Effect of finite thickness on the surface impedance of high T_c thin films

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ABSTRACT

The effect of the finite film thickness on the microwave surface impedance is investigated both theoretically and experimentally. It was found that the surface resistance is enhanced due to the altered current density distribution in the film as well as power transmission through the film. The surface resistance of an $YBa_2Cu_3O_{7-\delta}$ thin film grown epitaxially on $LaAlO_3$ by laser ablation has been determined from data measured at 87GHz by closed cavity method. At T=77K an effective surface resistance of (30±8) mΩ was measured resulting in a corresponding value in the limit of infinite film thickness of (15±8) mΩ.

INTRODUCTION

At present a large number of experimental data for the oxide high-T_c superconductors are available [1] and the results achieved with some epitaxially grown $YBa_2Cu_3O_{7-\delta}$ thin films are very promising for applications to passive microwave components [2]. To allow the measurement data obtained with films of different thickness to be compared to each other the effect of finite thickness has to be included within the analysis. The objective of the present paper is to focus on this thickness effect by means of theoretical and experimental investigations.

To characterize the microwave properties of superconducting materials either the complex valued and frequency dependent conductivity

$$\sigma = \sigma' - j\sigma'' \quad \text{with } \sigma'' = 1/\omega\mu_0\lambda^2$$

or the surface impedance

$$Z_s = R_s + j\,X_s = \sqrt{\frac{j\omega\mu_0}{\sigma}} \qquad (1)$$

can be utilized [3]. Since the thickness d of presently available epitaxially grown high T_c films is in the order of the penetration depth λ the effective surface impedance Z_{eff} differs from Z_s ($= Z_{eff}$ for $d \to \infty$) due to both an altered current density distribution within the film and power transmission through the film. This fact has to be taken into account

(α) if the value of Z_s is to be determined experimentally e. g. from closed cavity method [5,6] or using patterned meander lines [4],

(β) if properties of microwave components (e. g. stripline resonators) composed of high T_c thin films have to be evaluated.

In the first part of this paper the relationship between Z_{eff} and Z_s is discussed and the range of validity of an approximation is outlined. These results are used in the second part of the paper to calculate R_S of $YBa_2Cu_3O_{7-\delta}$ thin films from R_{eff}. New results for the surface resistance at 87GHz of a film grown epitaxially by laser ablation on $LaAlO_3$ are presented.

THEORY

Whereas in the case of $d \gg \lambda$ the tangential part $\vec{E}_t$ of the electric field at the surface (with normal vector $\vec{n}$) is related to the magnetic field at the same point by $\vec{E}_t = Z_s(\vec{H} \times \vec{n})$, for thinner films $\vec{E}_{t1}$ at the "front surface" is not only related to $\vec{H}_{t1}$ at the same surface but also to $\vec{H}_{t2}$ at the "back surface":

$$\vec{E}_t = Z_L\,(\vec{H}_1 \times \vec{n}) + Z_t\,(\vec{n} \times \vec{H}_2) \qquad (2)$$

The impedance Z_L as well as the transfer impedance Z_t are independent of the transverse variations of the fields along the surfaces and can therefore be well approximated by

$$Z_L = Z_s/\tanh(jkd) \quad \text{and} \quad Z_t = Z_s/\sinh(jkd) \qquad (3)$$

where the complex valued wave number k is related to the surface impedance Z_s by

$$k = \beta - j\,\alpha = \sqrt{-j\omega\mu_0\sigma} = k_0\, Z_0 / Z_s \qquad (4)$$

(Z_0, k_0 : wave impedance and wave number of free space).
If the structure behind the film (e. g. substrate with metallic cover) is characterized by Z_2 with $\vec{E}_{t2} = Z_2\,(\vec{H}_{t2} \times \vec{n})$, the effective surface impedance at the front surface can be deduced from eqs.(2) and (3):

$$Z_{eff} = Z_L - \frac{Z_t^2}{Z_2 + Z_L}$$

$$= \frac{Z_s}{\tanh(jkd)} - \frac{Z_s^2}{\sinh^2(jkd)\;[Z_2 + Z_s/\tanh(jkd)]} \,. \qquad (5)$$

Note that in contrast to Z_L and Z_t the value of Z_2 is in general dependent on the transverse variations of $\vec{E}_t$ and $\vec{H}_t$ at the surface. Under certain conditions which are outlined below the second term in eq. (5) may be neglected, leading to a value of Z_{eff} which does not depend on Z_2. If additionally

$$R_s \ll X_s = k_0 \lambda\, Z_0 \qquad (6)$$

holds true, with $\lambda = 1/\alpha$ as the penetration depth, one obtains for the effective surface resistance and - reactance

$$R_{eff} \approx R_s\,[\,1/\tanh(d/\lambda) + (d/\lambda)/\sinh^2(d/\lambda)\,] \qquad (7a)$$

$$X_{eff} \approx X_s/\tanh(d/\lambda) = k_0 \lambda\, Z_0/\tanh(d/\lambda) \,. \qquad (7b)$$

The range of validity of approximation (7a,b) can be estimated by means of the inequality

$$\frac{|\delta Z|}{Z_0} > \frac{k_0^2\,\lambda^2}{\sinh^2(d/\lambda)}\;\frac{Z_0}{|\Delta Z_{eff}|_{max}} \,. \qquad (8)$$

If the error in $Z_{eff} = R_{eff} + j\,X_{eff}$ has to be less than $|\Delta Z_{eff}|_{max}$ the complex value of Z_2 has to be outside the hatched region shown in Fig.1 and with $|\delta Z|$ given by eq. (8).
If eq. (8) does not hold, the value of Z_{eff} according to eq.(7a,b) is changed by:

$$\frac{\Delta Z_{eff}}{Z_0} = \frac{(k_0\lambda)^2 Z_0}{\sinh^2(d/\lambda)\;[Z_2 + R_L + jX_L]} \qquad (9)$$

The strongest effect on the effective surface resistance R_{eff} results if $X_2 = -X_L$. In this case which e. g. arises for a resonant structure behind the film the increase in R_{eff} caused by power transmission through the film is given by

$$\frac{\Delta R_{eff}}{Z_0} = \frac{(k_0\lambda)^2 Z_0}{\sinh^2(d/\lambda)\, R_2} \qquad (10)$$

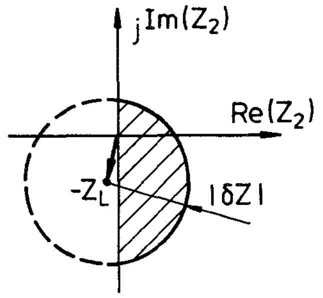

Fig. 1
Range of validity of eqs. (7a,b).
The value of Z_s has to be outside the hatched region, $|\delta Z|$ is given by eq. (8).

APPLICATION TO THE CHARACTERIZATION OF THIN FILMS FROM CAVITY MEASUREMENTS

The analysis described above is a necessary requirement for the correct experimental determination of the surface impedance of high T_C thin films. For that purpose epitaxially grown thin films prepared by excimer laser ablation have been provided by Siemens Research Laboratories, Erlangen. It has already been shown that for such films on $SrTiO_3$ the surface resistance R_S and the magnetic field penetration depth λ in the limit of infinite film thickness can be determined from the measured surface impedance [6]. Here first experimental results for a film on $LaAlO_3$ are presented.

The resonant cavity is sketched in Fig.2. The film sample is mounted as an endplate to the cavity which can be excited in the TE013 mode at 87GHz. A more detailed description of the cavity and the measurement technique is presented elsewhere [5]. Since the permittivity of $LaAlO_3$ is 25, the impedance Z_2 is in good approximation independent of transverse variations of $\vec{E}_t$ and $\vec{H}_t$ at the surface. The surface impedance of the copper disc which is pressed to the film sample from the reverse side was measured seperately. The actual value of the substrate thickness rules out resonances in the substrate. Fig.3 shows R_{eff} as a function of R_S calculated by two numerical impedance transformations for different values of the film thickness at a frequency of 87GHz, ε_r=25, $\tan\delta=10^{-4}$ and λ=260nm corresponding to $LaAlO_3$ and $YBa_2Cu_3O_{7-\delta}$ at T=77K. The parallel displacement of the curves arises from the altered current density within the film as described by eq.(7a). Transmission losses represented by the constant offset values $R_{eff}(R_S=0)$ are a neglegible contribution to R_{eff} for realistic R_S values of $>10^{-4}\Omega$ as expected from eq.(8). Therefore, in contradiction to films on $SrTiO_3$, R_S can be determined unambigiously from R_{eff} and d/λ independently of the precise ε_r and $\tan\delta$ values of the substrate.

Fig.4 shows the measured R_{eff} values as a function of temperature and the corresponding R_S values calculated by inverting two impedance transformations. Therefore some input data were required. For the normal conducting state the normal skin effect i.e. $R_S=X_S=(\omega\mu_0\rho/2)^{1/2}$ holds true, for the superconducting state $\lambda(0)$=150nm and $\lambda(T)/\lambda(0)$ from weak coupling BCS theory in the clean limit is in good agreement to $\lambda(T)$ data determined from the effective surface reactance of the same sample [7]. Finally the film thickness d=(170±10)nm was determined after patterning the film. From R_s(100K) a dc resistivity ρ(100K) of (85±10)$\mu\Omega$cm was calculated being in good agreement to a dc resistance measurement. At T=77K R_{eff} =(30±8)mΩ and R_S =(15±8)mΩ, the latter being close to the best value of 8mΩ obtained with a film grown on $SrTiO_3$ [5,6].

Alternatively to the characterization by the surface resistance R_s and the penetration depth λ the material can also be described by the complex valued conductivity $\sigma = \sigma' - j\sigma''$. From eq.(1) and with $\sigma' << \sigma''$ one obtains for the real part

$$\sigma' \approx \frac{2\,R_s}{\omega^2\mu_0^2\,\lambda^3} \quad . \qquad (11)$$

With the data from Fig. 4 and λ(77K) ≈ 260 nm one finds

$$\sigma'(77K) \approx 4\cdot 10^6 \ \ 1/\Omega m \ .$$

Since σ' can be expected to be nearly frequency independent it offers some advantages, if it is used instead of R_s to characterize the rf dissipation in the material. On the other hand, the determination of σ' requires both the value of R_s and λ to be known.

The imaginary part of σ is directly related to λ. Taking λ to be independent of the frequency one obtains for the material from Fig. 4

$$\sigma''(77K) \approx \frac{2000}{f/GHz}\cdot 10^6 \ \ \frac{1}{\Omega m} \ .$$

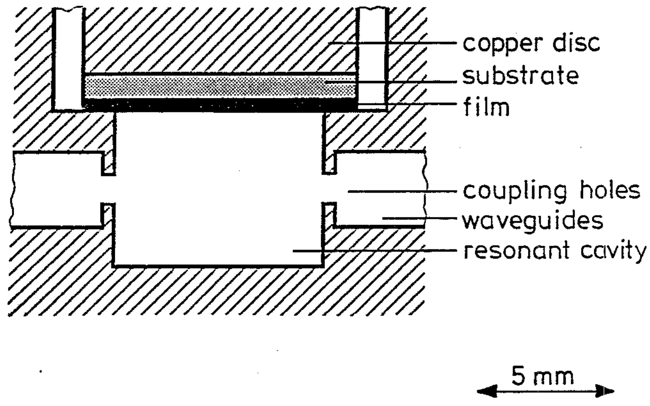

Fig.2
Cross section of the cylindrical microwave copper cavity for measuring the effective surface impedance of high T_c thin films.

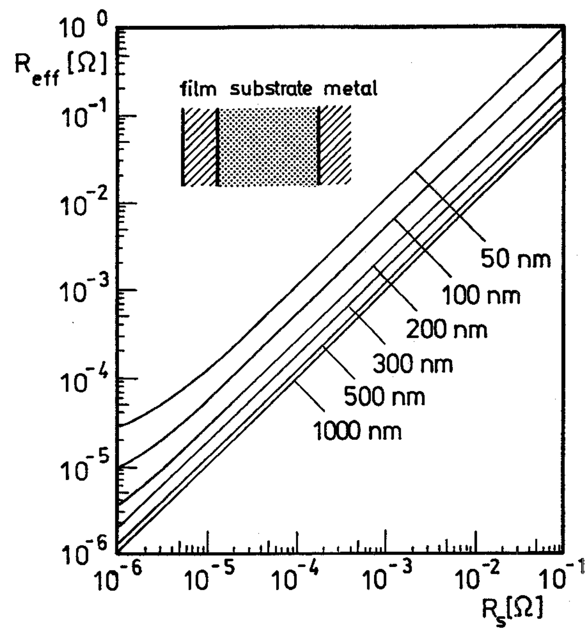

Fig.3
R_{eff} versus R_S calculated by two impedance transformations for ε_r=25, $\tan\delta=10^{-4}$ and λ=260nm for different values of the film thickness d.

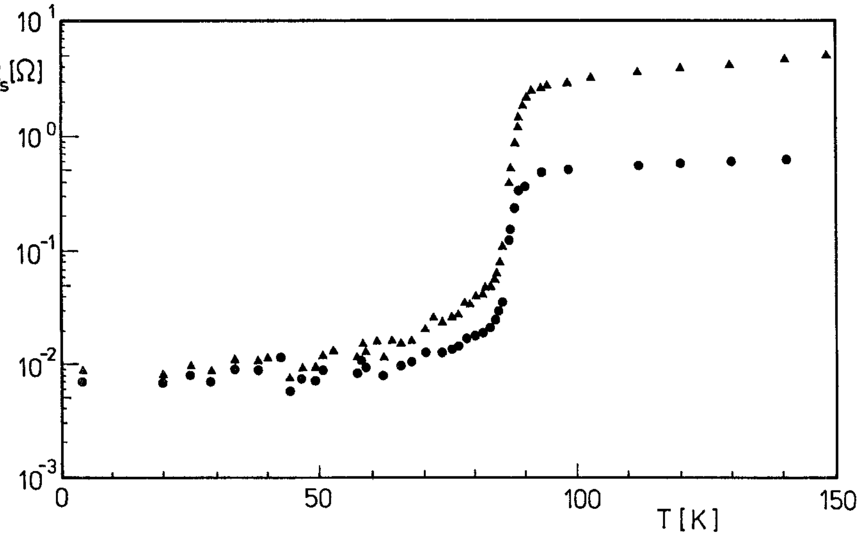

Fig.4
Measured R_{eff} (triangles) and R_S(circles) determined from R_{eff} as a function of temperature for a film on $LaAlO_3$ with d=270nm.

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