Doping dependence of charge dynamics in SmLa$_{1-x}$Sr$_x$CuO$_{4-\delta}$

T.Kakeshita$^{1,3}$, S.Adachi$^2$, S.Uchida$^1$

$^1$ Dept. of Physics, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656 Japan
$^2$ Superconductivity Research Laboratory, ISTEC, Shinonome 1-10-13, Koto-ku, Tokyo 155-0062, Japan
E-mail: KAKESHITA.Teruhisa@nims.go.jp

Abstract. Mono-layer cuprates show various Tc from $\sim$30K to $\sim$90K. In spite of the absence of impurity in CuO$_2$ plane, T$^*$ cuprate, SmLa$_{1-x}$Sr$_x$CuO$_4$(SLSCO) shows a fairly low Tc ($\sim$30K). Recent investigation of mono-layer Bi-based cuprate indicates that Tc is intimately related with local lattice distortion induced by chemical substitution of out-of-plane. We grew some compositions of wide range of Sr and carefully investigated the change of Tc. We consider the origin of strong suppression of Tc in T$^*$ cuprates, compared with the other mono-layer cuprates.

1. Introduction

As empirical laws by numerous experiments for high-Tc cuprates so far, we know some factors to control Tc. Some of them are the lattice properties, Cu-O bond length and angle. There are three kinds of mono-layer cuprates composed of octahedron network, LSCO, Bi(Tl)2201, Hg1201. LSCO and Bi2201 have much lower Tc than HgBa$_2$CuO$_{4+\delta}$(Hg1201) and Tl$_2$Ba$_2$CuO$_{6+\delta}$(Tl2201, Tc$\sim$93K). It is considered that the large suppression of Tc in LSCO results from dimpling of CuO$_2$ plane. The plane of LSCO becomes unevenness by long periodic buckling of octahedron which strongly suppresses the nodal quasiparticle and the superconducting state, particularly, around x=1/8 in LTT phase[1, 2]. In case of 2201-system, Bi2201 has much lower Tc than an isostructual cuprate Tl2201. It is suggested as the origin to reduce Tc in Bi2201 that local lattice distortion by chemical substitution of ou-of plane enhances inhomogeneity of CuO$_2$ plane[3]. Thus, the mechanism to suppress Tc is intimately connected with lattice properties.

In general, CuO$_2$ plane composed of pyramid structure is easier to be flat than that of octahedral structure. A pyramid-type mono-layer cuprate SmLa$_{1-x}$Sr$_x$CuO$_\delta$ (SLSCO), so-called, T$^*$-type cuprate, has also a flat CuO$_2$ plane[4], similar to other pyramid-type bi-layer "high"-Tc cuprates HgBa$_2$CaCu$_2$O$_{6+\delta}$(Hg1212)[5] and Bi2212[6]. Tc of SLSCO is, however, much lower than that of Hg1212 and Bi2212. These facts indicate the existence of other origin to strongly reduce Tc in the mono-layer cuprate. In this paper, we show the result of the doping dependence of Tc for pyramid-type mono-layer cuprate SLSCO, and discuss the origin to reduce Tc by comparing with other mono-layer cuprates, mainly in view of lattice properties.

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$^3$ Present address: National Institute for Materials Science, Sengen 1-2-1, Tsukuba 305-0047, Japan
2. Experimental details

We grew the single crystals of SLSCO in wide range of $x$ by TSFZ method. We were not able to grow the compositions of $x < 0.10$ and $0.25 < x$, even by applying high pressure of $P(O_2)=12$atm. Since as-grown crystals of SLSCO do not show superconductivity due to heavy deficiency of apical oxygen as explained in previous works, all the compositions were oxygenized under $P(O_2)=400$atm[7]. Hence we got the samples which show bulk superconductivity.

3. Results and Discussion

Fig.1(a) shows the dependence of Sr concentration for SLSCO ($0.1 \leq x \leq 0.225$). The systematical change of carrier concentration was carefully investigated by in-plane optical reflectivity and will be reported elsewhere. $T_c$(max) is 33K in $x=0.10$, and $T_c$ is gradually decreasing with increasing Sr concentration. In general, the other hole-type cuprates have an optimum $T_c$ around the carrier concentration of $0.15 \sim 0.20$, however, how to change $T_c$ in SLSCO is fairly different from that of the others. Instead, the behavior of SLSCO reminds us that of electron-type cuprate NCCO.

The resistivity shows a smooth temperature-dependence and a discontinuous jump such as a structure phase transition from LTO to LTT like Nd-LSCO and LBCO is not seen. Therefore, the suppression of $T_c$ in $T^*$ cuprates is not due to structure phase transition. As the mechanism to suppress $T_c$, we refer two things, impurity effect of in-plane and chemical disorder effect of out-of-plane. The transport measurements on impurity effect demonstrate that $T_c$ is closely correlated with the residual resistivity[8]. Nodal quasiparticles are strongly scattered by Zn and therefore Cooper pairs are destroyed around the impurity[9]. The metallic term in normal state which corresponds to nodal quasiparticle shift parallel up by the effect of strong scattering due to the contribution of unpaired spin by Zn and hence $T_c$ is scaled with residual resistivity. However, the residual resistivity of SLSCO is much smaller than impurity effect and therefore the possibility can be entirely ruled out. On the other hand, chemical substitution in La214 system causes local lattice distortion[10] and strongly suppresses $T_c$. The chemical effect is a physically different way from impurity effect because impurity effect is a factor within CuO$_2$ plane, while chemical disorder effect is one out of plane. Attfield et al. also suggested that $T_c$ has a relation with local lattice distortion of A-site (rock-salt structure), $\sigma^2 \equiv <r^2> - <r>^2$, and an average ionic radius $<r>$ in LSCO. $T_c$ is gradually suppressed with increasing $\sigma^2$ by

Figure 1. (a) The measurements of $T_c$ for various $x$. (b) In-plane resistivity of SLSCO ($x = 0.15$ and 0.20) and estimate of residual resistivity by extrapolation with a linear term.
the cation substitution such as Sr for La, and is also increasing with \(< r >\). Also in case of RE-Bi2201, Tc is sensitively influenced by A-site substitution. Tc is systematically decreasing with shrinking the ionic radius of rare earth substituted for Sr. Transport measurements on RE-Bi2201 showed such a disorder effect of out-of-plane does not cause so strong a scattering effect as impurity (Zn) in CuO$_2$ plane, but a residual resistivity is scaled with $\sigma^2$[3]. It is suggested as the reason for decreasing Tc that local lattice distortion enhances the inhomogeneity of CuO$_2$ plane, as discussed below.

Since SLSCO has also disorder effects by randomness of apical oxygen and chemical substitution in rock-salt layers, we should consider the effect of local lattice distortion. We also note that the bond length between Cu and apical oxygen of SLSCO is \(\sim 2.25 \text{Å}\) which is considerably short compared to the other mono-layer cuprates, and therefore it is expected that the disorder effect in out-of plane works more strongly in SLSCO. In fact, the rock-salt layer of SLSCO has a larger effect of local lattice distortion $\sigma^2$ than that of LSCO, because fluorite(Sm) layer is not chemically substituted and the substitution of Sr is concentrated into only rock-salt(La) layer. Therefore the effect by chemical substitution is much more enhancing with Sr concentration than in LSCO, which might be connected with the reason why Tc is monotonically decreasing.

In addition, empirically, T$_c$ is increasing with the distance between Cu and apical oxygen. Fig.2(a) shows the plot of Tc against Cu-O(apical) bond length for mono-layer cuprates. SLSCO clearly follows the trend that Tc is gradually increasing with the bond length. Fig.2(b) shows the plot of Tc against \(< r >\). The value corresponds to kinds of A-site cations, which is La(Sr) for LSCO and SLSCO, Ba for Tl2201 and Hg1201, respectively. Thus the average ionic radius in A-site is directly related with Cu-O(apical) bond length. \(< r >\) of SLSCO is \(\sim 1.22 \text{Å}\), which is also smaller than that of the other mono-layer cuprates.

![Figure 2](image)

**Figure 2.** (a) The plot of Tc against the bond length between Cu and apical oxygen for various mono-layer cuprates. (b) The plot of Tc against the average ionic radii of block layer.

Here, we discuss the effect of local lattice distortion on Tc. Recent experiments demonstrate the existence of two kinds of gaps in some cuprates[11, 12]. One is a large gap, ”pseudogap”, which is open even above Tc around ($\pi$,0), and the other is a small gap, ”superconducting gap”, which is abruptly open at Tc around ($\pi$/2, $\pi$/2). The result is consistent with inhomogeneous picture of CuO$_2$ plane, the coexistence of superconducting domains comparable to coherent length (2~3nm) and nonsuperconducting pseudogap phase, observed by STM. Recent results of STM demonstrate that chemical disorder effect of out-of-plane makes coherence peaks of small gap depress in RE-Bi2201 and the width of the gap distribution wider[13]. As the reason why the resistivity in normal state slightly shift up and Tc is strongly suppressed with increasing $\sigma^2$
by chemical disorder effect, ARPES spectra of systematic RE-substituted Bi2201 show that the scattering rate of nodal quasiparticle is broader and the superconducting gap is suppressed with increasing $\sigma_2[14]$. Thus local lattice distortion $\sigma_2$ does not work for a strong scattering center as Zn, but enhances the inhomogeneity of the electronic state in CuO$_2$ plane and obstructs the coherency of Cooper pairs.

Finally, we also consider the effect of Cu-O bond on Tc. As for the reasons why Tc is closely connected with the bond length, it is suggested that Cu-O(apical) bond length controls Madelung potential[15] or mixing of orbital between Cu and apical oxygen controls in-plane hopping integral $t, t', t''[16]$. As shown in Fig.2(a), for example, one of the most remarkable differences between two isostructural materials Bi2201 and Tl2201 is the Cu-O(apical) bond length. Recent ARPES measurement shows the difference of the Fermi surface between the two materials[17]. The Fermi surface of Tl2201 has long parallel regions around ($\pi,0$) similar to Bi2212 and no shadow band, whereas that of Bi2201 is fairly rounded and has a shadow band which corresponds to orthorhombicity. This indicates that Cu-O bond length and lattice distortion significantly influence the electronic state in CuO$_2$ plane and Tc.

4. Conclusion

In summary, we discuss the origin of strong Tc suppression of T$^*$ cuprate, SLSCO. Tc of SLSCO is monotonically decreasing with carrier concentration, unlike the other hole-type cuprates. The bond length between Cu and apical oxygen is smaller and the effect of local lattice distortion by chemical substitution is stronger than any other mono-layer cuprates. Thus SLSCO has some disadvantages for Tc and therefore the maximum Tc is only 33K.

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