Nanoscale Multi-modal Manipulation and Imaging of Multiferroics in 3-Dimensions

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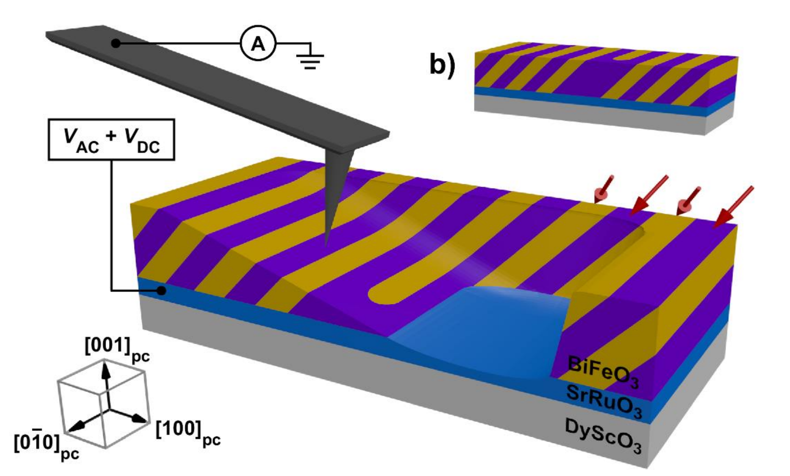
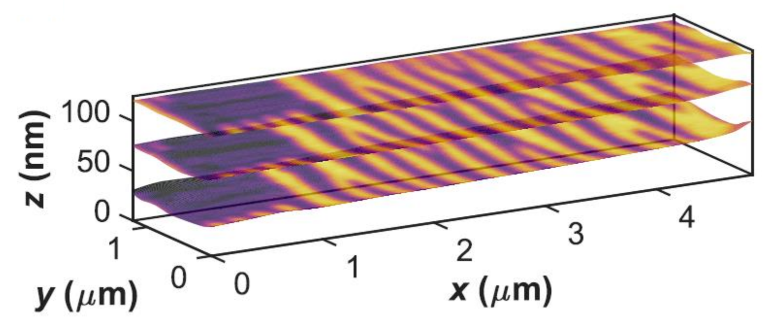
Ferromagnetic and multiferroic nanostructures are promising for next generation memory, logic, sensors, actuators, and nanoelectronics. In this work, we apply advanced scanning probe microscopy techniques including Magnetic Force Microscopy (MFM), Piezoresponse Force Microscopy (PFM), and Tomographic Atomic Force Microscopy (T-AFM) for nanoscale characterization of three multiferroic systems: homogeneous $BiFeO_3$ thin films, self-assembled $BiFeO_3$-$CoFe_2O_4$ (BFO-CFO) vertically aligned nanocomposites, and Lanthanum Strontium Manganite (LSMO) nanoarrays. Correlations between domain nanostructure and microstructural and engineered feature geometries are studied. Additionally, correlations between ferroelectric polarization and interfacial strain are directly investigated in 3 dimensions. Such correlated, multi-modal nanoscale imaging is promising for future optimization of multiferroic devices.

Tomography: $BiFeO_3$ thin films

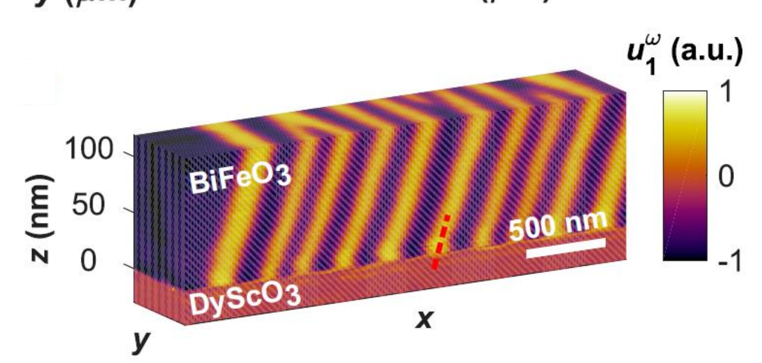
- Functional properties such as ferroelectric domain patterns are mapped with PFM.



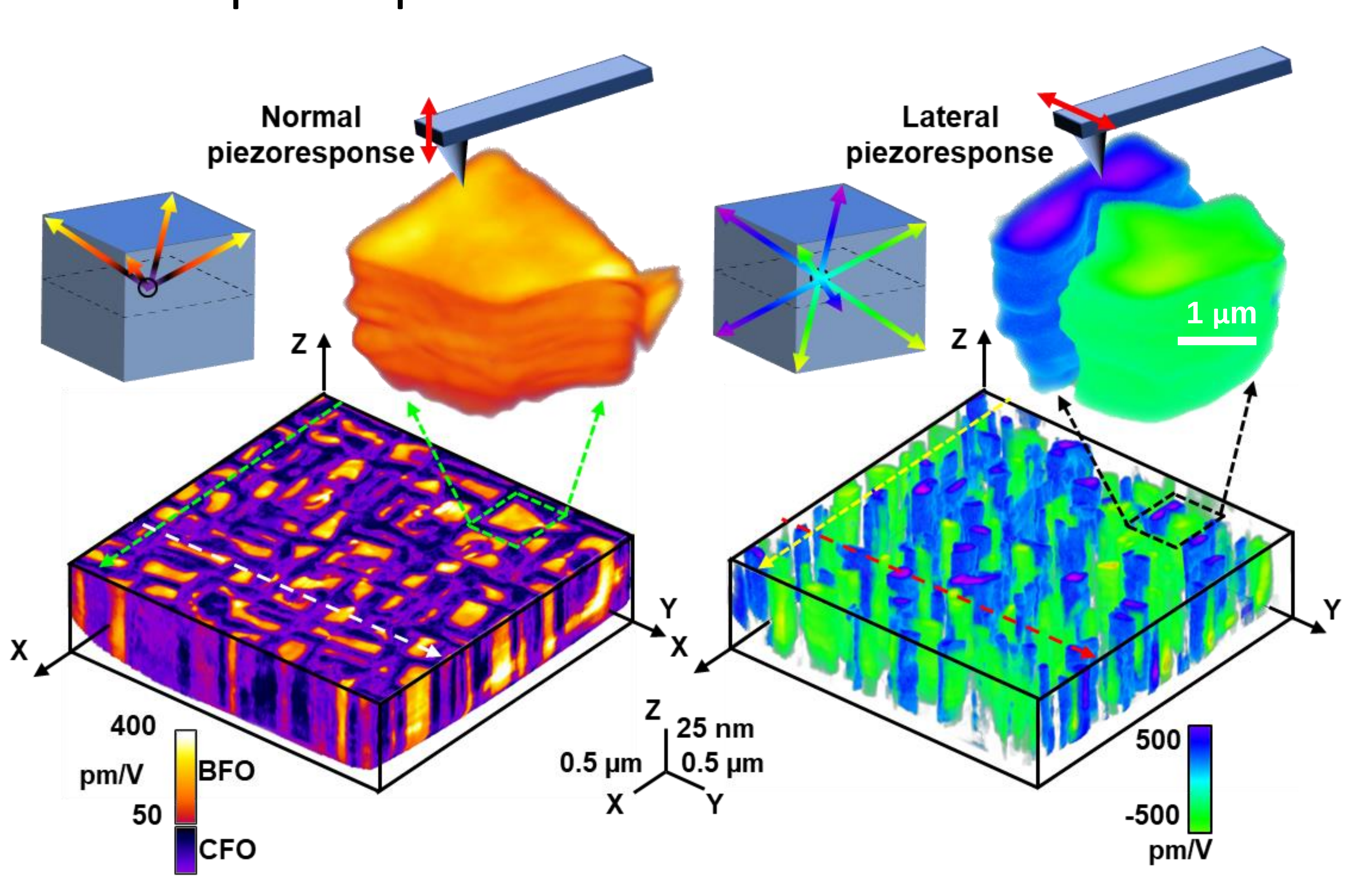
- Combined with serial sectioning, nanoscale volumetric resolution is uniquely feasible.



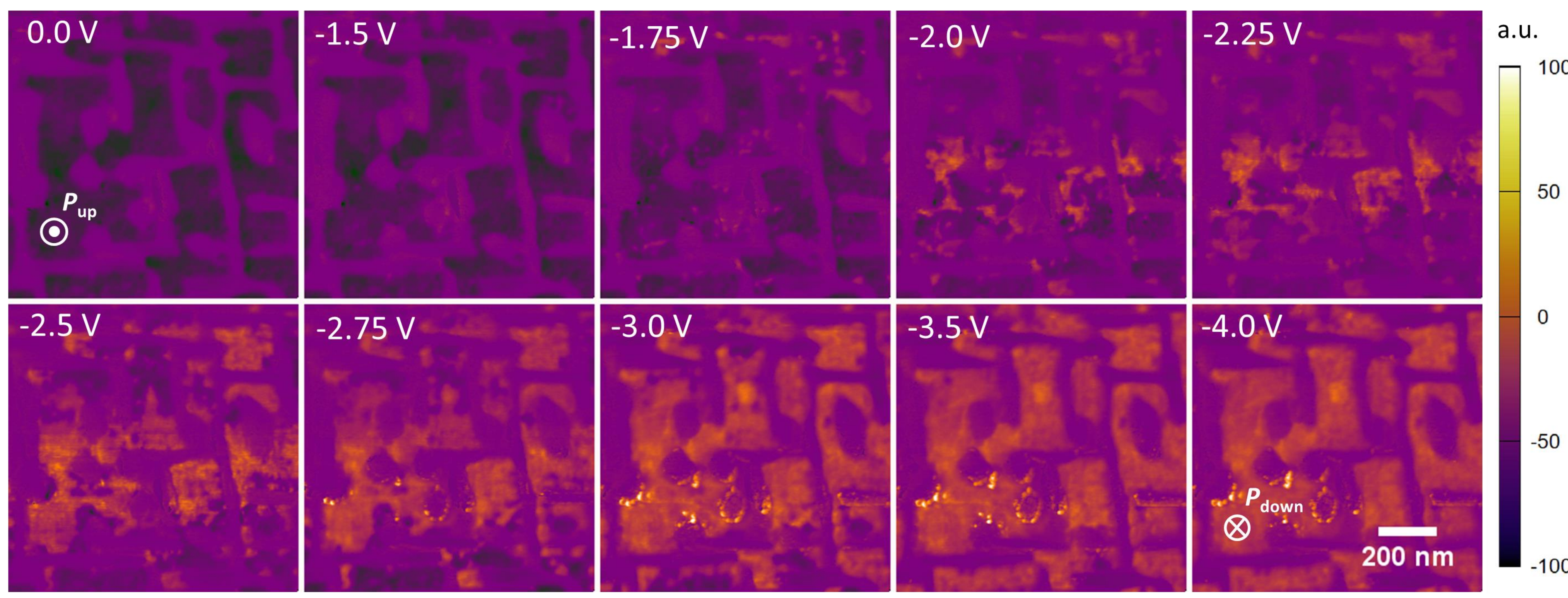
- For a homogeneous BFO thin film, TAFM reveals the sub-surface domain tilt and converging / diverging domains.



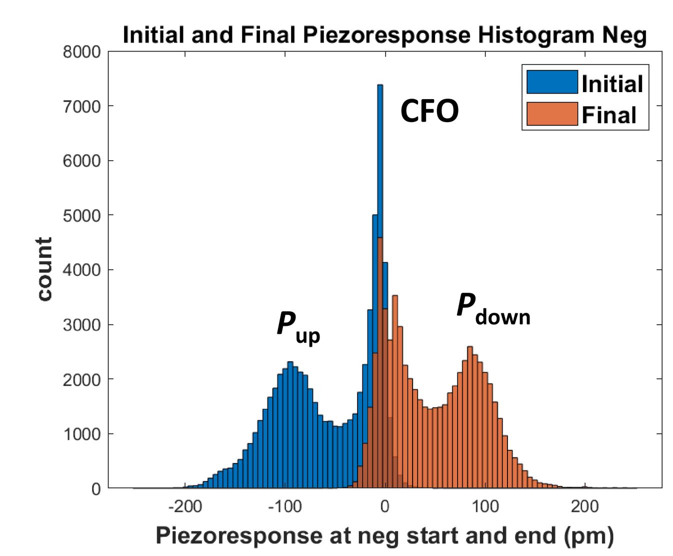
- With BFO-CFO vertically aligned nanocomposites (strained BFO mesas epitaxially embedded within a matrix of ferromagnetic CFO), combined in-plane and out-of-plane tomographic PFM even uncovers 3D ferroelectric domain configurations and Depth dependencies.

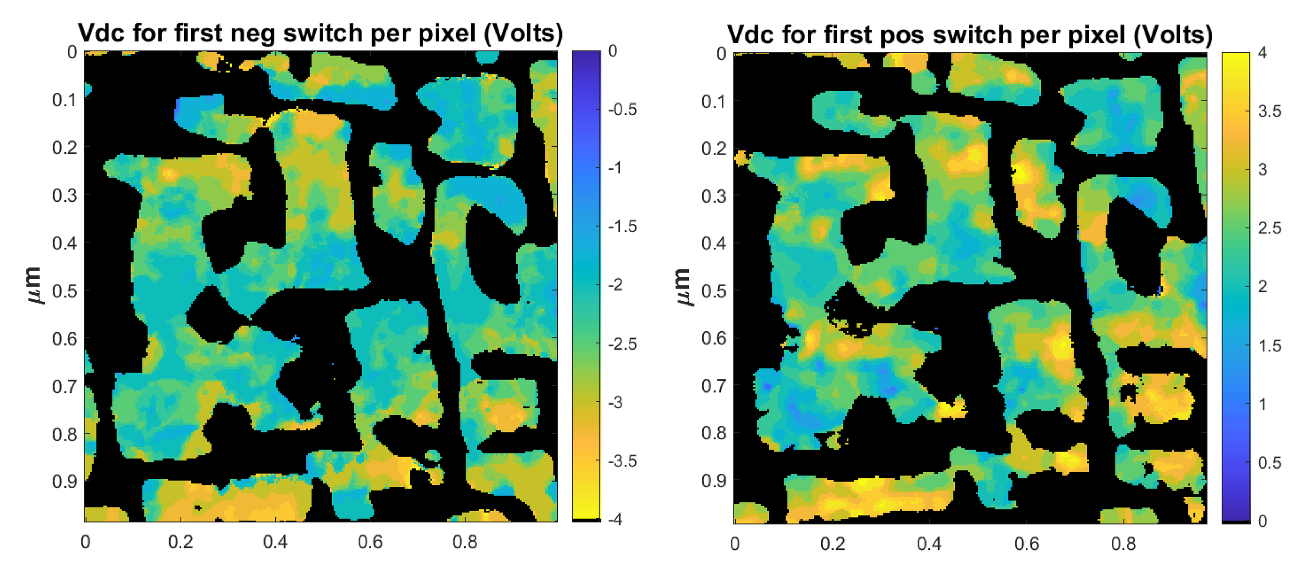


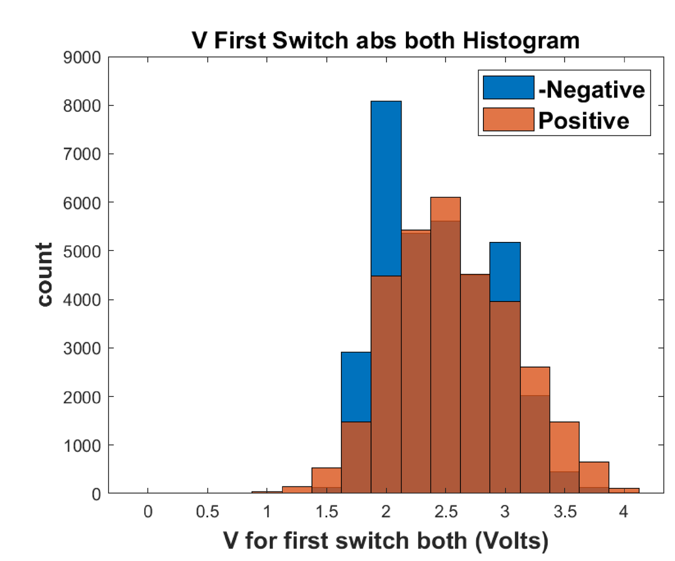
BFO-CFO vertically aligned nanocomposites



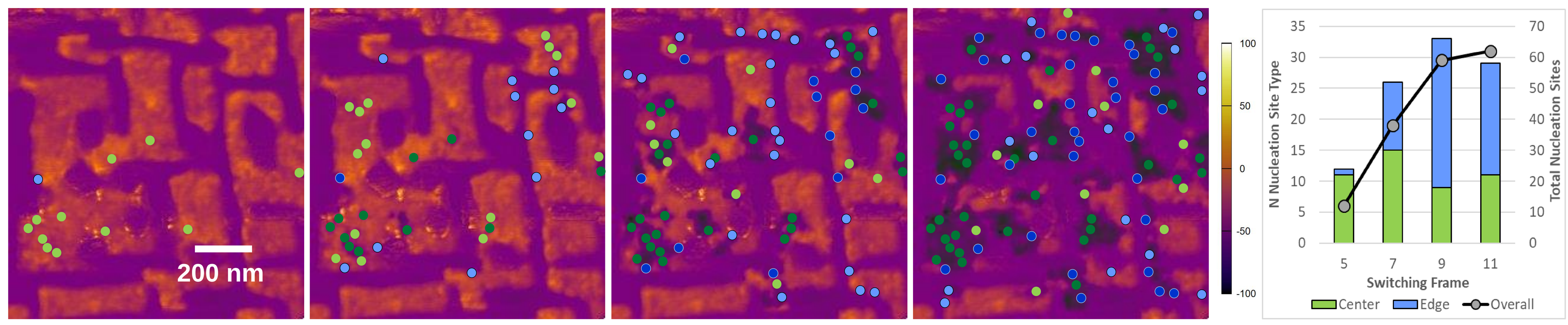
- Sequential ferroelectric switching of BFO imaged with PFM and V_{DC}.
  - No response for CFO matrix.
- BFO mesas exhibit consistent:
  - piezoactuation and switching patterns,
  - switching voltages for both positive and negative biases.





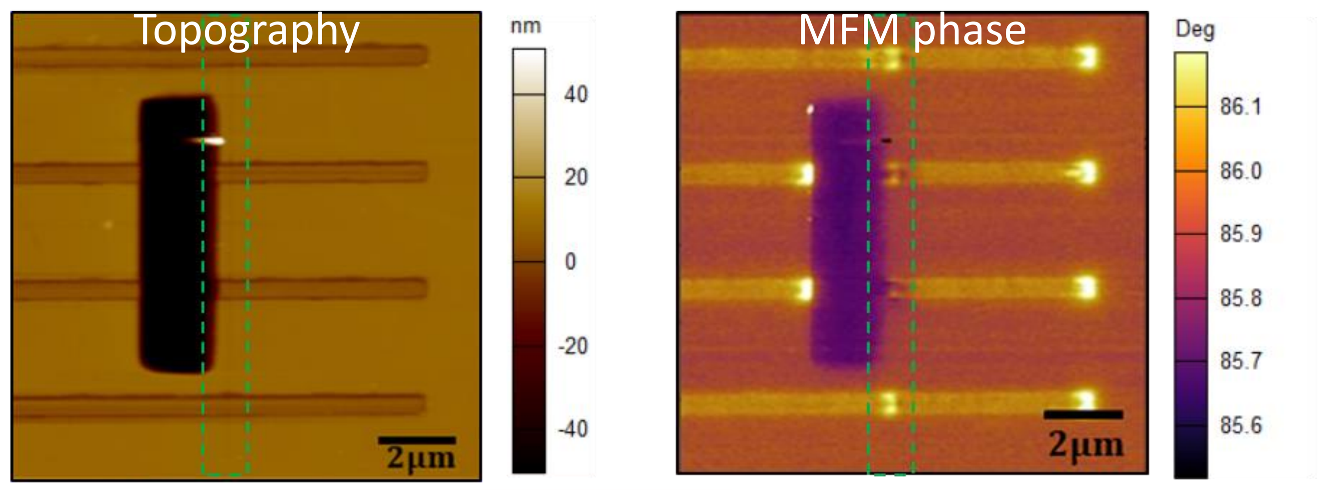


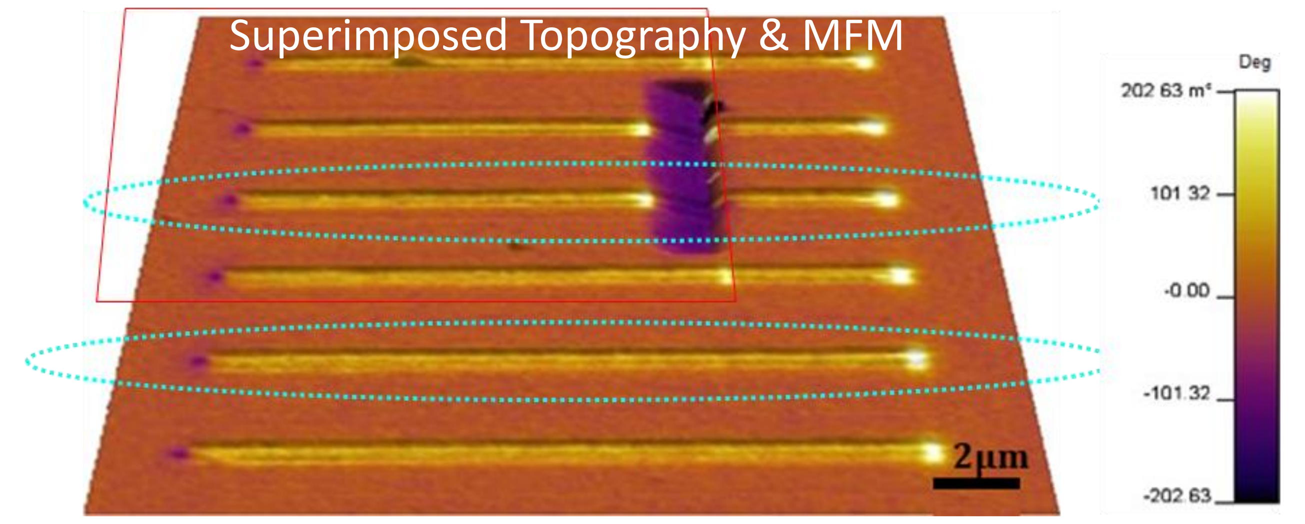
- Statistical analysis of nucleation sites reveals preferential nucleation at:
  - relaxed BFO mesa centers for low voltages,
  - epitaxially strained BFO/CFO interfaces for higher voltages.



LSMO Measurements

- Patterned functional features fabricated in LSMO surface, by masking those areas and damaging the surrounding film surface using ion implantation.
- Edge-geometry-controlled magnetic domain patterns analyzed with MFM.
- AFM-based nanomilling further used to manipulate / isolate functional features.
- In addition to separating features, even low loads can manipulate the in-plane domain patterns.





Conclusions

Multiferroic materials have been uniquely modified and investigated, even in 3 dimensions, using advanced AFM methods. This reveals volumetric ferroelectric domains, the influence of lateral strain gradients, and electrical and magnetic domain manipulation with unprecedented (x,y,z) control.

Acknowledgments

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