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Determination of the doping dependence of the penetration depth using YBCO microstrip ring resonators

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Abstract

We present a method to determine the temperature dependent London penetration depth measured by a microstrip ring resonator for YBCO thin films with various oxygen contents. It allows us to get the following important results of the superconducting properties in the underdoped cuprate superconductors. With increasing δ (e.g. $\delta = 0.05$, 0.2, and 0.4), the superfluid density, $\lambda^2(5\ \mathrm{K})/\lambda^2(T)$, is linear in the low temperature range ($T < T_c/3$), and the slope changes with increasing oxygen deficiency. After the temperature normalization with respect to the critical temperature, the temperature dependence of the superfluid density is shown to be independent of doping concentration. Moreover the maximum energy gap can be estimated from the model of the d-wave pairing. We found that the ratio Δ/T_c is nearly fixed value, 3.0 ± 0.4.

Keywords: YBCO; Penetration depth; Microstrip ring resonator

One of the important issues concerning the fundamental aspects of the high T_c superconductors (HTS) is a full understanding of the influence of the low lying quasiparticle excitations on the superconducting properties in the nodal line of d-wave pairing state. Among many methods, the measurements of ac susceptibility, muon spin relaxation (μSR), and microwave techniques are commonly employed to extract the complementary information of the penetration depth. In particular, the μSR is unique in determining the absolute value of $\lambda(0)$, but is cumbersome in extracting $\lambda(T)$. Microwave resonator technique, on the other hand, is unable to yielding absolute value of $\lambda(0)$, but is one of the most sensitive methods is measuring the change of the penetration depth, $\Delta\lambda$. Because a small shift of resonance frequency, $\Delta f(T)$, due to the variation of $\lambda(T)$, could be measured with high resolution. In this report, nevertheless, we will present a reliable method to get the absolute of $\lambda(T_0)$ and $\lambda(T)$ from the raw data of the resonance frequency shift. Therefore it becomes possible to test different proposed underlying microscopic theories related to the superconducting state in a quantitative manner.

The YBCO thin films were deposited epitaxially on both sides of a 0.5 mm thick $LaAlO_3$ substrate by pulsed laser deposition. The substrate temperature was kept at 830°C with an oxygen partial pressure of 280 mTorr during the deposition. The as-deposited films were all *c*-axis oriented, with a

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typical thickness of 500 nm and T_c of 90 K. One side of the YBCO film was then patterned into a ring oscillator [1]. The line width and the outer radius of the ring are 0.5 and 3.625 mm, respectively.

Since the frequency shift results from a change in the penetration depth of the microstrip ring resonator, its relation in a superconductor strip transmission line can be realized from Chang's inductive formula [2]

$$\frac{f(T)}{f(T_0)} = \frac{\sqrt{1+\frac{2\lambda(T_0)}{d}\left\{\coth\left(\frac{t}{\lambda(T_0)}\right)+g\,\mathrm{csch}\left(\frac{t}{\lambda(T_0)}\right)\right\}}}{\sqrt{1+\frac{2\lambda(T)}{d}\left\{\coth\left(\frac{t}{\lambda(T)}\right)+g\,\mathrm{csch}\left(\frac{t}{\lambda(T)}\right)\right\}}}, \tag{1}$$

where T_0 is an arbitrary temperature (taken as 5 K here), d is the thickness of the dielectric spacer, and t is the film thickness. Due to the complication of electromagnetic field distribution in our system, the thickness of the dielectric space "d" would be replaced by the effective thickness h if the mean radius of the ring is much greater than the strip width. From the modified Eq. (1), we know that once $\lambda(T_0)$ is known, $\lambda(T)$ at any T can be determined accurately from Eq. (1). Adopting the reference value of $\lambda(5\ \mathrm{K})$ in the optimal doping ($\delta = 0.05$) obtained by Tallon et al. [3], we fit the raw data of $f(T)/f(5\ \mathrm{K})$ by Eq. (1) and a generalized two-fluid model equation

$$\lambda(T) = \lambda(5\ \mathrm{K})[1-(T/T_c)^2]^{-1/2}. \tag{2}$$

The best least-squares fit yields $h = d/4$ and $\lambda(5\ \mathrm{K}) = 150$ nm for $\delta = 0.05$ (see Table 1). The optimal value of $\lambda(5\ \mathrm{K})$ is close to that in a single crystal [3]. Using Eq. (1) with the obtained value h and Eq. (2), we can easily get the following results in the underdoped cases.

Table 1
Some parameters for $YB_2C_3O_y$ thin films from microwave measurements

Oxygen content y	T_c (K)	$\lambda(0)$ (nm)	$2\Delta_0/k_BT_c$	$d(\lambda^2(0)/\lambda^2(T))/dT$ (1/K)	α^2
6.95	90.5	150	6.1	1/214	0.40
6.8	83	216	6.5	1/200	0.47
6.6	55	282	5.4	1/85–1/90	0.95–1.07

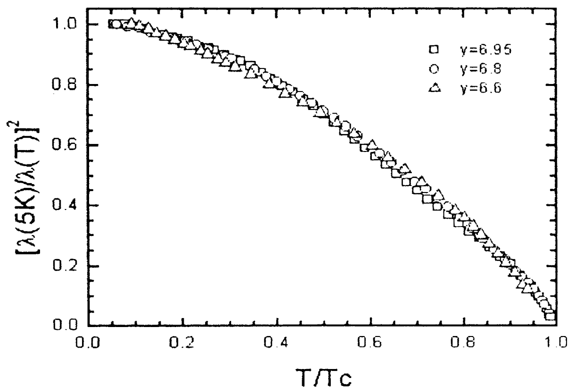

Fig. 1. $\lambda^2(0)/\lambda^2(T)$ vs. reduced temperature T/T_c for $YB_2C_3O_y$ thin films.

Fig. 1 shows the normalized temperature dependence of the $\lambda^2(5\ \mathrm{K})/\lambda^2(T)$, which denotes the superfluid density. It is clearly evident that its dependence is independent of the doping concentrations. In the low temperature regime ($T < T_c/3$), the linear T dependence is also observed, as shown in Fig. 2 while the slope increases as δ increasing. The former reflects a fact that the Cu–O chain in the YBCO material is irrelevant in the consideration of superconductor properties. And the latter will provide a valuable data to estimate the Fermi-liquid correction factor, α, with the measurement

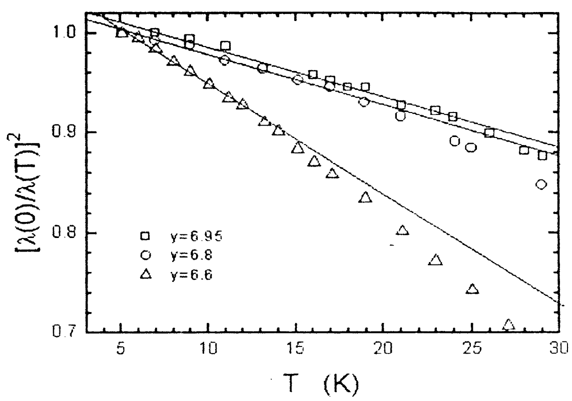

Fig. 2. $\lambda^2(0)/\lambda^2(T)$ vs. temperature ($T < 30$ K) for the $YB_2C_3O_{7-\delta}$ thin films.

of the thermal conductivity. It allows us to test the theoretical model suggested by Lee and Wen [4,5]. Some important findings are listed in Table 1.

In particular, the value of α can be extracted from the data of Fig. 2 and the reference value of the thermal conductivity κ/T [6]. There are two cases presented. One is $\alpha = 1$ and the other $\alpha < 1$. $\alpha < 1$ is in the high T_c phase in the YBCO materials, while $\alpha = 1$ is in the low T_c phase. Following Lee and Wen's model [4,5], the high T_c phase corresponds to the single boson condensation and the low T_c phase to the boson pair condensation.

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