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TITLE

"GROWTH OF HIGH T_C SUPERCONDUCTING THIN FILMS FOR MICROWAVE APPLICATIONS"

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Growth of high T_c superconducting thin films for microwave applications

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ABSTRACT

High T_c superconducting thin films of $YBa_2Cu_3O_{7.8}$ (YBCO) were deposited on sapphire substrates with buffer layers of yttria-stabilized zirconia and cerium oxide by using pulsed laser deposition (PLD) technique. The epitaxial relationship between the substrate and buffer layers as well as the buffer layer and the superconducting film was established. Furthermore, using the same thin film technique, YBCO superconducting thin films were deposited on both sides of substrates of up to 5 cm in diameter. The superconducting properties of the films on both the sapphire with buffer layers and large-area substrates were comparable to the ones of the best YBCO films.

1. INTRODUCTION

The first application of the high temperature superconductors would be passive microwave devices such as filters, delay lines, phase shifters, resonators and so on. Since all the high T_c superconductors have to be in the crystalline phases in order to be superconducting, the best superconducting thin films can be obtained only on few crystalline oxide substrates. Sapphire is a preferred substrate for high frequency applications where a small dielectric constant and low-loss tangent are required. Unfortunately, sapphire is not chemically compatible with the superconductors at the processing temperature required to obtain a good superconducting phase. Therefore, an appropriate buffer layer on sapphire is required. In this paper, we present our results on preparation of YBCO thin films on sapphire with epitaxial buffer layers of yttria-stabilized zirconia $(Y_2O_3)_m(ZrO_2)_{1-m}$ (YSZ) and CeO_2 .

In parallel to developing buffer layer materials for sapphire, we have also deposited large-area YBCO films. The motivation behind this research is that for complex microwave device applications films of few cm^2 are required. At present, the high T_c superconducting thin films, deposited by a number of thin film methods, are limited to the size of typically $1\ cm^2$. More recently, off-axis sputtering^{1,2} and PLD³ were used to deposit one-sided YBCO films on 5 cm diameter substrates. Here, we report, to our knowledge, the first successful deposition of double-sided YBCO films on 5 cm diameter substrates.

2. FILM PREPARATION & PROPERTIES

2.1 Buffer layers on sapphire

The properties of YSZ and CeO_2 have been described in two previous publications^{4,5}. Both YSZ and CeO_2 have a fluorite structure with a lattice constant of $5.11\ \text{\AA}$ ($m=0.09$ for Y_2O_3) and $5.41\ \text{\AA}$, respectively. We have used the (1102) sapphire (also called R-cut sapphire) as the substrate. The YSZ and

CeO₂ will match with sapphire along the [1011] and [1210] directions of the sapphire. Both YSZ and CeO₂ buffer layers were prepared by the PLD technique. Pulsed excimer lasers were employed. The laser energy density was about 1.5-2 J/cm² for both YSZ and CeO₂. The typical deposition rate is 0.1-0.4 Å/pulse for a substrate-target distance of ~5-7 cm. The thickness for the buffer layers was typically 1000 Å. The substrate temperature was held at ~800 °C. The typical oxygen pressure during deposition was 150 mTorr. YSZ (m=0.09) single crystals were used as target. For CeO₂ films, high temperature sintered disks were used.

The oxygen pressure is a very critical parameter for obtaining films with the desired orientation. Fig 1 shows the X-ray diffraction scan over the region of (111) and (200) diffraction peaks of YSZ. As evident from the figure, the YSZ orientation can be rotated from (111) to (200) by simply increasing the oxygen pressure from below 0.1 mTorr to over 50 mTorr. Similar behavior has been observed for CeO₂ films. orientation. Fig 2 show a full θ -2 θ scan for a CeO₂ film on sapphire deposited under the standard processing condition. In addition the substrate peaks, only (200) and (400) diffraction peaks of the CeO₂ were observed, indicating the a-axis of the CeO₂ film is perpendicular to the substrate surface. The orientation of the YSZ or CeO₂ films was not dependent of the oxygen pressure during cooling.

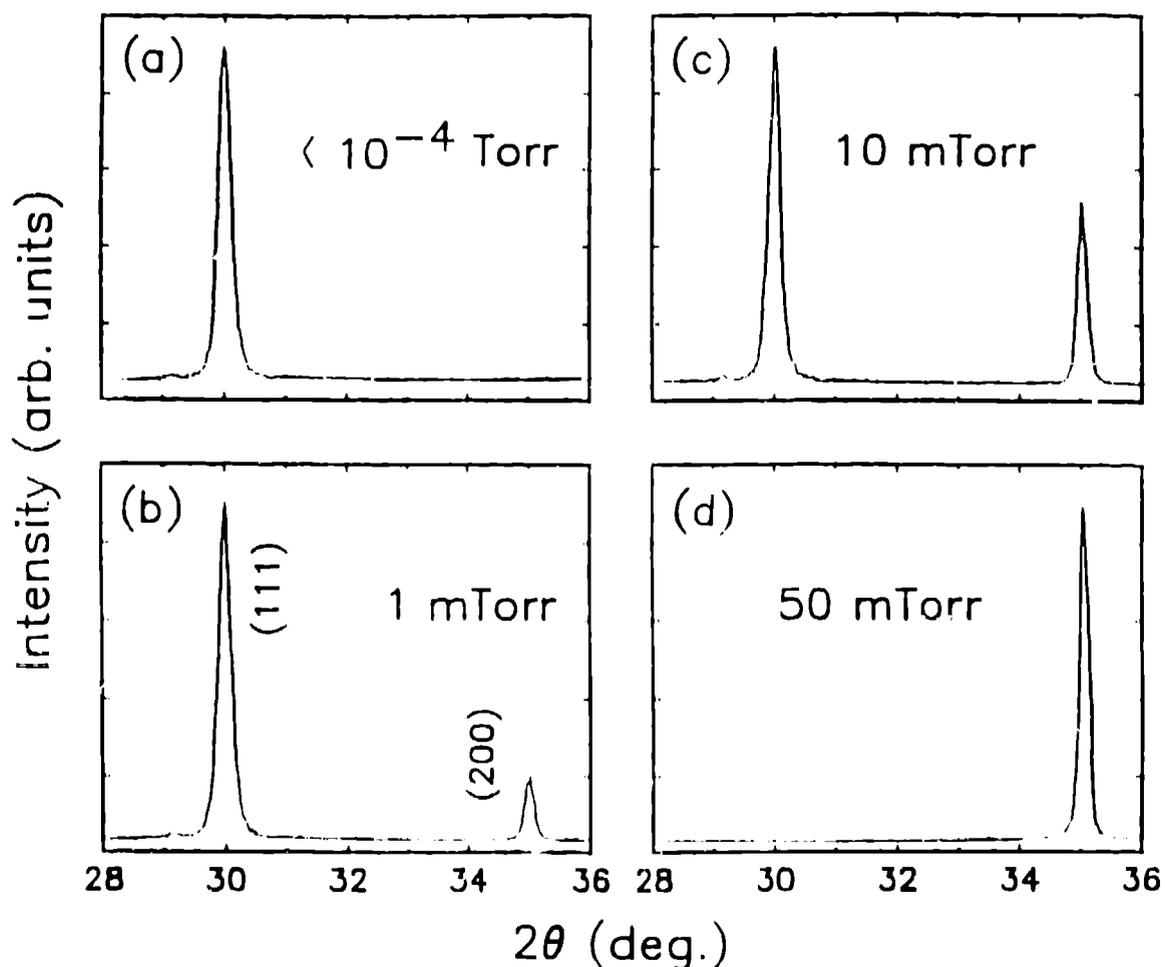


Fig. 1 X-ray diffraction scan over the region of (111) and (200) diffraction peaks of YSZ for a YSZ film deposited on sapphire at 800 °C under various oxygen pressures.

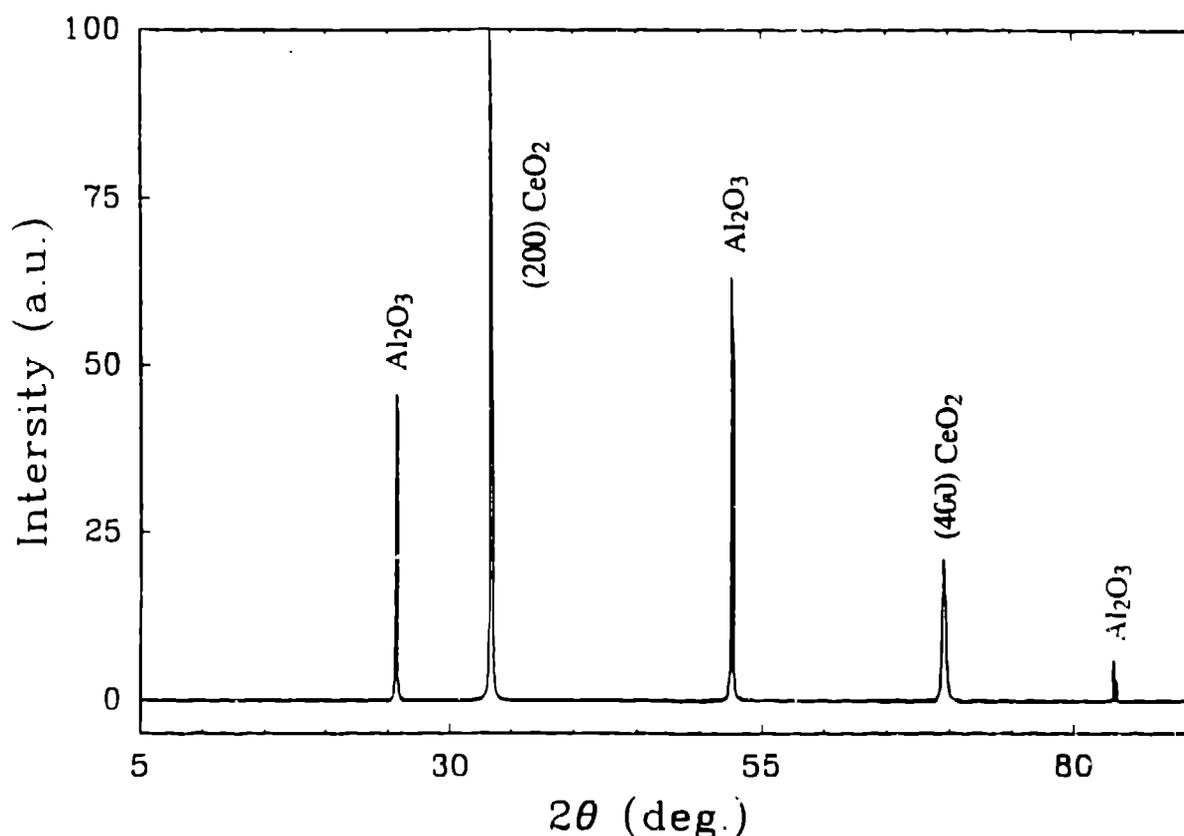


Fig. 2 A full θ - 2θ X-ray for a CeO_2 film on sapphire.

The crystallinity of the films was examined by Rutherford backscattering spectrometry (RBS) in the channeling mode. The He ion energies in RBS were either 2.2 MeV or 2.8 MeV. In Fig. 3, RBS random and aligned spectra (2.2 MeV) are shown for a CeO_2 film on sapphire. The minimum yield is 7% for Ce near the surface. A similar minimum yield was obtained for Zr for a YSZ film on sapphire⁴. The channeling spectra for both the films have the same tendency: the dechanneling increases as the He ions approach the substrate-film interfaces, which is believed to be the result of the in-plane anisotropic lattice mismatch between YSZ or CeO_2 and sapphire. As one can see from Fig. 3, a thick film on sapphire may yield a small minimum yield in the film surface.

The interface between the YSZ and sapphire was studied by a cross-section transmission electron microscopy (TEM)⁴. From the lattice image as well as the selected area diffraction studies of the interface, the growth orientations of the film with respect to the substrate were established. The epitaxial relationship was obtained as following: (100) YSZ// $(1\bar{1}02)$ sapphire, and (110) YSZ// $(01\bar{1}2)$ sapphire. Though TEM study has not been performed on CeO_2 /sapphire, the epitaxial relationship for CeO_2 and sapphire just as YSZ and sapphire was obtained from the in-plane X-ray scan.

2.2 YBCO on buffer layers/sapphire

YBCO films were deposited by PLD. The detailed processing parameters were reported in a previous publication⁶. The YBCO films were either deposited in the same or different vacuum system for the buffer layers. No differences were observed for the YBCO film properties.

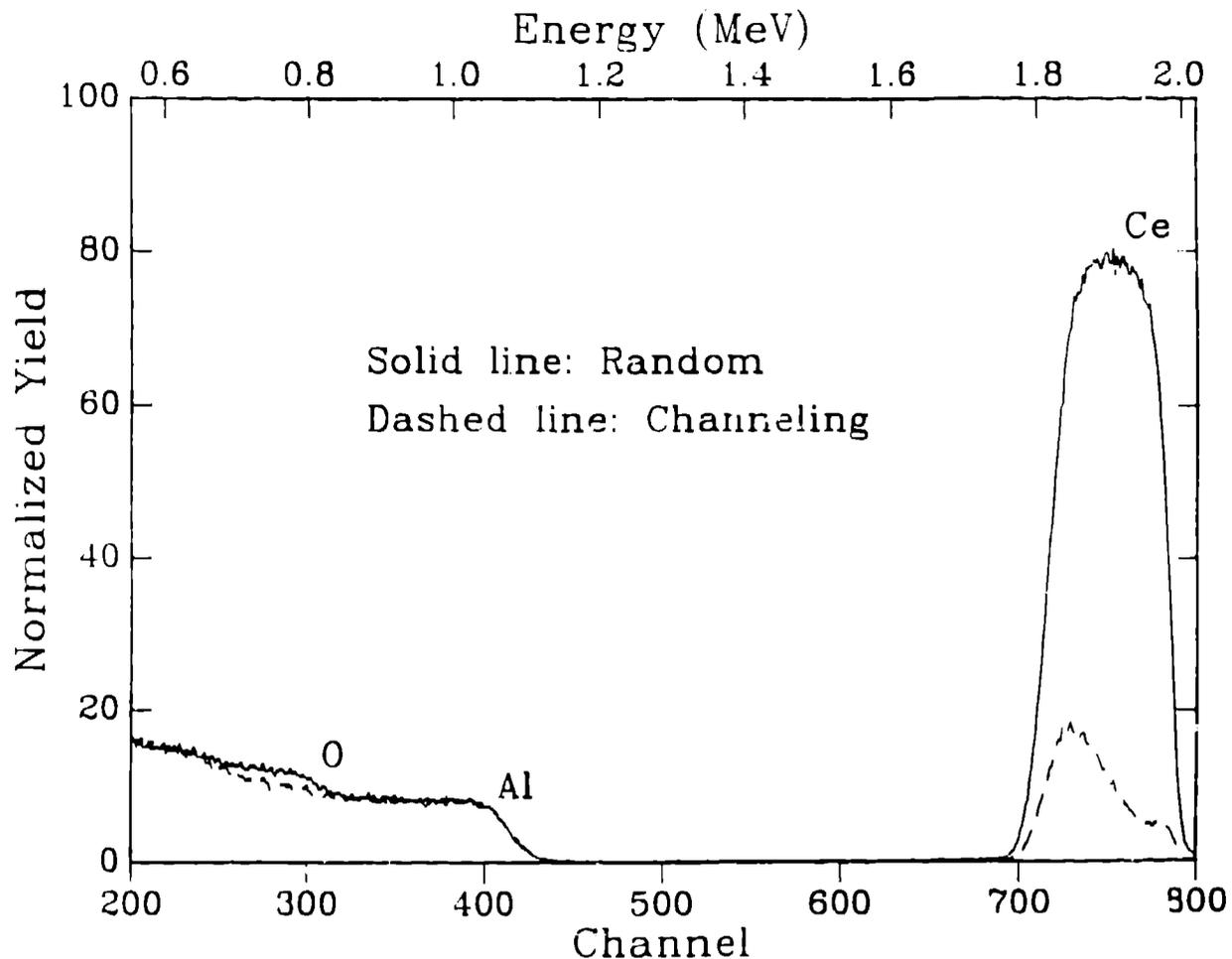


Fig. 3 RBS spectra (2.2 MeV) for a CeO_2 film on sapphire.

The YBCO films were superconducting after cooling down from the deposition temperature to room temperature within 20 min. Fig. 4 shows X-ray diffraction 2θ - θ scan for a YBCO film on YSZ/sapphire. This figure indicates the c-axis oriented nature of the YBCO film, and YBCO (001)/YSZ (100) relationship. The major in-plane orientation between YBCO and YSZ was YBCO (100)/YSZ (011). The 45° rotation in the basal planes between YSZ and YBCO gives the best lattice match between the two systems. In Fig. 5, X-ray in-plane Φ -scan for a YBCO film on CeO_2 /sapphire is shown for YBCO (102) peak and CeO_2 (202) peak. A rotation of 45° is again observed just like the YBCO/YSZ/sapphire system. The result is expected since the lattice constant of 5.41 Å of CeO_2 is very close to the a-axis and b-axis constants of YBCO multiplied by $\sqrt{2}$. RBS channeling study also showed that the YBCO films were epitaxially grown.

The best YBCO on either YSZ/sapphire or CeO_2 /sapphire had a zero resistance temperature of ~ 90 K, and a critical current density of over 1×10^6 A/cm² at 77 K.

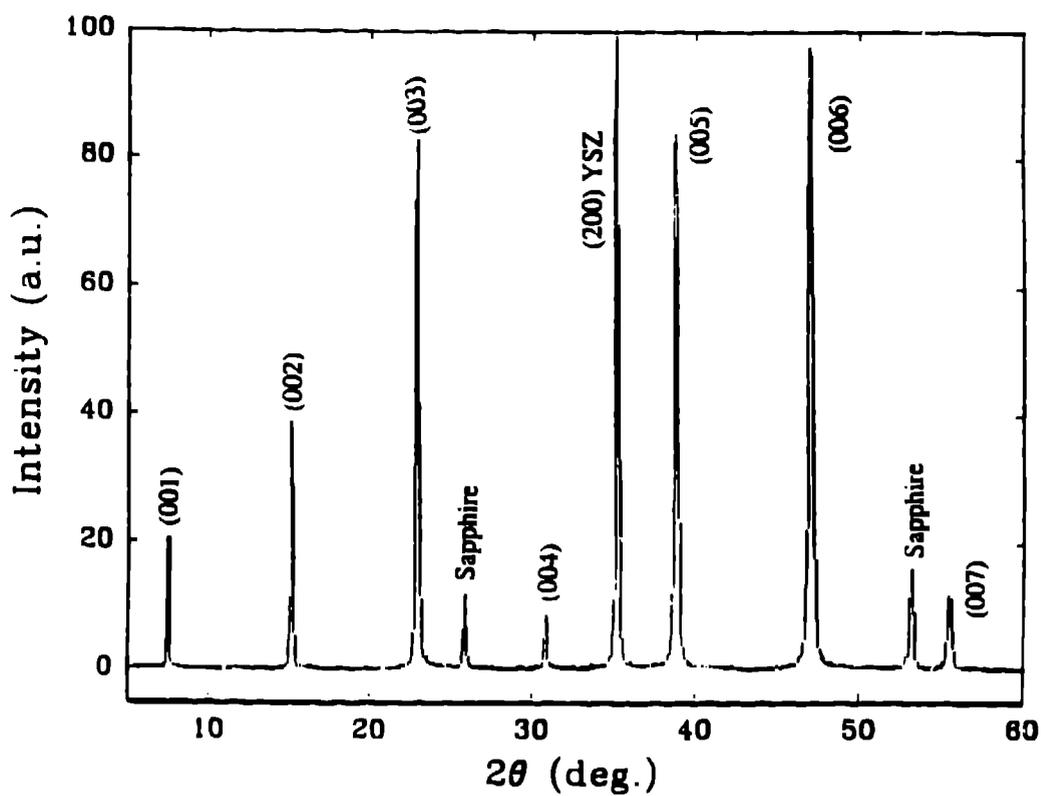


Fig. 4 A full θ - 2θ X-ray scan for a YBCO film on YSZ/sapphire.

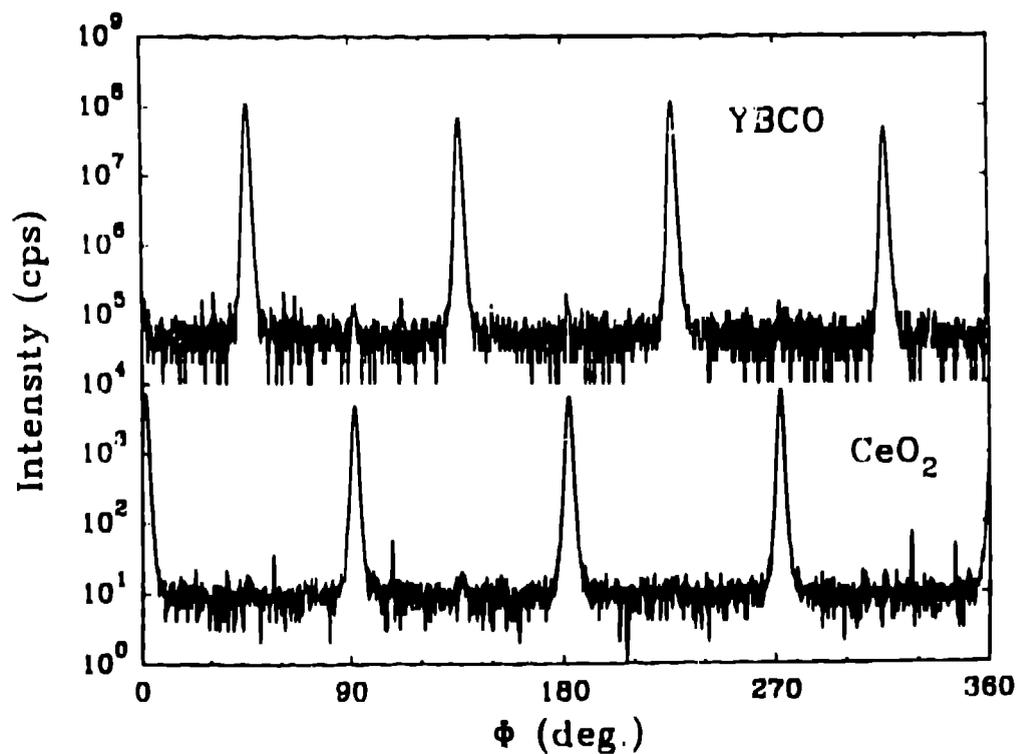


Fig. 5 X-ray in-plane Φ -scan for a YBCO film on CeO₂/sapphire.

2.3 Large-area YBCO films

The major problem involved in deposition of large-area superconducting films is how to heat the large substrate uniformly. A radiative heater with three quartz lamps behind the substrate was used. The design of the heater was described in a previous publication ⁷. In this experiment, a slight modification was made to heat the substrate radiatively without any silver or nickel paste ⁸.

5 cm in diameter LaAlO_3 and NdGaO_3 substrates were used. We have used PLD method for the experiment. A 1" YBCO target was used. Both the substrate and target were rotated during the experiment to ensure the thickness uniformity. 5 cm wafers can be coated with $\sim 4000 \text{ \AA}$ YBCO film within 20 min by using a laser repetition rate of 10 Hz. The deposition time is significantly shorter than ones by using off-axis sputtering method. The substrates were rotated to deposit the second side after finishing the first side. More detailed description of this experiment can be found in another publication ⁸.

Using the experiment setup, film thickness uniformity of better than 10% can be routinely obtained over 5 cm. The film composition is very close to the "123" stoichiometry over the entire 5 cm wafers. Superconducting transition temperatures measured by an inductive method are over 90 K for center and edge of the both sides. Critical current densities of few 10^6 A/cm^2 at 77 K were obtained for both sides ⁸.

The surface resistances of the films were measured by a number of methods ⁸. In Fig. 6, the surface resistance of a 3.8 cm YBCO film measured by end-well replacement in an 18 GHz Cu cavity is shown. The surface resistance dropped below the resolution of the cavity ($1 \text{ m}\Omega$) about 80 K. Using a 10 GHz parallel-plate resonator, surface resistances of two pairs of 1 cm^2 samples cut from a 5 cm diameter YBCO films were measured. Values of $40\text{-}60 \mu\Omega$ were obtained at 4 K.

Microwave devices are currently under fabrication from the double-side YBCO films. At the same time, large-area YBCO films are being deposited on sapphire with the buffer layers described above.

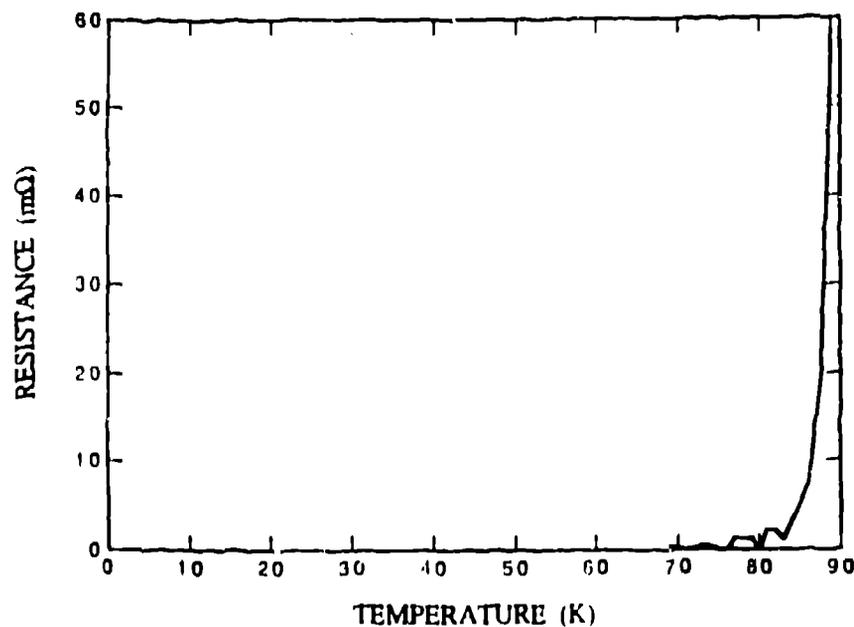


Fig. 6 Surface resistance for a YBCO measured by end-well replacement in an 18 GHz Cu cavity. The cavity resolution is $1 \text{ m}\Omega$.

3. CONCLUSIONS

We have shown that high quality YBCO films can be made on sapphire with the right buffer layers. Large-area and double-sided YBCO films were obtained by using pulsed laser deposition technique.

4. ACKNOWLEDGMENTS

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