

# Room Temperature Electric Field Tuning of Thermal Conductivity in Ferroelectric Thin Films

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## Motivation

Mechanisms to actively tune thermal conductivity in a solid-state material are limited. Current room temperature mechanisms include:

- Physically separating components
- Passing through phase transitions
- Mechanical strain
- Intercalation/Deintercalation of ions
  - Changing chemical composition

Cryogenic active mechanisms include:

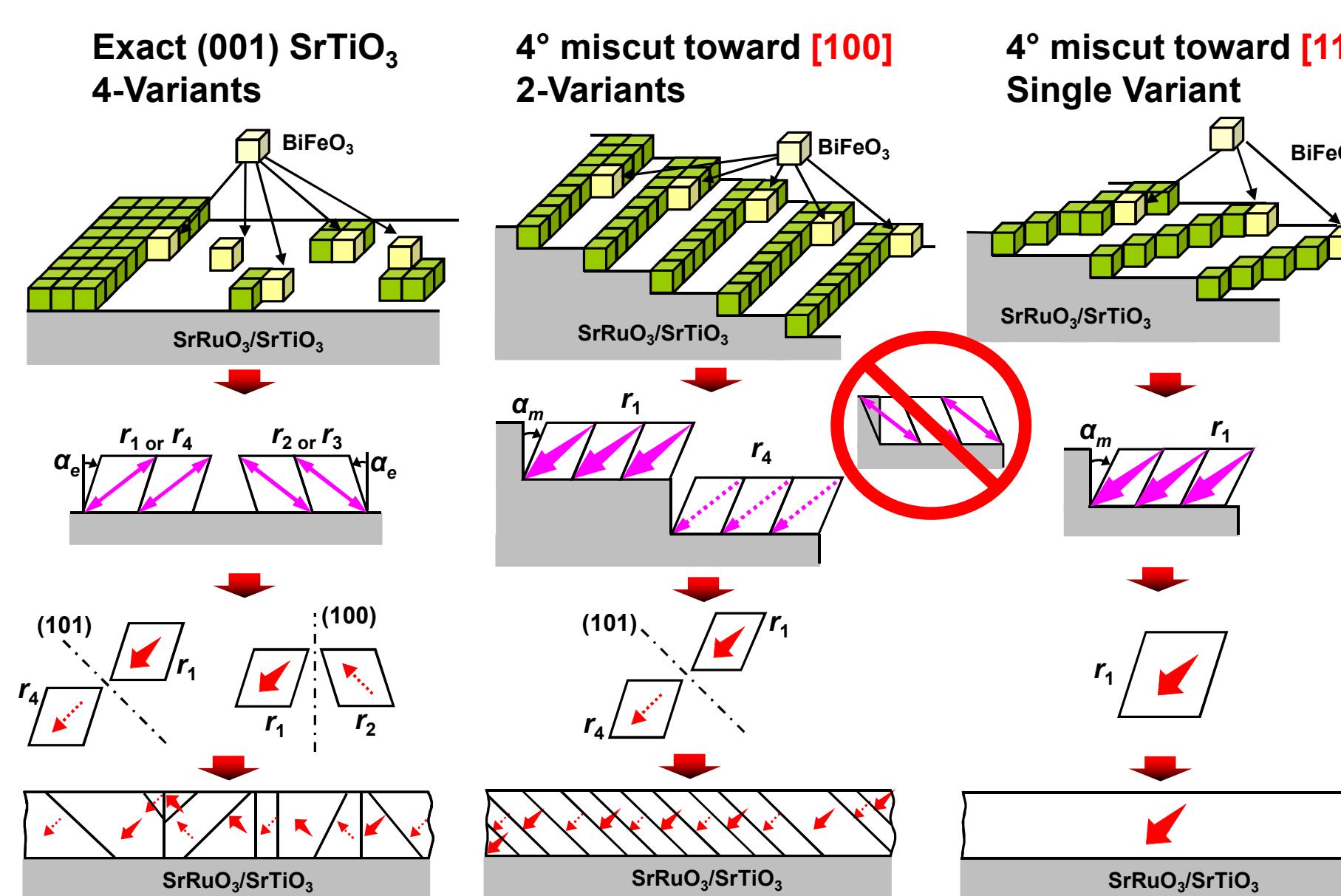
- Magnetic fields on superconductors
- Electric fields on paraelectrics and ferroelectrics

For rapid, low input-energy response at room temperature and above, ferroelectric materials may be promising if domain boundaries can be made smaller than phonon mean free paths. In this work we explore such an effect in thin film ferroelectrics.

## Samples Studied and Techniques

- 30 nm thick  $001_p$ -oriented epitaxial  $\text{BiFeO}_3$  thin films prepared on non-vicinal and vicinal (001)- $\text{SrTiO}_3$  via molecular-beam epitaxy
- Solution derived polycrystalline PZT bilayers: 142 nm  $\text{PbZr}_{0.3}\text{Ti}_{0.7}\text{O}_3$ /60 nm  $\text{PbZr}_{0.7}\text{Ti}_{0.3}\text{O}_3$ /100 nm Pt/40 nm  $\text{ZnO}/\text{SiO}_2/\text{Si}$
- Thermal measurements via Time Domain Thermoreflectance (TDTR) using 90 nm platinum top electrode transducers.
- Domain imaging via PiezoForce Microscopy (PFM), Bright Field Scanning Transmission Electron Microscopy (STEM), and Channeling Contrast Scanning Electron Microscopy (CC-SEM)
- CC-SEM utilized a 3 nm Pt electrode enabling electron transparency for backscattered electron imaging, but sufficient conductivity to apply a field *in operando*.

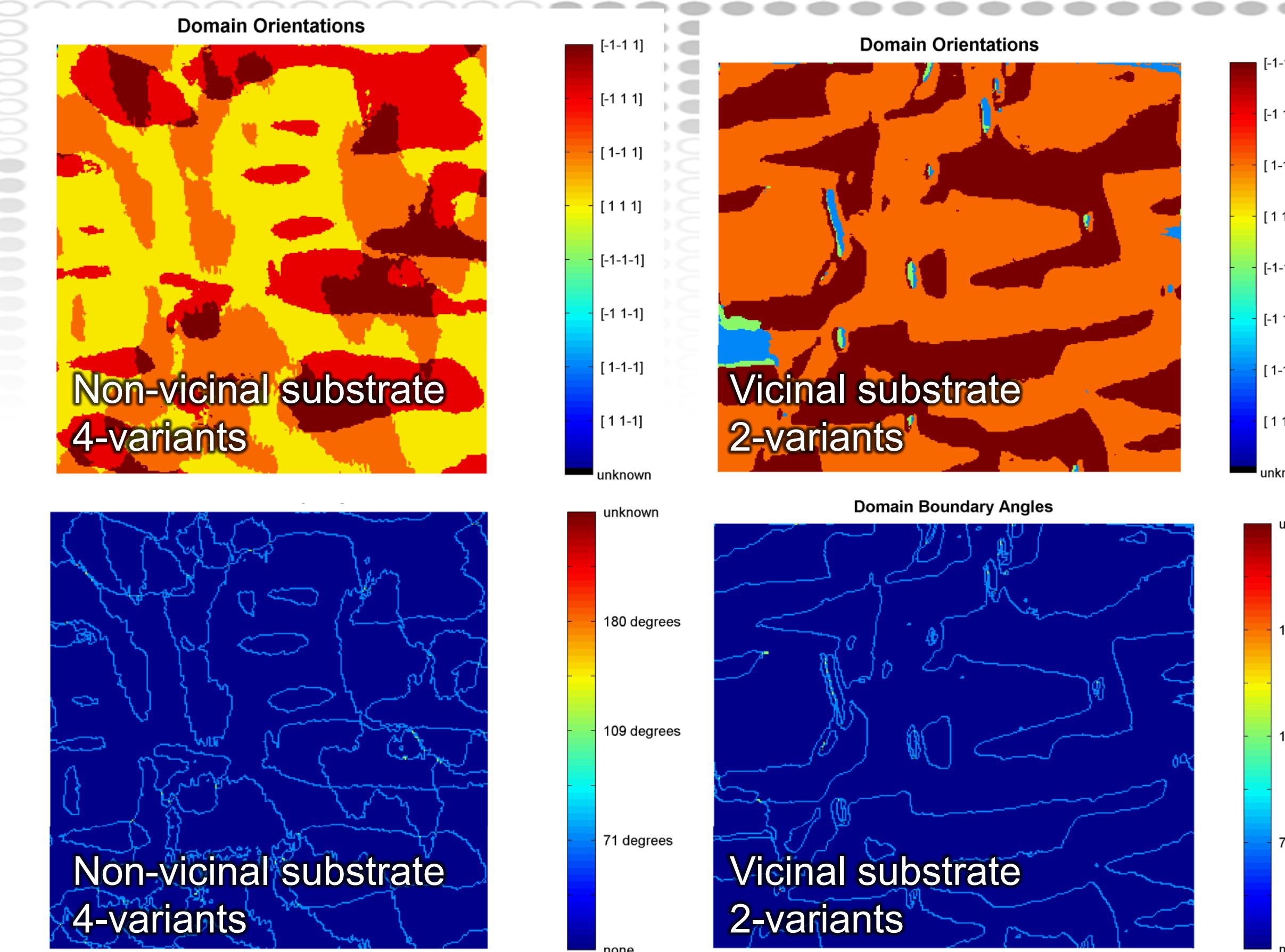
## Domain Engineered $\text{BiFeO}_3$ Epitaxial Films



\*Schematic courtesy of Chang-Beom Eom, University of Wisconsin

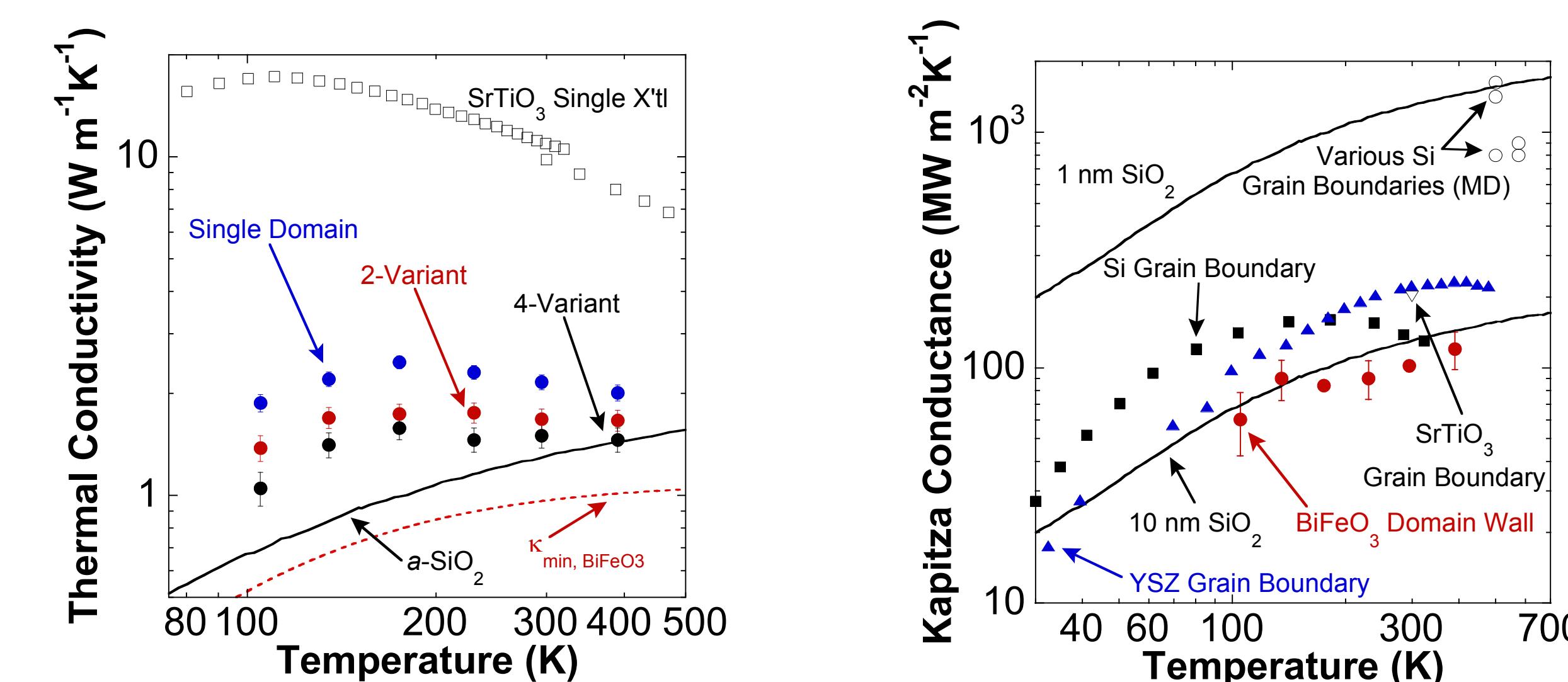
- Vicinal compressive substrates can impose symmetry breaking step edges that control number of domain variants

## $\text{BiFeO}_3$ Domain Characterization



## • Domain wall densities depend on number of variants

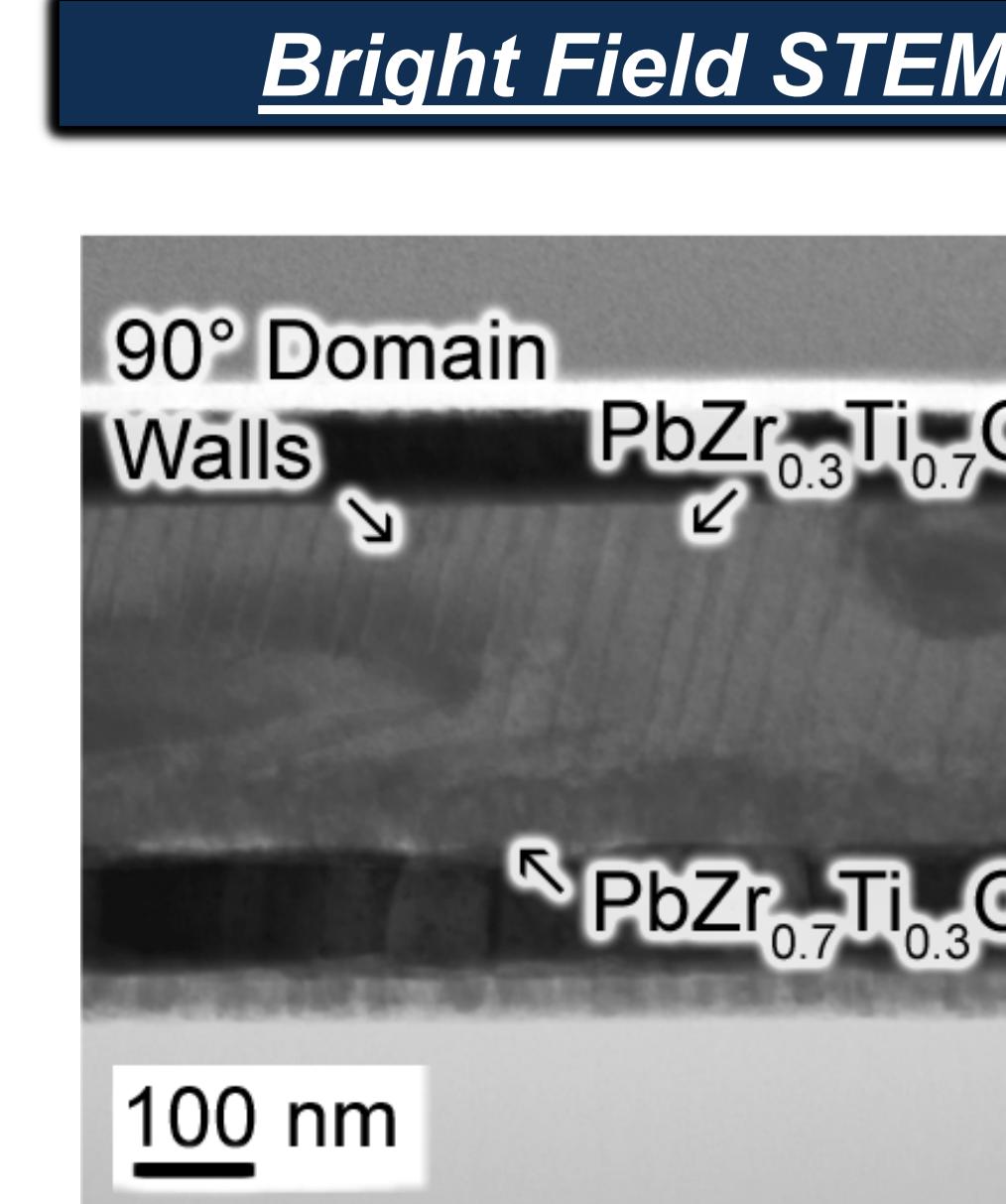
- 4-Variants =  $16 \mu\text{m}/\mu\text{m}^2$
- 2-Variants =  $11 \mu\text{m}/\mu\text{m}^2$
- 1-Variant = No observable domain walls
- Virtually all domain walls are  $71^\circ$  boundaries



P.E. Hopkins and J.F. Ihlefeld, et. al., *Applied Physics Letters*, 102 121903 (2013)

- $71^\circ$  Domain boundaries significantly scatter phonons
- Thermal resistance of domain walls similar to grain boundaries

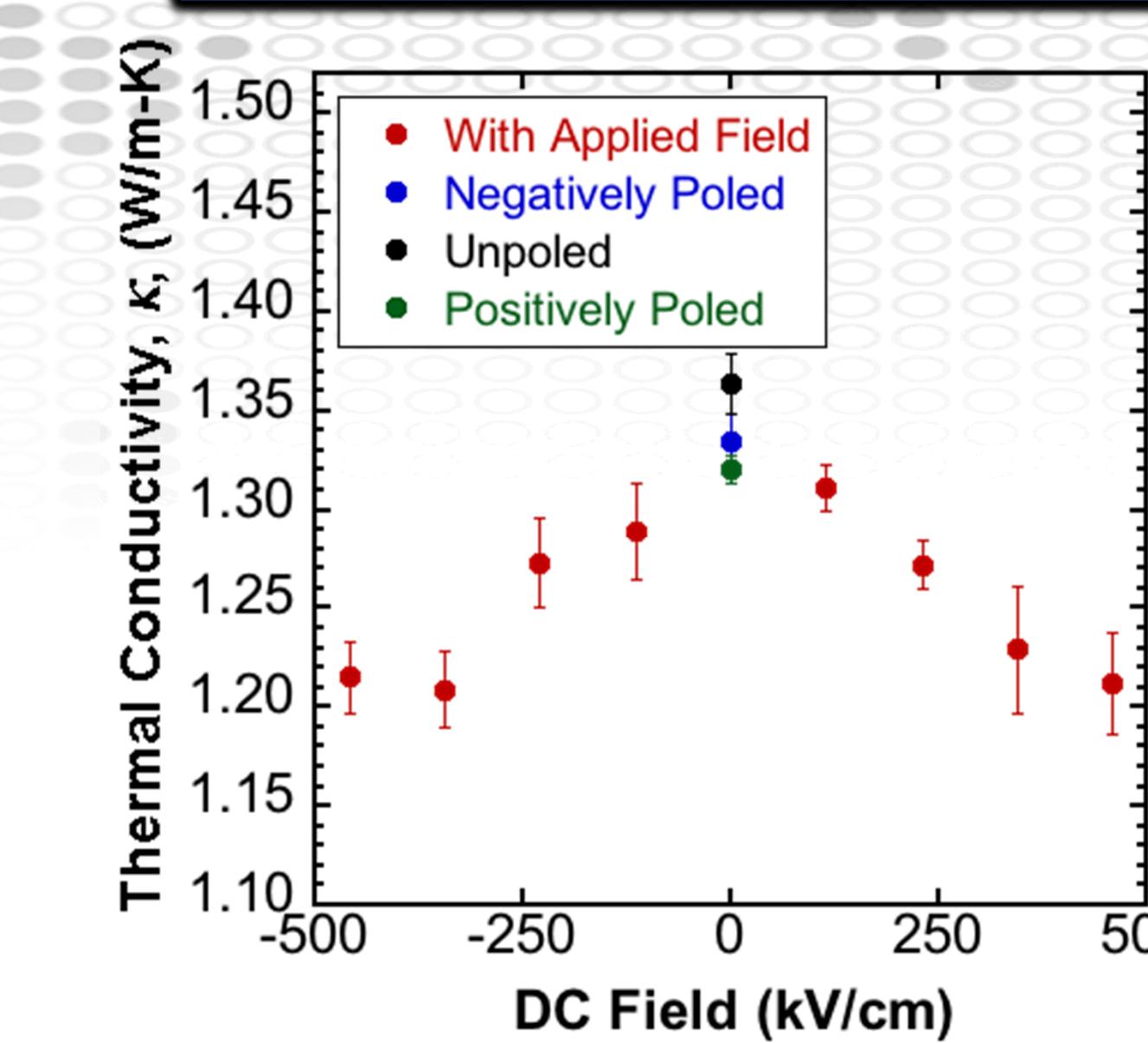
## Bilayer PZT Films



- Domain boundaries clearly visible in bright field STEM in the PZT 30/70 layer
- SAED reveals domain boundaries to be of  $90^\circ$  type
- No domain boundaries observed in the PZT 70/30 layer
- Film shows clear ferroelectric hysteresis

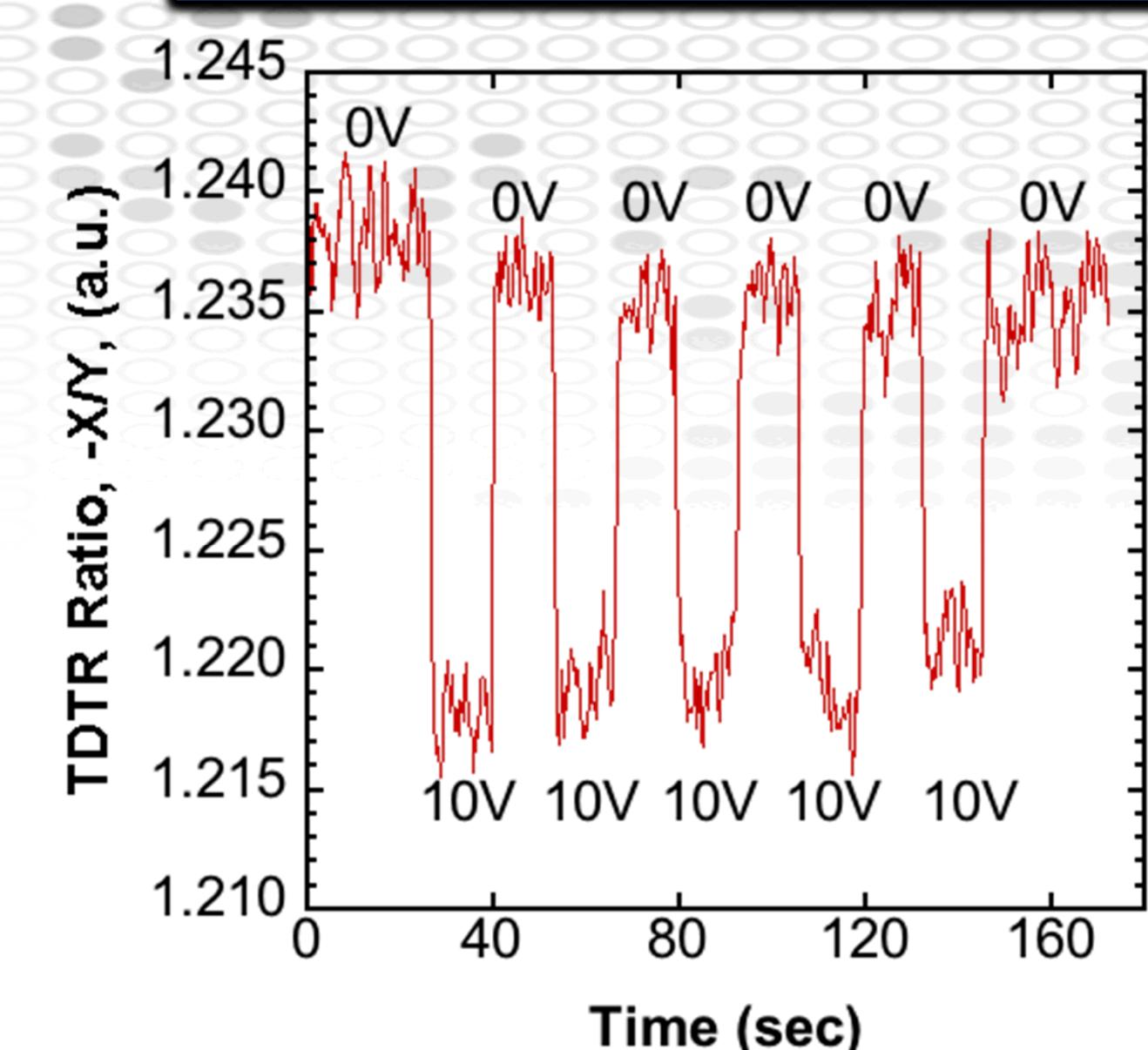
## PZT Thermal Properties

### Static DC Fields



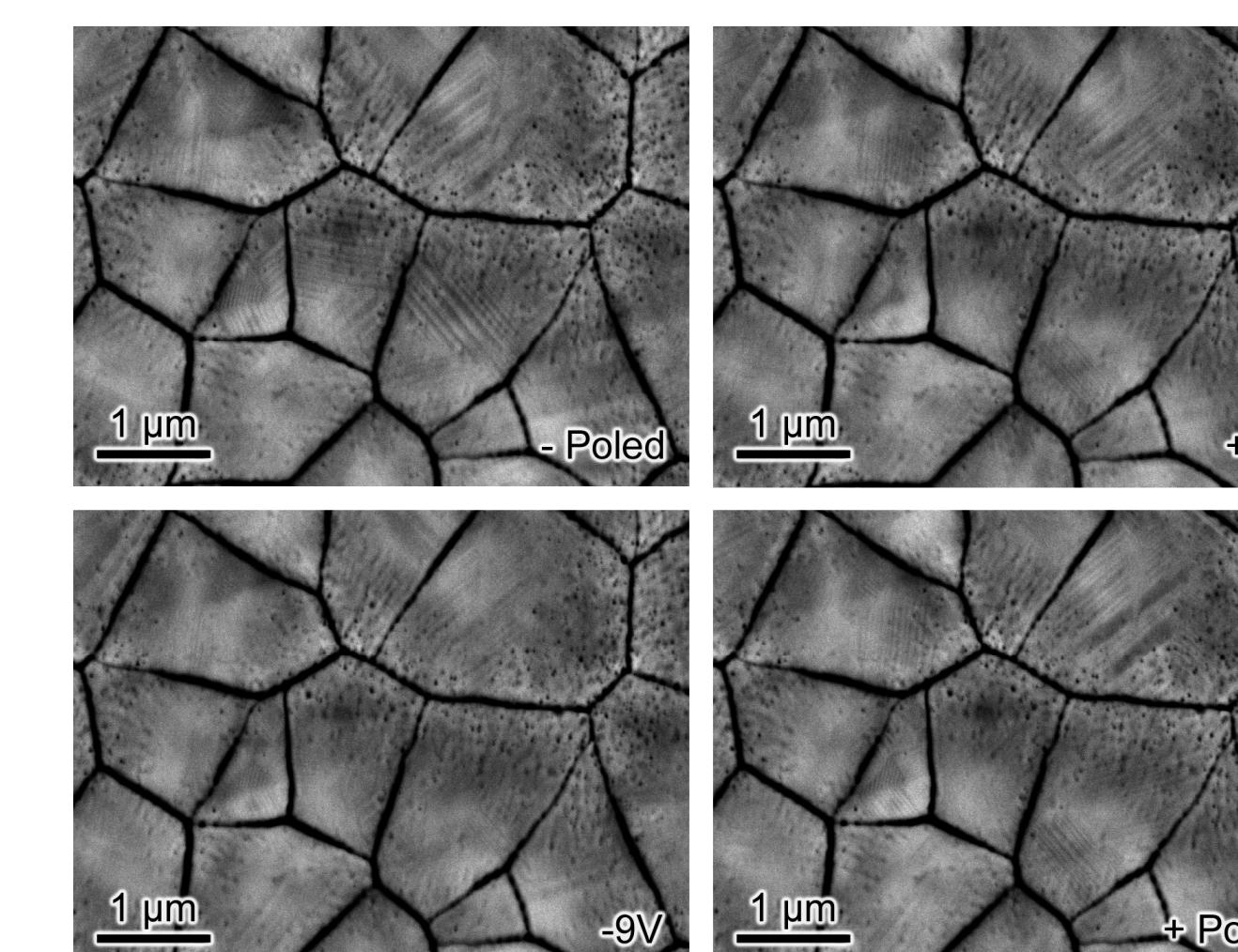
- Thermal conductivity decreases with applied electric field
- Thermal conductivity decreases after ferroelectric poling
- Tuning effect is reversible and rapid

### Realtime TDTR



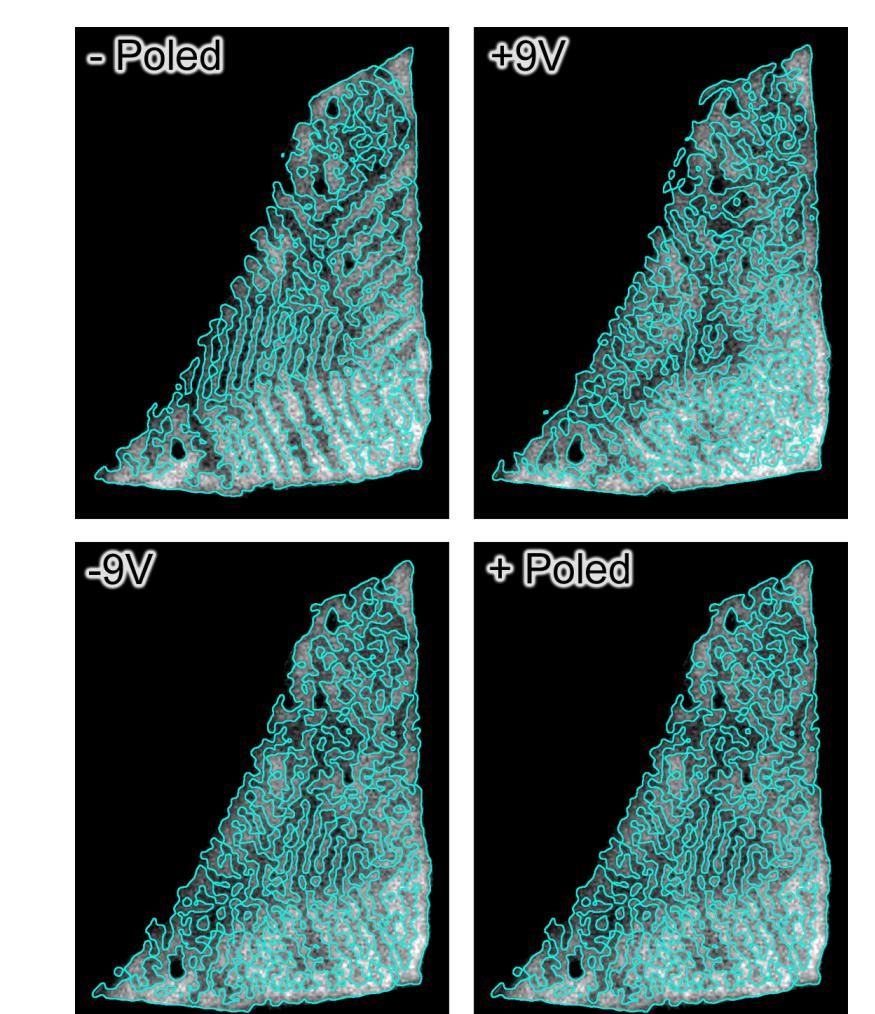
## PZT Domain Structure Changes During Measurement

### Channeling Contrast SEM

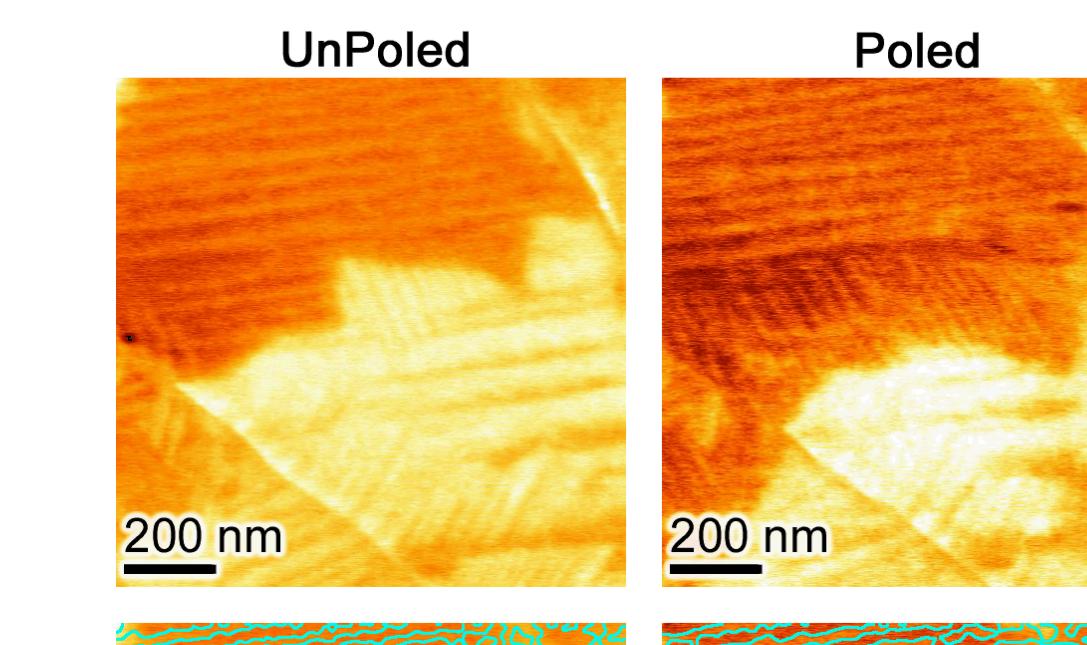


- Clearly observe domain structure changes during the application of an electric field

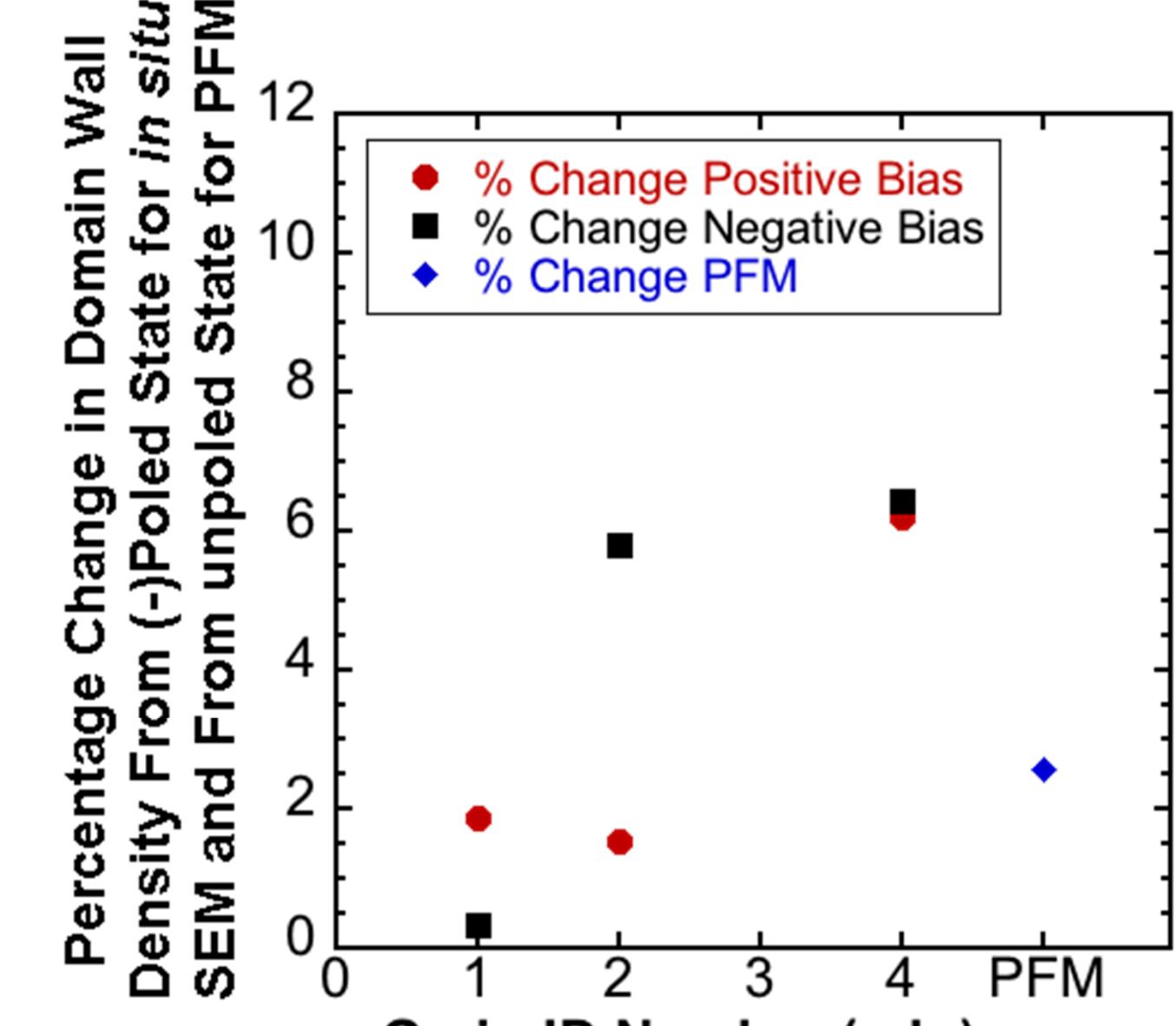
### Edge Identification



## PFM and Edge Identification



## Quantification of Domain Densities



- Domain wall density *increases* after poling in PFM
- Domain wall density *increases* during application of field in clamped PZT-based films

## Conclusions

- Ferroelastic domains in ferroelectric thin films can affect thermal conductivity at room temperature
  - Demonstrated for  $71^\circ$  rhombohedral and  $90^\circ$  tetragonal boundaries
- Domain wall density *increases* with applied field in clamped PZT-based films
- Increased domain wall density results in decreased thermal conductivity due to phonon scattering at domain walls