HIGH-T_c MATERIALS FOR MICROWAVE APPLICATIONS: UPDATE, PROGRESS, AND TRENDS

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Characterization methods and measurement results of the surface resistance of high-T_c materials are reviewed in this paper. After a brief introduction of the newly discovered HgBaCaCuO systems, material parameters like T_c, J_c, and R_s are discussed. Available surface resistance measurement methods are examined and categorised, followed by new results and progress achieved in the last two years.

KEY WORDS: **high-T_c superconductor, microwave property, surface resistance R_s**

1 INTRODUCTION

Although the discovery[1,2] of high-T_c superconductors has not yet had much direct impact on SRF (superconducting radio frequency) technology applications like accelerating cavities, the non-BCS like behavior in their surface resistance has imposed a great challenge to physicists and material scientists in the field.[3,4] Well-designed RF characterization methods which are accurate, highly sensitive, and reliable now become a necessity as the quality of high-T_c materials improves with improvements of fabrication methods.[5,6] As a result, there are more questions generated than answered as more results and characterization methods come into being. This calls for more systematic studies in microwave properties of high-T_c materials.

Results on the microwave properties of high-T_c superconductors were first published in the Third SRF Workshop[7] and reviewed by Müller and Klein in the Fourth and Fifth SRF Workshops.[3,4] Along with those available results, new results from the last two years will be presented in this paper and used to discuss the trend for future development. This paper is not, and does not intend to be, a complete review of the enormous amount of work in this fast growing field. Therefore, results will be mainly on $YBa_2Cu_3O_7$ and its surface resistance. Relevant parameters like penetration depth[8] and complex conductivity[9] will not be covered. Interested readers can use references used in the two previous review papers and this paper.

In Section 2, the newly discovered HgBaCaCuO systems will be introduced and important material parameters of T_c, J_c, and R_s will be discussed. In Section 3, surface resistance measurement methods will be reviewed. Design concepts of

cavities and resonators will be discussed by presenting cavity design evolution in the past. Measurement results will follow in Section 4, which will lead to the challenging question of what should be used to define a good superconducting film: the surface resistance or the power handling capability. Understanding this question is very important for future improvements in fabrication methods of high T_c superconducting thin films. Some application issues will be addressed at the end of the section. Finally, in Section 5, the present status and the challenges in the field will be summarized.

2 HIGH-T_c MATERIALS

2.1 New occurrences

Mercury-based high-T_c superconducting oxides ($HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$, where n is the number of CuO_2 layers) have been reported recently by several groups around the world. It is not surprising that the first member discovered is $HgBa_2CuO_{4+\delta}$ ($n = 1$), which is structurally simple and easy to make.[10] This material has a high transition temperature of 94 K, the highest among any of the one-CuO_2-layer systems known to date, and a relatively short distance between CuO_2 layers. Then $HgBa_2CaCu_2O_{6+\delta}$ ($n = 2$) was discovered, having a T_c of above 130 K as conjectured.[11] With a transition temperature of 147 K, $HgBa_2Ca_2Cu_3O_{8+\delta}$ ($n = 3$) under high pressure[12] broke the record set by $Tl_2Ba_2Ca_2Cu_3O_{10}$ in 1988.[13] These discoveries brought the number of distinct superconducting cuprate systems to nearly 40. They all have hole doped CuO_2 layers, and all showed a positive relationship between T_c and n (the number of CuO_2 layers).

Having a high critical current density J_c is as important as having a high-T_c, because T_c distinguishes the superconducting state from the normal state and determines its possible application temperature, while J_c determines whether the superconductor is applicable and its working temperature. The critical current density J_c of polycrystal $HgBa_2CuO_{4+\delta}$ was measured by Umezawa *et al.* This superconducting oxide has a low maximum intergrain J_c of 6×10^3 A/cm^2 and an intragrain J_c of 2×10^6 at 4 K.[14] From past experiences, it is known that higher intergrain J_c could be achieved in epitaxially grown thin films. Moreover, internal stresses of thin films might enhance the transition temperature, substituting the external pressure effect on bulk materials.[15] As pointed out by Umezawa *et al.*, compounds with double HgO layers are preferred for high grain-to-grain J_c values.[14] If there exists another family of superconductors Hg-2212 and Hg-2223, their T_c would also be expected to be higher. Doubtlessly, more work will be done in the near future on material synthesis to improve these two important material parameters.

In the meantime, physical properties and other material parameters such as thermodynamical critical field H_c, penetration depth λ, coherence length ξ, energy gap Δ, etc., also need to be investigated. This will be dependent on fabrication of high-quality single crystal samples and epitaxial thin films. With the advantage

of experience on previous high-T_c materials, it should take less time to have these parameters measured and see the results published.

2.2 Composition and structure effect on T_c and J_c

Because results on HgBaCaCuO systems are still preliminary, it is helpful to review briefly what is known about T_c and J_c before the discussion of surface resistance R_s of high-T_c materials.

Right stoichiometry is critical to the transition temperature T_c and the transition width ΔT_c. Extra metallic components in the fabrication process will result in impurity phases like CuO, $BaCuO_2$, and Y_2BaCuO_5. These impurities normally broaden ΔT_c and contribute to RF losses, yielding high residual surface resistance R_{res} of high-T_c superconductors. Impurity phases are usually reduced to a minimum in high-quality epitaxial thin films and single crystal samples, which are required for studying intrinsic material properties. In addition, the dependence of T_c on oxygen content δ has been well established.[16] With decreasing oxygen content (δ from 0 to 1), $YBa_2Cu_3O_{7-\delta}$ changes from a superconductor to a semiconductor, and then an insulator.

For all the high-T_c materials discovered so far, the best J_c of polycrystal bulk samples is at least two orders of magnitude lower than that of high-quality thin films. This shows the importance of grain alignment in improving J_c. With a short coherence length ξ in high-T_c oxides, the grain boundaries between grains serve as Josephson junctions and limit the intergrain J_c. Pinning is weak due to short coherence length, which has an influence on $J_c(H)$. These properties also affect microwave properties of high-T_c materials[16,17] such as the high residual surface resistance and the power handling capability in future high-T_c microwave components.

2.3 Surface resistance of superconducting materials

Thanks to improvements of fabrication processes, high-quality high-T_c superconductors can be fabricated reproducibly, having high transition temperatures (> 90 K) with a sharp transition (< 1 K) and a comparable J_c ($> 10^6$ A/cm^2)[5,18] to that of low temperature superconductors like Nb. On the other hand, the improvement in sample quality has generated more unanswered questions about microwave properties. In the following part, background knowledge on the surface resistance of low T_c and high-T_c superconductors will be summarized.

RF losses in a conductor or a superconductor are characterized by surface resistance R_s, or the real part of surface impedance Z_s:

$$Z_s = R_s + iX_s \tag{1}$$

where X_s is the surface reactance. According to BCS theory or the more frequently used two-fluid model,[19] there are two kinds of conducting carriers in a superconductor. One is the superconducting carriers, or Cooper pairs, and the other is the normal conducting electrons. The normal electrons are unpaired due to thermal

excitation, and are only a small fraction of the total conducting carriers at low temperature. On one hand, the Cooper pairs are responsible for the supercurrent, which limits the electromagnetic field penetration within a much smaller penetration depth than the normal skin depth. On the other hand, the interaction between the penetrating field and the small fraction of normal electrons contributes to the surface resistance R_s, which is four to five orders of magnitude smaller than that in a normal conductor.

A strict solution of the electrodynamics of BCS superconductors was given by Mattis and Bardeen.[20] Programs calculating surface resistance based on the theory were written by Halbritter[21] and Turneaure.[22] There are three external environment parameters and five intrinsic material parameters which determine surface resistance. They are temperature T, frequency f, surface magnetic field H_{rf}, and transition temperature T_c, energy gap $\Delta(0)$, coherence length ξ, London penetration depth λ_L, mean free path ℓ, respectively. For $T < T_c/2$, the surface resistance of low-T_c superconductors can be expressed as

$$R_s = R_{BCS} + R_{res} \simeq A \left(\frac{\omega^2}{T}\right) \exp(-\alpha T_c/T) + R_{res} \qquad (2)$$

where R_{BCS} is the contribution from unpaired electrons, and R_{res} is the so-called residual resistance, which is independent of temperature and frequency for low-T_c superconductors like Nb and Pb. Loss mechanisms of R_{res} are quite difficult to identify.[23]

One difference in surface resistance between the superconducting state and the normal state is the frequency dependence. The former (R_{BCS}) is proportional to f^2, the latter to $f^{1/2}$. The other difference is that BCS surface resistance is so small at low temperatures that the residual resistance can finally play an important role. This is the reason that great effort has been put into surface treatment to reduce the residual resistance of Nb cavities. For Nb, R_{res} can be reduced to several nΩ.

Since the mechanism of high-T_c superconductivity is still unknown, there is no definite understanding of the surface resistance of high-T_c materials. It has been known that R_s has a slow temperature dependence below $T < 0.9\,T_c$. Moreover, it has been suggested that the frequency dependence of R_{res} is quadratic.[3,4]

It may be worthwhile to point out that although this f^2 scaling was supported or suggested by a large number of data points at 4.2 K and 77 K, and might also be proved by some simplified theoretical model, the so-called f^2 "law" has never been verified carefully and systematically. Data collected in the early stage (see Sec. 3.1) have problems like scattered sample qualities, different measurement methods, and most importantly, unspecified error bars or accuracies. However, the f^2 "law" has been so completely accepted by some material scientists that some publications do not even mention in their results the actual measurement frequency f_0 and the measured R_s value. This was, of course, not the intention when the frequency dependence data were collected and compiled. To be precise, the f^2 dependence observed in many different laboratories is only valid in limited conditions. For example, the frequency dependence relies strongly on the surface magnetic field H_{rf}.

Another problem becoming common is that some groups try to get material parameters like ξ, λ and ℓ from BCS fit programs. These numbers are not convincing because it is not clear that high-T_c superconductors are BCS superconductors. As can be seen from this and the previous two review papers, the study of microwave properties of high-T_c materials is still at the level of examining the influence of the external parameters, i.e., the dependence on temperature, frequency, and surface magnetic field. Similar to the well accepted f^2 scaling "law", it is more or less a postulation. Using such a simple postulation to discuss such a complex system is probably misleading and may not be the right direction to pursue.

Based on what has been said above, results reviewed and discussed in this paper are limited to those systematic studies which are useful for one to investigate first principles and application potentials.

3 CHARACTERIZATION METHODS OF SURFACE RESISTANCE

3.1 Historical review

So far, RF characterization methods have gone through three different stages:

(1) Right after the discovery of high-T_c materials in 1987, polycrystal samples were first measured with existing TE_{011} and TM_{010} cavities.[24,25] No special consideration was given to the placement of the sample.

(2) Measurement methods were improved by placing the sample in the high magnetic field location.[26] Cavities were specially designed and fabricated for samples with different shapes,[27,28] and RF characterization was done by many groups around the world by 1990.[29] The measurement method itself has progressed from qualitative measurement of superconducting transition to quantitative measurement of surface resistance.

(3) As the sample quality is further improved, high sensitivity and accuracy become a necessity. New types of cavities have been made by having high field concentrated around the sample to improve the sensitivity, eliminating unwanted extra losses like indium joints and edge losses, and employing the calorimetry method to measure power losses of the sample.[30,31] For planar resonator measurement methods, there are similar improvements in numerical modeling and processing methods.[32]

Measurement results on polycrystal samples, highly-aligned polycrystal samples, and epitaxial thin films were reviewed in the last two workshops. The characterization methods were also reviewed and discussed.[3,4] In the following parts, cavities and planar resonators will be discussed from first principles and basic concepts.

3.2 Characterization fundamentals

According to the definition (1) and the Poynting theorem, power dissipation per unit area P_s inside a conductor is proportional to the surface resistance R_s:

$$P_s = \frac{1}{2} R_s H_{rf}^2 \tag{3}$$

where H_{rf} is the RF surface magnetic field. For a given area S, the power dissipation is:

$$P = \frac{1}{2}\int_S R_s H_{rf}^2 \, da \tag{4}$$

It can be seen that measuring R_s is converted to measuring P under a given surface magnetic field H_{rf}. Two methods are usually used to measure P. One is the microwave method, which measures the quality factor, and the other is the calorimetry method, which measures the temperature change due to the RF dissipation of the sample.

3.3 Cavity method

For bulk materials and thick films which can be used to make a cavity, surface resistance can be measured as has been done on copper and niobium. For planar samples with limited sizes, the end-plate replacement method and the Q-perturbation method are usually used.

3.3.1 Cavity made from one material The technique to measure surface resistance from a uniform cavity has been well developed in the last thirty years.[33] Surface resistance R_s can be measured by measuring the quality factor Q:

$$Q = \frac{\omega U}{P} = \frac{G}{R_s} \tag{5}$$

where G is the geometry factor of the cavity, which can be calculated analytically (for TE_{011}) or with programs like URMEL or MAFIA.[34] Q can be measured with either a network analyzer ($Q = f/\Delta f$ for $Q < 10^6$) or the transient response method ($Q = \omega\tau$ for $Q > 10^6$).[35] Surface resistance as low as several nΩ has been measured, corresponding to a Q of the order of 10^{11} for a TE or TM cavity. The measured surface resistance is an weighted average value for the whole cavity, because (5) assumes a uniformly distributed R_s on all the surfaces. For characterization purpose, TE_{011} or TE_{0mn} modes are normally used because there is no current across the joints between the cylindrical part and the end plates. For applications in accelerators, TM_{010} is used because of its axial accelerating field.

3.3.2 End-plate replacement method The end-plate replacement method is usually used in a cylindrical cavity in its TE_{011} modes. When one end-plate is replaced with a different material (designated by "i" below), the Q of the cavity is changed from

$$\frac{1}{Q_c} = \frac{1}{Q_1} + \frac{1}{Q_2} + \cdots = \sum_i \frac{1}{Q_i} \tag{6}$$

to

$$\frac{1}{Q_c'} = \frac{1}{Q_1'} + \frac{1}{Q_2} + \cdots = \frac{1}{Q_1'} + \sum_{i\neq 1} \frac{1}{Q_i} \tag{7}$$

where Q_c is the Q of the cavity and Q_c' is the Q of the cavity with the substituting end plate. Defining a filling factor

$$\eta_i \equiv \frac{1/Q_i}{1/Q_c} = \frac{G}{G_i} = \frac{\int_{S_i} H_{rf}^2\, da}{\int_S H_{rf}^2\, da} \tag{8}$$

where $S = \sum_i S_i$ is the total area of the cavity, and subtracting (6) from (7), gives:

$$\frac{\Delta R_s}{R_s} = -\frac{1}{\eta_i}\frac{\Delta Q}{Q_c'} \tag{9}$$

where $\Delta R_s = R_s' - R_s$ and $\Delta Q = Q_c' - Q_c$. For a given accuracy of $\Delta Q/Q_c'$, which is determined by the measurement method of Q, the filling factor η_i needs to be maximized for a smallest measurable ΔR_s. This is why samples are always placed in a strong field region. Moreover, a superconducting parent cavity is usually used, so that the resolution ΔR_s is as small as possible for a given η_i. For TE_{011} cavities, η_i is usually 20% to 30%, depending on the ratio of the height and the diameter.[36,37]

3.3.3 Q-perturbation method Because the size of the sample usually has strong influence on the resonant frequency, the end-plate replacement method usually works at frequencies higher than 18 GHz due to the limited sizes of high-quality high-T_c samples. The Q-perturbation method is therefore widely used to measure the surface resistance of crystal samples and epitaxial thin films of high-T_c materials. The filling factor of such an arrangement is normally no more than 1%, and could be much smaller depending on the sample's size. In such a case, the superconducting parent cavity is always used to improve measurement sensitivity.

Another way to improve the sensitivity is to use the calorimetry method. The RF losses on the sample are proportional to the temperature change measured by highly sensitive temperature sensors. It was reported that carbon resistor sensors have a high resolution of detecting 1 μK of temperature change at 2 K.[38] The method is extremely sensitive and excludes other possible losses like coupling probe losses and indium joint losses. Therefore, it not only provides the most sensitive R_s measurement in the world, but also gives the most accurate and reliable results.[31]

As mentioned earlier, for high sensitivity, the entire sample has to be placed at the maximum magnetic field location. This is one major disadvantage because some extra unwanted losses may be created on the sample edge and between the interface of the thin film and the substrate, or even in the substrate itself. The current flowing on the sample surface has to flow over the edge, and the sample quality at the edge is usually poor. In addition, any component of the current flowing parallel to the edge will cause a very large magnetic enhancement.

Another disadvantage is that the sample is normally not in a cylindrically symmetric position inside the cavity. This makes it impossible to calculate G_i (geometry factor of the tested sample) with URMEL because the program requires cylindrical symmetry. Three-dimensional codes such as MAFIA do not have sufficient resolution to deal with small samples. Therefore, a calibration run, using a sample which has a known R_s and is the same size as the tested one, is always needed. This is

not an easy task for an accurate measurement and will introduce some error in the result. In fact, some unusually good surface resistance results in the past might come from unreliable calibration runs.

3.3.4 Improvements of cavity method Tab. 1 gives an outline of several types of cavity design. The TE_{011} cavity is most popularly used due to its field distribution. It has been employed to measure all kinds of samples: crystal chips, epitaxial thin films, thick films, and bulk samples. For crystal chips, due to their very small sizes, the calorimetry method was used, which improved the sensitivity from 1 mΩ of microwave measurement to 15 $\mu\Omega$.[26] For epitaxial thin films, both the Q-perturbation method and the end-plate replacement method are used depending on their sizes. For the Q-perturbation method, the normally used superconducting parent cavity limits the temperature range of the measurement. For the end-plate replacement method, the resonant frequency is high due to limited sample sizes ($>$ 18 GHz). Cavities made from high-T_c thick films or bulk materials can have a low frequency, but their quality is not as good as that of crystal samples and thin films.[36,37] Therefore, a TE_{011} cavity is a convenient setup to measure the R_s of high-T_c samples with different sizes and shapes.

One interesting modification of the TE_{011} cavity is the truncated cylindrical cavity.[39] It breaks the degeneration of the TE_{011} mode and the TM_{111} mode, but still keeps the cylindrical symmetry so that the joint losses can be kept to the minimum. Because the parent cavity is made of copper, it can be used to measure the temperature dependence of surface resistance. However, its sensitivity is limited by the R_s of copper and is 0.5 mΩ for a 20 mm diameter sample.

To lower the resonant frequency and increase the filling factor, a superconducting $\lambda/4$ TEM coaxial cavity was used by Delayen *et al.* of Argonne.[28] The frequency is 820 MHz, and the filling factor is improved to 1.32%. The sample is placed on the bottom plate, where the magnetic field concentrates. The maximum magnetic field in the cavity can reach 300 Gauss before magnetic breakdown. Its sensitivity is 20 $\mu\Omega$ for a 24 mm diameter sample. The same as other Q-perturbation methods where samples are placed on strong magnetic field positions, the geometry factor of the sample cannot be calculated. Calibration with similar stainless steel samples was done.

A superconducting triaxial niobium cavity was designed and fabricated at CEBAF after studying the existing problems mentioned above.[31] Fig. 1 shows the structure of the cavity. The central coaxial line is excited in the TEM mode at a frequency of 1.5 GHz. The center line is tapered for two reasons: (1) it improves the filling factor of a 25.4 mm diameter sample by one order of magnitude, and (2) it makes the coupling problem in such a compact structure trivial (inside dimensions: 10 cm by 5 cm). The sample is placed in the center of the top plate, and its geometry factor is calculable with URMEL. The filling factor is as high as 1.19% for a 1 mm gap between the sample and the cone tip. The field distribution was carefully designed so that there is negligible magnetic field, or RF losses, at the edges of a 25.4 mm diameter sample. To further improve the sensitivity, 16 carbon resistor sensors were used on the other side of the cavity and the thickness

of the niobium wall between the two vacuum chambers was as thin as 1.6 mm. The calorimetry method, compared with those used in superfluid helium,[38] is more sensitive and reliable. Given a 2 μK resolution limit at 2 K, the calorimetry method has a detection threshold of 0.02 nΩ under a surface magnetic field of 52 Gauss. Its reliability is guaranteed by both the microwave method and the calorimetric method using 16 temperature sensors.

3.4 Planar resonators

Planar resonator methods are getting more and more popular in measuring surface resistance R_s and penetration depth λ of high-T_c materials.[40] The resonators are normally made from the same kind of material, with no limitation from parent cavity losses. Therefore, they can be used to measure the temperature dependence of surface resistance, except near T_c where coupling is too weak. When used to measure penetration depth λ, the methods are more sensitive to λ change than cavity methods.[8] Surface resistance is measured by measuring the quality factor Q, which is given by

$$\frac{1}{Q} = \frac{R_{ss}}{G_s} + \frac{R_{sm}}{G_m} + p_e \tan\delta \tag{10}$$

The three contributions to Q come from superconducting, conducting, and dielectric materials in the resonators. Without metallic enclosure, the second term can be viewed as total radiation losses. G_s and G_m are the geometry factors of the superconductor and the conductor inside the resonator, which are determined by the current distribution on their surfaces and the spatial distribution of the stored electromagnetic energy in the resonator (normally $G_m \gg G_s$). R_{ss} and R_{sm} are the corresponding surface resistances, p_e is the fraction of the electric energy in the dielectric material, and $\tan\delta$ is the dielectric tangent value. Neglecting the radiation losses ($G_m \to \infty$, or negligible losses on metallic enclosure surfaces) and dielectric losses ($\tan\delta \to 0$), it yields the same relation of $R_s = G/Q$ as (5).

3.4.1 Parallel plate resonator The parallel plate resonator method was first employed to measure surface resistance by Taber.[41] It does not need any sample preparation and the current distribution within the resonator can be accurately calculated. With a Teflon sheet between two parallel high-T_c thin films, its quality factor is determined by

$$\frac{1}{Q} = \frac{\beta R_s}{s} + \alpha s + \tan\delta \tag{11}$$

where s is the thickness of the Teflon sheet, $G = s/\beta = \pi\mu_0 f s$, αs comes from radiation losses, and $\tan\delta$ comes from dielectric losses ($p_e = 1$). With a 12.5 μm Teflon layer, the sensitivity is as low as 5 $\mu\Omega$, and its upper limit is 1 - 2 mΩ due to limitation from the coupling. The method has later been modified to measure complex conductivity.[9] Another modification of the method uses liquid nitrogen to substitute for the Teflon layer, having an adjustable spacing s from 200 μm to zero.[42]

Because it is the only planar resonator method which does not need a patterning process, the parallel plate resonator method is being adopted by more and more groups. It is necessary to point out that in the normal measurement range, the accuracy of the R_s measurement is determined by those of Q and s, while near the detection limit, the accuracy is affected by that of $\tan\delta$ of the Teflon sheet. The accuracy of Q is determined not only by the network analyzer but also by the true weak coupling between the coupling probe and the resonator. The accurate measurement of such a small spacing is also challenging.[44] Moreover, accurate calibration of $\tan\delta$ with different spacings is not an easy task for measurements near the detection limit.

3.4.2 Stripline resonator The stripline resonator method has been used to study the surface resistance and the power handling capability of high-T_c thin films prepared under different conditions in MIT Lincoln Laboratory.[43] Fig. 2 shows the cross section and the top view of the resonator. The losses of the two ground plates are two orders of magnitude lower than the losses of the center conductor, and the losses in the dielectric material are negligible compared to those of YBCO thin films. Its resonant frequency is determined by the length of the center line, and different modes can be used to study the frequency dependence of surface resistance (1 - 17 GHz). The lowest surface resistance measured is 3 $\mu\Omega$ at 4.3 K and 1.5 GHz. According to the current distribution calculation,[32] the current density concentrates on the edges of the center line. This makes the stripline resonator very suitable to study the power handling capability (R_s vs H_{rf}) of superconducting thin films. In addition, measurements of the patterned films provide more information for future applications.

3.5 Summary

Both the cavity methods and the planar resonator methods have advanced remarkably in the last two years. So far, there is no definite preference among them. The final research goal determines which method to use, with the help of the general discussions above.

The cavity or resonator design is based on the measurement principle given by (5) and (10). First, the field or current distribution needs to be known. Second, the unwanted sources of power dissipation have to be eliminated or reduced to a negligible level. Third, the placement of the sample should not create any change about the current or field distribution. Otherwise, the method would have to be calibrated by itself with a different material having well known properties. In addition, the measurement results at least have a 5% to 10% measurement error.

The major difference between the planar resonator and the cavity resonator is the surface-to-volume ratio. In general, planar resonators are more convenient to use and require smaller cryogenic volume. Their sensitivity is limited by radiation losses and dielectric losses. The cavity method has large volume for sample arrangement, providing more flexibility for different requirements of a variety of kinds of samples. However, it is not as flexible as the planar resonator method when used to measure

R_s dependence on temperature, frequency, and surface magnetic field.

4 RESULTS OF SURFACE RESISTANCE MEASUREMENTS

Since the last workshop in Hamburg, there has not been much new and systematic work done about surface resistance measurements. Most of the published results are R_s values of high-T_c materials made by different fabrication methods. In this section, the effect of oxygen content and order on R_s, the power handling capability of improved YBCO samples, and work on thick films will be reviewed. Then some of the application issues will be addressed.

4.1 Effect of oxygen content and order

Orbach *et al.* studied the effect of oxygen content and order on surface resistance.[16] Fig. 3 shows four different R_s vs T curves corresponding to different annealing and treatment procedures. Two conclusions were obtained: (1) the transition curve is broadened due to oxygen deficiency, and (2) the value of surface resistance is increased by oxygen disordering. The drop can be understood with a two-gap theory, which predicts a second gap due to the CuO chain.[45] Samples which were reported to show the second drop were prepared by high-oxygen-pressure sputtering, and were measured at 18.7 GHz and 87 GHz.[30] Surprisingly, the second drop was not observed when similar samples were patterned into stripline resonators. Neither was it observed after heat retreatment.[46] It seems that there are more unanswered questions than the oxygen deficiency and disordering explanation.

4.2 Power handling capability

Fig. 4 showed the relationship between surface resistance and surface magnetic field measured by the stripline resonator method. As can be seen, films made by different methods have about the same magnitude of surface resistance at zero field, but their responses to the surface magnetic field are quite different. The standard off-axis results are poorer than those of cylindrical magnetron sputtering samples. Using 25 $\mu\Omega$ as a reference, the H_{rf} values are about 280 Oe and 1800 Oe respectively. In addition, substrate temperature seems to have an important effect on the power handling capability. The experimental results can be understood with the coupled-grain model,[47] which predicts another order of magnitude of improvement in H_{rf} (Fig. 5). However, the improvement may occur after understanding the difference between the off-axis films and the cylindrical sputtering films.

The granular behavior of $R_s(H_{rf})$ was also studied in NbTiN, NbN, and Nb thin films.[48,49] The nonlinear electrodynamics in a granular system will draw more attention in the future as more experimental results are available.

4.3 Thick film development

Several preparation methods have been used to make high-T_c thick films: electrophoresis, melt-processing, and plasma spraying.[50,51,36] None of them will be introduced here. The major problems of thick film preparation are related to the composition and the granularity of the high-T_c materials. They are how to reduce or eliminate the impurity phases and how to achieve a good alignment of grains. Hein *et al.* fabricated high-quality thick films under high magnetic field. The sample sizes are mainly 25.4 mm diameter.[50] Button *et al.* obtained best results by using ZrO substrates to improve the alignment.[51] The surface resistance of their melt-processed thick films fabricated on yttria stabilized zirconia oxide was reduced to 1.09 mΩ at 5.66 GHz, with a total surface area of 230 cm^2. For any real application, the substrate has to be flexible and have good thermal conductivity. Silver and nickel-coated copper substrates have been tried by Ezura *et al.* of KEK.[36] At 3 GHz, their results are comparable to copper at 77 K. Zhang *et al.* eliminated Al_2O_3 powder in their fabrication process. The surface resistance is improved by one order of magnitude and the field penetration through their $\sim 30\,\mu$m thick film has disappeared.[52]

It is good news to thick film research that Foltyn *et al.* have achieved a J_c of larger than 10^6 A/cm^2 at 75 K in 6 μm thick thin films. This shows that superconducting property does not have to deteriorate as films are made thicker. However, even though the J_c of thick films could be improved, the power handling capability shown above will still be a problem for cavity applications.

4.4 Application issues

From what has been discussed above, it is obvious that applications of high-T_c materials are able to be utilized first in the low field region and at 77 K, while power handling capability needs to be improved further. Reliability in preparing large and uniform thin films will still be a major task.[53] Substrate selection for both thin films and thick films will also draw more attention.[54] Moreover, environment resistance of high-T_c materials is still a problem for future applications.[55]

Components made from high-T_c materials have excelled those made from copper at 77 K. New components like antennas have been developed in many laboratories.[56] Delay lines and filters have also been fabricated and studied.[57] As a whole, the progress achieved in thin film fabrication methods still comes from the empirical approach.

5 CONCLUSION

Today, surface resistance measurement of high-T_c superconductors has become one of the fundamental characterization methods. As a material parameter, surface resistance R_s is no less important than the critical temperature T_c and critical current density J_c. However, there are more problems about R_s than about T_c and

J_c. This is partly because there is no standardized measurement method of R_s. This will become more serious as more and more new superconducting materials are discovered.

Systematic studies of the microwave properties of high-T_c materials will have a high priority in the future. The measurement results are not only important to theoretical understanding about the superconducting mechanism, which is still an unsolved problem, but also critical to its application in electronics. After the natural evolution from getting measurement results to improving measurement methods to achieving high sensitivity, reliable as well as convenient methods will come out in the next stage. Planar resonator methods will find more and more applications as they become more sophisticated.

Even though the definition of good thin films is still unclear, samples with good enough properties have been prepared in many laboratories around the world, and will be used to fabricate a variety of superconducting components working at 77 K. For real applications, more effort will be put into solving problems on reproducibility and reliability of high-quality high-T_c materials.

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TABLE CAPTIONS:

Table 1: Comparison of different cylindrically symmetric cavities

FIGURE CAPTIONS:

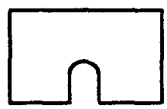
Figure 1: Configuration of the niobium triaxial cavity.

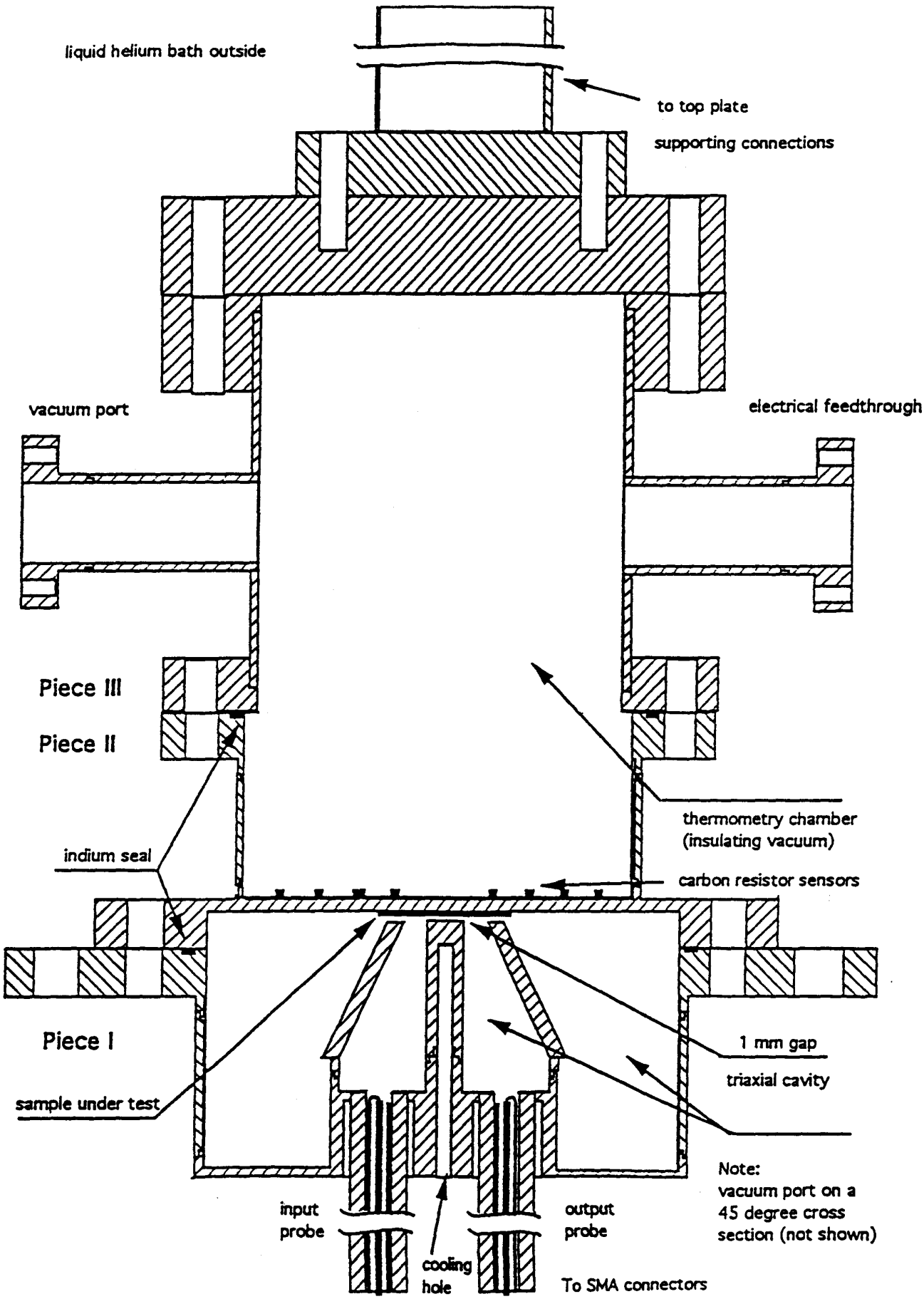
Figure 2: Stripline resonator.

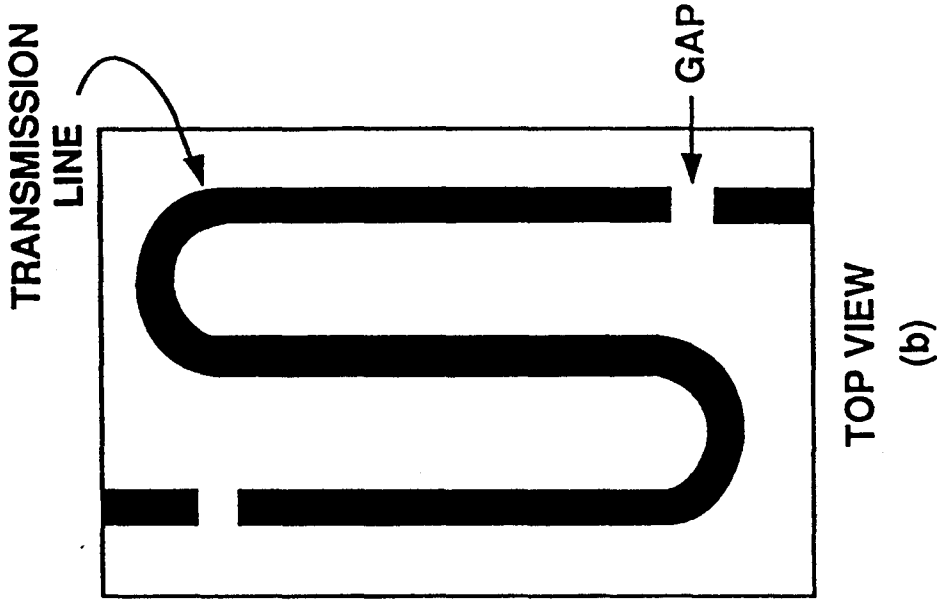
Figure 3: $R_s(T)$ as a function of oxygen content and order (•: as prepared, ◇: 1 h, 500 ^{0}C, 1 bar O_2, quench cooled, +: 0.5 h, 250 ^{0}C, 1 bar O_2, slowly cooled, △: 1 h, 500 ^{0}C, 0.15 bar O_2, slowly cooled).

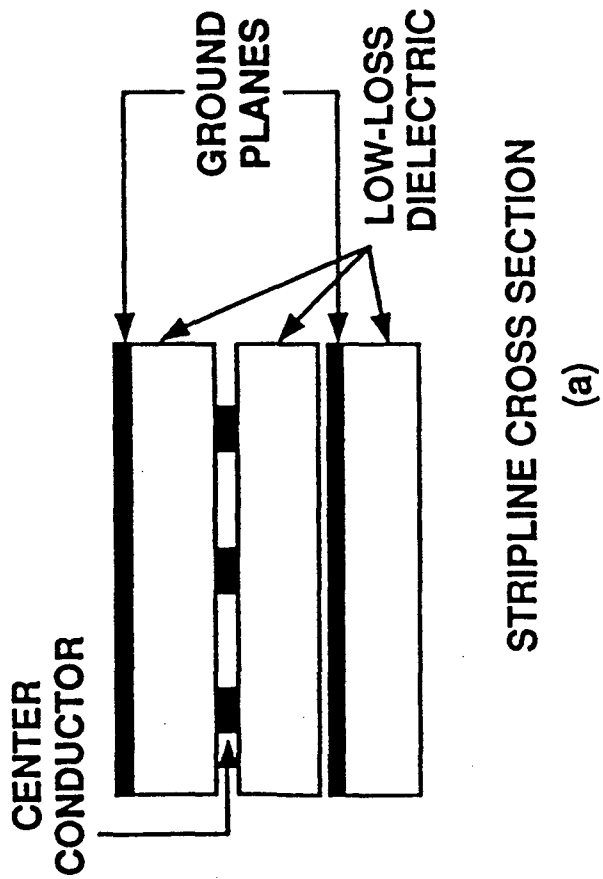
Figure 4: R_s vs H_{rf} of different thin films.

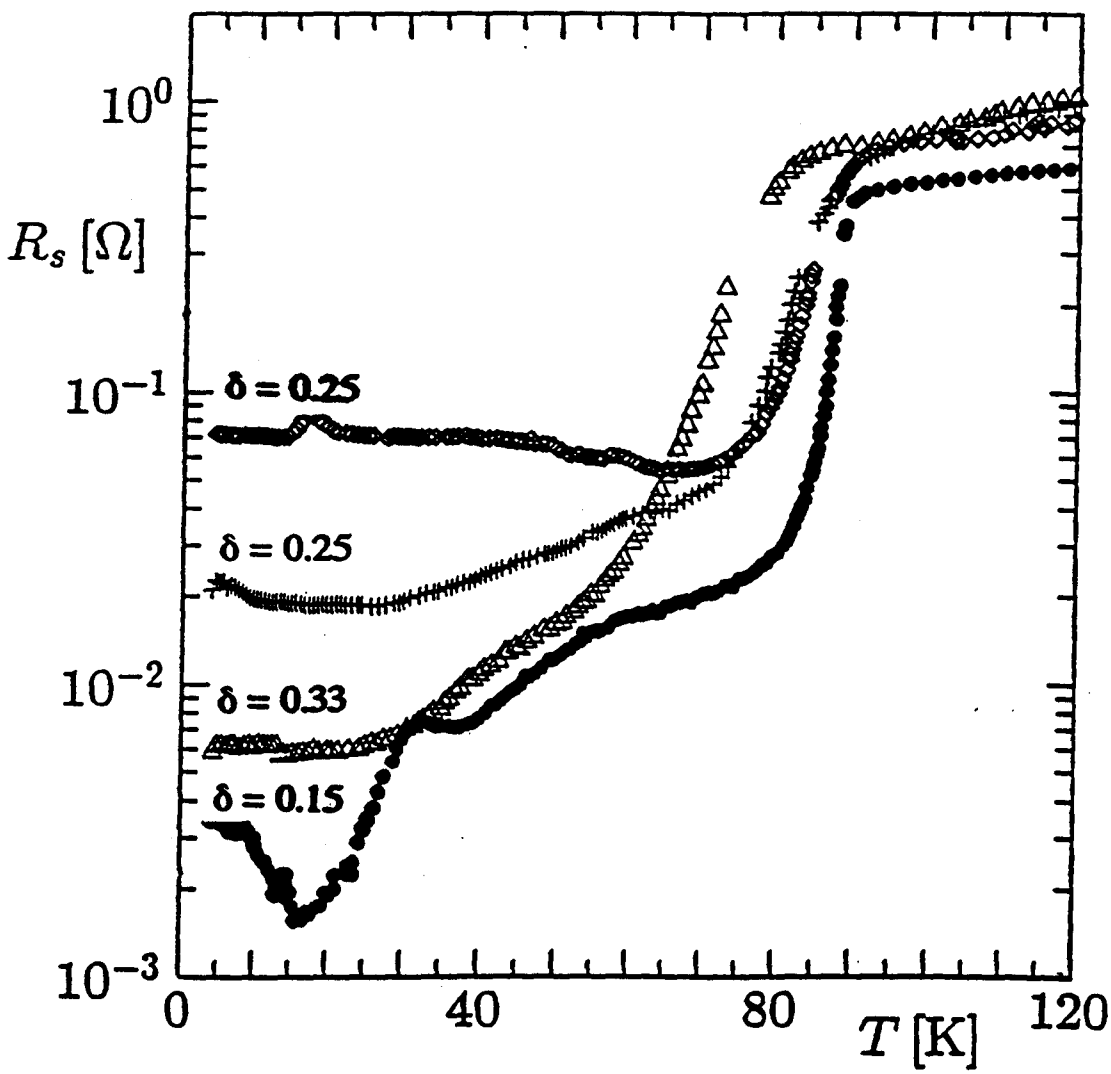
Figure 5: $b_R(T)$ of different thin films as compared to the theoretical value.

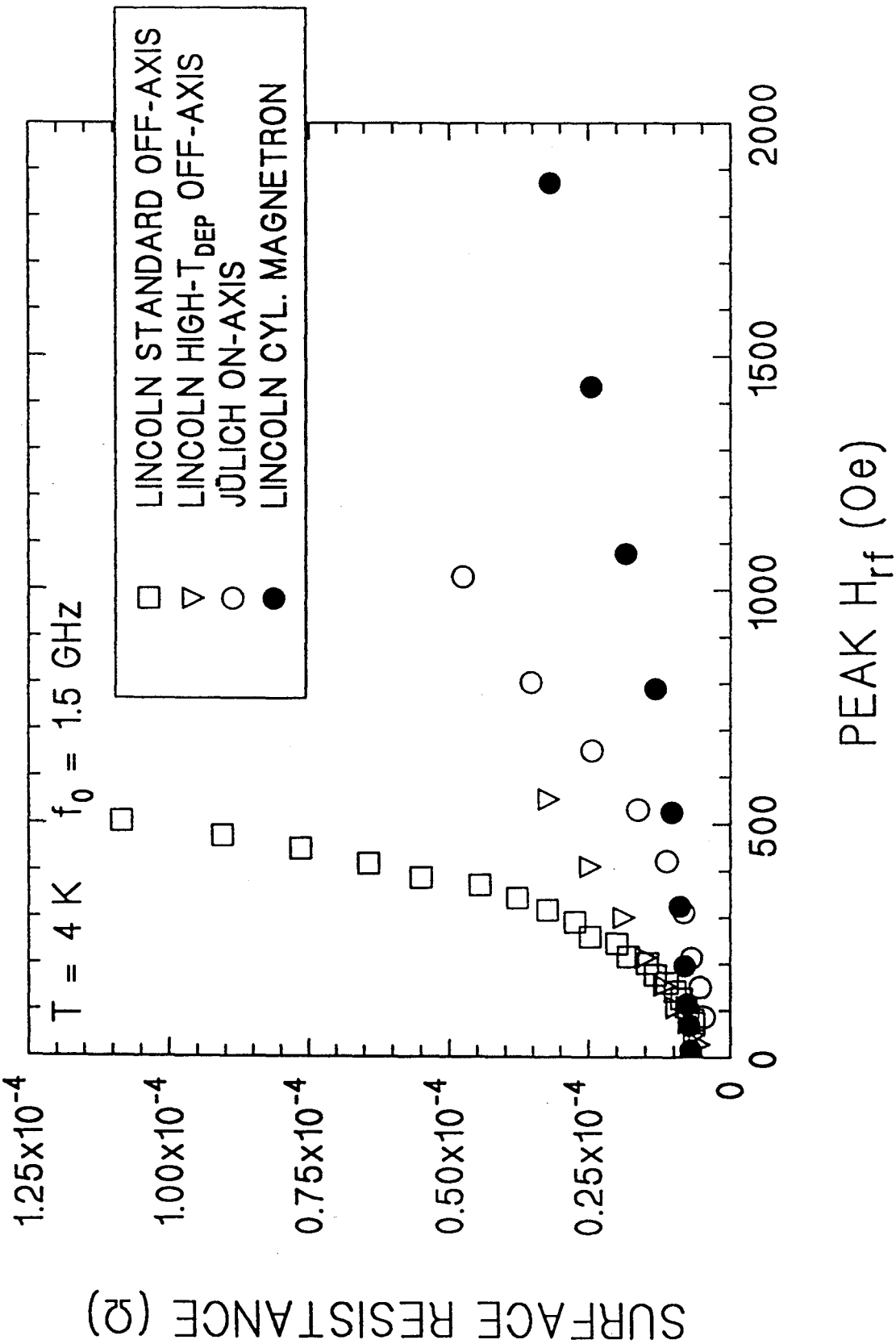
TYPE	TE_{011}	Modified TE	$\lambda/4$ TEM	Triaxial TEM
shape				
material	Nb, Cu, YBCO	Cu	Nb	Nb
f [GHz]	> 3	52	0.82	1.5
Rs vs *T*	Yes	Yes	4.2 K	2.0 K
η_i	0.001 to 1	0.238	0.013	0.012
sample area	crystal size, cavity size	20 mm dia.	25, 36 mm dia.	25, 50 mm dia.
Rs resol.	1 mΩ, 15 μΩ	0.5 mΩ	20 μΩ	0.02 nΩ
advan-tage	most popular, no joint current	no mode degeneration, improved sensitivity	low frequency, improved sensitivity	ultrahigh sensitivity, accurate, low frequency
disad-vantage	high frequency	high frequency	edge effect, η_i calibration	working at 2 K

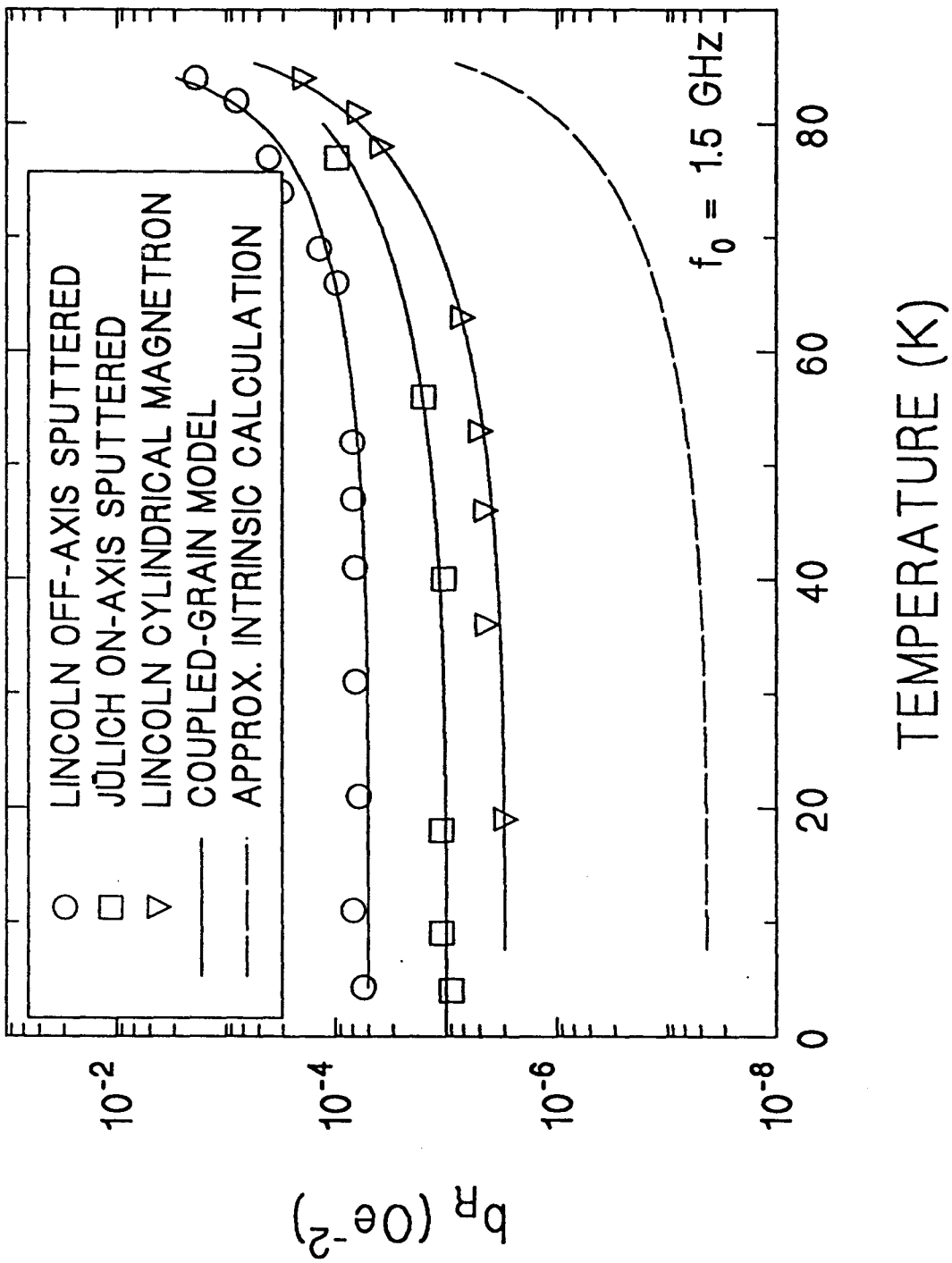

liquid helium bath outside
to top plate
supporting connections
vacuum port
electrical feedthrough
Piece III
Piece II
thermometry chamber
(insulating vacuum)
indium seal
carbon resistor sensors
Piece I
1 mm gap
triaxial cavity
sample under test
Note:
vacuum port on a
45 degree cross
section (not shown)
input
probe
output
probe
cooling
hole
To SMA connectors


TRANSMISSION LINE
GAP
TOP VIEW
(b)


GROUND PLANES
LOW-LOSS DIELECTRIC
CENTER CONDUCTOR
STRIPLINE CROSS SECTION
(a)


10^0
$R_s\,[\Omega]$
10^{-1}
$\delta = 0.25$
$\delta = 0.25$
10^{-2}
$\delta = 0.33$
$\delta = 0.15$
10^{-3}
0
40
80
120
T [K]


LINCOLN STANDARD OFF-AXIS
LINCOLN HIGH-T_{DEP} OFF-AXIS
JÜLICH ON-AXIS
LINCOLN CYL. MAGNETRON
T = 4 K f_0 = 1.5 GHz
SURFACE RESISTANCE (Ω)
1.25x10^{-4}
1.00x10^{-4}
0.75x10^{-4}
0.50x10^{-4}
0.25x10^{-4}
0
500
1000
1500
2000
PEAK H_{rf} (Oe)


LINCOLN OFF-AXIS SPUTTERED
JÜLICH ON-AXIS SPUTTERED
LINCOLN CYLINDRICAL MAGNETRON
COUPLED-GRAIN MODEL
APPROX. INTRINSIC CALCULATION
f_0 = 1.5 GHz
b_R (Oe^{-2})
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
20
40
60
80
TEMPERATURE (K)