Thermal-conductivity study on the electronic state in the overdoped regime of La$_{2-x}$Sr$_x$CuO$_4$: Phase separation and anomaly at $x \sim 0.21$

T. Adachi$^1$, S. M. Haidar$^1$, T. Kawamata$^2$, N. Sugawara$^1$, N. Kaneko$^1$, M. Uesaka$^1$, H. Sato$^1$, Y. Tanabe$^1$, T. Noji$^1$, K. Kudo$^3$, N. Kobayashi$^3$ and Y. Koike$^1$

$^1$Department of Applied Physics, Tohoku University, 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
$^2$Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako 351-0198, Japan
$^3$Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan
E-mail: koike@teion.apph.tohoku.ac.jp (Y. Koike)

Abstract. Measurements of the in-plane thermal conductivity, $\kappa_{ab}$, in magnetic fields parallel to the c-axis have been carried out in the overdoped regime of La$_{2-x}$Sr$_x$CuO$_4$ with $x = 0.18 - 0.30$. At low temperatures, $\kappa_{ab}$ is enhanced by the application of magnetic field for $x < 0.22$ due to the Volovik effect, while $\kappa_{ab}$ is suppressed for $x > 0.22$. No Volovik effect for $x > 0.22$ is explained as being due to the phase separation into superconducting and normal-state regions. Moreover, the enhancement of $\kappa_{ab}$ has been found to be singularly weak at $x \sim 0.21$ where $T_c$ is a little suppressed in zero field. A so-called stripe order might be stabilized by the application of magnetic field at $x \sim 0.21$, as in the case of $x \sim 0.115$.

1. Introduction
Thermal conductivity is a powerful tool for study of the dynamics of elementary excitations in a superconducting (SC) state, for elementary excitations such as quasiparticles, phonons and spin excitations carry heat, giving a finite value of thermal conductivity even in a SC state.

In recent years, magnetic-field effects on the so-called dynamical stripe correlations of spins and holes [1], which might be in the heart of the mechanism of the high-$T_c$ superconductivity [2], have been an issue of note. In La-214 high-$T_c$ cuprates, experiments such as neutron scattering [3] and electrical resistivity [4] have suggested the stabilization of the stripe order by the application of magnetic field around the hole concentration, $p$, of 1/8 per Cu. Moreover, our former measurements of the in-plane thermal conductivity, $\kappa_{ab}$, in La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) and La$_{2-x}$Ba$_x$CuO$_4$ around $x = p = 1/8$ have revealed the marked suppression of $\kappa_{ab}$ by the application of magnetic field parallel to the c-axis, suggesting the field-induced stabilization of the stripe order [5, 6, 7].

As for the overdoped regime of LSCO around $x = 0.21$, significant anomalies have been observed so far; a slight depression of $T_c$ [8, 9], a development of the Cu-spin correlation at low temperatures [10] and an enhancement of the lattice instability by the application of magnetic field [11]. These are suggestive of a possible development of the stripe correlations around
Figure 1. Temperature dependence of the in-plane thermal conductivity, $\kappa_{ab}$, in various magnetic fields along the c-axis up to 14 T for La$_{2-x}$Sr$_x$CuO$_4$ with $x = 0.190 - 0.300$. Arrows indicate the superconducting transition temperature, $T_c$, estimated from the magnetic-susceptibility measurements.

$x = 0.21$ as well as around $x = 1/8$. If this is the case, suppression of $\kappa_{ab}$ by the application of magnetic field is expected to be observed around $x = 0.21$. Sun et al., on the other hand, have revealed from $\kappa_{ab}$ measurements in magnetic fields for LSCO with $x \leq 0.22$ that the application of magnetic field brings about an enhancement of $\kappa_{ab}$ at low temperatures in the overdoped regime of $x = 0.17 - 0.22$ [12]. They have concluded that the enhancement of $\kappa_{ab}$ is due to the Volovik effect, that is, due to an increase in the number of quasiparticles owing to the Doppler shift. For $x > 0.22$, however, the details have not yet been clarified. Therefore, in order to investigate the possible development of the stripe correlations around $x = 0.21$ and the dynamics of quasiparticles for $x > 0.22$, we have carried out $\kappa_{ab}$ measurements in various magnetic fields in the overdoped regime of LSCO with $x = 0.18 - 0.30$, changing $x$ finely.

2. Experimental

Single crystals of LSCO used for the $\kappa_{ab}$ measurements were grown by the traveling-solvent floating-zone method. The details have been reported elsewhere [9]. The $\kappa_{ab}$ was measured by the standard steady-state method [5]. Magnetic fields were applied along the c-axis up to 14 T.
3. Results and discussion

Figure 1 shows the temperature dependence of $\kappa_{ab}$ in various magnetic fields in the overdoped regime of LSCO. Focusing on temperatures just below $T_c$ estimated from the magnetic-susceptibility measurements, the decrease in $\kappa_{ab}$ with decreasing temperature is relaxed and a shoulder-like behavior is observed in zero field for $x = 0.190 - 0.229$. This behavior is interpreted as being due to a reduction of the scattering between quasiparticles and between a phonon and a quasiparticle owing to the decrease in the number of quasiparticles in the SC state.

By the application of magnetic field, $\kappa_{ab}$ is suppressed at temperatures just below $T_c$. Since the change of $\kappa_{ab}$ by the application of magnetic field is negligibly small for non-SC $x = 0.300$, the suppression of $\kappa_{ab}$ at temperatures just below $T_c$ for $x = 0.190 - 0.229$ is probably due to an increase of the scattering of quasiparticles and/or phonons by vortex cores.

At the lowest measured temperature of $\sim 3$ K, $\kappa_{ab}$ is enhanced by the application of magnetic field for $x \leq 0.215$, while the enhancement of $\kappa_{ab}$ is negligibly small for $x = 0.207$. For $x > 0.221$, on the other hand, $\kappa_{ab}$ is suppressed by the application of magnetic field. Figure 2 shows the $x$ dependence of the ratio of $\kappa_{ab}$ in magnetic fields to $\kappa_{ab}$ in zero field, $\kappa_{ab}(H)/\kappa_{ab}(0)$, at 3.2 K. Roughly speaking, it is found that $\kappa_{ab}$ is enhanced by the application of magnetic field for $x < 0.22$, while it is suppressed for $x > 0.22$, followed by the almost field-independent $\kappa_{ab}$ for non-SC $x = 0.300$. It is found, on the other hand, that the enhancement of $\kappa_{ab}$ is negligibly small around $x = 0.21$.

The enhancement of $\kappa_{ab}$ by the application of magnetic field for $x < 0.22$ can be understood in terms of the Volovik effect. On the other hand, the negligibly small increase in $\kappa_{ab}$ by the application of magnetic field around $x = 0.21$ is interpreted as being probably due to the development of the stripe correlations as follows. That is, supposing the stripe correlations are developed around vortex cores as in the case of $x \sim 1/8$ [5, 6, 7], quasiparticles are strongly scattered at the boundary of the stripe-ordered regions and moreover the mobility of quasiparticles in the stripe-ordered regions decreases, resulting in the suppression of $\kappa_{ab}$. Therefore, this suppression of $\kappa_{ab}$ cancels the enhancement of $\kappa_{ab}$ due to the Volovik effect, leading to the almost unchanged behavior of $\kappa_{ab}$ by the application of magnetic field.

![Graph showing Sr-concentration dependence of the change of $\kappa_{ab}$ by the application of magnetic field along the c-axis](image_url)
As for the suppression of $\kappa_{ab}$ by the application of magnetic field for $x > 0.22$, it seems of much importance to take into account the electronic inhomogeneity proposed in the overdoped high-$T_c$ cuprates. Recent measurements of the magnetic susceptibility [13] and specific heat [14] in the overdoped regime of LSCO have revealed a decrease in the SC volume fraction and an increase in the density of states of quasiparticles in the SC state with increasing $x$, respectively. These results have strongly suggested that a phase separation into SC and normal-state regions takes place in the overdoped LSCO. At $x \sim 0.22$, the ratio between volume fractions of SC regions and normal-state ones has been estimated to be 1 : 1, implying the occurrence of marked scattering of quasiparticles at the boundary between both regions. Moreover, it has been found that the SC regions shrink with increasing $x$, so that the Volovik effect is guessed to be suppressed. Accordingly, the suppression of $\kappa_{ab}$ by the application of magnetic field for $x > 0.22$ is interpreted as being due to the phase separation.

4. Summary

We have measured $\kappa_{ab}$ in various magnetic fields parallel to the c-axis in the overdoped regime of LSCO single crystals. It has been found that the enhancement of $\kappa_{ab}$ is negligibly small at the lowest temperature 3.2 K for $x \sim 0.21$ where the superconductivity is slightly suppressed. This is interpreted as being due to the development of the stripe correlations canceling the enhancement of $\kappa_{ab}$ owing to the Volovik effect. For $x > 0.22$, on the other hand, the suppression of $\kappa_{ab}$ by the application of magnetic field has been observed at 3.2 K. This has been understood to be due to both the enhancement of scattering of quasiparticles and the suppression of the Volovik effect in the presence of phase separation into SC and normal-state regions. These results convince us of the occurrence of the phase separation in the overdoped regime and strongly suggest a significant effect of the phase separation on the dynamics of quasiparticles in the overdoped high-$T_c$ cuprates.

Acknowledgements

Thermal-conductivity measurements were performed at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University. This work was supported by a Grant-in-Aid for Scientific Research from Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

[1] Tranquada J M, Sternlieb B J, Axe J D, Nakamura Y and Uchida S 1995 Nature (London) 375 561
[2] Kivelson S A, Fradkin E and Emery V J 1998 Nature (London) 393 550
[3] Lake B, Rønnow H M, Christensen N B, Aeppli G, Lefmann K, McMorrow D F, Vorderwisch P, Smeibidl P, Mangkorntong N, Sasagawa T, Nohara M, Takagi H and Mason T E 2002 Nature (London) 415 299
[4] Adachi T, Kitajima N, Manabe T, Koike Y, Kudo K, Sasaki T and Kobayashi N 2005 Phys. Rev. B 71 104516
[5] Kudo K, Yamazaki M, Kawamata T, Adachi T, Noji T, Koike Y, Nishizaki T and Kobayashi N 2004 Phys. Rev. B 70 014503
[6] Kawamata T, Yamazaki M, Takahashi N, Adachi T, Noji T, Koike Y, Kudo K and Kobayashi N 2005 Physica C 426-431 469
[7] Kawamata T, Takahashi N, Yamazaki M, Adachi T, Manabe T, Noji T, Koike Y, Kudo K and Kobayashi N 2006 AIP Conf. Proc. 850 431
[8] Kakinuma N, Ono Y and Koike Y 1999 Phys. Rev. B 59 1491
[9] Kawamata T, Adachi T, Noji T and Koike Y 2000 Phys. Rev. B 62 R11981
[10] 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
[11] Suzuki T, Ota J, Tonishi J and Goto T 2006 AIP Conf. Proc. 850 409
[12] Sun X F, Komiya S, Takeya J and Ando Y 2003 Phys. Rev. Lett. 90 117004
[13] Tanabe Y, Adachi T, Noji T and Koike Y 2005 J. Phys. Soc. Jpn. 74 2893
[14] Wang Y, Yan J, Shan L, Wen H H, Tanabe Y, Adachi and Koike 2007 Phys. Rev. B 76 064512