Electric-Field Control of Polar Vortices

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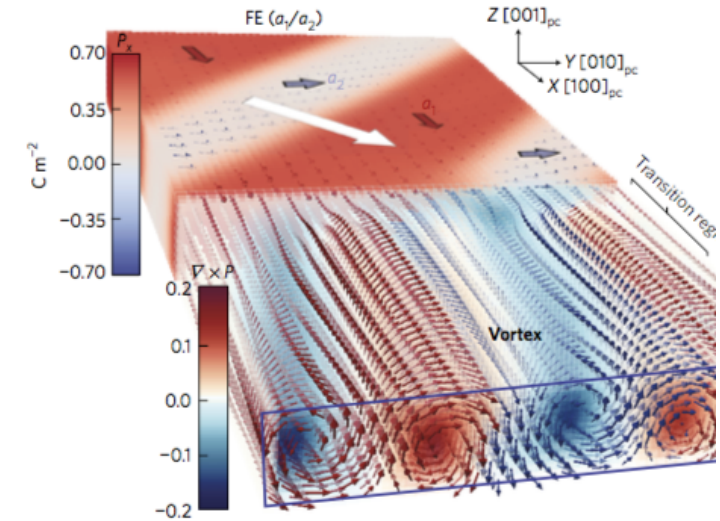
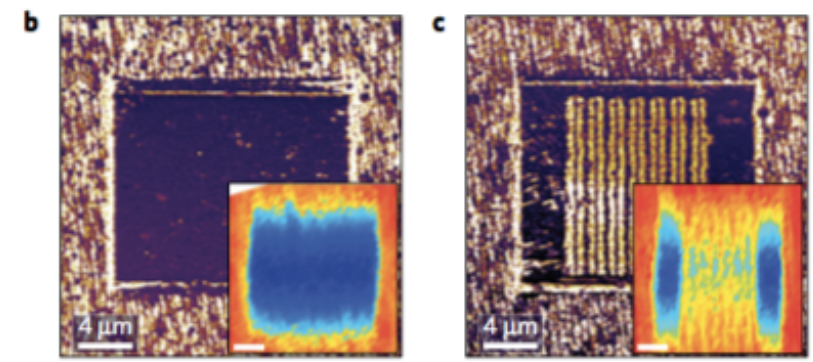
Systems that exhibit phase competition, order parameter coexistence, and emergent order parameter topologies constitute a major part of modern condensed-matter physics. Here, by applying a range of characterization techniques, and simulations, we observe that in $PbTiO_3/SrTiO_3$ superlattices all of these effects can be found. By exploring superlattice period-, temperature- and field-dependent evolution of these structures, we observe several new features. First, it is possible to engineer phase coexistence mediated by a first-order phase transition between an emergent, low-temperature vortex phase with electric toroidal order and a high-temperature ferroelectric *a*1/*a*2 phase. At room temperature, the coexisting vortex and ferroelectric phases (**Figure**) form a mesoscale, fiber-textured hierarchical superstructure. The vortex phase possesses an axial polarization, set by the net polarization of the surrounding ferroelectric domains, such that it possesses a multi-order-parameter state and belongs to a class of gyrotropic electrotoroidal compounds. Finally, application of electric fields to this mixed-phase system permits interconversion between the vortex and the ferroelectric phases (Figure) concomitant with order-of-magnitude changes in piezoelectric and nonlinear optical responses. Our findings suggest new cross-coupled functionalities.





(top) A zoom-in of the phase-field calculation focusing on a single $PbTiO_3$ in a $PbTiO_3/SrTiO_3$ superlattice revealing that the ferroelectric *a*1/*a*2 superdomain smoothly transitions to the vortex phase comprising of alternating clockwise and anticlockwise polarization vortices. (below, left) a window of Vortex region written electrically in a matrix of mixed phase, and (right) striped of mixed phase within the vortex window.

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