Short Papers

High Q-Value Resonators for the SHF-Region Based on TBCCO-Films

Martin Manzel, Stefan Huber, Hans Bruchlos, Siegfried Bornmann, Peter Görnert, Martin Klinger, and Michael Stiller

***Abstract*— We used a sapphire dielectric resonator with a copper cylindrical shield and two endplates replaced by HTS layers for very accurate surface resistance measurements of TBCCO films made by the two step method. This technique allows for the preparation of high quality 2-in diameter Tl-2223 superconducting films with surface resistance values (R_s) smaller than 100 $\mu\Omega$ at 5.6 GHz and 77 K. The use of these films in sapphire dielectric resonators yields resonators for the C-band with very high unloaded quality factors ($Q_o > 2 \times 10^6$ at 77 K). Such high Q_o-values are not reached with any conventional resonators of comparable size.**

I. Introduction

The surface resistance (R_s) of superconducting high T_c-films (HTS) is a very sensitive parameter of the film composition and crystalline structure. We have used the R_s-value in order to optimize the preparation of Tl-HTS films of the 2223-phase. A number of different methods have been developed for the determination of the microwave surface resistance. One nondestructive method frequently used is the sapphire dielectric resonator [1]–[4].

The sapphire dielectric resonator is not only a measurement tool, but also a basic component for many other microwave devices. For example, HTS-films in sapphire dielectric resonators yield components with extremely high unloaded quality factors (Q_o). These devices can markedly improve the phase noise of microwave oscillators. A typical industrial application for these oscillators is in radar systems with an improved detection threshold by two orders of magnitude, when compared to conventional systems.

In this paper we present the preparation of high quality Tl-2223 films and the processing and characterization of high Q_o-resonators at different frequencies using Tl-2223 films up to 2 in diameter. Furthermore, we investigate the power dependence of these high Q_o-resonators.

II. Film Preparation

Epitaxial $Tl_2Ba_2Ca_2Cu_3O_x$(TBCCO)-films were prepared by a two-step method (5, 6). Ba-Ca-Cu-O precursor films were sputter deposited on $LaAlO_3$-substrates up to 2 in diameter. The precursor films were reactively deposited from a metallic $Ba_2Ca_2Cu_3$-alloy target by means of dc high-rate sputtering. The as-deposited films on (100)-$LaAlO_3$ substrates are amorphous, insulating and appear mirror-smooth.

Thallium oxide was incorporated into the precursor films by post annealing in a Tl-oxide loaded atmosphere for 10 minutes at 1168 K and subsequent cooling in O_2 with a special computer controlled temperature program. During this step, the sample was enclosed in a gold/platinum container together with a presintered pellet of Tl high T_c-bulk ceramic. Thallium-diffusion experiments with pellets of different compositions (2223, 2222, and 2201) have shown that $Tl_2Ba_2Ca_2Cu_2O_x$ is an useful composition with respect to the durability of the thallium source.

Manuscript received October 16, 1995; revised February 27, 1996. This work was supported by the BMBF under Grant FKZ 13 N 5927 A.

M. Manzel, S. Huber, H. Bruchlos, S. Bornmann, and P. Görnert are with the Institut für Physikalische Hochtechnologie, D-07702 Jena, Helmholtzweg 4, Germany.

M. Klinger and M. Stiller are with the Forschungsgesellschaft für Informationstechnik, D-31162 Bad Salzdetfurth, Germany.

Publisher Item Identifier S 0018-9480(96)04784-9.

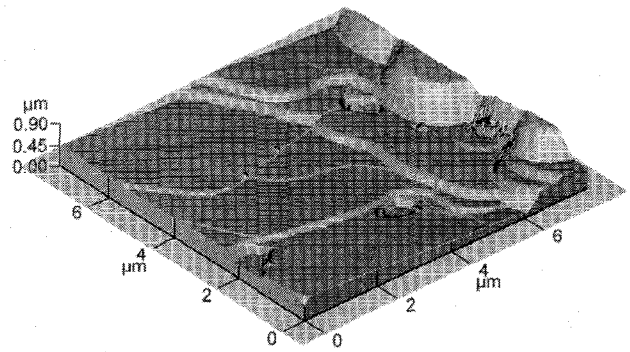

Fig. 1. AFM micrograph of a Tl-2223 film surface.

The film texture and compostion of the Tl-2223 film was investigated by means of (Θ-2Θ)-, Ω- und Φ- scan X-ray diffraction measurements (5, 6). The film morphology was studied by SEM and AFM. The detailed structure of the growth surface becomes visible with atomic force microscopy at very high magnification. The surface shows typical growth surfaces (terraces), growth steps, hollows and particles. The growth terraces are limited by growth steps. These growth steps are not straight and the macro steps are composed of several minor steps. The split into the minor steps and how they run into each other is shown in Fig. 1. The step heights varied in the range between 6 nm and 500 nm and within the margin of the measuring error, these steps are a multiple of the Tl-2223 c-axis constant. The surface of the growth terraces shows hillocks and indications of elementary steps with a height of about 1.5 nm.

The 2-in Tl-2223 films on $LaAlO_3$-substrates which have surface morphology shown in Fig. 1 have the following superconducting properties: critical temperatures higher than 110 K and typical current densities of 1.4×10^6 A/cm^2 at 77 K.

III. R_s Measuring System

The surface resistance (R_s) of the Tl-HTS films with diameters up to 2 in was measured with dielectric sapphire resonators, proposed by (2–4). This technique has many advantages (e.g., high sensitivity) and does not require attaching any contacts, patterning or etching. Fig. 2 shows the modified design of our R_s measuring set up.

A c-axis oriented sapphire puck is sandwiched between a pair of superconducting thin films. The rf input and output is achieved by a pair of semi-rigid cables with a coupling loop at the end. The coupling can be varied during the measurement by a tuning mechanism. The coupling can be optimized for each pair of films in the liquid nitrogen during the measurement. A copper housing prevents any radiation losses. Alignments pins, which are screwed back during the measurement assure the exact placement of the puck in the center of

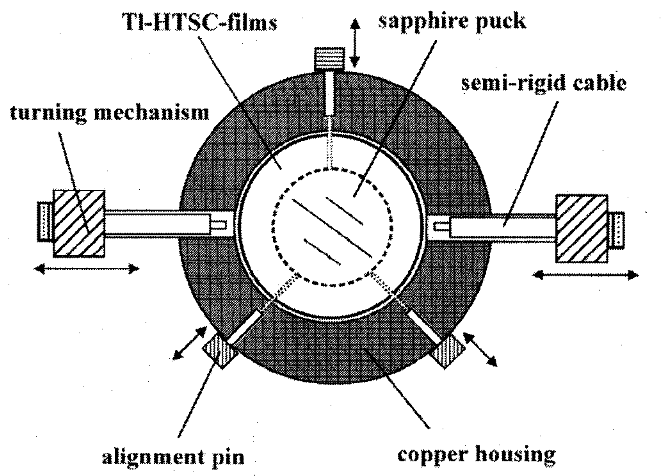

Fig. 2. Design of the dielectric sapphire resonators with tuning devices for coupling and exact placement of the sapphire in the cooled state.

TABLE I
SURFACE RESISTANCE (R_s) FOR THREE 2-IN Tl-2223 FILMS (A, B, C) AT 5.6 GHz AND THREE 10 mm SQUARE Tl-2223 FILMS (D, E, F) AT 17.85 GHz AND 77 K

Surface resistance:	Film A	R_s = (70 ± 25) μΩ
(5.6 GHz)	Film B	R_s = (75 ± 25) μΩ
	Film C	R_s = (85 ± 25) μΩ
Surface resistance:	Film D	R_s = (500 ± 250) μΩ
(17.85 GHz)	Film E	R_s = (500 ± 250) μΩ
	Film F	R_s = (1000 ± 150) μΩ

the cavity. The pucks used have the following dimensions yielding the resonance frequencies (f_r):

diameter 25.0 mm,	height 12.0 mm,	center frequency 5.6 GHz and
" 7.2 mm,	" 4.2 mm,	" 17.85 GHz,

instead of 17.4 GHz, because the copper wall losses distort f_r.

The measurement of the resonance curves was made with a HP spectrum analyzer and a HP tracking generator (upper frequency limit 18 GHz). The unloaded quality factor (Q_o) of the resonant system using the TE_{011} mode was determined by the 3 dB bandwidth method at 77 K. From these values according to [2]–[4] the surface resistances of the superconducting films were calculated. The calculation was carried out with a measured loss tangent of the sapphire puck of $\tan\delta = 1 \times 10^{-7}$ at 77 K (7).

A round robin experiment involving three films, makes it possible to calculate the surface resistance of each individual film, since the unloaded quality factor is inversely proportional to the sum of the surface resistances of the two films belonging to the sandwich. Table I shows the surface resistance (R_s) for several Tl-2223 films. The accuracy of the surface resistance measurements by means of dielectric sapphire TE_{011} cavity is limited not only by the surface resistance of the HTS-films, but unfortunately also by the mechanical alignment and the loss tangent of the sapphire puck and the parasitic losses in the metal wall of the cavity.

For our 5.6 GHz resonator the surface resistance of the HTS-films is the limiting factor. The limiting factor for our 17.85 GHz resonator is the metal wall, because the distance between the sapphire puck and the copper cavity wall is very small. Fig. 3 shows the relationship

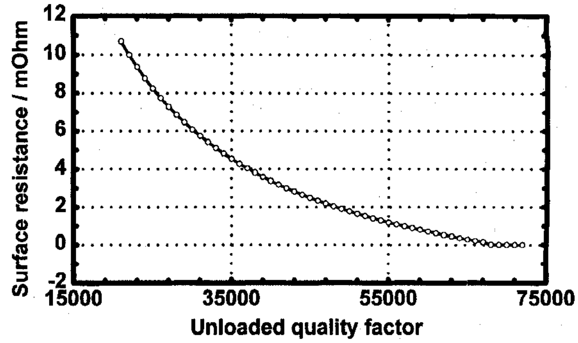

Fig. 3. Relationship between the surface resistance (R_s) and the unloaded quality factor (Q_o) of the dielectric sapphire resonator at 17.85 GHz and 77 K.

TABLE II
UNLOADED QUALITY FACTORS (Q_o) OF SAPPHIRE DIELECTRIC RESONATORS WITH 2-IN Tl-2223 FILMS AT 5.6 GHz AND 77 K

Film combination:	Film A/ Film B	$Q_o = 2.33 \times 10^6$
	Film A/ Film C	$Q_o = 2.17 \times 10^6$
	Film B/ Film C	$Q_o = 2.15 \times 10^6$

between the surface resistance and the Q_o-value for the resonator operating at 17.85 GHz with the formulas given in [2]–[4].

According to Fig. 3, a measurement error of 6% in the Q_o-value ($Q_o > 60\,000$) results in an error of about 50% in the calculated R_s-value for the individual film, estimated from a round robin experiment [2]. Our best 10 mm square Tl-HTS films reached R_s-values of $(500 \pm 250)\ \mu\Omega$ at 17.85 GHz and 77 K, corresponding to a quality factor of 64 000 approaching the absolute limit of $Q_o = 70\,000$. This result indicates that the accuracy of our 17.85 GHz sapphire dielectric resonator is not sufficient for highest quality films. Therefore, the high quality film D was measured with a cylindrical copper cavity at 87 GHz. The surface resistance of this film was actually found to be smaller and reached a value of $R_s = 6.5\ mOmega$ at 87 GHz and 77 K [8]. Scaled down to a frequency of 17.85 GHz using the f^2-law for the frequency dependence of the R_s-value, the surface resistance of the film D amounts to 275 $\mu\Omega$ at 77 K. This R_s-value is slightly lower than those of the best 12 mm square Tl-based films [9], [10] and slightly lower than those of high quality $YBa_2Cu_3O_x$ films [11] reported up to now.

IV. HIGH Q_o-RESONATORS

Operating our measuring system with two 2-in Tl-2223 films (Fig. 2) we observed Q_o-values of the resonant system of more than 2 million. Therefore we intend to use this set up to make high Q_o-resonators (Table II). In this arrangement, the quality factor is not limited by the losses of the copper walls.

For many TBCCO-film applications in microwave devices the power dependence of the surface impedance of the superconducting films is very important. Fig. 4 shows the unloaded quality factor of a dielectric resonator with two 2-in diameter TBCCO-films as a function of the surface magnetic field (h_{rf}). The power dependence of Q_o is evident. For large fields ($h_{rf} > 1$ Oe) the Q_o-values strongly decrease since the lower critical field (H_{c1}) of the superconductor is exceeded in the most unfavorable crystal direction [12]. Better power handling capability for TBCCO-films has been reported in [4] for Tl-2212 films, but this material is not as strong anisotropic as

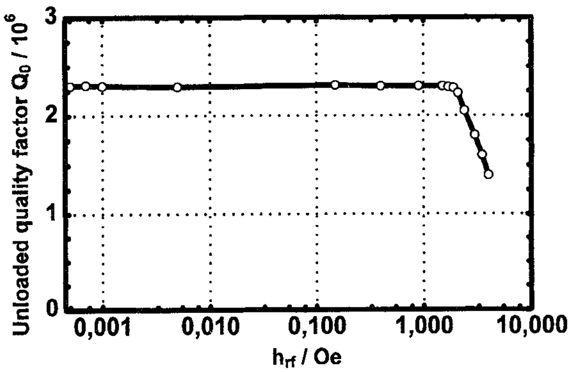

Fig. 4. Dependence of unloaded quality factor (Q_o) for a dielectric sapphire resonator using 2 in TBCCO-films on the surface magnetic field (h_{rf}) at 5.6 GHz and 77 K.

the Tl-2223 phase with two Tl-O planes. At present the rf-power dependence of R_s is in detail not clear.

V. Conclusion

The two step technology allows to prepare high quality 2-in Tl-2223 superconducting films with surface resistance values (R_s) smaller than 100 $\mu\Omega$ at 5.6 GHz and 77 K. The use of these films in sapphire dielectric resonators yields resonators for the C-band with very high unloaded quality factors ($Q_o > 2 \times 10^6$ at 77 K). Such high quality factors are only reached with Whispering Gallery Modes sapphire resonators and Fabry-Perot mirror resonators, but these resonators are very voluminous and heavy below 10 GHz. Acoustic resonators such as SAW (surface acoustic wave), BAW (bulk acoustic wave) and HBAR (high overtone bulk acoustic resonators) are limited to operating frequencies below 1 GHz and therefore require frequency multiplication for application in the C-band and X-band with the consequence of a large increase in noise. The unloaded quality factor of normal-conducting dielectric resonators with ceramic or sapphire pucks is two orders of magnitude lower than the Q_o-values of the described superconducting resonators. Therefore, superconducting dielectric sapphire resonators on compact stirling cycle cryocoolers can be used in microwave oscillators with very low phase noise behavior. A typical industrial application for these oscillators is in cryoradar systems with an improved detection threshold.

References

[1] W E. Courtney, "Analysis and evaluation of a method of measuring the complex permittivity and permeability of microwave insulators," *IEEE Trans. Microwave Theory Tech.*, vol. 18 no. 3, pp. 476–485, 1970.

[2] J. Krupka, M. Klinger, M. Kuhn, A. Baranyak, M. Stiller, J. Hinken, and J. Modelski, "Surface resistance measurements of films by means of sapphire dielectric resonators," *IEEE Trans. Appl. Superconduct.*, vol. 3 no. 1, pp. 3043–3048, 1993.

[3] C. Wilker, Z-Y Shen, V. X. Nguyen, and M. S. Brenner, "A sapphire resonator for microwave characterization of superconducting thin films," *IEEE Trans. Appl. Superconduct.*, vol. 3 no. 1, pp. 1457–1460, 1993.

[4] Z. Y. Shen, C. Wilker, P. Pang, W. L. Holstein, D. Face, and D. J. Kountz, "High Tc superconductor-sapphire microwave resonator with extremely high Q-values up to 90 K," *IEEE Trans. Microwave Theory Tech.*, vol. 40 no. 12, pp. 2424–2432, 1992.

[5] M. Manzel, H. Bruchlos, E. Steinbeiß, T. Eick, M. Klinger, J. Fuchs, and B. Kley, "TlBaCaCuO-films for passive microwave devices," *Physica C*, no. 201, pp. 337–339, 1992.

[6] M. Manzel, H. Bruchlos, F. Sandiumenge, G. Bruchlos, M. Kuhn, M. Klinger, and J. H. Hinken, "Planar and cavity microwave resonators using TBCCO-films," in *Applied Superconductivity*, H.C. Freyhardt, Ed. Oberursel, Germany: DGM Informationsgesellschaft Verlag, 1993, vol. 2, pp. 995–998.

[7] J. Krupka, private communication.

[8] S. Huber, M. Manzel, H. Bruchlos, S. Hensen, and G. Müller, "Thallium-based high-Tc films with very low surface impedance," *Physica C*, no. 244, pp. 337–340, 1995.

[9] W. L. Holstein, L.A. Parisi, C. Wilker and R.B. Flippen, "Epitaxial $Tl_2Ba_2Ca_2Cu_3O_{10}$ films with very low microwave surface resistance up to 110 K," *IEEE Trans. Appl. Superconduct.*, vol. 3 no. 1, pp. 1197–1200, 1993.

[10] W. L. Holstein and L. A. Parisi, "Highly oriented very low surface resistance $Tl_2Ba_2CaCu_2O_8$ Films on $NdGaO_3$ and $LaAlO_3$," *Appl. Phys. Lett.*, vol. 60 no. 16, pp. 2014–2019, 1992.

[11] S. Hensen, S. Orbach-Werbig, G. Müller, H. Piel, N. G. Chew, J. A. Edwards, and R. G. Humphreys, "Effect of small changes in metal stoichiometry on microwave losses of epitaxially grown $YBa_2Cu_3O_{7-\delta}$ films," *Applied Superconductivity*, H.C. Freyhardt, Ed. Oberursel, Germany: DGM Informationsgesellschaft Verlag, 1993, vol. 2, pp. 1053–1056.

[12] M. Manzel, H Bruchlos, S. Huber, M. Kuhn, J. Keppler, and J. H Hinken, "Preparation and microwave characterization of TBCCO-films," *Physica C*, no 235–240, pp. 713–714 1994.

Twenty-GHz Broadband Microstrip Array with Electromagnetically Coupled High T_c Superconducting Feed Network

Jeffrey S. Herd, Livio D. Poles, James P. Kenney, John S. Derov, Michelle H. Champion, Jose H. Silva, Marat Davidovitz, Kenneth G. Herd, William J. Bocchi, Steven D. Mittleman, and Dallas T. Hayes

***Abstract*— The use of high-temperature superconducting (HTS) feed lines and phase shifters can substantially improve the performance of microwave and millimeter-wave printed phased array antennas. A novel antenna architecture is described that provides a broadband radiating aperture to be used as a scanning array with compatible low-loss HTS phase shifters. The approach follows an earlier design demonstrated at 12 GHz, and this work extends the approach to 20 GHz. The antenna design, radiation patterns, bandwidth measurements, and thermal analysis are reported. A prototype thermal isolator design is described that reduces the heat load of coaxial interconnections between cryocooled and room temperature systems.**

I. Introduction

Ohmic losses in passive microwave and millimeter-wave printed phased array antennas severely limit the achievable gain and noise figure. Active antenna arrays utilize amplifiers at each element to compensate for losses, but practical factors such as heat dissipation, stability, calibration, and reliability introduce significant technological challenges. Alternatively, components fabricated using high-

Manuscript received October 23, 1995; revised February 22, 1996.

J. S. Herd, L. D. Poles, J. P. Kenney, J. S. Derov, M. H. Champion, J. H. Silva, M. Davidovitz, W. J. Bocchi, S. D. Mittleman, and D. T. Hayes are with Rome Laboratory, Hanscom AFB, MA 01731-3010 USA.

K. G. Herd is with General Electric Corporate Research and Development, Schenectady, NY USA.

Publisher Item Identifier S 0018-9480(96)04786-2.