Surface resistance measurements of HTS thin films using SLAO dielectric resonator

Mohan V. Jacob1), Janina E. Mazierska1), Kenneth Leong2), Dimitri O. Ledenyov1) and Jerzy Krupka3)

1) Electrical and Computer Engineering Department, School of Engineering, James Cook University, Townsville, QLD4811, Australia.
2) National Institute of Standards and Technology, Boulder, CO80305, U.S.A.
3) Instytut Mikroelektroniki i Optoelektroniki Politechniki Warszawskiej, Koszykowa 75, 00-662, Warszawa, Poland.

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Abstract — Surface resistance of HTS films is typically measured using Sapphire dielectric rod resonators enclosed in a copper cavity. In this paper we present surface resistance measurements of $YBa_2Cu_3O_{7-\delta}$ films using Strontium Lanthanum Aluminate (SLAO) at a resonant frequency of 18.2 GHz. We have performed the error analysis of the cavity loaded with SLAO dielectric rod and also verification measurements using two Sapphire ($Al_2O_3$) rod resonators operating at resonant frequencies of 24.6 GHz and 10 GHz respectively. Good agreement between the values of $R_s$ of two sets of $YBa_2Cu_3O_{7-\delta}$ films measured using the SLAO and the Sapphire dielectrics has been obtained after a frequency scaling of $R_s$ was applied. Using different dielectric rods of the same size in the same cavity for measurements of $R_s$ of HTS films it is feasible to do microwave characterization of the same films at differing frequencies.

Introduction

The use of High Temperature Superconducting (HTS) planar filters in base station receivers increased significantly during the last few years e.g. [1]. The low insertion loss and sharp skirts are one of the most important characteristics of superconducting filters and their values depend on the surface resistance of the HTS thin films used. In order to fabricate HTS filters with very low insertion loss, it is important to identify HTS samples with low surface resistance at the frequency of interest. The surface resistance can be measured using different methods such as the cavity method [2], planar resonator method [3] and the dielectric resonator method [4]–[7]. The sensitivity and the error of the measurements are different for each technique [5]. The Sapphire dielectric resonator technique has been widely accepted for characterization of HTS samples due to its high sensitivity and the accuracy [5]. To characterize HTS thin films at different frequencies, different Sapphire rods and different cavities are required. However instead of using Sapphire rods of different diameters it is feasible to use different dielectric materials of the same dimensions in the same cavity.

Dielectric resonator technique for microwave characterization of HTS films

The schematic diagram of the Hakki–Coleman (H–C) dielectric resonator used in this work is shown in Fig. 1. The resonator consisted of a SLAO dielectric rod of permittivity of 16.8 between two $YBa_2Cu_3O_{7-\delta}$ films measured using the SLAO and the Sapphire dielectrics has been obtained after a frequency scaling of $R_s$ was applied. Using different dielectric rods of the same size in the same cavity for measurements of $R_s$ of HTS films it is feasible to do microwave characterization of the same films at differing frequencies.

\[ k_{\rho_1}J_0(k_{\rho_1}a)F_1(b) + k_{\rho_2}J_1(k_{\rho_2}a)F_0(b) = 0 \]

where

\[ F_0(\rho) = I_0(k_{\rho}a) + K_0(k_{\rho}a) \frac{I_1(k_{\rho}a)}{K_1(k_{\rho}a)} \]
\[ F_1(\rho) = -I_1(k_{\rho}a) + K_1(k_{\rho}a) \frac{I_0(k_{\rho}a)}{K_0(k_{\rho}a)} \]

\[ k_{\rho_1}^2 = \frac{\omega^2\varepsilon_r}{c^2} - k_z^2, \quad k_{\rho_2}^2 = k_z^2 - \frac{\omega^2\varepsilon_r}{c^2}, \quad k_z = \frac{\pi}{L} \]
and $\omega$ is the angular frequency ($2\pi f$, $c$ is velocity of light, $\varepsilon_0$ is free space permittivity, $\varepsilon_r$ is the real part of relative permittivity of the sample and $J_0$, $J_1$, $I_0$, $I_1$, $K_0$, $K_1$, denote corresponding Bessel and Hankel functions.

\[ R_S = A_S \left[ \frac{1 - R_M}{A_M} - \rho_e \tan \delta \right] \]  

where $R_M$ is the surface resistance of the metallic part of the cavity, $A_S$ and $A_M$ are the geometric factors of the superconducting part and metallic parts of the cavity and $\rho_e$ is the electric energy filling factor.

| Dielectric     | $A_S$ | $A_M$ | $\rho_e$ |
|----------------|-------|-------|----------|
| SrLaAlO$_4$    | 212.7 | 20241 | 0.98     |
| Al$_2$O$_3$    | 280.6 | 22319 | 0.97     |

*Tab. 1. Geometric factors and $\rho_e$ of the H-C resonator.*

Fig. 2. The experimental set-up to measure $R_s$ of $YBa_2Cu_3O_7$ films with the SLAO resonator.

The measurement system consisted of a Network Analyzer (HP 8722C), Temperature Controller (Conductus LTC-10), Vacuum Dewar, close cycle refrigerator (APC-HC4) and a computer as shown in Fig. 2.

The method of the surface resistance measurements was in principle the same as used by several groups e.g. [6], [7]. The main advantage (and difference) of our measurements was that the unloaded $Q_0$-factor was calculated from the exact equation, namely [8], [9]

\[ Q_0 = Q_e (1 + \beta_1 + \beta_2) \]  

where $\beta_1$ and $\beta_2$ are coupling coefficients of the resonator to the external circuitry. The loaded $Q_L$-factor and the coupling coefficients were obtained from multi-frequency measurements of $S_{21}$, $S_{11}$, and $S_{22}$ parameters measured around the resonance, using the Transmission Mode Q-Factor Technique [9], [10]. The TMQF method accounted for noise, delay due to uncompensated transmission lines and its frequency dependence, and crosstalk, which occurred in measurement data, and hence it provided accurate values of surface resistance.

The dielectric resonator loaded with the superconducting samples was mounted in the vacuum dewar and cooled down to 13 K. The $S$-parameters were measured around the resonance from 13 K to 85 K. The $Q_0$-factor was calculated using the TMQF method for all temperatures.

The average surface resistance ($R_s$) of the HTS thin films was calculated using software SUP12 [11], based on the well known equation [6]:

Fig. 3. The most probable error in surface resistance of HTS measured with the SLAO rod for different uncertainties in $Q_0$ at 18.2 GHz.

Fig. 4. The most probable error in $R_s$ of A films measured with AO rod for varying uncertainties in $Q_0$ at 24.6GHz.

Geometric factors $A_S$, $A_M$ and $\rho_e$, used in (4) were computed using the incremental frequency rules as [6] follows:

\[ A_S = \frac{\omega^2 \mu_0}{4} \frac{\partial \omega}{\partial L} \]  

\[ A_M = 2 \frac{\partial \omega}{\partial \mu_0} \]  

\[ \rho_e = 2 \frac{\partial e_r}{\partial e_r} \]
Error analysis of Rs measurements using the SLAO resonator

The most probable error in measured surface resistance using the dielectric resonator technique depends on surface resistance of the films and the cavity walls, loss tangent of the dielectric, geometrical factors of the resonator and uncertainties of their values. The error $\Delta R_s/R_s = \Delta \tan \delta$ can be calculated on the basis of the following equation [5]:

$$
\Delta R_s = \frac{R_s A_M}{Q_s A_S} \left[ \frac{1}{R_s A_S} \frac{A_S}{Q_s A_s} \left( \frac{\Delta Q_s}{Q_s} \right)^2 + \left( \frac{\Delta R_s}{R_s} \right)^2 + \left( \frac{\Delta M}{M} \right)^2 \right]^{1/2}
$$

where $Q_s = (\rho_s \tan \delta)^{-1}$; For the general error analysis of the SLAO and AO resonators we have assumed uncertainty in factor of 1%, uncertainty in geometric factors of 0.5%. The loss tangent of SLAO was assumed as $3 \times 10^{-6}$ and of AO as $1.25 \times 10^{-7}$ with the 6% and 25% uncertainty respectively. The surface resistance of copper was assumed to be $20 \text{ m}\Omega$ at 18.2 GHz and $23.6 \text{ m}\Omega$ at 24.6 GHz. Figs. 3 and 4 show the most probable error in $R_s$ at 18.2 GHz with the SLAO rod and at 24.6 GHz with the AO rod respectively.

In practice the loss tangent of SrLaAlO$_4$ rod varied from $6 \times 10^{-7}$ to $3.1 \times 10^{-7}$, and its uncertainty $\Delta \tan \delta$ was between 11.7% and 4.5%, when temperature changed from 13 K to 80 K as shown in Figs. 5 and 6.

Results and discussion of Rs measurements of HTS films with SLAO and AO rods

Two sets (A: 1", diameter and B: 0.5", diameter) of thermally co-evaporated YBa$_2$Cu$_3$O$_{7-\delta}$ films on LaAl$_2$O$_3$ substrates were tested using the SLAO dielectric resonator. Measured surface resistance of the set A at frequency of 18.2 GHz using the SrLaAlO$_4$ dielectric rod is shown on Fig. 7 as squares. The $R_s$ of the same films measured with the Sapphire rod in the same cavity scaled to 18.2 GHz is shown by triangles. The circles in the Fig. 7 represent $R_s$ of the same films measured at 10 GHz with a different Sapphire rod (12.32 mm in diameter and 7.42 mm in height) in a bigger cavity of 24.05 mm in diameter scaled to 18.2 GHz. The agreement in $R_s$ values measured with SLAO and Sapphire resonator is good. The deviation in $R_s$ was approximately 2% for temperatures from 13 K to 70 K and approximately 8% in the temperature range from 70K to 80 K.
The uncertainty analysis of $R_S$ of the films $A$ using the SLAO rod and assuming the $\tan \delta$ and its uncertainty as in Fig. 5 and 6 gives the uncertainty in $R_S$ of films $A$ presented in Fig. 8. The $\Delta R_S$ varies between 2.5% at 13K to 1.2% at 80K assuming 1% uncertainty in the $Q_\sigma$ factor.

On the basis of performed measurements of the films $A$ with SLAO resonator at 18.2 GHz and AO resonators at frequencies 10 GHz and 24.6 GHz, it is feasible to present the frequency dependence of the YBa$_2$Cu$_3$O$_{7-\delta}$ film (Fig. 9). We have obtained the frequency dependence of 2.1 (2.1) for $R_S$.

Fig. 10 shows the of YBa$_2$Cu$_3$O$_{7-\delta}$ films $B$, half inch diameter, measured at 18.2 GHz frequency. The squares represent the measured values $R_S$ using the SLAO rod and the triangles represent the using the AO resonator at frequency of 24.5 GHz and scaled to 18.2 GHz. The deviation in $R_S$ values was approximately 3% for temperatures from 13 K to 70 K and 10% in the temperature range from 70 K to 80 K.

![Fig. 9. Frequency dependence of YBa$_2$Cu$_3$O$_{7-\delta}$films A at temperatures 40 K, 60 K, 77 K and 80 K.](image1)

![Fig. 10. Surface resistance of YBa$_2$Cu$_3$O$_{7-\delta}$films B at 18.2 GHz.](image2)

**Conclusion**

The surface resistance of two sets of YBa$_2$Cu$_3$O$_{7-\delta}$ samples was measured using the SrLaAlO$_4$ resonator at frequency of 18.2 GHz and the Al$_2$O$_3$ resonator at frequencies of 10 GHz and 24.6 GHz. We have obtained two tests frequencies using same copper cavity and two dielectric materials of the same dimensions. The uncertainty analysis for the 18.2 GHz SLAO resonator showed that the maximum most probable error in $R_S$ was 2.5% (Fig. 8), while for the 24.6 GHz Sapphire resonator the maximum $\Delta R_S$ was 1.8% assuming $\Delta Q_\sigma$ of 1%. The verification measurements showed that difference between $R_S$ values measured with SLAO and AO was below 2% for temperatures up to 70 K when the frequency scaling to the power 2.1 was used. Therefore by swapping the Sapphire rod with the SLAO, we will be able to measure the $R_S$ of YBa$_2$Cu$_3$O$_{7-\delta}$ thin films at two different frequencies without compromising the accuracy of measurements.

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E-mails: janina.mazierska@jcu.edu.au.