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Temperature dependence of superfluid density in $YBa_2Cu_3O_{7-\delta}$ and $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin films: A doping dependence study of the linear slope

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Abstract

By using a microstrip ring resonator to measure the temperature dependence of the in-plane magnetic penetration depth $\lambda(T)$ in $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ (Ca-YBCO) epitaxially grown thin films, the linear temperature dependence of the superfluid density $\rho_s/m* \equiv 1/\lambda^2(T)$ was observed from the under- to the overdoped regime at the temperatures below $\frac{T}{T_c} \approx 0.3$. For the underdoped regime of YBCO and Ca-YBCO thin films, the magnitude of the slope $\mathrm{d}(1/\lambda^2(T))/\mathrm{d}T$ is insensitive to doping, and it can be treated in the framework of projected d-density-wave model. Combining these slope values with the thermal conductivity measurements, the Fermi-liquid correction factor α^2 from the Fermi-liquid model, suggested by Wen and Lee, was revealed here with various doping levels.

Keywords: Magnetic penetration depth; Superfluid density

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1. Introduction

To understand the mechanism of the Cooper-pair formation in the high-T_c cuprate superconductors, one often deals with the problem of doping a Mott insulator at first [1]. Understanding the manner in which superconducting order gives way to the antiferromagnetic insulator at half filling would provide important clues to elucidate the mechanism of Cooper formation in the high-T_c cuprates superconductors [2,3]. Despite years of intense research, these high-T_c copper-oxide superconductors are still on the list of great mysterious of physics. Therefore, from the empirical standpoint to find somewhat universal trends and correlations amongst physical quantities may provide a

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clue to the origin of the superconductivity. So far, there are still some consensus in the scientific viewpoints between theoretical and experimental works in this respect. These cuprates which have the low hole concentrations p (significantly so-called "underdoped" cuprates) possess many of the most of enigmatic and mysterious experimental properties. In particular, the underdoped cuprates possess a "pseudogap" Δ_p in the single-particle excitation spectrum that persists above T_c [4], and as p is reduced, Δ_p grows while the zero-temperature superfluid stiffness $\rho_s(0)$ and transition temperature T_c decrease [5]. We note that a d-density wave model (DDW) [6,7] have been presented to illustrate why $T_c(p)$ is to trace out the familiar "superconducting dome" in the doping-temperature phase diagram of the cuprates, which originates from the competition between the DDW order parameter and the superconducting order parameter. On the other hand, another pseudogap theory was set forward by Lee and Wen [8,9] based on the Fermi-liquid-described superconductivity along the lines of a phenomenology. Their point of view is that the well defined quasiparticles (low-lying excitations) can be described in terms of Fermi-liquid theory (conventional BCS theory). They also introduced a Fermi-liquid correction factor α^2 to explain and fit the linear temperature dependence of the superfluid density $\rho_s(T)$. The justification of the Lee and Wen's model or the DDW model can be inferred from the evidences in p and T dependences of the superfluid density $\rho_s(T,p)$ of variously underdoepd cuprates in the experiment directly.

In this report, we attempt to enlighten the issue which is at the heart of the nature of quasiparticles in cuprates; that is, whether the quasiparticle is Fermi-liquid described by conventional BCS theory or comes from the "d-density-wave" order, questions of considerable debate in the recent literature. The importance of $1/\lambda^2(T)$ to an understanding of cuprate superconductivity derives from the early observation of a linear T suppression of $1/\lambda^2(T)$, since this is explained most naturally by the thermal excitations of quasiparticles near the nodes of a d-wave superconducting gap, as in Lee and Wen's model. Then, the Fermi-liquid correction factor α^2 from the model was revealed here to be nearly independent of doping as $0.12 < p \leqslant 0.16$ in the underdoped regime of YBCO thin film, which is consistent with theoretical prediction. But out of this doping range, α^2 is more or less sensitive to hole concentration p. At last, for YBCO and Ca-YBCO thin films in the underdoped regime ($p \leqslant 0.16$), the magnitude of the initial slope of $1/\lambda^2(T)$ versus p can be treated in the framework of projected *d*-density-wave model. However, in the overdoped regime, its behavior is far away from this model.

2. Experimental

The same high quality YBCO and Ca-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 790 °C for YBCO film and at 760 °C for Ca-YBCO film with the same oxygen partial pressure of 0.3 Torr during the deposition. The as-deposited films were all *c*-axis oriented, with a typical thickness of 500 nm and T_c of 91 K for YBCO film and T_c of 60 K for Ca-YBCO film. One side of the double-sided samples (for YBCO and Ca-YBCO films) was then patterned into a ring resonator [10]. The line width and the outer radius of the ring are 0.5 and 3.625 mm, respectively.

The desired oxygen contents of the two samples were obtained by controlling the oxygen pressure and the corresponding temperature carefully which follows the pressure–temperature phase diagram established for YBCO system [11]. This process had been verified to be capable of obtaining designated oxygen content (in comparison with T_c in YBCO bulk) of YBCO films in a controllable and reversible manner. By using this method, we can control the oxygen content of the YBCO film and Ca-YBCO film in the same oxygen content precisely and reversibly [12]. We emphasize here that each set of results reported in this paper, either the temperature dependence of the superfluid density $1/\lambda^2(T)$ or other physical properties, was obtained from a single film subject to repeated cycles of treatment. Consequently, possible complications that may arise from individual film microstructures are minimized and the changes in

Table 1
Some parameters for YBCO and Ca-YBCO thin films are obtained from microwave measurements

Material	T_c (K)	Hole concentrations p	λ (5 K) nm	$-\mathrm{d}(1/\lambda^2(T))/\mathrm{d}T$ (μm^{-2} K^{-1})	v_F/v_2 ([a])	α^2
YBCO	91	0.160	145	0.158	11.5	0.469
YBCO	90	0.148	150	0.147	11.1	0.452
YBCO	86	0.134	160	0.148	10.6	0.476
YBCO	63	0.098	170	0.172	9.4	0.625
YBCO	54.5	0.090	190	0.198	9.1	0.743
YBCO	36.4	0.074	265	0.199	8.5	0.799
Ca-YBCO	60	0.218	210	0.128	23.1	0.189
Ca-YBCO	68.5	0.207	165	0.163	20.9	0.266
Ca-YBCO	78.5	0.188	155	0.165	17.1	0.329
Ca-YBCO	73.5	0.121	170	0.172	10.1	0.581
Ca-YBCO	68	0.111	200	0.169	9.8	0.589
Ca-YBCO	48.5	0.088	250	0.178	9.0	0.675

[a] The v_F/v_2 values are taken from thermal conductivity measurements in Ref. [16].

physical properties presented below should be due mainly to the effects associated with the oxygen content of the film. In order to get the hole concentration p, then 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 Ca-YBCO film and $T_{c,\max} = 91$ K for YBCO film which has been reported previously [13,14]. Then various hole concentrations p were determined (see Table 1).

3. Results and discussion

We have measured the temperature dependence of in-plane magnetic penetration depth $\lambda(T)$ of YBCO and Ca-YBCO thin films using microstrip ring resonators [10,15]. The superfluid density $\rho_s(T)$ is inversely proportional to the square of the in-plane magnetic penetration depth $\lambda(T)$. Figs. 1 and 2 show the temperature dependence of $1/\lambda^2(T)$ with various T_c by controlling oxygen content for the YBCO and Ca-YBCO films at $T < 35$ K. We pointed out that the ratio of linear decrease of $1/\lambda^2(T)$ with temperature (which was the earlier experimental evidence for d-wave symmetry), listed in Table 1, maintains its magnitude between 0.15 and 0.20 ($0.074 \leqslant p \leqslant 0.207$) for YBCO and Ca-YBCO thin films.

Lee and Wen [8] have argued that the linear decrease of $1/\lambda^2(T)$ with temperature is caused by the thermal excitation of quasiparticles near the nodes and is an electromagnetic response function of these quasiparticles. Based on BCS theory, it was pointed out that the electromagnetic response consists of two parts, the diamagnetic current and the paramagnetic current. The physical origin of the paramagnetic current is a perturbative response of the excited quasiparticles. Due to the absence of the Meissner effect in the normal state, the paramagnetic current cancels the diamagnetic current at $T \geqslant T_c$. The key to their argument is the assumption that the current carried by each quasiparticle is $\alpha e v_F$ [9], where v_F is the quasiparticle velocity normal to the Fermi surface at the node

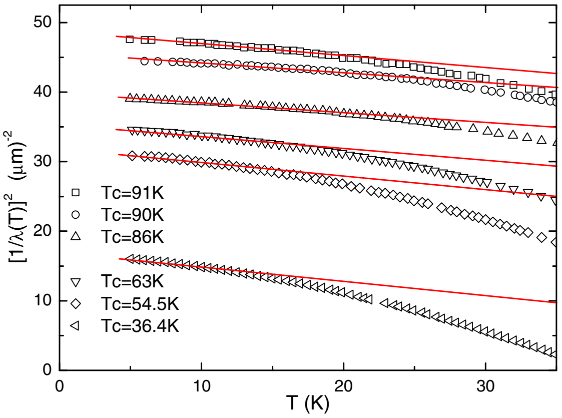

Fig. 1. The temperature dependence of $1/\lambda^2(T)$ with various T_c by controlling oxygen content for the same YBCO film at $T < 35$ K.

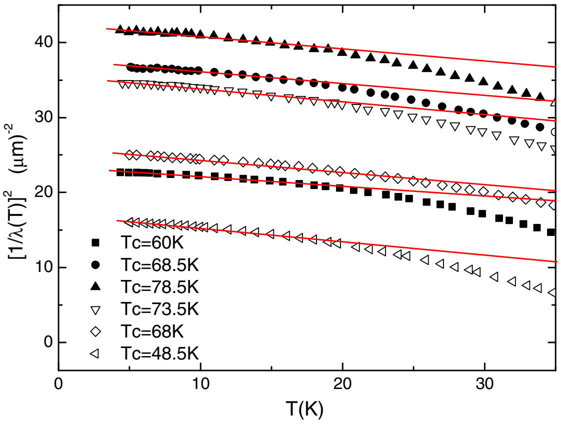

Fig. 2. The temperature dependence of $1/\lambda^2(T)$ with various T_c by controlling oxygen content for the same Ca-YBCO film at $T < 35$ K.

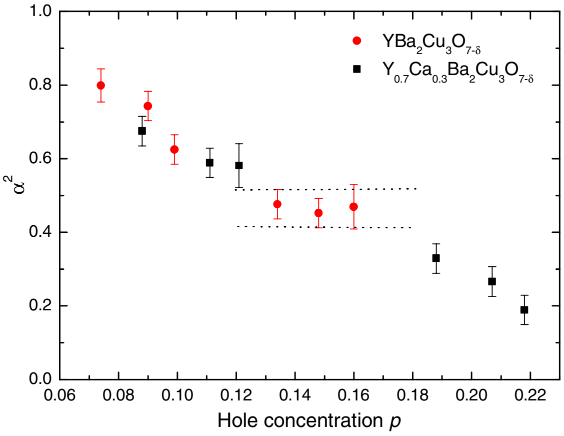

Fig. 3. The Fermi-liquid correction factor α^2 versus p for the YBCO and Ca-YBCO films. Error bars correspond to experimental accuracy.

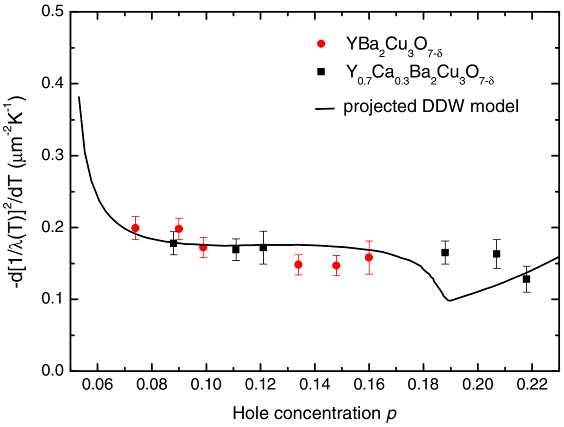

Fig. 4. The doping dependence of the $-\mathrm{d}[1/\lambda^2(T)]/\mathrm{d}T$ with various hole concentrations p for the YBCO and Ca-YBCO films. Error bars correspond to experimental accuracy. The solid line agrees with the behavior of this quantity in the projected DDW model.

and α is a Fermi-liquid parameter inherited from the normal state. The slope of $1/\lambda^2(T)$ versus T is proportional to two factors, α^2 and v_F/v_2, where v_2 is the quasiparticle velocity tangential to the Fermi surface at the node. The thermal conductivity (κ) measurements have reported the values of v_F/v_2 with various doping levels using the residual term of thermal conductivity divided by temperature, κ_0/T [16]. Hence the Fermi-liquid correction factor α^2 can be extracted from the measurements of linear T-dependence of $1/\lambda^2(T)$ and v_F/v_2. The importance of α^2 can help us to elucidate the nature of quasiparticles in cuprates; that is whether they are Fermi-liquid or not. Fig. 3 shows the Fermi-liquid correction factor α^2 versus p for the YBCO and Ca-YBCO films. In the underdoped regime, $\alpha^2 \approx 0.4 \sim 0.5$ as $0.12 < p \leqslant 0.16$, $\alpha^2 \approx 0.5 \sim 0.6$ as $0.10 < p \leqslant 0.12$, and $\alpha^2 \approx 0.6 \sim 0.7$ as $p \simeq 0.09$ are consistent with Sutherland et al. results [16]. Our experimental results show that α^2 is nearly independent of doping as $0.12 < p \leqslant 0.16$, which is consistently with Lee and Wen's model. But as $p \leqslant 0.12$, α^2 is more or less dependent on doping, which may reveal that the nature of quasiparticles in cuprates may not be described by conventional Fermi-liquid. Moreover, in the overdoped regime, α^2 decreases steadily with increasing p ($\alpha^2 < 0.4$).

In Fig. 4, we show the linear slope $-\mathrm{d}(1/\lambda^2(T))/\mathrm{d}T \propto |\mathrm{d}\rho_s(T)/\mathrm{d}T|$ of $1/\lambda^2(T)$ curves obtained from $\lambda(T)$ measurement at the temperatures below $\frac{T}{T_c} \approx 0.3$. The value of $-\mathrm{d}(1/\lambda^2(T))/\mathrm{d}T$ changes slightly with all doping levels. In fact, its value becomes a little large for YBCO thin film at $p < 0.09$; particularly, the $1/\lambda^2(T)$ slope increases 1.3 times with p decreasing from 0.16 to 0.074. The solid line is the projected DDW prediction and it fits the data roughly at $0.074 \leqslant p \leqslant 0.16$ for YBCO and Ca-YBCO films by using the same parameters in Ref. [6]. It should be noted that the theoretical prediction $d\rho_s(T)/dT$ is dimensionless, so we produce theoretical prediction $d\rho_s(T)/dT$ with a factor $\frac{1}{c_1}$ in order to match the order of magnitude of $-d(1/\lambda^2(T))/dT$ measured by experiments. We take the constant $c_1 = 4.8$ here. No matter what, the experimental data in Fig. 4 qualitatively agrees with the behaviors of these quantities in the projected DDW model [6] (solid line) at $p \leqslant 0.16$, but in overdoped regime the $-d(1/\lambda^2(T))/dT$ behavior disagrees with the one of projected DDW model.

4. Summary

We study the low-temperature dependence down to 5 K of the superfluid density $1/\lambda^2(T)$ of the $YBa_2Cu_3O_{7-\delta}$ and $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ thin films, which the two samples were controlled with various oxygen contents in varying doping levels from the under- to the overdoped regime. In agreement with previous studies, the samples display a predominantly linear dependence, $\lambda^{-2}(5K) - \lambda^{-2}(T) \propto T$, below $\frac{T}{T_c} \approx 0.3$, which gives evidence of thermally excited BCS-like quasiparticels near the nodes in *d*-wave gap, as in Lee and Wen's model. Then, the Fermi-liquid correction factor α^2 from the model was revealed here to be nearly independent of doping as $0.12 < p \leqslant 0.16$ in the underdoped regime of YBCO thin film, which is consistent with theoretical prediction. But out of this doping range, α^2 is more or less sensitive to doping levels p. The experimental results also show that the magnitude of the initial slope of $1/\lambda^2(T)$ is insensitive to doping in the underdoped regime of YBCO and Ca-YBCO thin films, and it can be treated in the framework of projected d-density-wave model. However, in the overdoped regime, its behavior is far away from this model.

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