NASA Technical Memorandum 103616

Determination of Surface Resistance and Magnetic Penetration Depth of Superconducting $YBa_2Cu_3O_{7-\delta}$ Thin Films by Microwave Power Transmission Measurements

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Abstract

A novel waveguide power transmission measurement technique has been developed to extract the complex conductivity ($\sigma^* = \sigma_1 - j\sigma_2$) of superconducting thin films at microwave frequencies. We obtained the microwave conductivity of two laser-ablated YBa$_2$Cu$_3$O$_{7\text{-}\delta}$ thin films on LaAlO$_3$ with transition temperatures (T$_c$) of approximately 86.3 and 82 K, respectively, in the temperature range 25 to 300 K. From the conductivity values we calculated the penetration depth (λ) to be approximately 0.54 and 0.43 μm, and the surface resistance(R$_s$) to be approximately 24 and 36 mΩ at 36 GHz and 76 K for the two films under consideration. We further compared the R$_s$ values with those obtained from the Q-factor of a 36 GHz TE$_{011}$-mode (OFHC) copper cavity by replacing one of its end walls with the superconducting sample. We found that this technique allows noninvasive characterization of high-T$_c$ superconducting thin films at microwave frequencies.

Introduction

Microwave measurements of the high-transition-temperature superconductors provide a convenient probe to be used in attempting to identify the conduction mechanisms and the nature of the superconducting state of these compounds.[1] Whereas dc resistance measurements provide information about the normal state above the transition temperature (T$_c$) and other techniques, such as magnetization measurements, give information on the superconducting state below T$_c$, microwave measurements can give useful information on both the superconducting and normal states.[2] Another main objective of the microwave studies of these high-T$_c$ superconductors is to evaluate the potential of these materials for microwave device applications.[3] In an attempt to uncover the intrinsic properties and the ultimate performance of these oxides at microwave frequencies, surface resistance measurements of very high-quality thin films have been carried out by different researchers.[4,5] Another parameter of fundamental importance in the characterization of these new materials is the microwave conductivity. Nevertheless, reports on measurements of this parameters are scarce, probably because more painstaking techniques are necessary to measure it directly. In this paper we report on the characterization of laser-ablated YBa$_2$Cu$_3$O$_{7\text{-}\delta}$ thin films by a power transmission measurement technique. We obtained values for the microwave conductivity ($\sigma^* = \sigma_1 - j\sigma_2$) in the normal and superconducting states and calculated the magnetic penetration depth (λ) and the surface resistance (R$_s$) from the conductivity values. Finally, we compared the R$_s$ values with those obtained from the change in the Q-factor of a 36 GHz TE$_{011}$-mode (OFHC) copper cavity, by replacing one of its end walls with the superconducting sample, to estimate the agreement between the two techniques in determining R$_s$.

Experimental Procedures

We used a pulsed-laser ablation technique to deposit the YBa$_2$Cu$_3$O$_{7\text{-}\delta}$ thin films onto 508-μm-thick LaAlO$_3$ substrates. The deposition was performed at a substrate temperature of 755 °C and at an ambient oxygen pressure of 170 mtorr. The laser wavelength was 248 nm, the pulse length was 20 to 30 ns, and the pulse rate was 2 pulses per second. During deposition the distance between the target and the sample was kept at 7.5 cm, and the laser fluence on the target was maintained at 2.0 J/cm^2 per pulse. For the deposition of the films we used YBa$_2$Cu$_3$O$_{7\text{-}\delta}$ stoichiometric targets with a density greater than 95% of theoretical. During this process the laser beam was scanned 1 cm across the target by using an external lens on a translator. At the end of the deposition process the oxygen pressure was raised to 1 atm, and the temperature was slowly lowered to room temperature. A more detailed description of the deposition technique can be found elsewhere.[6]

We analyzed the films by x-ray diffraction, dc resistance versus temperature measurements, and scanning electron microscopy (SEM). The T$_c$ was 86.3 K for one of the films (hereinafter called sample 1) and at 82.0 K for the other (hereinafter called sample 2). The dc resistance versus temperature for sample 1 is shown in Fig. 1. The x-ray diffraction pattern revealed that both films are singled phased with a predominantly c-axis orientation. The SEM's showed the presence of

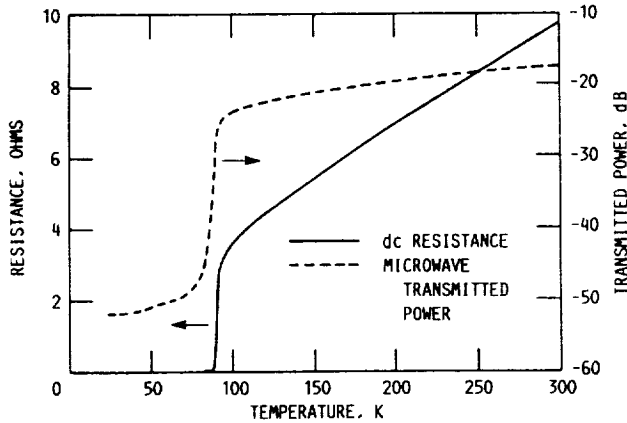randomly distributed particulate inhomogeneities whose average size was $\approx 1/4 \ \mu m$.

FIGURE 1. - dc RESISTANCE AND MICROWAVE TRANSMITTED POWER AT 35 GHz VERSUS TEMPERATURE FOR A $YBa_2Cu_3O_{7-\delta}$ THIN FILM (2655 Å) ON A $LaAlO_3$ SUBSTRATE.

We performed the power transmission and phase measurements on a Hewlett-Packard 8510 automatic network analyzer connected to a helium gas closed-cycle refrigerator by Ka-band (26.5 to 40.0 GHz) waveguides. All the measurements were made under vacuum ($< 10^{-3}$torr) in a custom-designed vacuum chamber. Inside the vacuum chamber the sample was clamped between two waveguide flanges mounted on top of the cold head of the refrigerator. The waveguides were made of thin-wall stainless steel to minimize heat conduction, and their inner surfaces were gold plated to reduce microwave energy losses. The flanges were made of brass; their inner surfaces were also gold plated. Inside the waveguides there were vacuum sealed mica windows. The temperature of the sample was monitored with silicon diode sensors mounted on the waveguide flanges that supported the sample.

The measured temperature dependence of the power transmission coefficient (T) (ratio of transmitted power to incident power) corresponding to sample 1 is given in Fig. 1. In the normal state the behavior of the transmitted power with decreasing temperature was similar to that of the dc resistance. At temperatures just below the onset temperature the transmitted power dropped abruptly, falling monotonically with decreasing temperature, until a lower limit was reached. This behavior was typical for both films.

Surface Resistance and Magnetic Penetration Depth

We calculated the surface resistance R_s and the magnetic penetration depth λ from the microwave complex conductivity. The real and imaginary parts of the complex conductivity are given in terms of the power transmission coefficient T and the phase shift ϕ by

$$R = \{(2n/T^{1/2})[ncos(k_0nt)sin(k_0t + \phi) - sin(k_0nt)cos(k_0t + \phi)] - n(n^2 - 1)sin(k_0nt)cos(k_0nt)\}/k_0d[n^2cos^2(k_0nt)+sin^2(k_0nt)]$$ (1)

and

$$I = \{(2n/T^{1/2})[ncos(k_0nt)cos(k_0t + \phi) + sin(k_0nt)sin(k_0t + \phi)] - 2n^2 cos^2(k_0nt) - (n^2 + 1)sin^2(nk_0t)\}/k_0d[n^2cos^2(k_0nt) + sin^2(k_0nt)]$$ (2)

where k_0 is the wave number of the normal incident transverse electric wave propagating in the rectangular waveguide, d is the film thickness, t is the thickness of the substrate with refraction index n, $R = 1 + 4\pi\sigma_2/\omega\epsilon$, $I = 4\pi\sigma_1/\omega\epsilon$, $\omega/2\pi$ = f is the frequency of the wave, and ϵ is the relative dielectric constant of the material.

Figure. 2 shows the temperature dependence of σ_1 and σ_2 for sample 1 at 35 GHz. The conductivity at room temperature ($\sim 3.9 \times 10^5$ S/m) compared reasonably well with reported values of dc conductivities in this type of film[7]. The change of σ_1 with decreasing temperature exhibited a metallic behavior down to the onset temperature, at which $\sigma_1 \sim 1.3 \times 10^6$ S/m. In the normal state σ_2 was close to zero, as expected for a good conductor. Note that both σ_1 and σ_2 increased upon going through the onset temperature, with σ_1 reaching values of 4.0×10^6 and 4.8×10^6 S/m at 76 and 50 K, respectively, and σ_2 reaching values of approximately 1.3×10^7 and 1.8×10^7 S/m at these same temperatures.
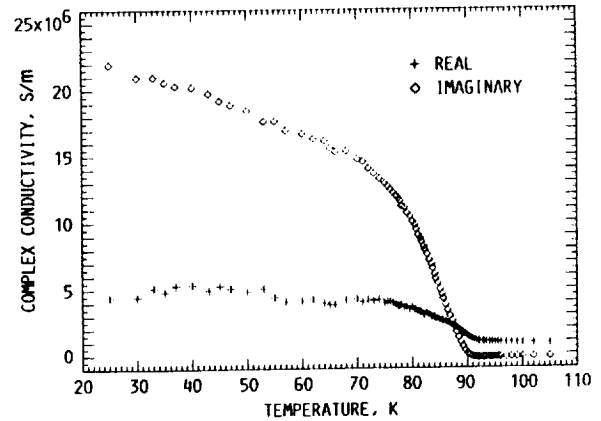

FIGURE 2. - REAL AND IMAGINARY PARTS OF THE MICROWAVE CONDUCTIVITY VERSUS TEMPERATURE AT 35 GHz FOR A $YBa_2Cu_3O_{7-\delta}$ THIN FILM (2655 Å) ON A $LaAlO_3$ SUBSTRATE.

We calculated the values of the magnetic penetration depth λ from the values of σ_2 and London's expression $\lambda = (\mu_0\omega\sigma_2)^{-1/2}$. For sample 1, λ of 0.57 and 0.40 μm were obtained at 76 and 25 K, respectively. Figure 3 shows a plot of λ versus temperature for this sample. For sample 2, λ of 0.43 and 0.26 were obtained at 76 and 25 K, respectively.

The values of λ obtained in this study were higher than the best reported values for strongly c-axis-oriented $YBa_2Cu_3O_{7\delta}$ thin films on $SrTiO_3$ ($\lambda \approx 0.14 \ \mu m$).[8] These larger λ values can be explained in terms of the existence of residual inhomogeneities. It has been shown[9] that these inhomogeneities can produce grain boundary Josephson junctions, which will increase the effective penetration depth. Furthermore, although the x-ray diffraction pattern for the films revealed
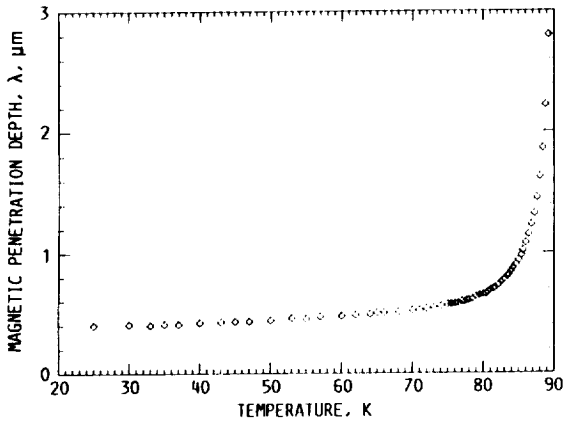
FIGURE 3. - MAGNETIC PENETRATION DEPTH VERSUS TEMPERATURE FOR A YBa$_2$Cu$_3$O$_{7-\delta}$ THIN FILM (2655 Å) ON A LaAlO$_3$ SUBSTRATE.

predominantly c-axis orientation, SEM micrographs revealed randomly distributed grains protruding through the surface that may be a-axis-oriented grains. The presence of a-axis oriented grains in a film increases the value of λ, since the penetration depth for shielding currents along the c-axis is greater than that for shielding currents in the a-b plane.[10]

The surface resistance R$_s$ for films in the superconducting state can be obtained by using the expression[11,12]

$$R_s = R_N \left\{ \frac{[(\sigma_1/\sigma_N)^2 + (\sigma_2/\sigma_N)^2]^{1/2} - \sigma_2/\sigma_N}{(\sigma_1/\sigma_N)^2 + (\sigma_2/\sigma_N)^2} \right\}^{1/2} \quad (3)$$

where $R_N = (\omega\mu_o/2\sigma_N)^{1/2}$ and σ_N are the surface resistance and the conductivity, respectively, at the onset temperature as determined from microwave power transmission measurements. The R$_s$ values at 36 GHz were obtained assuming of f^2 dependence for R$_s$. The change in R$_s$ for sample 1 with decreasing temperature is shown in Fig. 4. At 76 K, R$_s$ of 24 and 36 mΩ were obtained for samples 1 and 2, respectively. At 25 K, an R$_s$ of 12 mΩ was obtained for both samples. The surface resistance for the samples was also measured by looking at the change in Q of a TE$_{011}$-mode (OFHC) copper cavity resonant at 36 GHz when one of its end walls was replaced with the superconducting sample. Values for R$_s$ at 76 K of 25 and 303 mΩ were measured for samples 1 and 2, respectively. The R$_s$ values for sample 1 as measured by the cavity technique are plotted in fig. 4. We have also plotted the R$_s$ of copper for comparison.

Note that both techniques give an R$_s$ that decreases rapidly when the sample is cooled through the transition temperature and then levels off at lower temperatures, showing a residual surface resistance that changes very slowly with decreasing temperature. Observe that although there is a considerable discrepancy between the R$_s$ values obtained by the two techniques at temperatures not far below T$_c$, they compare better at lower temperatures. The same feature was observed for sample

2. The normal skin depth $\delta_N = 2R_s/\omega\mu_o$ for sample 1 calculated from the R$_s$ value at 87 K as measured by the cavity technique is approximately 5.4 μm. The largeness
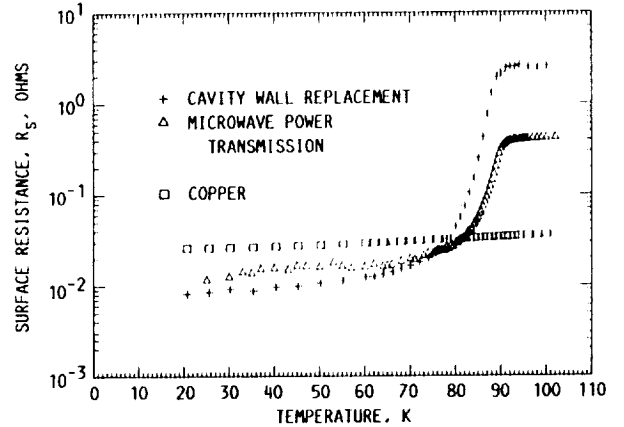

FIGURE 4. - SURFACE RESISTANCE VERSUS TEMPERATURE AT 36 GHz FOR A YBa$_2$Cu$_3$O$_{7-\delta}$ THIN FILM (2655 Å) ON LaAlO$_3$ AS MEASURED BY A CAVITY WALL REPLACEMENT METHOD AND BY A MICROWAVE POWER TRANSMISSION METHOD. THE R$_s$ FOR COPPER IS ALSO PLOTTED FOR COMPARISON.

of this value relative to the film thickness of approximately 2655 Å suggests that a great deal of energy could be leaking through the substrate, an effect that would result in an overestimation of R$_s$. Because of the inhomogeneous nature of these films, it is very probable that some leakage can persist at temperatures lower than T$_c$, but not at temperatures far below T$_c$, since at these temperatures most of the film is superconducting. The increasing agreement between the R$_s$ values obtained by the two techniques at lower temperatures seems to be consistent with this argument.

The results obtained by the microwave power transmission technique were strongly influenced by the intrinsic behavior of the superconducting intragranular material as well as by nonintrinsic losses due to normal inclusions and grain boundary effects in the interior of the film. Therefore, the R$_s$ values obtained with this technique may be affected more by the nonintrinsic properties of the films than those measured by the cavity technique, which is only sensitive to the surface properties of the film. However, in view of the good correspondence obtained in this study for the R$_s$ values at low temperatures, we believe that the microwave power transmission measurement technique provides an alternative way for determining R$_s$ particularly at temperatures far below T$_c$.

Conclusions

We have used a microwave power transmission measurement technique to determine the surface resistance R$_s$ and the magnetic penetration depth λ of YBa$_2$Cu$_3$O$_{7-\delta}$ superconducting thin films. The calculated λ values were higher than the best reported values perhaps because of the effect of the film's inhomogeneities. Comparing the R$_s$ values obtained by this technique with those measured by using a cavity wall-replacement technique suggests the suitability of the

microwave power transmission measurement technique for estimating R_s values of superconducting thin films.

References

1. K. Khachaturyan, E. R. Weber, P. Tejedor, A. M. Stacey, and A.M. Portis, "Microwave observation of magnetic field penetration of high-T_c superconducting oxides", *Phys. Rev. B*, 36, 8309-8314, 1987.

2. Tyagi, S., et al., "Low-field ac susceptibility and micrwave absorption in YBaCuO and BiCaSrCuO superconductors", *Physica C* 156, 73-78, 1988.

3. S. Sridhar and W. L. Kennedy, "Novel technique to measure the microwave response of high T_c superconductors between 4.2 and 200 K", *Rev. Sci. Instrum.* 59, 531-536, 1988.

4. J. P. Carini, A. M. Awasthi, W. Beyermann, G. Gruner, T. Hylton, K. Char, M. R. Beasly and A. Kapitulnik, "Millimeter-wave surface resistance measurements in highly oriented $YBa_2Cu_3O_{7\delta}$ thin films", *Phys. Rev. B.*, 37, 9726-9729, 1988.

5. N. Klein, G. Muller, H. Piel, B. Roas, L. Shultz, U. Klein, and M. Peiniger, "Millimeter wave surface resistance of epitaxially grown $YBa_2Cu_3O_{7-x}$ thin films", *Appl. Phys. Lett.*, 54, 757-759, 1989.

6. J. D. Warner, J. E. Meola, and K. A. Jenkins "Study of Deposition of $YBa_2Cu_3O_{7-x}$ on Cubic Zircomia" *NASA TM* 102350 (1989).

7. Q. Hu and P. L. Richards, "Design and analysis of a high T_c superconducting microbolometer", *Appl. Phys. Lett.* 55, 2444-2446, 1989.

8. A. T. Fiory, A. F. Hebard, P. M. Mankiewich, and R. E, Howard, " Renormalization of the mean-field superconducting penetration depth in epitaxial $YBa_2Cu_3O_7$ films", *Phys. Rev. Lett.* 61, 1419-1426, 1988.

9. L Drabeck, J. P. Carini, G. Gruner, T. Hylton, K. Char, and M. R. Beasley, "Power-law temperature dependence of the electrodynamics properties in oriented $YBa_2Cu_3O_{7\delta}$ and $Y_2Ba_4Cu_8O_{16\delta}$ films". *Phys. Rev. B.*, 39, 785-788, 1989.

10. S. M. Anlage, H. Sze, H. J. Shortland, S. Tahara, B. Langley, C. B. Eom, M. R. Beasly, and R. Taber, " Measurements f the magnetic penetration depth in $YBa_2Cu_3O_{7\delta}$ thin films by the microstrip resonator technique", *Appl. Phys. Lett.*, 54, 2710-2712, 1989.

11. J. I. Gittleman and B. Rosenblum, "Microwave Properties of Superconductors", *IEEE Proc.*, 52, 1133-1147, 1964.

12. J. I. Gittleman and J. R. Matey, "Modeling the microwave properties of the $YBa_2Cu_3O_{7-x}$ superconductors", *J. Appl. Phys.*, 65, 688-691, 1989.

16. Abstract

A novel waveguide power transmission measurement technique has been developed to extract the complex conductivity ($\sigma^* = \sigma_1 - j\sigma_2$) of superconducting thin films at microwave frequencies. We obtained the microwave conductivity of two laser-ablated YBa$_2$Cu$_3$O$_{7-\delta}$ thin films on LaAlO$_3$ with transition temperatures (T$_c$) of approximately 86.3 and 82 K, respectively, in the temperature range 25 to 300 K. From the conductivity values we calculated the penetration depth (λ) to be approximately 0.54 and 0.43 μm, and the surface resistance (R$_s$) to be approximately 24 and 36 mΩ at 36 GHz and 76 K for the two films under consideration. We further compared the R$_s$ values with those obtained from the change in the Q-factor of a 36 GHz TE$_{011}$-mode (OFHC) copper cavity by replacing one of its end walls with the superconducting sample. We found that this technique allows noninvasive characterization of high-T$_c$ superconducting thin films at microwave frequencies.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Surface resistance; Magnetic penetration depth; Superconducting YBa$_2$Cu$_3$O$_{7-\delta}$ thin films; Microwave power transmission	Unclassified – Unlimited Subject Category 76

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 7	22. Price* A02