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Critical fluctuations and phase diagram of $La_{2-x}Sr_xCuO_4$ thin films

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ABSTRACT

We present a systematic study of the critical fluctuations of the superconducting to the normal-state transition of $La_{2-x}Sr_xCuO_4$ (LSCO) thin films with a wide range of hole concentrations ($x = 0.07$–0.20), which are probed by the frequency-dependent complex conductivity measurements and their dynamic scaling analyses. Our results clearly indicate that the critical dynamics of LSCO is essentially two-dimensional, except for the 3D-*XY* critical dynamics observed only near the optimally doped region. We argue possible origin of the anomalous dimensional crossovers with hole doping, including an implication of a hidden quantum critical point near the optimally doped region.

1. Introduction

One of the unresolved issues in the high-T_c cuprates is the strong doping dependence of the critical temperature, T_c. As well known, a plot of T_c versus the carrier doping forms a bell-shaped superconducting dome with two quantum critical points (QCPs) at both endpoints. Some theoretical models consider that the bell-shaped phase diagram is related to another QCP, which is assumed to be hidden between two well established QCPs [1,2]. In other models, the strong doping dependence of T_c is explained by a different concept from the quantum criticality, for instance, the gauge field fluctuations in the *t*–*J* model [3] or the classical phase fluctuations of the superconducting orders, which are assumed to survive even in the pseudogap region in the underdoped region [4]. Thus, it is quite important to investigate the possibility of a hidden quantum phase transition, in order to settle this issue. Although several experiments have suggested the existence of such a hidden QCP, their interpretation is still debated [5].

As a new route to resolve this issue, we focus on the critical charge dynamics in the superconducting to the normal-state transition across the phase diagram. If there is no hidden QCP in the phase diagram, the critical dynamics should be basically universal, except for the neighborhood of two well established QCPs. On the other hand, if there is a hidden QCP, the critical dynamics may be affected by the quantum fluctuation around the hidden QCP.

In this paper, we present the systematic investigations of the frequency-dependent complex conductivity, $\sigma(\omega) = \sigma_1(\omega) - i\sigma_2(\omega)$, and their dynamic scaling analyses for $La_{2-x}Sr_xCuO_4$ (LSCO) thin films with a wide range of hole concentrations ($x = 0.07$–0.20). Surprisingly, we found that the critical charge dynamics of the LSCO system was changed twice with hole doping. We also investigated the finite size effects by applying small finite magnetic fields, and confirmed that the observed change of the universality class is never induced by the finite size effect [6]. Together with our previous study [7], we discuss a whole picture of the critical charge dynamics in the phase diagram of LSCO in terms of various proposed models.

2. Experimental

Epitaxial LSCO thin films were grown on $LaSrAlO_4$ (001) (LSAO) substrates by a pulsed laser deposition technique. Details of the growth condition were described elsewhere [8]. All films were carefully annealed to remove oxygen deficiencies. We confirmed that the LSCO thin films used in this study were of sufficiently high quality to investigate the critical phenomenon near T_c experimentally, through the results of the in-plane dc resistivity and the X-ray diffraction for each film [6]. As was already pointed out [7], the use of LSAO substrate prevents the corrugation in the

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CuO_2 plane, which is attributed to a staggered rotation of CuO_6 octahedra in low-temperature orthorhombic (LTO) phase of bulk LSCO. Thus, we can expect that ideal flat square CuO_2 planes, which are free from disorders, are realized in LSCO films on LSAO substrate.

As shown in Fig. 1, both the real and imaginary parts of $\sigma(\omega)$ were obtained from the complex reflection coefficient, $S_{11}(\omega)$, using a non-resonant broadband technique [9]. When the film thickness, t, is sufficiently smaller than the skin depth, $\sigma(\omega)$ is given as follows:

$$\sigma(\omega) = \frac{1}{tZ_0}\frac{1 - S_{11}(\omega)}{1 + S_{11}(\omega)}, \tag{1}$$

where t and $Z_0 = 377\ \Omega$ are the film thickness and the impedance of free space, respectively.

The critical behaviors near T_c were analyzed by using a general formulation of the dynamic scaling hypothesis for the frequency-dependent complex fluctuation conductivity, $\sigma_{fl}(\omega)$, as follows [10]:

$$\sigma_{fl}(\omega) \approx \xi^{z+2-d} S(\omega\xi^z), \tag{2}$$

where ξ is a correlation length which diverges at T_c, $S(x)$ is a complex universal scaling function, d is a spatial dimension, and z is a dynamic critical exponent, respectively. As was emphasized in our papers [6,7], the most important part of our analyses is that we can check the validity of the dynamic scaling hypothesis, by measuring $\sigma_{fl}(\omega)$. We used both the magnitude, $|\sigma_{fl}|$, and the phase, $\phi_\sigma(\equiv \tan^{-1}[\sigma_2^{fl}/\sigma_1^{fl}])$, of $\sigma_{fl}(\omega)$ as scaled quantities in the scaling analysis of $\sigma_{fl}(\omega)$. The data sets of $\phi_\sigma(\omega)$ and $|\sigma_{fl}(\omega)|$ at different temperatures are scaled by using two normalizing factors, ω_0 and σ_0, respectively. Note that ω_0 and σ_0 are independently obtained in our procedure, since the data sets of $\sigma_{fl}(\omega)$ are complex quantities with two independent components. This is a unique feature of our scaling procedure. Details of the advantage of our procedure over other scaling procedures are described elsewhere [6].

3. Results and discussion

Fig. 2 shows the zero-field phase-stiffness temperature, $T_\theta(T) \equiv (\hbar/e^2k_B)\hbar\omega\sigma_2 d_s$, for several LSCO thin films from the underdoped region to the overdoped region, where d_s is the effective thickness of a multi-layered superfluid. As was already reported [7,11], we found that T_θ of the underdoped LSCO started to show the strong frequency dependence above T_{BKT}, while it was independent of frequency below T_{BKT}. Here, T_{BKT} is the the Berezinskii–Kosterlitz–Thouless (BKT) transition temperature, which is given by a relationship that $T_\theta(T_{BKT}) = (8/\pi)T_{BKT}$. Note that this behavior disappeared almost completely for the optimally doped LSCO and the overdoped LSCO. These results strongly suggest that the critical behavior in the underdoped LSCO is dominated by the BKT type of superconducting phase fluctuations, in contrast to the critical behaviors in the optimally doped LSCO and the overdoped LSCO.

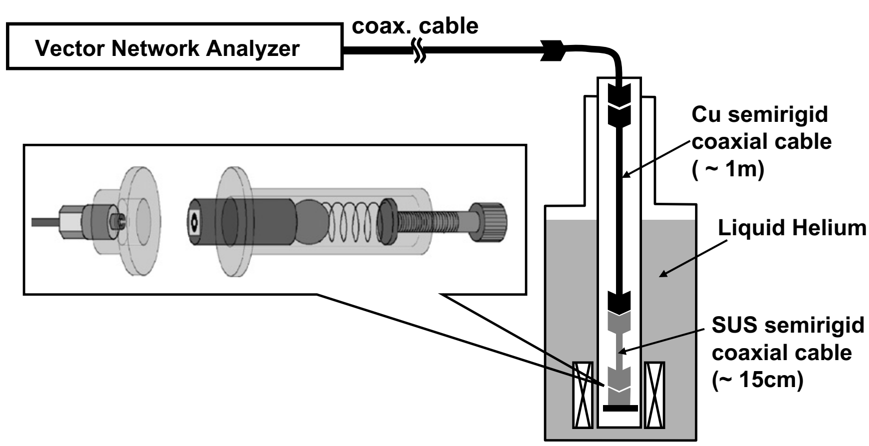

Fig. 1. The schematic set up of the non-resonant broadband measurement system.

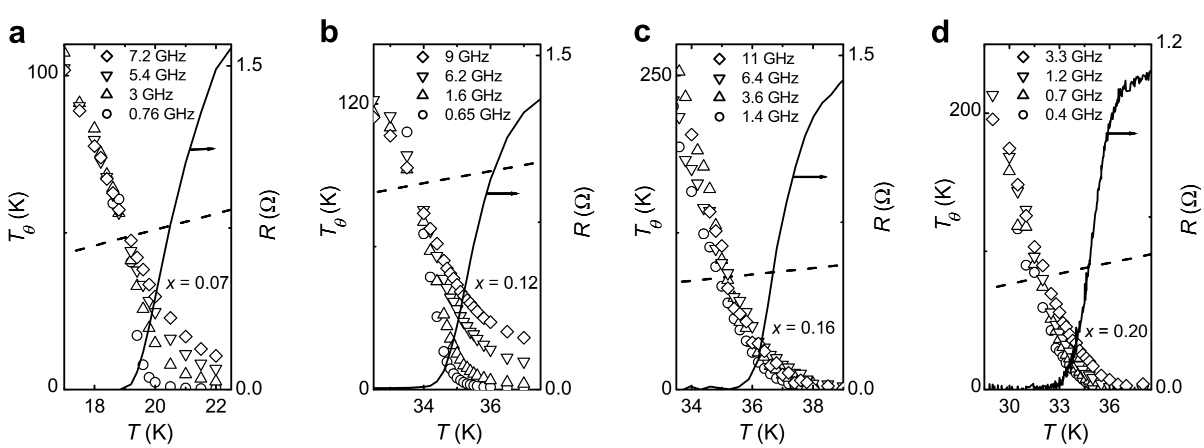

Fig. 2. The phase-stiffness temperature for the LSCO with (a) $x = 0.07$, (b) $x = 0.12$, (c) $x = 0.16$, and (d) $x = 0.20$. The dashed straight line represents $(8/\pi)T$. The solid curve is the dc resistance.