Manipulation of Topological Ferroelectric Domain by Nanoindentation and Nanoscratch

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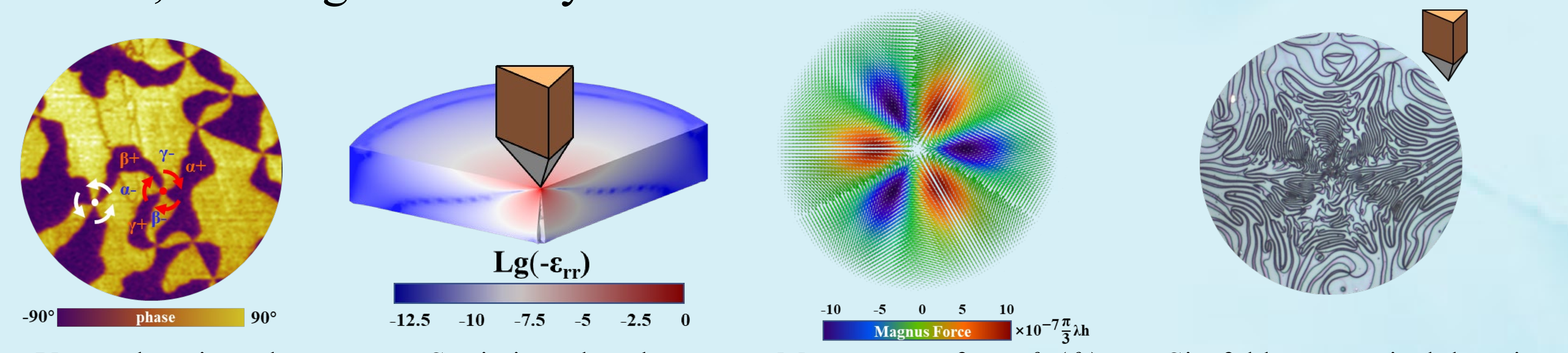
1. Introduction

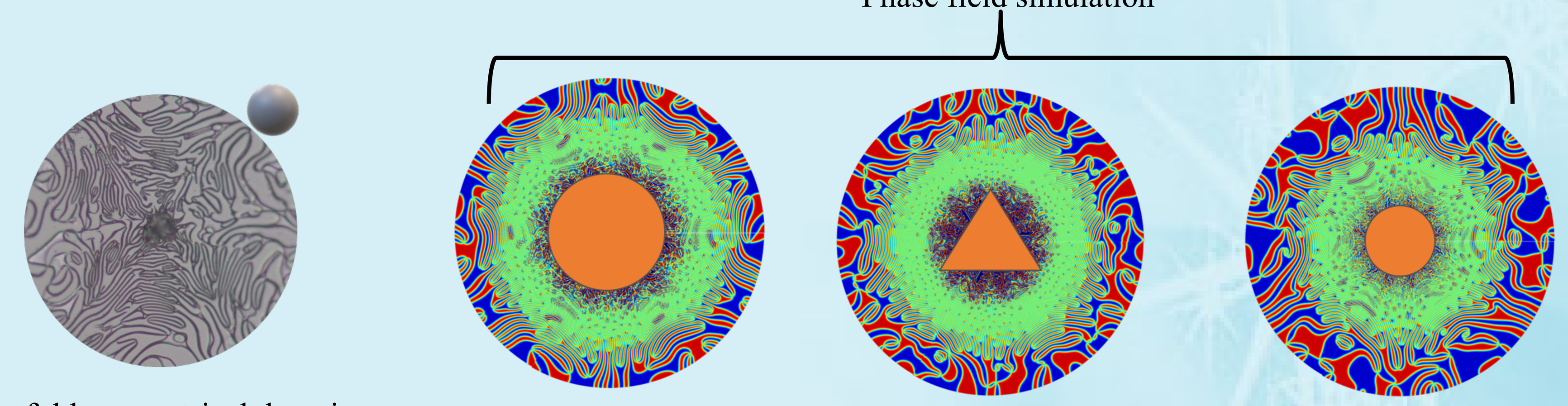
- High temperature annealing across T_C ($T > T_C$) of hexagonal manganites h-$RMnO_3$ crystal induces randomly distributed ferroelectric vortex domains.
- Due to the lattice distortion and trimerization, the vortex domains form $Z_2 \times Z_3$ type vortex-antivortex pairs, as characterized by (α+, β-, γ+, α-β+ γ-) and (α+, γ-, β+, α-, γ+, β-) with reversed vorticity.
- Nanoindentation is utilized to create an indent on the surface of as-grown $LuMnO_3$ single crystal to induce local stress/strain distribution.
- Under the alternately three-fold symmetry Magnus force, the induced strain gives rise to a rearrangement of the topological ferroelectric vortex, forming six-fold symmetrical domains.



Vortex domain and Vortex-antivortex pairs | Strain introduced by nanoindentation | Magnus-type force f_A (f_V) around the nanoindentation | Six-fold symmetrical domains induced by Berkovich indenter

2. Manipulation domains by Nanoindentation

- Six-fold symmetrical domains is independent of indenter shape.



Phase field simulation

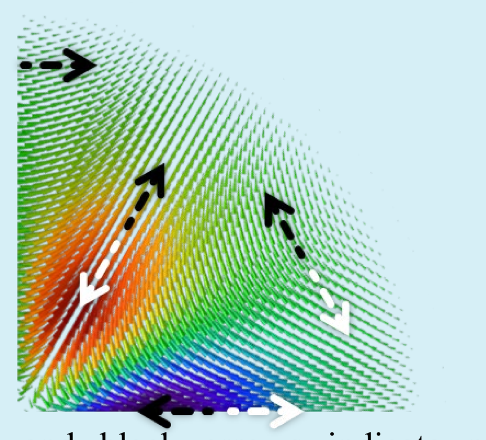
Six-fold symmetrical domains induced by spherical indenter | Spherical indenter | Berkovich indenter | Conical indenter

- Finite element simulation and random direction nanoindentation experiments confirm that the induced strain distribution (Magnus force) is coupled to the hexagonal crystalline lattice.
- Interaction energy F_{int} between strain and the vortex-antivortex positions:

$$F_{int} = \frac{\pi}{3}\lambda h\left[(\varepsilon_{xx}-\varepsilon_{yy})(y_A - y_V) + 2\varepsilon_{xy}(x_A - x_V)\right]$$

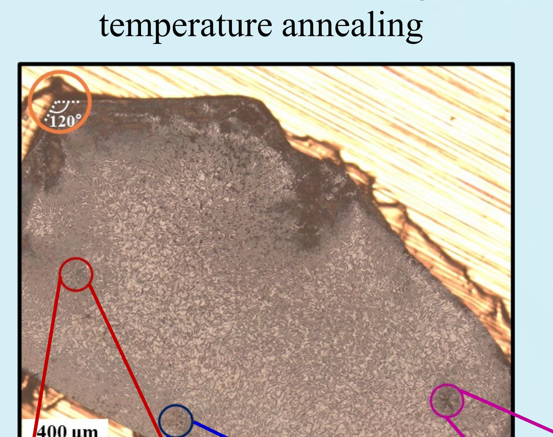
- Magnus force: $f_V = -\frac{\partial F_{int}}{\partial x_V} = -f_A = \frac{\pi}{3}\lambda h(2\varepsilon_{xy}, (\varepsilon_{xx}-\varepsilon_{yy}))$

First quadrant of Magnus force f_A (f_V) around the nanoindentation

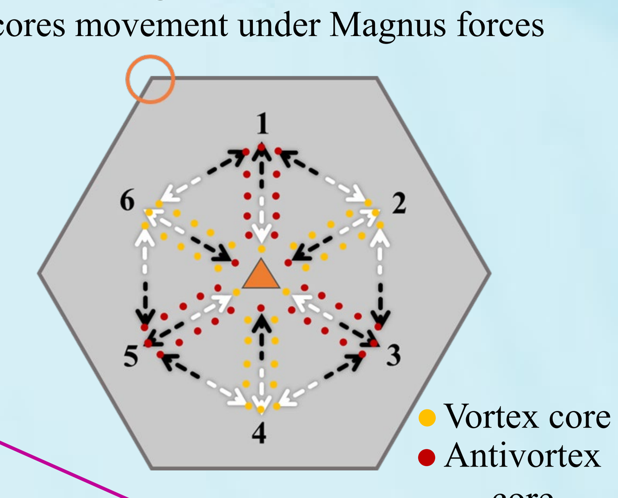


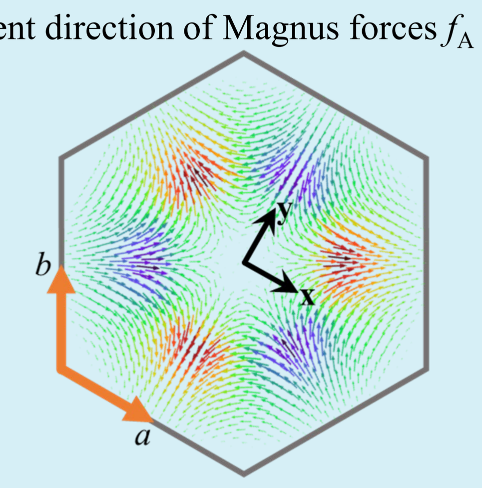
The white and black arrows indicate main component direction of Magnus forces f_A and f_V

Vortex domains after high temperature annealing

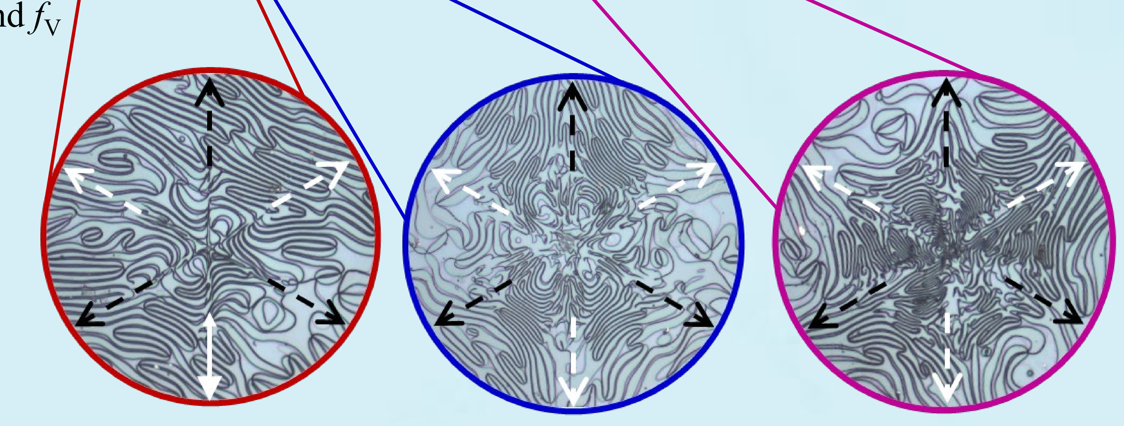


Schematic diagram of vortex and antivortex cores movement under Magnus forces

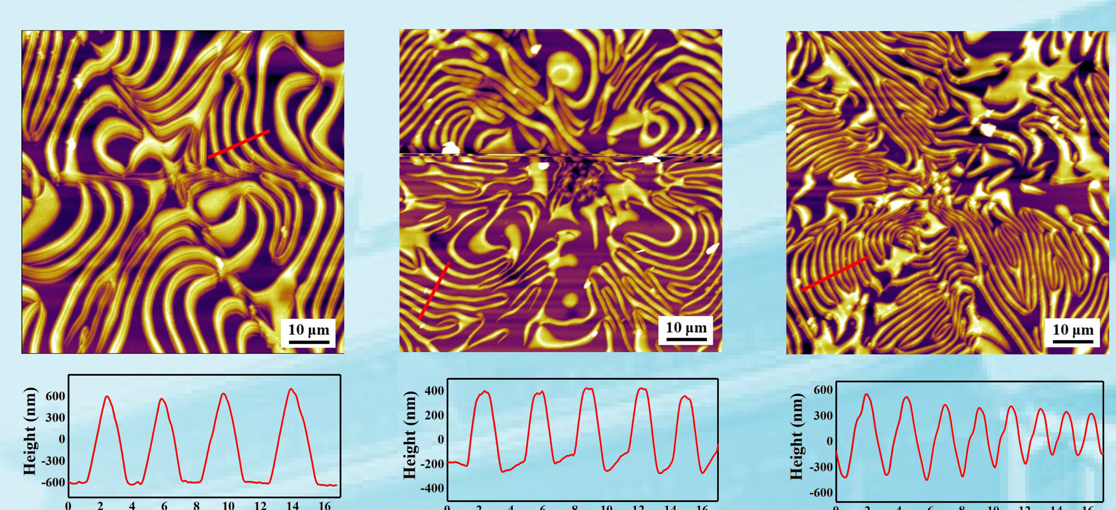




Magnus force distribution by finite element simulation



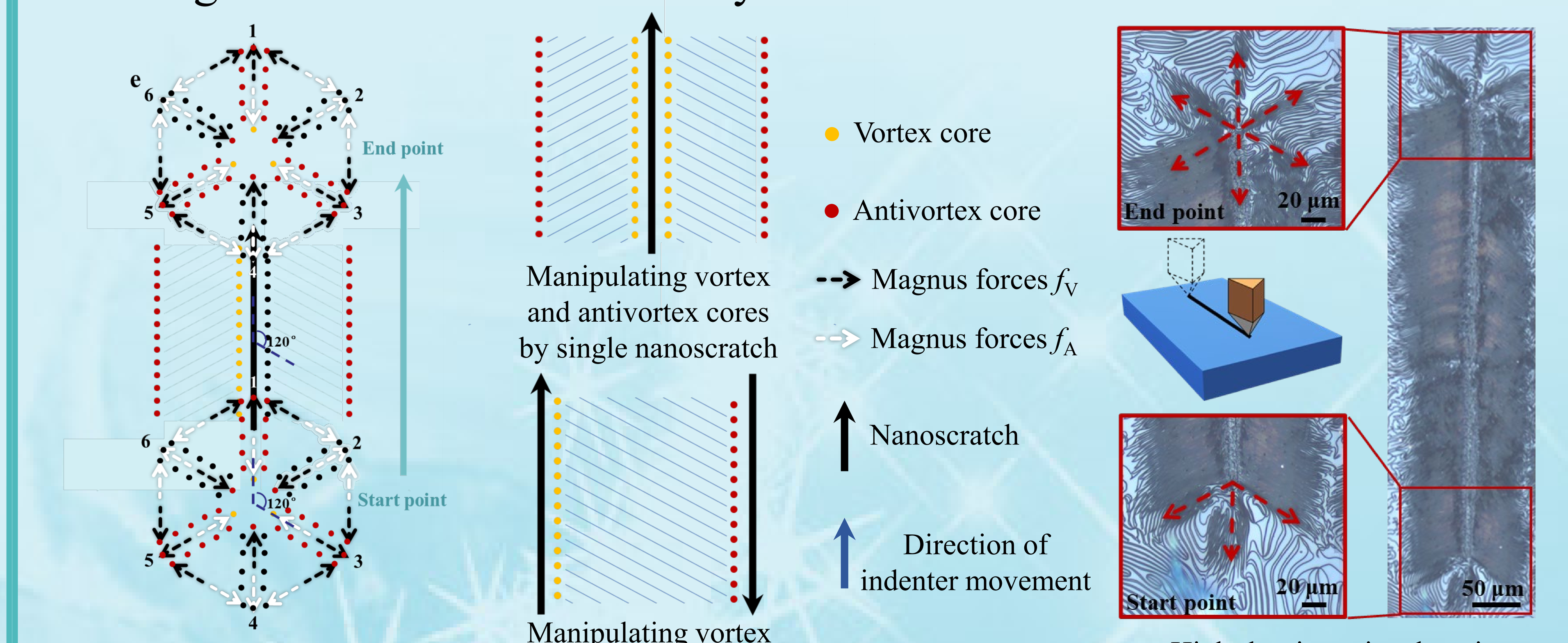
50 mN loading | 100 mN loading | 400 mN loading



- The periodicity of domain distribution reduced as increasing the mechanical load.

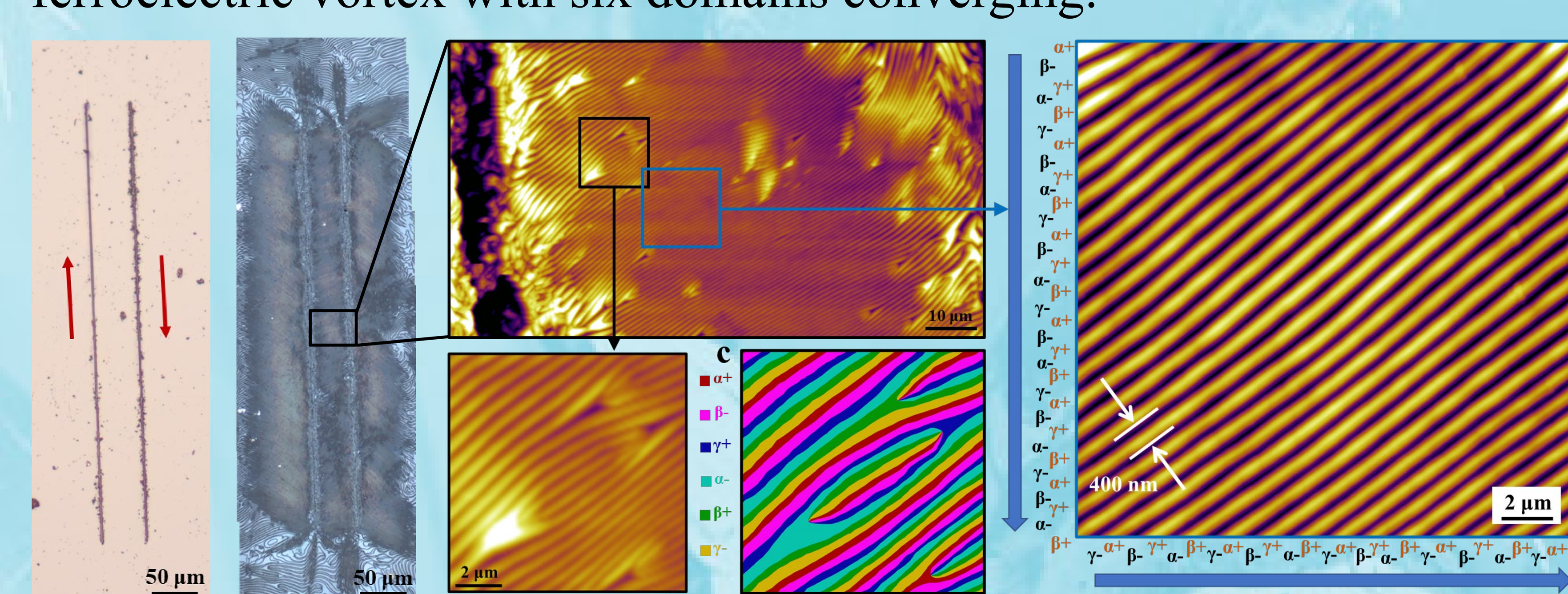
3. Manipulation domains by Nanoscratch

- Based on the mechanism of nanoindentation, we design and extend the vortex domain manipulation to a larger area (nanoscratch).
- Following the tangential Magnus force which pushes the vortex and antivortex cores in opposite directions, the stripe domains are formed in the region between the six-fold symmetric distribution axes.



The process of manipulating vortex and antivortex cores by nanoscratch | Manipulating vortex and antivortex cores by single nanoscratch | Manipulating vortex and antivortex cores by antiparallel nanoscratch | High-density stripe domains induced by nanoscratch

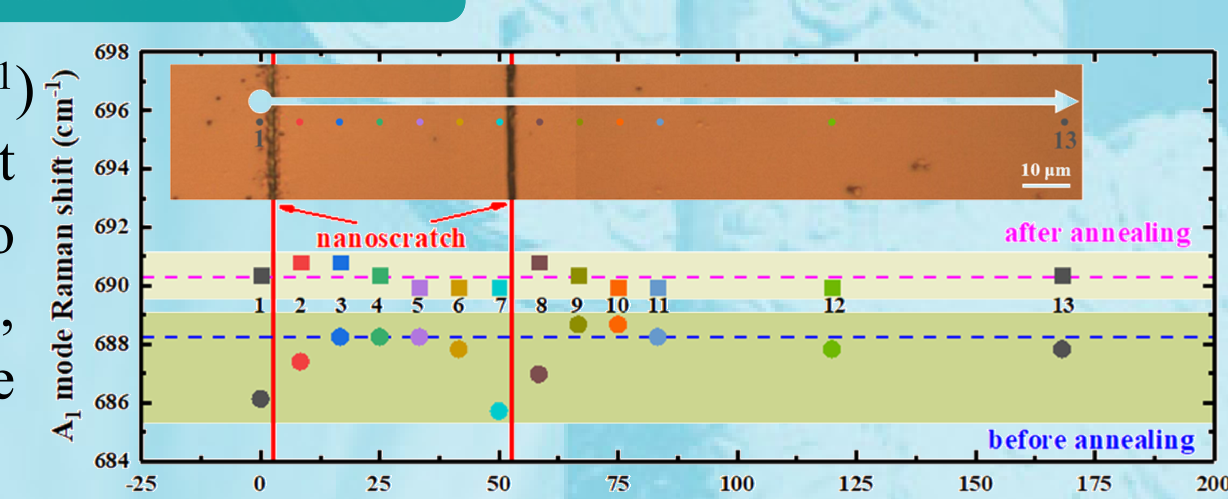
- In the light of nanoscratch strategy, we design antiparallel nanoscratches.
- A mono-chiral topological stripe domain is formed due to elongated vortex-antivortex pairs.
- Both ends of the stripe domains are still topological protected ferroelectric vortex with six domains converging.



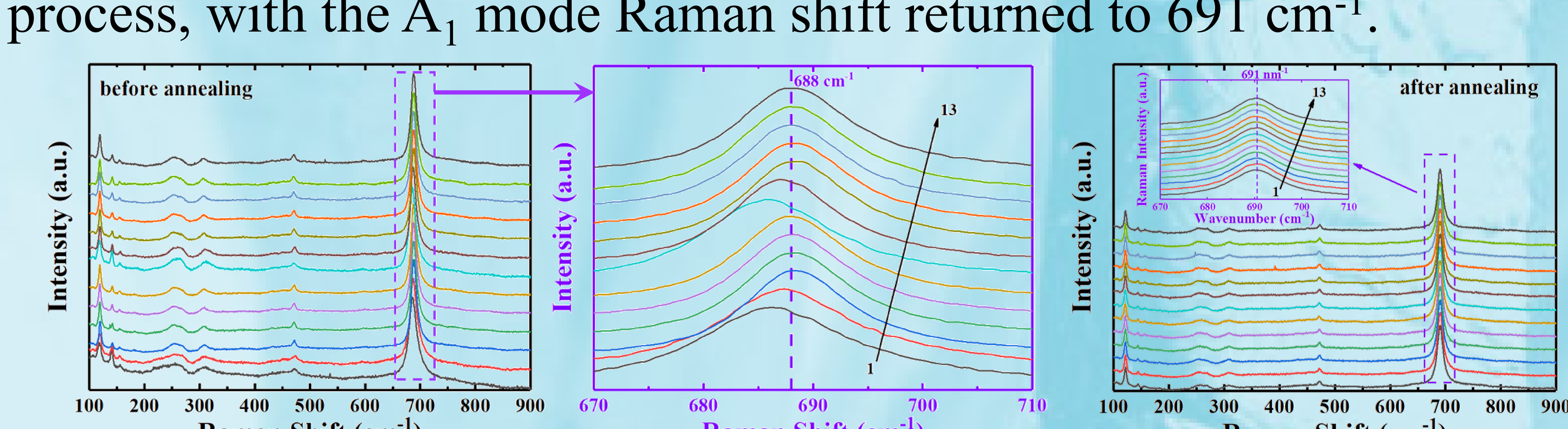
High-density mono-chiral topological stripe domains induced by antiparallel nanoscratches

4. Strain field of nanoscratch

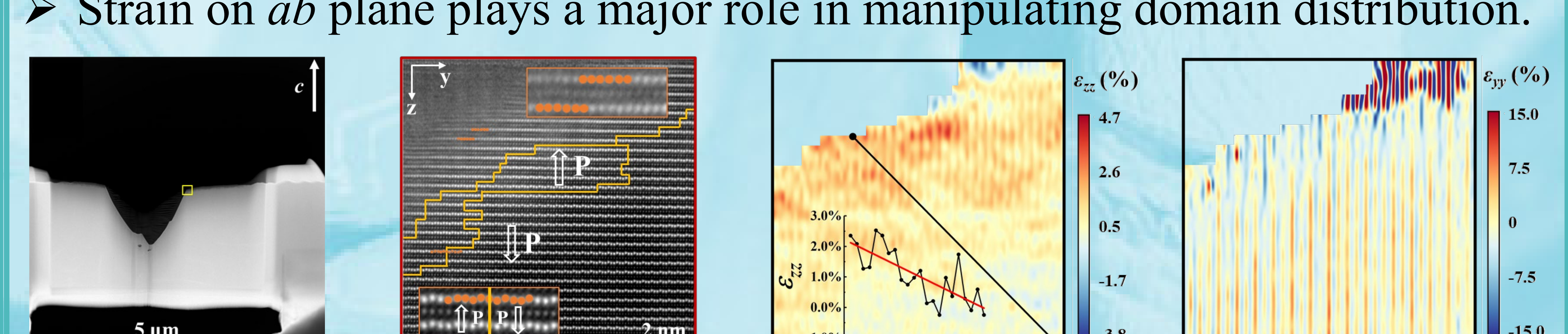
- The A_1 mode (691 cm^{-1}) Raman shift is lower at the position closer to the nanoscratch, indicating that the tensile strain is larger.



- The tensile strain of all measured locations is relaxed after the annealing process, with the A_1 mode Raman shift returned to 691 cm^{-1}.



- Compared with the range (20 μm on ab plane) of strain obtained by Raman, the range of strain is 20 nm along c axis below nanoscratch.
- Strain on ab plane plays a major role in manipulating domain distribution.



The cross-section of nanoscratch prepared by FIB | The high-resolution atomic map near nanoscratch on ac-plane | The strain ε_{zz} map calculated by Lu atomic displacement | The strain ε_{xy} map calculated by Lu atomic displacement

5. Conclusion

We propose and demonstrate a mechanical designable strategy to manipulate alignment of topological domain networks.

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