PHYSC 51149
18 October 2003 Disk used

ARTICLE IN PRESS

No. of Pages 6, DTD = 4.3.1

ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Physica C xxx (2003) xxx–xxx

PHYSICA C

www.elsevier.com/locate/physc

Surface resistance measurements of single domain $YBa_2Cu_3O_x$

Awanish K. Mishra [a], N. Hari Babu [b], P. He [c], D. Isfort [d], X. Chaud [d], Altan M. Ferendeci [a], D.A. Cardwell [b], Robert Tournier [d], David Mast [e], Donglu Shi [c,*]

[a] *Department of Electrical and Computer Engineering and Computer Science, University of Cincinnati, Cincinnati, OH 45221-0012, USA*

[b] *IRC in Superconductivity, University of Cambridge, Cambridge, UK*

[c] *Department of Chemical and Materials Engineering, University of Cincinnati, Cincinnati, OH 45221-0012, USA*

[d] *Consortium de Recherches pour l'Emergence de Technologies Avancées, CNRS, BP 166, F-38042 Grenoble Cedex 9, France*

[e] *Department of Physics, University of Cincinnati, Cincinnati, OH 45221-0012, USA*

Received 16 June 2003; received in revised form 6 October 2003; accepted 6 October 2003

Abstract

Large single domain $YBa_2Cu_3O_x$ materials have been successfully fabricated with superb RF properties by employing the seeded melt growth (SMG) method. Grown samples were diced, polished and oxygenated. Surface resistances of various samples were measured by a cavity perturbation technique. A sapphire loaded parallel plate cavity was used. Measured results indicate that surface resistance of the SMG bulk samples approach that of high quality YBCO thin films.

1. Introduction

Cellular telecommunications systems and networks have expanded rapidly in recent years, which require much higher efficiency of both equipment components and use of available electromagnetic spectrum. However, conventional filtering techniques do not perform well enough to provide the level of filtering that will be required by dense, heavily used RF communication systems. More selective filters with lower insertion losses must be designed to satisfy this rapidly increasing demand in telecommunications. The recent development of extremely low loss RF components using high temperature superconductors (HTS) such as $YBa_2Cu_3O_x$ has succeeded in achieving the extremely low surface resistance at the appropriate cellular frequencies. The current technologies in fabrication of HTSs for RF applications have been primarily the thin film approaches that can produce well-textured $YBa_2Cu_3O_x$ materials with extremely low surface resistance [1–6]. HTS thin films deposited by laser ablation or sputtering are lithographically processed to implement many type of planar microwave filters. Even though films deposited directly on substrates such as $LaAlO_3$ and MgO have very

* Corresponding author. Tel.: +1-513-5563100; fax: +1-513-5561004.
E-mail address: shid@email.uc.edu (D. Shi).

0921-4534/$ - see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/j.physc.2003.10.004

low ohmic losses, the loaded Q of these filters is dictated by the loss tangent of the dielectric substrate material. On the other hand, for low loss substrates such as r-cut sapphire which has an extremely small $\tan\delta$, the presence of buffer layers decreases the overall conductivity of the YBCO film [7]. The recent development in seeded melt growth (SMG) of $YBa_2Cu_3O_x$ (YBCO) has shown great promise in the fabrication of RF components with superb RF properties. Not only has the surface resistance of the SMG reached a value comparable to those of thin films, great advantages in utilizing this HTS material also lie in its suitability for mass production, easy control of device geometry, and low cost.

One of the concerns, however, for single domain YBCO is that it inherently contains second phase particles such as Y_2BaCuO_5 (2 1 1) which is an insulating phase. As RF waves travel through the surfaces, great loss can take place at these 2 1 1 regions. There have been few systematic studies so far to investigate the effects of 2 1 1 particles on RF losses. Recently, several new approaches have been developed to refine these 2 1 1 particles. Although the purpose of 2 1 1 refinements was for an enhanced flux pinning, we expect a significantly reduced RF loss in these materials

In this paper, we present experimental results on surface resistance measurement of single domain YBCO which can be used to implement a RF cavity resonator with very low losses.

2. Sample measurements

The seeded melt growth (SMG) method was originally developed for the purpose of producing large domains for levitation applications [8–14]. In SMG, based on the concept of crystal growth, a small "seed" crystal of a higher melting point (compared to that of the precursor) is placed on the surface of the partially molten precursor material, and the initial growth can take place at the interface between the seed surface and the liquid during cooling. Furthermore, the growth assumes the orientation of the seed and eventually proceeds throughout the entire precursor material. In this way, a large single-crystal-like domain can be obtained in the sense that the whole material possesses only one crystal orientation.

In this growth experiment, the samples were disc shaped pellets (50 mm in diameter and 30 mm in height). As precursors, 70 wt.% $YBa_2Cu_3O_x$, 30 wt.% Y_2BaCuO_5, and 0.15 wt.% Pt were used. These powders were thoroughly mixed and uniaxially pressed at 100 MPa into a disc shaped green pellet. The green pellet was sintered in air at 930 °C for 24 h. A $SmBa_2Cu_3O_x$ single domain was used as seed having a dimension of $2\times2\times1.5$ mm^3. The seed was put on the top of the green pellet before the growth process. The green pellet was placed on an alumina plate with an intermediate layer of Y_2O_3 powder to avoid liquid spreading on the interior surfaces of the furnace. A sintered thin plate of a mixture of $YbBa_2Cu_3O_x$ and $YBa_2Cu_3O_x$ was also used between the green pellet and the Y_2O_3 layer. The details about the YBCO single domain growth can be found in Refs. [8–10]. The single domain was then sectioned into a disc dimension of 15 mm in diameter and 3 mm in thickness. The top of the single domain disc was hand-polished down to 1/4 μm with diamond paste. The polished samples were annealed in flowing oxygen at 400 °C for 10 days.

3. Experimental

The surface resistance, R_s, measurements were based on a dielectric cavity perturbation technique [15–17]. The cavity was composed of a lower plate, a cylindrical sapphire puck and a movable upper plate. Fig. 1 shows the schematic representation of the cavity and the measurement set-up. The cavity was excited in the TE_{011} mode. In this mode, the fields decayed radially so that most of the fields were concentrated around the sapphire puck. Before a thin film sample is placed in the vicinity of the resonator, the electric field E_1 of the TE_{011} mode circulates around the z-axis. The corresponding magnetic field H_1 is partly radial and partly in the z-direction. After a sample has been brought in the position, the new fields E_2 and H_2 are assumed to retain the same symmetry. The fields within the dielectric puck are hardly changed, but the fields above the films are strongly

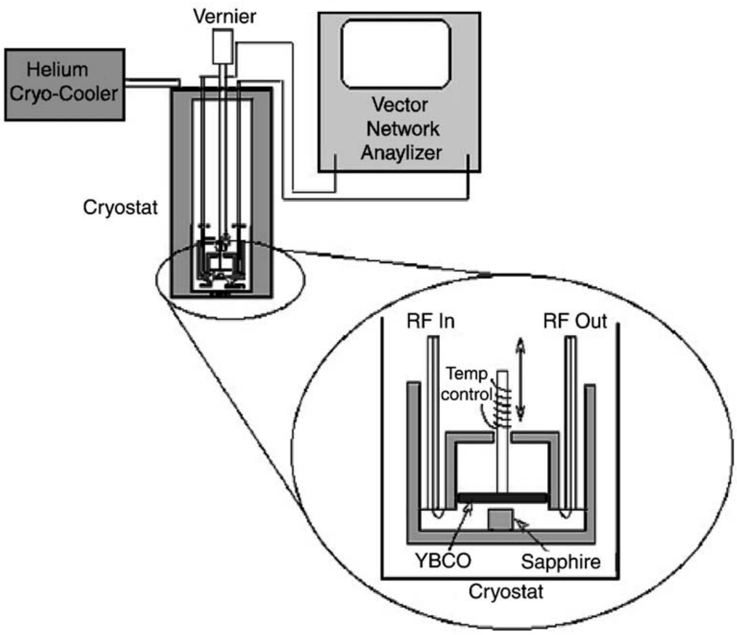

Fig. 1. Cavity perturbation set-up and details of the cavity.

screened; in fact, to a good approximation H_2 can be taken to be parallel to the front of the sample and zero behind it, and independent of the thickness and conductivity of samples.

The lower plate was Niobium and this plate was kept at constant liquid He temperature at 4.2 K during the measurements. The upper sample plate was connected to an external micrometer movement mechanism by a sapphire rod which was then connected to a heater. A sensor monitored the temperature. Heater–sensor combination set and controlled the measurement temperature of the sample.

The theory of cavity perturbation shows that as a result of the film, there is a change in the formal resonant frequency of the cavity and is given by:

$$\Delta f = \Delta f_0 + \frac{i}{2}\Delta f_B - \left\{ \frac{i}{2\pi} \int_S H_2 \cdot Z_s H_2 \, dS' \right\} \Big/ 4W = \frac{i}{2} \Gamma Z_s, \tag{1}$$

where the surface integral is taken over the lower surface of film, W is the total energy stored in the resonator. Note that real part of the formal frequency change Δf correspond to the shift in the actual resonant frequency f_0 and is associated with the surface reactance of the film, while the imaginary part of Δf is half the change in half power bandwidth, and is related to the surface resistance of the film. The quantity is known as *the resonator constant*; it is independent of the thickness and conductivity of the film, but varies with its height in the resonator.

In principal, it is necessary to calibrate the resonator constant by measuring a film of known surface resistance for each height of the film. However, over a considerable range of heights, the bandwidth changes introduced by the film are proportional to the corresponding frequency change Δf_0. This frequency change is very much larger than that associated with changes in surface reactance and is therefore, almost independent of the thickness and conductivity of the film.

The movement of the upper plate perturbed the cavity parameters. The changes in the resonant frequency and the bandwidth as a function of the upper plate movement provided the R_s data. There was no need for absolute cavity calibration. The

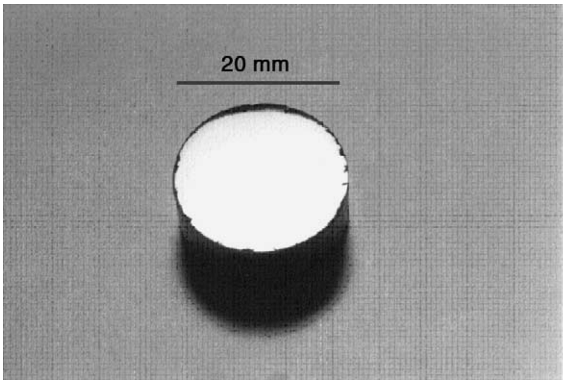

Fig. 2. Optical photograph showing SMG-processed single domain $YBa_2Cu_3O_x$.

measured data was compared to a known material, in this case copper whose surface resistance was already known as a function of the temperature ranges used for the HTS measurements.

4. Results and discussion

Fig. 2 shows the typical single domain YBCO with polished top surface. The sample was characterized with ac susceptibility and X-ray diffraction (XRD). The results indicate that the single domain sample has a single domain structure and a sharp superconducting transition near 90 K. These data can be found in our previously published papers [8–14].

It was essential that TE_{011} mode was properly identified among other possible modes of the cavity. In order to locate the resonant frequency associated with the TE_{011} mode for the dielectric resonator shunted with top and bottom ground planes, the structure was simulated using Ansoff HFFS® software.

The parameters used for the simulations were: Sapphire cylinder with $\varepsilon_r = 9.4$, diameter: 6.99 mm, and height: 3.42 mm.

In order to verify the TE_{011} mode, fields of various modes were plotted. Two verifications were necessary for the TE_{011} mode. First was based on the premise that E-fields circulated around the z-direction, i.e., in the ϕ-direction, and the H-fields were partly radial and partly in the z-direction. A second verification of the TE_{011} mode was that the fields decayed radially away from the sapphire cylinder. Simulated fields satisfying these requirements are shown in Fig. 3. In these simulations, it was assumed that the top and bottom plates had infinite conductivity.

Various simulations were made by moving the top plate. Simulated change in the resonant frequency as a function of sample separation from the top of the sapphire rod is shown in Fig. 4.

The R_s values of SMG YBCO samples were measured using the apparatus shown in Fig. 1. Fig. 5 shows the changes in ΔBW as a function of Δf_0 at a fixed temperature for a given sample. The slope of the HTS sample is compared with the slope of a known Cu sample.

Fig. 6 shows the change in the Q of the cavity as a function of the top plate distance away from the

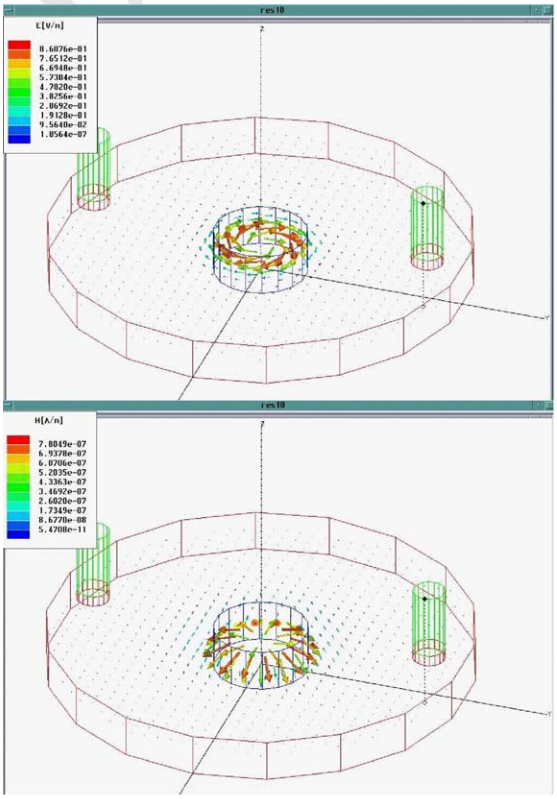

Fig. 3. Simulated electric and magnetic field vectors for TE_{011} mode.

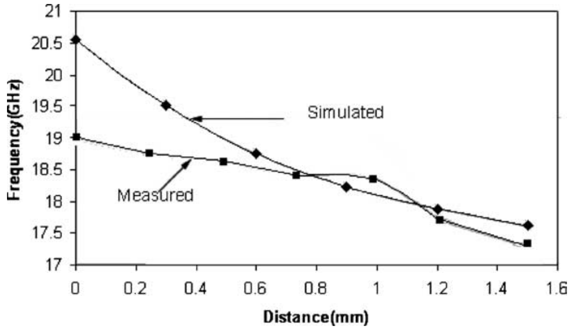

Fig. 4. Simulated and measured resonant frequency of the cavity as a function of upper plate distance.

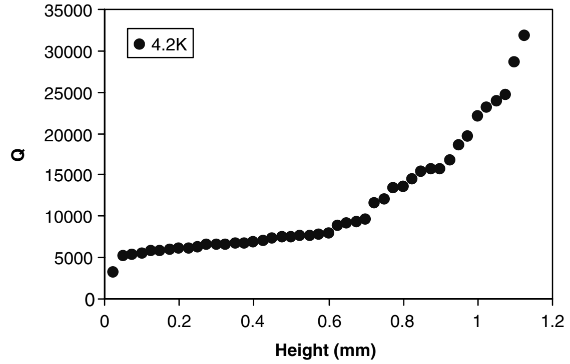

Fig. 6. Variation of cavity Q as function of top plate separation at 4.2 K.

top of the sapphire cylinder at 4.2 K. While the top plate was moved away from the sapphire cylinder, the only loss terms were due to the Niobium lower plate and the loss tangent of the sapphire cylinder.

Fig. 7 shows the measured R_s values for three SMG-YBCO samples. Two samples were annealed in flowing oxygen at 400 °C for 10 days. One sample was measured using He in the chamber dewar and the R_s values were measured from room temperature dawn to 4.2 K (Fig. 7a). For the second sample, liquid nitrogen was used and the R_s measurements were made from room temperature down to 77 K (Fig. 7b). As can be seen from these plots that there is relatively small change in the R_s values. R_s value of YBCO in the superconducting

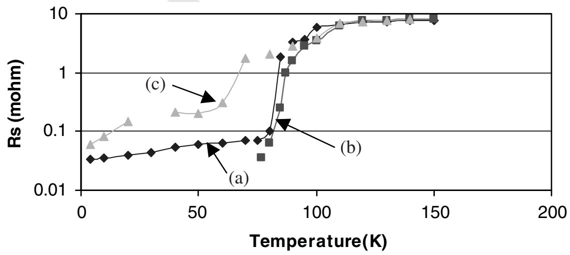

Fig. 7. Measured R_s values. Lowest temperatures: (a) 4.2 K, (b) 77 K, and (c) sample annealed for a short period.

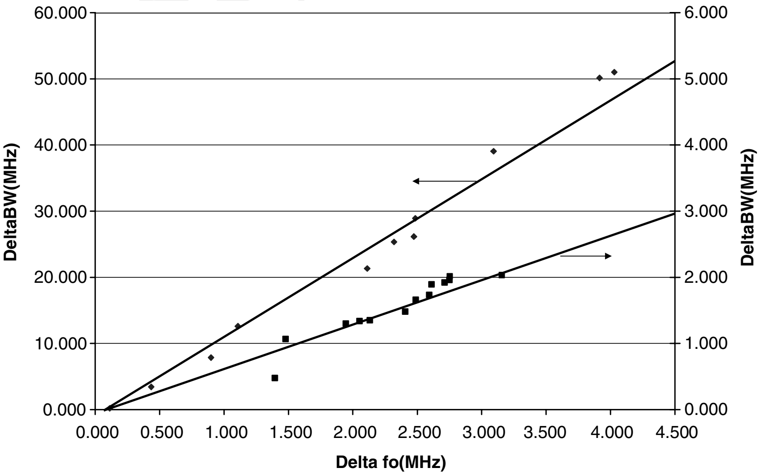

Fig. 5. Measured slope of copper and high temperature superconductor at 10 K.

PHYSC 51149 ARTICLE IN PRESS No. of Pages 6, DTD = 4.3.1
18 October 2003 Disk used

state decreases as the temperature decreases. The minimum surface resistance value observed was 35 μΩ. As expected, above the transition temperature, the values of R_s were even higher than that of the Cu sample. A third sample was oxygenated for a shorter period. For this sample, measured R_s values were higher as shown in Fig. 7c.

5. Conclusions

Microwave properties of seeded melt grown (SMG) YBCO samples were measured using a cavity perturbation technique around 18.5 GHz. Well annealed samples exhibited R_s values that were comparable to high quality thin film YBCO samples. These SMG samples are cheaper to produce compared to the thin films. At the same time they can easily be formed into desired geometrical shapes before sintering. Therefore, various cavity structures can easily be processed from these low loss SMG YBCO samples, thus opening up many communications application areas over the microwave and millimeter wave spectra.

References

[1] D. Zhang et al., IEEE Trans. Appl. Supercond. 5 (1995) 2656.
[2] M. Schmidt, W.L. Olson, IEEE Trans. Microwave Theory Tech. 39 (1991) 1475.
[3] D. Dijkkamp, T. Venkatesan, X.D. Wu, S.A. Shaheen, N. Jisrawi, Y.H. Min-Lee, W.L. McLean, M. Croft, Appl. Phys. Lett. 51 (1987) 619.
[4] H.C. Li, G. Linger, F. Ratzel, R. Smithey, J. Greerk, Appl. Phys. Lett. 52 (1988) 1098.
[5] R.L. Sandstrom, W.J. Gallagher, T.R. Dinger, R.H. Koch, Appl. Phys. Lett. 53 (1988) 444.
[6] C.B. Eom, J.Z. Sun, K. Yamamoto, A.F. Marshall, K.E. Luther, S.S. Laderman, T.H. Geballe, Appl. Phys. Lett. 55 (1989) 595.
[7] R. Wordenweber, J. Einfeld, R. Kutzner, A.G. Zaitsev, M.A. Hein, T. Kaiser, G. Muller, Appl. Supercond., IEEE Trans. 9 (1999) 2486.
[8] D. Shi, W. Zhong, U. Welp, S. Sengupta, V. Todt, G.W. Crabtree, S. Dorris, U. Balachandran, IEEE Trans. Magn. 5 (1994) 1627.
[9] D. Shi, K. Lahiri, S. Sagar, D. Qu, V. Pan, V.F. Solovjov, J.R. Hull, J. Mater. Res. 12 (1997).
[10] D. Shi, K. Lahiri, J.R. Hull, D. LeBlanc, M.A.R. LeBlanc, A. Dabkowski, Y. Chang, Y. Jiang, Z. Zhang, H. Fan, Physica C 246 (1995) 253.
[11] P. Gautie-Picard, X. Chaud, E. Beaugnon, A. Erraud, R. Tounier, Mater. Sci. Eng. B 53 (1998) 66.
[12] P. Cautier-Picard, E. Beaugnon, X. Chaud, A. Sulpice, R. Torunier, Physica C 308 (1998) 161.
[13] P. Bautier-Picard, E. Beaugnon, R. Tournier, Physica C 276 (1997) 35.
[14] D. Shi, P. Odier, A. Sulpice, D. Isfort, X. Chaud, R. Tournier, P. He, R. Singh, Physica C 384 (2003) 149.
[15] R.J. Ormeno, D.C. Morgen, D.M. Broun, J.R. Walfram, Rev. Sci. Instrum. 68 (5) (1997) 2121.
[16] E. Selcuki, M.S. thesis, Department of Physics, University of Cincinnati, 1992.
[17] A. Farahat, J. Supercond. 8 (3) (1995).