Fluctuation Conductivity Analysis in Zn-Doped YBa$_2$Cu$_3$O$_7$ and Related Systems

H Enomoto$^1$, Y Takano$^2$, H Ozaki$^3$ and N Mori$^4$

$^1$ Division of Electronics and Applied Physics, Graduate School of Engineering, Osaka Electro-Communication University, Hatsu-cho 18-8, Neyagawa, Osaka 572-8530, Japan
$^2$ Department of Physics, Nihon University, Kanda-surugadai 1-8, Chiyoda-ku, Tokyo 101-8308, Japan
$^3$ Department of Electrical Engineering and Bioscience, Waseda University, Ohkubo 3-4-1, Shinjuku-ku, Tokyo 169-8555, Japan
$^4$ Department of Electrical and Computer Engineering, Oyama National College of Technology, Nakakuki 771, Oyama-shi, Tochigi 323-0806, Japan

E-mail: Hiroyuki Enomoto, h-enomot@isc.osakac.ac.jp

Abstract. Fluctuation conductivity $\sigma'(\epsilon)$ above $T_c$ as a function of the reduced temperature $\epsilon$ was measured in polycrystalline YBa$_2$Cu$_3$O$_7$ and LaBaCaCu$_3$O$_7$ with Zn doping. The results for $\sigma'(\epsilon)$ are analyzed in terms of the Aslamazov-Larkin theory for a layered superconductor in which effect of $d$-wave pairing as well as that of short-wavelength cutoff is taken into account. The $d$-wave character appears in the $\sigma'(\epsilon)$ formula as renormalization effects on the fluctuation amplitude and the reduced temperature. Good agreement is attained between theory and experiment even in a high $\epsilon$ region, which allows us to discuss the doping dependence of the fluctuation amplitude and the out-of-plane coherence length. The $d$-wave nature could be responsible for the doping dependence of the fluctuation amplitude.

1. Introduction

Much attention has been devoted to the fluctuation conductivity (FC) above $T_c$ of copper oxide superconductors in the short-wavelength fluctuation (SWF) regime [1]. However, impurity effect or doping effect on the SWF still remains as a matter of debates. There are two kinds of dopants in high-$T_c$ materials. One of them is aliovalent substitution with respect to the copper valence, which gives rise to change the number of mobile carriers on account of charge imbalance. The other one is isovalent substitution which can also alter superconducting properties without controlling the carrier density. A typical example for the latter kind of impurities is Zn, which is known to induce a large $T_c$ reduction in spite of its non-magnetic nature [2].

While a number of FC studies on the first kind of the doping effects have been presented [1,3-5], few reports are available for those of the second one [6,7]. In this paper we study the FC in Zn-doped YBa$_2$Cu$_3$O$_7$ (YBCO) and LaBaCaCu$_3$O$_7$ (LBCCO) systems from a viewpoint of the SWF. Experimental data on the FC are analyzed on the basis of a theory for a $d$-wave superconductor in the SWF regime [8], and doping dependences of the fluctuation amplitude and the out-of-plane coherence length are presented.
2. **Experimental aspect**

A solid-phase reaction method was employed to fabricate two types of Zn-doped samples, one of which was YBa$_2$(Cu$_{1-x}$Zn$_x$)$_3$O$_7$ (0 ≤ x ≤ 10%) while the other being LaBaCa(Cu$_{1-x}$Zn$_x$)$_3$O$_7$ (0 ≤ x ≤ 4%). The fabrication procedure for samples of the former type was essentially the same as reported elsewhere [9] but with the sintering temperature at 950 °C. On the other hand, LBCCO samples with Zn dopant were prepared in a similar way as in our recent report [10]. In this case, post-annealing at 575 °C for 48h in flowing oxygen gas was performed in all the Zn-doped samples as well as in a non-doped one to assure high sample quality. From X-ray diffraction measurements, the crystal structure was confirmed to be orthorhombic in samples of the YBCO type while being tetragonal in those of the LBCCO type. Temperature dependence of the resistivity in our samples was measured in a manner as described previously [9].

3. **Results and discussion**

3.1. $T_c$ suppression effect

Temperature dependence of the resistivity $\rho(T)$ is displayed in figure 1 (a) for a number of Zn-doped YBCO samples. In the higher doping range (x ≥ 5%), the resistivity in the normal-state $\rho_n(T)$ clearly shows behaviour with a slightly upward curvature, and a close observation reveals that such behaviour can also be seen in samples with 0 ≤ x ≤ 3%. Consequently, as indicated by the solid lines in figure 1 (a), all the results for $\rho_n(T)$ could be well described by the formula [11]

$$\rho_n(T) = A T + B - C \ln(T)$$

(1)

where $A$, $B$ and $C$ are determined by the least squared fits. Values of $T_c$ were determined as a temperature at which the derivative $d\rho(T)/dT$ becomes maximal. Doping variations of $T_c$ are displayed in figure 1 (b) for YBCO and LBCCO systems with Zn impurities. For a $d$-wave superconductor with nonmagnetic impurities, an equation for $T_c$ is given by [12,13]

$$\ln(T_{c0}/T_c) = \psi(1/2 + \Gamma/2\pi n_i) - \psi(1/2)$$

(2)

where $\psi(z)$ is the digamma function, and $\Gamma = n_i/\pi N_0$, with $n_i$ and $N_0$ being the impurity density and the electronic normal-state density of states at the Fermi level, is the nonmagnetic scattering rate in the unitary limit which acts as the pair-breaking parameter. $T_{c0}$ is a $T_c$ value in the absence of the impurity.

![Figure 1](image_url)

**Figure 1.** (a) The resistivity $\rho$ vs. temperature $T$ for Zn-doped YBCO. The solid lines are obtained from equation (1). (b) $T_c$ vs. Zn doping level $x$ in YBCO and LBCCO systems. The solid and broken lines show theoretical fits to experimental data obtained from equation (2).

The solid and broken lines along the experimental data in figure 1 (b) show theoretical fits calculated from equation (2), from which values of $\Gamma$ with 1% Zn doping ($n_i = x = 0.01$) are evaluated as $\Gamma_1 = 0.99$ meV and 0.70 meV for YBCO and LBCCO, respectively, in reasonable agreement with those reported in other studies of Zn impurity effects [2].
3.2 Fluctuation conductivity analysis

Temperature dependence of the FC in this study is defined as the excess conductivity $\sigma'(T)$ deviated from the inverse of the normal-state resistivity:

$$\sigma'(T) = [\rho(T)]^{-1} - [\rho_n(T)]^{-1}$$

(3)

where $\rho(T)$ is measured resistivity and $\rho_n(T)$ is given by equation (1). For a layered superconductor with $d$-wave pairing symmetry, we have derived the Aslamazov-Larkin (AL) term in the context of a resonance scattering theory for a heavy-Fermion superconductor [14], and the result is given by Eq. (4) which also takes account of a total-energy cutoff effect in the SWF region [8]:

$$\sigma^{AL}_d(\epsilon, \alpha_E) = C^{AL}_d \left[ (\epsilon_d^2 + r^2 \epsilon_d) \right]^{1/2} - \frac{2\alpha_E^2 - (\epsilon_d^2 + \frac{1}{2} r^2)}{\alpha_E^2}$$

(4)

where $\alpha_E$ is a cutoff parameter and $r = 2\xi_0^0 / s$ is the Lawrence-Doniach (LD) anisotropic parameter with $\xi_0^0$ and $s$ being the out-of-plane coherence length and the interlayer distance, respectively. It can be seen from the above formula that the AL term in a $d$-wave superconductor takes the same formula as in the $s$-wave case [1] but with renormalization effects on the fluctuation amplitude and reduced temperature. The renormalized amplitude is given by

$$C^{AL}_d = \gamma \cdot C^{AL}_s = | \psi^{(1)}(1/2 + \Gamma/2\kappa_T T)|/|\psi^{(1)}(1/2)| \text{ and } C^{AL}_s = e^2/16\hbar s$$

(5)

and the renormalized reduced temperature $\epsilon_d$ can be expressed, in a low doping region, as

$$\epsilon_d = [1 - (\Gamma/2\kappa_T T)|\psi^{(1)}(1/2 + \Gamma/2\kappa_T T)|] \epsilon$$

(6)

where $\epsilon = \ln(T/T_c)$ is the usual (unrenormalized) reduced temperature. In equations (5) and (6), $\psi^{(1)}(z)$ is the trigamma function.

![Figure 2](image-url)

**Figure 2.** Bi-log plots of normalized FC ($\sigma_0 = [\rho_0(300)]^{-1}$) in Zn-doped YBCO systems with (a) $x=0\%$, (b) $x=3\%$ and (c) $x=7\%$. The solid lines display theoretical fits with a $d$-wave theory while the broken and dotted lines display those with the $s$-wave theory (see text). Values of the normalized amplitude $C_T(x)/C_T(0)$ and the LD parameter $r$ used in fittings are displayed in (d), where the solid line denotes a theoretical prediction obtained from equation (5) while the broken line is only for guide to the eye.

Typical results for FC analyses in Zn-doped YBCO samples are illustrated in figure 2 (a)-(c). Satisfactory agreement is attained between theory and experiment, especially for samples with higher doping level. The solid lines are obtained from equations (4) and (6) with the parameters $r$, $C^{AL}_d$, and $\alpha_E$ being adjusted. Although $C^{AL}_d$ is determined uniquely from equation (5) in a $d$-wave theory, its
experimental value is usually different from a theoretical one due to sample imperfection [15], so that we treat it as a free parameter $C_F(x)$ at Zn content $x$. The broken lines (AL-(s)-1) show theoretical results for the $s$-wave formula which is given by the replacement $\varepsilon_d \rightarrow \varepsilon$, with the same values of the fitting parameters. The $s$-wave theory can also describe well the experimental data if appropriate parameter values are chosen as indicated by the dotted line (AL-(s)-2) in figure 2 (c).

Of fitting parameters, values of the normalized amplitude $C_F(x)/C_F(0)$ and the LD parameter $r$ as a function of Zn content $x$ are displayed in figure 2 (d). The solid line, which is calculated from equation (5) with $\Gamma = 0.99$ meV obtained from the fit in figure 1, shows a reasonable agreement with the $d$-wave theory of the fluctuation. We must bear in mind, however, that the observed reduction in $C_F$ as $x$ increasing could also be explained by the enhanced inhomogeneity induced by the Zn doping [15]. Another parameter $r$ shown in figure 2 (d) seems to be increased with increasing $x$, which is indicative of expanded $\xi^\perp$ in agreement with a report on Zn doping effects [16]. As to the SWF effects, no clear relation has been observed between the parameter $\alpha_E$ and the doping level $x$, in contrast to our previous studies [3,5].

4. Conclusion
The fluctuation conductivity measurements have been performed to study Zn impurity effects in YBCO-type superconductors. Doping dependence of $T_c$ can be explained by nonmagnetic impurity effects in a $d$-wave superconductor. Results for the fluctuation conductivity can be described successfully in terms of an extended AL theory for a $d$-wave pairing in which effect of a total energy cutoff is taken into consideration. From values of fitting parameters obtained, it is found that the reduction in the fluctuation amplitude upon doping could be consistent with the theoretical prediction for a $d$-wave pairing, and that the out-of-plane coherence length tends to increase with increasing Zn doping level.

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