A NOVEL MICROSTRIP-COMPATIBLE TECHNIQUE FOR DEPOSITING $YBa_2Cu_3O_{7-\delta}$ ON BOTH SURFACES OF A SUBSTRATE

J. M. Pond, K. R. Carroll, D. B. Chrisey, J. S. Horwitz, and V. C. Cestone
Naval Research Laboratory
Washington, DC 20375-5000

Abstract — A novel technique for the deposition of $YBa_2Cu_3O_{7-\delta}$ on both the top and bottom surface of a substrate by pulsed laser deposition is reported. This approach employs a metallic buffer layer to protect the first $YBa_2Cu_3O_{7-\delta}$ film while the second film is deposited. It is particularly applicable to microstrip-based circuit topologies where the ground plane 'conductor' requires minimal patterning. The performance of microstrip ring resonators, fabricated by this technique, is substantially better than can be achieved with microstrip ring resonators which consist of a superconducting ring and a normal-conductor ground plane. This approach allows the deposition of $YBa_2Cu_3O_{7-\delta}$ on both sides of the substrate without the need for radiative heating schemes and can accommodate any size and shape of substrate.

I. INTRODUCTION

The potential usefulness of high-transition-temperature superconductors (HTS) in passive microwave devices and circuits has been well demonstrated [1]. Many passive and active microwave circuits rely heavily on microstrip transmission line as the guiding structure for routing and distributing microwave signals. Microstrip consists of a dielectric layer which separates a ground plane from a finite width conducting strip. Depending on the dielectric constant, dielectric thickness and the width of the strip, approximately 90% of the attenuation in microstrip can be attributed to the conductor losses of the strip and as little as 10% of the attenuation can be attributed to the conductor losses of the ground plane. Obviously, a significant advantage in circuit performance can be achieved by replacing a normal-conducting strip with a superconducting strip.

For a superconductor with a surface resistance an order of magnitude less than copper at a given frequency and temperature, the resultant superconducting-strip/normal-ground transmission line would have only about one fifth the loss of an all normal conductor structure. Consequently, replacing the normal ground plane with a similar superconductor results in only another factor of two reduction in the attenuation. However, when the surface resistance of the superconductor is a factor of 100 less than the surface resistance of a normal conductor, the additional benefit gained from replacing the ground plane as well as the strip with a superconductor can be quite substantial. In this case, the superconducting-strip/normal-ground transmission line would have about one tenth the loss of the all normal conductor structure while replacing the normal-ground plane with a similar superconductor would result in an additional factor of ten reduction in the attenuation, yielding a total loss which is a factor of 100 less than the normal-strip/normal-ground configuration. This level of performance is necessary to realize very narrow band filters in the upper microwave frequency range.

These advantages are illustrated in Fig. 1. These calculations are based on expressions derived by Schneider [2] and applied to the case of a 50 Ω microstrip transmission line on a 0.254 mm-thick MgO substrate at 10 GHz. The relative dielectric constant of MgO is 9.65 and the loss tangent of MgO is assumed to be 10^{-5} [3]. The surface resistance is normalized to an experimentally determined value for oxygen-free high-conductivity copper at 77 K. Although the exact locations of the curves are dependent on the substrate choice and the geometry chosen, the general dependence indicated in Fig. 1 is valid. It can be seen that the performance advantage of a YBCO-strip/YBCO-ground transmission line compared to a YBCO-strip/normal-ground is minimal unless the the surface resistance of YBCO is at least an order of magnitude less than copper. It also follows that, when considering realistic dielectric loss tangents, there is little advantage to be gained by reducing the surface resistance of YBCO below about three orders of magnitude less than copper. Thus, as the surface resistance of superconductors is reduced it becomes increasingly important to replace all normal conductors with superconductors in order to fully realize the advantages of this material.

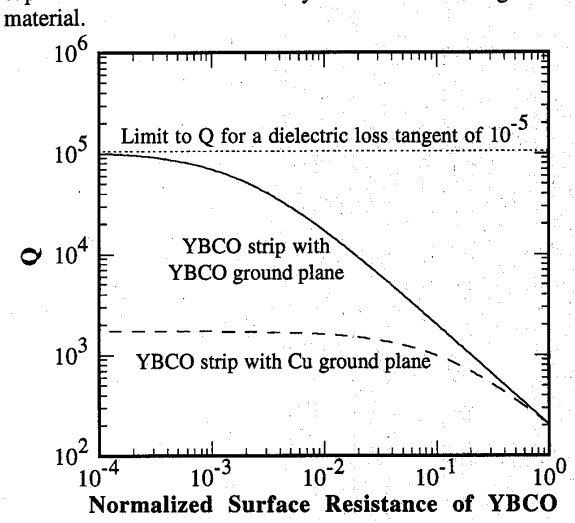

Fig. 1 Comparison of the predicted Q of an all YBCO and a YBCO-strip/normal-ground microstrip transmission line as a function of the surface resistance of YBCO normalized to copper at 77 K.

Manuscript received August 24, 1992

1051-8223/93$03.00 © 1993 IEEE

There are several methods of depositing high-quality high-temperature superconducting films on dielectric substrates. To obtain superconducting films without resorting to post-processing, one of the most critical parameters is the substrate temperature. To assure a uniform and stable thermal environment, silver paste is often used to provide a high thermal conductance between the substrate and a heated table. Generally, readily available low-surface-resistance films have been fabricated from this approach using either pulsed laser deposition or off-axis sputtering.

This technique does not work for deposition on the second side of the substrate because the properties of the first HTS film are greatly degraded due to contamination by components of the silver paste. One method of preventing the contamination is to replace the thermally conductive silver paste with a radiant heating system which may involve either elaborate heating elements and shrouds or simply setting the substrate on a heated stage [4,5]. While many films deposited in this fashion do not require post annealing the mechanical fixturing required can be more complicated than the conductive heating method which can easily accommodate different sizes and shapes of substrates. Another disadvantage is having to provide active cooling of portions of the deposition chamber because of the high levels of radiant heat. Another approach to providing a HTS ground plane is to use a second substrate with a single HTS layer deposited on it and then clamp both substrates together. A severe deficiency exists with this approach since there is always a small uncontrolled gap between the substrates. This gap greatly perturbs the phase velocity of the microwave signal and thus precludes accurate fabrication of highly tuned circuits such as narrowband filters.

II. YBCO DEPOSITION AND SAMPLE PREPARATION

The technique described below is appropriate for many applications, such as microstrip transmission lines, where minimal patterning of one of the HTS films (i.e., the ground plane) is required. The superconductor on this surface is only required to have low surface resistance at the superconductor - dielectric interface. At distances greater than about three penetration depths from the surface, the microwave characteristics of the superconductor can be degraded without affecting the microwave performance of the circuit. Thus, it is reasonable to cover one entire side of the substrate with HTS followed by a passivation layer providing that this layer does not degrade the superconducting characteristics near the dielectric and also permits electrical contact. There are many advantages to using silver paste, including the ability to provide good thermal contact for odd sizes and shapes of substrates. If the passivation layer can prevent silver paste contamination during a deposition cycle, then an HTS film can be easily deposited onto the second side of the substrate.

The deposition steps are illustrated in Fig. 2. Both MgO and $LaAlO_3$ (LAO) substrates have been used in these experiments. Both types of substrates were 1.59 cm x 1.59 cm with thicknesses of 0.508 mm and 0.254 mm for the LAO and MgO, respectively. The procedure is identical for both types of substrates, however, the specific values cited in the remainder of this section correspond to a LAO substrate. The HTS material used for both sides of the substrate was pulsed-laser-deposited $YBa_2Cu_3O_{7-\delta}$ (YBCO).

The first step, as shown in Figs. 2a and 2b, was to deposit a 1-μm-thick YBCO layer under standard pulsed laser deposition conditions for a given substrate [6]. The substrate was thermally attached to the heated stage using silver paste. This film was then characterized by standard low frequency inductive techniques. The transition temperature T_c and the critical current J_c were determined to be 90 K and 2 x 10^6 A/cm^2 at 77 K.

The substrate was then placed in an electron-beam evaporator where, see Fig. 2c, a 3.0-μm-thick layer of silver was deposited directly onto the 1.0-μm-thick YBCO layer at a rate of 1.5 nm/s with the substrate at ambient temperature. The substrate was removed from the electron-beam evaporator. The silver film was then covered with a thin layer of glycol thalate in order to protect the YBCO and silver layers while the silver paste residue was removed from the reverse side of the substrate. Removal of the silver paste was accomplished by lapping the substrate on a polishing pad using a slurry of 0.3-μm Al_2O_3 grit mixed with distilled deionized water. The polishing residue was thoroughly removed with flowing distilled deionized water. The glycol thalate was then removed with acetone and followed with an ethanol rinse. The substrate, at this point of the processing, is shown in Fig. 2d. The T_c and J_c were remeasured using the same inductive technique and found to be unchanged.

The substrate was then returned to the YBCO pulsed laser deposition chamber. This time, the silver covered YBCO side of the substrate was pushed into the silver paste to provide the thermal conduction path between the substrate and the heated table as shown in Fig. 2e. A 500-nm-thick film of YBCO was then deposited under the same conditions as the first YBCO deposition as illustrated in Fig. 2f. Inductive measurements confirmed that T_c and J_c of the second YBCO film were of the same high quality.

The second YBCO film was then patterned into a ring resonator. Photolithographic processing, using Shipley 1350J photoresist, was employed in order to pattern the YBCO film. After a standard bake and exposure, the film was etched in a saturated EDTA solution. The ring has a mean diameter of 10.03 mm, a strip width of 432 μm and is gap coupled to short microstrip lines of the same width by a 1.27-mm gap.

The substrate was mounted in an enclosed test fixture constructed of copper and brass which contains two SMA sparkplug launchers. The short input and output microstrip lines were connected to the center conductor of the sparkplug launchers by Au bond wires which are thermocompression bonded to the center conductors of the sparkplug launchers and attached to the YBCO with Ag epoxy. The test fixture was mounted in a closed-cycle refrigerator in which temperature can be accurately controlled from 20 to 300 K. To measure the transmission line characteristics, coaxial cables were connected from the sparkplug connectors to a Hewlett Packard 8510B vector network analyzer.

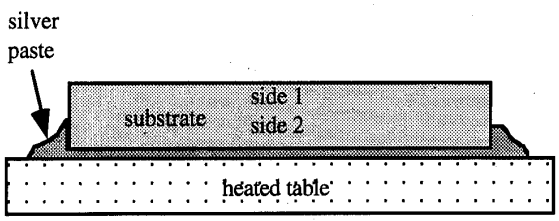

Fig. 2a Substrate thermally sunk to heated table by thermally conductive paste.

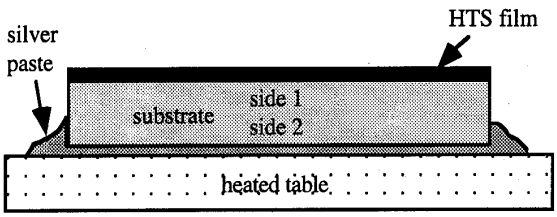

Fig. 2b HTS thin film deposited onto side 1 of substrate.

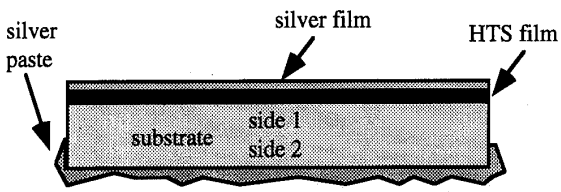

Fig. 2c 3μm layer of silver deposited on top of HTS film.

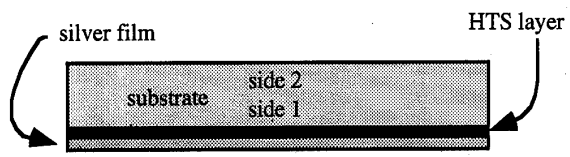

Fig. 2d Thermally conductive paste residue removed from side 2 and polished.

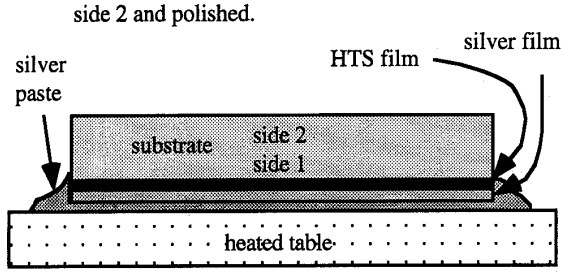

Fig. 2e Substrate thermally sunk to table by thermally conductive paste for deposition of second HTS layer.

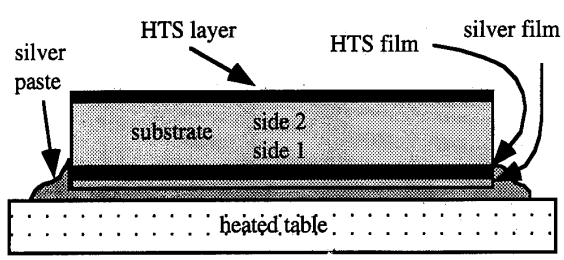

Fig. 2f HTS film deposited onto side 2 of substrate.

III. RESULTS

Microwave measurements of ring resonators fabricated with this process demonstrate unloaded quality factors Q_u that are much higher than similar ring resonators fabricated using HTS-rings with copper or silver ground planes. It is illustrative to consider the theoretical Q_u of a copper-strip/copper-ground ring resonator at 5 GHz. Ignoring any radiation losses or dielectric losses and assuming the resistivity of copper is 0.55 μΩ-cm at 77 K, the expected Q would be approximately 300 for a 50-Ω transmission line on 0.254-mm-thick MgO and approximately 570 for the geometry described above for the LAO substrate.

A summary of the best results achieved with this double-sided process are shown in Fig. 3 and are compared to the best results obtained using equivalent pulsed-laser-deposited films in conjunction with a normal-metal ground plane. The best Q_u obtained with a YBCO-strip/normal-ground plane device was for the dominant mode of a ring resonator on a 0.254-mm-thick MgO substrate at approximately 5 GHz. The Q_u of this mode was determined to be 2158 at 77 K, approximately seven times higher than the maximum value expected for an all copper microstrip of the same dimensions on MgO. The performance of the double-sided YBCO on LAO ring resonator at 5 GHz is dramatically higher. The Q_u was determined to be 9650 at 77 K which is about 17 times larger than the best value for an all copper structure at the same temperature.

In practice, it is extremely difficult to determine surface resistance values from measured ring-resonator performance. The near-field interaction of the ring with its environment greatly complicates the calculations of parasitic losses which may be different for each mode. Fig. 4 shows the calibrated magnitude and phase, ϕ, of the forward transmission coefficient, S_{21}, response of a typical double-resonance signature. Defining the center of the ring as the center of a polar coordinate system with $\theta = 0$ in the direction of the input port, the dominant resonance corresponds to a modal pattern where the electric field is maximum at the coupling gaps while the smaller resonance corresponds to a modal pattern where the magnetic field is maximum at the coupling gaps. Due to a lack of perfect symmetry the modes are not degenerate. Since the transmitted signals of the two modes add vectorially

$$S_{21} = \sum_{n=1}^{2} A_n \frac{\omega/\omega_{0_n}}{\left(\frac{\omega}{\omega_{0_n}}\right)^2 - \frac{j\,\omega}{Q_{u_n}\omega_{0_n}} - 1} \tag{1}$$

where $|A_n| < 1$ and $n = 1$ is the $\cos\theta$ mode and $n = 2$ is the $\sin\theta$ mode. Assuming $|A_2| << |A_1|$ and both Q_us are large it is easily shown from Eq. 1 that phase of S_{21} is given by

$$\tan\phi \cong C \frac{\omega^3}{\left(\omega^2 - \omega_{02}^2\right)^2 + (\omega\omega_{02})^2 Q_{u_2}^{-2}} \tag{2}$$

where C is a constant, and ω_{02} is the center frequency of the $\sin\theta$ mode. The Q_u's of both modes are compared in Tab. 1. Note, that since the frequency is practically identical, the

dielectric and conductor losses should be nearly identical yet the Q_u values are significantly different. Discounting inhomogeneities in the YBCO or dielectric, these differences are most likely attributed to parasitic losses in the packaging.

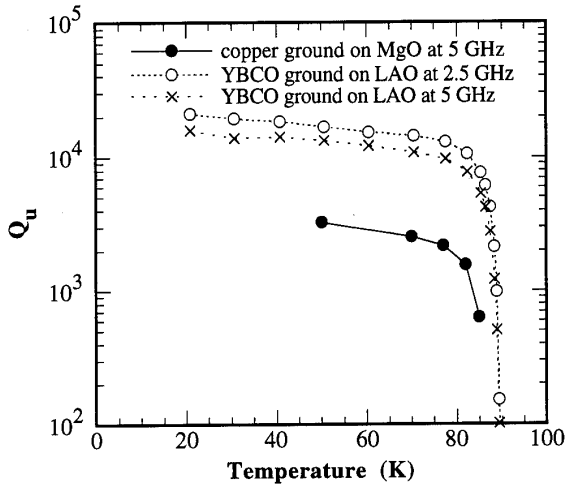

Fig. 3 Q_u as a function of temperature for ring resonators with a YBCO strip and various ground planes.

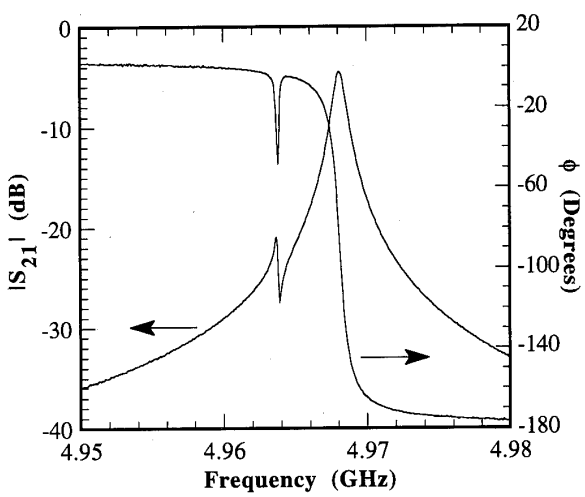

Fig. 4 Calibrated response of a double-sided ring resonator showing the double resonance signature due to modes with cos2θ (4.968 GHz) and sin2θ (4.964 GHz) dependence of the electric field.

Table 1. Q_u of cos2θ and sin2θ modes at 5 GHz

Temperature	Q_u of cos2θ mode	Q_u of sin2θ mode
20 K	15775	20588
77 K	9650	13015
85 K	5347	6178

IV. CONCLUSIONS

A technique for depositing high-quality HTS films on both sides of a dielectric substrate has been presented. The quality of both films, as evidenced by the measured J_c and T_c after all processing, is consistent with the quality of single-sided films made in the same deposition system. This approach is particularly attractive for microstrip circuits which require little patterning of one of the HTS films. This process has several advantages in that no post-processing or special fixturing is required. This process is applicable in any system which is capable of producing high-quality single-sided HTS films. The Q_u of a ring resonator fabricated using this process indicates that the microwave properties of both HTS films are excellent.

Improvements may arise by investigating alternatives to the 3-μm-thick silver layer. The requirements of this layer are to provide good electrical contact to the HTS-film and to maintain a region of high quality HTS at the substrate interface, and hence, some other material or layers of materials may yield improved performance. More sophisticated methods of preparing the surface after removal of the silver paste could lead to a higher quality second HTS film.

V. ACKNOWLEDGEMENTS

The authors wish thank Drs. M. Nisenoff, C. Rauscher, and D. Webb for their insights, comments and encouragement, Mr. R. Neidert for assistance in modeling the conductor losses, and Mr. H. Heddings for skillful assembly of the circuits. One of the authors (KRC) held a National Research Council/Naval Research Laboratory Fellowship during the course of this work. The work was sponsored, in part, by the Space and Naval Warfare Systems Command through the High Temperature Superconductivity Space Experiment program whose support is gratefully acknowledged.

REFERENCES

[1] See, for example: Special issue on microwave applications of superconductivity, IEEE Trans. Microwave Theory Tech., vol. 39, no. 9, Sept. 1991.

[2] M. V. Schneider, "Microstrip lines for microwave integrated circuits," Bell System Technical Journal, vol. 48, no. 5, pp 1421-1444, May-June 1969.

[3] T. Konaka, M. Sato, H. Asano, and S. Kubo, "Relative permittivity and dielectric loss tangent of substrate materials for high-Tc superconducting film," J. Superconduct., vol. 4, no. 4, pp. 283-288, 1991

[4] T. T. Braggins, J. R. Gavaler, and J. Talvacchio, "In-situ deposition of YBaCuO films on both sides of two-inch diameter wafers by off-axis sputtering," Advances in Cryogenic Engineering (Materials), vol. 38a, F. R. Fickett and R. P. Reed, Eds. New York: Plenum Press, 1991, pp. 1013-1018.

[5] J. H. Takemoto, C. M. Jackson, H. M. Manasevit, D. C. St. John, J. F. Burch, K. P. Daly, and R. W. Simon, "Microstrip resonators using two-sided metalorganic chemical vapor deposited Er-Ba-Cu-O thin films," Appl. Phys. Lett., vol. 58, no. 10, pp. 1109-1111, 11 March 1991

[6] D. B. Chrisey, J. S. Horwitz, H. S. Newman, M. E. Reeves, B. D. Weaver, K. S. Grabowski, and G. P. Summers, "Proton-induced reduction of R_s, J_c, and T_c in $YBa_2Cu_3O_{7-\delta}$ thin films," J. Superconduct., vol. 4, no. 4, pp. 283-288, 1991