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Millimeter Wave Transmission Studies of $YBa_2Cu_3O_{7-\delta}$ Thin Films in the 26.5 to 40.0 GHz Frequency Range

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MILLIMETER WAVE TRANSMISSION STUDIES OF $YBa_2Cu_3O_{7-\delta}$ THIN FILMS IN THE 26.5 TO 40.0 GHz FREQUENCY RANGE.

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ABSTRACT

Millimeter wave transmission measurements through $YBa_2Cu_3O_{7-\delta}$ thin films on MgO, ZrO_2 and $LaAlO_3$ substrates, are reported. The films (0.2 to 1.0 μm) were deposited by sequential evaporation and laser ablation techniques. Transition temperatures T_c, ranging from 89.7 K for the laser ablated film on $LaAlO_3$ to approximately 72 K for the sequentially evaporated film on MgO, were obtained. The values of the real and imaginary parts of the complex conductivity, σ_1 and σ_2, are obtained from the power transmitted through the film, assuming a two fluid model. The magnetic penetration depth is evaluated from the values of σ_2. These results will be discussed together with the frequency dependence of the normalized power transmission, P/P_c, below and above T_c.

INTRODUCTION

Millimeter wave measurements of the new high T_c superconductors are of fundamental importance due to the potential applicability of these oxides in the fabrication of devices operational in these frequency ranges.[1] Through these measurements, information on the nature of superconductivity in these new superconductors can be obtained from the temperature dependence of parameters such as the surface resistance,[2-6] and the complex conductivity.[7-9] Another important question is the applicability of millimeter wave measurements for the characterization of superconducting thin films. While dc resistance versus temperature measurements give no further information once the zero resistance state is achieved, millimeter wave transmission and absorption measurements provide a sensitive, contactless technique, which yield important information about the microstructure of superconducting films[10] and their behavior at temperatures below the critical temperature (T_c). Millimeter and microwave absorption studies in low and high T_c superconductors have been performed using resonant cavities.[10-16] Usually, those studies applying millimeter or microwave transmission analysis, have reported results at just one particular frequency.[8,9]

In this work we have measured the power transmitted through $YBa_2Cu_3O_{7-\delta}$ thin films at frequencies within the frequency range from 26.5 to 40.0 GHz and at temperatures from 20 to 300 K. From these measurements and assuming a two fluid model, we have obtained values of the normal and complex conductivities above and below T_c respectively. The zero temperature magnetic penetration depth has been obtained using the value of the imaginary part of the complex conductivity, σ_2.

ANALYSIS

We have applied the two fluid model due to its simplicity and because in the past it has given good results for the microwave properties of metallic type II superconductors in cases for $\hbar\omega \ll E_{gap}$.[17] Since the energy gap for $YBa_2Cu_3O_{7-\delta}$ superconductors corresponds to frequencies in the terahertz range, we expect the model to be applicable in the frequency range studied. In this phenomenological model, the complex conductivity is defined as

$$\sigma = \sigma_1 - i\sigma_2 \tag{1}$$

with

$$\sigma_1 = \sigma_c t^4 \qquad \text{and} \qquad \sigma_2 = \sigma_c(1 - t^4)/\omega\tau \ . \tag{2}$$

Here, σ_c is the normal conductivity at $T = T_c$, $\omega = 2\pi f$ is the angular frequency, t is the reduced temperature T/T_c, and τ is the mean carrier scattering time. Thus, to determine either σ_1 or σ_2 we need to know the transition temperature T_c and the value of σ_c. Furthermore, the value of τ must be known beforehand if σ_2 is to be obtained from Eq. (2).

In this study, the value of T_c was determined from the standard four-point probe versus temperature measurements. To determine the normal and complex conductivities, we used the method applied by Glover and Tinkham.[18] In this method, the transmission of a normally incident plane wave through a film of thickness d($\ll$ wavelength or skin depth) deposited on a substrate of thickness ℓ and index of refraction n, is measured. Following the notation of Glover and Tinkham[18] the power transmission is given by

$$\mathbf{T} = \frac{8n^2}{A + B\cos 2k\ell + C\sin 2k\ell} \tag{3}$$

where

$$A = n^4 + 6n^2 + 1 + 2(3n^2 + 1)g + (n^2 + 1)(b^2 + g^2)$$

$$B = 2(n^2 - 1)g - (n^2 - 1)^2 + (n^2 - 1)(b^2 + g^2)$$

$$C = 2(n^2 - 1)nb$$

$$k = n\omega/c$$

and

$$y = g - ib = YZc = (G - iB)Z_c = (\sigma_1 - i\sigma_2)dZ_c$$

is the dimensionless complex admittance per square of the film in units of the characteristic admittance, Z_c^{-1}, of the wave guide ($Z_c = Z_0/\sqrt{1 - (f_c/f)^2}$, $Z_0 = 377\ \Omega$, mks; $Z_0 = 4\pi/c$, cgs; f_c = cutoff frequency of the TE mode wave guide and f is the operational frequency).

In the normal state, Eq. (3) becomes

$$\mathbf{T}_N = \frac{8n^2}{\sigma_N^2 d^2 Z_c^2 Q + \sigma_N dZ_c R + P} \tag{4}$$

where

σ_N = normal conductivity

$Q = (n^2 + 1) + (n^2 - 1)\cos 2k\ell$

$R = 2(3n^2 + 1) + 2(n^2 - 1)\cos 2k\ell$

$P = n^4 + 6n^2 + 1 - (n^2 - 1)^2 \cos 2k\ell.$

The normal state conductivity of the film can be expressed conveniently in terms of the power transmission as

$$\sigma_N = \frac{-R\mathbf{T}_N \pm \sqrt{R^2\mathbf{T}_N^2 - 4Q\mathbf{T}_N(P\mathbf{T}_N - 8n^2)}}{2Q\mathbf{T}_N dZ_c} \tag{5}$$

where only the expression with the + sign has physical relevance. It is convenient to use the ratio $\mathbf{T}_S/\mathbf{T}_N$ in the analysis of the superconducting state, where $\mathbf{T}_S$ refers to the transmission in the superconducting state given by Eq. (3). Thus,

$$\frac{\mathbf{T}_S}{\mathbf{T}_N} = \frac{\sigma_N^2 d^2 Z_c^2 Q + \sigma_N dZ_c R + P}{A + B\cos 2k\ell + C\sin 2k\ell} \tag{6}$$

Solving (6) for the imaginary part, σ_2, of the conductivity, and using the value of σ_N at $T = T_c$ we have

$$\sigma_2/\sigma_c = -\beta/2\,\frac{1}{\sigma_c dZ_c} + \left\{\frac{1}{(\sigma_c dZ_c)^2}\left[(\beta/2)^2 - \gamma\right] - \frac{\alpha\sigma_1}{\sigma_c^2 dZ_c} - \left(\frac{\sigma_1}{\sigma_c}\right)^2 + (\mathbf{T}_c/\mathbf{T}_S)\left[1 + \frac{\alpha}{\sigma_c dZ_c} + \frac{\gamma}{(\sigma_c dZ_c)^2}\right]\right\}^{1/2} \tag{7}$$

where σ_c and $\mathbf{T}_c$ are the conductivity and the transmissivity at $T = T_c$, and

$$\alpha = \frac{1}{D} [6n^2 + 2 + 2(n^2 - 1)\cos 2k\ell]$$

$$\beta = \frac{1}{D} [-2n(n^2 - 1)\sin 2k\ell]$$

$$\gamma = \frac{1}{D} [n^4 + 6n^2 + 1 - (n^2 - 1)\cos 2k\ell]$$

$$D = n^2 + 1 + (n^2 - 1)\cos 2k\ell \ .$$

Thus, from the relation for σ_1 in Eq. (2), and Eq. (7), the real and imaginary parts of the complex conductivity can be determined.

The magnetic penetration depth, λ, can be obtained from the London expression

$$\lambda = \left(\frac{1}{\mu_o \omega \sigma_2}\right)^{1/2} \tag{8}$$

which can be written in terms of the superfluid density N_S, as

$$\lambda = \left(\frac{m}{\mu_o N_S e^2}\right)^{1/2} \tag{9}$$

where m is the effective mass of the charge carriers. From the two fluid model

$$\frac{N_S}{N} = 1 - t^4 \tag{10}$$

where $N = N_n + N_s$ is the total number of carriers per unit volume, we have

$$\lambda = \left[\frac{m}{\mu_o N e^2}\right]^{1/2} (1 - t^4)^{-1/2} = \lambda_o \ (1 - t^4)^{-1/2} \tag{11}$$

From this expression the zero-temperature penetration depth, λ_o, can be obtained. Because Eq. (9) applies to homogeneous superconductors, the values of λ_o obtained in this method are larger than those that would be obtained for homogeneous films.

Our measurements were made on thin films (0.2 to 1.0 µm thickness) of $YBa_2Cu_3O_{7-\delta}$ on $LaAlO_3$, MgO and ZrO_2 substrates. The substrates were generally between 0.025 and 0.100 cm thick. The deposition techniques used for the preparation of the films used in this study are described in Refs. 19 and 20. For the laser ablated films, X-ray diffraction data showed that the films were c-axis oriented on $LaAlO_3$ and partially c-axis oriented for those on MgO and ZrO_2. They had T_c's ranging from 89.7 K for the film on $LaAlO_3$ to 79 and 78 K for those deposited on MgO and ZrO_2 respectively. The film deposited by sequential evaporation on MgO had a T_c of approximately 72 K.

The power transmission measurements were made using a Hewlett-Packard model HP-8510 automatic network analyzer connected to a modified closed cycle refrigerator by Ka-band (26.5 to 40.0 GHz) waveguides. Inside the vacuum chamber of the cryosystem, the sample was clamped between two waveguide flanges which were in direct contact with the cold head of the refrigerator. The power transmitted through the sample was obtained by measuring the scattering parameters as described in Ref. 21. The temperature gradient of the waveguide flanges between the top and bottom of the sample, was estimated to be 2.5 K or less at 90 K. The system was properly calibrated with short, open, load and through calibration standards before each measurement cycle was started.

RESULTS

Figures 1 and 2 show the temperature dependence of the normalized power transmitted through $YBa_2Cu_3O_{7-\delta}$ thin films deposited by laser ablation on $LaAlO_3$ and MgO respectively. The data are normalized with respect to the transmitted power at the critical temperature T_c. The measurements of the power transmitted through the films were started at room temperature and then carried out during sample cooling. In Fig. 1, it can be observed that the rapid decrease in transmitted power occurs at T_c. This is typical of films with a high degree of homogeneity, where all the regions of the film undergo the superconducting transition simultaneously. This is not the case for the film considered in Fig. 2, for which the transmitted power starts to decrease rapidly at temperatures just below an onset temperature (~90 K) approximately 11 K above its transition temperature of 79 K. This behavior may be associated with the presence of inhomogeneities, resulting in a distribution of transition temperatures. For temperatures below T_c both films are characterized by a smooth decrease of the power transmitted through them.

The behavior shown in Figs. 1 and 2 for the power transmitted through the film-substrate combination, as a function of decreasing temperature, was also observed for the laser ablated film on ZrO_2 and for

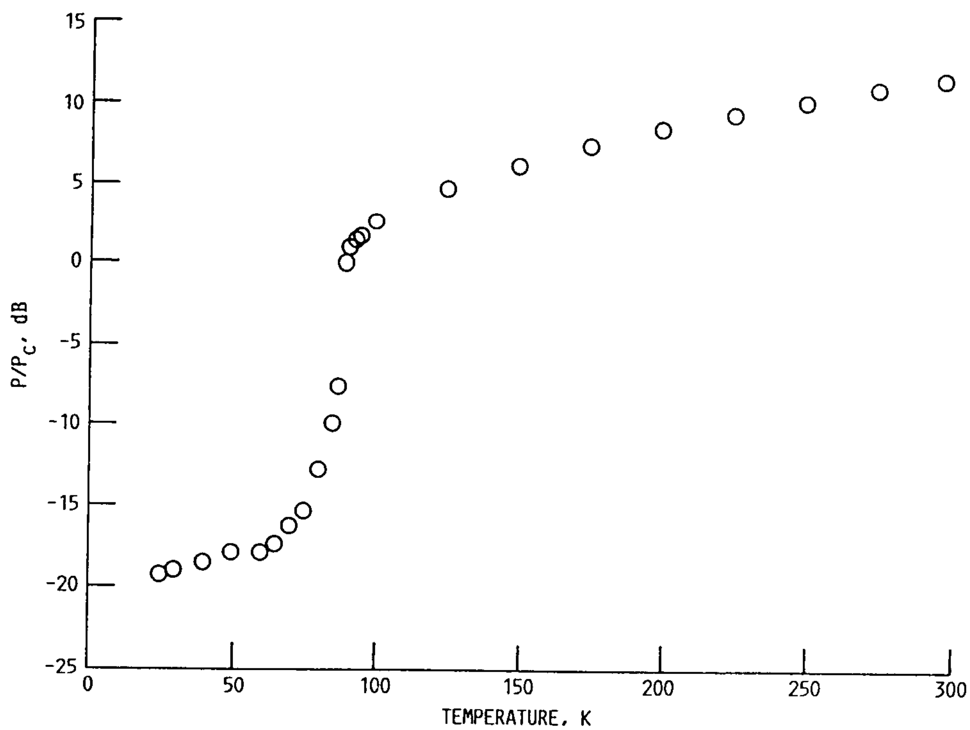

FIGURE 1. - NORMALIZED TRANSMITTED POWER VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.7 MICRONS) ON $LaAlO_3$ AT 37.0 GHz.

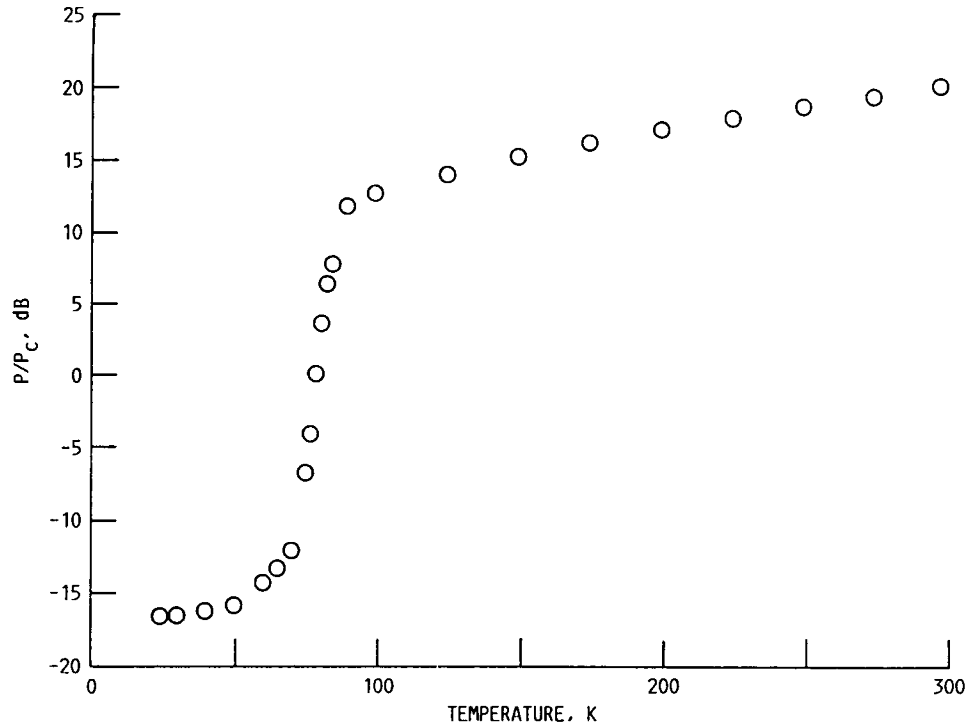

FIGURE 2. - NORMALIZED TRANSMITTED POWER VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.2 MICRONS) ON MgO AT 28.5 GHz.

the sequentially evaporated film on MgO. For the latter film the transmission data suggest a lower film quality when compared to the film deposited on MgO by laser ablation. The films on ZrO_2 and sequentially evaporated on MgO also show a wide transition region. This temperature behavior was verified to be frequency independent for the frequencies employed in this study, and our analysis suggest that it is related to the degree of homogeneity and quality of the films.

Figures 3 to 10 and Table I, show the results for the conductivity above and below T_c, and at different frequencies, for the various films considered in this study. Figures 3 and 4 show the real and imaginary parts of the conductivity, σ_r and σ_2 respectively, corresponding to the $YBa_2Cu_3O_{7-\delta}$ film deposited on $LaAlO_3$ by laser ablation. The value for the normal conductivity at room temperature, 2.0×10^5 S/m, compares reasonably well with reported values of the dc conductivity in this type of film.[22,23] The cusp in σ_r at the transition temperature can be observed clearly in Fig. 3 and again indicates the high level of homogeneity and quality of this film. The imaginary part of the conductivity increases as a function of decreasing temperature, as can be seen in Fig. 4. Values of 5.17×10^6 S/m and 6.80×10^6 S/m are obtained at 70 and 40 K respectively. Using Eq. (8) we find $\lambda = 0.81$ µm at 70 K and $\lambda = 0.70$ µm at 40 K. From the value of λ at 40 K we found $\lambda_o = 0.69$ µm.

Figures 5 to 10 show the real and imaginary parts of the complex conductivity for the laser ablated films on MgO and ZrO_2, and for the sequentially evaporated film on MgO. Note that the normal to the superconducting transition region has been clearly identified in Figs. 5, 7 and 9. In the absence of a physical model which can account for the

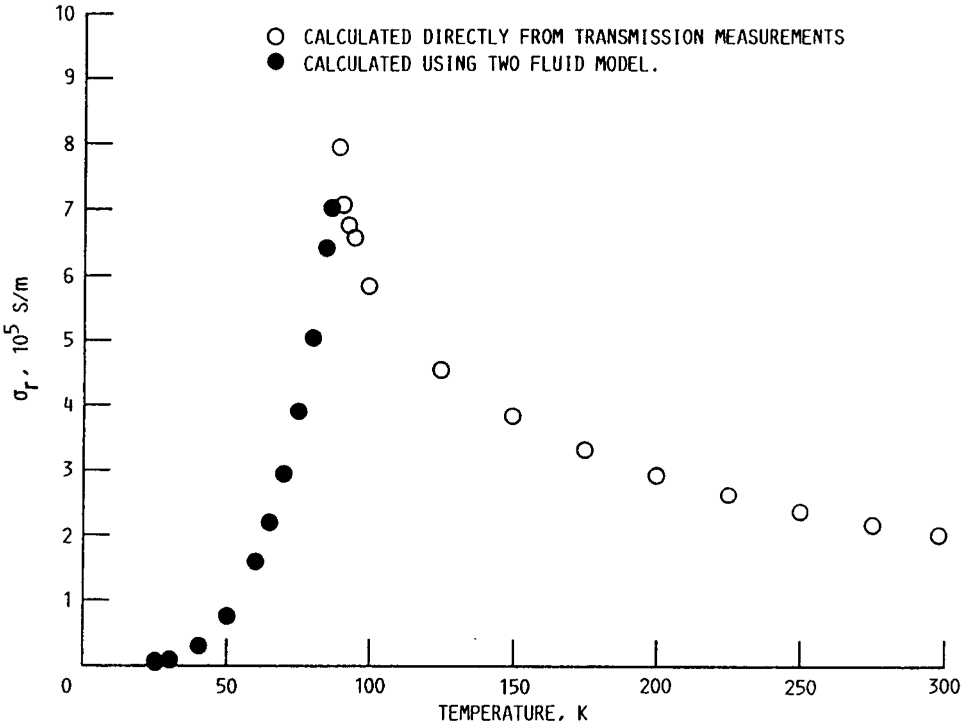

FIGURE 3. - REAL PART OF THE CONDUCTIVITY, σ_r, VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.7 MICRONS) ON $LaAlO_3$ AT 37.0 GHz. $\sigma_r = \sigma_N$ FOR $T > T_c$ AND $\sigma_r = \sigma_1$ FOR $T < T_c$.

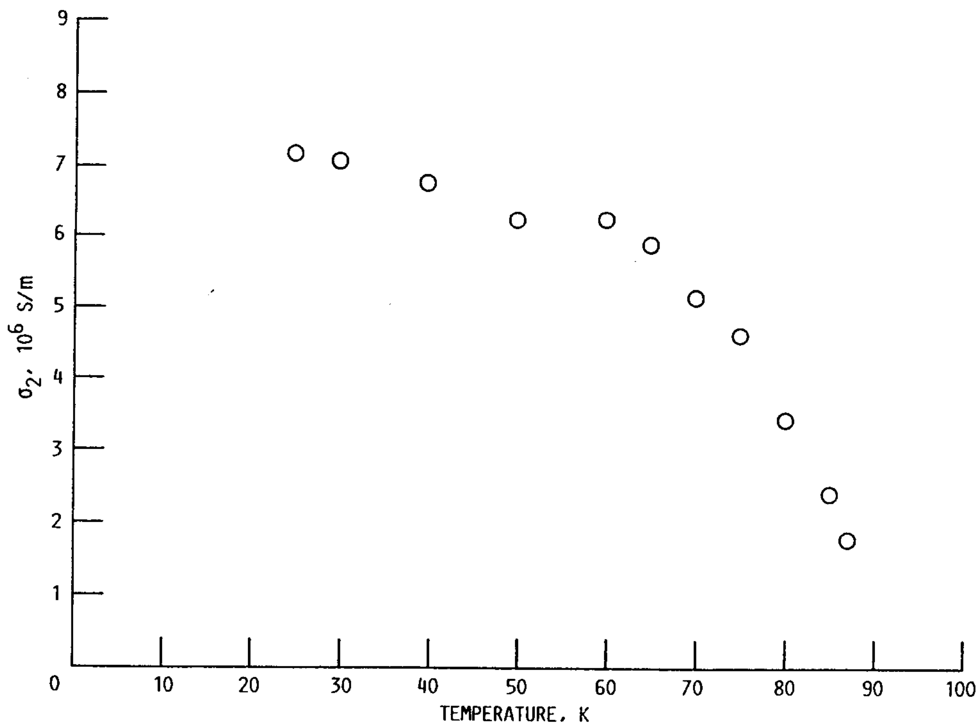

FIGURE 4. - IMAGINARY PART OF THE CONDUCTIVITY, σ_2, VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.7 MICRONS) ON $LaAlO_3$ AT 37.0 GHz.

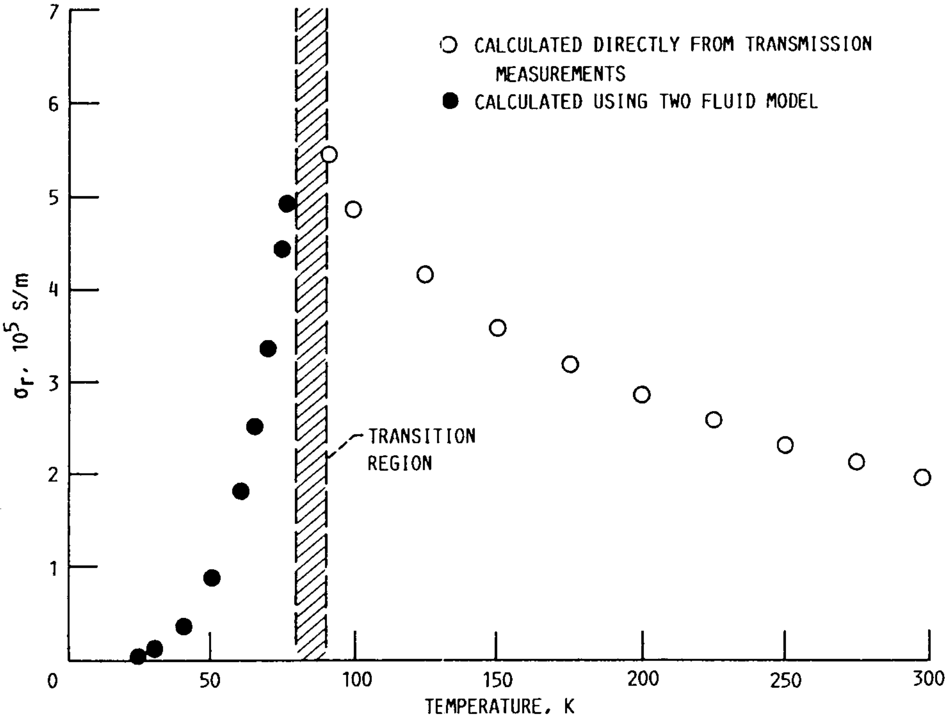

FIGURE 5. - REAL PART OF CONDUCTIVITY, σ_r, VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.2 MICRONS) ON MgO AT 28.5 GHz. $\sigma_r = \sigma_N$ FOR $T > T_c$ AND $\sigma_r = \sigma_1$ FOR $T < T_c$.

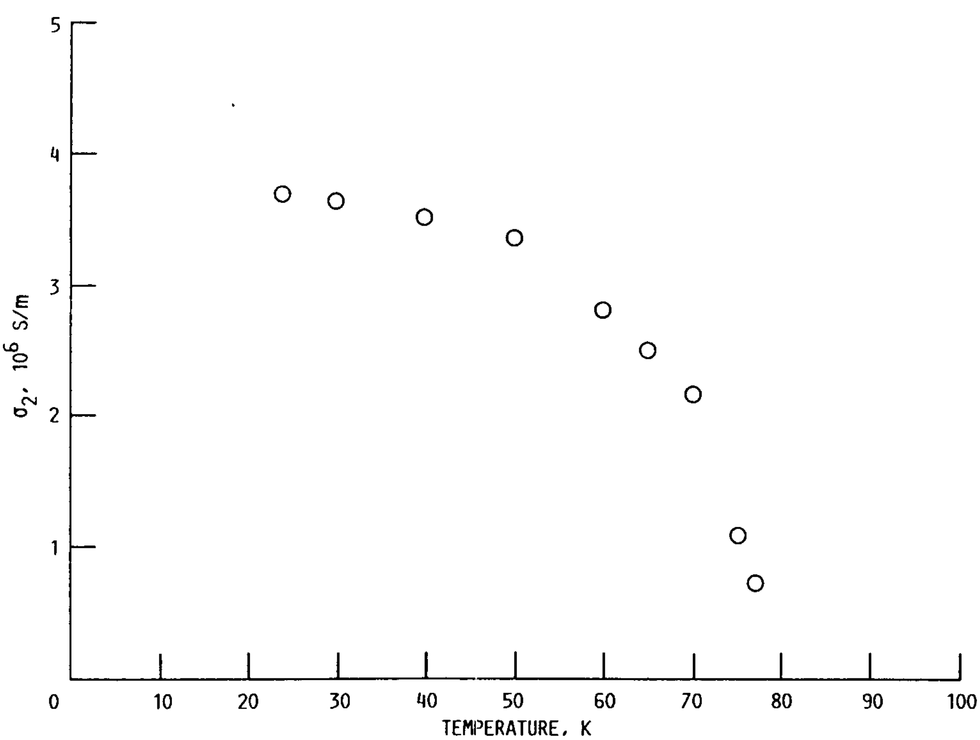

FIGURE 6. - IMAGINARY PART OF THE CONDUCTIVITY, σ_2, VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.2 MICRONS) ON MgO AT 28.5 GHz.

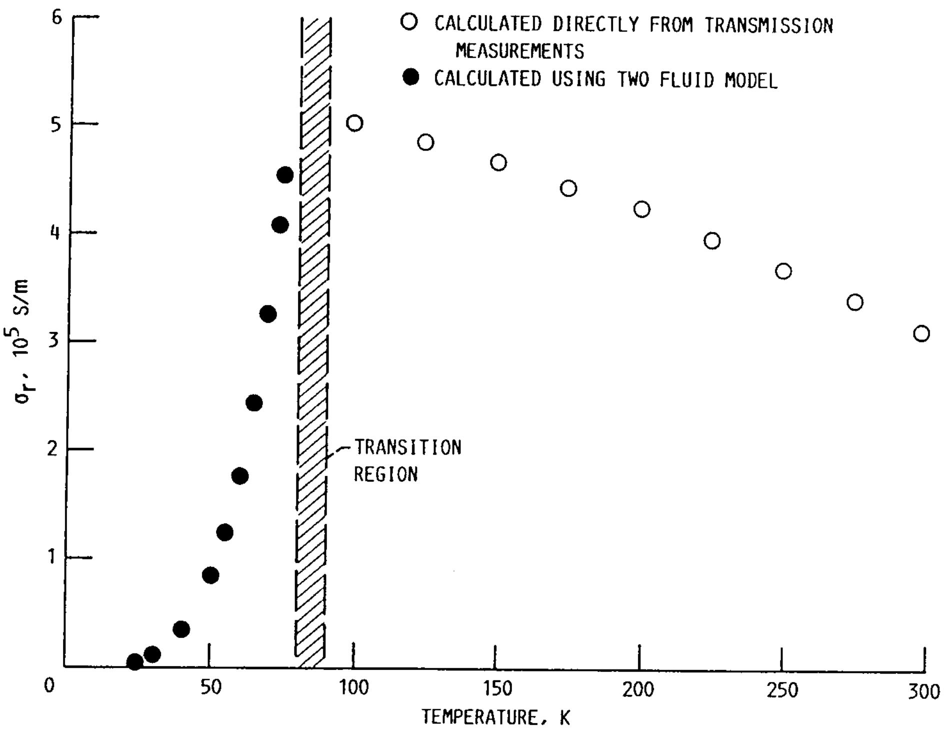

FIGURE 7. - REAL PART OF THE CONDUCTIVITY, σ_r, VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.75 MICRONS) ON ZrO_2 AT 37.0 GHz. $\sigma_r = \sigma_N$ FOR $T > T_c$ AND $\sigma_r = \sigma_1$ FOR $T < T_c$.

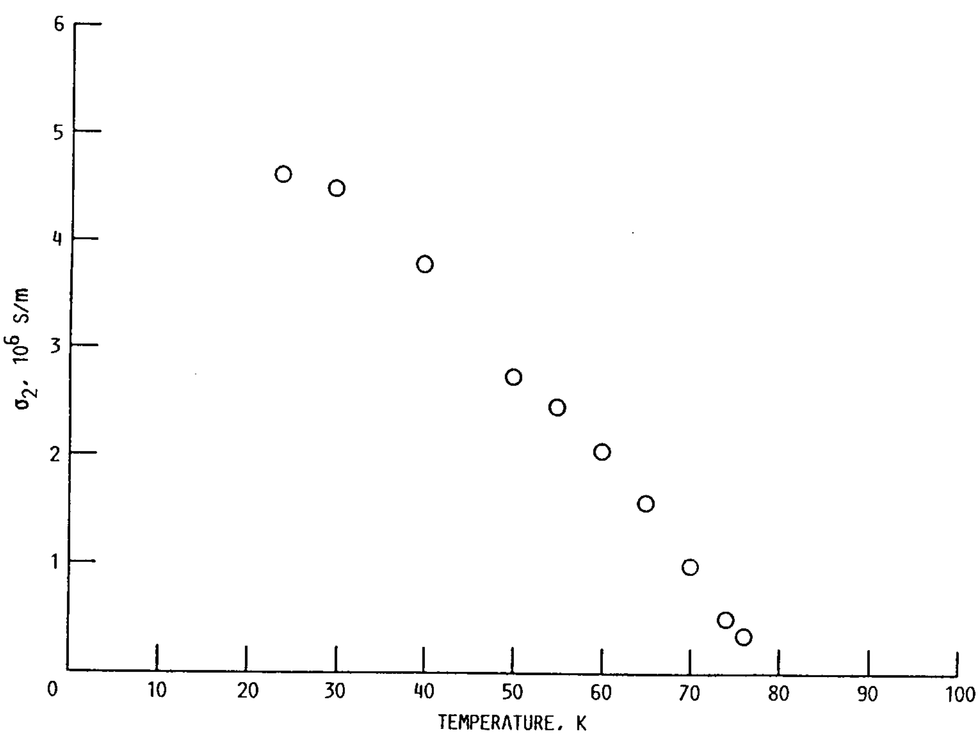

FIGURE 8. - IMAGINARY PART OF THE CONDUCTIVITY, σ_2, VERSUS TEMPERATURE FOR A LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (0.75 μm) ON ZrO_2 AT 37.0 GHz.

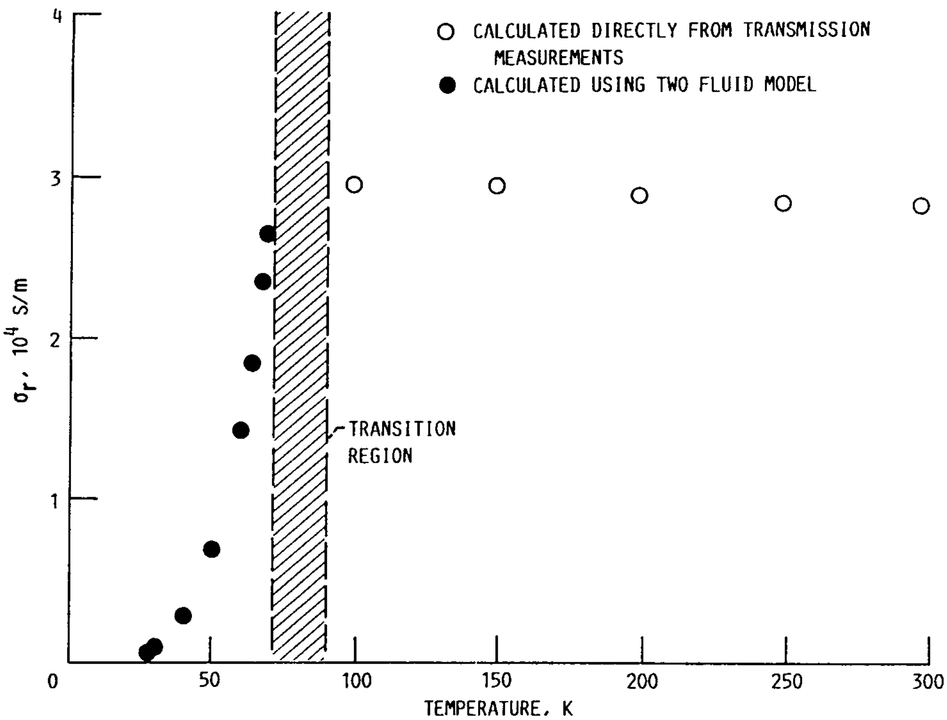

FIGURE 9. - REAL PART OF THE CONDUCTIVITY, σ_r, VERSUS TEMPERATURE FOR A SEQUENTIALLY EVAPORATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (1.0 MICRON) ON MgO AT 33.0 GHz. $\sigma_r = \sigma_N$ FOR $T > T_c$ AND $\sigma_r = \sigma_1$ FOR $T < T_c$.

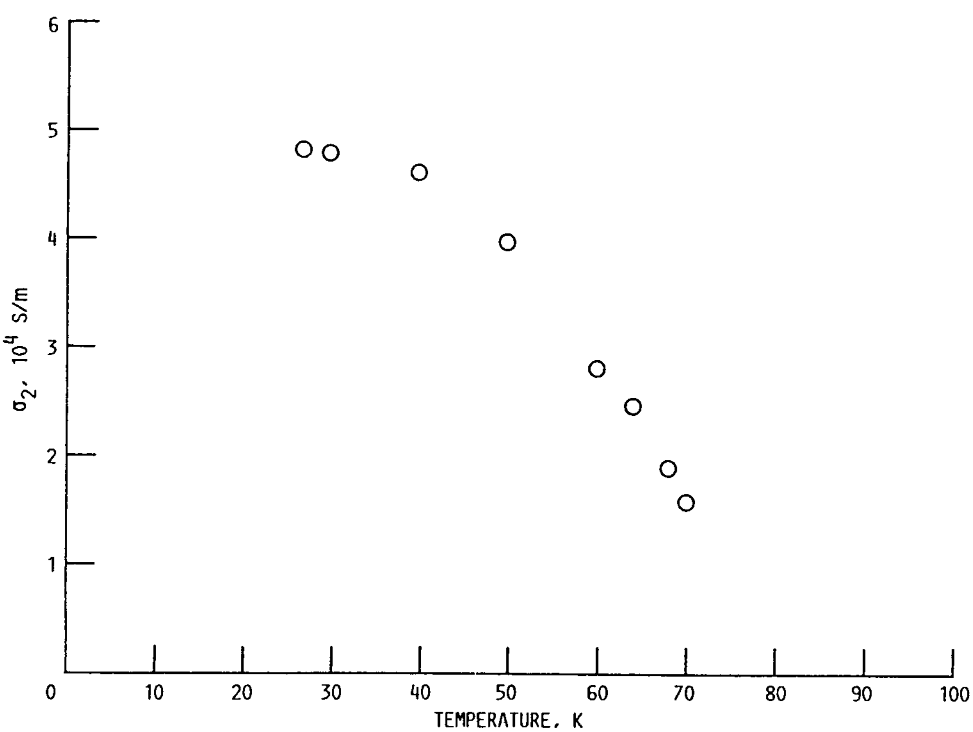

FIGURE 10. - IMAGINARY PART OF THE CONDUCTIVITY, σ_2, VERSUS TEMPERATURE FOR A SEQUENTIALLY EVAPORATED $YBa_2Cu_3O_{7-\delta}$ THIN FILM (1.0 MICRON) ON MgO AT 33.0 GHz.

TABLE I. - MILLIMETER WAVE CONDUCTIVITIES (σ_1,σ_2) AND ZERO TEMPERATURE PENETRATION DEPTH (λ_o) AT 35.0 GHz FOR $YBa_2Cu_3O_{7-\delta}$ THIN FILMS DEPOSITED ON DIFFERENT SUBSTRATES BY LASER ABLATION (LA) AND SEQUENTIAL EVAPORATION (SE)

Parameter	Substrates			
	MgO		$LaAlO_3$	ZrO_2
	SE	LA	LA	LA
σ_1 (70K)	$3.0x10^4$ S/m	$3.9x10^5$ S/m	$3.3x10^5$ S/m	$1.7x10^5$ S/m
σ_2 (70K)	$1.9x10^4$ S/m	$1.1x10^6$ S/m	$6.4x10^6$ S/m	$1.1x10^6$ S/m
σ_1 (40K)	$3.1x10^3$ S/m	$4.1x10^4$ S/m	$3.5x10^4$ S/m	$1.9x10^4$ S/m
σ_2 (40K)	$7.1x10^4$ S/m	$4.0x10^6$ S/m	$7.7x10^6$ S/m	$3.6x10^6$ S/m
λ_o	6.8 µm	0.91 µm	0.67 µm	0.96 µm

distribution of normal and superconducting material in the transition region, we can not accurately determine the normal conductivity down to the transition temperature T_c. Therefore, we have considered the critical conductivity to be the conductivity at or just above the onset temperature. Since the two fluid model approximation is based upon the assumption that the normal to the superconducting state transition is a sharp one, as for the film on $LaAlO_3$, the values of σ_1 obtained using $\sigma_c = \sigma_{onset}$ in Eq. (2) will be less than those expected for a sharp transition. The magnitude of this difference will depend upon the width ΔT of the transition region and the overall film quality. To estimate the size of the discrepancy between using σ_c at T_{onset} and σ_c at T_c, one can extrapolate σ_r above T_{onset} to T_c. When this is done, the σ_c obtained is 12 percent larger for the laser ablated film on MgO, 3.3 percent for the laser ablated film on ZrO_2 and 1.7 percent larger for the sequentially evaporated film on MgO. In the better films the discrepancy between σ_{onset} and the extrapolated value of σ_r at T_c, is larger due to the larger slope of σ_r for temperatures above the onset temperature as can be seen in Figs. 5, 7, and 9. This discrepancy becomes smaller as T_{onset} nears T_c, as for the film on $LaAlO_3$.

Figures 6, 8 and 10 show the imaginary part of the complex conductivity for the laser ablated films on MgO and ZrO_2, and for the sequentially evaporated film on MgO. Using Eq. (8) we obtain values for λ of 1.1, 0.95, and 9.1 µm, at 40 K, for the laser ablated films on MgO and ZrO_2 and for the sequentially evaporated film on MgO respectively. Additional values for the conductivities and for λ_o at 35.0 GHz are given in Table I. The value for λ_o obtained for the laser ablated film on $LaAlO_3$, compares favorably with that reported by Kobrin, et al.[24] ($\lambda_o \sim 0.48$ µm, at 60.0 GHz) for ion-beam sputtered $YBa_2Cu_3O_{7-\delta}$ films on $LaAlO_3$.

CONCLUSIONS

Millimeter wave power transmission studies have been performed on $YBa_2Cu_3O_{7-\delta}$ thin films at frequencies within the frequency range from 26.5 to 40.0 GHz and at temperatures from 20 to 300 K. The normal, σ_N, and complex, $\sigma_1 - i\sigma_2$, conductivities have been determined for laser ablated films on $LaAlO_3$, MgO and ZrO_2. The conductivities of films on MgO grown by laser ablation and sequential evaporation have been compared. From the results obtained in this study, it is apparent that at least for films deposited on MgO, films deposited by laser ablation appear to have a higher quality than those deposited by the sequential evaporation technique. We have also shown that millimeter wave transmission and conductivity measurements can be used as a test of thin film quality. It was observed that for a film with a narrow transition region, the two fluid model should be more applicable than for those films with a wide transition region. Finally, values for the zero-temperature magnetic penetration depth have been determined from the obtained values of σ_2 .

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16. Abstract

Millimeter wave transmission measurements through $YBa_2Cu_3O_{7-\delta}$ thin films on MgO, ZrO_2 and $LaAlO_3$ substrates, are reported. The films ($\sim 1\ \mu m$) were deposited by sequential evaporation and laser ablation techniques. Transition temperatures T_c, ranging from 89.7 K for the Laser Ablated film on $LaAlO_3$ to approximately 72 K for the sequentially evaporated film on MgO, were obtained. The values of the real and imaginary parts of the complex conductivity, σ_1 and σ_2, are obtained from the transmission data, assuming a two fluid model. The BCS approach is used to calculate values for an effective energy gap from the obtained values of σ_1. A range of gap values from $2\Delta o/K_BT_c = 4.19$ to 4.35 was obtained. The magnetic penetration depth is evaluated from the deduced values of σ_2. These results will be discussed together with the frequency dependence of the normalized transmission amplitude, P/P_c, below and above T_c.

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