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Microwave properties of a $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ microstrip ring resonator with various hole concentrations

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Abstract

Superconducting ring resonator with a $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ ground plane was fabricated by using $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film deposited on both sides of a $LaAlO_3$ (LAO) substrate. The resonator exhibits a high quality factor $Q > 10^4$ at $T < 30\,K$, and from empirical relation, $T_c/T_{c,\max} = 1 - 82.6(p - 0.16)^2$, we obtained the hole concentration p. By controlling the oxygen contents of the ring resonator, the hole concentration p was controlled from 0.218 to 0.088, determined by the empirical relation, in the same film. The temperature dependence of the resonance frequency, $f(T)$, was then systematically studied. By using Chang's inductive formula and taking a functional form $(\lambda(5\,K)/\lambda(T))^2 = 1 - (T/T_c)^2$ at $T < 0.6T_c$, the London penetration depths $\lambda(5\,K)$ for various oxygen contents at 5 K were obtained, respectively. Finally, it allows us to test the Uemura relation $1/\lambda^2(5\,K) \propto T_c$ from the over- to the underdoped regime in the same sample.

Keywords: Microwave ring resonators; $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$; Penetration depth

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1. Introduction

Until now, there is as yet no consensus theory for high-T_c superconductors (HTSC) several systematic trends in their phenomenology have been discerned. One of these is the universal relation $\rho_s(5\,K)/m^* \equiv 1/\lambda^2(5\,K) = \text{const} \times T_c$ between the superfluid density and the superconducting (SC) critical temperature T_c, known as the Uemura relation [1,2]. The Uemura relation has been extremely influential and is generally discussed as a test to theoretical models, for example, resonating valence bond (RVB) model [3] and precursor pairing model [4]. However, several experimental results show that Uemura relation is not a universal relation. For example, for YBCO single crystal in the

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underdoped regime, Trunin et al. [5] by using muon-spin rotation found that superfluid density should be proportional to the hole concentration p not T_c, that is the $1/\lambda^2(5\,\mathrm{K}) = \mathrm{const} \times p$. Furthermore, Barnea et al. [6] has recently used zero-field electron spin resonance to observe that in the underdoped regime for YBCO single crystal above $T_c = 56\,\mathrm{K}$ the Uemura relation is not valid. However, all of these results are only for polycrystalline or single crystal samples and very little data about thin films.

In this report, the high-Q microstrip ring resonator ($Q > 10^4$) made of double-sided $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film were studied. By controlling the oxygen content in a reversible manner over the same resonator, no microstructural changes other than oxygen content was occurring during the process. Using this method, we believe that our sample obeys the empirical relation, $T_c/T_{c,\max} = 1 - 82.6(p - 0.16)^2$, very well. And then the various hole concentrations p per one copper atom in the CuO_2 plane were determined. Finally, the high-Q ring resonators made of $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ films give us the London penetration depth $\lambda(5\,\mathrm{K})$ as exactly as possible and then the superfluid density $1/\lambda^2(5\,\mathrm{K})$ related to T_c can be determined. In fact the Uemura relation can be retested in the structure of thin films.

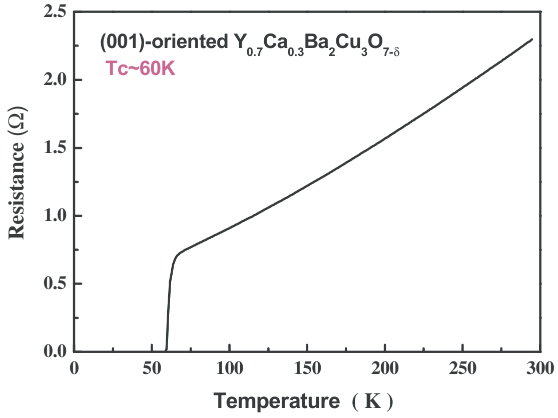

Fig. 1. The temperature dependence of resistance for the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film ($\delta \approx 0.05$), which shows that the zero resistance critical temperature $T_c \approx 60\,\mathrm{K}$. At $T = 0\,\mathrm{K}$, the extrapolated value of the resistance is not equal to 0, and the reason maybe is due to lattice antisite disorder or defects after doping calcium impurities.

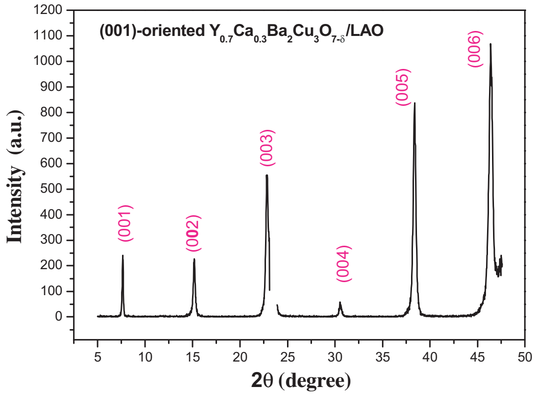

Fig. 2. X-ray diffraction shows that the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film is c-axis orientation. The substrate peaks are removed for clarity.

2. Experimental

The $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin films that were deposited epitaxially on both sides of a 0.5 mm thick $LaAlO_3(1\,0\,0)$ substrate by a KrF excimer pulsed laser deposition. The substrate temperature was kept at 760 °C with an oxygen partial pressure of 0.3 Torr during the deposition. The energy density and the repetition rate of the laser pulse were 2–4 J/cm^2 and 5 Hz, respectively. The as-deposited films typically have zero-resistance temperature of 60–61 K, as shown in Fig. 1. The extrapolated value of the resistance at $T = 0\,\mathrm{K}$ is not equal to 0 which maybe due to the lattice antisite or defects by doping calcium impurities. The X-ray diffraction analysis has revealed that the films are epitaxialy grown with c-axis oriented perpendicular to the substrate surface, as shown in Fig. 2. The films with a typical thickness of 500 nm are performed. One side of the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ film was then patterned into a ring resonator [7]. The line width and the outer radius of the ring are 0.5 and 3.625 mm, respectively.

The desired oxygen contents of the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ films were obtained by putting the $YBa_2Cu_3O_{7-\delta}$ film and the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ films in the same housing and the whole assembly was situated in an oxygen annealing chamber for just varying the oxygen pressure and keeping the temperature at 450 °C in 30 min. Then the sample housing was quenched into the ice water at 0 °C. These experimental conditions are optimal for changing the oxygen content of the $YBa_2Cu_3O_{7-\delta}$ film according to the pressure–temperature phase diagram [8] and it is noted that all the measurements can be performed on a single film. By using this method, we can control the oxygen content of the $YBa_2Cu_3O_{7-\delta}$ film and $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ film in the same condition precisely and reversibly [9]. In order to get the hole concentration p, we use the empirical relation

$$\frac{T_c}{T_{c,max}} = 1 - 82.6(p - 0.16)^2, \tag{1}$$

here we take $T_{c,max} = 84$ K for $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ film and $T_{c,max} = 91$ K for $YBa_2Cu_3O_{7-\delta}$ film which has been reported previously [2,10,11]. Surprisingly, in our samples the $T_c/T_{c,max}$ vs p phase diagram also obeys the empirical relation very well, as shown in Fig. 3, and this means that our samples have very high quality which calcium substitutes preferentially for yttrium in the $YBa_2Cu_3O_{7-\delta}$ compound. As a result, the critical temperature T_c of the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ film corresponding to the hole concentration p was listed in Table 1.

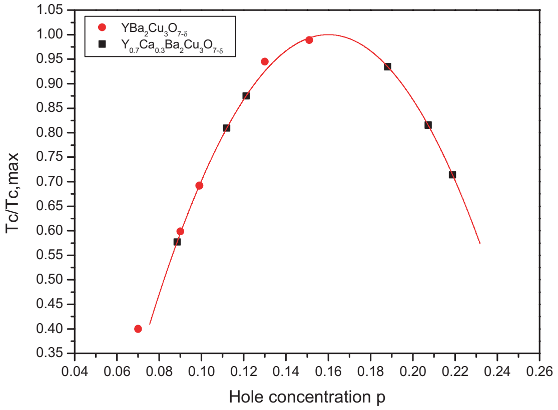

Fig. 3. The hole concentrations of the $YBa_2Cu_3O_{7-\delta}$ and the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin films are obtained by using the empirical relation $T_c/T_{c,max} = 1 - 82.6(p - 0.16)^2$. Here $T_{c,max}$ for $YBa_2Cu_3O_{7-\delta}$ thin film is taken as 91 K and the one for $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film is taken as 84 K.

Table 1
Some parameters for $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_y$ thin films from microwave measurements

Oxygen content $7 - \delta$	T_c (K)	P	f (GHz) (5 K)	λ(5 K) nm
6.95	60.0	0.218	3.62037	210
6.88	68.5	0.207	3.62269	165
6.85	78.5	0.188	3.62740	155
6.76	73.5	0.121	3.62595	170
6.74	68.0	0.111	3.62532	200
6.50	48.5	0.088	3.62364	250

The temperature dependence of the resonance frequency $f(T)$, frequency shift $\Delta f(T)$ and the forward transmission coefficient S_{21} were measure by a HP8510C microwave vector network analyzer at about 3.62 GHz. The temperature controller is Lake Shore 330 autotune temperature controller to control the temperature of the sample space to better than 0.1 K. And the unloaded quality factor, Qu, is defined as $Qu = f/((1 - S_{21})\delta f)$, where δf is the resonator bandwidth at −3 dB.

3. Results and discussion

Fig. 4 shows that the temperature dependence of the unloaded quality factor, Qu, of the same $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ ring resonator with various hole concentrations p. It is evident that, except $p = 0.088$, the quality factor reaches a value over

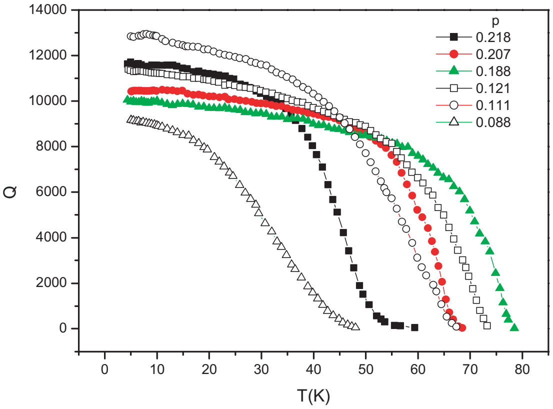

Fig. 4. The temperature dependence of the unloaded quality factor, Qu for the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin films.

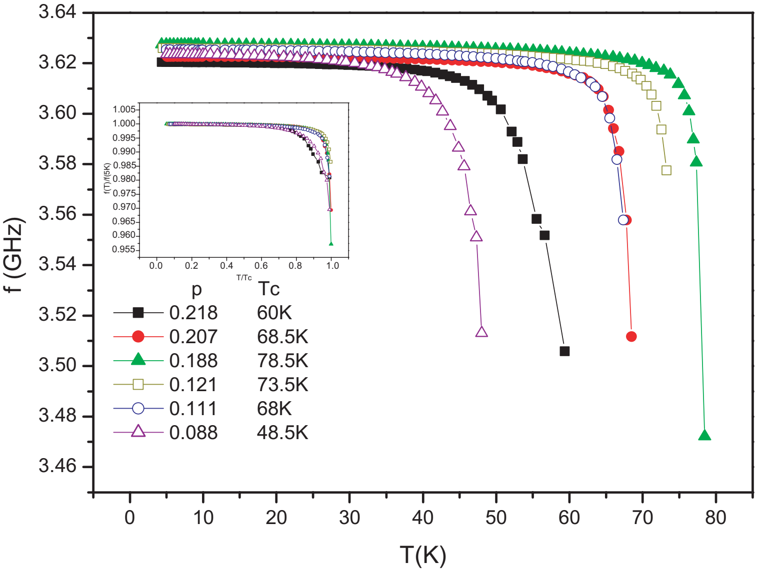

Fig. 5. The temperature dependence of resonance frequency $f(T)$ of the same ring resonator for $p = 0.218$, 0.207, 0.188, 0.121, 0.111 and 0.088, respectively.

10^4 at lower temperatures ($T < 30\,K$). This value is compatible with that the best $YBa_2Cu_3O_{7-\delta}$ ring resonator [12]. Fig. 5 shows the temperature dependence of resonance frequency $f(T)$ of the same ring resonator for $p = 0.218$, 0.207, 0.188, 0.121, 0.111 and 0.088, respectively. For various hole concentrations p, the resonance frequency decreases as increasing temperature T. In the overdoped regime, $p = 0.218$, 0.207 and 0.188, and in Fig. 5 it shows that the resonance frequency for $p = 0.218$ at any temperature is smaller than the one for $p = 0.218$ and 0.207. However, in the underdoped regime, it shows that the resonance frequency for $p = 0.121$ at any temperature is larger than the one for $p = 0.111$ and 0.088. Then Table 1 lists the resonance frequency at 5 K for various hole concentrations p, and it also be seen that the resonance frequency increases with decreasing p until $p = 0.188$ and then the one decreases with decreasing p until $p = 0.088$. In Fig. 5, the inset shows that the normalized temperature dependence of resonance frequency $f(T)/f(5\,K)$ of the ring resonator, and it shows the same behavior at $T < 0.6T_c$. The rapid shift in the resonance frequency near T_c indicates the effect of Cooper pair breaking. Since the results were obtained from the same sample, the results have to be understood within the scenario in which their only difference stems from the oxygen content of the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ film only. Furthermore, by using Chang's inductive formula [13] and at $T < 0.6T_c$ taking a functional form $(\lambda(5\,K)/\lambda(T))^2 = 1 - (T/T_c)^2$, which has been observed by THz pulse spectroscopy [14], the London penetration depth $\lambda(5\,K)$ for $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin films at 5 K was obtained (see in Table 1). The penetration depth $\lambda(5\,K)$ for $p = 0.212$ is close to that in a single crystal [15]. Then the superfluid density $1/\lambda^2(5\,K)$ was obtained. Fig. 6 shows that the plot of the superfluid density $1/\lambda^2(5\,K)$ vs p for the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ and the $YBa_2Cu_3O_{7-\delta}$ thin films. From Fig. 6, the relation between the superfluid density $1/\lambda^2(5\,K)$ and p do not have the linear property in the underdoped regime, and moreover it does not have this one in the overdoped regime.

Fig. 7 shows T_c vs the superfluid density $1/\lambda^2(5\,K)$ for the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ and the $YBa_2Cu_3O_{7-\delta}$ thin films. For $YBa_2Cu_3O_{7-\delta}$ thin film in the underdoped regime ($0.07 < p < 0.16$), the Umuera relation $1/\lambda^2(5\,K) \propto T_c$ was justified

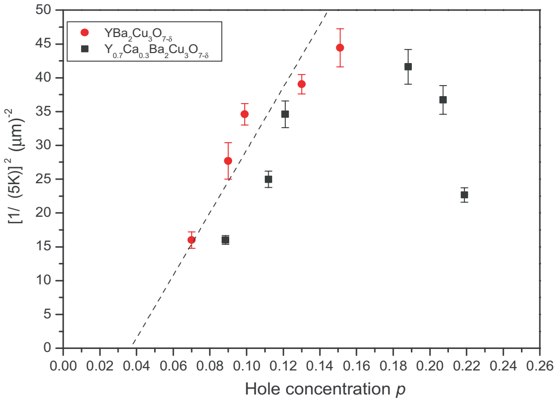

Fig. 6. The $1/\lambda^2(5\,K)$ vs p for the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ and the $YBa_2Cu_3O_{7-\delta}$ thin films. Obviously, for $YBa_2Cu_3O_{7-\delta}$ thin film, it does not depend linearly on p for $0.7 < p < 0.16$.

and this result is against that $1/\lambda^2(5\,K)$ depends linearly on p. For $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film, the typical "boomerang" shaped path was observed and it was indicated by the solid lines, the arrows point towards increasing hole concentrations p. A plateau-like was also observed when p is between 0.121 and 0.188, which corresponding to δ between 0.15 and 0.24. Moreover, for $p = 0.218$ ($\delta = 0.05$) it approaches to the underdoped Uemura line similarly as Kopec's model [16] that in a phase-fluctuation-dominated superconductor a parametric Uemura plot is revealed, which the changeover from the under- to the overdoped regime in high-T_c cuprates is somehow related to the passage from strong to weak coupling. Finally, the Uemura suggestion may relate the Bose Einstein-BCS crossover scenario to the under/overdoped phenomenology of high-T_c superconductors.

In summary, we have performed microwave measurements on epitaxial superconducting $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film deposited on LAO single crystal substrate by PLD technique. We observed that the superfluid density $1/\lambda^2(5\,K)$ is not proportional to hole concentrations p for the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ and the $YBa_2Cu_3O_{7-\delta}$ thin films, instead $1/\lambda^2(5\,K)$ is proportional to T_c. The first complete data for thin films are presented here to test the Uemura relation which may correlate with phase-fluctuation picture.

Acknowledgments

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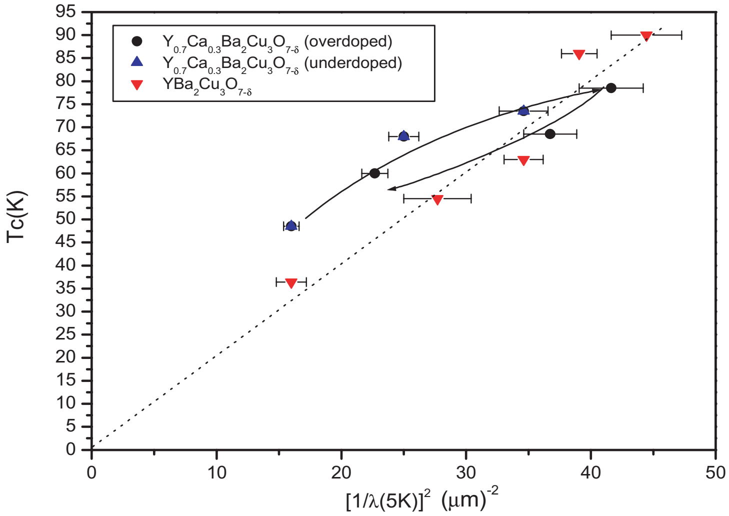

Fig. 7. The T_c vs $1/\lambda^2(5\,K)$ for the $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ and the $YBa_2Cu_3O_{7-\delta}$ thin films. The typical "boomerang" shaped path for $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin film are indicated by the solid lines, the arrows point towards increasing hole concentrations p.

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