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Temperature dependence of the penetration depth and effective dielectric constant measured by $YBa_2Cu_3O_{7-\delta}$ microstrip ring resonators

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Abstract

$YBa_2Cu_3O_{7-\delta}$(YBCO) superconducting ring resonators with a YBCO ground plane were successfully fabricated using double-side YBCO films deposited on $LaAlO_3$ (LAO) substrates. The temperature dependent London penetration depth, $\Delta\lambda = \lambda(T) - \lambda(5\text{ K})$, was systematically studied by varying the oxygen content of the same resonator structure. For fully oxygenated case ($\delta = 0.05$), the resonator exhibits a quality factor $Q > 10^4$ at 16 K, and $\Delta\lambda(T)$ displays a linear behavior over a wide range of temperatures. With increasing δ (e.g. $\delta = 0.2$, 0.4), although $\Delta\lambda$ is still linear in temperature, the slope changes with increasing oxygen deficiency. The results suggest that, in the underdoped regime, the inelastic scattering of charged carriers may become increasingly prominent. From the effective dielectric constant obtained from the ring resonator the dielectric constant of the LAO substrate was estimated to be $\varepsilon_r \cong 25.5$ at 5 K and a frequency of about 3.6 GHz. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

One of the important issues concerning the fundamental aspects of the high-T_c superconductors (HTS) is the understanding of the low-lying excitations in the pairing state, and how they are influenced by phonon contributions. However, the short coherence lengths of HTS have hindered the direct probe of the superconducting pairing state by traditional experimental techniques, such as superconductor–insulator–superconductor (SIS) tunneling junctions. Recently, measurements of the temperature dependence of the penetration depth are beginning to yield a consistent picture of the pairing state of the HTS materials. Among the many methods, the measurements of the a.c. susceptibility [1], muon spin relaxation (μSR) [2], and microwave techniques are commonly employed to extract the complementary information of the penetration depth [3–7]. 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

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sensitive methods in measuring the change of the penetration depth, $\Delta\lambda$. A small shift of resonance frequency, $\Delta f(T)$, due to the variation in $\lambda(T)$, could be measured with high resolution. Moreover, due to the technological demand, microstrip line circuits made of HTS have become important realistic applications of these materials [8,9]. Consequently, in addition to their superior performance as microwave devices, these structures are also playing essential roles for investigating important characteristics of the penetration depth of HTS materials at such frequencies.

For d-wave pairing states, due to the existence of the line nodes in the gap order parameter, $\lambda(T)$ is expected to exhibit a linear temperature dependence at low temperatures [3–5]. Nonetheless, in extreme dirty limit, impurity defects can change the temperature dependence of $\lambda(T)$ from T to T^2. The effects of oxygen content are very dramatic on the superconducting properties of YBCO. For instance, it is believed that the peculiar T_c plateaus, observed immediately after the discovery of YBCO, are due to the oxygen deficiency on the Cu–O chains [10]. As a consequence, there have been tremendous efforts devoted to investigate many of the fundamental physical parameters as a function of oxygen content in such a way that their implications for the superconductivity mechanisms can be correlated.

In this study, the London penetration depth of YBCO films is measured by using high-Q ring resonators made of double-sided YBCO films in the microwave range. The ring structure with its unique geometrical configuration has the advantage of minimizing the edge effects commonly suffered in strip line structures. We believe that the merit would further provide an unambiguous result in our following work. On the one hand, the structure allows one to determine effective dielectric constant of the resonator structure, which in turn can be used to determine the dielectric constant of the substrate at microwave frequencies by analyzing the fundamental mode of the standing wave. On the other hand, by controlling the oxygen content in a reversible manner over the same oscillator, the effect of the pseudogap opening on the temperature dependent behavior of penetration depth, $\Delta\lambda = \lambda(T) - \lambda(5\ \mathrm{K})$, is revealed.

2. Experimental

The YBCO thin films were deposited epitaxially on both sides of a 0.5 mm thick $LaAlO_3$ (LAO) 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 typical thickness of 500 nm and T_c of 90 K. One side of the YBCO film was then patterned into a ring oscillator [11], as depicted schematically in Fig. 1. The line width and the outer radius of the ring are 0.5 and 3.625 mm, respectively. The coupling gap between the microstrip feeding line and the ring resonator is about 0.4 mm. The main difficulty for double side deposition was the contact between the substrate and the heater, which has been solved by inserting a thin Si wafer between the substrate and the heater. This effectively prevents the backside of the polished substrates as well as the first film from contamination during each deposition run.

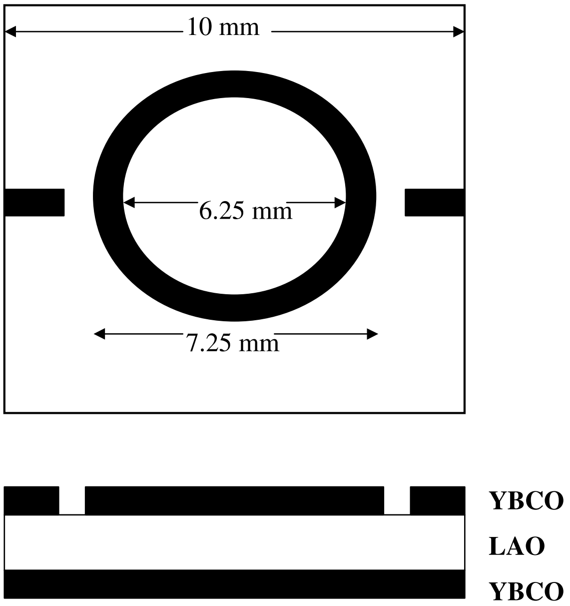

Fig. 1. The schematics of the ring-shaped microstrip resonator made of double-sided YBCO thin films adopted for surface impedance measurements.

To obtain the desired oxygen content of the YBCO films, the sample was put in a YBCO bulk housing and the whole assembly was situated in an oxygen annealing chamber. The oxygen pressure and the corresponding temperature were then carefully monitored following the pressure–temperature phase diagram established for YBCO system [12]. This process had been confirmed to be capable of obtaining designated oxygen content of YBCO films in a controllable and reversible manner [13].

The microstrip ring resonator was put into a gold-coated aluminum device housing, with SMA connectors. The package was placed in a vacuum tube and immersed in liquid He. We used a Lake Shore 330 autotune temperature controller to control the temperature of the sample space to better than 0.1 K. The temperature dependence of the resonance frequency $f(T)$, frequency shifts $\Delta f(T)$ and the forward transmission coefficient S_{21} were measured by a HP8510C microwave vector network analyzer at frequency about 3.6 GHz.

The temperature dependence of the real and imaginary parts of the surface impedance, $Z_s = R_s + iX_s$, were then determined with the aid of the following equations: $R_s = \Gamma_s/Q_u$ and $\Delta X_s = 2\Gamma_s \Delta f/f$, respectively [14]. Where R_s is the surface resistance and ΔX_s is the change in the surface reactance, Γ_s ($\approx \pi\mu_0 df$) is a geometrical form factor and d is the thickness of the dielectric spacer [15], the unloaded quality factor, $Q_u(T)$, is defined as $Q_u = f/(1 - S_{21})\delta f)$, where δf is the resonator bandwidth at -3 dB and S_{21} is the forward transmission coefficient, it is a measure of the sharpness of the response of the resonator to external excitation.

3. Results and discussion

Fig. 2 shows the temperature dependence of the unloaded quality factor, Q_u, of the same YBCO ring resonator with $\delta = 0.05$, 0.2 and 0.4, respectively. It is evident that, for $\delta = 0.05$, the quality factor reaches a value over 10^4 at lower temperatures. This value is compatible with that of the best microstrip resonators [16]. As the oxygen content decreases, the low-temperature Q_u value drops by about 30%. The other feature is that the $Q_u(T)$ displays a linear dependence over a wide range of temperatures for $\delta = 0.05$ and 0.2. As will be seen later, this implies a linear $\lambda(T)$ over a temperature range well beyond $T_c/2$. This unusual behavior, nonetheless, has changed with further decreasing of oxygen content, namely for $\delta = 0.4$.

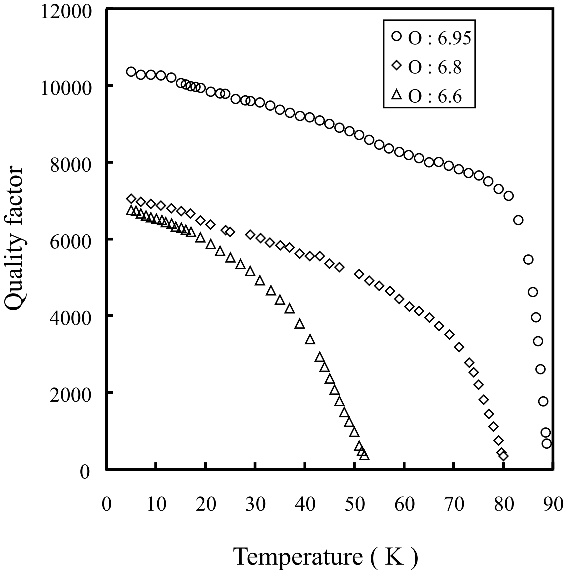

Fig. 2. The temperature dependence of the unloaded quality factor of the same ring resonator measured at $\delta = 0.05$, 0.2 and 0.4, respectively.

Fig. 3(a) shows the temperature dependence of resonance frequency $f(T)$ of the same ring oscillator for $\delta = 0.05$, 0.2 and 0.4, respectively. The rapid shift in the resonance frequency near T_c indicates the effect of Cooper pair breaking. Again it is apparent that the $f(T)$ of the $\delta = 0.4$ case is drastically different from that of the other two cases. Since the results were obtained from the same sample, the current results have to be understood within the scenario that their only difference is the oxygen content of the YBCO films. We shall come back to this point later.

Practically, the resonance frequencies of the current device structure also serves as a viable tool for measuring the temperature dependence of the effective dielectric constant of the ring resonator. The oscillation modes of the present ring resonator

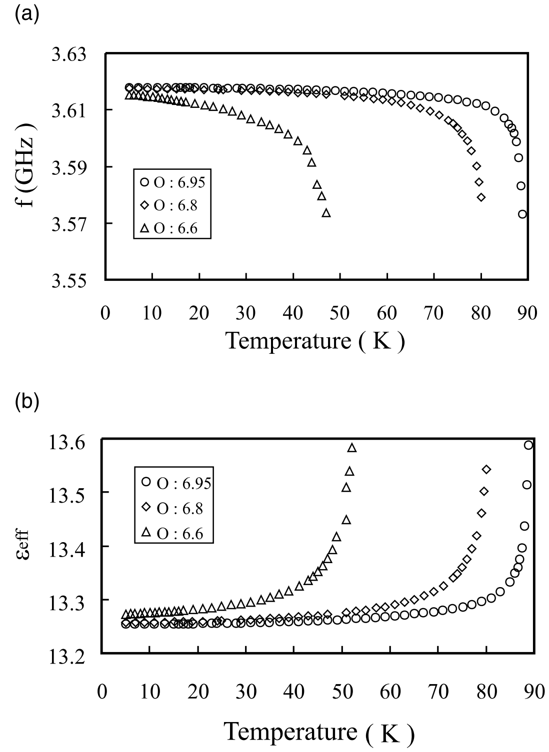

Fig. 3. (a) The temperature dependence of resonance frequency $f(T)$ of the same ring resonator for $\delta = 0.05$, 0.2 and 0.4, respectively. (b) The results of $\varepsilon_{\rm eff}$ obtained from Fig. 3(a).

have a field distribution similar to the quasi-TEM mode of the microstrip line [17]. The existence of E_z modes have a pure longitudinal electric field and the magnetic field is perpendicular to the z-axis. A solution to the Maxwell's equations of the problem is

$$\begin{aligned} E_z &= [AJ_n(kr) + BN_n(kr)]\cos(n\phi), \\ H_r &= \left(\frac{n}{\mathrm{j}\omega\mu_0 r}\right)[AJ_n(kr) + BN_n(kr)]\sin(n\phi), \\ H_\phi &= \left(\frac{k}{\mathrm{j}\omega\mu_0}\right)[AJ'_n(kr) + BN'_n(kr)]\cos(n\phi), \end{aligned} \tag{1}$$

where $k = \omega\sqrt{\varepsilon_0\varepsilon_{\rm eff}\mu_0}$ is the wave number, J_n is a Bessel function of first kind and order n, N_n is a Bessel function of second kind and order n. The J'_n and N'_n are the derivatives of the functions. The eigenvalue equation of the resonator resulting from the boundary conditions is

$$\frac{J'_n(kr_{\rm i})}{J'_n(kr_{\rm o})} - \frac{N'_n(kr_{\rm i})}{N'_n(kr_{\rm o})} = 0, \tag{2}$$

where $r_{\rm o}$ is the outer radius and $r_{\rm i}$ the inner radius of the ring resonator. The existence of the Meissner effect implies that the magnetic field is exponentially screened from the interior of a sample with penetration depth, λ. Since the outer radius, $r_{\rm o}$, of the ring is much greater than λ, one can neglect the curvature effects and obtain a result of $2\pi r_{\rm o} \cong n\lambda_{\rm g}$ from Eq. (2), where $\lambda_{\rm g}$ is the wavelength in the ring resonator and n is arbitrary integer. It turns out that the ring resonator can serve as a convenient probe for obtaining the effective dielectric constant, $\varepsilon_{\rm eff}$, of microstrip ring resonator at the first resonance frequency, $n = 1$, from $\varepsilon_{\rm eff}(T) \cong [c/2\pi r_{\rm o} f(T)]^2$. Fig. 3(b) shows the results of $\varepsilon_{\rm eff}(T)$ for the ring resonator with $\delta = 0.05$, 0.2 and 0.4. It is evident that at the microwave frequencies the effective dielectric constant of the resonator has a value around 13.25 at 5 K in all cases with a smooth temperature dependence for $T < T_{\rm c}$. If we have the solution [18] of

$$\varepsilon_{\rm eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12d/\lambda}}, \tag{3}$$

then when $r_{\rm o} > d \gg \lambda$ (as in our case), it is straightforward to estimate the substrate dielectric constant $\varepsilon_{\rm r}$ from the measurement of $\varepsilon_{\rm eff}$. In our case, a $\varepsilon_{\rm r} \cong 25.5$ for LAO is obtained. It is very close to the value reported for LAO substrate. The removal of oxygen from the Cu–O chains appears to have only slight effect on the effective dielectric constant of the system when YBCO becomes superconducting.

By analyzing the frequency shift as a function of temperature, the temperature dependence of the London penetration depth can be extracted from the surface impedance. In the local limit, the surface impedance can be expressed as $Z_{\rm s} = R_{\rm s} + {\rm i}X_{\rm s}$. Here $R_{\rm s}$ is the surface resistance originated from the inelastic scattering between quasiparticles and various types of defects and $X_{\rm s}$ is the reactance reflecting the nondissipative energy stored in the superconductor. In the local limit, where $X_{\rm s} \gg R_{\rm s}$, the change in penetration depth $\Delta\lambda(T)$, defined as $\Delta\lambda(T) \equiv \lambda(T) - \lambda(T_0)$, can be further reduced to $\Delta\lambda(T) = [X_{\rm s}(T) - X_{\rm s}(T_0)]/\omega\mu_0$. We took $T_0 = 5$ K for simplicity. Fig. 4 shows $\Delta\lambda(T)$ as a function of oxygen content. It is noted that for $\delta = 0.05$, the linear dependence of $\Delta\lambda(T)$ extends over almost entire temperature range measured. Within the scenario of d-wave pairing, this would imply that the line node feature of the gap order parameter could persist to temperatures near T_c. We also note that the temperature dependence of $\Delta\lambda(T)$ (see the inset in Fig. 4) has a slope of 2.1 Å/K, which is about 50% smaller than the measurements in pure YBCO single crystals [7], but is very close to that found in the very recent results reported by Farber et al. [5]. Following the prediction from the model of d-wave superconductor with line nodes in order parameter, the linear $\Delta\lambda(T)$ is understood from the following expression:

$$\Delta\lambda(T) \cong \left[\frac{\lambda(0)\ln 2}{\Delta(0)}\right]T, \tag{4}$$

where $\Delta(0)$ is the d-wave gap value at zero temperature [3–5]. Thus the smaller value of $\Delta\lambda(T)$ slope would imply either a larger gap value or a smaller $\lambda(0)$ within the framework of d-wave pairing [4]. For thin films, as observed here and by Farber et al. [5], it is unlikely that one would have a smaller $\lambda(0)$ than that of a single crystal. Thus, we are left with a possible enhancement of $\Delta(0)$ for films. Since films are microstructurally consisted of a number of crystalline grains, the observed enhancement might have been a consequence of statistical average or reducing geometric from factor [14]. Another possible origin of the enhanced gap value is the effect of microwave enhancement of superconductivity at our frequency range (3.6 GHz). Hall et al. had observed a 100% enhancement in the energy gap of Al films when irradiated with microwaves at frequency range 2–4 GHz [19]. Moreover, if we stay with the d-wave interpretation, then in the case of $\delta = 0.2$ one would reach the following conclusions. Firstly, the characteristic of the d-wave pairing does not change significantly with moderate changes in decreasing hole concentration with reducing oxygen content. Secondly, the increase in the slope of $\Delta\lambda(T)$ with decreasing oxygen stoichiometry may result from either an increase in $\lambda(0)$ or a decrease in $\Delta(0)$, or even a combination of both.

On the other hand, for $\delta = 0.4$, the behavior of $\Delta\lambda(T)$ has changed from T to T^2 dependence as is evident in Fig. 5. Within the same d-wave pairing scenario, an even larger suppression of T_c due to tremendous increase in oxygen defect level would

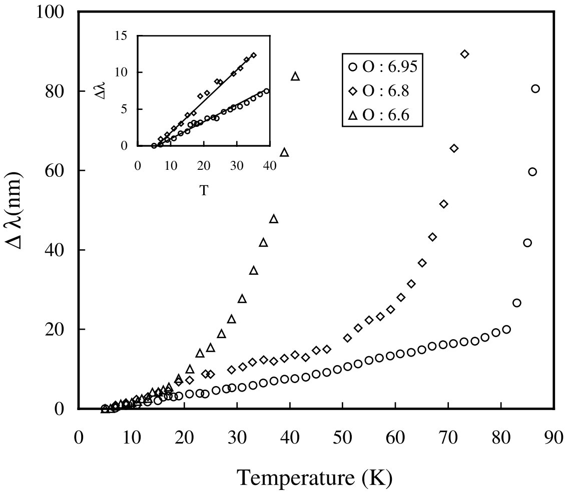

Fig. 4. The temperature dependence of $\Delta\lambda(T)$ as a function of oxygen content. The inset shows the linear temperature dependence of the $\Delta\lambda(T)$ with a slope of 2.1 Å/K and 4.5 Å/K at $\delta = 0.05$ and 0.2, respectively.

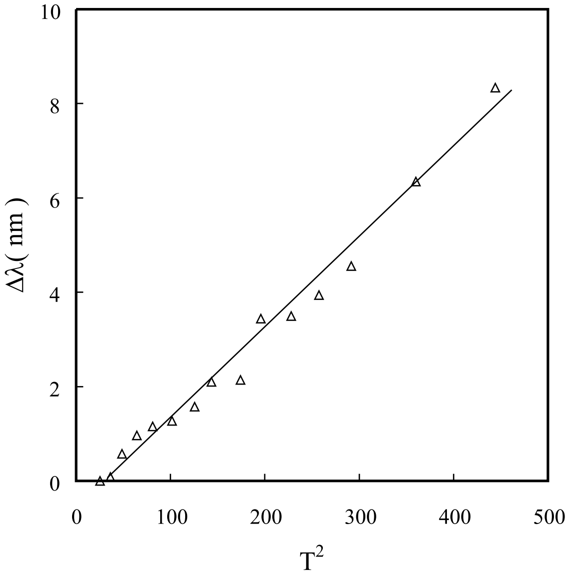

Fig. 5. The behavior of $\Delta\lambda(T)$has a T^2 dependence at $\delta = 0.4$.

be required to produce a T^2 dependence in $\Delta\lambda(T)$ [7]. We argue that this is unlikely in the present case, since the oxygen controlling process is completely reversible, indicating no microstructural changes other than oxygen content was occurring during the process [13]. Thus, it seems that a pure d-wave pairing picture may be inadequate to reconcile the evolving changes in $\Delta\lambda(T)$ (including the slope changes and even the temperature dependence) with the reducing oxygen content obtained in the same YBCO films. Alternatively, the results may be due to the opening of pseudogap in the underdoped regime, which is known to enhance the inelastic scattering of carriers, in addition to reducing its density, significantly [20]. However, since the theoretical treatments of the pseudogap effects are still in progress, no quantitative comparisons are made at present. In any case, we note that the results presented above were obtained from a single YBCO ring resonator with oxygen content as the only changing parameter. Thus, any satisfactory theoretical interpretation should take this into account.

4. Summary

The temperature and oxygen stoichiometry dependencies of the London penetration depth of the YBCO superconducting thin films were studied by using a ring resonator. It was observed that for $\delta = 0.05$ and 0.2 (in $YBa_2Cu_3O_{7-\delta}$), $\Delta\lambda(T)$ is linear over a wide temperature range. The results though can be interpreted consistently with the framework of d-wave pairing symmetry for its linearity, there exist several points to be clarified. The slope of 2.1 Å/K implies the magnitude of the gap for YBCO films is twice as large as that of single crystals, which is not straightforwardly conceivable. The changes in the slope of $\Delta\lambda(T)$ and even its functional form of temperature dependence (i.e. from T to T^2 dependence) with reducing oxygen content are not easy to be reconciled by d-wave pairing alone. It is believed that as the material is in underdoped state the effects of pseudogap on the inelastic scattering of quasiparticles may become more prominent and, thus, changes behaviors of $\Delta\lambda(T)$. Finally, it was found that the superconducting microstrip ring resonator can be used as an effective tool for measuring the dielectric constant of the substrate.

Acknowledgements

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