Measurements of Millimeter-Wave Surface Resistance and Temperature Dependence of Reactance of Thin HTS Films Using Quasi-Optical Dielectric Resonator

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***Abstract*—The technique proposed by authors earlier for accurate measurement of large-area HTS thin film surface resistance (R_s) is developed further. It is based on application of quasioptical dielectric resonators (QDR). Data on R_s of individual Y-123 films obtained at 77 K by using "round robin" procedure are presented. The main attention is paid to developing technique of temperature dependence measurement of thin film surface reactance variation (ΔX_s). The dependence obtained by experiment is analyzed by means of fitting procedure that allows one to determine the validity of theoretical models for the temperature dependence of field penetration depth. Particularly, the 3D XY critical regime, Ginzburg-Landau behavior and two-fluid model are compared near T_c. Our data show that the former approach best follows the observed dependence.**

***Index Terms*—Films, millimeter wave measurements, resonator, superconductors (high-temperature).**

I. Introduction

We REPORTED in [1], [2] the development of a method for measuring the microwave surface resistance R_s of large-area HTS films. This technique is based on quasioptical dielectric resonators (QDR) with conducting endplates (CEP) (Fig. 1). Here sapphire cylindrical disks sandwiched between HTS films are used and the films act as CEP. In the technique the highest quality factor modes, namely whispering gallery modes, are excited in the disk. The proposed technique has a number of advantages in comparison with dielectric resonator-based technique used earlier [3]–[7]: i) measurement sensitivity at low temperatures is determined only by loss tangent of sapphire that provides possibility of HTS residual resistance R_{res} study; ii) measurements are carried out in the millimeter wavelength range that gives additional possibility to enhance sensitivity; iii) there is possibility to control coupling between resonator and feeder microwave transmission lines continuously and directly during measurement process, which extends the range of measured values of R_s by variation of temperature from the lowest up to T_c.

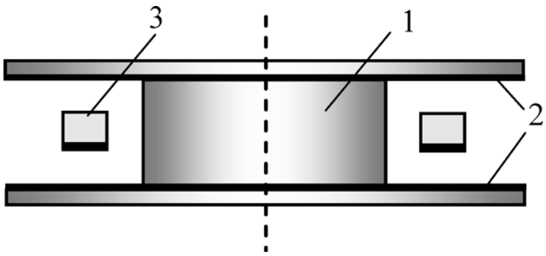

Fig. 1. Quasioptical dielectric resonator with conducting endplates: 1—sapphire disc; 2—HTS-films on dielectric substrates: 3—feeder quasi-image dielectric waveguides.

The R_s measurement technique, as proposed in [1], [2], has also a disadvantage which lies in the fact that the measured value is the averaged value of R_s for two films, and hence additional efforts need for determination of individual values of R_s. Besides, for the complete study of HTS impedance properties, it is also necessary to have a chance to measure the surface reactance X_s.

This work summarizes to a certain extent the approach to HTS thin film R_s measurement by using QDR. Here data on measurement of individual R_s values of separate films are presented and minimal values of R_s, which can be measured at low temperatures (liquid-helium level), are evaluated. The technique of temperature dependence measurement of surface reactance variation ΔX_s is described and the results of comparison between measured and calculated ΔX_s values are presented.

II. R_s-Measurements of Y-123 Films. Round-Robin Procedure. Sensitivity at Very Low Temperatures

Values R_s of HTS films are determined experimentally by using QDR from relation [1]:

$$Q^{-1} = k \tan\delta + A_s R_s, \tag{1}$$

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TABLE I
MEASURED Q-FACTOR VALUES OF SAPPHIRE QDR WITH DIFFERENT PAIRS OF Y-123 FILMS, $T = 78$ K

Films i+j	1+2	1+3	2+3
Q_{ij}	37540	33170	35720

TABLE II
R_s VALUES OF SEPARATE Y-123 FILMS OBTAINED FROM (2) ON THE BASE OF TABLE I

Films	1	2	3
R_s, mΩ	9.7	8.3	10.1

where k is a coefficient close to 1, A_s is the filling factor for HTS films. Factors k and A_s are calculated for known distribution of fields in resonator. Here

$$A_s = \frac{2}{\omega_0 \mu_0 l R_{HE}}, \tag{1a}$$

where $\omega_0 = 2\pi f_0$, f_0 is a resonant frequency, $\mu_0 = 4\pi \cdot 10^{-7}$ Hn/m, l is the height of the dielectric disc and R_{HE} is a coefficient, which depends on geometric dimensions of resonator disc, dielectric permittivity and wave mode in resonator. In (1) a term accounting the normal metal losses is omitted because there is no necessity to apply normal conducting screen which used as a rule earlier in dielectric resonator-based technique of impedance measurements [4]–[7]. For our sapphire resonator and its dimensions ($l = 2.4$ mm and diameter $d = 14.4$ mm) value R_{HE} equals ~1 in Ka-band. We use HE_{n10} wave mode, where n is azimuthal index ($n = 12$–14). Schematic sketches of the measurement unit with sapphire QDR for impedance measurements of HTS films are presented in [1], [2]. Acceptable dimensions of the films are limited only to permissible length of feeder transmission lines (dielectric waveguides) and dimensions of the cryogenic chamber in which the measurement cell is placed. In practice $YBa_2Cu_3O_{7-\delta}$ (Y-123) films with diameter ranging from 18 to 55 mm were measured. Using "round-robin" procedure [6] for determination of individual values R_s of separate films, quality factor Q of QDR with three different pairs of three films can be written

$$Q_{ij}^{-1} = k \tan\delta + \frac{A_s \left(R_s^{(i)} + R_s^{(j)}\right)}{2}, \tag{2}$$

where i and j are film numbers $i, j = 1, 2, 3, i \neq j$. Thus, by calculating k and A_s for known properties of sapphire ($\tan\delta$, ε'), one can determine R_s of each film from three measurements.

As an example we used Y-123 films of thickness $d_f = 300$ nm sputtered on 20×20 mm^2 sapphire substrate with a CeO_2 sublayer. Measured Q_{ij} at $T = 78$ K are presented in Table I. Data obtained on a base of Table I and in accordance with (2) on individual values R_s of the separate films, are given in Table II.

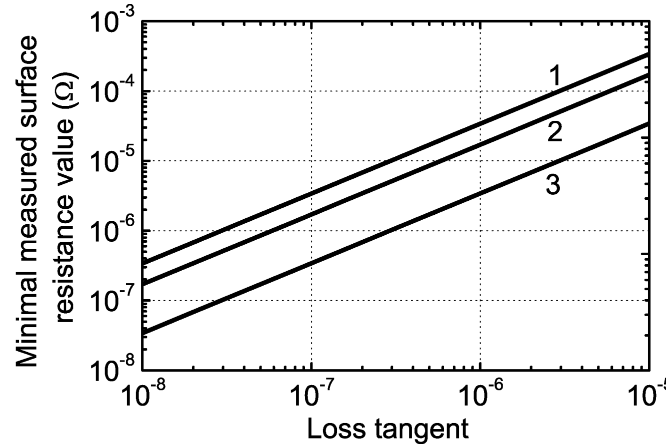

Fig. 2. The dependence of minimal measured surface resistance value $R_s^{\min}$ on $\tan\delta$: $1 - \delta Q/Q = 0.1$; $2 - \delta Q/Q = 0.05$; $3 - \delta Q/Q = 0.01$.

For accurate R_s measurements both a dielectric with minimal loss $\tan\delta$ as well as the oscillation wave mode with maximal A_s should be used. The coefficient R_{HE} depends very little on the resonator geometric dimensions, the resonator material permittivity ε' and the wave mode. For the sapphire resonator one obtains $A_s = 2.92 \cdot 10^{-3}\ \Omega^{-1}$ and $\delta A_s/A_s \approx 0.005$. It should be noted that the most probable error $\delta R_s/R_s$ depends on the value of R_s itself (Fig. 2). Using the approach discussed in [7], the effects of the other separate factors on $\delta R_s/R_s$ have been analyzed in [8]. For an accurate measurement of $R_s \leq 10^{-3}\ \Omega$ we need to use a dielectric material with low $\tan\delta$ (such as sapphire where $\tan\delta = 5 \cdot 10^{-9}$ at 4.2 K in Ka-band) and to measure Q-factor with an accuracy at least 1%. One can also calculate the minimal measured value of R_s [8]:

$$R_s^{\min} = \left|\frac{\Delta Q}{Q}\right| \frac{k \tan\delta}{A_s}. \tag{3}$$

As follows from (3), R_s^{min} is determined by the resolution of the Q-meter, the loss tangent of the dielectric and filling factor A_s of the superconductor. One can see that even for $\delta Q/Q = 0.1$ and $\tan\delta = 10^{-6}$, the value of R_s^{min} is equal to $4 \cdot 10^{-5}\ \Omega$. This value is lower than R_s for the best HTS films in the Ka-band [9], which allows one to make new experiments on R_s study at very low temperatures.

III. PROBLEM OF $X_S(T)$ MEASUREMENTS OF HTS FILMS. COMPARISON WITH PHENOMENOLOGICAL MODELS

Surface reactance X_s is the next important impedance characteristic of the HTS thin film. As a rule, the same resonant structure is used for both R_s and X_s measurements. However, the method does not allow obtaining absolute values of X_s (in contrast to R_s) which is due to impossibility to determine eigen frequency of resonators with ideal conducting surfaces and insufficient reproducibility of the frequencies at reassembling of the resonator.

Consideration of the above mentioned difficulties allows one to conclude that, evidently, in a given case, analogously to all other resonator techniques, the most appropriate approach can be one at which reactance variation $X_s(T)$ with temperature is determined and the relations [9]

$$\Delta X_s(T) = -\frac{2\Delta f}{A_s f_0} \tag{4a}$$

and

$$\Delta\lambda(T) = \frac{\Delta X_s(T)}{2\pi f_0 \mu_0} \tag{4b}$$

are used, where δf_0 is shift of eigen frequency and $\Delta\lambda(T)$ is temperature variation of λ.

In our case the dependence $X_s(T)$ for HTS films can be determined by using experimental dependence of the resonant frequency variation $\Delta f_0(T)$ with temperature for QDR with HTS films as CEP. However, observed dependence $\Delta f_0(T)$ is connected with both variation of reactance $X_s(T)$ and variation $\Delta\varepsilon'(T)$ of permittivity $\Delta\varepsilon(T) = \Delta\varepsilon'(T) + i\Delta\varepsilon''(T)$ of the dielectric which the resonator made of, i.e.

$$\Delta f_{0S}(T) = \Delta f_S(T) + \Delta f_\varepsilon(T). \tag{5}$$

Correctness of (5) follows from the condition $\Delta f_{0S} \ll \Delta f_0$. One can exclude $\Delta f_\varepsilon(T)$ from (5) by carrying out additional measurements $\Delta f_{0N}(T)$ of QDR with CEP made of normal metal, best of all, of metal with normal skin-effect

$$\Delta f_{0N}(T) = \Delta f_N(T) + \Delta f_\varepsilon(T). \tag{6}$$

From (5) and (6), we obtain the expression

$$\Delta f_{0S}(T) - \Delta f_{0N}(T) = \Delta f_S(T) - \Delta f_N(T) = \Delta F(T). \tag{7}$$

For small variations $\Delta f_\varepsilon(T)$ the true relation is

$$\Delta X_s(T) - \Delta X_s^N(T) = -\frac{2\Delta F(T)}{A_s f_0}. \tag{8}$$

In (8) an unknown $\Delta X_s^N(T)$ will remain. However, use of the normal metal allows one to determine $\Delta X_s^N(T)$ on its measured $\Delta R_s^N(T)$ because $\Delta X_s^N(T) = \Delta R_s^N(T)$. It is worth noting that measurements of frequency shift depending on temperature are carried out at rather weak coupling. Here the coupling change is shown to produce a negligible effect in the frequency shift even contrary with the change in a loaded quality factor.

The above stated approach was used for finding $X_s(T)$ of Y-123 films, $R_s(T)$ of which are measured in a preceding section. As a normal metal, Ti was used ($R_s = 203.1$ mΩ, $T = 78$ K, Ka-band). Fig. 3 shows temperature dependence of $\Delta f_{0S}(T)$, $\Delta f_{0N}(T)$ and their difference $\Delta F(T)$. The Y-123 thin film dependence $X_s(T)$ obtained from (8) is presented in Fig. 4. The error of $X_s(T)$ in temperature interval from 78 K to 89 K changes from 20% to 2% (at the absolute value $\approx$ 8 mΩ of X_s measurement error). It is necessary to emphasize that the $X_s(T)$ displayed in Fig. 3 is the dependence of variation of effective reactance because the film thickness $d_f \approx \lambda$ and surface impedance is a function of d_f. Connection of the effective impedance $Z_s = Z_s(d_f)$ with intrinsic value $Z_s(d_f \to \propto) = Z_{s\propto}$ can be found on the base of impedance transformation rule in view of substrate properties [9]. This enables to compare experimental and calculated dependences of $X_s(T)$ taking into account the film thickness d_f. (Fig. 5).

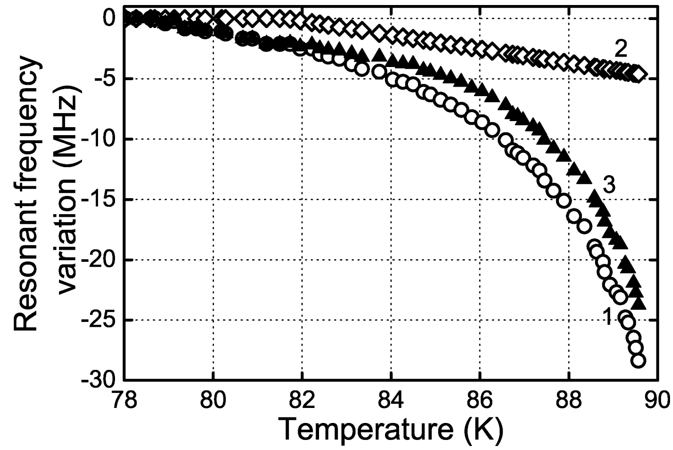

Fig. 3. Temperature dependence of resonance frequency variation for QDR with CEP: 1—Y-123; 2—Ti; 3—curve is difference of curves 1 and 2.

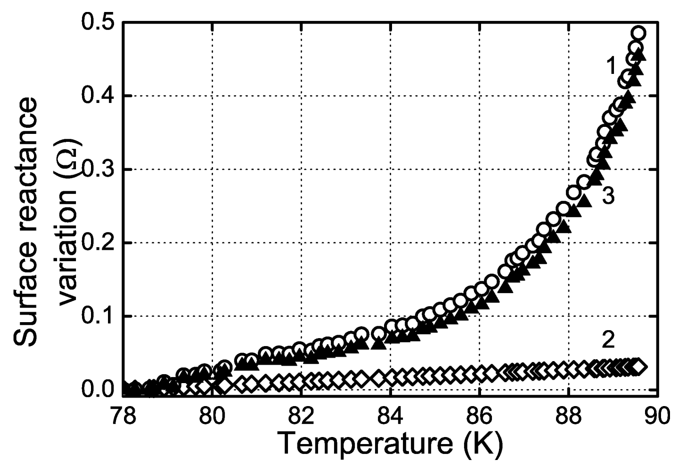

Fig. 4. Temperature dependence of surface reactance variation: 1—Y-123; 2—Ti; 3—curve is difference of curves 1 and 2.

Restricting so far to only phenomenological models for $X_s(T)$ calculation, one can generalize an expression for $\lambda(T)$ on the base of works [10]–[12] in a form

$$\frac{\lambda(T)}{\lambda(0)} = \left[1 - \left(\frac{T}{T_s}\right)^\gamma\right]^{-n}, \tag{9}$$

where $\lambda(0)$ and coefficients γ and n are fitting parameters. Use of different physical models causes different values of $\lambda(0)$, γ and n which are obtained by applying fitting procedure (Table III).

As follows from Fig. 5 the XY (3D) critical regime approach follows the observed temperature dependence closer than Ginzburg-Landau (GL) behavior and two-fluid (TF) model. This result seems to be in agreement with a number of measurements of the field penetration depth in single crystals Y-123 for temperatures very close to T_c [10] and is inconsistent with [12], where the experimental data have displayed good agreement with GL theory.

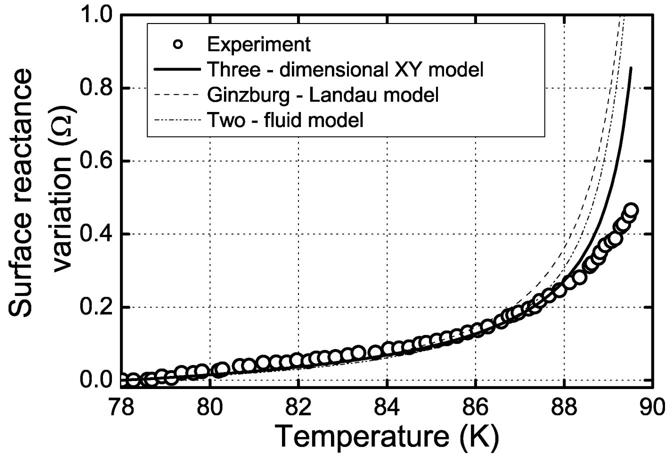

Fig. 5. Comparison of experimental and calculated dependencies of surface of Y-123 thin films.

TABLE III
THE FITTING PARAMETERS FOR THREE PHENOMENOLOGICAL MODELS OF $\lambda(T)$

Model	$\lambda(T)$, nm	n	γ
XY	180	1/3	1
GL	100	1/2	1
TF	130	1/2	2

IV. CONCLUSION

The obtained results show that the technique using whispering gallery mode dielectric resonators allows one not only to measure the HTS films surface resistance R_s with a high sensitivity, but also to study the film reactance X_s properties. Additionally the technique allows determining individual values R_s of separate films. The obtained evaluation of R_s measurement sensitivity enhancement at very low temperatures indicates possibility to study microwave residual resistance problem. Comparison of temperature dependences of reactance variation, obtained by experimental and calculated ways, has been carried out. Possibility to measure microwave and millimeter-wave impedance properties of unpatterned HTS films will enable to determine their differential tangent $r = \Delta X_s/\Delta R_s$ containing important information about the microscopic nature of the surface impedance.

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