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Field-induced magnetic order in $La_{2-x}Sr_xCuO_4$ $(x=0.10, 0.115, 0.13)$ studied by in-plane thermal conductivity measurements

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We have measured the thermal conductivity in the *ab* plane of $La_{2-x}Sr_xCuO_4$ $(x=0.10, 0.115, 0.13)$ in magnetic fields up to 14 T parallel to the *c* axis and also parallel to the *ab* plane. By the application of magnetic fields parallel to the *c* axis, the thermal conductivity has been found to be suppressed at low temperatures below the temperature T_κ which is located above the superconducting transition temperature and is almost independent of the magnitude of the magnetic field. The suppression is marked in $x=0.10$ and 0.13, while it is small in $x=0.115$. Furthermore, no suppression is observed in the 1% Zn-substituted $La_{2-x}Sr_xCu_{0.99}Zn_{0.01}O_4$ with $x=0.115$. Taking into account the experimental results that the temperature dependence of the relative reduction of the thermal conductivity is quite similar to the temperature dependence of the intensity of the incommensurate magnetic Bragg peak corresponding to the static stripe order and that the Zn substitution tends to stabilize the static order, it is concluded that the suppression of the thermal conductivity in magnetic fields is attributed to the development of the static stripe order. The present results suggest that the field-induced magnetic order in $La_{2-x}Sr_xCuO_4$ originates from the pinning of the dynamical stripes of spins and holes by vortex cores.

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I. INTRODUCTION

The so-called 1/8 anomaly, namely, the anomalous suppression of superconductivity at *p* (the hole concentration per Cu in the CuO_2 plane) ~1/8 in the La-based high-T_c superconductors has been understood in terms of the stripe model proposed by Tranquada *et al.*[1] From their neutron scattering experiment, a static stripe order of spins and holes was suggested to be formed at low temperatures in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$. Meanwhile, a spatially modulated dynamical spin correlation has been found to exist in a wide range of *p* from the underdoped to overdoped region in $La_{2-x}Sr_xCuO_4$.[2–5] Since the dynamical spin correlation may be regarded as a spin part of the dynamical stripe correlations of spins and holes, it has been understood that the dynamical stripes tend to be statically stabilized around $p=1/8$ and are easily pinned, leading to the static stripe order and the 1/8 anomaly.[1,6–12] For the pinning, the buckling of the CuO_2 plane in the tetragonal low-temperature (TLT) structure (space group: $P4_2/ncm$) is regarded as being effective in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ and $La_{2-x}Ba_xCuO_4$. Moreover, a small amount of nonmagnetic impurities such as Zn has also been found to be effective for the pinning from the transport measurements[10–12] and also from the muon-spin-relaxation (μSR) measurements.[13–18]

Recently, Katano *et al.*[19] and Lake *et al.*[20] have found from the neutron scattering experiments in magnetic fields that the intensity of the incommensurate magnetic Bragg peak corresponding to the long-range static stripe order is enhanced around $p=1/8$ in $La_{2-x}Sr_xCuO_4$ by the application of magnetic fields parallel to the *c* axis. The enhancement of the magnetic Bragg peak intensity is marked in $x=0.10$,[20] while it is observable but small in $x=0.12$.[19] A similar enhancement has also been found in the excess-oxygen-doped $La_2CuO_{4+\delta}$.[21] Such a field-induced magnetic order may be interpreted as being due to the pinning of the dynamical stripes by induced vortex cores in the *ab* plane, though the pinning effect of vortex cores is not certain. From the NMR measurements of the nearly optimally doped $Tl_2Ba_2CuO_{6+\delta}$, on the other hand, a magnetically ordered state has been detected only inside vortex cores, while the electronic state outside vortex cores remains superconducting.[22] This seems to be inconsistent with the above results of the neutron scattering experiments, suggesting the development of the long-range magnetic order in magnetic fields. As for the theoretical study on the field-induced magnetic order, before the report of these experimental results, the SO(5) theory had already predicted that the electronic state in vortex cores was an antiferromagnetically ordered one.[23,24] According to the recent theoretical study by Demler *et al.*,[25] on the other hand, the results of the neutron scattering experiments in a magnetic field may be explained as being due to the approach of the superconducting phase to the coexisting phase of the superconducting state and the magnetically ordered state as a result of the increase of the spin fluctuations with low energy induced by the proximity effect. Accordingly, the origin of the field-induced magnetic order in the La-based high-T_c cuprates has not yet been settled.

The thermal conductivity measurement is a renewed technique for study of the spin and charge state in transition-metal oxides. For example, it has been found that the thermal conductivity due to phonons is markedly enhanced in the spin-gap state of $CuGeO_3$ (Ref. 26) and $SrCu_2(BO_3)_2$ (Refs. 27–29) and also in the charge-ordered state of $Sr_{1.5}La_{0.5}MnO_4$.[30] The enhancement of the thermal conductivity due to phonons has also been reported in the static

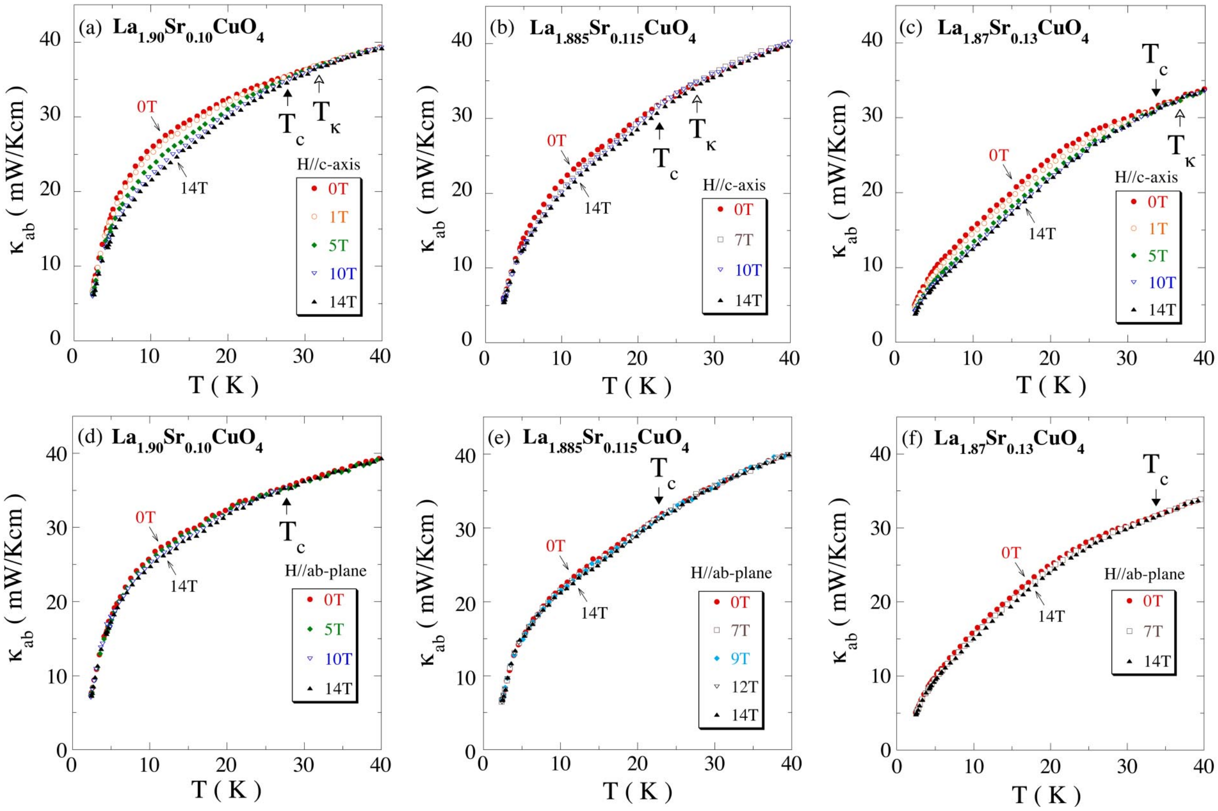

FIG. 1. (Color online) Temperature dependence of the in-plane thermal conductivity, κ_{ab}, of La$_{2-x}$Sr$_x$CuO$_4$ ($x=0.10, 0.115, 0.13$) in magnetic fields [(a)–(c)] parallel to the *c* axis and [(d)–(f)] parallel to the *ab* plane. Closed and open arrows denote the superconducting transition temperature T_c and the temperature T_κ below which the thermal conductivity is suppressed by the application of magnetic fields, respectively.

stripe-ordered state of La$_{1.28}$Nd$_{0.6}$Sr$_{0.12}$CuO$_4$ (Ref. 31) and La$_{2-x}$Sr$_x$NiO$_4$,[30] while the suppression of the thermal conductivity due to phonons has been reported in the possible short-range (dynamical) stripe-ordered state of YBa$_2$Cu$_3$O$_{7-\delta}$ and HgBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+2+\delta}$ ($n=1,2,3$) around $p=1/8$.[32] In the antiferromagnetically ordered state of La$_2$CuO$_4$ (Refs. 33–35) and YBa$_2$Cu$_3$O$_6$,[36] large contribution of magnons to the thermal conductivity in the *ab* plane has been observed.

In this paper, in order to investigate the field-induced magnetically ordered state of La$_{2-x}$Sr$_x$CuO$_4$ around $p=1/8$, we have performed the thermal conductivity measurements in the *ab* plane of La$_{2-x}$Sr$_x$CuO$_4$ ($x=0.10, 0.115, 0.13$) and 1% Zn-substituted La$_{2-x}$Sr$_x$Cu$_{0.99}$Zn$_{0.01}$O$_4$ ($x=0.115$) single crystals in magnetic fields parallel to the *c* axis and also parallel to the *ab* plane. This is because the suppression of the superconductivity occurs around $x=0.115$ in La$_{2-x}$Sr$_x$CuO$_4$ and because the suppression becomes most marked at $x=0.115$ through the partial substitution of Zn for Cu.[37]

II. EXPERIMENT

Single crystals were grown by the traveling-solvent floating-zone method in a similar way to that described in Ref. 38. Thermal conductivity measurements were carried out by a conventional steady-state method. One side of a rectangular single crystal, whose typical dimensions were $3\times1\times1$ mm^3, was anchored on the copper heat sink with indium solder. A chip resistance of 1 kΩ (Alpha Electronics Corp., MP1K000) was attached as a heater to the opposite side of the single crystal with GE7031 varnish. The temperature difference across the crystal ($0.02-1.0$ K) was measured with two Cernox thermometers (LakeShore Cryotronics, Inc., CX-1050-SD). Magnetic fields up to 14 T were applied parallel to the *c* axis and also parallel to the *ab* plane, using a superconducting magnet.

III. RESULTS AND DISCUSSION

Figures 1(a)–1(c) show the temperature dependence of the thermal conductivity in the *ab* plane, κ_{ab}, of La$_{2-x}$Sr$_x$CuO$_4$ ($x=0.10, 0.115, 0.13$) in magnetic fields parallel to the *c* axis. As formerly reported by Nakamura *et al.*,[33] κ_{ab} in zero field decreases with decreasing temperature, and it exhibits a slight enhancement below the superconducting transition temperature T_c, defined as the onset temperature of the Meissner diamagnetism. By the application of magnetic fields, κ_{ab} is suppressed at low temperatures. Strictly speaking, it appears that the temperature T_κ, below which κ_{ab} is suppressed, is located above T_c and is almost independent of the magnitude of the magnetic field. The suppression by the application of magnetic fields is marked in $x=0.10$ and 0.13, while it is small in $x=0.115$. By the application of magnetic fields parallel to the *ab* plane, on the other hand, the suppres-

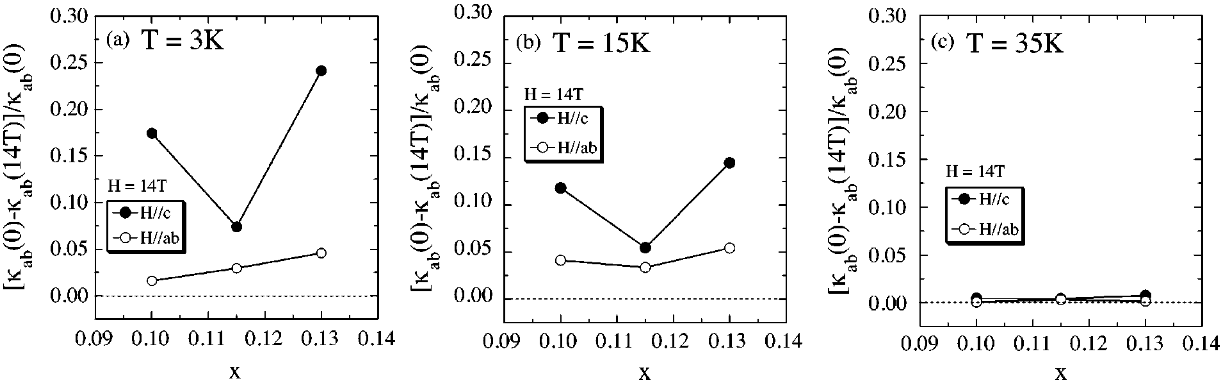

FIG. 2. Dependence on x of the relative reduction of the in-plane thermal conductivity of $La_{2-x}Sr_xCuO_4$ ($x=0.10,0.115,0.13$), $[\kappa_{ab}(0\ T)-\kappa_{ab}(14\ T)]/\kappa_{ab}(0\ T)$, in a magnetic field of 14 T parallel to the c axis and also parallel to the *ab* plane at (a) 3 K, (b) 15 K, and (c) 35 K.

sion is so small in all x that T_κ is hard to be determined, as shown in Figs. 1(d)–1(f).

Figures 2(a)–2(c) display the x dependence of the relative reduction of κ_{ab}, $[\kappa_{ab}(0\ T)-\kappa_{ab}(14\ T)]/\kappa_{ab}(0\ T)$, in a magnetic field of 14 T parallel to the c axis and also parallel to the *ab* plane. It is clearly seen that the relative reduction in a field parallel to the c axis exhibits a dip at $x=0.115$ at low temperatures below T_κ, while that in the field parallel to the *ab* plane is almost independent of x in the whole temperature range. The former x dependence with a diplike shape is similar to the diplike shape around $p=1/8$ in the T_c vs x diagram, being associated with the 1/8 anomaly and the stripe order.

First, we try explaining the observed field dependence of κ_{ab} in terms of conventional mechanisms. It is well known that the thermal conductivity in the high-T_c cuprates exhibits an increase just below T_c with decreasing temperature, which is explained as being due to the increase of the thermal conductivity due to both phonons and electrons on account of the decrease of the phonon-electron scattering rate and the increase of the lifetime of quasiparticles, respectively.[39,40] By the application of magnetic fields, the thermal conductivity due to quasiparticles is expected to be enhanced in such d-wave superconductors as the high-T_c cuprates owing to the Volovik effect,[41] namely, the increase of the density of states at the Fermi level, because the supercurrent surrounding vortices causes the Doppler shift of the energy of quasiparticles around the nodes of the superconducting gap.[42,43] In detail, recent theories have suggested two kinds of pictures for the state of quasiparticles in magnetic fields. One is a group of discrete states induced by the Andreev reflection which are composed of localized states within vortex cores[44,45] and quantized states expanding outside vortex cores.[46–49] The other is an energy-band state due to the periodic vortex potential.[50,51] In any case, however, these are contrary to the present experimental result. In order to understand the suppression of the thermal conductivity due to quasiparticles in magnetic fields, we should consider that the increase of quasiparticles leads to the increase of the electron-electron scattering rate and/or the increase of the electron-vortex scattering rate. The latter has been proposed to understand the field dependence of the in-plane thermal conductivity in $Bi_2Sr_2CaCu_2O_8$.[52,53] As for the thermal conductivity due to phonons, on the other hand, it is expected to be suppressed by the application of magnetic fields owing to the increase of the phonon-vortex scattering rate and/or the increase of the phonon-electron scattering rate, because the number of quasiparticles increases due to the Doppler shift. Hence, at a glance, the suppression of the thermal conductivity does not seem anomalous at all. However, these conventional mechanisms cannot explain the fairly small field dependence of κ_{ab} in $x=0.115$ compared with κ_{ab} in $x=0.10$ and 0.13. Therefore, a new concept is necessary to explain the suppression of the thermal conductivity by the application of magnetic fields in $La_{2-x}Sr_xCuO_4$.

Next, in order to explain the anomalous x dependence of the suppression of the thermal conductivity in magnetic fields, we focus our attention on the development of the static stripe order in magnetic fields. In the following discussion, the field-induced magnetic order is regarded as the field-induced static stripe order. For comparison with the neutron scattering data, the temperature dependence of the relative reduction of the thermal conductivity, $[\kappa_{ab}(0\ T)-\kappa_{ab}(H)]/\kappa_{ab}(0\ T)$, in several magnetic fields H parallel to the c axis is plotted in Figs. 3(a)–3(c). For $x=0.10$, it is found that the relative reduction rapidly increases at low temperatures below T_κ with decreasing temperature and that T_κ is almost independent of the magnitude of the magnetic field. The relative reduction is found to increase with increasing magnetic field. These temperature and field dependences are quite similar to those of the intensity of the magnetic Bragg peak corresponding to the static stripe order in magnetic fields in $x=0.10$.[20] Moreover, T_κ of $x=0.10$ coincides with the temperature T_M of $x=0.10$ below which the magnetic Bragg peak in magnetic fields develops.[20] Therefore, it is naturally understood that the suppression of the thermal conductivity in magnetic fields is related to the development of the static stripe order.

As mentioned in Sec. I, there are some previous reports on the relation between the thermal conductivity due to phonons and the static stripe order. It has been reported that the thermal conductivity due to phonons is enhanced by the formation of the static stripe order for $La_{1.28}Nd_{0.6}Sr_{0.12}CuO_4$ (Ref. 31) and $La_{2-x}Sr_xNiO_4$ (Ref. 30) and that, on the contrary, it is suppressed in the possible short-range (dynamical)

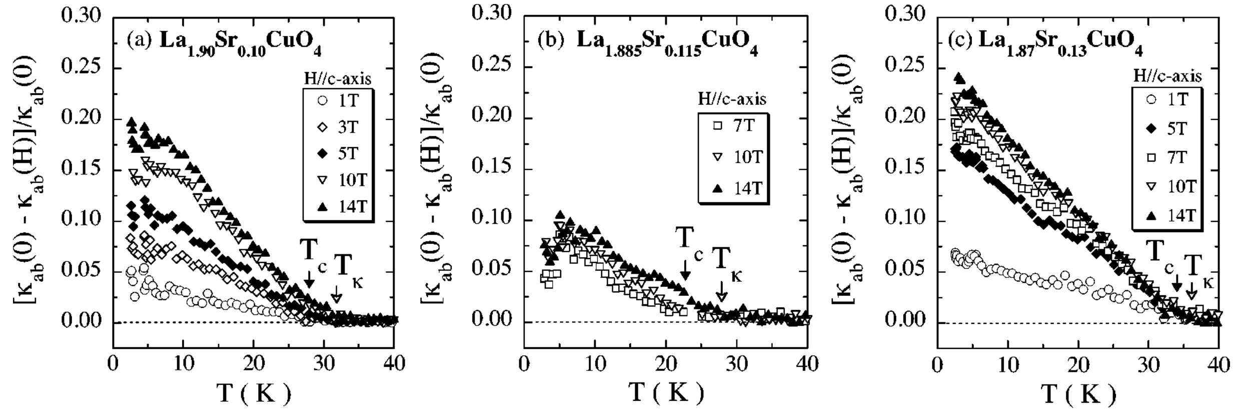

FIG. 3. Temperature dependence of the relative reduction of the in-plane thermal conductivity, $[\kappa_{ab}(0\text{ T})-\kappa_{ab}(H)]/\kappa_{ab}(0\text{ T})$, in several magnetic fields for $La_{2-x}Sr_xCuO_4$ with (a) $x=0.10$, (b) $x=0.115$, and (c) $x=0.13$. Closed and open arrows denote the superconducting transition temperature T_c and the temperature T_κ below which the thermal conductivity is suppressed by the application of magnetic fields, respectively.

stripe-ordered state of $YBa_2Cu_3O_{7-\delta}$ and $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ $(n=1,2,3)$ around $p=1/8$.[32] The enhancement of the thermal conductivity due to phonons in $La_{1.28}Nd_{0.6}Sr_{0.12}CuO_4$ has been interpreted as being due to the disappearance of the scattering of phonons by the dynamical stripes which make the mean free path of phonons strongly limited.[31] In this case, phonons are expected not to be scattered so strongly by the lattice distortion induced by the static stripe order in $La_{1.28}Nd_{0.6}Sr_{0.12}CuO_4$, because the correlation length of the static stripe order is more than ~170 Å, so that the lattice distortion is regarded as being rather periodic.[54] In the case of $YBa_2Cu_3O_{7-\delta}$, on the other hand, the suppression of the thermal conductivity due to phonons has been interpreted as being due to the possible formation of the short-range stripe order, namely, the dynamical stripe correlations, which was suggested from the inelastic neutron scattering experiment in $YBa_2Cu_3O_{6.6}$ by Mook *et al.*[55] Accordingly, it is found to depend on the correlation length of the stripe order whether the thermal conductivity is enhanced or suppressed, but the present suppression of the thermal conductivity in magnetic fields in $La_{2-x}Sr_xCuO_4$ cannot be explained on these lines, because the correlation length of the static stripe order of $x=0.10$ in a magnetic field of 14.5 T (Ref. 20) is as long as that of $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ in zero field.[54] According to the detailed investigation on the effect of the structural phase transition on the thermal conductivity for $La_{2-x-y}Nd_ySr_xCuO_4$ by Sera *et al.*,[56] on the other hand, the enhancement of the thermal conductivity is explained as being due to the increase of the phonon velocity through the structural phase transition to the TLT structure. Very recently, moreover, it has been pointed out by Hess *et al.*[57] that the enhancement in the TLT phase of $La_{2-x-y}R_ySr_xCuO_4$ (R denotes rare earth element) is probably not due to the formation of the static stripe order but due to the suppression of the lattice instability. At present, therefore, it appears that the formation of the static stripe order does not have a large effect on the thermal conductivity due to phonons and it is hard to clearly explain the present suppression of the thermal conductivity in magnetic fields on the basis of the thermal conductivity due to phonons.

Alternatively, we try to understand the suppression of the thermal conductivity on the basis of the change of the thermal conductivity due to quasiparticles through the field-induced static stripe order. In the CuO_2 plane where the static stripe order is formed, charge carriers (holes) are confined in the one-dimensional path of the stripe, so that they cannot move so easily as in the carrier-homogeneous CuO_2 plane,[58] leading to the decrease of the mobility of quasiparticles carrying heat. In fact, it has been pointed out from the electrical resistivity[59] and thermal conductivity[42] measurements that quasiparticles tend to be localized by the application of magnetic fields in the underdoped region of $La_{2-x}Sr_xCuO_4$. Moreover, when both the static stripe-ordered phase and the superconducting phase coexist and form domains, the mean free path of quasiparticles carrying heat is expected to be reduced by the domain wall. Accordingly, the suppression of the thermal conductivity in magnetic fields in $La_{2-x}Sr_xCuO_4$ is able to be ascribed to the decrease of the thermal conductivity due to quasiparticles through the development of the static stripe order, and its anomalous x dependence is also explained as follows. That is to say, the small field dependence in $x=0.115$ is attributed to the fact that the static stripe order is already developed in $x=0.115$ even in zero field,[60,61] while the large field dependence in $x=0.10$ and 0.13 is able to be regarded as being due to the marked development of the static stripe order by the application of magnetic fields. As shown in Figs. 3(a)–3(c), in fact, the field dependence of the relative reduction of the thermal conductivity is very small in $x=0.115$, compared with the large field dependence in $x=0.10$ and 0.13. Here, it is noted that the temperature dependence of the relative reduction of the thermal conductivity in $x=0.115$ and 0.13 roughly indicate the temperature dependence of the intensity of the magnetic Bragg peak corresponding to the static stripe order in magnetic fields, as in the case of $x=0.10$. Furthermore, it is worth while noting that Figs. 3(a)–3(c) perhaps represent the development of the charge stripe order in $x=0.10, 0.115$, and 0.13. By the way, this model gives a possible answer for the well-known question why the enhancement of the thermal conductivity at low temperatures below T_c is relatively small in $La_{2-x}Sr_xCuO_4$ (Ref. 33) compared with the other high-T_c cuprates.[39,40] In

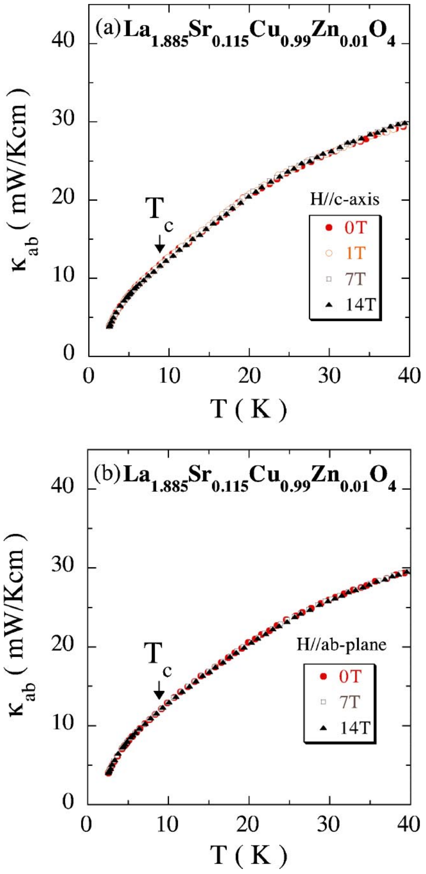

FIG. 4. (Color online) Temperature dependence of the in-plane thermal conductivity, κ_{ab}, of the 1% Zn-substituted $La_{2-x}Sr_xCu_{0.99}Zn_{0.01}O_4$ ($x=0.115$) in magnetic fields (a) parallel to the c axis and (b) parallel to the ab plane. Arrows denote the superconducting temperature T_c.

the underdoped region, this is because at least a small amount of the static stripe order exists even in zero field to strongly suppress the thermal conductivity, though the magnetic Bragg peak detected in the neutron scattering experiments is very weak.[60–62]

The above model is confirmed by the following experimental result for the 1% Zn-substituted $La_{2-x}Sr_xCu_{0.99}Zn_{0.01}O_4$ with $x=0.115$, as shown in Fig. 4. It is found that the thermal conductivity exhibits no field dependence in magnetic fields parallel to the c axis and also parallel to the ab plane. According to the above model, no field dependence is reasonably understood, because the static stripe order is fully developed even in zero field on account of the strong pinning effect of Zn,[10–18] so that further development of the static stripe order by the application of magnetic fields is not expected.

Now, there remains a question why T_κ is almost independent of the magnitude of the magnetic field, though this question has already been pointed out from the neutron scattering experiment.[20] Before answering the question, first we suppose the stripe pinning model by vortex cores. Taking into account the result that the dynamical stripes of spins and holes are pinned in such an inhomogeneous electronic background as the partially Zn-substituted CuO_2 plane,[10–18,63,64] vortex cores induced in the CuO_2 plane are also expected to operate to pin the dynamical stripes, as mentioned in Sec. I. Surely, the existence of impurities such as Zn atoms or vortex cores induces the energy loss in the dynamical stripes, but the most important point is that the energy loss depends on whether an impurity such as Zn or a vortex core is located at a charge stripe or a spin stripe. The stripe order should be located in a way which make the energy loss the smallest, so that the dynamical stripes are pinned, resulting in the development of the static stripe order. The stripe pinning model by vortex cores is supported by the present experimental result that the suppression of the thermal conductivity is not observed by the application of magnetic fields parallel to the ab plane. This is because, in magnetic fields parallel to the ab plane, vortex cores penetrate the so-called blocking layer preferably, so that no vortex core appears in the CuO_2 plane, leading to neither pinning of the dynamical stripes nor development of the static stripe order. Recurring to the question, the distance between vortex cores is ~130 Å in a magnetic field of 14 T. Therefore, the pinning effect of vortex cores seems to be so local that T_κ does not depend on the number of vortex cores, at least in magnetic fields up to 14 T. Meanwhile, it is found that T_κ is located above T_c, but this is not inconsistent with the above discussion, because the superconducting fluctuation exists above T_c. In fact, recent reports on the Nernst effect have suggested that the vortex state survives even above T_c.[65,66] Thus, the field independence of T_κ is explained in terms of the stripe pinning model by vortex cores.[67]

Finally, in order to examine the stripe pinning model by vortex cores, we compare the present results with the neutron scattering results[20,60–62] and also the recent μSR results revealing a peculiar x dependence of the temperature T_μ below which the development of the dynamical spin correlations was detected in zero field from the μSR measurements.[68,69] Figure 5 shows x dependences of T_κ, T_c, T_μ, $T_M(0)$ in zero field and $T_M(14.5\ T)$ in a magnetic field of 14.5 T parallel to the c axis. It is found that both $T_M(0)$ and T_μ exhibit the maximum at $x\sim0.115$, while T_κ exhibits the minimum at $x=0.115$. That is, the x dependences of $T_M(0)$ and T_μ are contrary to that of T_κ, so that T_κ is directly correlated with T_c rather than $T_M(0)$ and T_μ. This suggests that T_κ is regarded as the temperature below which vortex cores are formed in the superconducting fluctuation region in the CuO_2 plane so as to pin the dynamical stripes and develop the static stripe order. In fact, the observed field dependence of the thermal conductivity is well explained as follows. For $x=0.115$, T_κ is lower than $T_M(0)$, so that further development of the static stripe order is not large at low temperatures below T_κ, leading to the fairly small field dependence of the thermal conductivity. For $x=0.10$ and 0.13, on the other hand, T_κ is much higher than $T_M(0)$, so that the development of the static stripe order is marked at low temperatures below T_κ, leading to the large field dependence of the thermal conductivity. The result that T_κ is much higher than $T_M(0)$ for $x=0.10$ and 0.13 is analogous to the result obtained from the μSR measurements that the long-range magnetic ordering temperature T_N is much higher in the lightly Zn-substituted $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ than in the Zn-free $La_{2-x}Sr_xCuO_4$ for x

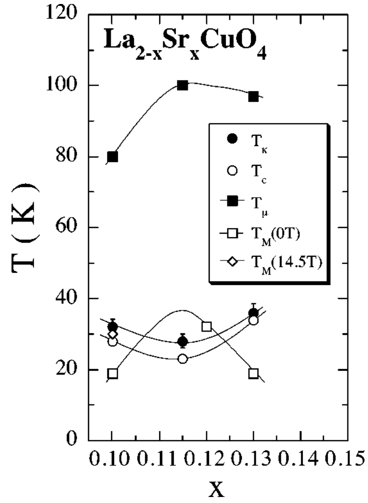

FIG. 5. Variations with x of the temperature T_κ below which the in-plane thermal conductivity is suppressed by the application of magnetic fields parallel to the c axis, the superconducting transition temperature T_c, the temperature T_μ below which the development of the dynamical spin correlation was detected in zero field from the μSR measurements (Refs. 68 and 69) and the temperatures $T_M(0)$ (Refs. 60–62) and $T_M(14.5\ T)$ (Ref. 20) below which the magnetic Bragg peak corresponding to the static stripe order develops in the neutron scattering measurements in zero field and in a magnetic field of 14.5 T parallel to the c axis, respectively. Solid lines are guides for eyes.

$=0.10$ and 0.13,[14–18] suggesting that vortex cores operate to pin the dynamical stripes as Zn atoms. This is consistent with the fact that $T_M(14.5\ T)$ deviates from $T_M(0)$ and roughly coincides with T_κ. Accordingly, the present results strongly suggest that the origin of the field induced magnetic order is the pinning of the dynamical stripes by vortex cores.

IV. CONCLUSIONS

We have measured the thermal conductivity in the ab plane of $La_{2-x}Sr_xCuO_4$ $(x=0.10, 0.115, 0.13)$ in magnetic fields up to 14 T parallel to the c axis and also parallel to the ab plane. By the application of magnetic fields parallel to the c axis, the thermal conductivity has been found to be suppressed at low temperatures below the temperature T_κ which is located above T_c and almost independent of the magnitude of the magnetic field. The suppression is marked in $x=0.10$ and 0.13, while it is small in $x=0.115$. Furthermore, no suppression is observed in the 1% Zn-substituted $La_{2-x}Sr_xCu_{0.99}Zn_{0.01}O_4$ with $x=0.115$. Taking into account the experimental results that the temperature dependence of the relative reduction of the thermal conductivity in $x=0.10$ is quite similar to the temperature dependence of the intensity of the magnetic Bragg peak corresponding to the static stripe order in magnetic fields and that the Zn substitution tends to stabilize the static order, it is concluded that the suppression of the thermal conductivity in magnetic fields is attributed to the development of the static stripe order. The temperature dependence of the relative reduction of the thermal conductivity in $x=0.115$ and 0.13 may indicate the temperature dependence of the intensity of the magnetic Bragg peak corresponding to the static stripe order in magnetic fields, as in the case of $x=0.10$. Moreover, it has been found that T_κ is directly correlated with T_c rather than $T_M(0)$ and T_μ, so that T_κ is regarded as the temperature below which vortex cores pin the dynamical stripes of spins and holes. The present results suggest that the field-induced magnetic order in $La_{2-x}Sr_xCuO_4$ originates from the pinning of the dynamical stripes of spins and holes by vortex cores.

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