{-2} \text{ K}^{-1}$ [10] and $h_{s-Cu} \sim 1 \text{ W cm}^{-2} \text{ K}^{-1}$ [11], and thus the first and third addends in the right hand side of equation 4 are of the order of $5 \text{ K} / \text{ W}$. Working out the value of the thermal resistance $R_{ts}$ is more tricky because the distribution of temperature inside the substrate must be taken into account. Heat is transferred into the substrate through the surface of the microbridge, and out of the substrate through its side adhered to the sample holder. The most simple geometry delimited by two surfaces of given areas is the spherical shell, of inner and outer radius $r_{\text{min}}$ and $r_{\text{max}}$, respectively. Therefore, a crude estimation of $R_{ts}$ that takes into account the distribution of temperatures may be worked out using the expression for the thermal resistance of a spherical shell:

$$R_{ts} \simeq \frac{1}{4\pi \kappa_s} \left( \frac{1}{r_{\text{min}}} - \frac{1}{r_{\text{max}}} \right),$$

with $S_m = 4\pi r_{\text{min}}^2$ and $S_s = 4\pi r_{\text{max}}^2$. $\kappa_s$ is the thermal conductivity of the substrate. From equation 5 the values of $R_{ts}$ for SrTiO$_3$ and sapphire are, respectively, $120 \text{ K/W}$ and $3 \text{ K/W}$. The values obtained with this naive approach are in agreement with more detailed calculations made using finite element methods [12]. As the dimensions of the microbridges under study are very similar, the greatest contribution to the difference of $h_{ef}$ between both materials comes from the contribution of the thermal resistance and, therefore, from their huge difference in thermal conductivity. Nevertheless, in general, the value of $T_{op}$ can also be tuned to some extent by changing the dimensions of the microbridge, which could allow in addition to set a temperature increment $1, \Delta T_b = E_J e_m / h_{ef}$, of the microbridge (relative to the refrigeration bath) to operate at temperatures closer to $T_{op}$.

4. Conclusions

We have implemented and studied the behaviour of superconducting microlimiters grown on SrTiO$_3$ substrates. By comparing with our previous results obtained on microlimiters grown on sapphire substrates, which have a thermal conductivity $\kappa_s$ about 50 times higher, our results show that the optimal operation temperature, $T_{op}$, appreciably depends on $\kappa_s$, although the
precise values of $T_{op}$ may be tuned by changing the microbridge dimensions. Our present results also suggest a way to bring the microbridge temperature in normal operation (i.e. in non-fault regime) closer to $T_{op}$.

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