Measurement of the Absolute Penetration Depth and Surface Resistance of Superconductors using the Variable Spacing Parallel Plate Resonator

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Abstract—**We have developed a modified Parallel Plate Transmission Line Resonator with a smoothly variable thickness of the dielectric spacer filled by liquid nitrogen. A cryogenic linear stage is made to vary the spacer from 200 μm down to contact with 0.1 μm resolution. Estimates of the absolute penetration depth and the surface resistance are based on the analysis of the spacer thickness dependencies of the resonator frequency and *Q*-factor. The measurements are performed at fixed temperature (77 K), so the result does not depend on an *a priori* model for the temperature dependence of the penetration depth. The ability of this technique to be employed as a standard for characterization of HTS films for microwave applications is pointed out.**

I. INTRODUCTION

Low loss High Temperature Superconducting (HTS) epitaxial thin films on appropriate dielectric substrates have enabled the development of superior microwave resonators, filters and delay lines [1]-[3]. To reach the optimum device performance, a knowledge of absolute values of the specimen's microwave surface resistance, R_s, and penetration depth, λ, is necessary. At the same time valuable information about intrinsic and extrinsic properties of the superconductor can be deduced from these quantities [4]. Another important issue is the establishment of a standard characterization technique for HTS thin films for microwave applications [5].

In the last decade great progress in the development of experimental techniques measuring R_s and λ in superconductors has been achieved [1]-[8]. However it is still a problem to accurately determine their absolute values, especially for the penetration depth. The most common way to estimate the absolute $\lambda(T{=}0)$ at microwave frequencies involves fitting of the measured temperature dependence for the frequency shift of a superconductive resonator to a theoretical dependence for $\lambda(T)$. This procedure works properly for conventional superconductors where appropriate models for $\lambda(T)$ are well established. However a difference of up to 2 times in the absolute λ values estimated from different $\lambda(T)$ models may be observed for HTS due to the lack of an appropriate $\lambda(T)$ model [9], [10]. The idea of our technique is to measure the resonant frequency (and Q-factor) of a superconducting resonator vs. its smoothly varying characteristic dimension (i.e. geometrical factor) at *fixed* temperature, to have a result independent of an *a priori* model for $\lambda(T)$ [7].

We have developed a Variable Spacing Parallel Plate Resonator (VSPPR), first suggested in [7], with a smoothly variable thickness of the dielectric spacer. The VSPPR is a sandwich of a thin (0-200 μm) dielectric spacer between two nominally identical superconducting films. Unlike the fixed thickness Teflon or sapphire dielectric used in conventional PPR [6], our spacer is filled by liquid nitrogen (liquid helium or vacuum can be used as well). This structure forms a two-conductor transmission line resonator with the operating frequency around 10 GHz. It can carry a TM electromagnetic wave [11] with phase velocity $v_{\mathrm{ph}} = c/\varepsilon^{1/2}(1+2\lambda_{\mathrm{eff}}/s)^{1/2}$, where c is the light velocity in vacuum, ε is the dielectric permittivity of the spacer, $\lambda_{\mathrm{eff}} = \lambda \coth(d/\lambda)$ is the effective magnetic penetration depth in the superconducting film of thickness d [10], and s is the thickness of the dielectric spacer. The accurate estimation of the absolute values of λ and R_s is based on the simultaneous analysis of the spacer thickness dependencies for the resonator frequency and Q-factor. The values obtained will be compared with the results measured by the conventional PPR technique [8], [12].

II. ELECTRODYNAMICS OF THE VSPPR

The PPR theory has been developed in several works [6], [7], [13], [14]. Here we only summarize the results concerning the dependencies of resonant frequency and Q-factor on the dielectric spacer thickness.

The resonant frequency of the fundamental PPR mode TM_{001} is given by [7], [13]:

$$f = f_0(1-\alpha s)(1+2\lambda_{\mathrm{eff}}/s)^{-1/2}, \qquad f_0 = c/2\sqrt{\varepsilon}L \tag{1}$$

where f_0 is the resonance frequency of the ideal PPR (made of an ideal conductor, with no fringe effects), $\alpha \approx 1/\pi L$ is the fringe effect geometrical factor, and L is the geometrical length of the resonator. For $s < (\pi L \lambda_{\mathrm{eff}})^{1/2}$ the penetration depth determines the reduction in the resonant frequency, while for thicker spacers, f is reduced by the fringe effect.

The unloaded Q-factor of the PPR is determined by ohmical losses in the superconducting films, dielectric losses in the dielectric spacer, and radiation losses [7], [13], [14]:

$$Q^{-1} = Q_\Omega^{-1} + Q_{\mathrm{d}}^{-1} + Q_{\mathrm{rad}}^{-1} =$$
$$= \frac{R^*_{\mathrm{eff}}}{\pi\mu_0 f^*(s+2\lambda_{\mathrm{eff}})}\,\frac{f_0}{f^*}\,\frac{(1-\alpha s)}{(1+2\lambda_{\mathrm{eff}}/s)^{1/2}} + \tan\delta + \beta s \tag{2}$$

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Here R_{eff}^{*} is the effective surface resistance [10] of the films at the fixed frequency f^{*}, $\tan\delta$ is the loss tangent of the dielectric spacer, and $\beta \approx 1/\sqrt{\varepsilon}L$ is the radiation geometrical factor. The assumption that $R_{\text{eff}} = R_{\text{eff}}^{*} f^{2}/f^{*2}$ is used to derive (2). For $s < (R_{\text{eff}}/\pi\mu_0 f\beta)^{1/2}$, Q is determined mainly by the ohmical losses, while for thicker spacers the radiation losses are dominant. We want to point out that the $2\lambda_{\text{eff}}$ term in the first parenthesis in Q_{Ω} describes the part of the resonator electromagnetic energy stored as kinetic energy of the superconducting carriers, and has to be taken in account for $ds < 20\lambda^2$.

III. EXPERIMENTAL SETUP

The experimental setup consists of a cryogenic slider, a linear actuator, a films aligner and microwave coupling probes (see Fig. 1). The slider is made from two coaxial thin-wall stainless steel tubes with the flexure bearings incorporated between the tubes at the top and the bottom ends of the slider. The diaphragm-type bearings are made from Cu/Be foil and work either at room or at cryogenic temperature. The outer tube is fixed and the inner one translates along the vertical axis by the linear actuator. The top of the slider is at room temperature, while the bottom is under cryogenic conditions (77 K). The slider provides 1.5-mm of fine rectilinear movement while eliminating friction and theoretically giving a resolution limited only by thermal fluctuations. To reduce the effects of thermal contraction, the tubes are made the same length and from the same material. A differential micrometer with resolution of 0.07 μm and accuracy of 1% is used as a linear actuator.

The films aligner consists of two pairs of pins made from Al. Each pair is connected to a separate flexible clamp. Each film is squeezed between the pair of pins and can be rotated around the pin-to-pin axis with enough friction to hold the film in the designated position. The clamp for the top film is connected to the inner tube, and the bottom film clamp is connected to the outer one. The film rotation axes are perpendicular to each other, so a full parallelism of their face surfaces can be achieved by bringing the films into contact, i.e. by self-aligning.

The coupling probes are two half-wavelength antennas of semi-circular shape connected to the coax cables via a symmetrizing transition [7], [14]. They excite the VSPPR effectively due to the similarity of the quasi-static electric fields at the resonator edge and the antenna ends. The probes provide a variable and contactless coupling to the resonator and allow studying the resonators with the Q-factors down to ~70.

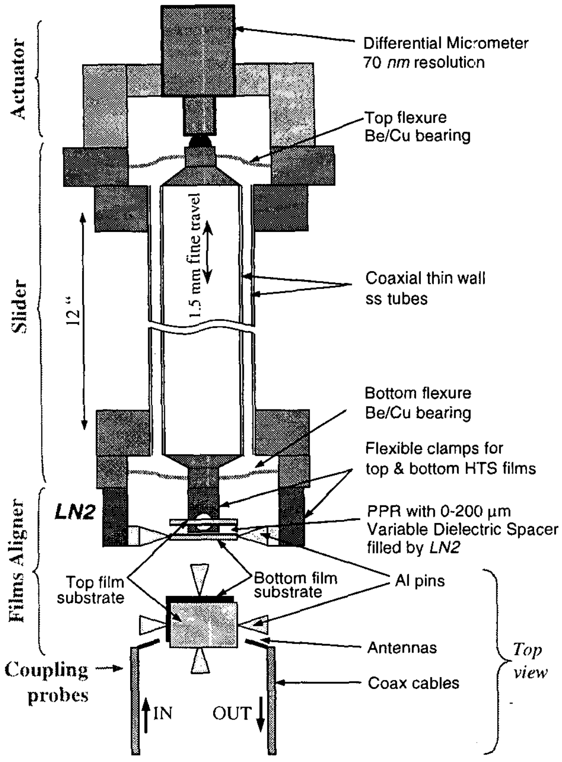

Fig. 1. Sketch of the experimental setup.

The experimental procedure consists of a room-temperature installation of the HTS samples within the clamps, followed by immersion of the bottom part of the apparatus inside a liquid nitrogen bath. Once the samples have reached thermal equilibrium with the bath, they are brought into contact and gently pressed together. The top film is then moved away up to 150-200 μm separation with steps of about 1 μm and the resonance frequency and Q-factor of the resonator vs. dielectric spacer thickness are measured for each separation value. The measurements were performed by an HP8722D vector network analyzer in the undercoupled regime. The experimental setup for the conventional PPR measurements is described elsewhere [8,14].

IV. RESULTS AND DISCUSSION

The samples under study are a pair of identical *c*-axis-oriented $GdBa_2Cu_3O_{7-x}$ (GBCO) epitaxial films, laser ablated on (100)-cut $LaAlO_3$ single crystal dielectric substrates. The substrates are 10.65 mm by 7.6 mm in linear dimensions and 0.5-mm-thick. The GBCO layer is 300-nm-thick, the critical temperature measured by AC susceptibility is 92.5 K, and the transition width is 0.3 K.

Figures 2 and 3 show the experimental dependencies for the resonance frequency and the Q-factor of the VSPPR vs. dielectric spacer thickness (operating temperature 77.4 K, liquid nitrogen dielectric spacer). The electromagnetic oscillations in the resonator do not disappear at the point of mechanical contact between the samples, where a Q-factor of about 500 was observed. Therefore the actual separation between the *two superconductors* at this point is much larger than the *c*-axis coherence length (~1 nm) in GBCO.

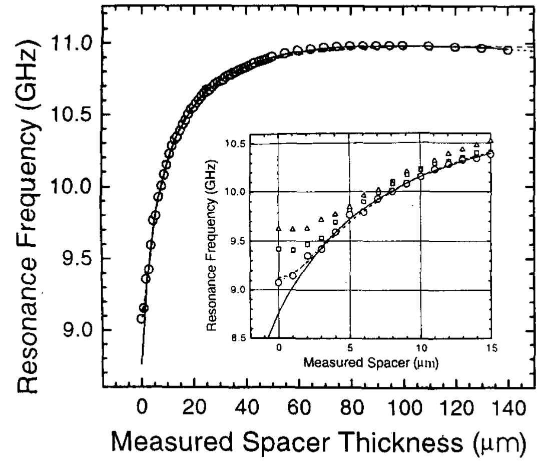

Fig. 2. Resonance frequency of the VSPPR vs. dielectric spacer thickness. Inset shows three measurements at small spacer thickness.

To extract the absolute values of λ_{eff} and R^*_{eff} from the experimental data, the latter have to be fit to the theoretical forms (1) and (2). The fitting parameters are λ_{eff}, f_0 and α for the frequency data, and R^*_{eff}, $\tan\delta$ and β for the Q-factor data. However two kinds of deviation of the data from the theory were observed.

The first deviation is the presence of an offset in the *measured* dielectric spacer thickness [7], so that the actual thickness of the dielectric spacer in (1) and (2) is:

$$s = s_{\text{m}} + s_0 \qquad (3)$$

where s_{m} is the displacement measured by the micrometer head from the point of contact, and s_0 is the effective separation between the films at this point. Along with the error in the estimation of the contact point, the non-flatness of the film surface (coming from the non-flatness of the substrate) also contributes to s_0. To image this non-flatness a 1/20-wavelength optical flat was employed [15]. We observed a bump-like structure of the film surfaces. The bumps have a lateral extent of 5-7 mm and an average height of 5-6 μm.

The second deviation is a small increase of the resonance frequency at s_{m} close to 0, compared to the dependence expressed in (1) with the offset (3). This behavior is shown for different experimental runs in the inset to Fig. 2. There are two possible reasons for this deviation: the bumpy structure of the film surfaces affects the electrodynamics of the resonator, invalidating the theory for the flat PPR; or a kind of mechanical deformation of the samples and/or pins occurs due to the contact between the samples. To overcome this problem, one can use instead of (3) the following empirical relations for the effective spacer thickness s:

$$s = s_0 + s_{\text{m}}^2 / (s_m + s_0) \qquad (4)$$

or:

$$s = s_0 + s_{\text{m}} \coth(s_{\text{m}}/h) \qquad (5)$$

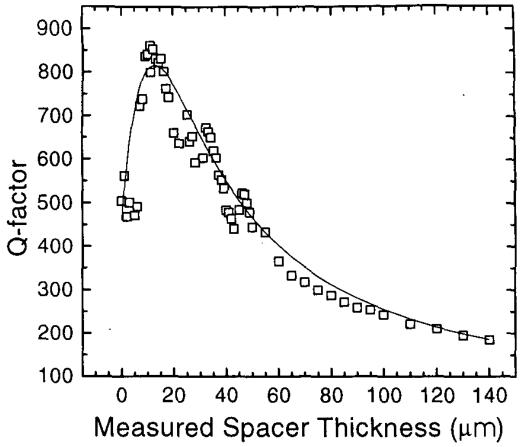

Fig. 3. Q-factor of the VSPPR vs. dielectric spacer thickness.

where s_0 and h are two more free parameters. The fits of (1) to the frequency data with s given by (3), (4) and (5) are shown in Figure 2 by the solid, dotted and dashed lines, respectively. The data for $s<3$ μm are not taken into account in the first case because of the reason discussed above. The values estimated from the fits are summarized in the Table I, where the error bars are the *fitting* errors. The fit value for the offset s_0 agrees well with the average height of the bumps measured with the optical flat.

To fit the Q-data, we have used (2) together with (3) and the experimental data for the resonance frequency. The fit is shown in Fig. 3 by the solid line. The parameters found are $R^*_{\text{eff}} = 0.53 \pm 0.07\,\text{m}\Omega$ at $f^* = 10$ GHz, $s_0 + 2\lambda_{\text{eff}} = 6 \pm 1$ μm, $\tan\delta < 10^{-6}$, and $\beta = 0.4 \pm 0.03$ cm^{-1}. Applying the finite thickness correction and using the average λ_{eff} from Table I, we find for the intrinsic values at 77 K, 10 GHz $\lambda(77\text{K}) = 660 \pm 70$ nm and $R_s = 0.12 \pm 0.03$ mΩ, which is in agreement with the commonly accepted data for thin films of 1-2-3 HTS compounds [1], [2], [4].

The accuracy of the absolute values of λ_{eff} and R^*_{eff} depends mainly on the fitting procedure, as well as systematic

TABLE I

FREQUENCY VS. DIELECTRIC SPACER THICKNESS FIT PARAMETERS

Fit range	$s \geq 3$ μm	$s \geq 0$ μm	$s \geq 0$ μm	
Equation # for s	(3)	(4)	(5)	Theory
f_0, GHz	11.39±0.02	11.20±0.02	11.41±0.02	11.66
α, cm^{-1}	1.70±0.08	0.8±0.1	1.8±0.1	0.32
λ_{eff}, nm	1993±53	1250±260	2095±60	N/A
s_0, μm	5.8±0.2	4.97±0.1	6.26±0.22	≈5-6
h, μm	N/A	N/A	1.02±0.1	N/A

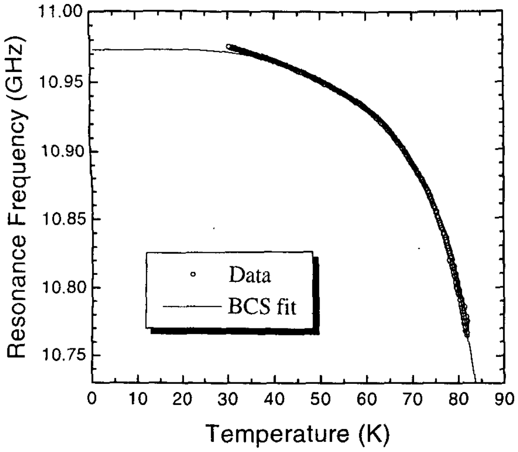

Fig. 4. Resonance frequency of GBCO PPR vs. temperature. The solid line is a BCS fit.

and random errors in measuring the dielectric spacer thickness. As one can see from the difference between the fit parameters estimated by using (3), (4) and (5) (Table I), the fitting procedure is very sensitive to the experimental data at small s, where there is a deviation of the data from the present theory. This shows the importance of flat substrates and the need to take data at small separations with higher resolution. The random error in λ_{eff} can be estimated as $\Delta\lambda_{\text{eff}}^{\text{ran}} \approx \Delta s / N^{1/2}$, where Δs is the accuracy in measuring spacer thickness, and N is the number of experimental dielectric spacer thickness points. For $\Delta s \sim 1$ µm and N~50, one has $\Delta\lambda_{\text{eff}} \sim 150$ nm.

We have also measured the resonance frequency vs. temperature from 30 to 80 K for the same samples by the conventional PPR technique. A 12.5-µm-thick Teflon™ film was used as dielectric spacer. Fig. 4 shows the measured dependence. The fit of the $f(T)$ data to s-wave BCS theory [14] gives $\lambda(0)=170\pm10$ nm and $\lambda(0)=205\pm10$ nm by using values for the spacer thickness of 12.5 and 12.5+5=17.5 µm, respectively. The latter $\lambda(0)$ gives $\lambda(77\text{K})=350$ nm, about two times less that the value found by the VSPPR technique. The observed difference may be due to an underestimation of the absolute λ from the temperature fit because of some discrepancy between the data and the BCS theory for $T < 40\,\text{K}$, and uncertainty in the Teflon spacer thickness. At the same time some overestimation coming from the VSPPR measurements is possible, if the actual dielectric spacer thickness is smaller than the micrometer head displacement.

V. SUMMARY

A Variable Spacing Parallel Plate Resonator to measure absolute values of the penetration depth and surface resistance in superconductive thin films is developed and preliminary penetration depth and surface resistance values have been presented. To improve the technique up to the level of established experimental methods, a direct measurement of the separation between the films and a theoretical model of a VSPPR made up of real non-flat samples have to be developed.

As pointed out in [5], currently there are only two techniques, namely a (conventional) PPR and a Dielectric Resonator, as contestants in the race to become a standard for characterization of HTS films for microwave applications. We believe that the VSPPR technique can fill this role as well.

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