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RF PROPERTIES OF LOW AND HIGH TEMPERATURE SUPERCONDUCTING FILMS

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In this paper we report on r.f. measurements performed on Nb_3Sn and $YBa_2Cu_3O_{7-\delta}$ (YBCO) films grown by sputtering in different configurations. The measurements are performed using a microstrip resonator technique. The r.f. power dependence of the surface impedance Z_s is studied at different temperatures ($4\,K < T < T_c$) and frequencies in the range 1–10 GHz. For Nb_3Sn films a set of consistent data is reported in describing the non-linear behavior observed. The nature of the breakdown field is investigated considering the effects of a d.c. field externally applied. For YBCO films, different loss mechanisms are observed, depending on the quality of the sample. The data are discussed in the context of different models, in the attempt to underline similarities and differences between Low Temperature (LTS) and High Temperature Superconductors (HTS).

Keywords: Superconductivity; Radiofrequency; Cavities; Surface impedance; Microstrip resonators

INTRODUCTION

Considerable progress has been made worldwide in the deposition of cuprates as well as intermediate T_c Nb-compounds and A15 materials for microwave applications. However, the r.f. performance

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of superconductors degrades drastically at high power. This represents one of the main limiting factors in many applications, and a deep understanding of the high power response of both low and high T_c superconductors is yet to be achieved.

The losses are usually well characterized by a residual surface resistance R_{res}, a breakdown field H_c^*, and the exponent n of the power law experimentally observed in the field dependence of the surface impedance: $Z_s(H) \propto H^n$. Considering the rich spectrum of causes for non-linearities, a good description of the loss mechanisms can be achieved only by investigation of the surface impedance dependence on several parameters, including the effect of a d.c. external field. In the case of HTS films, the comprehension of the r.f. response is also complicated by the difficulty in discriminating between extrinsic effects, connected to the morphological and structural properties of the samples, and intrinsic behavior, related to the unconventional microscopic mechanism of superconductivity in cuprates.

In this paper, we are mainly focusing on the study of the loss mechanisms observed in HTS films in comparison with LTS films, since in this last case the intrinsic behavior is well described by the BCS theory. In particular, we report on microwave measurements performed on YBCO, which appears nowadays the most promising material to use in superconducting microwave devices,[1] and on Nb_3Sn, which has attracted a renewed interest for recent results obtained on coated cavities.[2]

EXPERIMENTAL DETAILS

The investigation of the r.f. properties is performed by a microstrip resonator technique. All details are reported in Ref. [3] The advantages of this method are:

- a good spatial uniformity in the electrodynamic response observed, due to the small dimensions of the resonator ($10 \times 10\,mm^2$);
- the achievement of high magnetic fields inside the microstrip with a relatively low input power;
- the possibility of studying the dependence of R_s and X_s not only on temperature and r.f. field but also on frequency, with the measurement of higher order modes.

One of the main disadvantages is the build-up of the current at the edges of the microstrip, where a degradation of the sample can be present due to the photolithographic process.

The resonator is formed by a couple of films deposited under identical conditions, separated by a thin spacer made of sapphire (thickness $h = 125\,\mu m$) or teflon ($h = 12\,\mu m$). The width w of the microstrip can be varied between 100 and 200 µm.

The top film is patterned by standard wet photolithography in a meander line geometry ($L = 30\,mm$) yielding, in the case of the sapphire spacer, a fundamental mode at 1.4 GHz.

The measurements are performed using a network analyzer in the frequency domain. The resonator is inserted in a liquid helium dewar and the temperature varied between 4.2 K and T_c. The signal launchers are capacitively coupled to the device and adjusted in order to measure the resonator in the unloaded regime. The maximum input power is $P_{in} = 33\,dBm$, using a commercial room temperature amplifier. A pair of Helmholtz coils can be externally applied with a variable orientation, to investigate the effect of a d.c. field ($H_{d.c.} \leq 200\,Oe$) on the microwave response.

The surface resistance R_s and the penetration depth λ (proportional to the surface reactance: $X_s = \mu_0 \omega \lambda$) of the sample are related respectively to the quality factor Q and to the resonance frequency f of the resonator by the following formulas:

$$Q = \frac{\Gamma}{R_s(\coth(t/\lambda) + (t/\lambda)/\operatorname{sech}^2(t/\lambda))}, \qquad \frac{\Delta f}{f} = \frac{-\mu_0 \omega \Delta(\lambda \coth(t/\lambda))}{2\Gamma}, \tag{1}$$

where Γ is the geometrical factor of the resonator and t the thickness of the films.

The peak magnetic field $H_{r.f.}$ (Oe) is evaluated considering a phenomenological relation between the current and the field inside a microstrip:[4]

$$H_{r.f} \approx 32.54 e^{-0.6 \ln w} I, \tag{2}$$

here w is the width of the microstrip (cm) and I the total current (A), evaluated as reported in Ref. [5].

RESULTS AND DISCUSSION

(a) Nb_3Sn

In Figure 1 the r.f. field dependence of a Nb_3Sn sample, measured at different temperatures, is reported. The residual surface resistance value is $R_{res} = 1\ \mu\Omega$ at $f = 1.4$ GHz. The frequency scaling of the surface resistance at $T = 4.2$ K is almost quadratic, as expected by the BCS theory (Figure 2).

The data in Figure 1 show a quick increase of the surface impedance at low fields, followed by a nearly linear dependence. At high fields ($H_{r.f.} \approx 120-140$ Oe) "breakdown" phenomena occur with a relevant distortion of the resonant peak. As described in Ref. [3], the data are well described by the Halbritter–Portis model which assumes losses related to Josephson coupling between grains.[6,7] The quick increase at low fields is related to the flux penetration in the grain boundaries above H_{c1j}, the Josephson junction critical field.

A quantitative agreement can be found between the values of H_{c1j}, R_{res} and λ predicted by the model and the measured ones, taking into

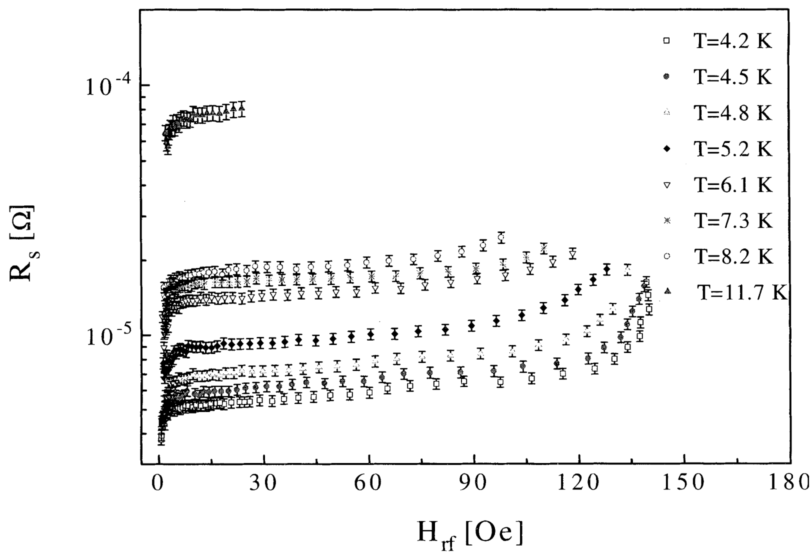

FIGURE 1 R_s vs $H_{r.f.}$ at different temperatures for the first resonant mode ($f_1 = 1.4$ GHz) of a Nb_3Sn sample.

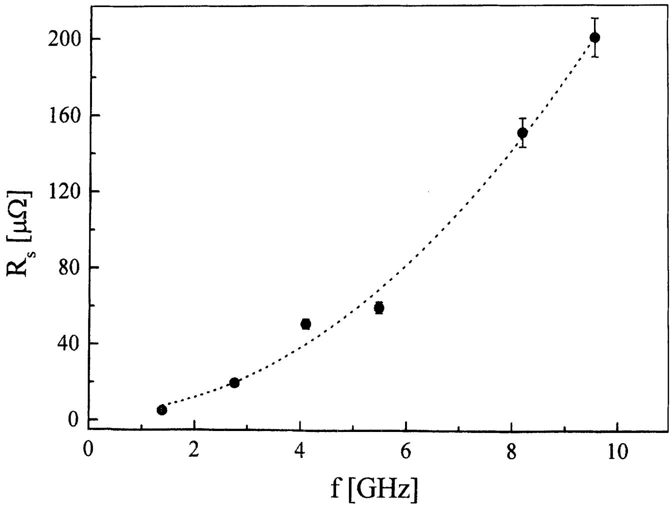

FIGURE 2 Frequency dependence of the surface resistance R_s at $T = 4.2\,K$ for Nb_3Sn. The dotted line represents the best fit of the data using the expression: $R_s = \alpha f^{\delta}$, with $\delta = 1.9 \pm 0.1$.

account the critical current density ($J_c = 5 \times 10^5\ A/cm^2$) and the averaged grain dimension ($a = 20\,nm$) as determined by experiments.[3]

As reported in Figure 3, a good consistence is observed between the "breakdown" field H_c^* as obtained increasing the input power feeding the microstrip or externally applying a d.c. magnetic field parallel to the film surface.

We believe that the nature of this field is related to the lower critical field H_{c1}, somewhat reduced by disorder effects due to the small dimension of the grains.

The temperature dependence of H_c^* in Figure 4 is well described by a linear law: $H_c^*(T) = H_c^*(0) \times (1 - T/T_c)$. A very similar behavior, likely due to the granularity of the films, is also observed in the critical current density measurements $J_c(T)$.

(b) YBCO

In case of films grown by an Inverted Cylindrical Magnetron Sputtering (ICMS) technique,[8] the dependence at low fields[9] appears very similar to what observed for granular Nb_3Sn superconductors (Figure 5).

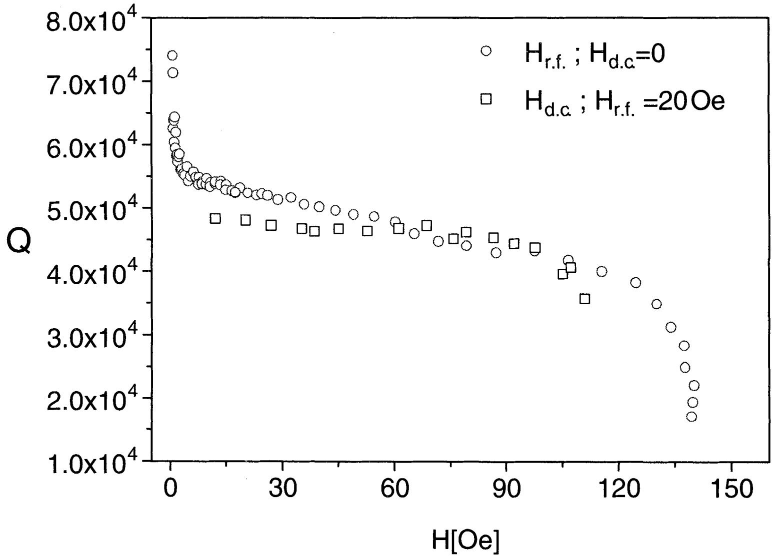

FIGURE 3 Q vs $H_{r.f.}$ (circles) and Q vs $H_{d.c.}$ (squares) at $T=4.2\,K$ for a Nb_3Sn sample. The measurements as a function of the d.c. field are performed with an input power $P_{in}=-10\,dB\,m$, corresponding roughly to $H_{r.f.}=20\,Oe$.

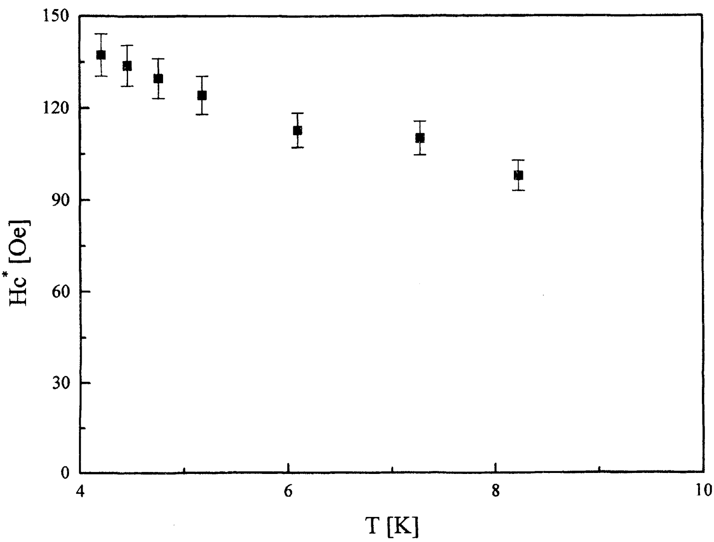

FIGURE 4 The breakdown field $H_c^*(T)$ at different temperatures evaluated by the r.f. field measurements.

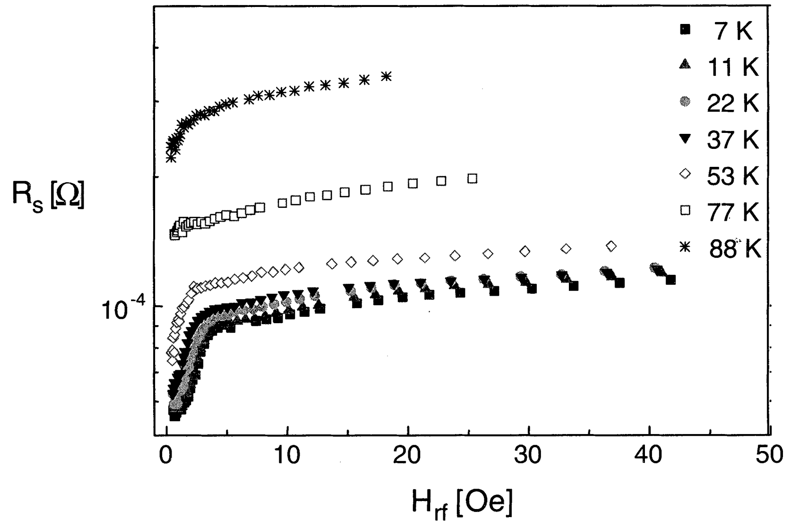

FIGURE 5 R_s vs $H_{r.f.}$ at different temperatures for the first resonant mode ($f_1 = 2.2$ GHz) for a YBCO film grown by the ICMS technique.[9]

On the contrary, the grain model is unable to describe the behavior observed on YBCO films obtained by a high pressure oxygen sputtering technique and reported in Figure 6. In this case, no relevant increase of the surface impedance was observed at low fields. The R_s vs r.f. field dependence appears flat up to $H_{r.f.} = 400$ Oe; at higher fields an almost linear increase is observed, but no breakdown effects are seen up to a maximum field higher than 800 Oe.

The residual surface resistance is lower than in case of films grown by ICMS technique ($R_{res} \approx 20\,\mu\Omega$ compared to $R_{res} \approx 50\,\mu\Omega$ at $f_1 = 2$ GHz) but higher than the best films reported in literature.[10]

Loss mechanisms related to the uniform or global heating of the sample[10] can also be excluded. A simple way to show this is to compare the R_s and X_s field dependence considering the r-factor,[11,12] defined as:

$$r_H = \frac{\Delta R_s}{\Delta X_s} = \frac{\Delta(1/Q)}{-2\Delta f/f}. \tag{3}$$

It can be easily shown that the r-factor is independent of the geometrical factor Γ and only sensitive to the properties of the superconductor.

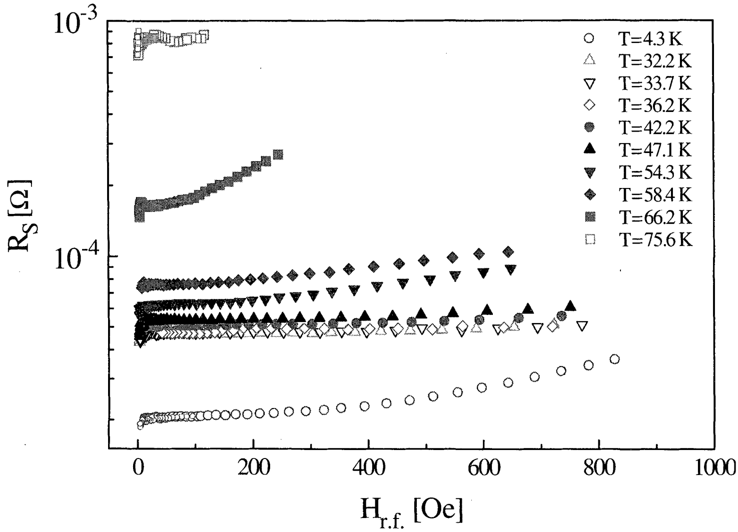

FIGURE 6 R_s vs $H_{r.f.}$ at different temperatures for the first resonant mode ($f_1 = 2.2\,\text{GHz}$) for a YBCO film grown by a high oxygen d.c. sputtering technique.

In the case of uniform heating the r_H value must be similar to what expected varying the temperature:

$$r_T = \frac{\partial Q^{-1}/\partial T}{-\partial f/2\partial T} \tag{4}$$

while the experimental data show $r_H \approx 0.6$, much larger than $r_T \approx 0.05$.

Local heating effects can also be excluded in this last case, in fact it should be $r_H \gg 1$,[12] which in our measurements is observed only on poor quality YBCO samples ($R_s \approx 1\,\text{m}\Omega$ at $f = 1.4\,\text{GHz}$).

CONCLUSIONS

R.f. measurements performed with a microstrip resonator technique on Nb_3Sn and YBCO films grown by sputtering techniques have been reported.

The Josephson junction model seems to describe the behavior of granular superconductors very well, independently of the material. In high quality YBCO films, a better understanding of the intrinsic properties is still lacking. Losses related to the heating of the sample do not seem to play a relevant role, and cannot explain the experimental data in this last case.

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