Inhomogeneity of Superconductivity and Stripe Correlations at $x \sim 0.21$ in La$_{2-x}$Sr$_x$CuO$_4$

M. Miyazaki$^a$, T. Adachi$^a$, Y. Tanabe$^{a,*}$, H. Sato$^a$, T. Nishizaki$^b$, K. Kudo$^{b,*}$, T. Sasaki$^b$, N. Kobayashi$^b$, Y. Koike$^a$

$^a$Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai, Japan

$^b$Institute for Materials Research, Tohoku University, Sendai, Japan

E-mail: adachi@teion.apph.tohoku.ac.jp (T. Adachi)

Abstract. With the aim at investigating the relationship between the anomalous decrease in $T_c$, the development of the Cu-spin correlation and the inhomogeneity of superconductivity at $x \sim 0.21$ in the overdoped regime of La$_{2-x}$Sr$_x$CuO$_4$, we have performed the in-plane electrical-resistivity, $\rho_{ab}$, and magnetization measurements. Measurements of the temperature dependence of $\rho_{ab}$ in magnetic fields have revealed that the superconducting (SC) transition curve shifts to the low-temperature side almost in parallel with increasing field above $\sim 9$ T at $x \sim 0.21$, which is similar to that observed for stripe-ordered La-214 systems with the hole concentration of $\sim 1/8$ per Cu. On the other hand, it has been found that the magnetization curve shows the so-called second peak in the SC state at $x \sim 0.21$, which is due to the strong vortex pinning in normal-state regions in the nano-scale inhomogeneous SC state. Accordingly, it is likely that the stripe correlations are developed in the nano-scale inhomogeneous SC state at $x \sim 0.21$.

1. Introduction

In recent years, significant anomalies have been observed at $x \sim 0.21$ in the overdoped regime of La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) so far; that is, a slight depression of $T_c$ [1,2], a development of the Cu-spin correlation at low temperatures [3], an enhancement of the lattice instability by the application of magnetic field [4] and a singularly weak enhancement of the in-plane thermal conductivity by the application of magnetic field [5]. These are suggestive of a possible development of the stripe correlations of holes and spins [6] at $x \sim 0.21$ as in the case at $x \sim 1/8$.

On the other hand, it has been pointed out that the so-called inhomogeneous superconducting (SC) state appears in the overdoped high-$T_c$ cuprates. In the overdoped regime of LSCO, muon-spin-relaxation ($\mu$SR) [7,8], specific-heat [9,10] and nuclear-magnetic-resonance measurements [11] have suggested the occurrence of a phase separation into SC and normal-state regions. From our magnetic-susceptibility, $\chi$, measurements in a low magnetic field, it has been found that the SC volume fraction decreases with increasing $x$ in the overdoped regime of LSCO [12]. Moreover, the temperature dependence of $\chi$ in high fields and the magnetization curve have exhibited a plateau and the so-called second peak in the SC state, respectively [13], suggesting that the phase separation takes place on a nano-scale.
At $x \sim 0.21$, however, it has not yet been clarified whether or not the SC transition curve in the temperature dependence of the in-plane electrical-resistivity, $\rho_{ab}$, in magnetic fields shifts to the low-temperature side almost in parallel which is characteristic of the stripe-ordered La$_2-x$Ba$_x$CuO$_4$ at $x \sim 1/8$ [14], and whether or not the phase separation takes place. Therefore, we have carried out $\rho_{ab}$ measurements in magnetic fields and magnetization measurements in LSCO at $x \sim 0.21$ in order to investigate the relationship between the stripe correlations and phase separation.

2. Experimental

Single crystals of LSCO with $x = 0.190 - 0.229$ were grown by the traveling-solvent floating-zone method [12]. The quality of the single crystals was checked by the x-ray back-Laue photography to be good. The Sr content of each single crystal was determined from the inductively-coupled-plasma (ICP) measurements. In order to make the demagnetizing-field effect in the magnetization measurements almost identical among crystals, we used crystals formed into the same rectangular shape within the error of ±14% in size. The $\rho_{ab}$ was measured by the standard dc four-probe method in magnetic fields parallel to the c-axis up to 17.5 T on field cooling. The magnetization measurements were carried out in magnetic fields parallel to the c-axis up to 7 T, using a SQUID magnetometer.

3. Results and discussion

Figure 1 shows the temperature dependence of $\rho_{ab}$ for $x = 0.195 - 0.215$ in various magnetic fields. In general, the SC transition curve of $\rho_{ab}$ shows fan-shaped broadening in magnetic fields in the underdoped regime, which is attributed to the large SC fluctuation originating from the small SC coherence length. On the other hand, the broadening tends to disappear with doping of holes and parallel-shift-like behavior is observed in the overdoped regime, which is attributed to the small SC fluctuation originating from the large SC coherence length [15].

In Fig. 1, it is found that fan-shaped broadening behavior is observed for $x = 0.195$ and $x = 0.215$. For $x = 0.204$, on the other hand, the SC transition curve exhibits parallel-shift-like behavior, suggesting that the SC fluctuation is small. To investigate the behavior of the SC transition in detail, the magnetic-field dependence of the SC transition width, $\Delta T_c$, normalized by $\Delta T_c$ in zero field for $x = 0.190 - 0.229$ is shown in Fig. 2. Here, $\Delta T_c$ is defined as $\Delta T_c = T_c^{90\%} - T_c^{10\%}$, namely, the difference of temperatures where the value of $\rho_{ab}$ drops to 90% and 10% of the normal-state value. For $x = 0.190$, it is found that the monotonic increase in the normalized $\Delta T_c$ with increasing field is marked. The increase weakens for $x = 0.215$ and $\Delta T_c$ is almost independent of field for $x = 0.220$ and 0.229, indicating that crossover from the fan-shaped broadening behavior to the parallel-shift-like behavior...
Figure 2. Magnetic-field dependence of the SC transition width, $\Delta T_c$, defined as $T_c^{90\%} - T_c^{10\%}$ and normalized by $\Delta T_c$ in zero field, for La$_{2-x}$Sr$_x$CuO$_4$ with $x = 0.190 – 0.229$. For comparison, the data of La$_{2-x}$Ba$_x$CuO$_4$ (LBCO) with $x = 0.11$ are plotted [14].

Figure 3. Magnetization curve at 10 K for La$_{2-x}$Sr$_x$CuO$_4$ with $x = 0.190 – 0.208$.

The observed parallel-shift-like behavior in $\rho_{ab}$ in magnetic fields is similar to that observed at $x \sim 1/8$ where the stripe order of holes and spins is formed [14]. Therefore, it is suggested that the stripe correlations are developed and more stabilized by the application of magnetic field singularly at $x \sim 0.21$ in the overdoped regime. On the other hand, the anomalous enhancement of vortex pinning, characterized by the second peak in the magnetization curve and by the plateau in the temperature dependence of $\chi$ in high fields, cannot be simply explained as being due to oxygen defects or the bad crystallinity [13]. Therefore, these results strongly suggest the occurrence of the nano-scale phase separation into SC and normal-state regions even at $x \sim 0.21$ as well as in the other overdoped crystals of LSCO [13].

To understand the dual existence of the developed stripe correlations and nano-scale phase separation at $x \sim 0.21$, following two scenarios are proposed. One is that there exists a nano-scale inhomogeneous state consisting of SC regions, non-SC metallic regions and non-SC regions in which...
the stripe correlations are developed. The other is that there exists a nano-scale inhomogeneous state consisting of SC regions and non-SC regions in which the stripe correlations are developed. In both cases, by the application of strong magnetic field, it is guessed that vortices tend to be pinned at the non-SC regions around the surface of a crystal, so that the vortices cannot penetrate into the inside of the crystal, resulting in the appearance of the second peak in the magnetization curve and the plateau in the temperature dependence of $\chi$ in high fields. On the other hand, it is guessed that the stripe correlations are further developed around the vortices in a crystal, resulting in the parallel-shift-like behavior in $\rho_{ab}$. In order to obtain further information on the relationship between the anomalous suppression of superconductivity at $x \sim 0.21$, the stripe correlations and the phase separation, experiments such as specific heat, $\mu$SR and neutron scattering in magnetic fields are under way.

4. Summary
We have carried out $\rho_{ab}$ and magnetization measurements in magnetic fields at $x \sim 0.21$ in LSCO where the superconductivity is anomalously suppressed. In the $\rho_{ab}$ measurements, it has been found that parallel-shift-like behavior is induced by magnetic field at $x \sim 0.21$. Moreover, both the second peak in the magnetization curve and a plateau in the temperature dependence of $\chi$ in high magnetic fields have been observed at $x \sim 0.21$ as well as in the other overdoped crystals of LSCO. These results suggest that the stripe correlations are anomalously developed in the nano-scale phase-separated state at $x \sim 0.21$.

Acknowledgement
We are indebted to M. Ishikuro for his help in the ICP analysis. The $\rho_{ab}$ measurements were performed at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University. The $\chi$ measurements were partially carried out at the Center for Low Temperature Science, Tohoku University.

References
[1] Kakinuma N, Ono Y and Koike Y 1999 Phys. Rev. B 59 1491
[2] Kawamata T, Adachi T, Noji T and Koike Y 2000 Phys. Rev. B 62 R11981
[3] Watanabe I, Aoyama M, Akoshima M, Kawamata T, Adachi T, Koike Y, Ohira S, Higemoto W and Nagamine K 2000 Phys. Rev. B 62 R11985
[4] Suzuki T, Ota J, Tonishi J and Goto T 2006 AIP Conf. Proc. 850 409
[5] Adachi T, Haidar S M, Kawamata T, Sugawara N, Kaneko N, Uesaka M, Sato H, Tanabe Y, Noji T, Kudo K, Kobayashi N, and Koike Y 2009 J. Phys.: Conf. Series 150 052115
[6] Tranquada J M, Sternlieb B J, Axe J D, Nakamura Y and Uchida S 1995 Nature (London) 375 561
[7] Uemura Y J, Keren A, Le L P, Luke G M, Wu W D, Kubo Y, Manako T, Shimakawa Y, Subramanian M, Cobb J L and Markert J T 1993 Nature (London) 364 605
[8] Niedermayer Ch, Bernhard C, Binninger U, Glückler H, Tallon J L, Ansaldo E J and Budnick J I 1993 Phys. Rev. Lett. 71 1764
[9] Loram J W, Mirza K A, Wade J W, Cooper J R and Liang W Y 1994 Physica C 235-240 134
[10] Wang Y, Yan J, Shan L, Wen H-H, Tanabe Y, Adachi T and Koike Y 2007 Phys. Rev. B 76 064512
[11] Ohsugi S, Kitaoka Y and Asayama K 1997 Physica C 282-287 1373
[12] Tanabe Y, Adachi T, Noji T and Koike Y 2005 J. Phys. Soc. Jpn. 74 2893
[13] Tanabe Y, Adachi T, Omori K, Sato H, Noji T and Koike Y 2007 J. Phys. Soc. Jpn. 76 113706
[14] Adachi T, Kitajima N, Manabe T, Kudo K, Sasaki T, Kobayashi N and Koike Y 2005 Phys. Rev. B 71 104516
[15] Suzuki M and Hikita M 1989 Jpn. J. Appl. Phys. 28 L1368