Measurements of the magnetic penetration depth in $YBa_2Cu_3O_{7-\delta}$ thin films by the microstrip resonator technique

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We have utilized the superconducting microstrip resonator technique to measure the magnetic penetration depth in high T_c oxide thin films in the 1–25 GHz regime. This technique is particularly well suited for thin films, where the absolute value of the penetration depth can be accurately determined. Results for high T_c superconducting thin films show that the value of the penetration depth is sensitive to the preparation conditions of the film, and the temperature dependence is that expected of conventional superconductors.

The determination of the magnetic penetration depth $\lambda(T)$ in high-temperature superconductors is of interest for a number of reasons. For a homogeneous superconductor, the value of λ is directly related to the superfluid density n_s by $\lambda^2 = m^*/\mu_0 n_s e^2$, where m^* is the effective mass of the charge carriers. Since $n_s = |\Psi|^2$, λ is sensitive to variations of the macroscopic superconducting order parameter in these exotic new materials. In practice, the effective penetration depth is increased because of inhomogeneities which affect the current flow, or by grain boundary Josephson junctions. Hence measurements of the penetration depth are sensitive to the quality of a superconductor near its surface, and in the case of thin films, to the quality of the entire film.

We have adapted a technique introduced by Young *et al.*[1] and later refined by Mason and Gould[2] and Henkels and Kircher,[3] which uses a finite length of superconducting microstrip transmission line as a microwave resonator. The magnetic penetration depth in the superconductors affects the series inductance of the transmission line, which in turn determines the propagation velocity for microwave signals. The phase velocity of an ideal lossless superconducting microstrip transmission line is $v_{ph} = 1/\sqrt{LC}$, where L and C are the total inductance and capacitance per unit length, given by[4,5]

$$L = \mu_0(d + \lambda \coth t/\lambda + \lambda' \coth t'/\lambda')/(Kw) \quad (1a)$$

$$C = \epsilon_0 \epsilon_r Kw/d \quad (1b)$$

where d is the dielectric thickness, w is the width of the strip line, and λ, λ' and t, t' are the penetration depths and thicknesses of the strip and ground plane films, respectively (see Fig. 1). The effects of fringing fields are taken into account by the geometric factor K,[5] and an effective relative dielectric constant ϵ_r, for the mixed dielectric system. The phase velocity is

$$\frac{v_{ph}}{c} = \frac{1}{\sqrt{\epsilon_r}}\left(1 + \frac{\lambda \coth t/\lambda + \lambda' \coth t'/\lambda'}{d}\right)^{-1/2}, \quad (2)$$

which is independent of the geometric factor K, but implicitly depends on the aspect ratio of the microstrip w/d through ϵ_r.

In practice, the propagation characteristics of the superconducting transmission line are measured by taking a finite length of transmission line, terminating it with large impedance mismatches, and creating a microwave resonator.[1-3,6] rf signals were transmitted to the resonator, located in a helium storage Dewar, by 50 Ω stainless-steel coaxial cables. Loose coupling to the resonator is obtained by both the impedance mismatch between the microstrip transmission line and the coax, and by means of a series coupling capacitor. In the loose coupling limit, the phase velocity is related to the measured resonant frequencies by $v_{ph} = 2Lf_n/n$, where L is the length of the resonator (3.915 cm in these measurements) and n is the harmonic number. Microstrip transmission line resonators have been constructed from two identically prepared superconducting thin films deposited on separate substrates. A meander line was etched on one of the films, and the unetched film was used as a ground plane. The two substrates were then clamped together with the films separated by a Mylar dielectric sheet 10 μm in thickness (see Fig. 1).

An example of transmission data obtained from an $YBa_2Cu_3O_{7-\delta}$ microstrip resonator is shown in Fig. 2. The Q, or full width at half maximum, of these resonance peaks can be a strong function of both the resonator coupling to the coaxial lines and the excitation power supplied to the resonator. Our measurements were performed in the weak coupling limit and at excitation levels below which the resonance Q is amplitude independent. Q's on the order of 1000 are evident in Fig. 2.

The accuracy of our determination of $\lambda(T)$ is limited by the measurement uncertainties in t, ϵ_r, v_{ph}, and d. The effective relative dielectric constant was particularly difficult to determine because there are actually three dielectrics in the microstrip configuration: the microstrip substrate, the dielectric separating the ground plane and strip line, and an air gap. In addition, ϵ_r may be both frequency and temperature dependent. The effective dielectric constant was best found by fitting the data to Eq. (2), which may be re-expressed as

$$(c/v_{ph})^2 = \epsilon_r + 2(\epsilon_r/td)\lambda_0^2 M(T) Y^2(T), \quad (3)$$

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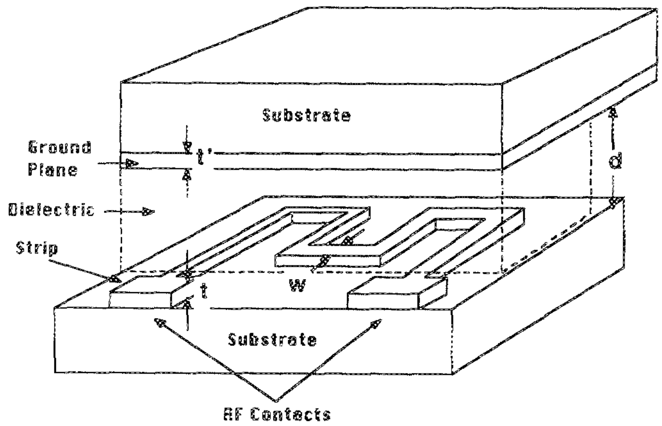

FIG. 1. Superconducting microstrip resonator formed by clamping a patterned strip film of thickness t, width w, penetration depth $\lambda(T)$, and an unpatterned superconducting ground plane film of thickness t' and penetration depth $\lambda'(T)$ around a dielectric sheet of thickness d and dielectric constant $\epsilon_0\epsilon_r$.

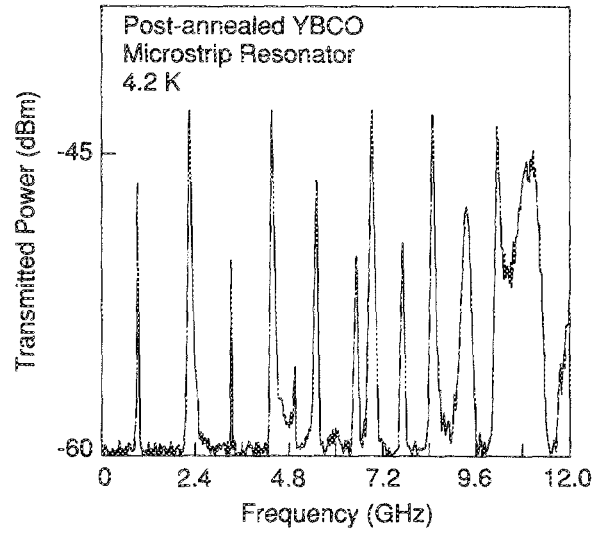

FIG. 2. Transmitted power vs excitation frequency of a post-annealed $YBa_2Cu_3O_{7-\delta}$ microstrip resonator at 4.2 K, showing discrete peaks corresponding to the fundamental mode and harmonics of the resonator. The excitation power was 1 mW and the microstrip film on $LaAlO_3$ has a T_c of 86.5 K.

where we have assumed identical films in both conductors and a Gorter–Casimir temperature dependence for the penetration depth, $\lambda(T) = \lambda_0/[1-(T/T_c)^4]^{1/2} \equiv \lambda_0 Y(T)$. To avoid the use of transcendental functions, we have defined a function $M(T)$ such that $\coth t/\lambda(T) \equiv M(T)\lambda(T)/t$, where in the limit of $\lambda \gg t$, $M(T) \approx 1$. Values of ϵ_r and λ_0 are found by iteratively fitting the experimental results $(c/v_{ph})^2$ to $M(T)Y^2(T)$ until convergence is achieved. The values of ϵ_r, T_c, and λ_0 obtained in this way are listed in Table I for the various samples studied. The temperature-dependent penetration depth determined this way for an *in situ* grown $YBa_2Cu_3O_{7-\delta}$ film is shown in Fig. 3. It should be mentioned that because of the field enhancement at the narrow microstrip, the measured λ is most heavily weighted by that of the strip film.

As a check on this fitting procedure, we also performed a nonlinear least squares fit of the data by allowing T_c, the Gorter–Casimir λ_0, and the film thickness t to vary. The resulting value of λ_0 is close to that obtained by the linear least squares fit, and the value of the film thickness t is approximately the same as that obtained from measurements with a surface profilometer. The rough surfaces of the high-T_c thin films as well as the large fringing field effects brought about by the high dielectric constant MgO and $LaAlO_3$ microstrip substrates account for the difference between measured and fit film thicknesses in Table I.

As seen from the table, thin-film resonators were made both with *in situ* and post-annealed thin films of the high T_c oxide superconductor $YBa_2Cu_3O_{7-\delta}$ and with Nb. The Nb resonators were used as a check on our measurement and data analysis procedure. The niobium thin films, 475 Å thick, were deposited by electron beam evaporation on $1\bar{1}02$ sapphire substrates,[7] have a residual resistivity ratio of 25–27, and have a sharp dc resistive transition at 9.0 K. The *in situ* $YBa_2Cu_3O_{7-\delta}$ films were deposited on MgO and ZrO_2 substrates using single-target rf sputtering.[8] The substrates were held at 650 °C during deposition and the resulting films showed strong c-axis orientation (no evidence of a-axis peaks in x-ray diffraction). The *in situ* microstrip film on MgO shows a sharp resistive transition with zero resistance at 80.6 K (see inset of Fig. 3), while the ground plane film on ZrO_2 had zero resistance at 83 K. The post-annealed $YBa_2Cu_3O_{7-\delta}$ films were first deposited on $LaAlO_3$ sub-

TABLE I. Magnetic penetration depth measurements for three superconducting thin films. Listed are the measured resistive T_c, fit T_c, fit relative effective dielectric constant [from Eq. (3)], measured film thickness, fit film thickness, measured linewidth, measured dielectric thickness, and zero-temperature penetration depth.

Material	T_c ($R=0$) (K)	T_c fit (K)	ϵ_r	t_{meas} (Å)	t_{fit} (Å)	w (μm)	d (μm)	λ_0 (Å)
Nb on sapphire	9.0	8.8	4.87	475	451	21	10	443
$YBa_2Cu_3O_{7-\delta}$ *in situ* on MgO, ZrO_2	80.6	80.6	5.43	1700	1211	16	10	2554
$YBa_2Cu_3O_{7-\delta}$ post-annealed on $LaAlO_3$	86.5	86.3	10.29	1200	1360	15	10	3651

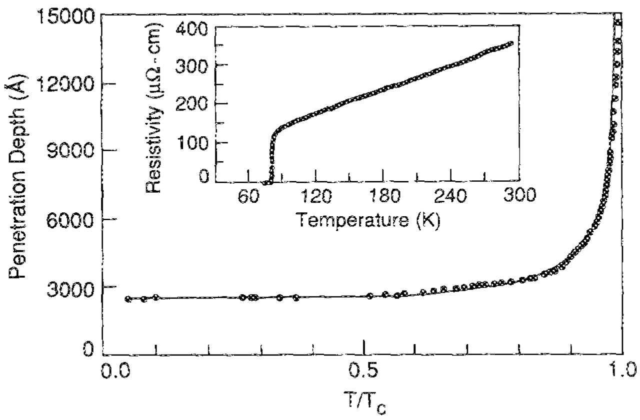

FIG. 3. Magnetic penetration depth as a function of temperature for an *in situ* sputtered $YBa_2Cu_3O_{7-\delta}$ film with a T_c of 80.6 K. The data (⊗) are compared to the best-fit Gorter–Casimir temperature dependence with a $\lambda_0 = 2550$ Å. The inset shows the dc resistive transition of the microstrip film.

strates in an amorphous form by electron beam coevaporation of Y, BaF_2, and Cu.[9] These films were then annealed in water-saturated oxygen at 850 °C for 1 h to crystallize a highly oriented *c*-axis film (no evidence of *a*-axis-oriented grains were found in x-ray diffraction). The post-annealed ground plane films on $LaAlO_3$ show a sharp resistive transition, with zero resistance at 90 K. After patterning, the microstrip film still shows a sharp transition, but acquired a resistive foot, showing zero resistance only at 86.5 K. Both films had a $\rho(100\text{ K}) \approx 150\ \mu\Omega$ cm and a $d\rho/dT \approx 1\ \mu\Omega$ cm/K above 100 K (Fig. 3 inset).

The magnetic penetration depth for our Nb films is in excellent agreement with the values we calculate using known material parameters.[10] Also we find that the temperature-dependent penetration depth follows both the BCS and Gorter–Casimir forms, to within a few percent, over the entire measured temperature range.

The penetration depth of the *in situ* $YBa_2Cu_3O_{7-\delta}$ film is $\lambda_0 = 2554$ Å and its temperature dependence is shown in Fig. 3. As was the case with the Nb film, the penetration depth follows the Gorter–Casimir dependence to within a few percent over the entire measured temperature range. Attempts to fit the penetration depth data below $T_c/2$ to a form $\Delta\lambda \propto BT^2$, yielded values for B some 50 times smaller than those found in Ref. 11. The penetration depth for the post-annealed $YBa_2Cu_3O_{7-\delta}$ film has a similar Gorter–Casimir dependence but, as seen in Table I, the value is larger than that for the *in situ* film.

Only two other measurements of the magnetic penetration depth in $YBa_2Cu_3O_{7-\delta}$ thin films are known to us. Hylton *et al.*[12] found a zero-temperature penetration depth of approximately 3000 Å in their predominantly *c*-axis post-annealed films on $SrTiO_3$. Fiory *et al.*[13] found a minimum value of $\lambda(0) \approx 1400$ Å for their thinnest post-annealed *c*-axis films on $SrTiO_3$, close to the values obtained on single-crystal samples.[14,15]

Presumably, the larger penetration depths measured in these films reflect residual inhomogeneities. As stressed by Hylton *et al.*, inhomogeneities which produce grain boundary Josephson junctions will increase the effective penetration depth.[11,16] Another contribution to larger penetration depths comes from the presence of *a*-axis grains, since the penetration depth for shielding currents along the *c* axis is much greater than for currents in the *ab* plane. It is known that there is a tendency to favor *a*-axis grain growth as the thickness of the films increases,[17] and this may also explain the smaller penetration depth seen in the very thin films of Ref. 13. Surface roughness also is known to increase the effective penetration depth measured in superconductors. Our *in situ* films are distinctly smoother than post-annealed films as revealed by scanning electron microscopy.[8]

In summary, the penetration depths of thin films of $YBa_2Cu_3O_{7-\delta}$ have been measured using a microstrip resonator technique. The results demonstrate both the dependence of λ on film quality and the utility of this method as an effective materials diagnostic. The method permits absolute measurement of λ and is particularly useful for sensitive determination of the temperature dependence of the penetration depth. Even in its present form these microstrip transmission lines may be of practical utility in passive microwave circuits.

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