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Sensitivity of surface resistance measurement of HTS thin films by cavity resonator, dielectric resonator and microstrip line resonator

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Abstract. Microwave surface resistance (R_s) of silver-doped $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film, deposited by laser ablation technique on 10 mm × 10 mm $LaAlO_3$ substrate, has been measured by resonant techniques in the frequency range from 5 GHz to 20 GHz. The geometrical factor of the sample and the resonator has been determined theoretically by the knowledge of the electromagnetic field distribution in the resonators. The microwave surface resistance of the superconducting sample is then extracted from the measured Q value as a function of temperature. The sensitivity of the R_s measurement, that is, the relative change in the Q value with the change in the R_s value is determined for each resonator.

Keywords. Microwave surface resistance; high-temperature superconductors.

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1. Introduction

The microwave surface resistance of high-temperature superconductor (HTS) thin films is one of the most important parameters to be characterized because the accurate knowledge of R_s is essential in the design of high frequency superconducting circuits and to assess the usefulness of HTS films. The surface resistance of HTS films is evaluated from the measured unloaded quality factor Q_0 of the microwave resonator structure used for the measurement. The calculation of R_s is made via an equation, which involves the geometrical constants of the resonator obtained from the mathematical model describing physical phenomena in resonator. Most of the resonant structures so far used in measurements of R_s of HTS films have the potential for accurate measurements of R_s, but not all of them provide the same accuracy.

In this paper, we report the measurement of R_s of laser ablated $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films deposited on 10 mm × 10 mm $LaAlO_3$ substrates by three resonating techniques, namely cavity resonator, dielectric resonator, and thin film microstrip line resonator. We also discuss the measurement sensitivity of these resonators with respect to the size of the samples.

2. Experiment

Ag-doped $YBa_2Cu_3O_{7-\delta}$ thin films of thickness $\sim$ 400 nm and $T_c \sim 89$ K were deposited by pulsed laser deposition technique on 10 mm $\times$ 10 mm single crystal $LaAlO_3$ substrate [1]. The R_s measurement of the un-patterned YBCO thin film was made by cavity partial end-plate substitution technique at 20 GHz and shielded dielectric resonator (SDR) technique at 18 GHz. The films were then patterned to fabricate a planar half wavelength microstrip line resonator providing fundamental resonance at 5 GHz. For the characterization of films, the resonators were mounted in an evacuated cryo-cooler and cooled down to lowest temperature. Microwave power was fed to the resonator through low loss cables and transmitted resonance signal was analyzed using scalar network analyzer (HP-8757D). The temperature is then slowly raised and 3-dB bandwidth, Δf and insertion loss, IL, are measured at resonant frequency f_0 in the temperature range 20 K to superconducting transition temperature T_c of the thin films. As all the resonators were weakly coupled, the unloaded Q value, Q_0, of the resonator was calculated using relation

$$Q_0 = \frac{f_0}{\Delta f}[1 - 10^{-(\mathrm{IL}/20)}]^{-1} . \tag{1}$$

The unloaded Q value, Q_0, of the weakly coupled shielded resonators is expressed in terms of conductor losses by the superconducting sample, conduction losses by the copper walls or ground plane and dielectric losses as

$$\frac{1}{Q_0} = \frac{R_s}{G_s} + \frac{R_{scu}}{G_m} + \rho_e \tan\ \delta \tag{2}$$

where G_s and G_m are respectively, the geometrical factors of the superconducting sample and the metallic conductor. In general, the geometrical factor can be separately evaluated from the knowledge of the electromagnetic field distribution in a resonator.

The conduction losses due to copper background are measured experimentally from all copper resonators with temperature. The change in the temperature influences the superconductor Q value, Q_{sup}, via R_s, resulting in the change of the unloaded Q value, Q_0, of the resonator. Thus, eq. (2) can be generalized as

$$\frac{1}{Q_0} = \frac{1}{Q_{other}} + \frac{1}{Q_{sup}} . \tag{3}$$

The surface resistance, R_s, of the superconducting sample is evaluated using

$$R_s = \frac{G_s}{Q_{sup}} . \tag{4}$$

3. Cavity resonator technique

The surface resistance of HTS film deposited on 10 mm $\times$ 10 mm is measured using a TE_{011} mode of a cylindrical cavity resonator at 20 GHz by partial end-plate substitution technique (CPEPS) [2]. In this method, the sample is embedded at the center of the end-plate, through annular opening of $2d = 9.6$ mm, of the copper cavity (diameter $2a = 22.42$ mm and length $L = 12.94$ mm) having surface resistance R_{scu} of metallic region. The unloaded quality factor Q_0 of the cavity containing sample of surface resistance R_s is derived using appropriate boundary conditions as [2]

$$\frac{1}{Q_0} = \left[\left\{ \frac{1}{G_m} - \frac{1}{G_s} \right\} R_{scu} + \frac{1}{G_s} R_s \right] \tag{5}$$

where G_m and G_s are the geometrical factors of the metallic cavity and that of the superconducting sample. The geometrical factors were calculated as $G_m = 716\ \Omega$ and $G_s = 10310\ \Omega$ for the sample of 9.6 mm diameter exposed to the microwave signal. The small contribution by the sample area to the total ohmic loss of the cavity can be seen by the ratio $G_m/G_s = 0.069$ and the fact that the Q_{other} value of cavity is almost the same as the measured Q_0, whereas the value of Q_{sup} is very large as shown in figure 1. This suggests that

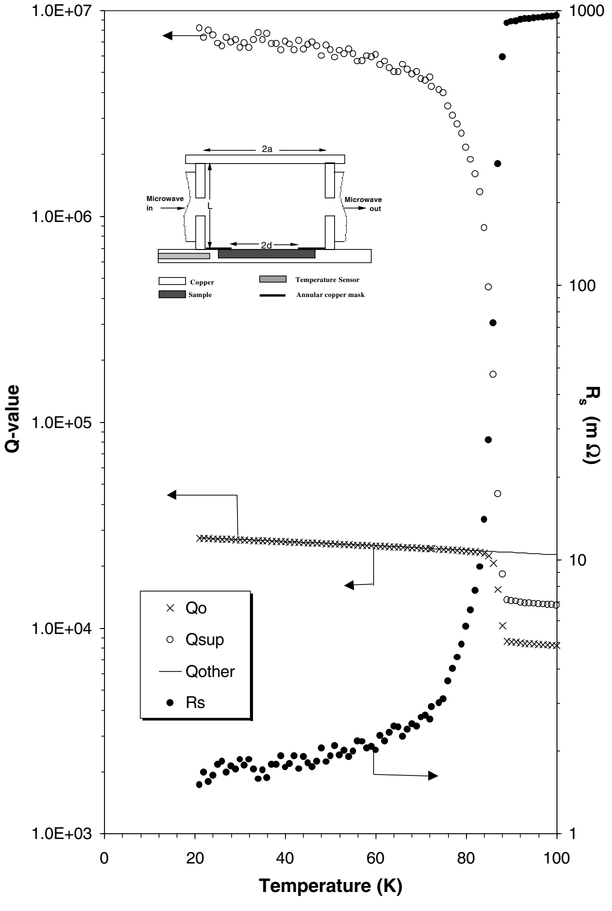

Figure 1. Variation of Q values and R_s of YBCO thin film with temperature estimated by cavity end-plate substitution at 20 GHz.

the Q value of the cavity is mainly governed by the ohmic loss in the metallic part of the cavity and that the change in R_s value of the HTS thin film has negligible influence on Q_0. The figure also shows the variation in the extracted R_s value with temperature.

4. Dielectric resonator

The dielectric resonator technique employs the measurement of TE_{011} mode of a dielectric puck sandwiched between the two test samples and surrounded by a cylindrical metallic shield [3]. A sapphire puck of diameter 7.0 mm and length 4.18 mm was used to fabricate a TE_{011} mode shielded dielectric resonator (SDR) operating at 18 GHz. The shield diameter of 9.8 mm was kept to ensure grounding of the 10 mm × 10 mm HTS thin film sample to

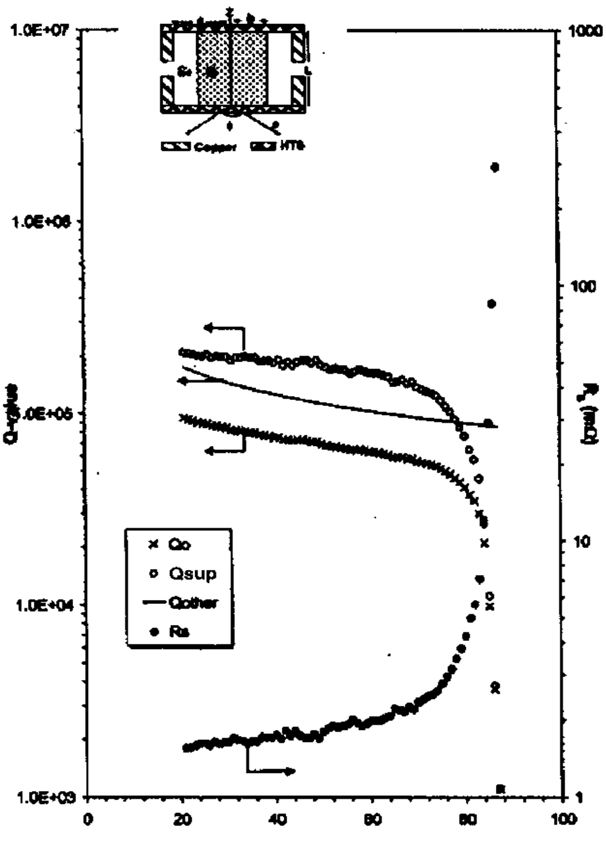

Figure 2. Variation of Q values and estimated R_s value of the YBCO thin film with temperature measured by dielectric technique at 18 GHz.

the shield. The surface resistance, R_s, of the YBCO thin film is obtained using eq. (6).

$$\frac{1}{Q_0} = \left[\left\{ \frac{R_s}{G_s} + \frac{R_{scu}}{G_m} \right\} + p_e \tan \delta \right]. \tag{6}$$

Here p_e and tan δ are respectively, dielectric filling factor and dielectric loss tangent of the dielectric puck. We have obtained exact expressions for geometrical factors of the superconducting sample G_s and metallic lateral wall G_m. The selected dimensions of the SDR provides $p_e = 0.989$ and the values of geometrical factors $G_s = 324\ \Omega$ and $G_m = 2105\ \Omega$. Figure 2 shows Q value of the SDR and average R_s value as a function of temperature for the two similar HTS YBCO thin films. In this case Q_{other} and Q_{sup} are close to each other, suggesting that the Q_{sup} has rather strong influence on the measured Q_0.

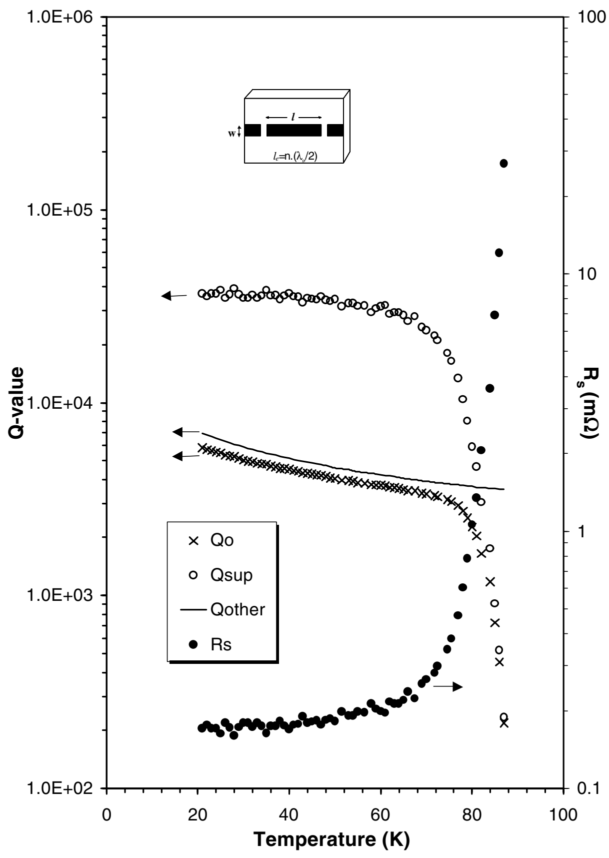

Figure 3. Variation of Q values and estimated R_s value of the YBCO thin film with temperature measured by microstrip resonator technique at 5 GHz.

5. Microstrip resonator technique

The half-wavelength microstrip line resonator is an open-ended transmission line, which supports a standing wave at a frequency for which the effective length l_e of the line is exactly a half-wavelength. The fundamental resonant mode of the resonator is accompanied by higher order harmonic modes at frequencies approximately integral multiple of the fundamental resonance frequency. We patterned a 5 GHz YBCO half-wavelength microstrip line resonator of length 7.8 mm on $LaAlO_3$ (LAO) substrate. The surface resistance of the strip material R_s can be estimated from the measured unloaded Q value, Q_0, using relation [4]

$$\frac{1}{Q_0} = \frac{2l_e}{n\pi}\left\{\left(\frac{G_s R_s + G_m R_{scu}}{2Z_0}\right) + (\rho_e \tan \delta)\right\} \tag{7}$$

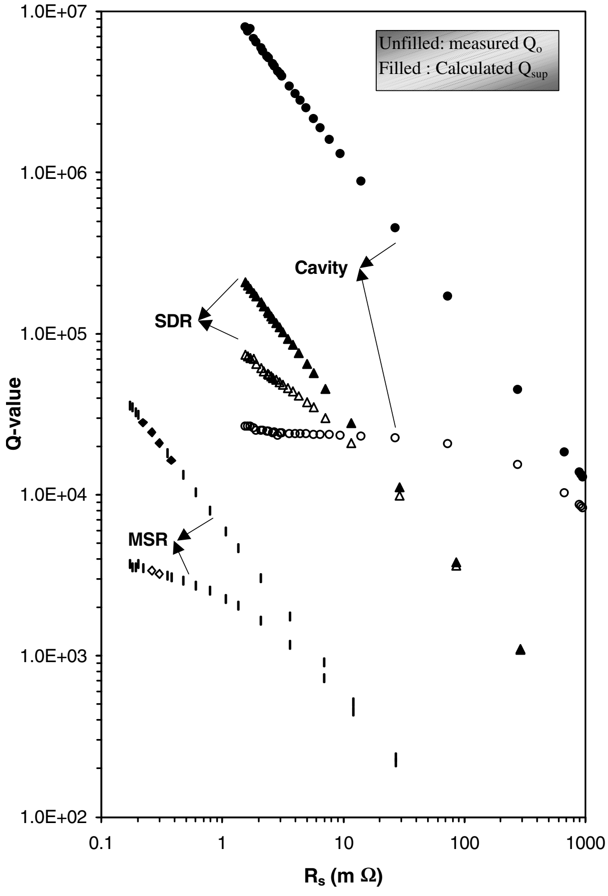

Figure 4. Variation of Q value as a function of R_s value of the YBCO thin film measured by the three resonators.

where Z_0 is the characteristic impedance of the microstrip line, G_s and G_m are respectively the geometrical factors of strip and metal ground plane. The geometrical factors for the resonator under consideration are having the values $G_s = 2187\ \Omega^{-1}$ and $G_m = 298.3\ \Omega^{-1}$. Figure 3 shows the variation of the Q values and extracted R_s value of the YBCO thin film with temperature measured by microstrip resonator at 5 GHz. In this case Q_{other} of microstrip resonator is much lower than Q_{sup} and close to Q_0. Thus, for this case too, the Q_0 is greatly influenced by Q_{other} and reduces the sensitivity of R_s measurement.

Figure 4 shows measured Q value, Q_0, of the three resonators as a function of R_s value of the HTS YBCO thin film. Figure 4 also shows the plots of Q_{sup} vs. R_s corresponding to the measured R_s value of the YBCO thin film by these techniques. The Q_{sup} value increases monotonically with the decrease in the R_s value. However, the measured Q_0 tends to saturate at lower R_s value for CPEPS and microstrip resonator technique. As R_s value decreases the difference in Q_0 and Q_{sup} increases, the difference is minimum for SDR and maximum for CPEPS technique. Also, the slope of the Q_0 for SDR technique is rather steady and higher compared to CPEPS and MSR techniques. It suggests that among those techniques, SDR technique provides the best dynamic range of Q value for the change in the R_s value of the sample.

6. Conclusion

The sensitivity of SDR for R_s measurement is maximum. The sensitivity of each technique can be improved: (i) for CPEPS, by increasing the area of sample exposed to microwaves, (ii) in SDR, by taking the shield diameter three times the diameter of sapphire puck, (iii) for MSR, by using double-sided HTS films to form HTS-HTS resonator. However, for CPEPS and SDR the condition of measurement of 10 mm $\times$ 10 mm thin film at low frequencies ($<$ 26 GHz) will be no longer possible in those conditions.

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