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Microwave properties of structured $YBa_2Cu_3O_{7-x}$ thin films

W. Rauch*, E. Gornik
Walter Schottky Institut, Am Coulombwall, D-8046 Garching, Germany
G. Sölkner, A. A. Valenzuela, F. Fox, H. Behner,
Siemens AG, Corporate Research and Development, D-8000 München 83 and D-8520 Erlangen, Germany

Abstract

The microwave properties of c-axis oriented $YBa_2Cu_3O_{7-x}$ (YBCO) thin films deposited by DC-magnetron sputtering were investigated between 5 and 20 GHz using coplanar transmission line resonators. From temperature dependent measurements of the quality factors of these resonators the magnetic penetration depths $\lambda_L(0)$ and the surface resistances R_s were evaluated. The lowest surface resistance values were in the range between 105 $\mu\Omega$ and 200 $\mu\Omega$ at 77 K and at 6.2 GHz, respectively. The magnetic penetration depths $\lambda_L(0)$ were between 160 nm and 270 nm. The surface resistance R_s turned out to be sensitive to the film quality represented by the critical current density j_c at 77 K. From an evaluation of the temperature dependence of the resonance frequency at low temperatures $T < T_c/2$ we determined energy gap values $2\Delta(0)/k_BT_c$ between 1.2 - 2.2.

1. Introduction

The microwave properties of $YBa_2Cu_3O_{7-x}$ (YBCO) thin films are particularly interesting with regard to applications as microwave devices or as interconnects on computer boards. A large number of investigations of these properties have been published up to date [1-3]. Most of these experiments were done by placing the films in cavity resonators or replacing one wall of a resonator with the film.

A versatile tool to investigate the microwave properties of these films are planar half-wavelength resonators as they allow a high sensitivity, a multi-frequency measurement on one chip, a clearly defined site of measurement and a realistic test of structured films [4]. The evaluation of the surface resistance and the magnetic penetration depth, however, requires the consideration of conductor, dielectric and radiation losses of the actual structure which can be done by a partial wave synthesis [4].

As YBCO thin films have already reached a high level of crystalline perfection these measurements also yield information about the intrinsic properties like the surface resistance, the magnetic penetration depth and the energy gap of YBCO.

In this paper we present an investigation of structured YBCO thin films in the frequency range between 5 and 20 GHz. The surface resistance and the magnetic penetration depth are determined from temperature dependent quality factor and resonance frequency measurements. Additionally, information about the energy gap in this material is deduced from these measurements.

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* experimental work done at Siemens Research Laboratories Munich and Erlangen

2. Experimental

C-axis oriented YBCO thin films were grown on 1 mm thick $LaAlO_3$ and MgO substrates using high pessure DC-magnetron sputtering. The films were deposited in a flowing gas mixture of $Ar:O_2 = 1:29$ at a pressure of 0.9 mbar. All films had a thickness of 200 nm and showed critical temperatures T_c of 90 K and critical current densities j_c well beyond 10^6 A/cm^2 at 77 K. The details of the deposition process as well as the properties of the films were described elsewhere [5].

Subsequently the films were patterned using a conventional photolithographical process (AZ 5218) and an Ar fast atom beam for dry etching. The YBCO films were patterned into coplanar waveguide (CPW) resonators. The different structures are listed in table 1.

Table 1: Investigated coplanar waveguide structures.

Structure	w [µm]	d [µm]	*l* [mm]
KR1	80	160	6.5
KR2	40	80	6.5
KR3	25	50	6.5

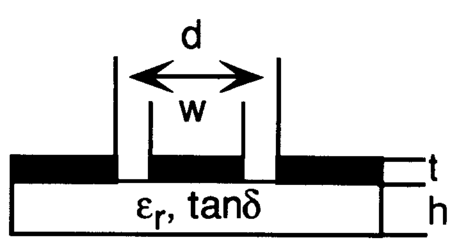

Fig. 1 A schematic of the coplanar waveguide lines. t is the thickness of the YBCO layer and h is the height of the dielectric with the loss tangent tanδ and the dielectric constant ε_r.

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The measurements of the temperature dependent resonator quality factors Q_0 and resonance frequencies f_0 were performed between 5 and 20 GHz at an electrical input power of 10 dBm with a scalar network analyser within a cryostat equipped with high frequency coplanar microwave probes.

3. Theory

The surface resistance can, in principle, be obtained from a partial wave synthesis where one has to consider the conductor, dielectric and radiation losses of the structure [4]. The complex conductivity of the superconductor is described by the London equations and the two-fluid model. One obtains a propagation constant $\gamma = \alpha + i\beta$ and thus an inductance $L(\lambda_L)$ of the line. The inductance is itself a function of $\lambda_L(T)$ and is composed of the external inductance L_{ext} and the kinetic inductance L_{kin} due to the inertia of the superconducting carriers. In the case of a much smaller damping coefficient α as compared to the phase coefficient β only limited accuracy is obtained and one has to resort to an approximation where the coplanar line is thought to be made up by a collection of parallel running lines each with a complex impedance. The unloaded quality factor Q_0 of a resonator is then related to the surface resistance of the film by [4]

$$R_s = \frac{n\pi\mu_0 Z_w \lambda_L}{Q_0 l L_{kin}}, \qquad (1)$$

where Z_w is the characteristic impedance, n is the harmonic number of the resonance, λ_L is the magnetic penetration depth, and L_{kin} is the kinetic inductance of the line. The magnetic penetration depth was obtained by a comparison of the measured and the calculated temperature dependence of the resonance frequency[4]:

$$\frac{f_0(T)}{f_0(T_0)} = \sqrt{\frac{L_{ext} + L_{kin}(\lambda_L(T_0))}{L_{ext} + L_{kin}(\lambda_L(T))}}. \qquad (2)$$

For the calculation the two-fluid model was used as a model of the temperature dependence of the penetration depth.
Additionally, the value of the energy gap $2\Delta(0)/k_BT_c$ can approximately be determined from the temperature dependence of the resonance frequency in the low temperature region. In the BCS theory the variation of the energy gap is < 4 % for $T < T_c/2$ [6]. Therefore, $\Delta(T) \approx \Delta(0)$ is a good approximation in this temperature range. At low temperatures the BCS theory yields an exponential behaviour of the magnetic penetration depth which can be expanded into a series resulting in [7]

$$\frac{\lambda_L(T)}{\lambda_L(0)} \approx 1 + \frac{1}{2}\sqrt{\frac{2\pi\Delta(0)}{k_BT}} \cdot \exp\left(\frac{\Delta(0)}{k_BT}\right). \qquad (3)$$

With the temperature dependence of the resonance frequency and the kinetic inductance per unit length L_{kin} of the transmission line the energy gap can be evaluated from

$$\ln\left(\frac{1}{f_0^2(T)} - \frac{1}{f_0^2(T_0)}\right) \approx \ln\left(\frac{\lambda_L(T)}{\lambda_L(T_0)} - 1\right) + c_1 \qquad (4)$$

with the resonance frequency f_0 and a geometry dependent variable c_1 which is negligible in this context. From the slope of $\ln(f_0^{-2}(T) - f_0^{-2}(T_0))$ the value of the energy gap can be determined. The reference temperature T_0 was 10 K throughout this work.

4. Results

The magnetic penetration depths $\lambda_L(0)$ evaluated from the temperature dependence of the resonance frequency were in the range between 160 nm and 270 nm. The magnetic penetration depth turned out to be not as sensitive to the film quality represented by the critical current density at 77 K as the surface resistance R_s.

In fig. 2 the temperature dependence of the surface resistance is shown for various films at 6.2 GHz.

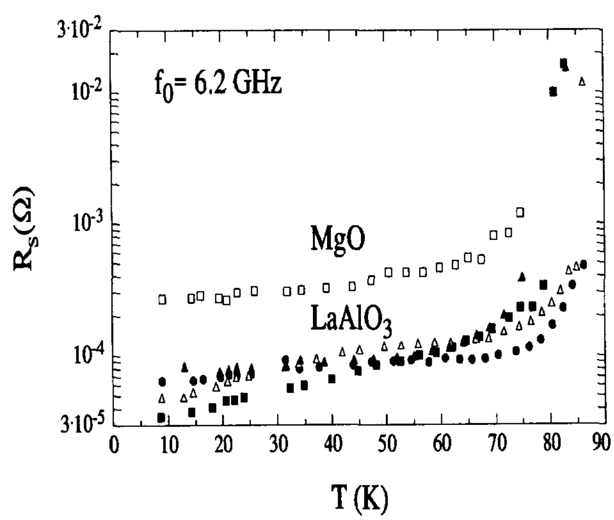

Fig. 2: Temperature dependence of the surface resistance for different films on $LaAlO_3$ and MgO.

Typical values at 77 K were between 100 μΩ and 250 μΩ. As our experiments revealed a clear ω^2-dependence of R_s on the frequency some of the values were normalized to 6.2 GHz using an ω^2-dependence which follows the two-fluid model. The R_s values at 77 K are already near the values for Nb at the same reduced temperature and are similar to the results obtained from unstructured films. Therefore we suggest these values to be close to the intrinsic ones. At lower temperatures the films show a different behaviour. While most of the films level off to a constant value some films show a further slight decrease below 40 K. A higher crystalline quality of the films should enable still lower values as has been shown recently for unstructured films [1]. However, for our applicational purpose the values at 77 K are relevant. A complete survey of the film properties is given in table 2.

Table 2: Critical current densities at 77 K, magnetic penetration depths and surface resistances (6.2 GHz) at 10 K and at 77 K for vaious samples.

Sample	Resona -tor type	j_c [10^6 A/cm^2, 77 K)	$\lambda_L(0)$ [nm]	R_s [μΩ, 10 K]	R_s [μΩ, 77 K]
591	KR1	1.7	160	150	356
	KR3		175	38	215
592	KR2	3.0	200	50	203
	KR3		185	84	400
598	KR1	4.2	155	170	280
	KR2		165	47	150
	KR3		170	65	105
602	KR1	1.0	240	270	> 1000
	KR2		270	310	-
	KR3		250	390	-

In contrast to the magnetic penetration depths the R_s values at 6.2 GHz differ by a factor of two on one film. Additionally, the R_s curves exhibit a different temperature behaviour. This is illustrated in fig. 3 where three different resonators on one single film were measured. From an investigation of the critical state of our films it can be deduced that our films should not reveal such a pronounced inhomogeneity [8]. Therefore we suggest this effect to be due to an inhomogeneous distribution of substrate faults causing misoriented grains on the chip.

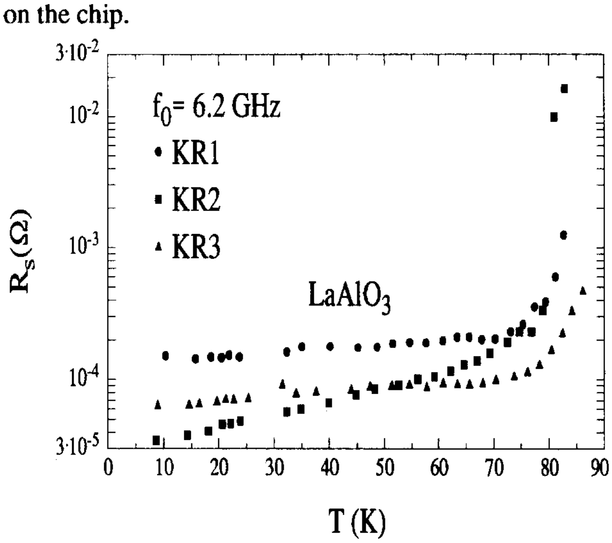

Fig. 3: Temperature dependent surface resistances evaluated from three different resonators on one film.

Despite of this scatter of the absolute R_s value a clear dependence of R_s on the average j_c at 77 K was obtained which is especially pronounced at critical current values below 10^6 A/cm^2. This is shown in fig. 4.

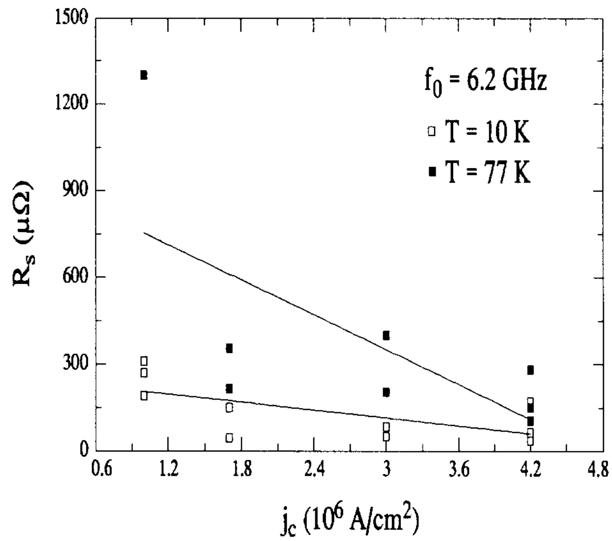

Fig. 4.: Dependence of R_s on the critical current density (77 K) at 77 K and at 10 K for several films.

Another important fact concerning the application of the films for microelectronic applications as well as for the characterization of the crystallinity of the films is the dependence of the surface resistance on the surface magnetic field. As a result we obtained that for high critical current densities above $4\cdot10^6$ A/cm^2 at 77 K the intrinsic properties of the material show up. This is expressed by a constant surface resistance up to surface magnetic field values of 8 mT.

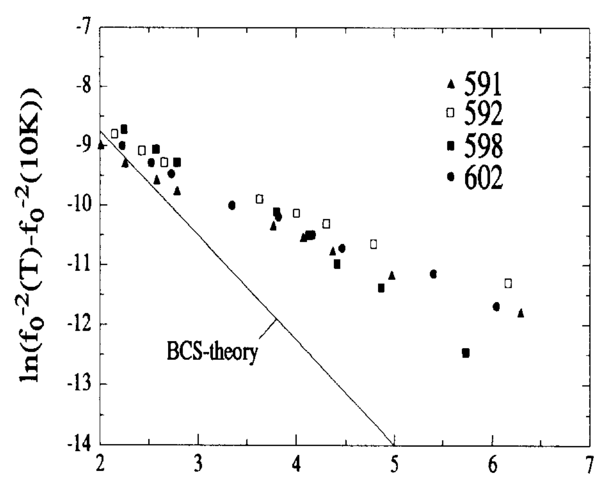

Fig. 5: Normalized value $\ln(f_0^{-2}(T) - f_0^{-2}(T_0))$ as a function of T_c/T together with the values according to the BCS theory.

For the understanding of the underlying physics as well as for applications in high bandwidth signal transmission the value of the energy gap is of importance. This was determined from the temperature dependence of the resonance frequency in a temperature range $T < T_c/2$. Fig. 5 shows the value of $\ln(f_0^{-2}(T) - f_0^{-2}(T_0))$ as a function of T_c/T together with the theoretical value for a BCS-like gap of $2\Delta(0)/k_BT_c = 3.5$. From the slope of the straight line we got values for $2\Delta(0)/k_BT_c$ between 1.2 and 2.2. From the slight decrease of the $R_s(T)$ in fig. 2 the value of the energy gap was determined according to the BCS theory to 1.2 [7].

These values are considerably lower than the values determined from FIR and Raman measurements [9,10] but they are consistent with recently published values from HF measurements [1]. The Raman investigations are widely accepted while there also exist FIR and tunneling measurements [11,12] which resulted in lower energy gaps in the range of $2\Delta(0)/k_BT_c \approx 1$. This was interpreted as an additional gap in the CuO chains while the higher gap values correspond to the gap in the CuO_2 planes [13]. However, there remains a controversial discussion about the existence of a second energy gap in this material which we cannot undoubtably decide from our measurements. Rather we assign our results to crystalline imperfections in the films. Consequently, an energy gap in this low range should be sensitive to the crystalline quality of the material while we cannot exclude the interpretation of a second gap in the CuO chains. We assume that for a reliable determination of the energy gap the problem of growing single crystalline material has to be solved. To conclude it should be noted that measurements of high quality films in cavity resonators resulted in a dependence of the low temperature R_s behaviour on the oxygen content and disorder of the samples which might also play a role in this context [14].

4. Summary

In summary, we have grown YBCO thin films and performed microwave measurements on structured films in the range between 5 and 20 GHz. From these measurements the surface resistance and the magnetic penetration depth were determined using an analytical approximation to a partial wave synthesis. The lowest R_s values were in the range between 105 $\mu\Omega$ and 250 $\mu\Omega$ at 77 K and at 6.2 GHz. Furthermore, a significant scatter by a factor of two was found for the R_s values on one film. The magnetic penetration depths were between 160 nm and 270 nm. The surface resistance turned out to be sensitive to the critical current density at 77 K. Additionally, the value of the energy gap was determined to $2\Delta(0)/k_BT = 1.2 - 2.2$ which we attribute to the still imperfect sample quality. However, a second energy gap in the CuO chains still remains under consideration.

Acknowledgement

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