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AN EXPERIMENTAL STUDY OF HIGH TC SUPERCONDUCTING MICROSTRIP TRANSMISSION LINES AT 35 GHZ AND THE EFFECT OF FILM MORPHOLOGY.

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Abstract

Microstrip transmission lines in the form of ring resonators have been fabricated from a number of in-situ grown laser ablated films and post-annealed co-sputtered $YBa_2Cu_3O_{7-X}$ (YBCO) films. The properties of these resonators have been measured at 35 GHz and the observed performance is examined in light of the critical temperature (Tc) and film thickness and also the film morphology which is different for the two deposition techniques. We find that Tc is a major indicator of the film performance for each growth type with film thickness becoming important as it decreases towards 1000Å. We find that the films with a mixed grain orientation (both 'a' axis and 'c' axis oriented grains) have poorer microwave properties as compared with the primarily 'c' axis oriented material. We speculate that this is due to the significant number of grain boundaries between the different crystallites, which may act as superconducting weak links and contribute to the surface resistance.

Introduction

Numerous papers to date have demonstrated the applicability of thin films of the oxide-based high temperature superconductors to passive microwave circuits. Cavity studies[1,2], conductivity measurements[3] and patterned resonator[4] studies have all demonstrated that high quality epitaxial films of these superconductors can have surface resistances significantly lower than normal metals typically used in microwave applications (i.e. gold and copper). Despite these encouraging results, there is still no definite understanding of which film properties are most important in determining the microwave characteristics of a thin film of these materials. It had been our observation, that films produced by processes that involved a high temperature anneal typically did not perform as well in a microstrip ring resonator as in-situ grown films. In an attempt to address this issue, we have undertaken a study comparing the performance of post-annealed and in-situ grown $YBa_2Cu_3O_{7-X}$ (YBCO) films on lanthanum aluminate ($LaAlO_3$) using a patterned microstrip ring resonator with a 3λ resonance at 35 GHz. The morphology of the films produced by the two growth methods is determined by X-ray diffraction (XRD) and scanning electron microscopy (SEM). We examine the unloaded Q vs temperature of each film type and note the effect of Tc and thickness on the performance. We compare the results from the resonators of the two growth types and observe the effect that the morphology has on the performance. Finally we propose an explanation of the observed differences based on the different film morphologies brought about by the different growth techniques.

Film Growth and Resulting Morphology

Two growth techniques were used to produce thin films of YBCO on $LaAlO_3$ with different film morphologies; these were in-situ laser ablation and co-sputtering with a high temperature anneal. The laser ablated films were formed by the ablation of a sintered YBCO pellet by a 248 nm excimer laser[5]. The substrate was mounted on a stainless steel block which was heated to 775°C in a background pressure of 170 mtorr for growth. The laser was pulsed at a rate of 4 pps and rastered over the target by means of an external lens. Following deposition, the sample block temperature was lowered to 450°C, the oxygen pressure raised to 1 atmosphere and the sample allowed to anneal for 2 hours. Then the block was allowed to slowly cool in oxygen to room temperature before removing the superconducting film from the growth chamber.

The post-annealed samples were prepared by simultaneous co-sputtering of Y, Cu, and BaF_2 targets onto a rotating $LaAlO_3$ substrate at ambient temperature[6]. This resulted in a non-superconducting amorphous film which was then annealed at 850°C in an H_2O saturated oxygen atmosphere for .5 hours to

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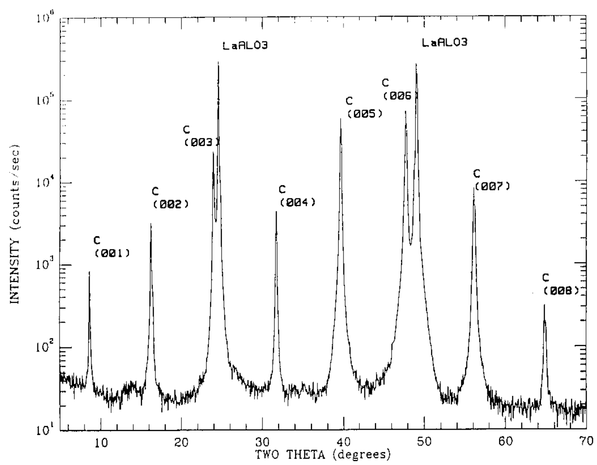

Figure 1. X-ray diffraction analysis of a laser ablated film on $LaAlO_3$.

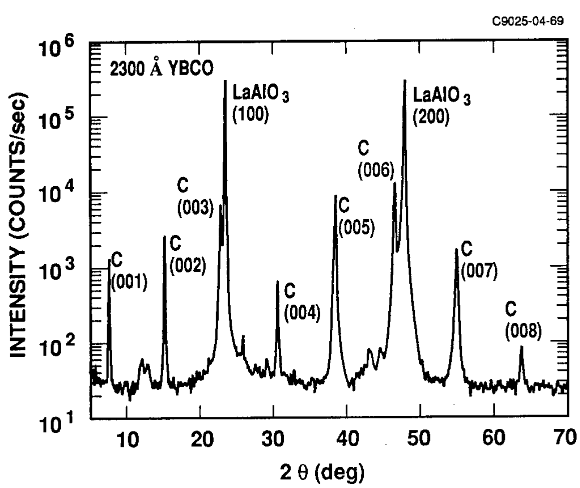

Figure 2. X-ray diffraction analysis of a co-sputtered post-annealed YBCO film on $LaAlO_3$.

produce the oriented superconducting film.

The morphology of the resulting films was examined using X-ray diffraction (XRD) and scanning electron microscopy (SEM). Typical XRD results from each type of film are shown in figures 1 and 2. Both show strong c-axis peaks and few spurious peaks indicating predominantly 'c' axis oriented material ('c' axis normal to the substrate). The co-sputtered films, however, tend to show the presence of extraneous phases more frequently than the laser ablated films.

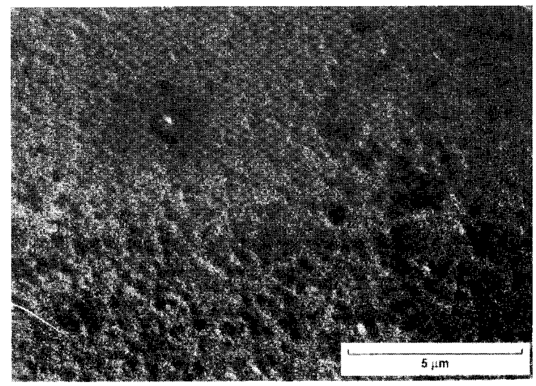

Figure 3. SEM micrograph of the surface of a laser ablated YBCO film on $LaAlO_3$. Note the absence of misoriented grains. This film shows some surface roughness and particulates; the best films are virtually feature-less.

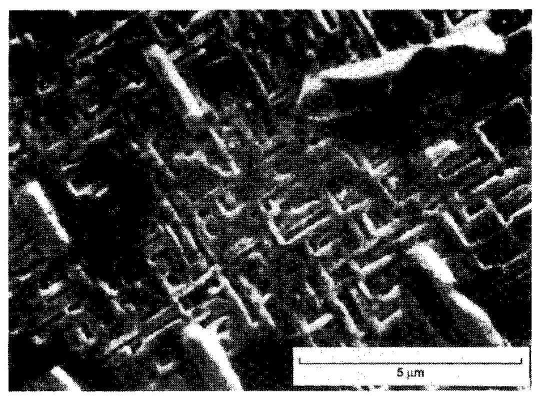

Figure 4. SEM micrograph of a 3000Å thick co-sputtered post-annealed YBCO film on $LaAlO_3$. The 'basket weave' structure is composed of YBCO grains with either the 'a' or 'b' axis normal to the substrate.

SEM investigation of the films (figures 3 and 4) shows a marked difference in the morphology of the two growth methods. The laser ablated films, in the best cases, are smooth and feature-less but sometimes (fig.3) show some surface roughness and particulates. These films show no evidence of large grains of misoriented material or secondary phases. TEM studies of other laser ablated films[7] seem to confirm that this deposition process produces mainly 'c' axis oriented material with few misoriented grains, though these same studies indicate that the 'c' material contains a high density of crystal defects. The post-annealed films, however (fig.4), in all cases show the development of a 'basket weave' structure indicative of material oriented with either the 'a' or 'b' axis normal to the substrate (referred to in the following as 'a' axis material or 'a' grains). That these grains have the 'a' axis normal to the substrate has been established by TEM studies[8] using electron micro-diffraction and cross sectional microscopy. That study of the microstructure of films produced in the same growth chamber has shown that for the post-annealed films the 'a' oriented material extends from the substrate upwards and that as the film grows thicker the upper portion of the material contains a higher fraction of 'a' material due to differential growth rates along the a,b,and c axes.

Fabrication and Testing

The superconducting films were patterned into microstrip ring resonators using standard photo-lithography. A positive photoresist was spun on, exposed through a UV contact mask aligner and developed. The resonator pattern was defined by etching in a dilute (<1%) solution of phosphoric acid which resulted in a well defined pattern with little undercutting. Finally a gold ground plane was evaporated on the reverse side of the circuit.

The circuits were fabricated on lanthanum aluminate 10 mils thick to avoid substrate modes at 35 GHz. The microstrip line width was 5.6 mil and the mean ring diameter was 77 mil and supported a 3λ mode near 35 GHz. The calculated impedance of the line was 45 ohms. The circuits were tested using an HP 8510B network analyzer in WR-28 waveguide. The Q's were extracted from the reflection response of the one port resonator.

Results and Discussion

The measured resonators showed a wide range of performance depending on film thickness, growth method and Tc. Figure 5 summarizes the Q data obtained from the laser ablated films and includes the performance of a gold resonator as a comparison. For films produced by a particular growth method, Tc appears to be a major indicator of the resonator performance. The best laser ablated film, #LA1, had the highest Tc. Two other films, #LA2 and #LA3 which were of thickness 2500Å and 4000Å but approximately the same Tc, 84°K, have similar performance further indicating that Tc is an important controlling factor in the film's microwave performance. Film #LA4 with a Tc of 87.2°K seems to deviate from this scaling trend as its Q values fall below the 84°K films. However, this film is only 1200Å thick and the lower Q values are most likely a reflection of the thinness of this film. It is expected that at some point film thickness will become a dominant factor in determining the microstrip losses just as in normal conducting strips, due to increased current density.

Figure 6 summarizes results from the post annealed films. Again, an examination of the data indicates the importance of film Tc on performance. The measured results scale quite well with the film Tc. However, the

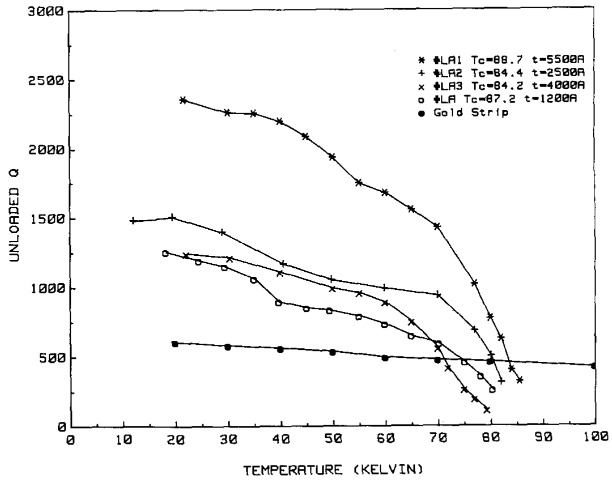

Figure 5. Unloaded Q vs temperature for several laser ablated films on $LaAlO_3$. All films eventually perform better than the gold implementation of the resonator. The best film is four times better at 20°K than the gold resonator.

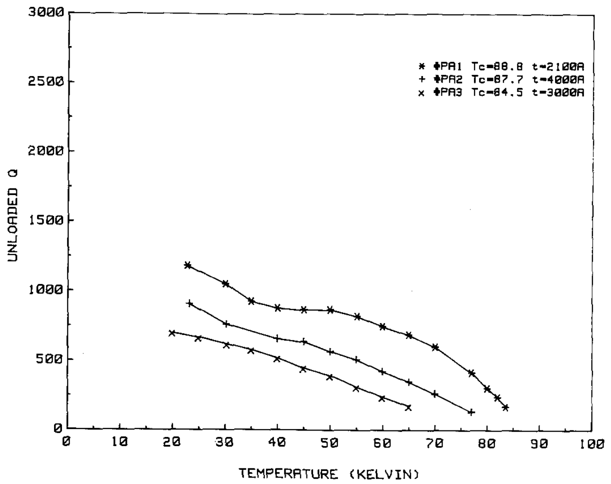

Figure 6. Unloaded Q vs temperature for several co-sputtered post-annealed YBCO films on $LaAlO_3$. The scale is the same as figure 5 to facilitate comparison between the two film types.

interpretation of the post annealed films and the relative importance of Tc vs film thickness for them is more involved. As discussed earlier, the most striking feature of the post annealed film morphology is the presence of a high density of 'a' axis oriented material. The presence of these 'a' grains and the resulting "basket weave" structure leads to a large number of grain boundaries.

These must act as either superconducting weak links or imbedded normal conducting material, either of which will cause additional loss in the film. The higher the number of grain boundaries, the more lossy the material would tend to be. Comparing performance by this criterion, it is significant that the film #PA1, with the best performance is also the film with the lowest density of 'a' axis oriented material.

The effect of the 'a' grains becomes more apparent when the post annealed and laser ablated films are compared. It is seen that as a group the post annealed films have lower Q's than the laser ablated films. The best post-annealed ring resonator, fabricated from a 2100Å film had a Q which was about half of that of the best laser ablated resonator, fabricated from a 5500Å film. Although some of the reduced performance in the post annealed resonator was probably due to the relatively thin film, the presence of 'a' axis grains also have an effect on the surface resistance. Because of the complexities of comparing films of different thickness and Tc's we have extracted values for the surface resistance of the films. This was accomplished by separately accounting for the dielectric loss (assuming $\tan\delta = 1E\text{-}4$) and the normal ground plane loss and matching the experimental Q values with values for the strip surface resistance. The strip and ground plane losses were calculated using the PEM[9] method which takes into account the conductor thickness. The results are tabulated in Table 1 and Table 2 with three temperature values for each film. The laser ablated films consistently show a surface resistance of approximately one half the value exhibited by the post annealed films.

Conclusions

We have measured several 35 GHz microstrip ring resonators fabricated from laser ablated and co-sputtered post annealed YBCO films. It was found that for a particular film type (growth method) Tc is a strong indicator of the resonator performance. Thickness effects on the performance of the resonators become apparent as the film decreases towards 1000Å; for thicknesses greater than this the performance is more dependent on the intrinsic properties of the material as indicated in Tc. Comparison of resonators fabricated from films of the two growth methods shows that the superconducting films with primarily 'c' axis orientation have better performance than the films with mixed grain orientation. We believe that weak links associated with the grain boundaries formed by the intersection among the 'a' grains and between the 'a' and 'c' material add an additional loss mechanism which limits the performance of circuits fabricated from this material.

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Table 1. Data for Laser Ablated Films.

			Rs (milliohms)		
Film	Tc	Thickness	20 K	40 K	70 K
#LA1	88.7 K	5500A	5.3	5.5	8.3
#LA2	84.4 K	2500A	8.4	9.2	15.9
#LA3	84.2 K	4000A	7.0	8.5	9.0
#LA4	87.2 K	1200A	4.0	5.9	7.7

Table 2. Data for Post-annealed Films.

			Rs (milliohms)		
Film	Tc	Thickness	20 K	40 K	70 K
#PA1	88.8 K	2100A	10.5	14.2	19
#PA2	87.7 K	4000A	8.0	10.9	24
#PA3	84.5 K	3000A	10.3	13.7	-

1. F.A. Miranda, W.L. Gordon, K.B. Bhasin and J.D. Warner, "Millimeter-wave surface resistance of laser-ablated $YBa_2Cu_3O_{7-X}$ superconducting films", Appl. Phys. Lett., 57(10), 1058-1060, 1990.

2. N. Klein, G. Muller, H. Piel, B. Roas, L. Shultz, U. Klein and M. Peiniger, "Millimeter wave surface resistance of epitaxially grown YBaCuO thin films", Appl. Phys. Lett., 54(8), 757-759, 1989.

3. K.B. Bhasin, J.D. Warner, F.A. Miranda, W.L. Gordon, H.S. Newman, "Determination of Surface Resistance and Magnetic Penetration Depth of Superconducting $YBa_2Cu_3O_{7-X}$ Thin Films by Microwave Power Transmission Measurements", IEEE Trans. Magnetics, This Issue.

4. A.A. Valenzuela and P. Russer, "High Q coplanar transmission line resonator of $YBa_2Cu_3O_{7-X}$ on MgO", Appl. Phys. Lett., 55(10), 1029-1031, 1989.

5. J.D. Warner, K.B. Bhasin, N.C. Varaljay D.Y. Bohman and C.M. Chorey, "Growth and Patterning of Laser Ablated Superconducting YBaCuO Films on $LaAlO_3$ Substrates", NASA TM-#102346, 1989.

6. E. Wiener-Avnear, J.E. Cooper, G.C. Kerber, J.W. Spargo, A.G. Toth, J.Y. Josefowicz, D.B. Rensch, B.M. Clemens and A.I. Hunter, "Laser Patterning of YBaCuO Weak Link Bridges", IEEE Trans. Mag. vol.25 no.2, 935-938, 1989.

7. D.M. Hwang, T. Venkatesan, C.C. Chang, L. Nazar, X.D. Wu, A. Inam and M.S. Hedge, "Microstructure of in situ epitaxially grown superconducting Y-Ba-Cu-O thin films", Appl. Phys. Lett., 54(17), 1702-1704, 1989.

8. C.W. Nieh, L. Anthony, J.Y. Josefowicz, F.G. Krajenbrink, "Microstructure of epitaxial $YBa_2Cu_3O_{7-X}$ thin films", Appl. Phys. Lett., 56(12), 2138-2140, 1990.

9. H.Y. Lee and T. Itoh, "Phenemenological Loss Equivalence Method for Planar Quasi-TEM Transmission Lines with a Thin Normal Conductor or Superconductor", IEEE MTT, vol.37, 1904-1909, 1989.