SUPERCONDUCTING Tl-Ca-Ba-Cu-O THIN FILM MICROSTRIP RESONATOR and its POWER HANDLING PERFORMANCE at 77K

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ABSTRACT

We report measurements of the temperature- and power-dependent surface resistance, Rs, of thin films of Tl-Ca-Ba-Cu-O at 9.55 GHz. At 77k these films are at least 20 times better than bulk OFHC Cu at the same temperature and frequency, in microwave magnetic fields up to 10 gauss. In addition, we report measurements of the power handling performance at 77K of a high-Q thin-film microstrip resonator made with these films. We measured loaded Q's up to 7300 at 2.6 GHz, >20 times higher than on identical silver resonators. At effective power levels in the resonator up to ~100 watts the Q was still at least three times higher than the silver resonator at all frequencies measured; 2.6, 5.2, and 7.3 GHz.

INTRODUCTION

It has been three years since the first demonstration of superconductivity above liquid nitrogen temperature, 77K. Since then there has been world-wide interest in evaluating the microwave performance of the new high temperature materials. Using cavity and resonator techniques, the surface resistance of thin-film materials has been measured at nearly all microwave and millimeter wave frequencies (1). In the best materials losses significantly lower than OFHC Cu have been measured at microwave frequencies at temperatures up to 77K. However, these results have nearly all been obtained at low power levels. Low losses at practical power levels have proved difficult to achieve (2,3). At the same time there has been effort, although on a smaller scale, to realize attractive performance in passive microwave devices using patterned thin films. Some success has been reported in achieving high Q devices at 77K; but only one result (Valenzuela and Russer) has been obtained at practical power levels (4,5).

In this paper we report measurements of the temperature and power dependent surface resistance in thin films of Tl-Ca-Ba-Cu-O grown on lanthanum aluminate, $LaAlO_3$, substrates. We employed a cavity-perturbation technique in a 9.55 GHz TE_{011}-mode superconducting niobium cavity for these measurements. In addition, we report measurements of loaded Q on a microstrip resonator fabricated from these films. We measured this device over a 95-dB dynamic range.

SURFACE RESISTANCE MEASUREMENTS

Tl-Ca-Ba-Cu-O Thin Films

Tl-Ca-Ba-Cu-O thin films were prepared by laser ablation deposition followed by post-deposition thermal processing. The amorphous precursor deposits were prepared by laser ablation because it is an effective method of retaining the stoichiometry of the target in the deposited film. The oxides were ablated at room temperature using a KrF excimer laser (249nm) onto chemically polished $LaAlO_3$ substrates. A laser pulse repetition rate of 10Hz was maintained during the deposition and the deposition time was varied to give the desired film thickness. The amorphous films were heated to high temperature (830-900C) under controlled thallium and oxygen pressures to prevent excessive loss of Tl_2O_3. Final film thicknesses were 9000±500 Å. X-ray diffraction showed the films to be oriented with the c-axis of the superconductor perpendicular to the substrate; and, in addition, sharp rocking curves (as sharp as 0.30^o) indicated an epitaxial orientation. Epitaxy was substantiated by selected area electron channeling, which showed electron channeling over the whole of the substrate, with the 100 orientation of the superconductor aligned with the 100 of the substrate.

Niobium Cavity

Perturbation of the 9.55 GHz TE_{011}-mode of a superconducting niobium cavity was used to determine thin-film surface resistance. The approach is the same as we reported previously (6). The thin film, 1 cm X 1 cm, is supported on top of a sapphire rod while the niobium cavity is held at 4.2K in a liquid helium bath. The film's temperature is changed by heating the thermally isolated sapphire rod. The cavity has an unloaded Q of over 22 million with only the sapphire rod present. Positioned in the center of the cavity, the film is exposed to the maximum magnetic field. Both input and output coupling ports are weakly coupled to provide negligible coupling Q's resulting in a direct measure of unloaded cavity Q. Under these conditions, the magnetic field is only a few milligauss.

The power into the cavity is increased and adjusted by using a 1 watt amplifier and step attenuator. To perform power dependent measurements of film losses, the output is kept weakly coupled while the input coupling is increased until critical coupling is reached. At critical coupling the maximum power is delivered into the cavity and losses are distributed between the cavity walls and the film. Since the cavity has no power dependence at these levels, decreases in the measured Q is attributed to the increased losses of the film. The magnetic field strength is determined from the stored energy. At 1 watt input, magnetic field strength can be >20 Gauss for films with losses of <1 mW per square.

Measurements are made with an HP8410 Network Analyzer and the RF signal is provided by an HP8340 Synthesizer. The measured 3-db bandwidth of the cavity with and without the sample are used to calculate surface resistance. At each power level the input coupling is adjusted for critical coupling since the film response to increasing power changes the impedance

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of the cavity. Coupling changes are made by changing the input loop's location through adjustments of a precision micrometer. As the power is increased, the magnetic field can be large enough to heat the sample. To eliminate sample heating, the sweep rate and bandwidth are adjusted to reduce the effective duty cycle of the power delivered to the cavity. The sweep rate is set at low power. The maximum rate that does not distort the shape of the measured resonance peak is chosen. The heater power to the sapphire rod is carefully monitored to insure that the heat dissipated in the rod does not change during the test. Thermal contact of the sample to the rod is provided by Apiezon N grease.

Rs Results

Figure 1 shows the measured surface resistance vs temperature at low power for three Tl-Ca-Ba-Cu-O thin films. The complete temperature scan is shown for film #V302. Films #V262 and #V266 were measured at three temperatures, 4.2K, 77K, and 150K. At 77K surface resistance in all three films is substantially lower than bulk OFHC Cu, which has a textbook value of 9 mW at this frequency and temperature. The surface resistance of films #V262 and #V266 are <0.25 mW.

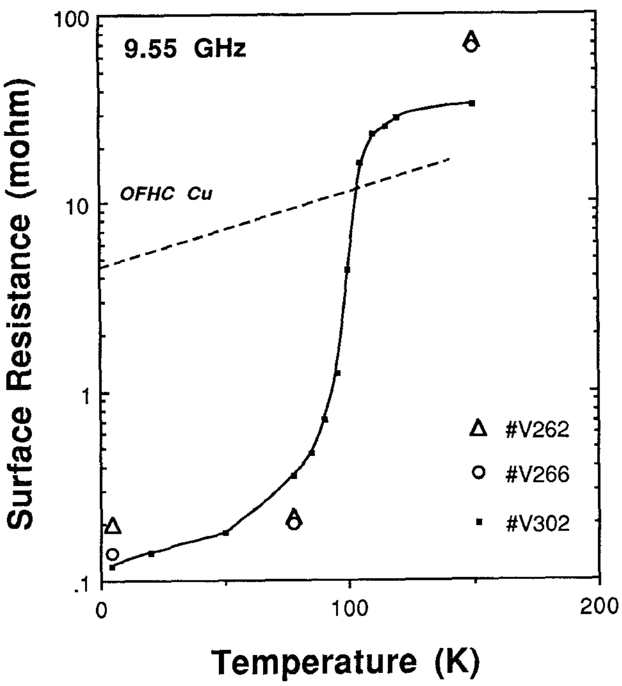

Figure 1 - Surface resistance of three Tl-Ca-Ba-Cu-O films.

Figure 2 shows the measured surface resistance vs microwave magnetic field at 77K, 9.55 GHz, for films #V262 and #V266. There is very similar power dependence in the two samples. There is a steady increase in loss as the microwave power is increased for both films, but the total increase in surface resistance over three decades in field (six decades in power) is less than a factor of three.

MICROSTRIP RESONATOR

Resonator Fabrication

We pattern Tl-Ca-Ba-Cu-O thin films using a conventional wet photolithography etching process. Film #V262 was patterned with mask #M10027A, a 2.6 GHz fundamental frequency end-coupled transmission line resonator. The mask layout is shown in Figure 3. The resonator linewidth is 0.020". Input and output coupling gaps were set at 0.031". The substrate material is LaAlO3, 0.017" thick, with a dielectric constant of approximately 18.5 at 77K (inferred from the device measurements). The substrate dimensions are 0.394" X 0.394". This film was paired with film #V266 and assembled into an SMA connectorized package in a microstrip configuration. The packaged resonator is shown in Figure 4.

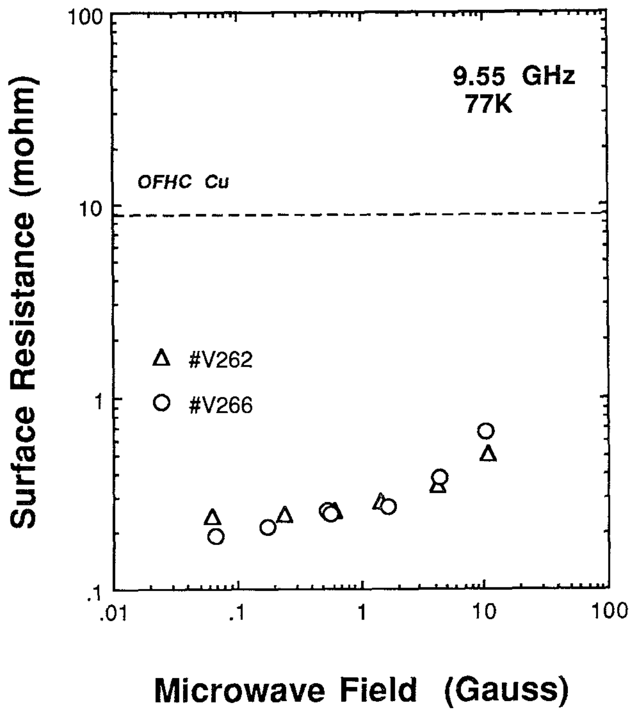

Figure 2 - Power dependent surface resistance of two Tl-Ca-Ba-Cu-O thin films.

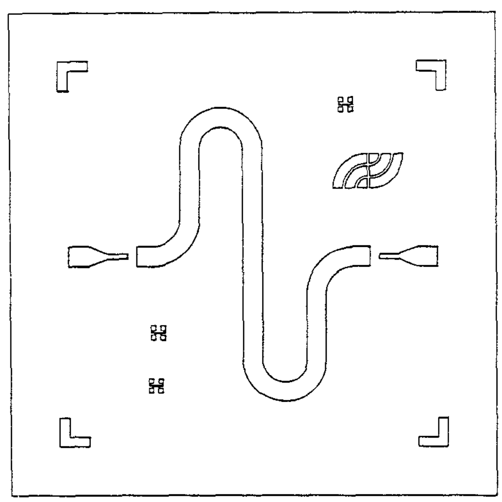

Figure 3 - Mask configuration for microstrip resonator.

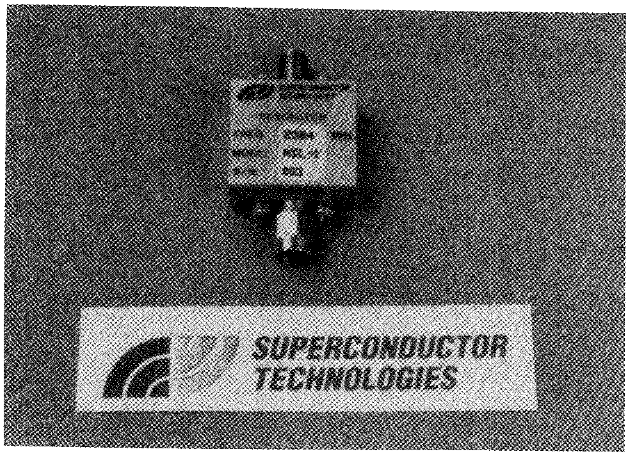

Figure 4 - Packaged microstrip resonator.

Resonator Measurements

The packaged microstrip resonator was cooled in liquid nitrogen to a temperature of 77K. An HP8340 Synthesized Sweeper and HP8757C Network Analyzer were used to make transmission measurements. Various power amplifiers were used to set appropriate signal levels at the device under test and at the test instrumentation ports. Measurements were made on the first three resonant peaks over a 95 dB dynamic range varying input power from -65 dBm to +30 dBm. Figure 5 is a plot of measured insertion loss at an input power of 0 dBm to the resonator. The first several resonances show clearly.

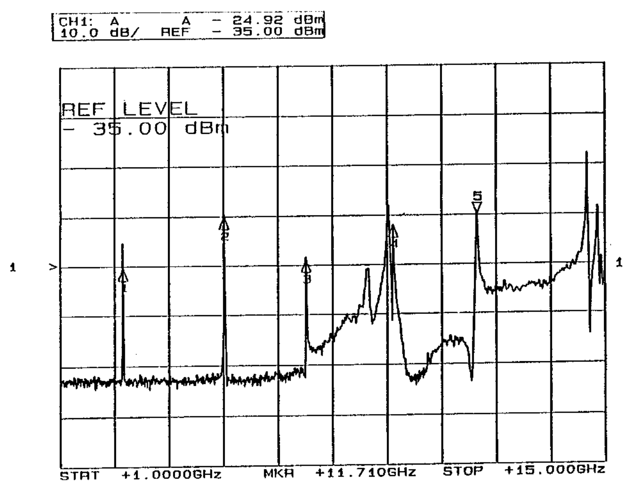

Figure 5 - Frequency scan of microstrip resonator insertion loss.

Loaded Q data were extracted from 3-dB bandwidth measurements on each of the first three resonances. Measurement of insertion loss at resonance allowed calculation of coupling Q's and the unloaded Q of the resonator. The measured loaded Q's for the Tl-Ca-Ba-Cu-O microstrip resonator are shown in figure 6. The measured insertion losses (at -10 dBm input power) were -19.7 dB at 2.6 GHz, -13.8 dB at 5.2 GHz, and -19.4 dB at 7.3 GHz. At the two lower frequencies we infer low power unloaded Q's of ~10,000. (We calculated coupling Q's of 63,000; 41,000; and 84,000 respectively.)

Identical resonator structures were fabricated using 3-micron-thick sputter-deposited silver films and also using 0.2-micron superconducting niobium films. Measured loaded Q's of the silver resonator at 77K were: 347, 430, and 520 respectively at the first three resonances. These Q's are only 40% lower than unloaded Q's we calculated using Touchstone where we assumed the textbook surface resistance of bulk OFHC Cu at 77K. Of course, this low surface resistance cannot be achieved in practice in any normal metal thin film at 77K. Our measured silver resonator Q's thus represent close to the highest Q's possible using any normal metal thin film at 77K in our device structure. Measured loaded Q's of the niobium resonator at 4.2K were higher than 20,000 at each resonance. These data indicate that our microstrip resonator design and package are not limiting the measured Q's in our HTSC resonator.

SUMMARY AND CONCLUSIONS

We have measured the surface resistance of Tl-Ca-Ba-Cu-O thin films at 9.55 GHz as a function of temperature and microwave magnetic field. At 77K the films are at least 20 times lower loss than OFHC Cu at fields up to 10 gauss. Also, we have measured high loaded Q's, up to 7300 at 2.6 GHz and up to 6000 at 7.3 GHz, in a Tl-Ca-Ba-Cu-O microstrip resonator at 77K. These Q's are 21 times and 11 times higher respectively than we measured in an identical thin-film silver device at the same temperature. The HTSC resonator Q's decreased monotonically with increasing input power. At the highest input power, 1 watt (+30 dBm) the HTSC resonator loaded Q's were still at least 3 times higher than the low power loaded Q's of the silver resonator. With +30 dBm input, at 7.3 GHz the effective power in the resonator was greater than 100 watts (+50.1 dBm) and the peak microwave magnetic field is greater than 100 gauss. Despite this very high power, the very high Q indicates that the line is still fully superconducting.

In addition, the measured loaded Q's in the HTSC resonator exhibit almost no variation with frequency. This behavior is expected when defects in the superconducting films produce weak links (7,8). Removing such defects should dramatically raise Q's and eliminate power dependent behavior.

REFERENCES

(1) G. Muller, "Microwave Properties of High Temperature Superconductors," Proceedings of the 4th Workshop on RF Superconductivity, KEK Tsukuba-Shi, August ,1989.

(2) J. R. Delayen and C. L. Bohn, "Temperature, Frequency, and RF Field Dependence of the Surface Resistance of Polycrystalline $YBa_2Cu_3O_{7-x}$," Physical Review, Volume B40, p. 5151, 1989.

(3) H. Padamsee, J. Kirchgessner, D. Moffat, D. L. Rubin, Q. S. Shu, A. Inam, X. D. Wu, L. Nazar, M. S. Hedge, and T. Venketesan, "Temperature and Field Dependence of the Microwave Surface Resistance of High Quality Laser Ablated Films of $YBa_2Cu_3O_{7-x}$," Cornell University, CLNS 89/929, 1989.

(4) A. A. Valenzuela and P. Russer, "High Q coplanar transmission line resonator of $YBa_2Cu_3O_{7-x}$ on MgO," Applied Physics Letters, Volume 55, pp. 1029-1031: Sept. 1989.

(5) D. E. Oates, P. M. Mankiewich, R. E. Howard, and M. L. O'Malley, "Dependence of surface resistance of Y-Ba-Cu-O thin films on frequency, temperature, and RF magnetic field," to be published in Applied Physics Letters, 1990.

(6) L. D. Chang, M. J. Moskowitz, R. B. Hammond, M. M. Eddy, W. L. Olson, D. D. Casavant, E. J. Smith, McD. Robinson, L. Drabeck, and G. Gruner, "Microwave surface resistance in Tl-based superconducting thin films," Applied Physics Letters, Volume 55, pp. 1357-1359, 1989.
(7) A. M. Portis, D. W. Cooke, and H. Piel, Proceedings of the International M^2S-HTSC Conference; Stanford, California, 1989; to be published in Physica C.
(8) J. Halbritter; to be published in Journal of Applied Physics, 1990.

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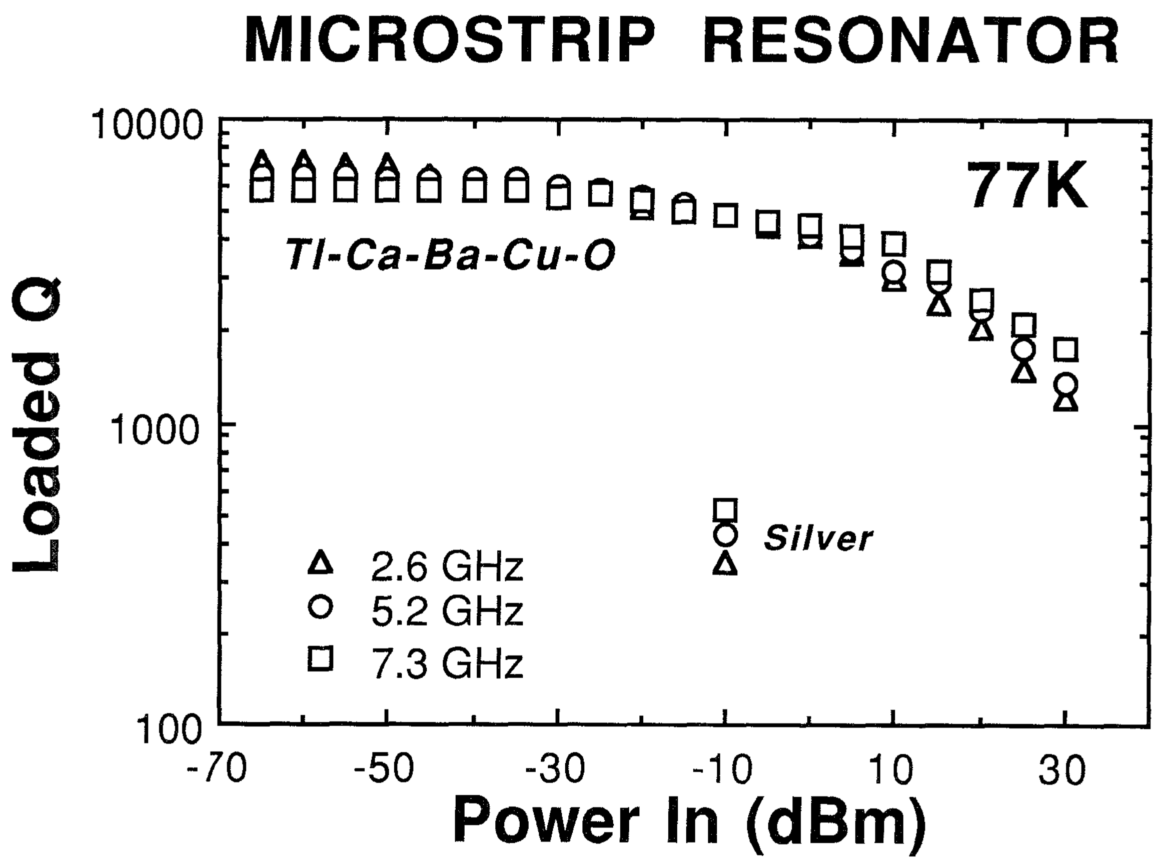

Figure 6 - Loaded Q vs input power for Tl-Ca-Ba-Cu-O microstrip resonator.