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Tracking motion of topological defects in a stripe charge-ordered phase with continuously variable temperature cryo-STEM

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Understanding the complex phase diagrams of quantum materials requires careful characterization and *in situ* control at the atomic scale. Scanning transmission electron microscopy (STEM) provides a powerful local probe which can measure structural modulations, such as the periodic lattice distortions (PLDs) associated with charge ordering, with high resolution and precision. The strong temperature dependence of many strongly correlated phenomena makes cryogenic temperature control key to studying the emergence, interaction, and transitions of these phases [1,2]. Using a recently developed side-entry holder which enables stable STEM imaging at temperatures from ~100–1000 K [3], we have measured the PLDs in a charge ordered manganite from the low temperature commensurate phase to just below T_c, near room temperature. The holder's high stability and fast temperature control enable tracking of the same region of interest through complete temperature cycles, allowing the picometer scale displacements of every atomic column in the field of view to be measured at each temperature step. This dynamic information reveals how topological defects in the PLDs travel through the material and how the PLDs restructure around the defects as the temperature is cycled between near-room temperature and cryogenic temperatures (~100 K).

$Bi_{.35}Sr_{.17}Ca_{.48}MnO_3$ (BSCMO) is a model charge ordered system with a T_c just above room temperature. Near room temperature, the wavevector of the PLDs associated with charge ordering is incommensurate, while cooling to liquid nitrogen temperature the wavevector lengthens to the commensurate position. Previous STEM work on the system showed that even at room temperature the PLD is locally commensurate at nanometer length scales, and the incommensuration is driven by phase inhomogeneity which manifests through topological defects and phase shifts in the PLD [4,5]. Here, we measure the displacements of the atomic columns associated with the striped PLD at several discrete temperature steps between 100 and 298 K over the same region of interest, revealing motion of topological defects upon heating. Figure 1 shows a topological defect in the PLD in a region of the sample that is otherwise free of crystalline defects. As the temperature of the sample is increased the topological defects present in the PLD move through the lattice causing a local restructuring of the PLD stripes; however, away from the defects the PLD remains almost entirely static. This is shown in Figure 2, which visualizes how the PLD stripes shift over 3 temperature steps. These findings suggest that the motion of topological defects may be a mechanism through which phase inhomogeneity in the PLD is propagated.

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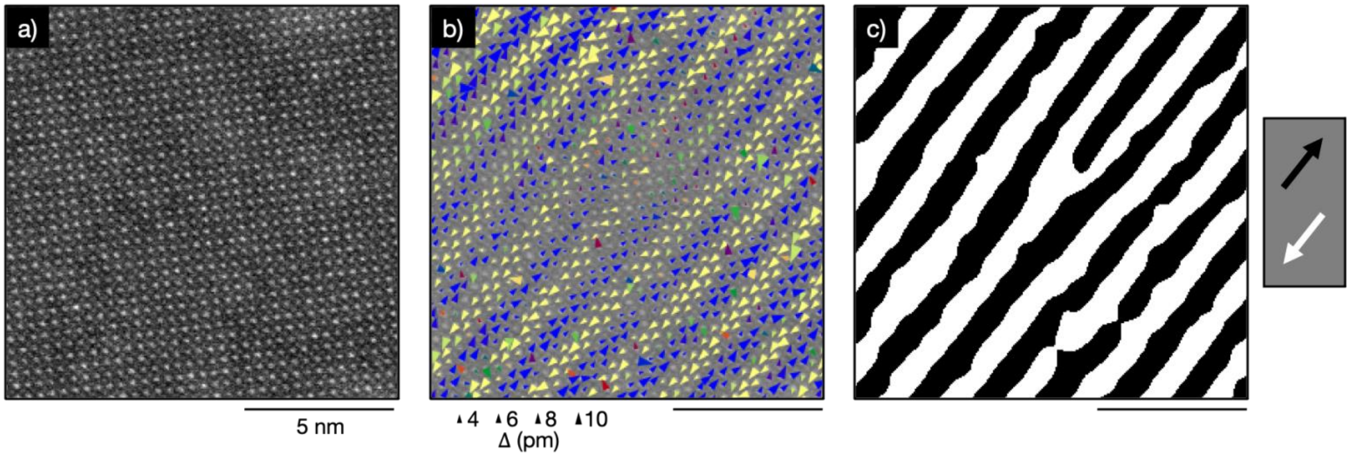

Figure 1. Measurement of a topological defect in a periodic lattice distortion (PLD) at ~115 K. a) Atomic resolution HAADF-STEM image shows a lattice free of crystalline defects. b) Map of picometer scale displacements of each atomic column in the low temperature phase reveal a topological defect in the PLD stripes. c) The defect and alternating directions of the stripes are highlighted by smoothing and thresholding the displacements from (b).

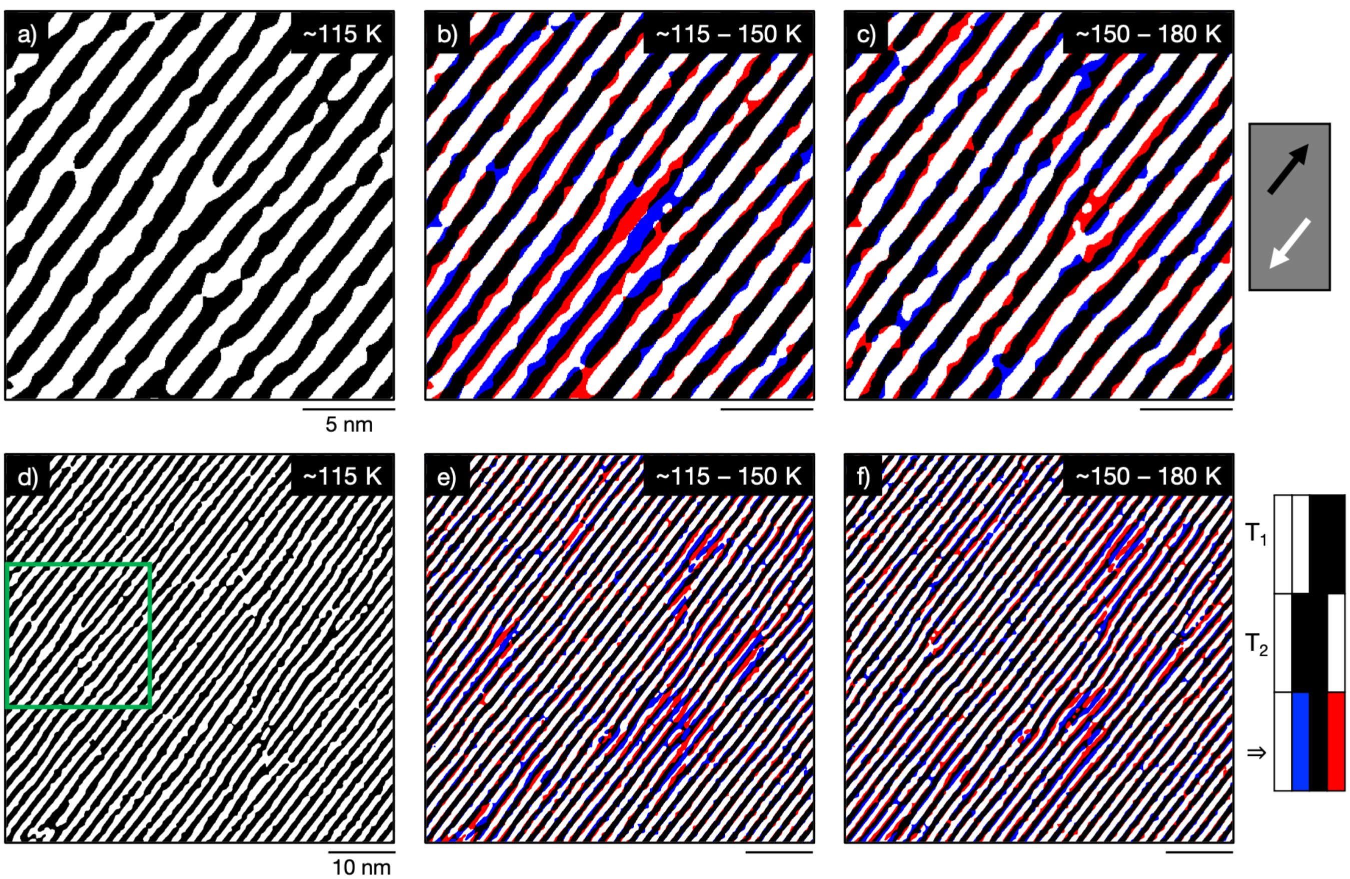

Figure 2. Motion of topological defects in PLD through temperature. a,d) Visualization of PLD stripes at ~115 K. Green box in (d) denotes the field of view shown in (a-c). b,e) Changes in stripes between ~115 and ~150 K. e,f) Changes in stripes between ~150 and ~180 K. Regions shown in blue reversed direction

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from white to black, regions shown in red reversed direction from black to white upon heating, as shown in schematic on right. Away from the defects, the PLD remains largely unchanged across all temperatures.

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