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TEMPERATURE AND FIELD DEPENDENCE OF THE RF SURFACE RESISTANCE OF HIGH T_c MATERIALS*

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The RF behavior of $YBa_2Cu_3O_{7-x}$ is being evaluated for its potential as a material used to make microwave cavities for particle accelerators. Single crystals and thin films are under study at 1.5 and 6 GHz. The best results have been obtained using the crystals of Schneemeyer, et al., which show a residual resistance below $5x10^{-4}$ Ω at 6 GHz at 77K. This is substantially below the resistance of 77K copper. The resistance of these crystals at the superconducting transition drops more than two orders of magnitude within a few degrees of T_c. The sharpness of this drop is comparable to that of niobium. It is believed that these crystals are still far from ideal and that their properties deteriorate with time, but they are of much higher quality than the other forms of YBCO studied. Progress is being made by our collaborators towards producing thin films with useful RF properties. Compared with films of a year ago the sharpness of the superconducting transition has increased substantially although the residual losses are still high. Our measurement techniques are now sensitive to as little as 20 mm^2 of material with a resistance of 20 μΩ.

Introduction

The emergence of high T_c superconductors over two years ago caused an explosive renewal of research in all areas of superconductivity. The possibility of using a cryogen other than liquid helium made it incumbent upon those already working in applied superconductivity to evaluate these new materials. In the intial excitement it was hoped that these materials might be quickly brought to bear on current applications. These high hopes have since subsided and the work of solving the complex problems which limit the utility of oxide superconductors is now underway. Despite their drawbacks, the high T_c superconductors remain an important class of materials and as such their properties should be measured periodically in order to evaluate any progress made in their development.

The superconducting RF (SRF) group at Cornell decided at the outset of its high T_c research program that it would be a misallocation of its available resources to attempt to fabricate its own oxide superconductors. Instead, we concentrated on developing the capability to measure the RF properties of interest to the accelerator community of any and all material which might be shared with us. The test vehicle that resulted has been described elsewhere [1,2] and is shown in Figure 1. This approach lead to establishing several fruitful collaborations which enabled us to measure the best materials available produced by a variety of techniques. The samples whose properties appear in this paper were generously offered by: W. Cooke (Los Alamos) [3], H. Hart (GE) [4], T-W Noh (Cornell) [5], R. Pandey (Texas A&M) [6], L. Schneemeyer (AT&T) [7], and T. Venkatesan (Belcor) [8]. It should be emphasized that the comparisons made between the different samples are not intended as a reflection on the relative capabilities of our collaborators, but rather as an indication of the variabilities which may be encountered during fabrication and of the potential offered by the different forms of these materials. We wish to credit those whose long and diligent efforts have enabled us to evaluate the suitability of high T_c materials for SRF use.

Single Crystal Measurements

Early in the course of high T_c superconductivity it became evident that single crystals would be the most desirable materials to measure. The problem of anisotropy could be avoided and insight into the intrinsic properties of these oxides could be obtained. It had been hoped that once single crystals became available their properties would not be affected by their source. Unfortunately this was not the case. By far the most impressive properties measured to date belong to the AT&T single crystals. Figure 2 compares R_s at 6 GHz as a function of temperature for $YBa_2Cu_3O_{7-x}$ single crystals from four sources.

*Work supported by the National Science Foundation with additional support from the US-Japan collaboration.

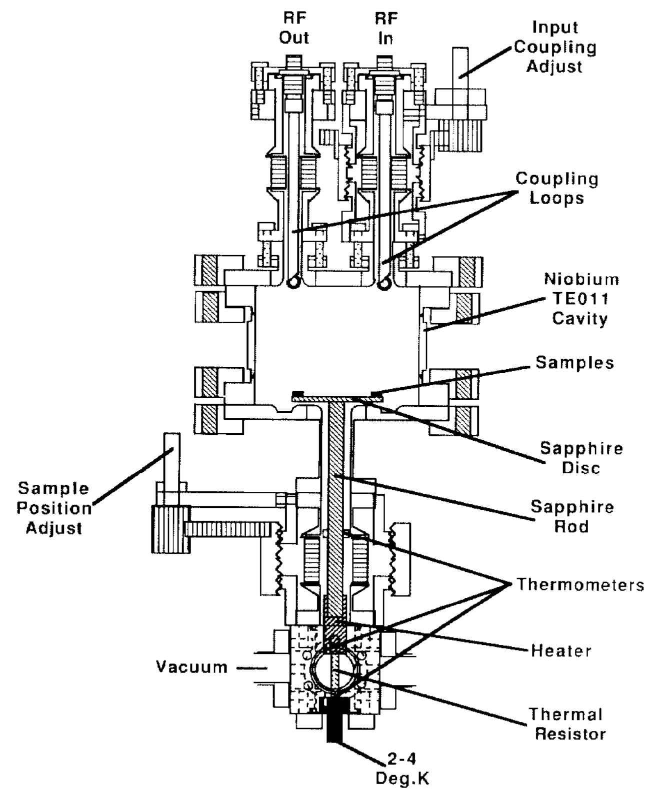

FIGURE 1 The 6 GHz TE_{011} niobium cavity used to measure R_s as a function of temperature. The temperature of the sample can be varied from the bath temperature to room temperature. The sample can be positioned at any point in the cavity.

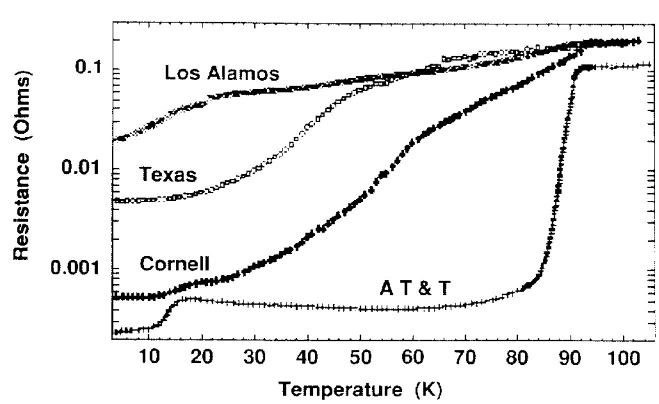

FIGURE 2 R_s as a function of temperature for single crystals from four sources. Data obtained at 6 GHz.

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The normal state resistance is quite high compared with copper and can vary from sample to sample. It should be noted that an absolute calibration of R_S for the Cornell, Texas and Los Alamos crystals was very difficult to perform due mostly to their small total surface area. A normal state value for R_S of 200mΩ has been assigned to these crystals which should be accurate to within a factor of two. The value of 125mΩ for the AT&T crystals was determined by calibration with a niobium foil of approximately the same surface area.

The sharpness of the drop in R_S at T_c also varies quite strongly from sample to sample. Using energy dispersive spectroscopy (EDS) on an SEM, no large variations in Y, Ba, Cu or O composition between the Cornell and AT&T crystals could be identified, nor were there any measurable amounts of additional elements. Since the RF magnetic field probes a much thinner layer of the crystal surface than does EDS, the possibility remains that the crystal surface may not be stoichiometric or may be contaminated. It was assumed that since all the crystals had the characteristic plate-like morphology, the c-axis was perpendicular to the plane of the crystals and to the RF magnetic field. The variations in microtwinning, or in stresses introduced when the crystals were removed from the crucible in which they were grown, between the different samples is unknown.

While the sharpness of the drop in resistivity is of importance, it is the limiting, or residual, R_S that the materials reach upon further cooling that is important for SRF applications. The resistance of the AT&T crystals fell to ~.5mΩ at 77K. This is at least a factor of 8 below copper at the same temperature and frequency. The 77K resistance shown in Figure 2 for these crystals, however, is limited by the MgO substrate used to support the crystals implying that .5mΩ is only an upper limit for the crystal resistance at this temperature. At about 16K the MgO substrate undergoes a transition and becomes even less lossy. The resistance value of .2mΩ at 3K is limited by a combination of crystal, substrate and cavity losses, again implying that the crystal resistance is even lower. The Cornell crystals eventually reach a residual R_S of about .5mΩ at 3K. These two sets of crystals demonstrate that there is not a strong connection between the sharpness of the superconducting transition and the residual resistance. Similar observations have been made by others working with sintered pellets [9].

Separate calorimetric measurements made early in our investigations indicated that the residual resistance of the AT&T crystals was as low as 15μΩ at 3K. Unfortunately, it was noted that the residual R_S increased by as much as a factor of 10 during the following months. The causes of this remain unclear. In an 8.6 GHz cavity it was determined that R_S of one of the Cornell crystals at 1.5K was ~20μΩ. This indicates that the low residual of the AT&T crystals was not anomalous and that the intrinsic residual resistance of YBCO crystals may be acceptably low.

The 77K resistance of the AT&T crystals justifies considering a future alternative to superconducting niobium at lower frequencies. Scaling .5mΩ with f^2, as warranted by frequency dependent data from others [9], a Q of 8.6×10^7 for a YBCO 500MHz accelerator cavity operating in liquid nitrogen can be expected. Multiplying by the factor of 25 gain in Carnot refrigerator efficiency between 77K and 4K, the equivalent Q of such a cavity becomes 2.2×10^9. This is comparable to that achieved with niobium cavities at 4K.

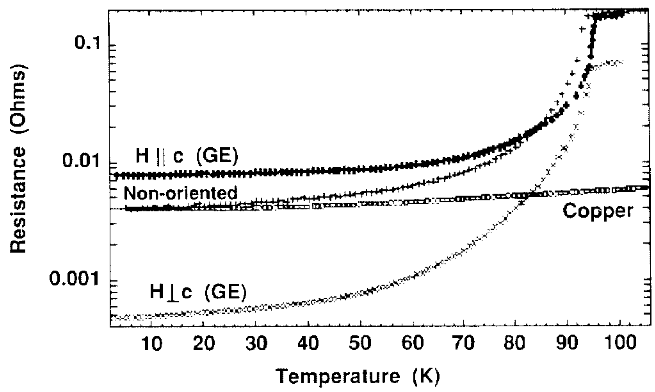

FIGURE 3 R_S as a function of temperature for sintered YBCO. Data obtained at 6 GHz.

It is well known that the DC critical current density is very sensitive to applied magnetic field. The RF analog is that the surface resistance can be affected by the strength of the applied RF field. The field dependence of R_S for the oriented and non-oriented pellets, and the AT&T crystals are shown in Figure 4. The lack of sensitivity of the AT&T crystals is quite encouraging. In contrast, the benefits gained by producing an oriented pellet are quickly removed by increasing the strength of the RF field.

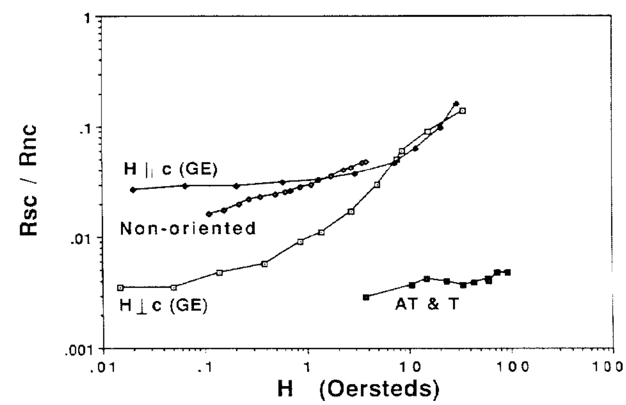

FIGURE 4 The dependence of R_S on the RF magnetic field intensity. Data obtained at 6 GHz. Sample temperatures less than 20K.

Sintered Pellets

There were two distinct drawbacks to measuring the properties of sintered material, both stemming from its polycrystalline nature. Until recently, pellets consisted of randomly oriented single crystals. This meant that all measurements were made on crystals aligned favorably simultaneously with those aligned unfavorably to the sampling field. The other difficulty lay with understanding the deleterious contribution of grain boundaries. The problem of maintaining the proper stoichiometric also existed when preparing pellets. The latter two problems are somewhat related and considerable progress has been made in the fabrication of non-oriented pellets [9]. Techniques have also been developed to produce oriented pellets. In Figure 3 we compare an early non-oriented pellet with copper and an oriented pellet from GE.

The advantage to aligning the grains in a pellet can be seen immediately. While the sharpness of the superconducting transition is not greatly affected, the residual resistance is. When the RF H field is perpendicular to the c-axis of the crystal structure, i.e. in the a-b plane, the residual resistance is about 18 times lower than when the H field is parallel to the c-axis. The 3K resistance in the lower set of data is ~.45mΩ. This is within a factor of two of the residual resistance of the AT&T crystals.

Films on $SrTiO_3$

$SrTiO_3$ has long been the choice of substrate for thin films as it allows for the growth of oriented, epitaxial films. The RF losses of $SrTiO_3$, however, are strongly temperature and frequency dependent. Measurements made at 1.5 GHz, shown in Figure 5, demonstrate that $SrTiO_3$ losses sufficiently diminish above ~60K to allow for evaluation of films deposited on substrates made of it. It should be noted that the vertical axis of this graph covers more than 4 orders of magnitude.

The data obtained from the laser-ablated Belcor film indicate that it is possible to obtain a sharp RF superconducting transition from a thin film. Similar results have been obtained by the group at Wuppertal using another film at 86 GHz [10]. The transitions of all other films we have measured have been broader, regardless of substrate. The sharpness of this transition is comparable to that of the AT&T crystals. The minimum resistance of this film could not be determined properly because of the $SrTiO_3$ substrate. The limited data available also suggest that post-annealing a film greatly increases R_S.

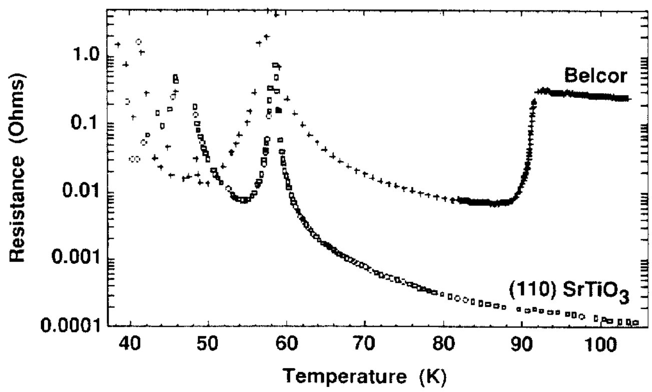

FIGURE 5 R_s as a function of temperature for a YBCO film on a (110) $SrTiO_3$ substrate. Data obtained at 1.5 GHz. The bare substrate data have been scaled so that the peaks at 61K coincide.

Summary

The intrinsic properties required for consideration of SRF applications of superconducting oxides appear to be available. The formidable task of obtaining these properties in material of a useful form still remains although measurable progress is being made.

Acknowledgements

We wish to reiterate our appreciation for the samples given to us by our collaborators. Their enthusiasm and openness have made it possible for all involved to make progress towards bringing high T_c materials closer to useful applications. The laboratory assistance of J. Potts is also gratefully acknowledged.

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