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A study on the microwave responses of YBCO and TBCCO thin films by coplanar resonator technique*

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$YBa_2Cu_3O_7$(YBCO) thin films have been prepared by thermal coevaporation on $LaAlO_3$(LAO) substrates, and $Tl_2Ba_2CaCu_2O_8$(TBCCO) thin films are synthesized by magnetron sputtering method on LAO substrates. The transition temperature T_c is 90 K for YBCO/LAO and 104 K for TBCCO/LAO. Microwave responses of the films are studied systematically by coplanar resonator technique. Energy gaps of the films obtained are $\Delta_0 = 1.04k_BT_c$ for YBCO films and $\Delta_0 = 0.84k_BT_c$ for TBCCO films by analysing the temperature dependence of resonant frequencies of coplanar resonator. Penetration depth at 0 K $\lambda_0 = 198$ nm for YBCO films and $\lambda_0 = 200$ nm for TBCCO films could also be obtained by using the weak coupling theory and two fluid theory. Results of penetration depth and energy gap confirm the weak coupling properties of the films. In addition, microwave surface resistances R_s of YBCO/LAO and TBCCO/LAO are also investigated by analysing the quality factor and insert loss of the coplanar resonator. Surface resistance of TBCCO/LAO is less than that of YBCO/LAO, so that TBCCO/LAO films may have more potential applications.

Keywords: YBCO, TBCCO, superconducting films, coplanar resonator
PACC: 7000, 7400, 7430C, 7430E

1. Introduction

At present, high-temperature superconducting thin films are extensively used to make microwave passive devices, such as filters, resonators, delay lines and antennas because of the very low loss in microwave field. In these applications, precise evaluation of the basic parameter of superconducting thin films, i.e. the microwave surface impedance Z_s, is essential. Measurement of Z_s of high-temperature superconducting films is a powerful tool for studying nonlinear processes in superconducting materials. Surface impedance at microwave frequencies plays an important role in exploring the properties of the mixed state of high-temperature superconductor (HTS). The real part of the surface impedance, the surface resistance, describes microwave power losses and can yield useful information about vortex dynamics in these materials. The imaginary part of the surface impedance, the surface reactance, is directly related to penetration depth of the magnetic field, which provides a measuring method of the superfluid density. The microwave surface impedance $Z_s = R_s + iX_s$, in high-T_c superconducting thin films is linear at low microwave power levels, but becomes nonlinear at higher microwave power. Nonlinearities limit power-handling capabilities of superconducting thin films and the applications of possible devices.[1−6] Despite numerous attempts worldwide, the sources of nonlinear microwave responses of superconductor are not understood at present, partially because of a lack of systematic studies on characterization of samples.[7−10] Many imperfections have been proposed to account for the nonlinear behaviours, such as grain boundaries and flux penetration that are usually proposed as sources of nonlinearity. Much of the experimental evidences is not able to identify the proposed mechanisms with any degree of certainty.[11,12]

Energy gap of superconductors can also be investigated by microwave resonance technique. Superconductors having zero-temperature energy gap $\Delta_0 < 2k_BT_c$ are regarded as weak coupling superconductors, while those having $\Delta_0 > 2k_BT_c$ are strong coupling superconductors. Energy gap structure can

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be related to the symmetry of wave function of superconducting electrons. The energy gap in a superconducting material is important for the understanding of the relevant pairing mechanism and for the determination of its application. Many theoretical models have been used to analyse the energy gap structure of superconducting materials.[13−15] Now, the energy gap structure of superconducting electrons is under discussion.

In this paper, the microwave responses of $YBa_2Cu_3O_7/LaAlO_3$ (YBCO/LAO) and $Tl_2Ba_2CaCu_2O_8/LaAlO_3$ (TBCCO/LAO) are investigated by the coplanar resonator technique. Energy gap, penetration depth and surface resistance of the films are analysed and discussed systemically.

2. Coplanar resonator theory

In the standard theory of distributed element transmission line resonator, the resonant frequency of the fundamental mode is given by $f_0 = \dfrac{1}{\lambda_g\sqrt{LC}}$. Here λ_g is the guide wavelength of the resonator ($\lambda_g = 2l$, l is the length of the central strip of the coplanar resonator). In the case of coplanar transmission lines, the total inductance per unit length L is the sum of the geometric inductance L^g and the kinetic inductance L^k, $L = L^g + L^k$. We can obtain an equation if assume that the capacitance of the line C does not change significantly with temperature,

$$\frac{f_0(T)}{f_0(T_0)} = \sqrt{\frac{L^g + L^k(T_0)}{L^g + L^k(T)}}. \tag{1}$$

Here T_0 is a reference temperature. In fact, T_0 is usually the lowest temperature among the experimental data. Coplanar transmission lines are suitable for superconducting materials which are hard to build multi-layer structure, since they require only one side of the substrates. It mainly consists of two ground planes and a central strip of conductor deposited on the substrate. The central strip forms the resonant section of the coplanar transmission line. Its length equals one-half of the guide wavelength at the fundamental mode. The geometric inductance L^g related to the external magnetic field is determined by the geometry of the line. The kinetic inductance L^k is determined by the transport properties of the charge carriers of the transmission line and depends on surface current density distributed across the conductor. The propagation characteristics of a coplanar resonator can be deduced analytically by conformal mapping techniques, resulting in an inductance per unit length of[16−18]

$$L^g = \frac{\mu_0 M(\sqrt{1-(w/a)^2})}{4M(w/a)}. \tag{2}$$

Here M is the complete elliptic integral of the first kind, μ_0 is the vacuum permeability, w is the width of the central strip line, the central strip spacing to each ground is s, and $a = w + 2s$.

$$L^k = \frac{\mu_0\lambda^2(T)k'}{t[1+(\omega\mu_0\sigma_n\lambda^2(T))^2]}. \tag{3}$$

Here $k' = \dfrac{1}{w}(A_1 + A_2)$, $\omega = 2\pi f_0$, t is the thickness of HTS films, σ_n is the normal fluid conductivity of HTS films, $\lambda(T)$ is penetration depth, and

$$A_1 = \frac{2}{\left[M\left(\frac{w}{a}\right)\right]^2\left[1-\left(\frac{w}{a}\right)^2\right]}\left[1+\frac{1}{4}\ln\left(\frac{w}{\lambda'(T)}-1\right)-\frac{w}{4a}\ln\left(\frac{a+w-2\lambda'(T)}{a-w+2\lambda'(T)}\right)\right], \tag{4}$$

$$A_2 = \frac{w/a}{\left[M\left(\frac{w}{a}\right)\right]^2\left[1-\left(\frac{w}{a}\right)^2\right]}\left[1+\frac{1}{4}\ln\left(\frac{w}{\lambda'(T)}+1\right)-\frac{a}{4w}\ln\left(\frac{a+w-2\lambda'(T)}{a-w+2\lambda'(T)}\right)\right]. \tag{5}$$

The edge penetration depth $\lambda'(T)$ is related to the penetration depth $\lambda(T)$ as $\lambda'(T) = \dfrac{2\lambda^2(T)}{t}$. If $\omega\mu_0\sigma_n\lambda^2(T) \ll 1$, we have $L^k \approx \dfrac{\mu_0\lambda^2(T)k'}{t}$. In weak coupling theory, the penetration depth $\lambda(T)$ can be described as[19,20]

$$\frac{\lambda(T)}{\lambda_0} = 1/\sqrt{1-\left(\frac{T}{T_c}\right)^{3-\frac{T}{T_c}}}, \tag{6}$$

where λ_0 is the zero-temperature penetration depth, T_c is superconducting transition temperature. For a strong coupling superconductor, the penetration depth $\lambda(T)$ can be described by two-fluid theory[21]

$$\frac{\lambda(T)}{\lambda_0} = 1/\sqrt{1-\left(\frac{T}{T_c}\right)^4}. \quad (7)$$

Therefore, λ_0 can be obtained using Eqs.(1)–(7) to fit experimental data $\frac{f_0(T)}{f_0(T_0)}$. Once the penetration depth λ is obtained, the surface resistance is determined as[16]

$$R_s = \frac{\omega L}{Q_u k'}, \quad (8)$$

where Q_u is the unload quality factor. The unload quality factor can be calculated from load quality factor (Q_l) and insert loss (IL) using the relation $Q_u = Q_l/(1-10^{-|IL|/20})$.

3. Experiment

High-quality TBCCO thin films were synthesized by magnetron sputtering method on LAO substrates. The YBCO thin films used in this study were deposited by thermal coevaporation on LAO substrates. The thickness of the TBCCO films was $t = 430$ nm with $T_c = 104$ K, and the thickness of YBCO films was $t = 700$ nm with $T_c = 90$ K. SEM pictures were taken to study the microstructure of the films (see Fig.1). As shown in Fig.1, the films show smooth surface, indicating that the films are of high quality. The crystal structures of the films have been studied using x-ray diffraction (XRD). In Fig.2, the films only display (0 0 l) peaks and substrate peaks. These results indicate that the films show c-axis preferred orientation. Coplanar resonators were designed using Sonnet software and fabricated by standard lithography and ion milling technique on the single-sided YBCO/LAO and TBCCO/LAO films with the dimensions of $10 \times 10 \times 0.5$ mm (see Fig.3). The width of the central strip line is 200 μm and the spacing to each ground is 180 μm. The length of the central strip line of the resonator is 6 mm, the gap between central strip and port lines is 0.5 mm. Resonant frequency f_0 and load quality factor Q_l of the resonator at fundamental mode can be obtained by Sonnet software before experiment ($f_0 = 6.99$ GHz, $Q_l \approx 4000$ at 77 K with parameters $\varepsilon_r = 23.6$, $\tan\delta = 6 \times 10^{-5}$, $d = 0.5$ mm for TBCCO/LAO and YBCO/LAO).

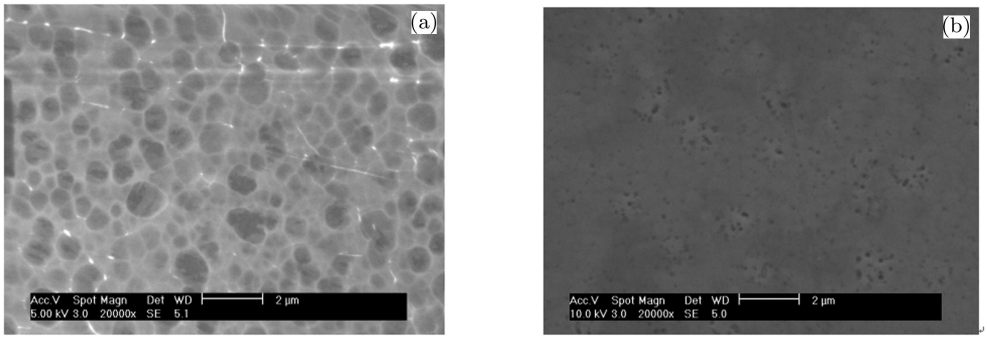


Fig.1. The SEM pictures of superconducting thin films. (a) TBCCO/LAO; (b) YBCO/LAO.

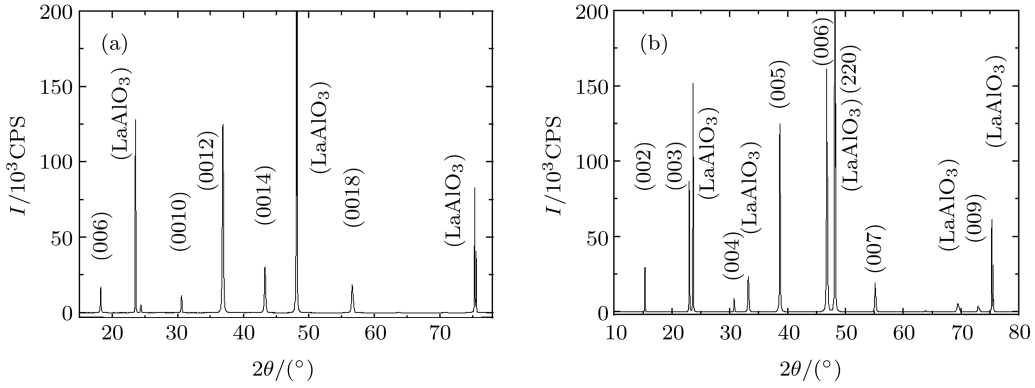


Fig.2. The XRD patterns of superconducting thin films. (a) TBCCO/LAO; (b) YBCO/LAO.

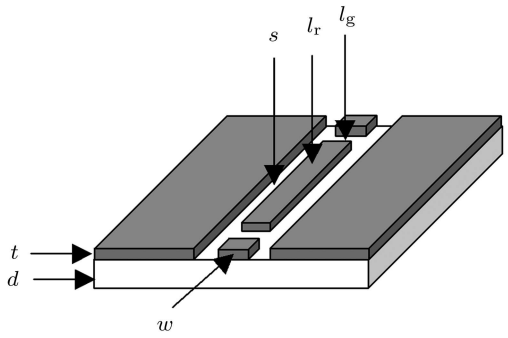


Fig.3. A coplanar waveguide resonator about YBCO/LAO and TBCCO/LAO (t is the thickness of the HTS film, d is the thickness of the substrate, w is the width of the central strip, s is the spacing between the central strip and the ground, l_r is the length of the central strip, l_g is the gap between the central strip and the port lines).

Microwave properties of the coplanar resonators were measured by Agilent 8510c Vector Network Analyser at low temperatures provided by a G-M refrigerator (CSW-71). The microwave signal through the coplanar resonator was measured by Agilent 8510c Vector Network Analyser with Lakeshore 340 temperature controller and CSW-71 helium compressor unit. In the experiment, the measurement temperature was between 15–90 K for YBCO film and 15–105 K for TBCCO film. The microwave input power was $P_{\text{input}} = 0$ dBm.

4. Results and discussion

The microwave properties of YBCO/LAO and TBCCO/LAO are investigated by coplanar resonant technique in this paper. The complex transmission coefficient of the resonator, S_{21} is measured as a function of the driving frequency at different temperatures. We can obtain resonant frequency f_0, load quality factor Q_l and insert loss IL by fitting the S_{21} resonance curves with the Lorentzian function. Figures 4, 5 and 6 show the temperature dependence of the resonant frequency, load quality factor and insert loss for YBCO/LAO and TBCCO/LAO. As shown in Fig.4, the resonant frequency reduces with increasing temperature, suggesting that the microwave current penetrates the superconducting sample gradually and the kinetic inductance L^{k} of the coplanar resonator increases at higher temperatures. Load quality factors of coplanar resonators are compared with the simulation results. The experimental results of load quality factors are smaller than those of simulated ones because the superconducting thin films are regarded as

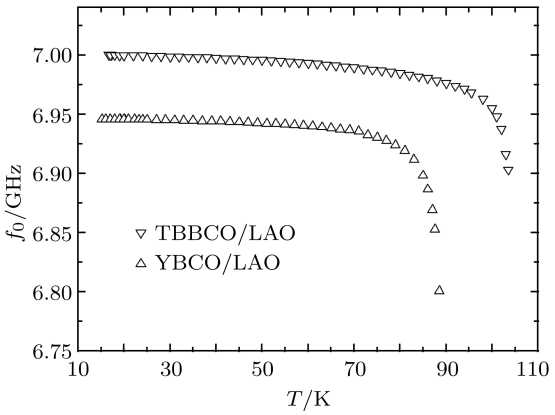


Fig.4. Temperature dependence of the resonant frequency of the coplanar resonator of YBCO/LAO and TBCCO/LAO at the fundamental mode with input power $P_{\text{input}} = 0$ dBm.

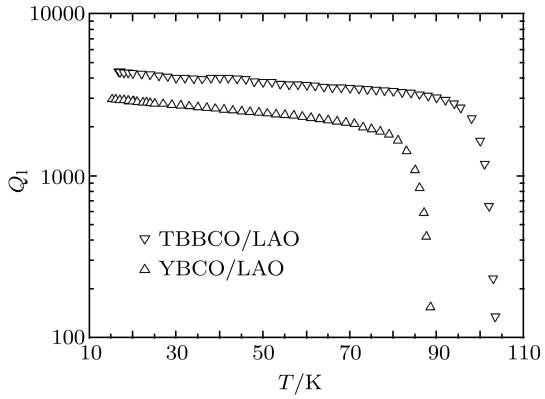


Fig.5. Temperature dependence of the load quality factor of the coplanar resonator of YBCO/LAO and TBCCO/LAO at the fundamental mode with input power $P_{\text{input}} = 0$ dBm.

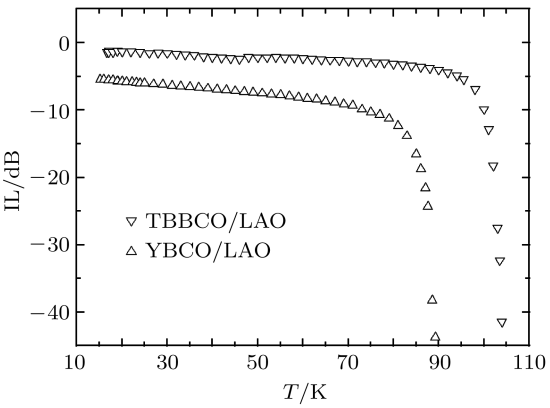


Fig.6. Temperature dependence of the insert loss of the coplanar resonator of YBCO/LAO and TBCCO/LAO at the fundamental mode with input power $P_{\text{input}} = 0$ dBm.

lossless in the course of simulation. We can also find that TBCCO/LAO has larger load quality factor and insert loss than those of YBCO/LAO at the same temperature. This indicates that TBCCO/LAO has less

loss at the microwave region. For the coplanar resonator of superconducting thin films, the shift of the resonant frequency, load quality factor and insert loss is small at low temperatures, but the shift of them becomes rapidly at temperatures near the transition.

In the superconducting theory, the energy-gap variation of a superconductor is $< 4\%$ below $T < T_c/2$, thus $\Delta(T) = \Delta_0$ is a good approximation within this temperature range at low temperatures. According to the coplanar resonator theory of superconductor, the energy gap of a superconductor can be related to resonant frequency of the coplanar resonator from the following equation[22]

$$\ln\left[\frac{1}{F_0^2(T)} - \frac{1}{F_0^2(T_0)}\right] \approx -\frac{\Delta_0}{k_B T} + 0.5\ln\left[\frac{\Delta_0}{k_B T}\right] + c'. \tag{9}$$

Here $F_0(T) = f_0(T)/m$, $m = 1\,\mathrm{GHz}$. c' is constant, which is dependent on the geometry factor of the coplanar resonator. Equation (9) shows that the value of energy gap $\Delta_0/k_B T_c$ can be determined approximately by the slope of $\ln\left[\frac{1}{F_0^2(T)} - \frac{1}{F_0^2(T_0)}\right]$. YBCO/LAO and TBCCO/LAO energy gaps may be obtained from the experimental data in Fig.7. $\Delta_0 = 0.84 k_B T_c$ for TBCCO/LAO and $\Delta_0 = 1.04 k_B T_c$ for YBCO/LAO. Energy gap value is $\Delta_0 < 2 k_B T_c$ for YBCO/LAO and TBCCO/LAO, thus weak coupling properties of YBCO and TBCCO is verified.

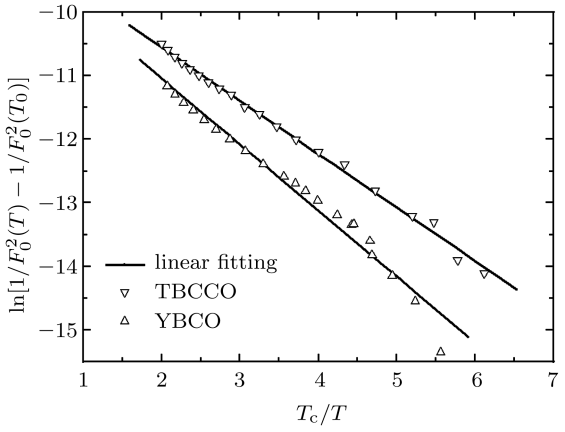


Fig.7. Normalized value of $\ln[1/F_0^2(T) - 1/F_0^2(T_0)]$ as a function of T_c/T. From the slope of linear fitting, HTS films energy gap can be obtained, $\Delta_0 = 0.84 k_B T_c$ for TBCCO/LAO, $\Delta_0 = 1.04 k_B T_c$ for YBCO/LAO.

Figure 8 shows the temperature dependence of the resonant frequency normalized by its value at the lowest temperature. The penetration depths of YBCO/LAO and TBCCO/LAO films $\lambda_0 = 198\,\mathrm{nm}$ and $\lambda_0 = 200\,\mathrm{nm}$ can be obtained using Eqs.(1)–(7) to fit the experimental data of $\frac{f_0(T)}{f_0(T_0)}$. In Fig.8, we can see that weak coupling theory is more appropriate to explain the behaviours of YBCO and TBCCO superconductors than strong coupling theory (two fluid model theory). Results of penetration depth and energy gap of the films all suggest that weak coupling theory is more rational for describing the microwave properties of YBCO and TBCCO. Previously, Huber *et al*[23] obtained penetration depth λ_0 for four TBCCO/LAO samples by using weak coupling theory, which was 170–300 nm. Values for high-quality YBCO films in the literature were in the range between 100 and 300 nm.[22,24] We believe that $\lambda_0 = 200\,\mathrm{nm}$ for TBCCO and $\lambda_0 = 198\,\mathrm{nm}$ for YBCO are appropriate by comparing with experimental results in the literature.

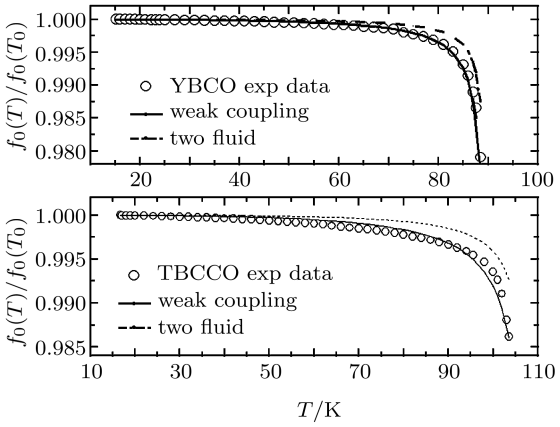


Fig.8. The temperature dependence of the normalized resonant frequency of coplanar resonators for YBCO/LAO and TBCCOLAO. The data have been fitted by weak coupling theory and two fluid theory.

Microwave surface resistances of YBCO/LAO and TBCCO/LAO films can be obtained by Eq.(8). In Fig.9, the surface resistance does change but not significantly at $T < 70\,\mathrm{K}$ for YBCO/LAO and at $T < 80\,\mathrm{K}$ for TBCCO/LAO. We can obtain microwave resistance at 7 GHz: $120\,\mu\Omega$ at 77 K for TBCCO/LAO; $520\,\mu\Omega$ at 77 K for YBCO/LAO. Surface resistance of TBCCO/LAO films is less than that of YBCO/LAO, thus TBCCO/LAO films may possess more potential applications. If assuming that microwave surface resistance of superconducting thin film is in line with frequency quadratic, experimental results of Hammond *et al*'s TBCCO/LAO[25] can be written as $107\,\mu\Omega$

at 77 K and 7 GHz. Experimental results of Rauch and Gornik's YBCO/LAO[22] can be written as 133–508 $\mu\Omega$ at 77 K and 7 GHz. Thus the results of surface resistance obtained in this paper are appropriate by comparing with experimental results in the literature.

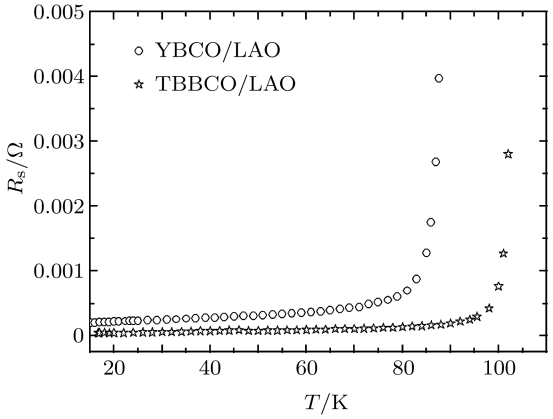


Fig.9. Surface resistance versus temperature measured at 7 GHz for YBCO/LAO and TBCCO/LAO.

HTS thin films can be grown by different techniques, such as sputtering, pulsed laser deposition, electron beam coevaporation. They are possible composed of inclusions of contaminating material, voids in the structure. Large and small grains of thin films may be connected by boundary regions of low critical current density. Weak links between grains can affect microwave surface impedance of the thin films, which makes surface impedance of HTS thin films larger. In order to reduce microwave surface resistance of the films, growth technique of high-temperature superconducting thin films need still be researched.

5. Conclusions

In this paper, microwave responses of YBCO/LAO and TBCCO/LAO films have been studied systematically by the coplanar resonator technique. Energy gap and penetration depth of HTS films can be obtained by analysing the dependence of resonant frequency on temperature. Results of energy gap and penetration depth confirm the weak coupling characteristics of YBCO and TBCCO. Surface resistances of YBCO and TBCCO films are calculated, TBCCO films possess smaller microwave surface resistance. Higher superconducting transition temperature and less surface resistance make TBCCO films more favourable to practical applications.

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