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Stripe order in $La_{1.875}Ba_{0.125-x}Sr_xCuO_4$

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Abstract. We have performed elastic neutron scattering measurements on $La_{1.875}Ba_{0.125-x}Sr_xCuO_4$ single crystals with $x = 0.075$ and 0.085. Both charge-density-wave (CDW) and spin-density-wave (SDW) orders are clearly observed below the structural transition temperature (T_{d2}) between the low-temperature orthorhombic (LTO) and the low-temperature less-orthorhombic (LTLO) phases. A possible reason for the coincident appearance is discussed from the viewpoint of the stripe model.

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Since the discovery of charge and spin-stripe order in lamellar copper oxides [1], the interplay between stripe correlation and superconductivity has been drawn considerable attention [1]. Systematic neutron scattering measurements on $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (LNSCO) system with $x \sim 1/8$ reveal a competition between the stripe order and superconductivity. In the framework of the stripe model, the anomalous suppression of T_c around the hole concentration of 1/8 [2, 3] is driven by the static stripe order which is well stabilized by the lattice potential of the low-temperature tetragonal(LTT) phase. The incommensurate (IC) peaks from SDW order were subsequently observed in the superconducting LTO phase, $La_{1.88}Sr_{0.12}CuO_4$ [4, 5] and La_2CuO_{4+y} [6]. However, no evidence of CDW order was so far obtained by diffraction measurements except for the LNSCO system. It is therefore important to clarify whether the static and/or the dynamical stripe correlations commonly exist in the high-T_c superconductors. To address this issue, we performed neutron scattering measurement on single crystals of 1/8-hole doped $La_{1.875}Ba_{0.075}Sr_{0.05}CuO_4$ (LBSCO) system. In this paper, we present neutron scattreing results showing the evidence of stripe order in the LTLO phase with Pccn symmetry of LBSCO system. In contrast to the case of LNSCO we newly found coincident appearance of both CDW and SDW orders below T_{d2}.

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1 Experimental details

We grew single crystals utilizing a standard traveling-solvent floating-zone method. Typical size of the grown crystal-rod is ~ 100 mm in length and 6mm in diameter. The final part of growth was cut into ~ 30 mm and annealed under oxygen gas flow to minimize oxygen deficiencies. To characterize the superconducting transition temperature (T_c), we measured diamagnetic susceptibility by using a SQUID magnetometer. Evaluated T_c's were 14.0 K and 32.0 K for the $x = 0.075$ and 0.085 samples, respectively [7, 8]. Elastic neutron scattering measurements were performed on the triple-axis spectrometers TOPAN and TAS-1 installed in the JRR-3M reactor at the Japan Atomic Energy Research Institute (JAERI) in Tokai. We selected the incident neutron energies of $E_i = 14.7$ meV for TOPAN and 13.7 meV for TAS-1 using the (0 0 2) reflection of a pyrolytic graphite monochromator. Horizontal collimator sequences were $15'$-$30'$-$30'$-$80'$ and $30'$-$30'$-$60'$-$80'$ at TOPAN and $30'$-$30'$-$30'$-$80'$ at TAS-1. We mounted the sample with the $(h\,k\,0)$ plane parallel to the scattering plane. All crystallographic indexes in this paper are described in the high-temperature tetragonal notation.

2 Results

In the $x = 0.075$ and 0.085 samples we observed a split of (0 1 0) superlattice peak reflecting the orthorhombic domains at low temperature. Therefore, the observed CDW order, which will be described below, is the first example of stripe order in the orthorhombic phase. As seen in Fig. 1a and b, the elastic IC peaks from CDW and SDW orders are clearly confirmed in the $x = 0.085$ sample at low temperature. Scans are made along $(0\,k\,0)$ and $(h\,0.5\,0)$ through the IC peaks. Qualitative analysis (detail will be presented elsewhere [9]) evaluates the incommensurability for the CDW peak (ε) to be 0.242 ± 0.003 and for the SDW peak (δ) to be 0.120 ± 0.001 which is close to total hole concentration. Therefore the incommensurabilities for both orders satisfy a simple relation of $\varepsilon = 2\delta$ within the error as seen in the LNSCO system [1, 10]. We note that ε and δ for the $x = 0.075$ sample are respectively, 0.240 ± 0.03 and 0.120 ± 0.001 and obey the above relation.

In Fig. 2 we show temperature dependence of the CDW and SDW peak intensities for the $x = 0.085$ sample together with that of the (0 1 0) peak intensity. Intensities are normalized by the data at the lowest temperature after subtracting the background. Both CDW and SDW peak intensities coincidentally appear at T_{d2} (~ 30 K) upon cooling and the peaks exhibit a similar temperature dependence to that of structural order parameter (0 1 0). In other words, both IC peaks are associated with the LTLO phase. As shown in Fig. 3, the same results on both CDW and SDW orders are obtained for the $x = 0.075$ ($T_{d2} = 32$ K) sample.

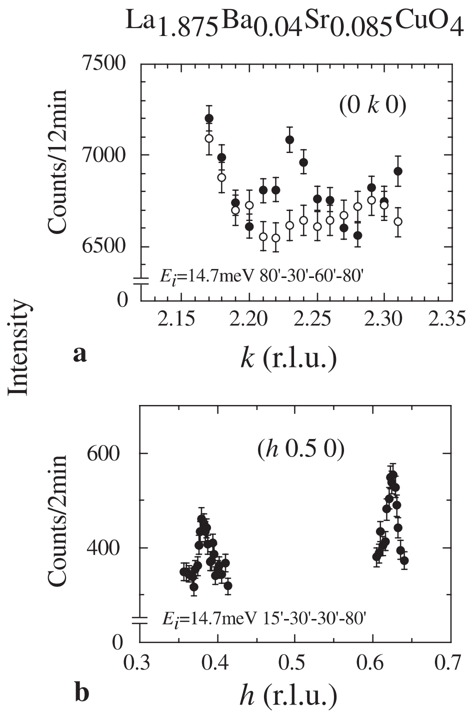

Fig. 1. a Incommensurate peaks from CDW order in the less-orthorhombic phase with *Pccn* symmetry of $La_{1.875}Ba_{0.04}Sr_{0.085}CuO_4$ measured at 1.8 K (*closed circles*) and 35 K (*open circles*). **b** SDW peaks measured at 2.2 K

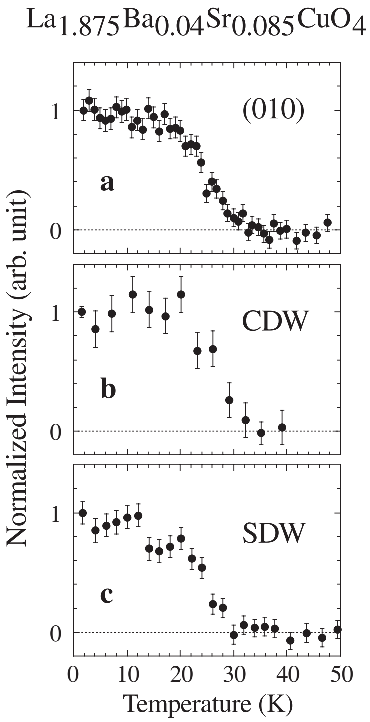

Fig. 2a–c. Temperature dependencies of **a** (0 1 0), **b** CDW and **c** SDW superlattice peak intensities for $La_{1.875}Ba_{0.04}Sr_{0.085}CuO_4$

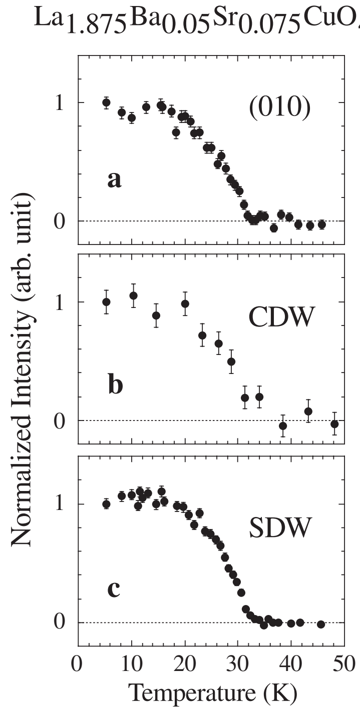

Fig. 3a–c. Temperature dependencies of **a** (0 1 0), **b** CDW and **c** SDW superlattice peak intensities for $La_{1.875}Ba_{0.05}Sr_{0.075}CuO_4$

3 Discussion

Elastic neutron scattering measurements on the LTLO phase of $La_{1.875}Ba_{0.125-x}Sr_xCuO_4$ observed incommensurate CDW and SDW orders with the incommensurabilities comparable with those of the LNSCO system. However, present result shows a clear contrast in the ordering sequence of CDW and SDW compared with the LNSCO system. For the latter, with decreasing temperature CDW is firstly formed below T_{d2} followed by SDW order at lower temperature as seen in nickelate systems [11, 12]. On the other hand, in the present system both CDW and SDW orders appear coincidentally below T_{d2}. We interpret that such discrepancy in ordering sequence is caused by the difference in T_{d2} of two systems. In the LNSCO with $x = 1/8$, T_{d2} (~ 70 K) is ~ 40 K higher than that in the present LBSCO system. In such a case, the SDW can thermally fluctuate even in the LTT or LTLO phase where the static CDW order is stabilized. Additionally, thermal fluctuation of Nd^{3+} spins in the LNSCO may enhance the fluctuation of Cu spins. The ordering sequence of sample with higher T_{d2} in the LBSCO system is important to confirm the above interpretation.

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