MM-WAVE SURFACE RESISTANCE MEASUREMENTS OF HTS FILMS USING A HIGHLY SENSITIVE CAVITY

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ABSTRACT

For the precise measurement of surface resistance of high temperature superconductors (HTS) a systematic design theory for truncated cone cavities is given. This kind of cavity avoids mode degeneration, which is a problem if cylindrical cavities are used. Also it offers a considerably higher sensitivity with regard to surface resistance measurements. A measurement system at 52GHz is described and results for three samples are given. The residual resistances of the three films were in the range of 5mΩ to 10mΩ at 52GHz. A measurement accuracy of ±0.5mΩ has been achieved.

INTRODUCTION

The precise determination of surface resistance of high temperature superconductors at mm-wave frequencies is of interest for both practical and theoretical reasons /1/. Among various methods /2,3,4/, the cavity method, where a part of the inner surface is replaced by a sample, has several advantages. The field distribution can be derived analytically for simple cavity shapes and deviates only negligibly from the theoretical field distribution under the influence of a superconductive sample. The sample substrates do not need to be of special shape, and patterning is not necessary. Because of the closed arrangement no radiation occurs and fringing fields are negligible or absent. For the measurement, the changes in both quality factor and resonance frequency may be evaluated /3/.

However, despite of the conceptual simplicity of the measurement and the evaluation procedure, problems are often encountered in practise with respect to measurement accuracy and reproducibility.

For precise Q_0 measurements and relative accuracies in the range of a few per mille, it is vital to take measurements at a resonance frequency where the cavity is free of mode degeneration. This is particularly necessary since any distortion of the resonance curve due to perturbation reduces the measurement accuracy considerably. Truncated cone cavities have been found to be free of mode degeneration and have been employed for the measurement with added advantages over the most commonly employed cylindrical cavities.

It is the purpose of this paper, to outline a design strategy which will lead to an optimum cavity design with regard to sensitivity and desired dynamic range, based on expected values of surface resistance.

TRUNCATED CONE CAVITY

Fig.1 depicts a cross-section of a truncated cone cavity for HTS measurements. The detailed analysis of this type of cavity has already been presented /5/.

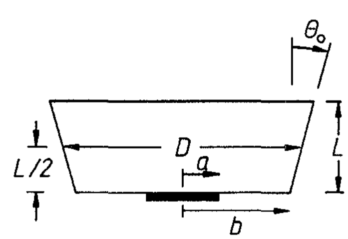

Fig.1 Cross section of truncated cone cavity

IF2

As it is the case with a cylindrical cavity only circumferential currents exist for H_{omn}-modes. However the corresponding E_{1mn}-modes of a truncated cone cavity are shifted in frequency i.e. no mode degeneration exists, except at some discrete frequencies.
The relative error in surface resistance as a function of relative error in measured unloaded quality factor Q_o can be expressed as

$$\left|\frac{dR_{Sa}}{R_{Sa}}\right| = \left(1 + \frac{R_{Su} \int_{Su} |H_t|^2 da}{R_{Sa} \int_{Sa} |H_t|^2 da}\right) \left|\frac{dQ_o}{Q_o}\right| \qquad (1)$$

where R_{Su} is the surface resistance of the cavity material and R_{Sa} is the surface resistance of the sample. Thus, optimizing the cavity geometrically with respect to measurement accuracy means minimizing the prefactor in parentheses in equation (1). As can be observed, the prefactor is minimal if

1) the surface resistance of the cavity material is low,

2) the surface resistance of the sample is high, or

3)the geometry dependent factor $\frac{\int_{Su} |H_t|^2 da}{\int_{Sa} |H_t|^2 da} = 1/S$ is small.

S is termed to be the sensitivity of the cavity.

Two important cases are considered in detail. Fig.2 shows the dependence of the sensitivity S on the inclination angle Θ_o. Positive values of Θ_o refer to the case where the sample serves as the topplate and negative values where the sample serves as the bottomplate. The best choice is to replace the bottomplate by the sample and to choose a large inclination angle. Of course, sensitivity increases with a larger sample diameter 2a or a higher resonance frequency $f_o = c_o/\lambda_o$.

Sufficient sensitivities are only possible for appropriate diameter to wavelength ratios. If this ratio is too small almost no sensitivity is attainable. But even in such a situation, the cavity can be modified to have an acceptable sensitivity, namely if only a part of the bottomplate serves as the sample. Calculations of the sensitivity enhancement by this step are shown in Fig.3. A sensitivity enhancement is also possible if there exists already an adequate a/λ_o value for b/a=1.
Another objective, not worked out here in detail, could be to optimize the cavity with respect to dynamic range, i.e. the range of measurable surface resistance values.

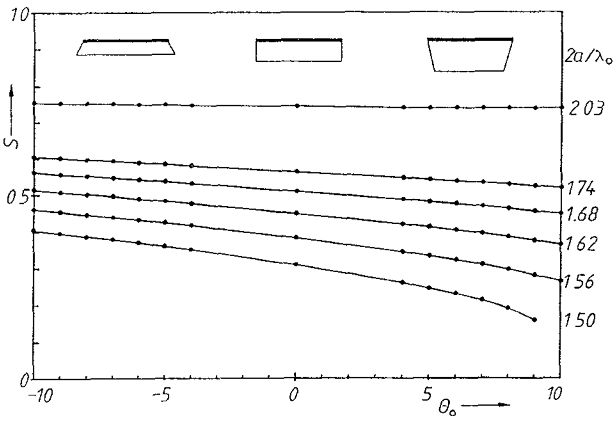

Fig.2 Sensitivity of cavity

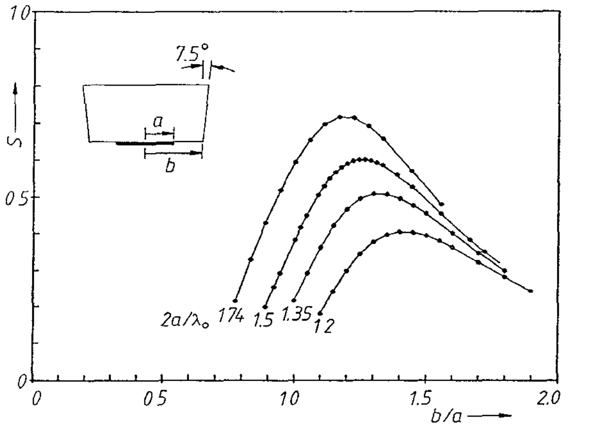

Fig.3 Sensitivity of improved cavity

EXAMPLE

Consider standard size 10mm*10mm samples and a 50 GHz synthesized source. Because of practical considerations, the measureable circular area of the sample is assumed to have an effective diameter of 9mm. This yields an a/λ_o ratio of 1.50. Using an inclination angle of $\Theta_o = 7.5^o$, the sensitivity is 0.2021 if the sample acts as the topplate and

0.3830 if the sample acts as the bottom plate. A cylindrical cavity would yield a sensitivity of 0.3091. It is obvious from Fig.3 that a further improvement would be possible by using a flatter cavity. Indeed, a cavity with a b/a ratio of 1.26 leads to a sensitivity of 0.6012. This is a surprising result because the sample covers only a part rather than the whole bottom plate. Comparing all the three cases considered above, it is evident that flattening the cavity increases the sensitivity. However, the sensitivity decreases if the cavity becomes too flat. Practically, presuming a cavity material surface restistance of 30 mΩ, a sample surface resistance in the range of 2mΩ and an accuracy of $3*10^{-3}$ for the quality factor measurements yields accuracies of ±0.45mΩ, ±0.24mΩ or ±0.15mΩ, for the three cases considered above.

A disadvantage is that a high sensitivity results in a reduction of the dynamic range, i.e. a reduction of maximum measurable surface resistances. Normally, the field distribution inside the cavity is approximated by the field distribution in the presence of lossless walls. This approximation is valid only for good conductors i.e. high Q_o values. Assuming a smallest allowed quality factor of 1000, this yields largest measurable surface resistance values of 3159mΩ, 2276mΩ or 1292mΩ, for the three cases under consideration.

MEASUREMENT SYSTEM

Measurements were carried out with the measurment system depicted in Fig.4.

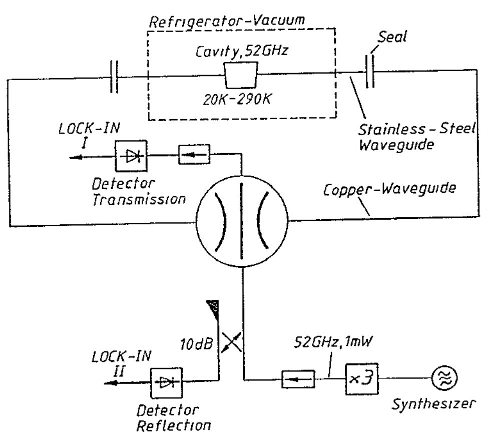

Fig.4 Schematic drawing of mm-wave Q_o measurement

With the waveguide switch in the straight position, as shown, the input power is adjusted to about 1mW. The other two positions are used to determine the attenuation due to the two feeding waveguides and one reflection coefficient at resonance. After that, the transmitted signal is measured over a given frequency range. The synthesizer is amplidude modulated and controlled in frequency by a computer. The output signals are measured with fin-line detectors and are recovered from noise by using two lock-in amplifiers. The measurement data are collected and stored in order to determine R_{Sa}, which is related to the unloaded quality factor by

$$Q_o = \frac{\omega_o \varepsilon \int_V |E|^2 dv}{R_{Su} \int_{Su} |H_t|^2 da + R_{Sa} \int_{Sa} |H_t|^2 da} \quad (2)$$

The unloaded quality factor of the cavity is calculated by using one of the reflection coefficients r_o, the transmission coefficient t_o at the resonance frequency and the loaded quality factor using equation (3):

$$Q_o = 2 \frac{1 - r_o}{1 - r_o^2 - t_o^2} Q_L \quad (3)$$

It is essential to measure the loaded quality factor Q_L most precisely because errors in it contribute directly to the error in the unloaded quality factor and therefore to the error in surface resistance. Errors in the measurements of r_o and t_o contribute only little to the total error. Therefore the Q_L value is determined by fitting the measured data onto the known theoretical resonance shape, given by

$$\frac{|S_{21}(f)|^2}{|S_{21}(f_o)|^2} = \frac{1}{1 + Q_L^2 \left(\frac{f}{f_o} - \frac{f_o}{f}\right)^2} \quad (4)$$

Our experience is that a bandwidth over which the transmitted signal is 10dB below the maximum value is a good choice.

The cavity was designed to give a moderate sensitivity and dynamic range. It is made of ordinary copper with the dimensions: Θ_o=7.5°, D=7.98mm and D/L=1.34. This leads to a resonance frequency of 52.0GHz and a sensitivity of 0.238. With an achieved accuracy of $4*10^{-3}$ for the quality factor measurement, a cavity material surface resistance of 30mΩ and sample surface resistances in the range of 2mΩ, equation (1) yields R_{Sa}=2mΩ±0.5mΩ. The highest measurable value is 3868mΩ.

The cavity is mounted onto the cold head of a closed cycle helium refrigerator. Temperature can be varied between about 20K and 290K.

RESULTS

We measured various films over temperatures between 25K and about 100K. Because of the limited dynamic range the pure normal conductive state is not measurable. Fig.5 shows typical measurements of two laser ablated films and one magnetron sputtered film on MgO. Residual resistances in the range of 5mΩ were achieved for films made by means of magnetron sputtering. The laser ablated films usually show higher residual losses of about 10mΩ, but have higher transition temperatures. A detailed description of the fabrication process is not given here, because the films were prepared elsewhere. A frequency shift of the cavity resonance frequency due to a superconductive sample was also observed but not yet evaluated.

CONCLUSIONS

A systematic method was presented to design cavities, which are suitable for the precise measurement of the surface resistance of HTS films.

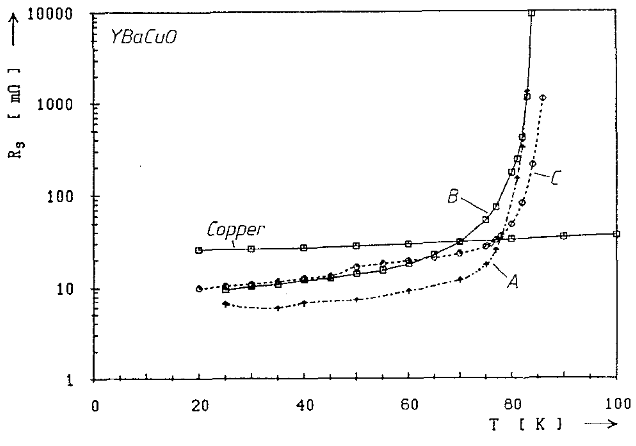

Fig.5 Typical measurements of surface resistance over temperature for sputtered films (A) and laser ablated films (B,C). Film thicknesses approximately 300nm.

Mode degeneration free truncated cone cavities were used. Design charts are given. The theoretical results were used to design a measurement system at 52GHz. Surface resistance measurements are presented for three YBaCuO films over temperature. The films show residual surface resistances in the range of 5mΩ to 10mΩ at 52GHz.

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