Proceedings of the Fifth Workshop on RF Superconductivity, DESY, Hamburg, Germany

*invited review talk presented at the*
*"5 th Workshop on RF Superconductivity"*
*Hamburg, Germany, August 19th–24th, 1991*
*Proc. ed. by D.Proch, DESY*

# HIGH $T_C$ MATERIALS FOR MICROWAVE APPLICATIONS: UPDATE ON ACTIVITIES, PROGRESS AND TRENDS

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## 1. Introduction

This year we celebrate the 5th anniversary of the discovery of high temperature superconductors (HTSC) by Bednorz and Müller [1]. Even after this short period of time we already have the first prototypes for applications. These are passive microwave devices and Josephson tunneling devices.

Since the 4th Workshop on RF Superconductivity in Tsukuba [2] no progress has been achieved in finding superconductors with higher critical temperatures $T_C$. The highest $T_c$ of 125K was reported for the $Tl_2Ba_2Ca_2Cu_3O_{10}$ compound [3]. For applications in passive microwave and tunneling devices the $ReBa_2Cu_3O_7$ (Re=rare earth=Y,Eu,etc.) compound is the most important one [4]. As will be discussed in chapter 4, the $Tl_2Ba_2Ca_1Cu_2O_8$ compound with a $T_c$ of 108K is an interesting alternative to $YBa_2Cu_3O_7$ for microwave applications. However, the $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ compounds with n=2 and 3 [5,6] are of great importance for the fabrication of HTSC wires.

Since the 4th Workshop a lot of progress has been achieved in the preparation of films, mainly of $YBa_2Cu_3O_7$. First, these are c-axis oriented, granular thick films on large area polycrystalline substrates and epitaxial c-axis oriented thin films on singlecrystalline substrates. Both are important for microwave applications and will therefore be discussed in chapter 2. Even more progress has been achieved in the fabrication of a-axis oriented films, epitaxial multilayers, super-normal-superconductor (SNS)-junctions and artificial grain boundaries [7]. These rapidly developing techniques have already resulted in HTSC-SQUID's (superconducting quantum interference devices) with a performance at 77K good enough for biomagnetic applications [8].

From the point of view of basic understanding of HTSC, we know that, roughly speaking, staggered $CuO_2$ layers, doped by positive charge carriers (holes) from the remaining part of the crystal [9], are responsible for superconductivity in the cuprates. However, open questions still remain about the pairing mechanism. Recent theoretical studies in connection with a large variety of experimental data have shown that the electron-phonon interaction plays at least an important role [10].

This article is not a complete review of the microwave properties of HTSC. This has been done in a very detailed manner by G. Müller in the Proceedings of the Tsukuba Workshop [11] and, in addition, by H. Piel and G. Müller at the Applied Superconductivity Conference last year [12]. Besides giving an update about recent results on the microwave properties of HTSC, I will discuss the different film deposition techniques and substrates with respect to the microwave properties as well as measurement techniques for the surface impedance of planar HTSC samples.

## 2. Film preparation techniques

One important consequence of the layered structure of the cuprate superconductors is a high degree of anisotropy of many physical properties. The penetration depth and the coherence length are the most relevant ones with respect to the microwave properties. For $YBa_2Cu_3O_7$ the penetration depth $\lambda$ at zero temperature is about 130nm in the a-b direction and a factor of 5 higher in the c direction [13]. According to the two-fluid model the surface resistance scales like $\lambda^3$ (see eq. 8 in chapter 4) indicating that c-axis oriented films are desired for microwave applications. The coherence length is about 2nm in the a-b and only 0.4nm in the c-direction [15]. These values are of great importance for the surface resistance at low temperatures, since in niobium, for example, the proximity effect reduces residual losses from material imperfections and allows nanoohms to be obtained in the GHz range at low temperatures [16].

Fortunately, the cuprate superconductors have a tendency to grow on smooth substrates with their c-axis perpendicular to the surface. This only holds true if a deposition technique is used where single atoms or clusters of atoms are deposited. The deposition of micron-sized grains, however, as used in many thick film techniques, does not automatically lead to a high degree of c-axis orientation.

The film deposition techniques available up to now can be distinguished as follows: first, the thick film techniques, starting from reacted powders of the superconducting phase. The most important techniques are the screen printing [17,18] and the electrophoresis technique [19,21]. All these techniques lead to

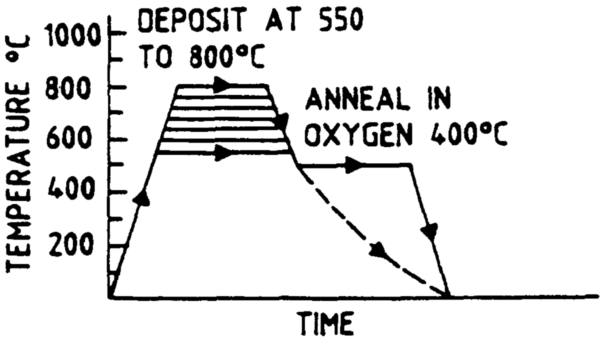


Figure 1
*In-situ* preparation of epitaxial $YBa_2Cu_3O_7$ films (from [88])

polycrystalline, i.e. granular films. As show by Hein et al., the size of the grains can be controlled by the parameters of the sintering process [20]. Recently, Alford et al. from ICI prepared thick films with c-axis oriented grains as large as $50\mu m$ by making use of a melt texturing in a sintering process at temperatures above the peritectic temperature of $YBa_2Cu_3O_7$ [17]. To improve the degree of c-axis orientation, the anisotropic paramagnetic properties of the $YBa_2Cu_3O_7$ crystal can be used to orient the powder already during deposition. This has been demonstrated by Hein et al. by performing the electrophoretic deposition in a high magnetic field [21]. Generally, thick film deposition techniques allow the deposition of granular c-axis-oriented films on large and curved substrates. Therefore they are useful for cavity resonator applications.

Secondly, epitaxial thin films are more important for planar microwave devices. They can only be grown on oriented surfaces of some single-crystalline substrates as discussed in the next chapter. The most relevant deposition techniques are the following: pulsed laser deposition, single target sputtering, thermal or electron beam evaporation, and metal-organic chemical vapor deposition. All these processes are carried out *in situ* according to Fig.1. Deposition is carried out in the phase stability region of the tetragonal phase $YBa_2Cu_3O_{7-x}$ with $x=0.5-1$ which is, depending on the oxygen pressure, between 650 and 850°C. In addition, a subsequent oxygen loading at about 500°C is required to form the superconducting $YBa_2Cu_3O_7$ phase. For the Tl compound *in-situ* processes are not yet possible, since Tl is volatile at the deposition temperature and has to be "loaded" after deposition under thermal equilibrium conditions. Therefore these films are always granular.

Since some review articles have already been written about the different deposition techniques [22,23], I will only show some distinguishing properties of the $YBa_2Cu_3O_7$ films prepared by the different techniques which may be relevant for microwave applications. First, for laser deposition, sputtering and evaporation techniques $T_C$-values as high as 91K and critical current densities as high as $5 \cdot 10^6$ A/cm$^2$ at 77K and about one order of magnitude higher at 4.2K have been obtained. The CVD technique, which is at an earlier stage of development, is now approaching these results [24,25]. Secondly, the surface quality is different. Smooth films without precipitates were first prepared by sputtering [26] and by evaporation [27]. Finally, the crystalline perfection differs for the different preparation techniques. In this respect, the sputtering technique has provided the best results to date as reported by Poppe et al. [26]. A disadvantage of the sputtering process, however, is deposition rates much lower than for the other techniques, especially for the laser deposition technique. Large films are most favored for the sputtering techniques [28]. Presently, the possible size of epitaxial films is limited to about 5cm diameter by the available substrates. The CVD process is most favored for deposition on curved substrates, although this has not been demonstrated yet. Laser and sputter deposition techniques have been used for the deposition of films of the Tl compounds [28,29].

Table 1 shows the most commonly used substrates for epitaxial films in the order of their lattice mismatch to $YBa_2Cu_3O_7$. The high $T_C$-values and critical current densities mentioned before have been achieved for all substrates except sapphire, $Zr(Y)O_2$, and silicon. For a long time $SrTiO_3$ was the most favored substrate because of the small lattice mismatch and good quality of the polished surfaces. However, the high $\varepsilon_r$ and tan$\delta$-values of $SrTiO_3$ make it useless for most microwave applications. For the latter the most commonly used substrates are $LaAlO_3$ and MgO. Since the lattice mismatch for MgO is quite big a high density of 45$^\circ$ grain boundaries often occurs in the films, but they can now be avoided [37]. The surfaces of the $LaAlO_3$ and $LaGaO_3$ substrates consist of slightly tilted twin lamellas with typical sizes up to a few millimeters. Although that does not affect the quality of the films, it may become a drawback for future microstrips with very thin dielectrics. $NdGaO_3$ is quite a new substrate material with very promising features. It is untwinned and has the smallest lattice mismatch with respect to $YBa_2Cu_3O_7$, and therefore the crystalline quality of the films is very good [38]. However, the dielectric losses are significantly

| chem. comp. | lattice parameter [Å] | $\varepsilon_r$(5-10GHz, 300K) | tanδ (77K, 10GHz) | remarks |
|---|---|---|---|---|
| $YBa_2Cu_3O_7$ | a=3.827<br>b=3.877 | | | |
| $NdGaO_3$ | a=3.837<br>b=3.889 | 23 | $3.24 \cdot 10^{-4}$ | untwinned |
| $SrTiO_3$ | a=b=3.905 | 300 | $1 \cdot 10^{-4}$ (90K, 1.3GHz) | paraelectric |
| $LaAlO_3$ | a=b=3.793 | 24 | $7.6 \cdot 10^{-6}$<br>$6 \cdot 10^{-5}$ (10GHz,77K) [35] | twinned |
| $LaGaO_3$ | a=3.885<br>b=3.903 | 25 | $10^{-3}$ (10GHz, 300K) [31] | twinned |
| MgO | a=b=c=4.213 | 10 | $6.2 \cdot 10^{-6}$ | |
| $YAlO_3$ | a=5.179<br>b=5.329 [36] | 16 | $1.2 \cdot 10^{-5}$ | |
| $Al_2O_3$ (sapphire) | a=b=4.758<br>[31] | 9.4-11.4<br>[33] | $10^{-7}$ (~GHz,77K [35])<br>[34] | diffusion<br>→ buffer |
| $Zr(Y)O_2$ | a=b=c=5.140<br>[31] | 29 | $7.4 \cdot 10^{-4}$ | |
| Si | a=b=5.431<br>[31] | 12 [31] | $<10^{-4}$ (10GHz, 300K) [31] | diffusion<br>→ buffer |

Table.1: Most important substrates for the epitaxial growth of HTSC thin films. The structural and dielectric data are from ref.30 and 32, respectively.

higher than for $LaAlO_3$ and MgO (see [38] and table 1). A lot of progress has been achieved in making films on sapphire, which is, because of its low loss tangent of $10^{-7}$ at 77K, the most favored material for many microwave applications. Buffer layers of $Zr(Y)O_2$, MgO or $SrTiO_3$ have to be used to avoid the diffusion of aluminium into the film. The growth of high quality epitaxial films on silicon is still one of the biggest challenges for two reasons. First, in order to build integrated active semiconductor devices (e.g. FET-microwave oscillators) with HTSC passive network. The second aspect is a defect density of the order of one per $cm^2$ for silicon, which up to now is about three orders of magnitude better than for all other HTSC substrates. However, the high preparation temperature required as yet for the growth of $YBa_2Cu_3O_7$ films causes a diffusion of silicon into the $YBa_2Cu_3O_7$ which degrades the film properties. Recently, films on silicon-on-sapphire using $Zr(Y)O_2$ as a buffer layer exhibited a $T_c$ of 88K and a critical current density of $4.6 \cdot 10^6 A/cm^2$ at 77K [39]. First results on the microwave surface resistance of both films on sapphire and on silicon will be shown in chapter 4.

## 3. Surface impedance measurement techniques

Since the discovery of HTSC a large variety of techniques have been developed to measure the surface impedance $Z_s=R_s+iX_s$ of HTSC samples. This is, generally speaking, the more complicated the lower the surface resistance $R_s$ and the smaller the samples are. Especially for thin films and single crystals it is not possible to build a complete cavity resonator out of the material to be investigated. There are two approaches ( 1 and 2) each with many different versions to measure the surface impedance of planar HTSC samples in the microwave range. In addition to that, submillimeter wave techniques (3) are also listed.

1 cavity and quasioptical resonator techniques [54]
1.1 endplate replacement of a $TE_{0np}$ cylindrical cavity resonator [41-43] (Fig.2)
1.2 shielded dielectric resonators [44-46] (Fig.3)
1.3 separately heated samples in superconducting host cavity resonators [47-50] (Fig.4)
1.4 $\lambda/2$ and $\lambda/4$ TEM niobium cavity resonators [51, 89]
1.5 quasioptical resonators [52, 53] (Fig.5)

2 planar resonator techniques [40]
2.1 parallel plate resonators [37,55]
2.2. coplanar resonators [56,57] (Fig.6a)
2.3. stripline and microstrip resonators [58,59] (Fig.6b)
2.4 planar lumped circuit resonators [60] (Fig.6c)

3 submillimeter wave techniques
3.1 picosecond pulse propagation [61,68]
3.2 non-resonant transmission (and reflection) measurements [62]

Table 2: Measurement techniques for the surface impedance of HTSC films.

Re 1.1:

The endplate replacement of a cylindrical cavity excited in a $TE_{011}$ mode is a widespread technique. In some cases higher order $TE_{0np}$ modes are used to improve the sensitivity as in Klein et al. where both the $TE_{013}$ and the $TE_{021}$ mode are used for different ranges of $R_s$ values (Fig.2) [41]. For $R_s$ measurements the sensitivity is limited by losses in the metallic walls of the cavity, which in most cases is made of high purity copper. In addition to these highly reproducible losses, undefined losses arise from small rf currents flowing across the joint between the sample and the cylinder walls [63] . Although they should be zero in the $TE_{0np}$ modes in cylindrical cavities, they may occur due to symmetry-breaking pertubations like coupling holes, etc. The typical sensitivity of this method is a few milliohms in the range between 50 and 100GHz. By using a niobium $TE_{011}$ cavity a sensitivity of $\pm 50\mu\Omega$ was achieved at 21.5GHz [42].

Re 1.2:

Our own approach to improve the sensitivity of the endplate replacement technique is shown in Fig. 3 [44]. The sapphire disk concentrates the electromagnetic field lines on the surface of the sample under investigation and reduces parasitic losses both from the other cavity walls and the joint. The obtained sensitivity is about $\pm 50\mu\Omega$ at 18.7GHz, which is as good as for the niobium cavity reported in 1.1. However, due to higher quality factors the niobium cavity technique allows the determination of the rf power dependence of $R_s$ at 4.2K for samples with a diameter of about 2.5cm, whereas our dielectric resonator technique allows the determination of $R_s(T)$ of samples as small as $1cm^2$ up to $T_c$.

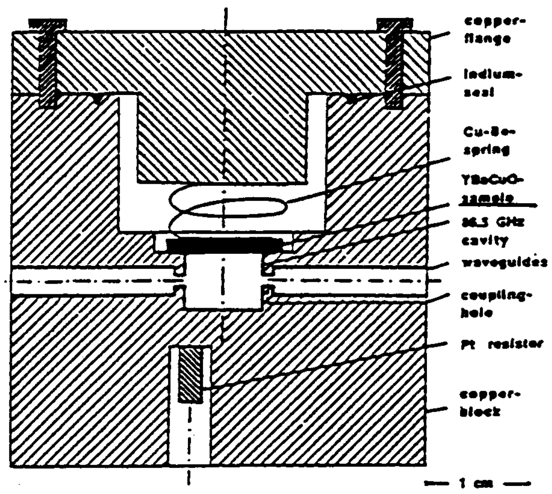


**Figure 2**
87GHz cylindrical $TE_{013/021}$ cavity (from [41]).

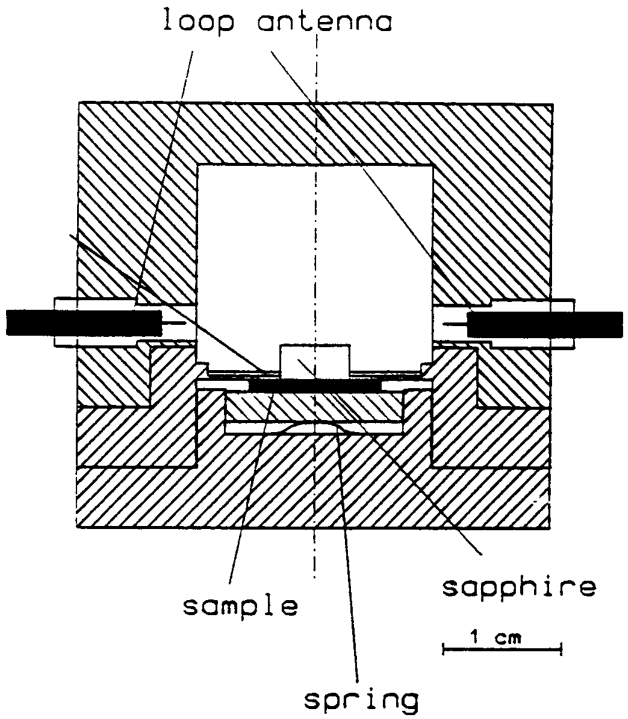


**Figure 3**
18.7GHz sapphire loaded cavity (from [44]).

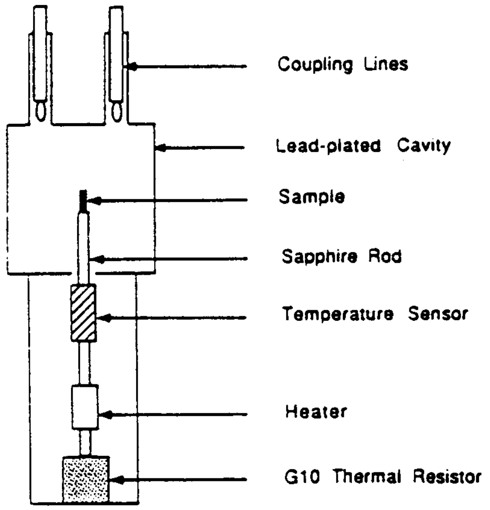


**Figure 4**
9.6 GHz $TE_{011}$ niobium cavity with separately heated sample (from [50]).

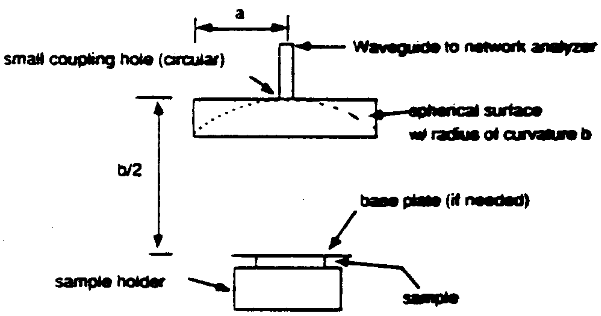


**Figure 5**
36 GHz semi-confocal Fabry-Perot resonator (from [52]).

Therefore, these techniques are complementary. In principal, a cylindrical dielectric resonator with two superconducting endplates should allow a higher sensitivity than our dielectric resonator system, but a sensitivity of only a few milliohms has been reported up to now [45].

Re 1.3:

Niobium host cavities with separately heated samples were first used in laboratories with experience in the preparation of niobium cavities [47-49]. It should be emphasized that this is the only method which can be used for single crystals. However, in the case of thin films on dielectric substrates losses or dielectric resonances in the substrates limit the sensitivity. The 9.5GHz $TE_{011}$ cavity used by the STI group [50] (Fig.4) has been optimized for thin films, since the sample is positioned in a region of homogeneous magnetic field parallel to the film surface and (ideally) zero electric field. The reported sensitivity at low temperatures is slightly lower than for the systems described before , but up to now it is the only system which allows the determination of the power dependence of $R_S$ at liquid nitrogen temperatures for unpatterned films.

Re 1.4:

TEM coaxial cavity resonators of both the $\lambda/2$ and $\lambda/4$ type were used by a group at Argonne in order to determine the surface resistance of superconducting wires or rods [51]. In this technique the sample replaces the inner conductor of the coaxial cavity. For thin films a special $\lambda/4$ niobium cavity, operating at 820MHz, was constructed by the Argonne group [51,89]. This technique allows $R_S$ to be determined at liquid helium temperatures as a function of rf power at a frequency relevant for particle accelerator applications.

Re 1.5:

Recently, Fabry-Perot-type confocal resonators have been used to determine $R_S$ at about 35GHz. In principal, this technique is most appropriate for planar samples. However, as long as the curved mirror is fabricated from a normal conducting material, the sensitivity cannot be much better than for the endplate replacement technique. It has already been shown that with a Fabry-Perot resonator constructed from two curved niobium mirrors a quality factor of $2 \cdot 10^7$ can be obtained at 4.2K [65]. Generally, for these resonators the quality factors are limited by radiation losses, e.g. from coupling holes.

Re 2.1

The parallel plate resonator technique was first used for the determination of $R_s$ of HTSC thin films by Taber et al. from Hewlett-Packard [55]. It is the only planar resonator technique which requires no patterning. Two opposite-faced thin films of the same size separated by a 20μm Teflon foil form a simple two-dimensional standing wave resonator. Radiation losses are minimized both by the small thickness of the spacer as well as by a metallic enclosure. Therefore, the sensitivity of ±5μΩ at 10GHz and 4.2K reported by the authors is superior to other techniques. However, due to the weak coupling to the fringe fields and possible parasitic resonances in the metallic enclosure $R_s(T)$ measurements up to $T_c$ are not possible at present. Another disadvantage is that this technique provides average information of two films. At University of Wuppertal a parallel plate resonator consisting of a niobium plate held at 4.2K and a separately heated HTSC plate with a small air gap in between is presently under construction [63].

Re 2.2 and 2.3

Transmission line resonators consist of a piece of transmission line with open ends and a length of $n \cdot \lambda / (2 \cdot \varepsilon_{eff}^{1/2})$ where n is an integer, λ the free space wavelength, and $\varepsilon_{ff}$ the effective dielectric constant, which for the stripline only is exactly equal to the dielectric constant of the substrate. Alternatively, ring resonators with a circumference being an integer of λ can be used.

Re 2.2

Coplanar resonators, as shown in Fig.6a, are used by some groups to determine $R_s$ of single epitaxial films. The main difficulty is to evaluate the influence of the contribution from dielectric losses in the substrate and from the surface resistance of the film from the measured quality factor. Therefore, a theoretical analysis of the field distribution as performed by Kessler et al. can be used [73]. This analysis takes into account the influence of the surface impedance on the field distribution. Furthermore, for the evaluation of $R_s$ it is useful to prepare different resonators with different linewidths of the conductor and the gap on one film [56]. Coplanar as well as stripline and microstrip resonators exhibit a maximum in the rf current density and thus in the rf magnetic field amplitude at the edge of the strip, i.e. in a region possibly degraded by the patterning procedure. Therefore, the $R_s$ values obtained by these techniques need not represent an intrinsic property of the HTSC film. On the other hand, they are more realistic for applications in planar microwave technology.

Re 2.3

Microstrip or stripline resonators require, besides the superconducting strip, one (microstrip) or two (stripline) ground planes. If the width of the strip is small enough, the groundplane(s) can be normal conducting. Nevertheless, similar to the coplanar resonator technique, an exact calculation of the electromagnetic field distribution as given in [66] is required to evaluate the surface resistance from the measured quality factor. It should be emphasized that the field distribution, especially the field enhancement factor at the edge of the strip, depends on the penetration depth of the magnetic field. If this is taken into account, the stripline resonator technique can be used to determine the dependence of $R_S$ on the rf magnetic field amplitude [58] (see chapter 4).

Re 2.4.

In principal, lumped circuit elements can be used to determine $R_S$ in the low GHz range, but up to now they are more relevant for some passive microwave devices. An example is the H-shaped HTSC patch antenna developed by Chaloupka et al. [60].

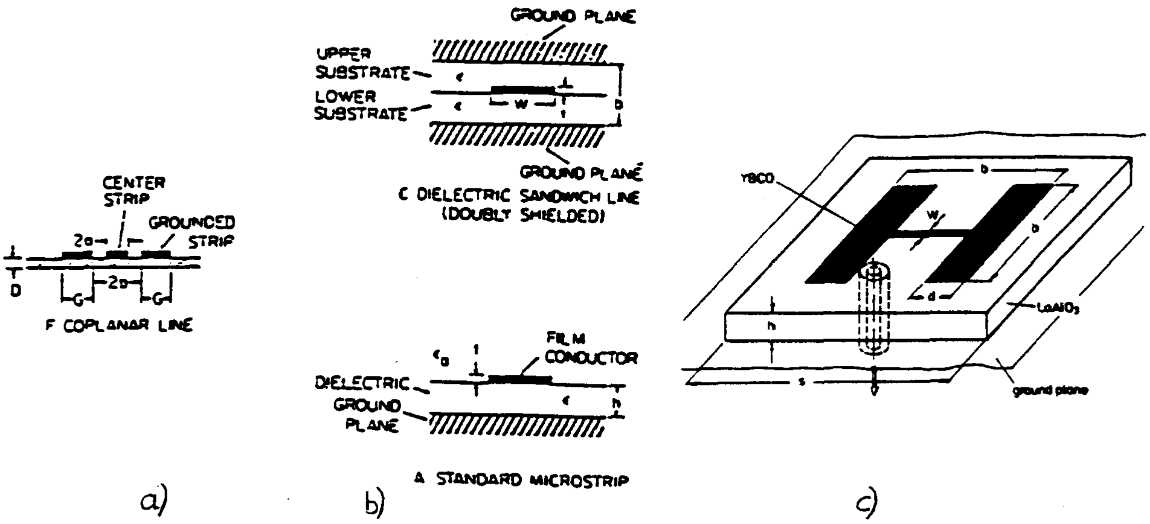


Figure 6
various types of planar resonators:
a) coplanar b) stripline, microstrip c) lumped element resonator (from [60]).

**Re 3**

The determination of the surface impedance in the submillimeter wave range is of special interest for two reasons. First, since $R_S$ scales like $f^2$, it should be easier to determine small residual losses in thin films of high quality. Secondly, those frequencies are closer to the gap frequency $f=\Delta/h$ where $\Delta$ is the energy gap. Therefore, deviations from the $f^2$ dependence are expected and can help to elucidate the questions about the (non)existence of electronic states in an (an)isotropic energy gap [67]. However, experimental techniques in this frequency range are very rare and only a few experimental results have been reported as yet.

**Re 3.1:**

Picosecond pulse analysis is an indirect method to determine $R_S$ from a Fourier transformation of a picosecond laser pulse after propagating along a superconducting stripline [68] or even an unpatterned film [61]. It has been used to determine $R_S(f)$ from about 500GHz to 2THz.

**Re 3.2:**

In the far infrared range (FIR), direct reflectivity measurements are used to determine the dynamic conductivity [69]. The reflectivity $|r|$ is related to $R_S$ by $|r|=1-4R_S/Z_0$, $Z_0=377\Omega$ being the wave impedance of the free space. For the submillimeter wave range the reflectivity of a superconductor is too close to one to be determined. However, using a careful analysis of the transmission through a very thin film both in amplitude and phase, it is possible to determine both $R_S$ and $X_S$, $X_S$ being the surface reactance. This has been performed by Volkov et al. [62] using a quasioptical system between 100GHz and 1THz in connection with submillimeter backward-wave oscillators. Moreover, the submillimeter wave range is accessible with multiplied millimeter wave sources and with lasers. In addition to direct reflectivity and transmission measurement techniques, quasi-optical resonator techniques are under investigation [70].

## 4. Results of the microwave surface impedance

Before giving an update on recent results of the microwave properties of high-$T_c$ superconductors, I will briefly discuss a simple expression for the surface impedance of a superconductor, which can be derived from the first London equation, Ohm's law, and Maxwell's equations [90]:

$$Z_s = R_s + iX_s = \left(\frac{i\omega\mu_0}{\sigma_1 - i\sigma_2}\right)^{1/2} \qquad [1]$$

Eq.1 holds true in the local limit, i.e. if the penetration depth is large in comparison to the mean free path and the coherence length. This is valid for high-$T_c$ superconductors. The resistive part of the screening current in the surface of the superconductor is described by the real part of the complex conductivity

$$\sigma_1 = \frac{N_u e^2}{m\Gamma} \qquad [2]$$

with m being the effective mass of the charge carriers, and $\Gamma$ the scattering rate. According to BCS theory the density of the unpaired charge carriers $N_u$ decreases with decreasing temperature as

$$N_u \sim \exp(-\Delta/kT) \quad (\Delta\text{=energy gap}) \qquad [3]$$

for $T<T_c/2$ and as

$$N_u \sim (T/T_c)^4 \qquad [5]$$

for temperatures close to $T_c$, according to the two-fluid model. The imaginary part, however, is proportional to the density of paired charge carriers $N_p$

$$\sigma_2 = \frac{2e^2 N_p}{m\omega} = \frac{1}{\omega\mu_0\lambda^2} \qquad [6]$$

with $\lambda$ being the London penetration depth. According to the two-fluid model the temperature dependence of $N_p$ is:

$$N_p \sim 1-(T/T_c)^4 \qquad [7]$$

For classical superconductors $\sigma_1 \ll \sigma_2$ is fulfilled since $N_u \ll N_p$ (not too close to $T_c$). As discussed in [14], however, this need not be true for high-$T_c$ superconductors. But $\sigma_1 \ll \sigma_2$ is also justified, since for microwaves $\omega \ll \Gamma$. In this case eq.1

can be approximated by:

$$R_S \approx \frac{1}{2}\,\omega^2 \mu_0^2\, \sigma_1 \lambda^3 \qquad \text{and} \qquad X_S = \omega\mu_0\lambda \qquad [8]$$

Eqs. 3,5,7,8 roughly describe the temperature and frequency dependencies of $Z_S$ observed for classical superconductors like niobium, if the very small residual losses are subtracted. For a more precise description an exact numerical calculation based on the BCS theory has to be performed, as e.g. by Halbritter [72]. As the most distinguishing feature of high-$T_C$ superconductors, $R_S$ exhibits a much weaker temperature dependence below about 0.7 $T_C$. As discussed in the proceeding paragraphs, this is at least partially a consequence of material imperfections.

Eq. 8 only holds true if the film thickness d is large in comparison to the penetration depth $\lambda$. This is not the case for epitaxial films. According to [77] the effective surface resistance (reactance) $R_{eff}(X_{eff})$ of a thin film in the superconducting state is proportional to $R_S(X_S)$:

$$R_{eff} \approx R_S\left(\coth(d/\lambda) + \frac{d/\lambda}{\sinh^2(d/\lambda)}\right) \quad \text{and} \quad X_{eff} = X_S \coth(d/\lambda) \qquad [9]$$

Eq. 9 holds true if power transmission through the film is neglected. Practically, deviations occur for films on $SrTiO_3$, since there transmission losses are enhanced due the high permittivity of $SrTiO_3$ [77]. For all other substrates listed in table 1 transmission losses can be neglected, except for ultrathin films (<10 nm) and for temperatures close to $T_C$. In the millimeter wave range, however, transmission losses are enhanced by resonances in the substrate, if the thickness of the substrate is equal to an integer multiple of the half wavelength in the substrate. Such situations should be avoided.

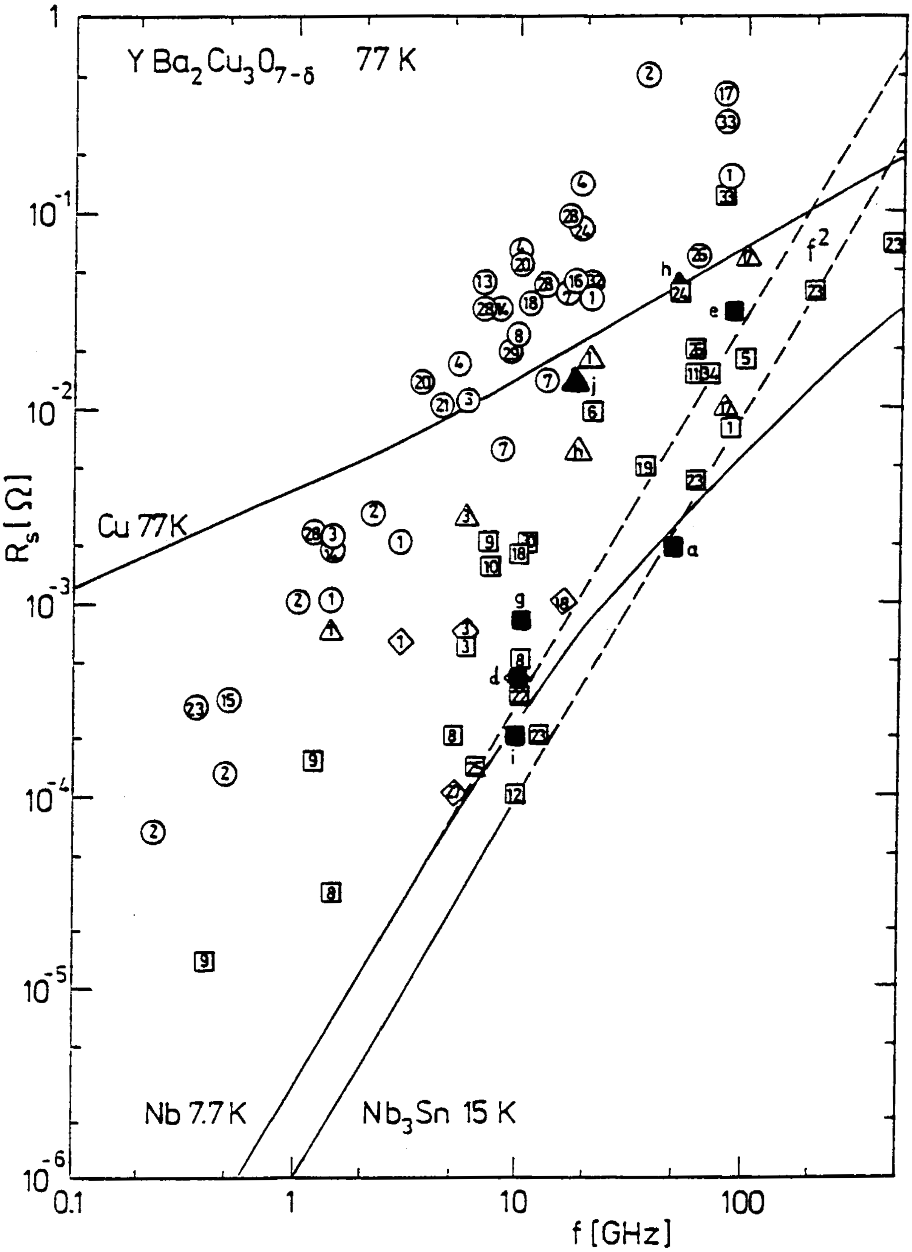
Fig.7 and 8 show the frequency dependence of $R_S$ for untextured (circles) and c-axis textured (triangles) polycrystalline bulk or thick film samples as well as for epitaxial thin films (squares) and single crystal platelets (rhombuses) of $YBa_2Cu_3O_7$ at 77K and 4.2K, respectively. Both plots are from a review given by H. Piel and G. Müller at the Applied Superconductivity Conference in 1990 [12]. The numbers in the open symbols identify the corresponding references in [12]. Moreover, I have added some more recent data (closed symbols with letters referring to table 3). The lines for copper, niobium and $Nb_3Sn$ are given for comparison. For the thin films, in some cases $R_{eff}$ is shown instead of $R_S$. For typical thickness values above 300 nm they only differ by less than a factor of 2.

First, the best results of $R_S$(77K) will be discussed, which is the most relevant quantity for applications. No significant improvement has been obtained in the last year. There is only one result from Asano et al. which indicates a slightly lower $R_S$(77K) value for an $EuBa_2Cu_3O_7$ film on MgO ( a in table 3). It should be emphasized that the present state of the art is still good enough for many planar microwave applications: $R_S$ scales about quadratically with frequency up to at least 200 GHz [61] and is smaller than $R_S$(77K) of copper below about 300 GHz. The absolute values of $R_S$ are comparable to niobium at the same reduced temperature, indicating that the intrinsic limit of $YBa_2Cu_3O_7$ has already been achieved. Thin films of $Tl_2Ba_2CaCu_2O_8$ are approaching these results (i), although they are still granular. Here the potential for improvement is larger, since 77K is not so close to $T_C$ as for $YBa_2Cu_3O_7$.

| * | material | References |
|---|---|---|
| a | $EuBa_2Cu_3O_7$ tf on MgO | [74] |
| b | $YBa_2Cu_3O_7$ tf on $LaAlO_3$ and $NdGaO_3$ | [44,75] |
| c | $YBa_2Cu_3O_7$ tf on MgO, one inch diameter | [42,76] |
| d | $YBa_2Cu_3O_7$ tf on $LaAlO_3$ by CVD | [24] |
| e | $YBa_2Cu_3O_7$ tf on $SrTiO_3$ by CVD | [71] |
| f | $YBa_2Cu_3O_7$ tf film on silicon-on-sapphire | [39] |
| g | $YBa_2Cu_3O_7$ tf on sapphire | [64] |
| h | melt-textured $YBa_2Cu_3O_7$ thick film | [17] |
| i | $Tl_2Ba_2Ca_1Cu_2O_8$ tf | [29] |
| j | $Tl_2Ba_2Ca_1Cu_2O_8$ thick film | [28] |

Table 3:
Recent data point from Figs. 7 and 8 referring to the letters in the symbols (*). tf=thin film

The $R_S$(77K) values representing the state of the art have been achieved with epitaxial thin films of $YBa_2Cu_3O_7$ prepared by pulsed laser deposition, sputtering, and thermal or electron beam evaporation on $SrTiO_3$, MgO, $LaAlO_3$, and $NdGaO_3$[44]. The best films prepared by CVD are now as good as those prepared by the physical vapor techniques (d,e). First results on sapphire (g) are very promising, but the films on silicon (f) still have broad $R_S$(T) transitions resulting in poor $R_S$(77K) results.



**Figures 7 and 8 (next page)**

**Frequency dependence of $R_s$ for untextured (circles) and c-axis textured (triangles) polycrystalline bulk or thick film samples as well as for epitaxial thin films (squares) and single crystal platelets (rhombuses) of $YBa_2Cu_3O_7$ at 77K and 4.2K, respectively. Both plots are taken from a review given by H. Piel and G. Müller at the Applied Superconductivity Conference in 1990 [12]. The numbers in the open symbols identify the corresponding references in [12]. Moreover, recent data are included (closed symbols with letters referring to table 3). The lines for copper, niobium and $Nb_3Sn$ are given for comparison (from [12]).**

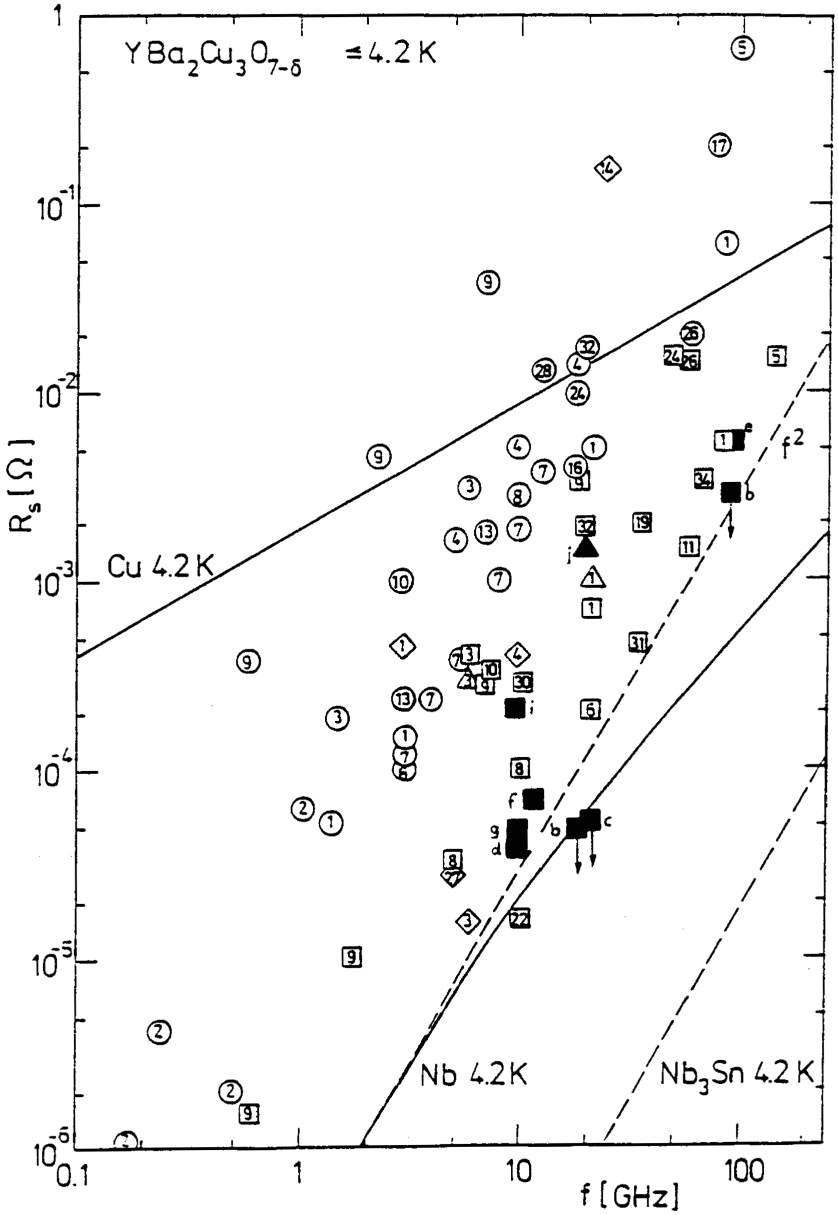


Figure 8 (caption see Fig.7)

The $R_S(77K)$ values for polycrystalline $YBa_2Cu_3O_7$ are about two orders of magnitude higher than for the best epitaxial films. However, granular c-axis oriented thick films prepared by electrophoresis are just in between. This was achieved by optimizing the sintering process with respect to large grains. Fig.9 from Ref.20 indicates a 1/d-dependence of $R_S(77K)$, d being the average grain size. The more recent data point from the melt-textured processed thick film (h) fits well into this correlation. The $R_S(77K)$ value of the $Tl_2Ba_2CaCu_2O_8$ film deposited on a large-area (11.4cm$^2$) Ag alloy by sputtering (j) is not better than the thick film results, indicating the necessity of singlecrystalline substrates for epitaxial growth.

In contrast to the 77K results, much progress has been achieved in the low temperature regime of the surface resistance of epitaxial thin films (b,c). Fig.10 from [26] shows $R_s$(T) at 87GHz for three different films prepared by high-pressure planar dc-sputtering. Film La2602 and La1601, both on $LaAlO_3$, exhibit a high degree of crystalline perfection, e.g. a minimum yield of 1-2% observed in He-ion channeling. High-resolution transmission electron microscopy (HRTEM) studies revealed a reduced density of defects in comparison to previous films like La0503 in Fig.10. Recently, $YBa_2Cu_3O_7$ films prepared by electron beam evaporation on MgO have shown similar low $R_s$(T)-values at low temperatures, if deviations of less than 1% from the nominal 1:2:3 stoichiometry are maintained [76]. Fig. 11 from [44] shows $R_s(T_c/T)$ in comparison to niobium for two of the best films prepared by high-pressure planar dc-sputtering. For $YBa_2Cu_3O_7$ the slope at low temperatures is still much smaller than for niobium indicating that extrinsic losses from remaining material imperfections are still dominant. On the other hand, an extremely small value of the energy gap or even unpaired charge carriers in the CuO chains of $YBa_2Cu_3O_7$ may result in anomalously high intrinsic losses [67]. From the applicational point of view it is worthwhile mentioning that $R_s$(10K) values from Fig.11 are as good as for niobium at 4.2K. This allows millimeter wave applications at closed cycle refrigerator temperatures.

The $R_s$(4.2K) results of the best epitaxial $YBa_2Cu_3O_7$ films are beyond the sensitivity limit of the cavity measurement technique as indicated by the error bars in Fig.10. However, if e.g. the density of grain boundaries increases, $R_s$(4.2K) increases well above the sensitivity limit. Fig.12 from [37] shows that $R_s$(4.2K) for films prepared by off-axis sputtering on MgO is correlated to the volume percent of c-axis grains misaligned at 45°. However, the scattering of the data and the positive intercept of the solid line (least squares fit) indicate that not only the 45° degree grain boundaries contribute to the residual losses of the best films.

Fig.13 shows the penetration depth $\lambda$ as a function of temperature for two films prepared either by laser ablation (L1) [78] or by sputtering (S1), determined from the measured surface reactance at 87GHz [75]. In contrast to $R_s$(T), $\lambda$(T) is in good agreement with the BCS temperature dependence (solid lines). Using eqs. 1 and 6 the temperature dependence of the real part of the conductivity, $\sigma_1$ can be determined from the surface impedance. As shown in Fig.14, $\sigma_1$(T) exhibits strange behavior with a maximum at about 50K. Similar behavior has been reported by Nuss et al. in a picosecond pulse experiment [79].

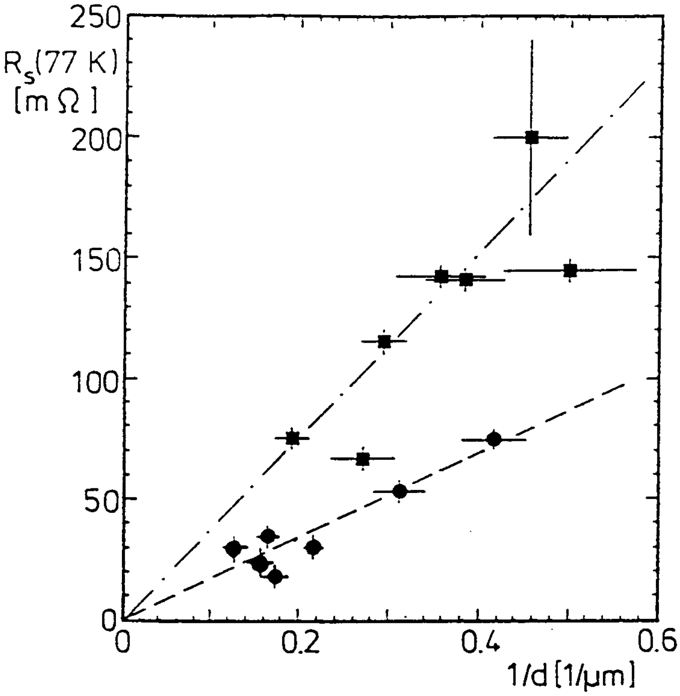


**Figure 9**

$R_S$(77K) at 21.5GHz as a function of the 1/d, d being the average grain size. The squares (circles) represent untextured (textured) $YBa_2Cu_3O_7$ thick films prepared by electrophoresis (from [20]).

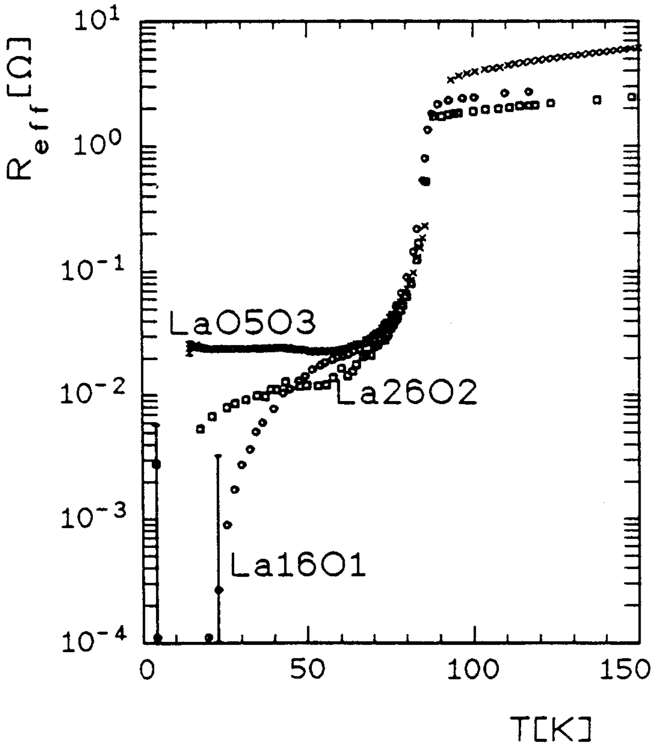


**Figure 10**

Temperature dependence of the surface resistance at 87GHz of 3 different epitaxial $YBa_2Cu_3O_7$ thin films prepared by planar high pressure sputtering on $LaAlO_3$ (from [26]).

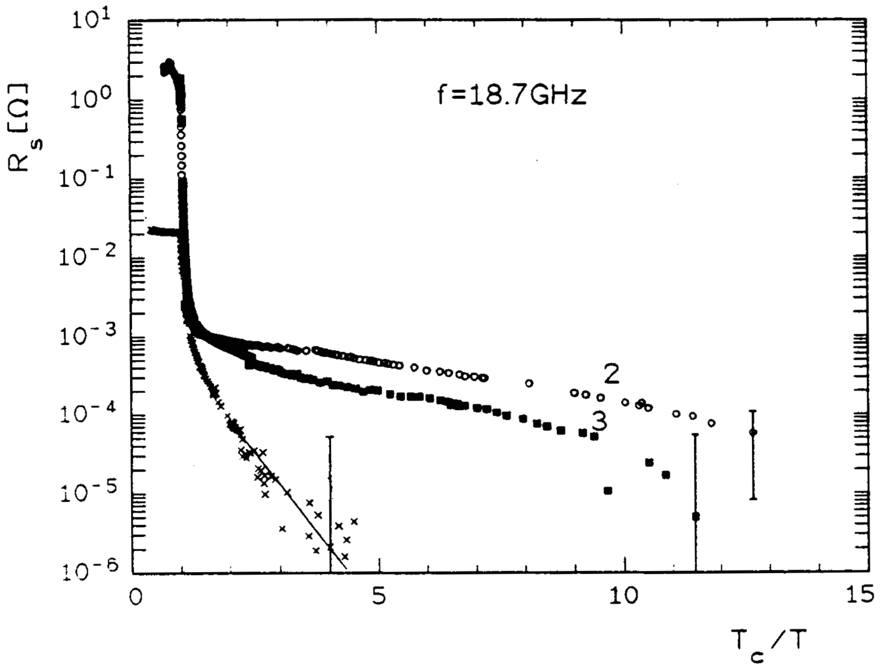


**Figure 11**

$R_S$ versus $T_C/T$ at 18.7GHz for an epitaxial $YBa_2Cu_3O_7$ thin film prepared by planar high-pressure dc-sputtering on $LaAlO_3$(2) and $NdGaO_3$(3) in comparison to niobium film. The straight line corresponds to a result obtained with a bulk niobium cavity (from [44]).

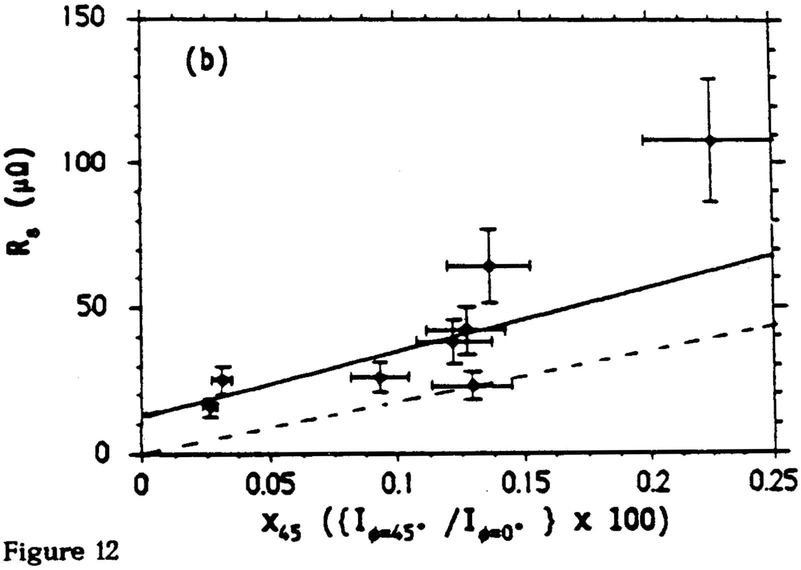


**Figure 12**

$R_S$(4.2K) at 10GHz versus the volume percent of c-axis grains misaligned at 45° in the plane for epitaxial $YBa_2Cu_3O_7$ thin films prepared by off-axis sputtering on MgO (from [37]).

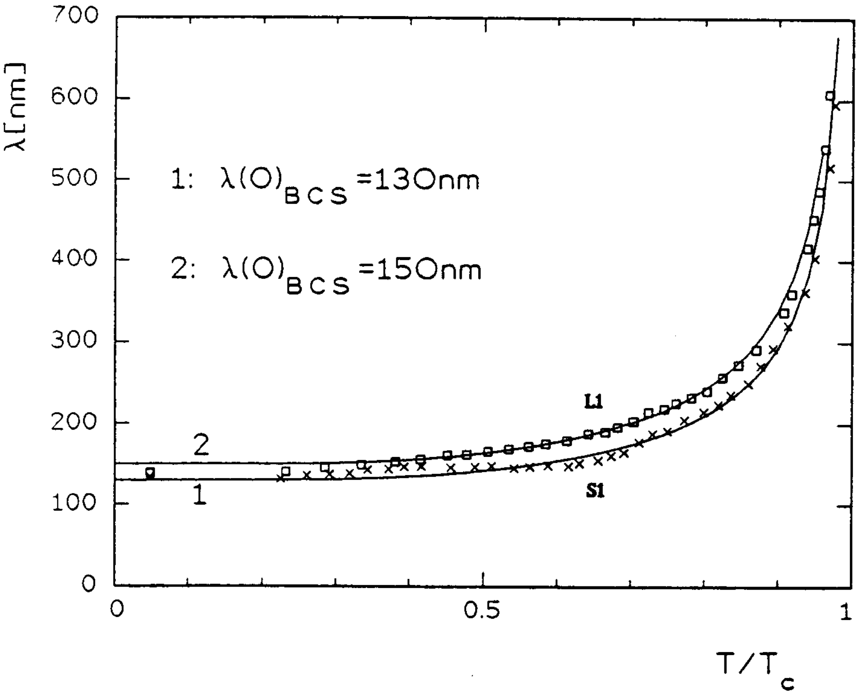


**Figure 13**

**Temperature dependence of the penetration depth, determined from the surface impedance at 87GHz of epitaxial $YBa_2Cu_3O_7$ thin films prepared by planar high pressure dc-sputtering (S1) and by pulsed laser deposition (L1) on $LaAlO_3$. The solid lines are fits to the BCS temperature dependence in the weak coupling limit.**

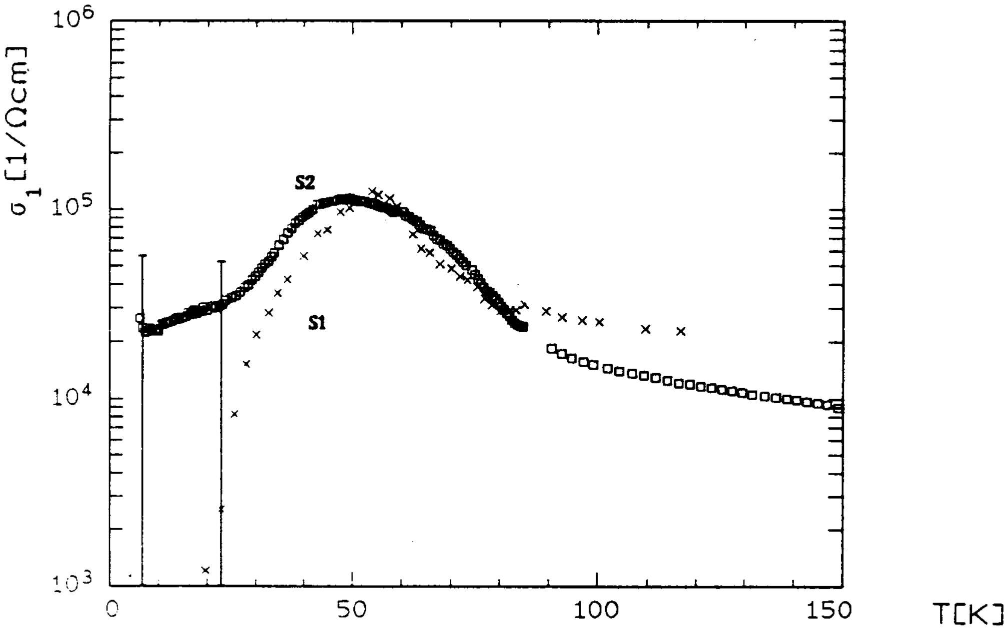


**Figure 14**

**Temperature dependence of the dynamic conductivity, determined from the surface impedance at 87GHz of epitaxial $YBa_2Cu_3O_7$ thin films prepared by planar high pressure dc-sputtering on $LaAlO_3$.**

It may be explained either by a strongly decreasing inelastic scattering rate below $T_C$ [79] or a BCS coherence peak [80], which is shifted to lower temperature by the influence of the charge carriers in the CuO chains [81].

For many applications low $R_S$-values at high rf field levels $H_{rf}$ are desirable. This not only holds true for cavity resonator applications e.g. in particle accelerators. Planar devices for rf communication, if not only used in the receiver circuit, require low losses at high rf-power levels.

Fig.15 shows $R_S(H_{rf})$ at 4.2K and 821MHz from [51] for a large number of granular samples from different species of HTSC materials. Without discussing the data in detail, it is clearly visible that all curves have a similar shape, which is typical for granular material. According to Halbritter [82] there are three different regions for $R_S(H_{rf})$. Below the lower critical field of the Josephon junctions $H_{C1\,j}$, $R_S$ is proportional to $H_{rf}^2$ (However, Fig.15 indicates constant $R_S$ below $H_{Cj}$). Above $H_{Cj}$, magnetic flux enters the samples, and $R_S$ scales linear with frequency. Above a field level where all Josephson junction have exceeded their critical currents, $R_S$ is almost field independent up to the limit given by the available rf power. This constant value is well below $R_S$ in the normal conducting state, since the grains are still in the superconducting state. Fig.15 indicates that $H_{C1\,j}$ is below 1G, which is more than two orders of magnitude below the intrinsic $H_{C1}$ of $YBa_2Cu_3O_7$ [83].

Completely different behavior has been observed for the best epitaxial thin films of $YBa_2Cu_3O_7$. Fig. 16 from [42] shows $R_S(H_{rf})$ at 4.2K and 21.5GHz for two epitaxial thin films prepared by electron beam evaporation on MgO (circles and rhombuses). The diameter of each sample is 2.5cm. $R_S$ is constant up to about 100Oe, limited by a quench in the niobium cavity. It should be emphasized that this is one of the lowest $R_S$(4.2K) values (c) in Fig.8. Granular, but c-axis oriented $YBa_2Cu_3O_7$ thick films prepared by electrophoresis (triangles) exhibit an almost constant $R_S(H_{rf})$ up to about 10Oe in contrast to the thick film without texturing (squares).

Fig. 17 from [29] shows $R_S(H_{rf})$ at 77K and 9.55GHz for a thin film of the $Tl_2Ba_2CaCu_2O_8$ compound. Here $R_S$ starts to increase significantly above about 10G. Below this value $R_S$ is as low as for the best epitaxial $YBa_2Cu_3O_7$ films. Fig.18 from [58] shows $R_S(H_{rf})$ of an epitaxial $YBa_2Cu_3O_7$ film both at 4.2K and 77K measured by a stripline resonator technique. The $H_{rf}$ values are peak values at the edge of strip and are enhanced by more than a factor of 10. These regions are possibly distorted by the patterning. In spite of this the 4.2K results are similar to the thin film results shown in Fig.16. At 77K $R_S$ starts to increase significantly at lower field levels.

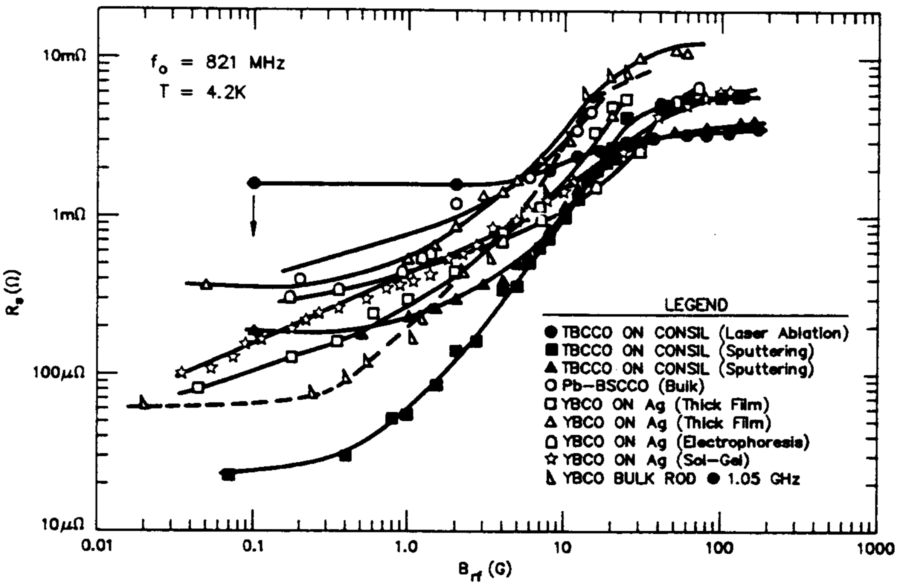


Figure 15

Surface resistance versus peak rf magnetic field at 821MHz and 4.2K for a variety of samples (from [51]).

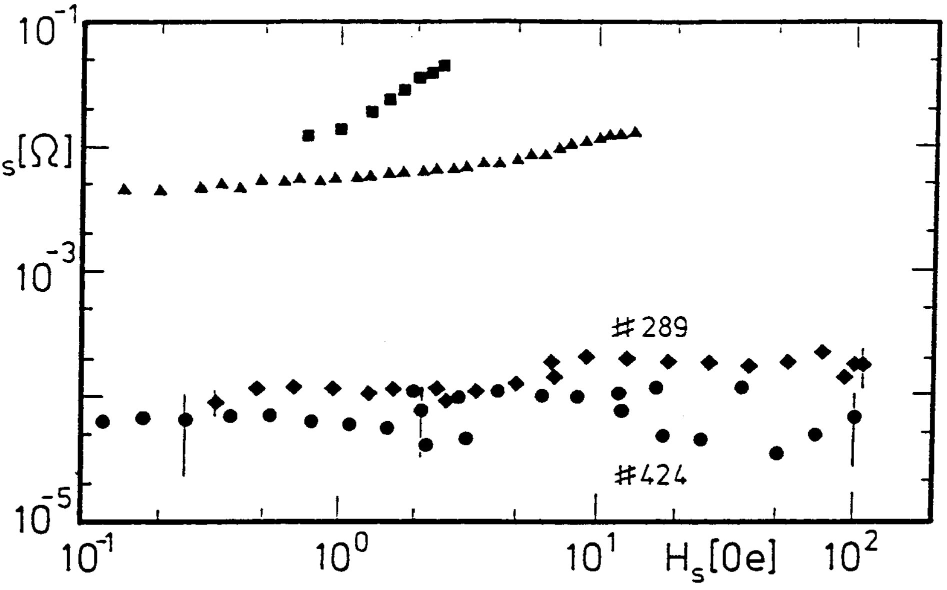


Figure 16

Surface resistance versus peak rf magnetic field at 21.5GHz and 4.2K for two $YBa_2Cu_3O_7$ thin films with a diameter of 2.5cm prepared by electron beam evaporation on MgO in comparison to results for untextured (squares) and c-axis textured (triangles) $YBa_2Cu_3O_7$ thick films prepared by electrophoresis (from [42]).

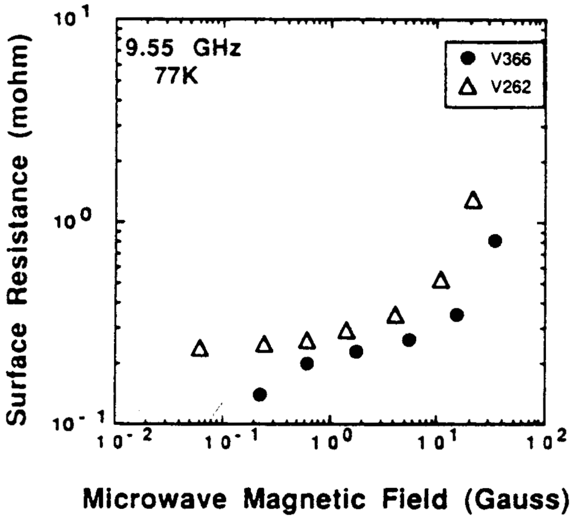


**Figure 17**
Surface resistance versus peak rf magnetic field at 9.55GHz and 77K for two $Tl_2Ba_2Ca_1Cu_2O_8$ thin films prepared by pulsed laser deposition on $LaAlO_3$ (from [29]).

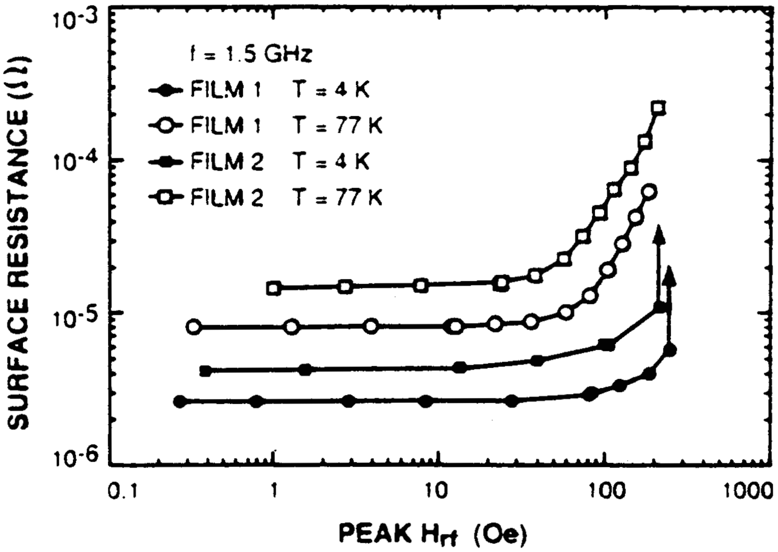


**Figure 18**
Surface resistance versus peak magnetic field at the edges of the center strip at 1.5GHz for two $YBa_2Cu_3O_7$ thin film stripline resonators prepared by off-axis magnetron sputtering on $LaAlO_3$ (from [58]).

In summary, the $R_s(H_{rf})$ results show that a high degree of c-axis orientation and a low degree of granularity are necessary for reasonable rf properties at high power levels. Up to now, thin films of $YBa_2Cu_3O_7$ are superior to thin films of $Tl_2Ba_2CaCu_2O_8$, which is a consequence of the ex-situ growth of the latter. But even the best results obtained so far for epitaxial $YBa_2Cu_3O_7$ films need not represent intrinsic material properties. To understand the influence of the granularity on the surface impedance more quantitatively, the static magnetic field dependence of the surface impedance has been investigated [20,85,86]. These experiments can be explained consistently by modeling the granularity by a network of resistively shunted weak links [20,84,85]. For the rf-field dependence the situation is more complicated since the fluxoid dynamics has to be taken into account [87].

## 5. Summary

Today we have the first applications of high-temperature superconductors (HTSC) in microwave technology. This has become possible due to the development of various preparation techniques for HTSC layers with low microwave losses. More specifically, thin films of $YBa_2Cu_3O_7$ grown epitaxially on a few species of planar, singlecrystalline dielectric substrates with reasonably low dielectric losses have already been used successfully to build planar devices with a performance at liquid nitrogen temperature superior to the corresponding normal conducting versions. This is mainly a result of the low surface resistance at 77K which is about $1.5 \cdot 10^{-4} \Omega \cdot (f[GHz]/10)^2$ for the best $YBa_2Cu_3O_7$ films. Films of $Tl_2Ba_2CaCu_2O_8$ show similary good results, although their performance at high rf field levels is worse. Large granular thick films with preferred c-axis texturing can be grown on polycrystalline curved substrates and are therefore useful for cavity resonator applications. Their $R_s$(77K) values are still about one order of magnitude higher than for the epitaxial films, and their performance at high rf-field levels is still poor. The surface resistance at low temperatures even of the best epitaxial $YBa_2Cu_3O_7$ thin films is still some orders of magnitude above the expectations from the classical superconductors. Nevertheless, the observed $R_s$(T) curves of some of the most recent films are no longer temperature-independent below about $0.7T_c$ as it was the case for a long time. At 10K $R_s$ values as low as for niobium at 4.2K have already been achieved. This will be important for millimeter wave applications at typical close cycle refrigerator temperatures.

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