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Heating and high frequency nonlinearities in the surface impedance of high T_c superconductors

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Abstract. Using the dielectric resonator method, we have investigated nonlinearities in surface impedance $Z_s = R_s + jX_s$ of $YBa_2Cu_3O_{7-\delta}$ thin films at 10 GHz as a function of the incident microwave power level and temperature. The use of a rutile dielectric resonator allows us to measure the precise temperature of the films. We conclusively show that the usually observed increase of the surface resistance of $YBa_2Cu_3O_{7-\delta}$ thin film as function of microwave power is due to local heating.

1. Introduction

The surface impedance of High Temperature Superconductor (HTSC) materials presents a strong dependence on the magnitude of the incident microwave magnetic field, H_{rf}. A nonlinear behavior is observed above a certain value of H_{rf}. Microwave losses are characterized by a decrease of the quality factor Q and a downward shift of the resonant frequency. The surface impedance of HTSC has been studied by many groups[1-2], however the physical origin of the observed nonlinearities is still under debate and the subject of present-day experimental investigation [3-5]. It has been proposed that a simple way to differentiate among the mechanisms leading to a nonlinear surface impedance is the examination of the r parameter [6]. This quantity is defined as the ratio of the surface reactance $\Delta X_s(H_{rf})$ and the surface resistance $\Delta R_s(H_{rf})$.

In this paper, we present a study of both the temperature and the microwave power-level dependence of the surface resistance and reactance of $YBa_2Cu_3O_{7-\delta}$ thin films from various sources.

2. Dielectrics and microwave background

Measurements of the surface impedance $Z_s = R_s + jX_s$ were performed on a series of $YBa_2Cu_3O_{7-\delta}$ thin films using the dielectric resonator method [7-8]. We have used a TiO_2 resonator with a resonant frequency in the TE_{011} mode near 10 GHz. Rutile is well-known for its very low tangent loss ($\tan\delta = 10^{-5}$ at 77 K, 10 GHz) and its very high dielectric constant (ϵ = 105 at 77 K)[9].

For each sample, we measure the resonant frequency f_o and the loaded Q-factor of the fundamental resonance of the resonator. At each microwave input power level, the reflection

coefficient from the resonator, or S_{11} parameter is measured. The loaded Q-factor of the resonator is given by :

$$Q_L = \frac{f_0}{\Delta f},\qquad(1)$$

where f_0 and Δf are, respectively, the resonant frequency and the -3 dB bandwidth corresponding to the resonant peak. The unloaded Q-factor is defined by :

$$Q_0 = (1 + \beta)Q_L,\qquad(2)$$

with β the coupling constant. All measurements were performed at critical coupling $i.e$ $\beta = 1$, and the unloaded Q-factor $Q_0 = 2Q_L$. The surface resistance R_s is obtained as:

$$R_{s,YBCO} = \frac{1}{B}\left(\frac{1}{Q_0} - A\tan\delta_{TiO_2} - CR_{s,Cu}\right)\qquad(3)$$

Here $\tan\delta_{TiO_2}$ is due to the dielectric losses and $R_{s,Cu}$ to the microwave losses in the copper. A,B and C are geometrical factors calculated using a numerical simulation (HFSS software).

3. Results

In order to understand the variation of the Q-factor and f_0 with increasing microwave power, we have measured the temperature dependence of the resonator's properties. Fig 1(a) represents the temperature dependence of the TiO_2 resonator frequency in the limit of small microwave power P_{rf}, for three different configurations. In the first configuration, the TiO_2 resonator is directly placed on the copper cavity; in the second, the resonator is placed on an MgO substrate; finally the resonator is placed on the $YBa_2Cu_3O_{7-\delta}$ film, itself deposited on MgO. The absolute value of f_0 depends on the distance between the resonator and the conducting wall of the cavity, copper or superconducting layer. However, we found exactly the same temperature dependence.
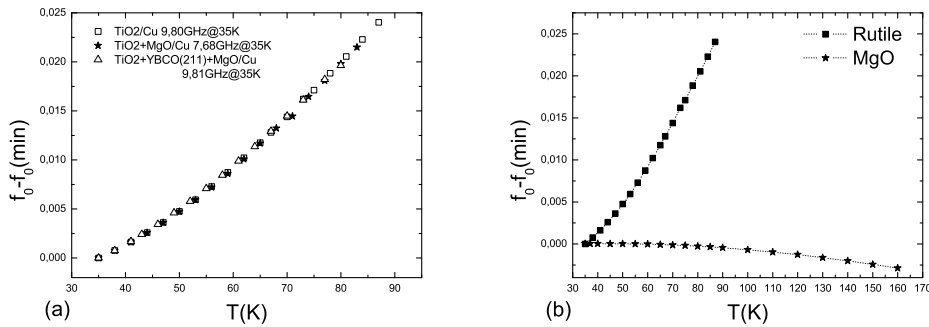

Figure 1. Plot of the resonant frequency for the TiO_2 resonator in three different configuration (1a) and resonant frequency temperature behavior of TiO_2 and MgO resonator (1b)

This shows that the thermal conductivity between the cryocooler cold head and the rutile resonator is not significantly affected by the intercalation of the 500 μm-thick MgO and the 400 nm-thick superconducting layer. Fig 1(b) represents the temperature dependence of f_0 for the rutile resonator and for a MgO resonator, which is near 8 GHz. Clearly, the variation with temperature of the MgO resonant frequency is much weaker than that of rutile. The
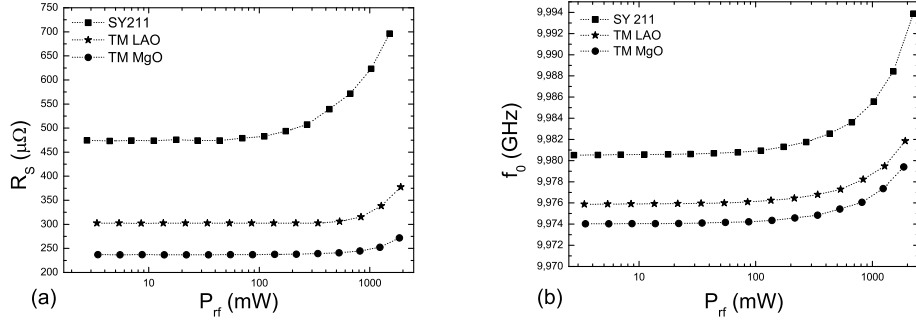
Figure 2. R_s (a) and f_0 (b) dependence of reactive microwave reactive power

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temperature dependence of frequency f_0 is the direct consequence of the increase (resp.decrease) with temperature of the dielectric constant $\epsilon(T)$ of rutile (resp. MgO).

Fig. 2 shows the dependence on microwave reactive power of R_s and f_0 for the investigated $YBa_2Cu_3O_{7-\delta}$ films at a given temperature of 74 K. The microwave reactive power is defined by $P_{rf} = P_{incident,rf} \times Q_L$. The zero power limit is taken as those values of P_{rf} below which $R_s(P_{rf})$ is essentially P_{rf}-independent. Curves for differents films present the same behavior, i.e $R_s(P_{rf})$ and $f_0(P_{rf})$ are independent of the microwave field in the zero field limit and become nonlinear (increase rapidly) above a threshold value of P_{rf}. Contrary to what is expected, the resonator frequency f_0 also increases with increasing microwave losses. We ascertain that the increase of $f_0(P_{rf})$ is due to the heating of the rutile resonator by the $YBa_2Cu_3O_{7-\delta}$ film.

In order to demonstrate this effect, we have also measured the temperature dependence of R_s and f_0 in the limit of small P_{rf} (Fig.3). The surface resistance of the $YBa_2Cu_3O_{7-\delta}$ films shows
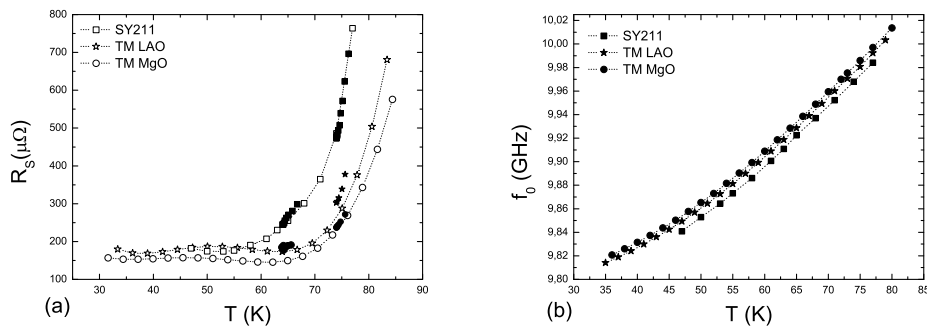

Figure 3. Temperature dependence of the R_s (a) and f_0 (b) in the regime of small microwave power

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the usual monotonous increase with temperature for all samples. Concerning the temperature dependence of the resonant frequency, we observe an increase with temperature, as discussed previously. The only observed difference is the nearly constant frequency offset between the three curves. We can now estimate the temperature of the resonator in the swept-power experiments

using the curves measured as a function of temperature. Fig. 4 shows the temperature calculated from the variation of the resonant frequency. The temperature obtained from the variation of the surface resistance gives exactly the same results. This means that no intrinsic P_{rf} dependence of R_s is measured.
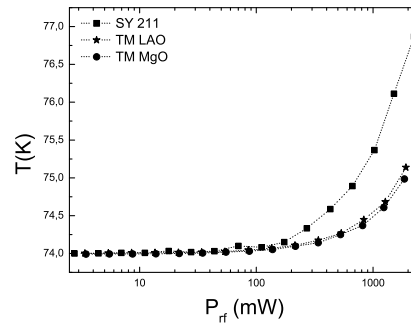

Figure 4. Estimated temperature increase as function of with reactive microwave power

In Fig 3(a) we superpose R_s as a function of the measured temperature in the low power regime and R_s measured as a function of the estimated temperature in the swept power experiments at 74 K and 63 K. A very good agreement is observed showing that any observed nonlinearity is the consequence of Joule heating.

4. Concluding remarks
The temperature dependence of the resonance frequency is the direct consequence of the increase with temperature of the dielectric constant $\epsilon(T)$ of rutile. Note that this behavior is opposite to the decrease with temperature of the dielectric constant of more commonly used sapphire or MgO resonators. Moreover, the variation with temperature of the MgO resonant frequency is much weaker than that of rutile. By consequence, it is difficult to separate the evolution of the intrinsic change of a MgO or sapphire resonator's frequency from that caused by the temperature variation of a superposed superconducting film: both weakly decrease as function of temperature. However, the intrinsic evolution of the rutile resonator's frequency being opposite to that expected from the presence of the superconducting film, the measurement of the rutile's resonator frequency can unambiguously serve as a local temperature measurement.

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