Origins of Electromechanical Strain Ascertained from *in situ* X-ray and Neutron Diffraction

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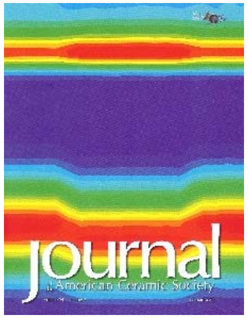

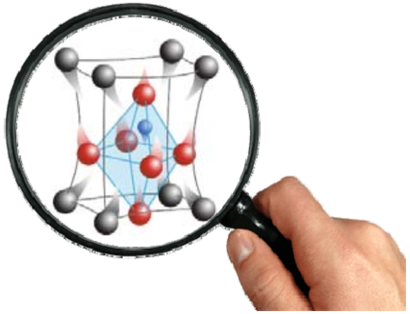

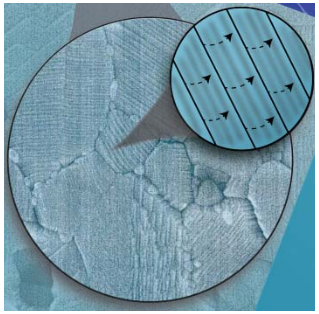

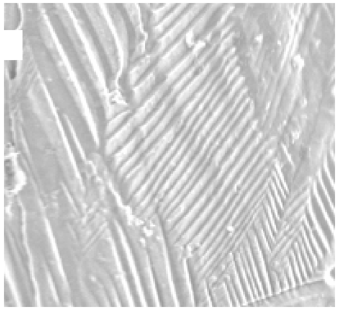

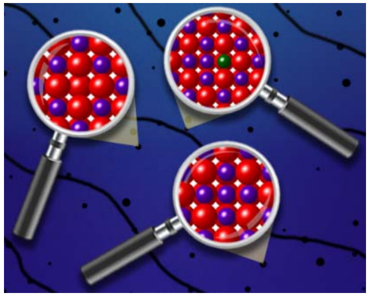

This work is the compilation of results from a number of students, postdocs, and collaborators, who are acknowledged in the next few slides...

Origins of Electromechanical Strain Ascertained from *in situ* X-ray and Neutron Diffraction

Contributors and Collaborators *on this Topic*

Jones Research Group

- ***John Daniels***, *UNSW*
- ***Dragan Damjanovic***, *EPFL*
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- ***Pam Thomas***, *Warwick*
- ***J. Chen***, *Univ. Sci. Tech. Beijing*
- ***K. Bowman***, *IIT*
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- ***Y. Ren***, *APS*
- ***A. J. Studer***, *ANSTO*

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Origins of Electromechanical Strain Ascertained from *in situ* X-ray and Neutron Diffraction

1. Introduction to Electromechanical Strain Mechanisms
2. *In situ* X-ray Diffraction experiments
3. Applications
    1. Polycrystalline *Pb(Zr,Ti)O$_3$ (PZT)* (dominant commercial material)
    2. High-temperature *BiScO$_3$ – PbTiO$_3$* piezoelectric
    3. Pb-free *Ba(Zr$_{0.2}$Ti$_{0.8}$)O$_3$–x(Ba$_{0.7}$Ca$_{0.3}$)TiO$_3$* as a function of *c/a*
    4. Classical *BaTiO$_3$* as a function of *grain size*
    5. Field-induced *phase transitions* in *Na$_{0.5}$K$_{0.5}$NbO$_3$*
    6. Polycrystalline *PZT thin films* for piezoMEMS, etc.

Applications of Piezoelectrics & Ferroelectrics

Actuating Material

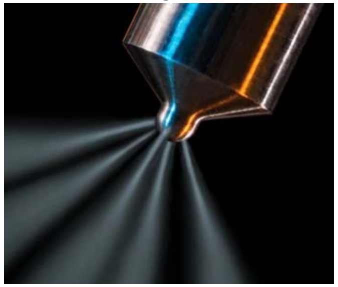
Electrostatics
Electrostriction
Piezodiffusivity
Flexoelectricity
Ferroelectricity
Piezoelectricity

Electronics

Mechanical displacement, vibration, acoustics, etc.

Sensing Material

Fuel Injectors

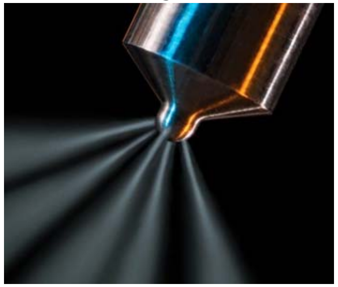


Ultrasound

Parking Sensor

Applications of Piezoelectrics & Ferroelectrics

Fuel Injectors



Electronics ← Ferroelectrics and Piezoelectrics → Mechanical displacement, vibration, acoustics, etc.

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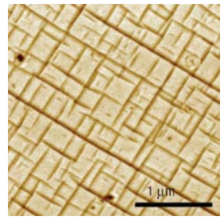
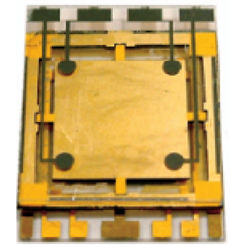
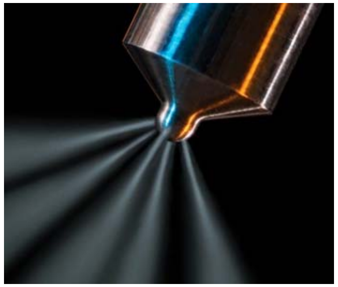
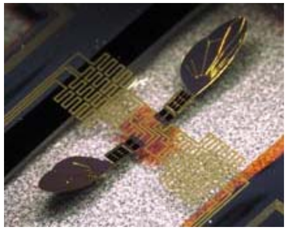
Applications of Piezoelectrics & Ferroelectrics

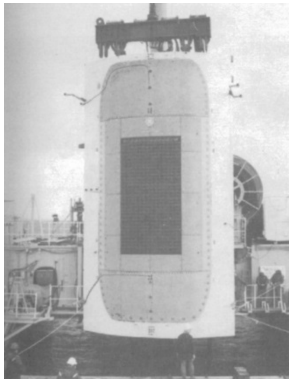


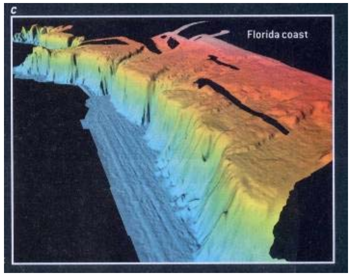


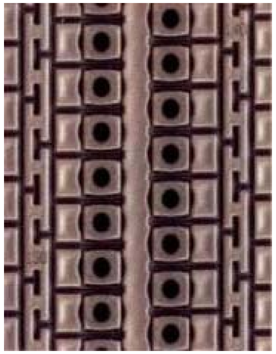


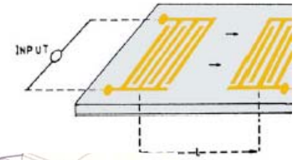
Electronics ⟵ **Ferroelectrics and Piezoelectrics** ⟶ **Mechanical displacement, vibration, acoustics, etc.**

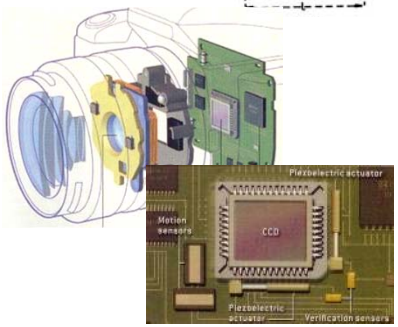




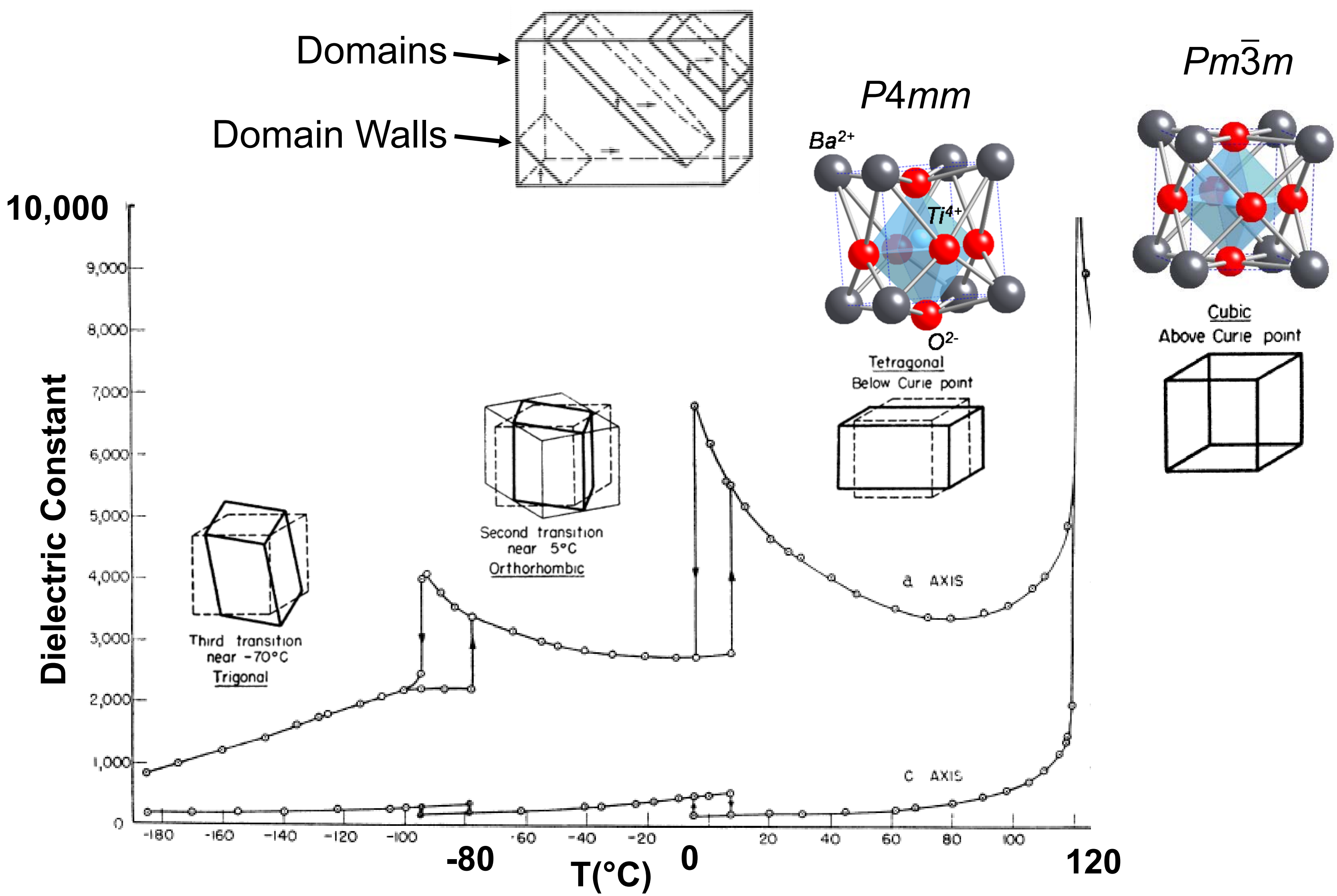








$BaTiO_3$ – a Classical Example

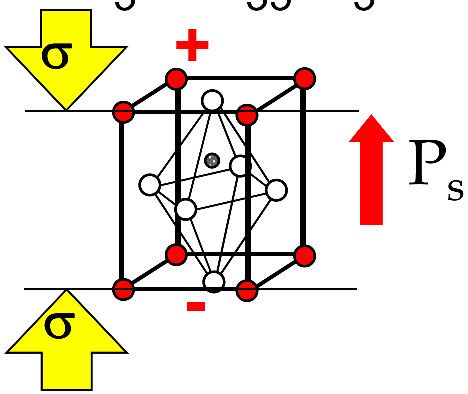


Adapted from A. von Hippel, Rev. Modern Physics, 22, 221 (1950).

Mechanisms of Electromechanical Strain

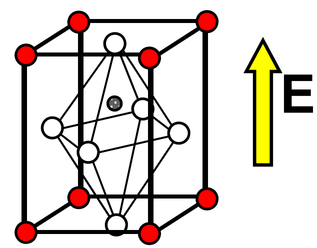
Direct

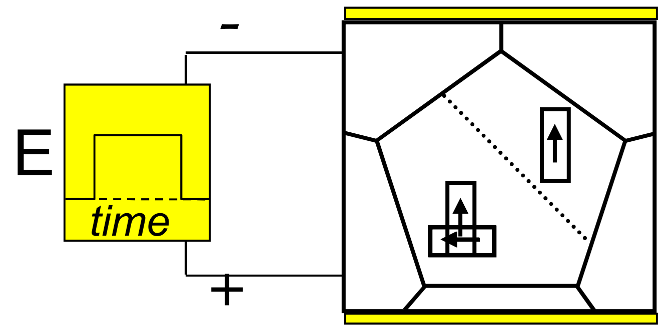
$D_3 = d_{33} \cdot \sigma_3$



Converse

$S_3 = d_{33} \cdot E_3$





<u>Piezoelectric strain</u>

- ***Intrinsic*** effect of polar structures
- Expect ***linear*** response of strain to field amplitude, or
- d_{33} being a “constant”

<u>Domain wall motion (ferroelectric effect)</u>

- ***Extrinsic*** effect
- Expect strain coefficient (strain/field) to be ***nonlinear*** and dependent upon many variables.

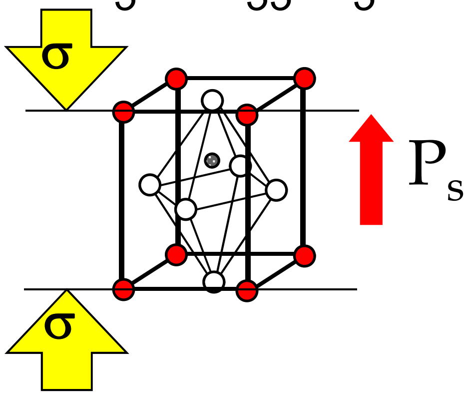
Mechanisms of Electromechanical Strain

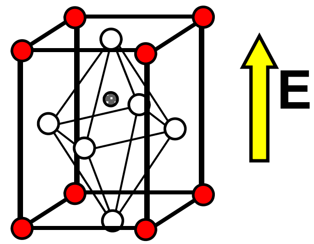
Direct

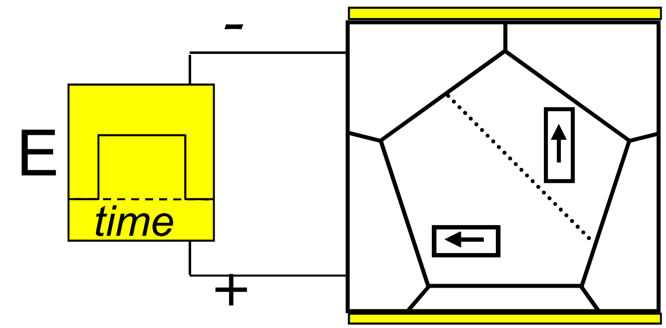
$D_3 = d_{33} \cdot \sigma_3$

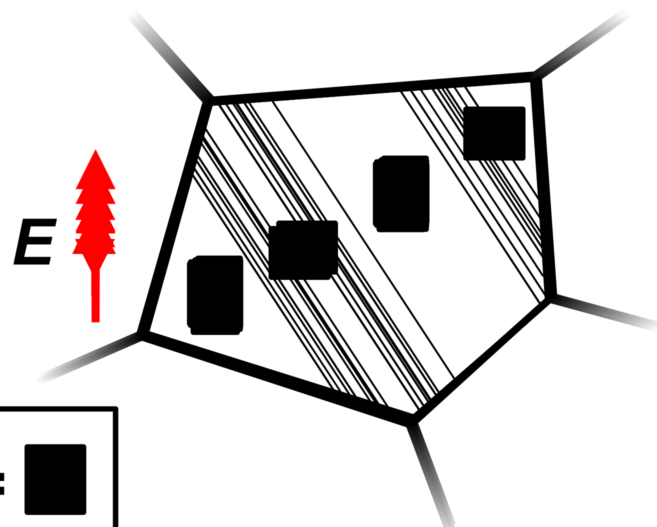
Converse

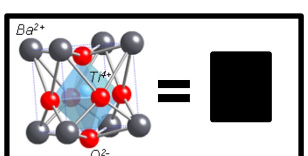
$S_3 = d_{33} \cdot E_3$

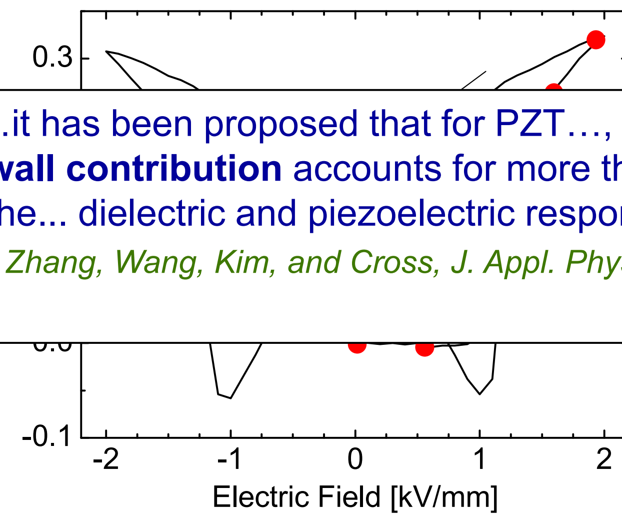








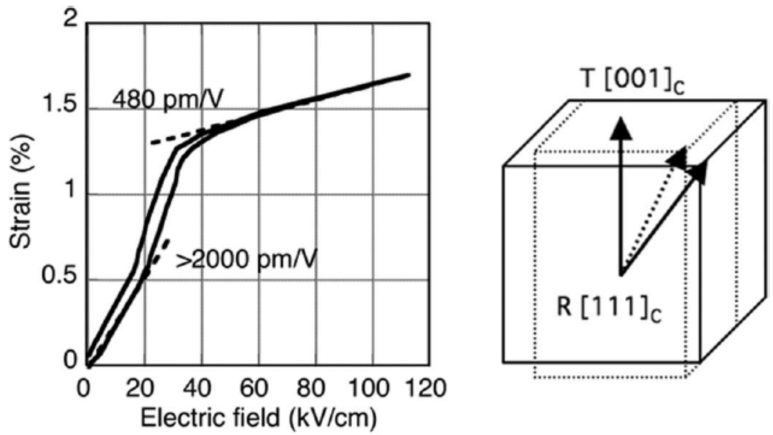




"…it has been proposed that for PZT…, the **domain wall contribution** accounts for more than half of the... dielectric and piezoelectric responses."

- Zhang, Wang, Kim, and Cross, J. Appl. Phys., 1994

- **Polarization rotation (intrinsic)**



(a) (b)

Fig. 1. (a) The field induced strain in $0.92Pb(Zn_{1/3}Nb_{2/3})O_3 - 0.08PbTiO_3$ crystal and (b) schematic presentation of the polarization "inclination" under electric field from rhombohedral $[111]_C$ toward tetragonal $[001]_C$ polar axis. The field is applied along $[001]_C$. After Ref [1].

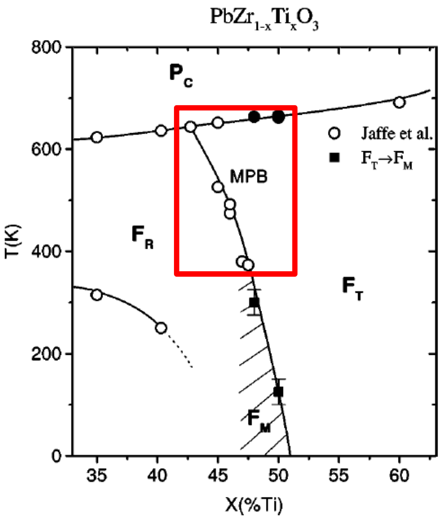
letters to nature

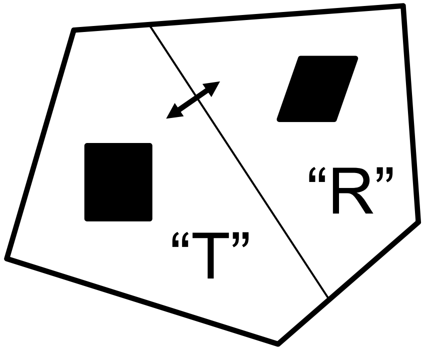
Polarization rotation mechanism for ultrahigh electromechanical response in single-crystal piezoelectrics

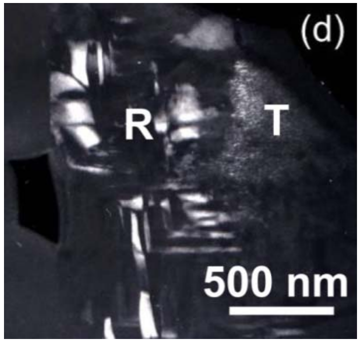
Huaxiang Fu & Ronald E. Cohen

Carnegie Institution of Washington, 5251 Broad Branch Road, NW, Washington DC 20015, USA

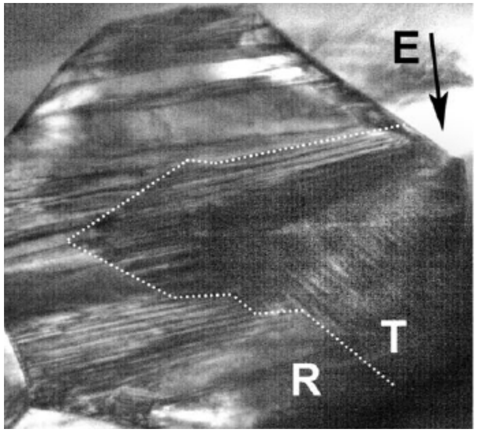
• Interphase boundary motion (extrinsic)



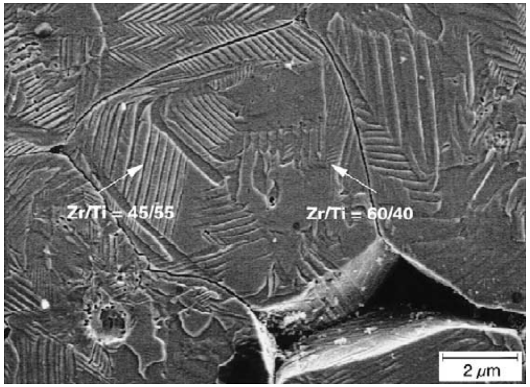




Levin et al., Adv. Funct. Mater. (2012).



Ma, Tan et al., PRL (2012)



Hoffmann et al., Acta Mater. (2001).

"the observed behavior of the electromechanical properties of the ceramics is based on the model of the domain wall and **interphase boundary motion**."

- Kugel and Cross, J. Appl. Phys., 1998

"It is tempting to speculate that in ferroelectric compositions close to the morphotropic phase boundary, … the **interfaces between different phases can be moved by external fields** and contribute to the properties in a similar way as the moving domain walls. At present, **there is no direct evidence that this interphase boundary displacement is actually happening.**"

- Damjanovic, Chapter 4, The Science of Hysteresis, 2005

Mechanisms of Electromechanical Strain

Intrinsic Effects

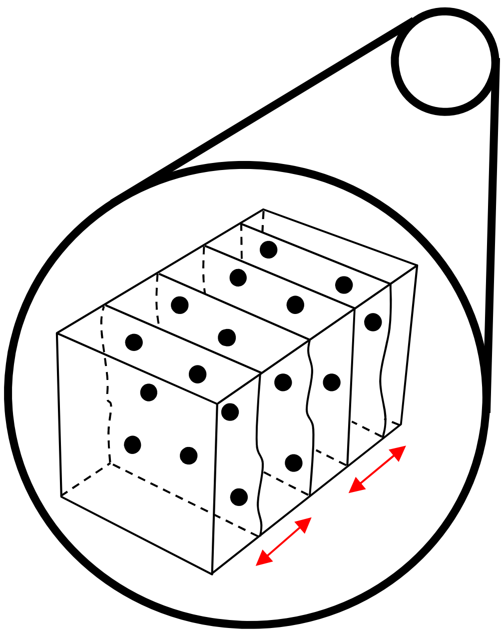
- Piezoelectric effect
- Polarization rotation

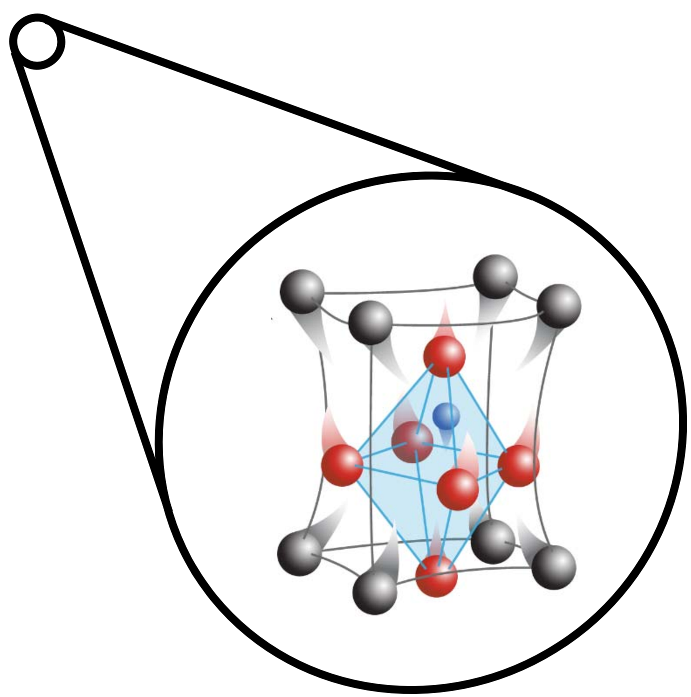
Extrinsic Effects

- Domain wall motion
- Interphase boundary motion

Mechanisms of Electromechanical Strain

Not so simple: ***Emergence*** and ***Complexity*** at length scales between 0.4 nm and ~10 μm





Mechanisms of Electromechanical Strain

Intrinsic Effects

- **Piezoelectric effect**
- **Polarization rotation**

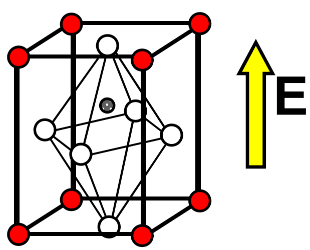
Extrinsic Effects

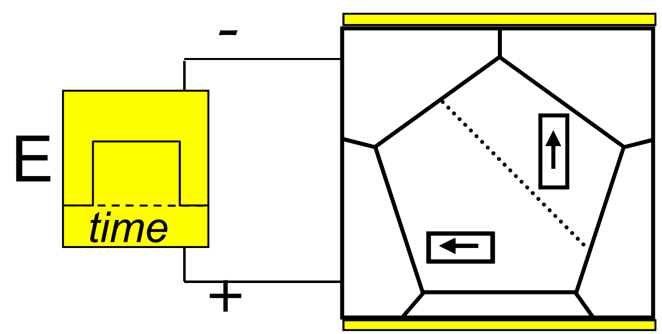
- **Domain wall motion**
- **Interphase boundary motion**

- **Domain wall pinning/depinning** with point and line defects
- **Domain wall – domain wall** interactions (i.e., ρ_{DW})
- **Competing mechanisms** of domain wall motion and intrinsic piezoelectricity
- **Domain wall interactions** with grain boundaries
- **Intergranular** (grain-grain) interactions and constraint or compliance
- **Intrinsic elasticity** affects this coupling
- **Grain size** effects
- **Domain size** effects (e.g., polar nanoregions)
- Effect of **stress** (i.e., thin films)
- Effect of **spontaneous strain** on domain wall contributions

Motivation

- When ***<u>electric fields are applied to insulating materials</u>***, several different physical phenomena are known to create mechanical strain (e.g. **piezoelectricity**, **electrostriction**, **ferroelectric/ferroelastic domain wall motion**, and **flexoelectricity**).





Motivation

- When ***electric fields are applied to insulating materials***, several different physical phenomena are known to create mechanical strain (e.g. **piezoelectricity**, **electrostriction**, **ferroelectric/ferroelastic domain wall motion**, and **flexoelectricity**).
- It is often difficult to ***distinguish which mechanisms are active or dominant*** in a particular material system, and how ***the highest or designed material responses*** can be achieved.

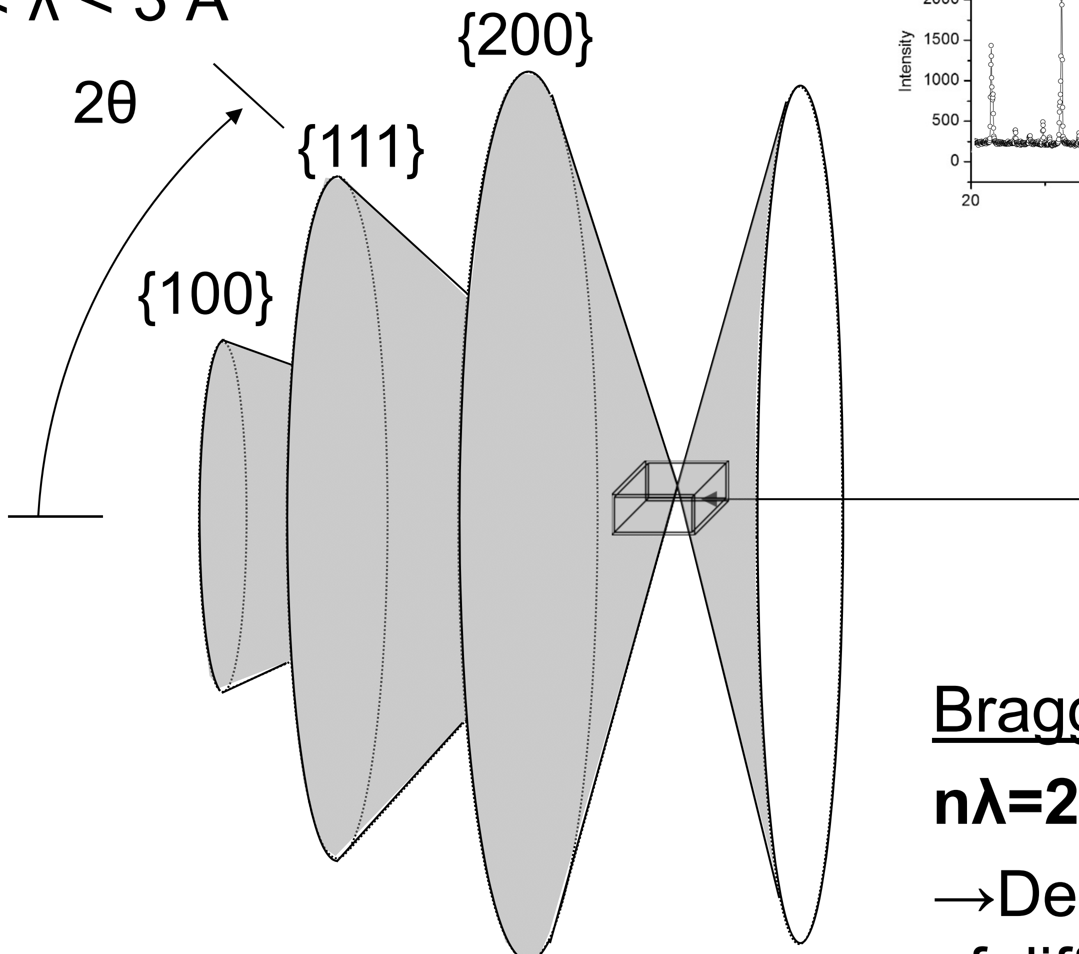
Motivation

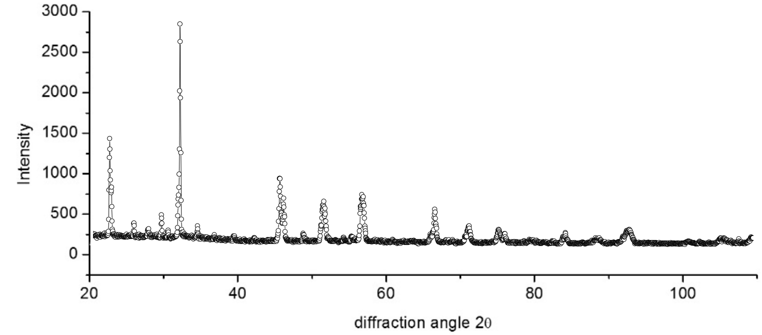
- When ***electric fields are applied to insulating materials***, several different physical phenomena are known to create mechanical strain (e.g. **piezoelectricity**, **electrostriction**, **ferroelectric/ferroelastic domain wall motion**, and **flexoelectricity**).
- It is often difficult to ***distinguish which mechanisms are active or dominant*** in a particular material system, and how ***the highest or designed material responses*** can be achieved.
- ***In situ characterization probes*** (e.g., X-ray and neutron scattering) can deconvolute some of these effects and provide quantitative assessment of contributions.

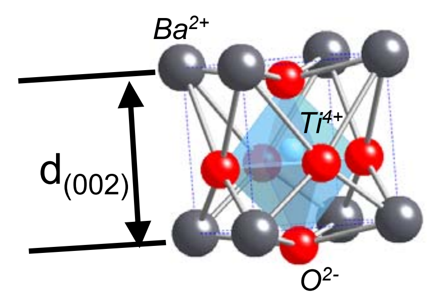
Methodology: X-ray Diffraction

X-ray diffraction

0.1 Å < λ < 3 Å







<u>Bragg's Law</u>

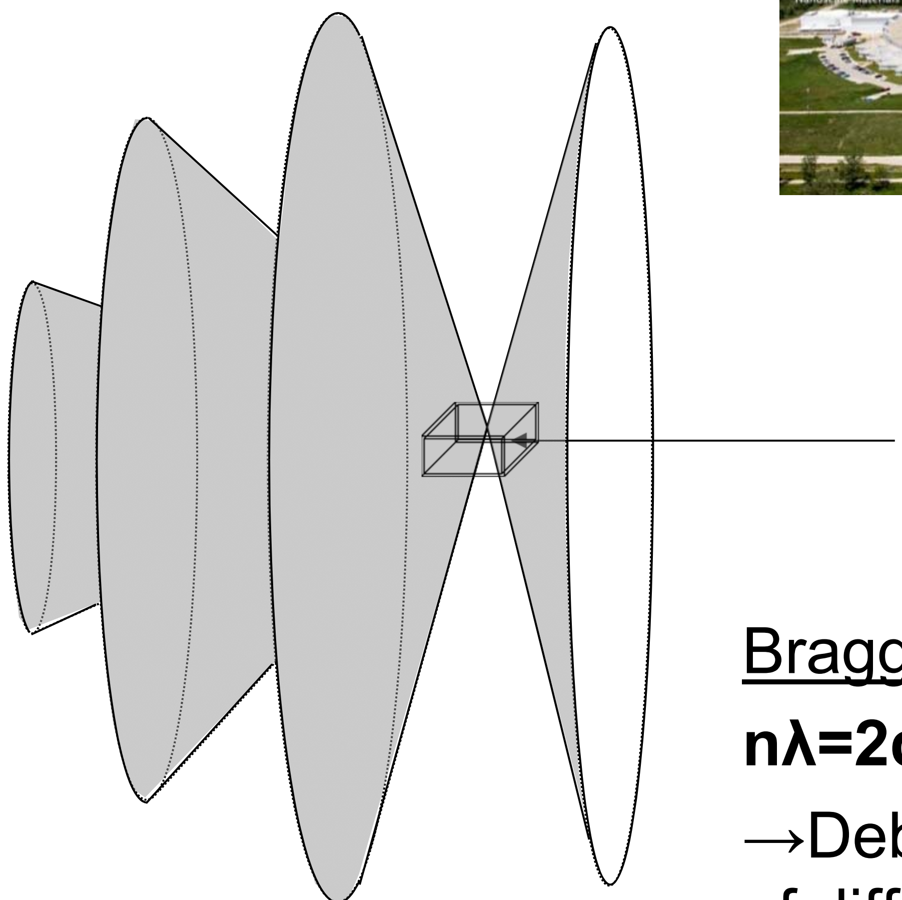
$n\lambda = 2d \cdot \sin\theta$

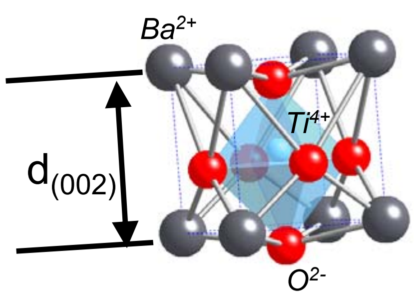
→Debye-Scherrer cones of diffraction intensity

Methodology: X-ray Diffraction

High-energy X-ray diffraction

$\lambda < 1$ Å





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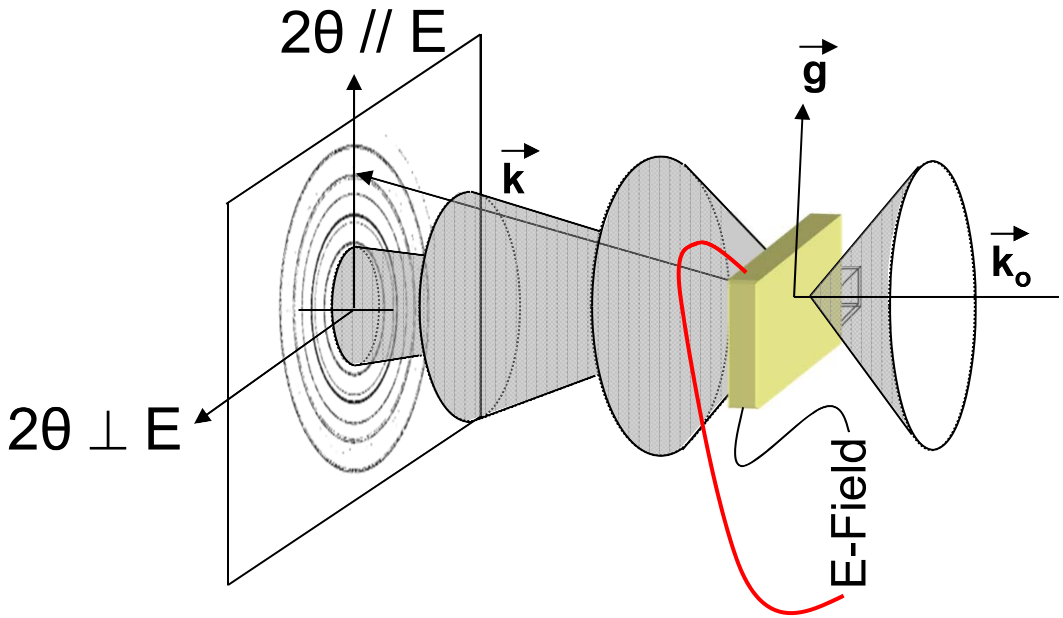
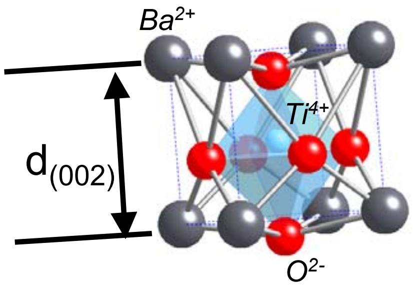




<u>Bragg's Law</u>

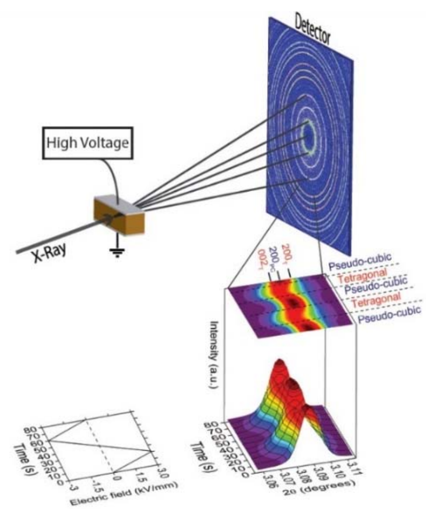
$n\lambda = 2d \cdot \sin\theta$

→Debye-Scherrer cones of diffraction intensity

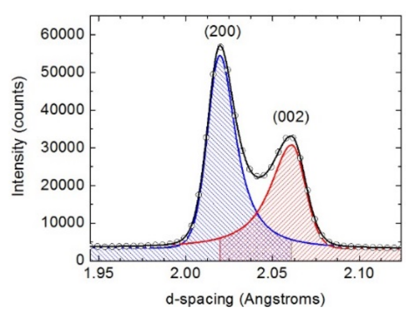
Methodology: X-ray Diffraction

Sophisticated *in situ* experiments → **Analysis including profile fitting** → **Quantifying extrinsic and intrinsic effects** → **Relation to macroscopic properties**

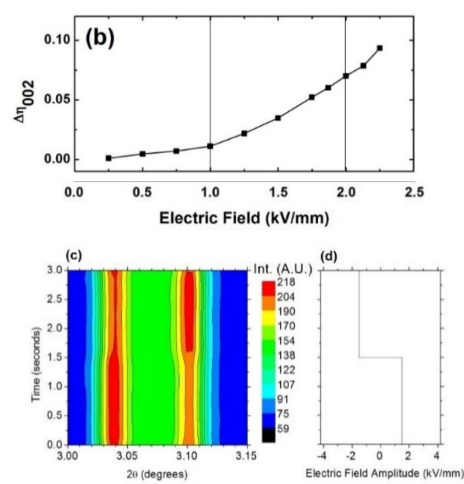
- *Strong and weak fields*
- *Electric field synchronization*
- *Stroboscopic*
- *Dependence on field direction*



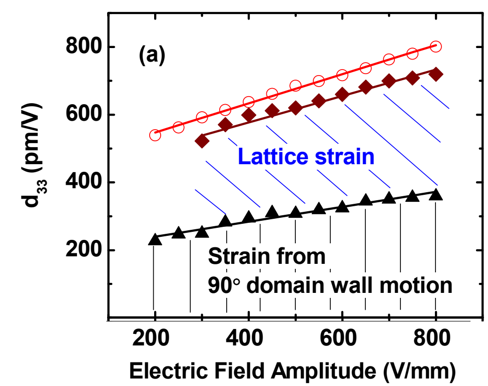
- *High intensities for resolving subtle effects*
- *Careful selection of profile shapes*
- *Automated for 1000s of datasets*



- *Domain volume fraction calculations* **(η)**
- *Quantifying other effects, e.g. interphase boundary motion and lattice strain*
- *Field-amplitude dependence*
- *Frequency dependence*

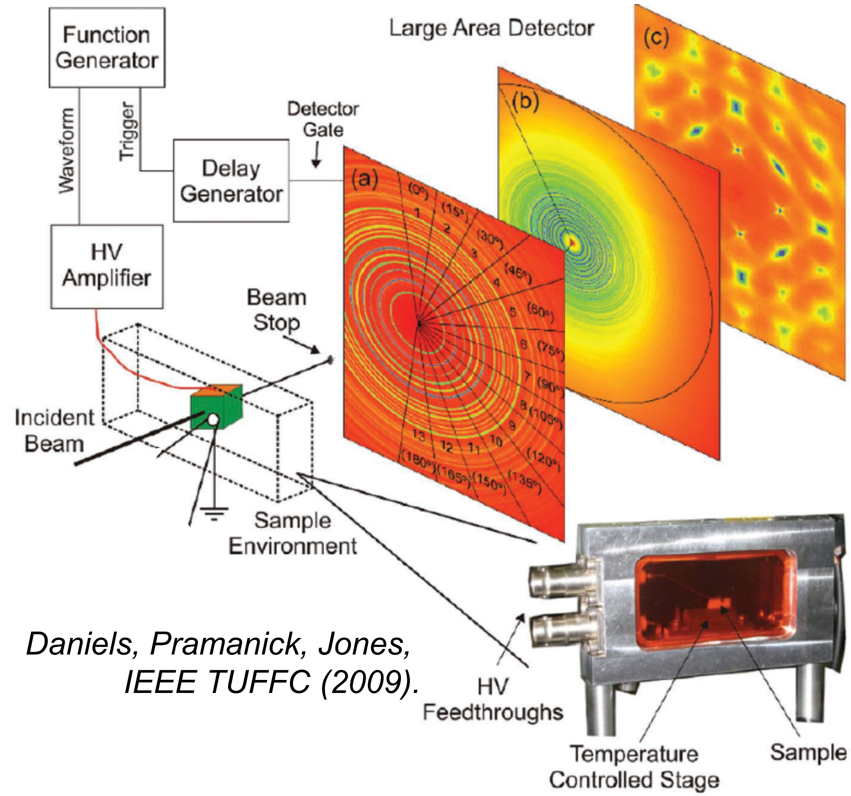


- *Calculate effective contribution to macroscopic property coefficients* **(e.g., d_{33})**
- *Measure macroscopic property coefficients*
- *Interpret without presumption of superposition*



Methodology: X-ray Diffraction

- APS, Beamline 11-ID-C
- 114 keV energy
  - through thin films (through the entire structure, including Si);
  - or through polycrystalline samples of 1 mm x 1 mm x 5 mm sample.
- Perkin Elmer area detector, 1.8 m from sample
- Voltages up to 6 kV, often stroboscopic methods
- ***High-energy (hard) X-ray scattering*** **lends itself to investigation of** ***sub-surface*** **phenomena, and allow easy** ***powder averaging*** **to relate to macroscopic properties.**



Daniels, Pramanick, Jones, IEEE TUFFC (2009).

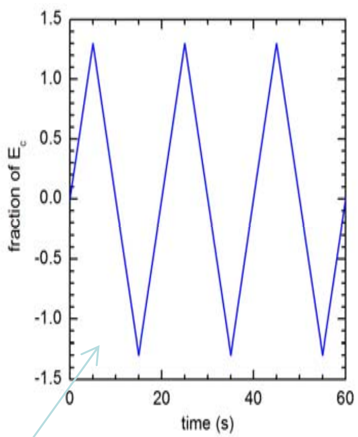
Methodology: X-ray Diffraction

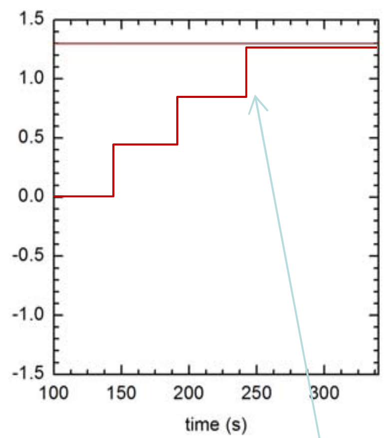
Strong bipolar fields – high field cycling

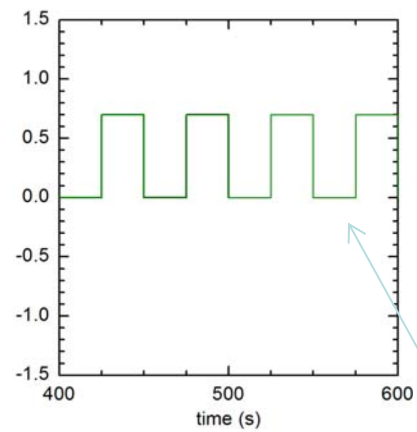
Strong DC fields - "poling"

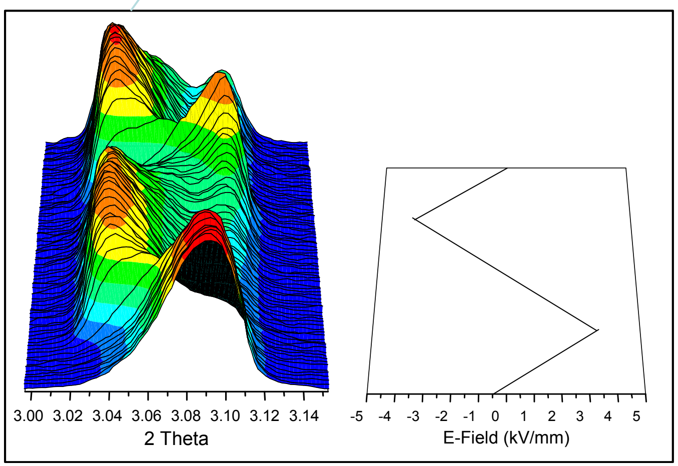
Weak unipolar or bipolar fields – property coefficients

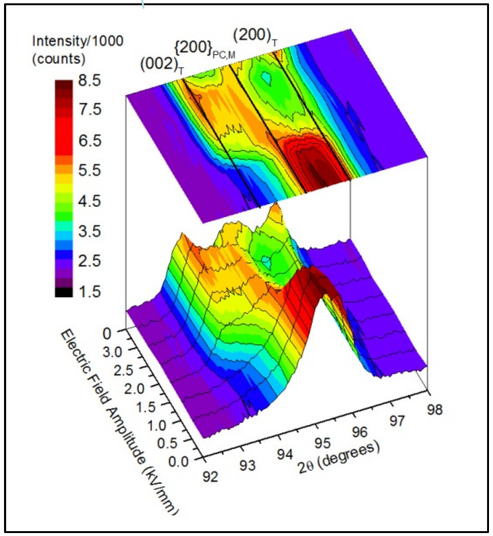
As a function of field amplitude, cycle number, etc. – Aging; Rayleigh behavior, etc.

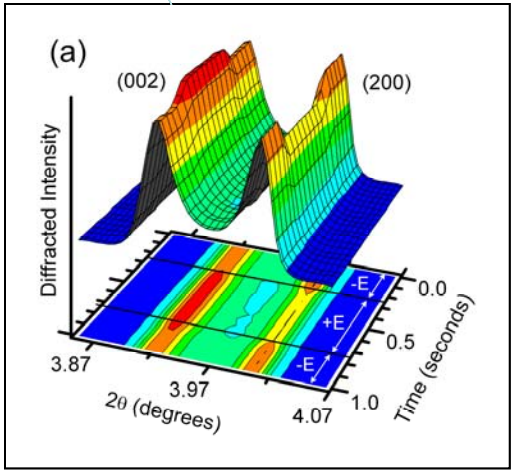




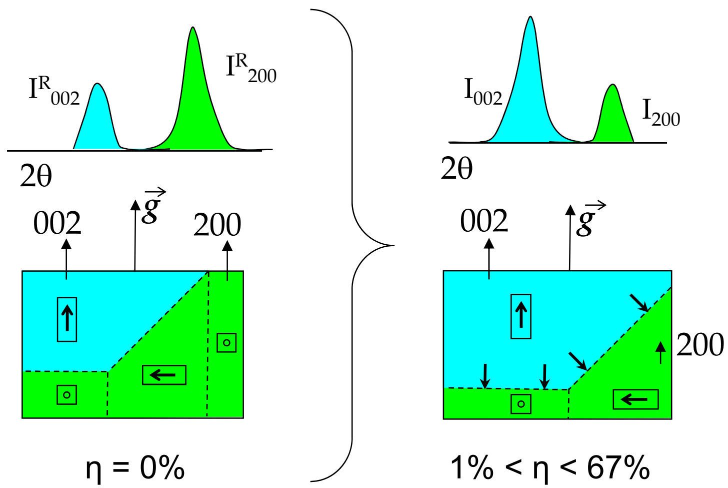








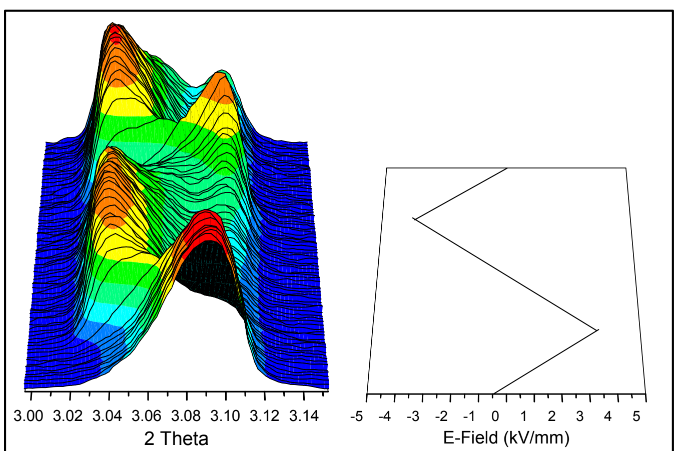
Methodology: X-ray Diffraction

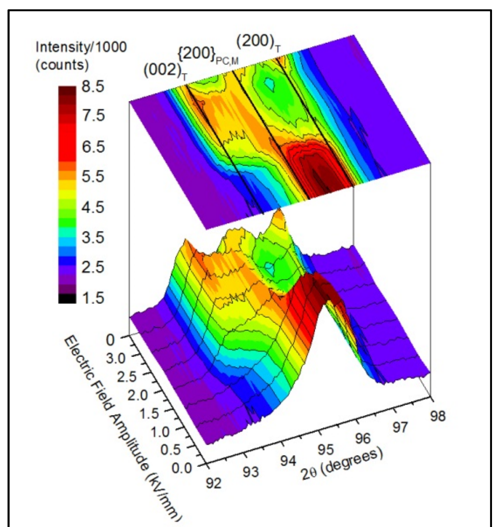


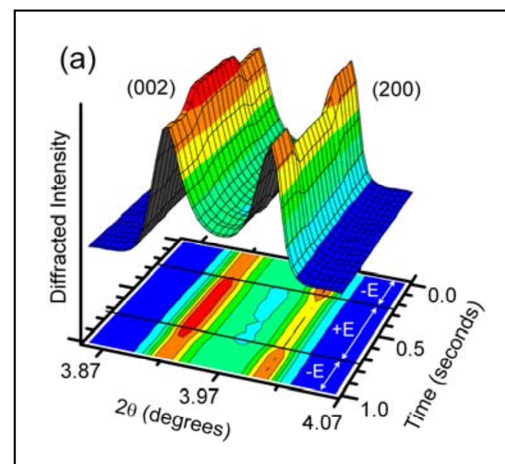
Jones et al., J. Appl. Phys., vol. 97, 034113, 2005.

- **Quantifying ferroelastic domain wall motion:** measured in diffraction by a change in the intensities of certain peaks

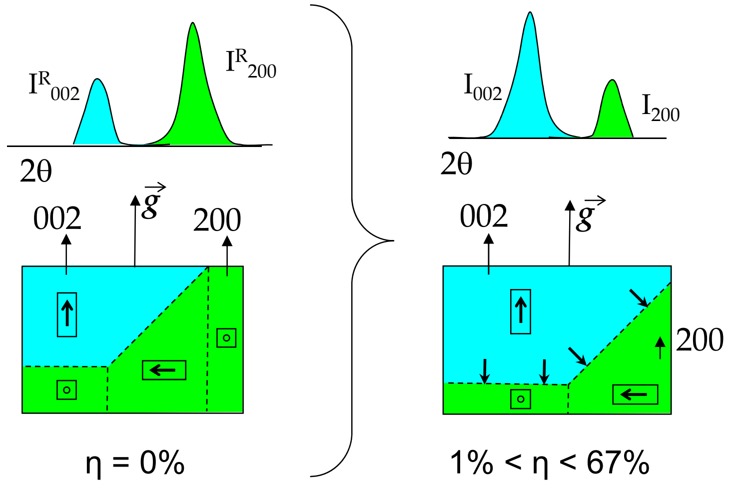
$$\eta_{002}(\%) = \frac{I_{002}/I_{002}^{unpoled}}{I_{002}/I_{002}^{unpoled} + 2\cdot\left(I_{200}/I_{200}^{unpoled}\right)} - \frac{1}{3}$$







Methodology: X-ray Diffraction



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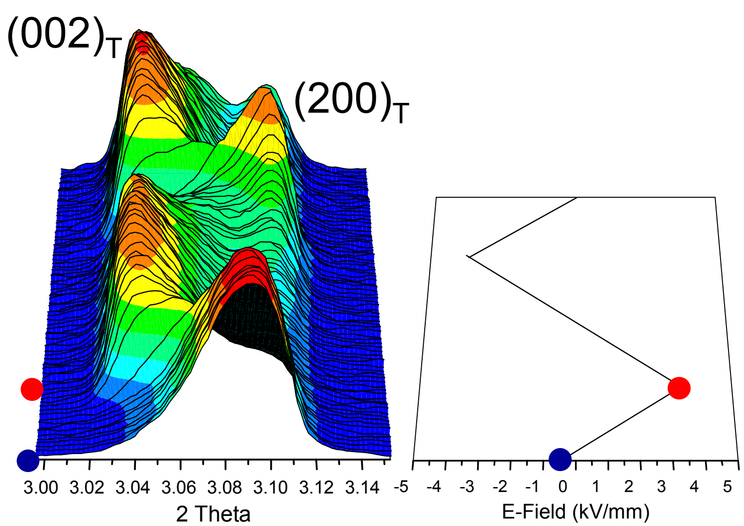
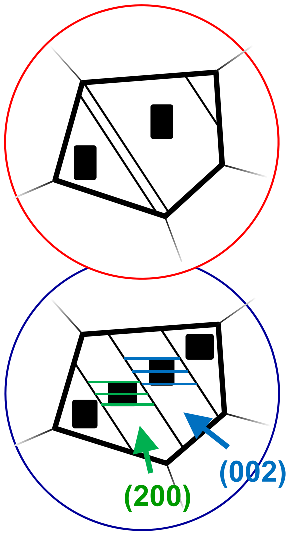
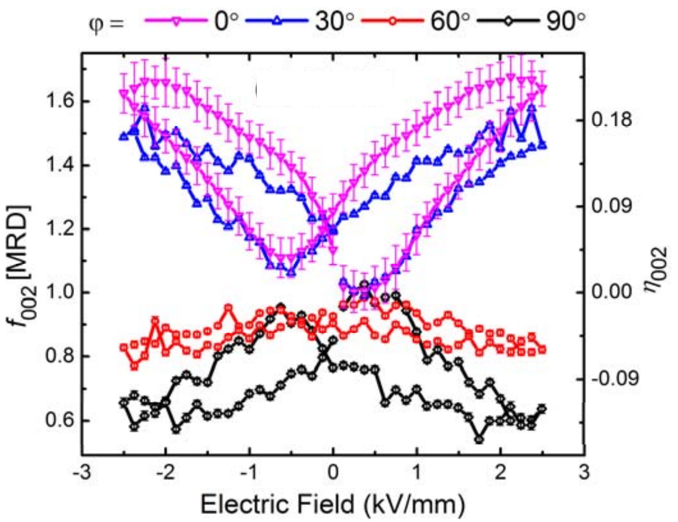






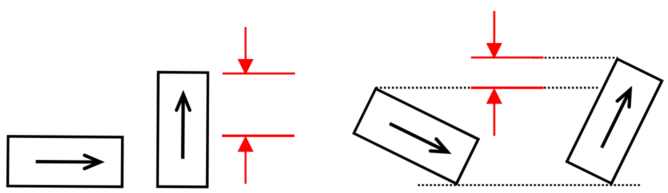
Methodology: X-ray Diffraction

Volume average of a tensorial quantity,[1] t(x)

$$\langle t \rangle = \frac{1}{V}\int_V t(x)dV$$

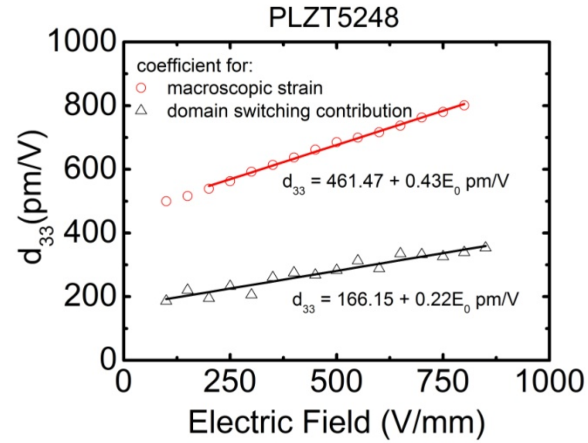
Arithmetic average of domain reorientation yields[2]

$$\langle \varepsilon_{\text{non-180}} \rangle = \frac{(c-a)}{a}\int_{\alpha=0}^{\pi/2} 3\cdot\Delta\eta(\alpha)\cdot\cos^2\alpha\cdot\sin\alpha\cdot d\alpha$$

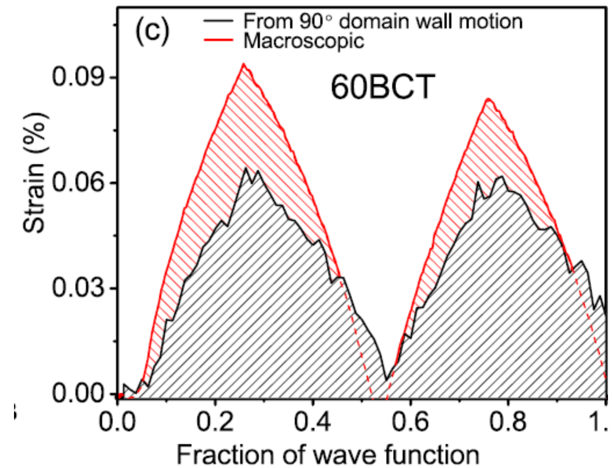


$$d_{\text{non-180}} = \frac{\langle \varepsilon_{\text{non-180}} \rangle}{2\cdot E_o}$$

[1]e.g. see Kocks et al., Texture and Anisotropy, Cambridge Press (1998).
[2]Jones et al., J. Appl. Phys., vol. 97, 034113, 2005.



Pramanick et al., J. Am. Ceram. Soc., 92 2300 (2009)

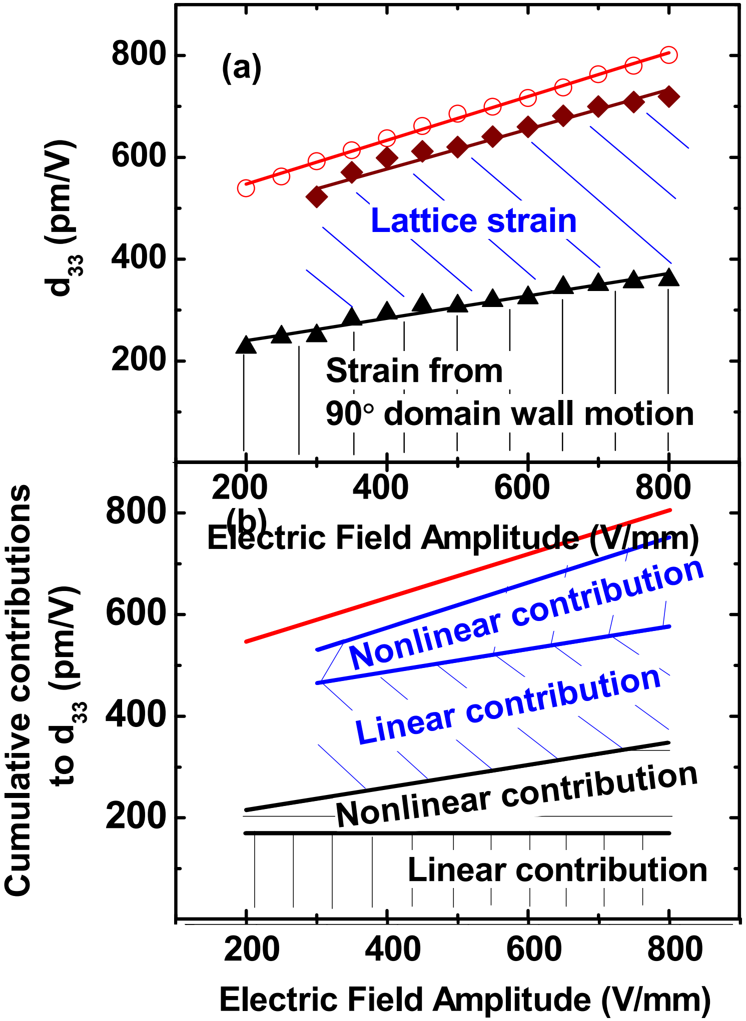


Tutuncu et al., J. Appl. Phys., 115, 144104 (2014).

Application to Diverse Materials Systems

1. Polycrystalline *$Pb(Zr,Ti)O_3$ (PZT)* (dominant commercial material)
2. High-temperature *$BiScO_3 – PbTiO_3$* piezoelectric
3. Pb-free *$Ba(Zr_{0.2}Ti_{0.8})O_3–x(Ba_{0.7}Ca_{0.3})TiO_3$* as a function of *c/a*
4. Classical *$BaTiO_3$* as a function of *grain size*
5. Field-induced *phase transitions* in *$Na_{0.5}K_{0.5}NbO_3$*
6. Polycrystalline *PZT thin films* for piezoMEMS, etc.

2at% La-substituted $Pb(Zr_{0.52}Ti_{0.48})O_3$



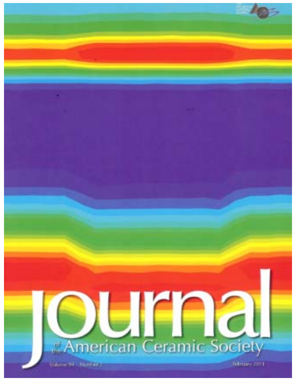
Take-home Message:

- ***Lattice strains are only weakly piezoelectric, and are mostly attributed to intergranular strain coupling.***
- ***Most of the piezoelectric property coefficients can be attributed to 90° domain wall motion.***

Take-home Message:

- ***~50% of piezoelectric coefficient in PZT results directly from 90° domain wall contributions.***

Pramanick et al., J. Am. Ceram. Soc., vol. 94, 293-309 (2011).



High-Temperature $.36BiScO_3$-$.64PbTiO_3$

- BS-PT can exhibit d_{33} > 460 pC/N and a high T_c of 450°C near the morphotropic phase boundary (MPB).

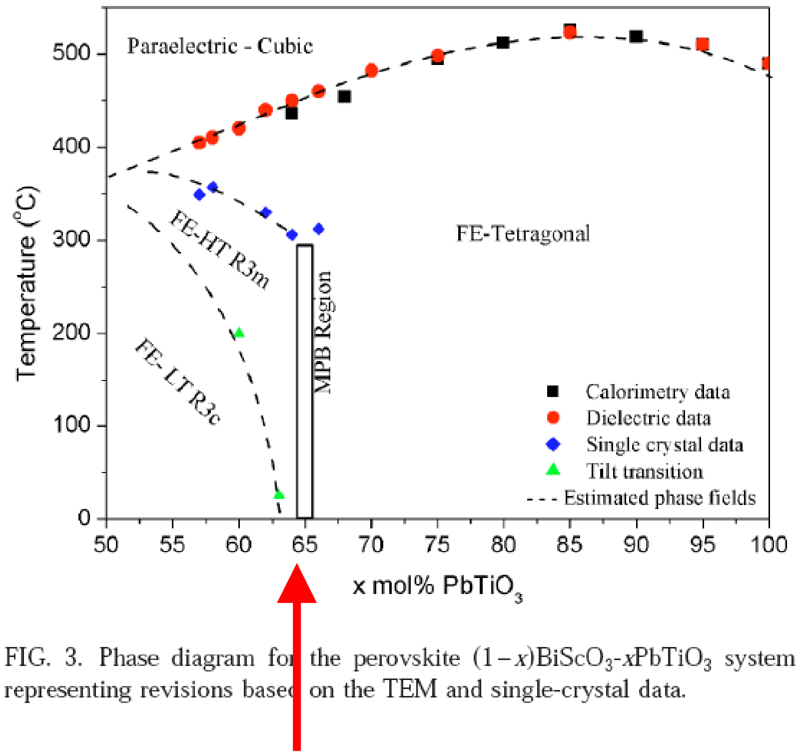
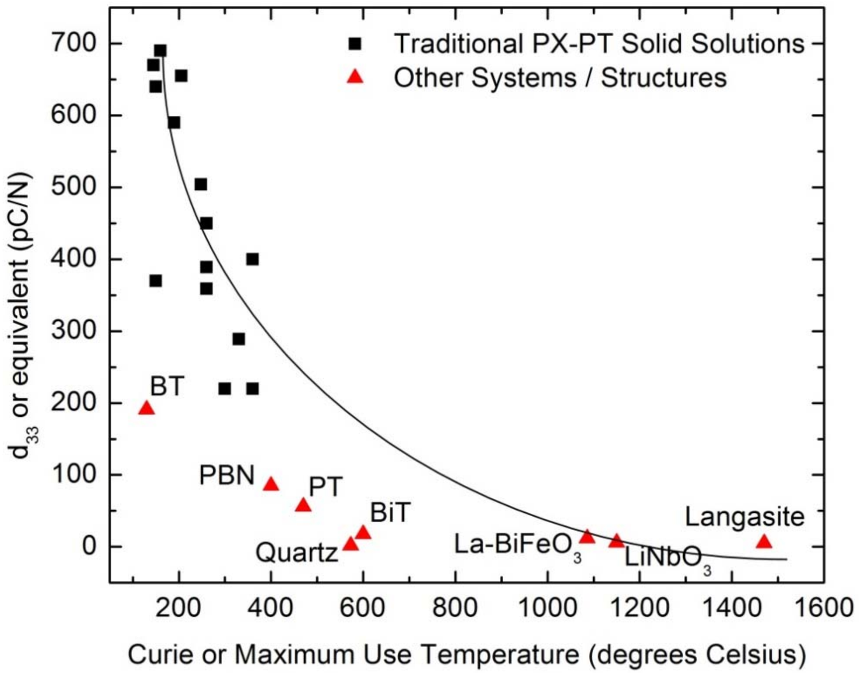


FIG. 3. Phase diagram for the perovskite $(1-x)BiScO_3$-$xPbTiO_3$ system representing revisions based on the TEM and single-crystal data.



Eitel et al., J. Appl. Phys., 96, 5, 2828+ (2004).

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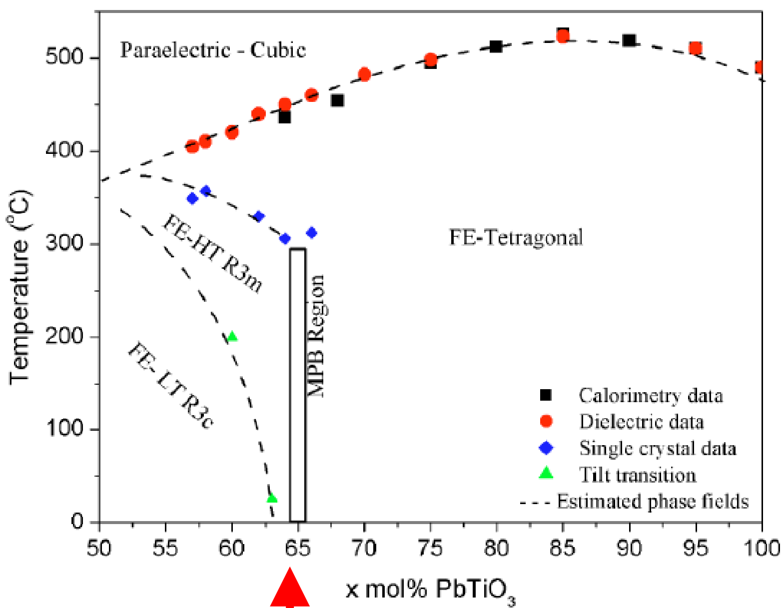
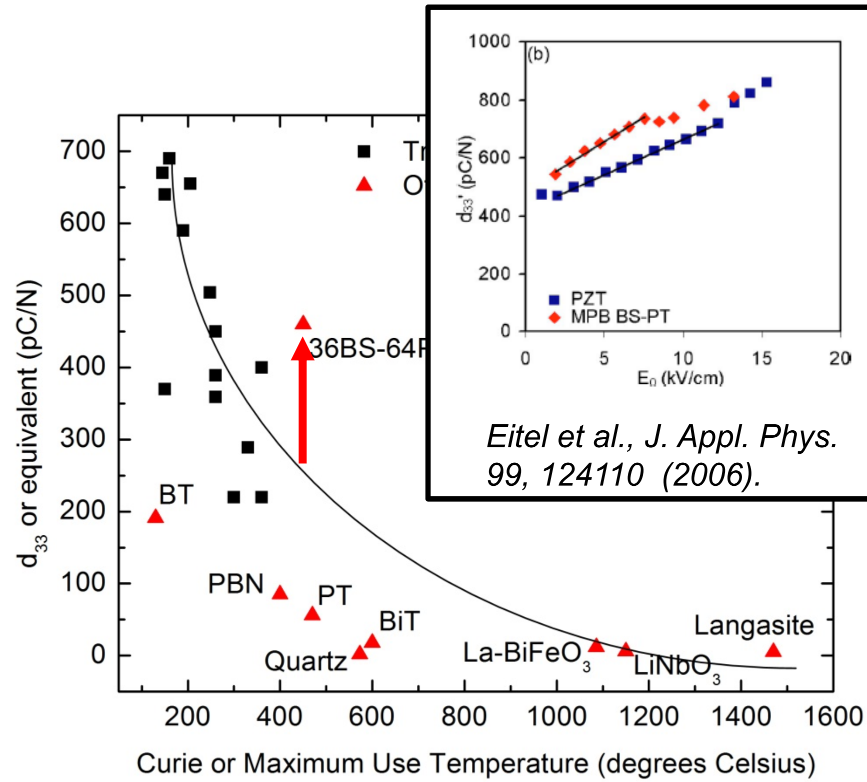
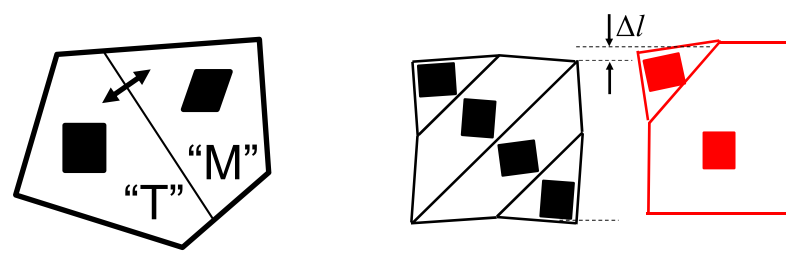


FIG. 3. Phase diagram for the perovskite $(1-x)BiScO_3$-$xPbTiO_3$ system representing revisions based on the TEM and single-crystal data.

*Mixture of monoclinic (*Cm*, ~50%) and tetragonal (*P4mm*, ~50%)



Eitel et al., J. Appl. Phys. 99, 124110 (2006).

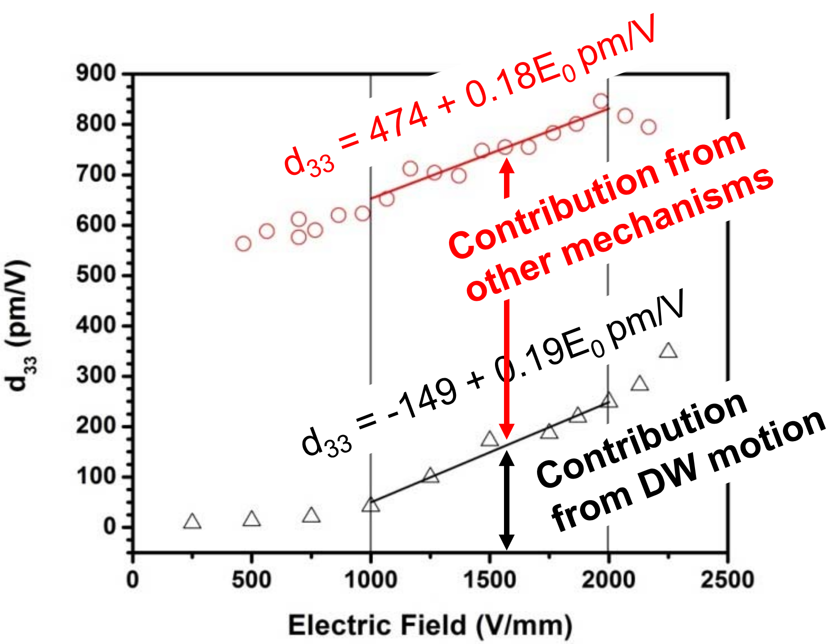


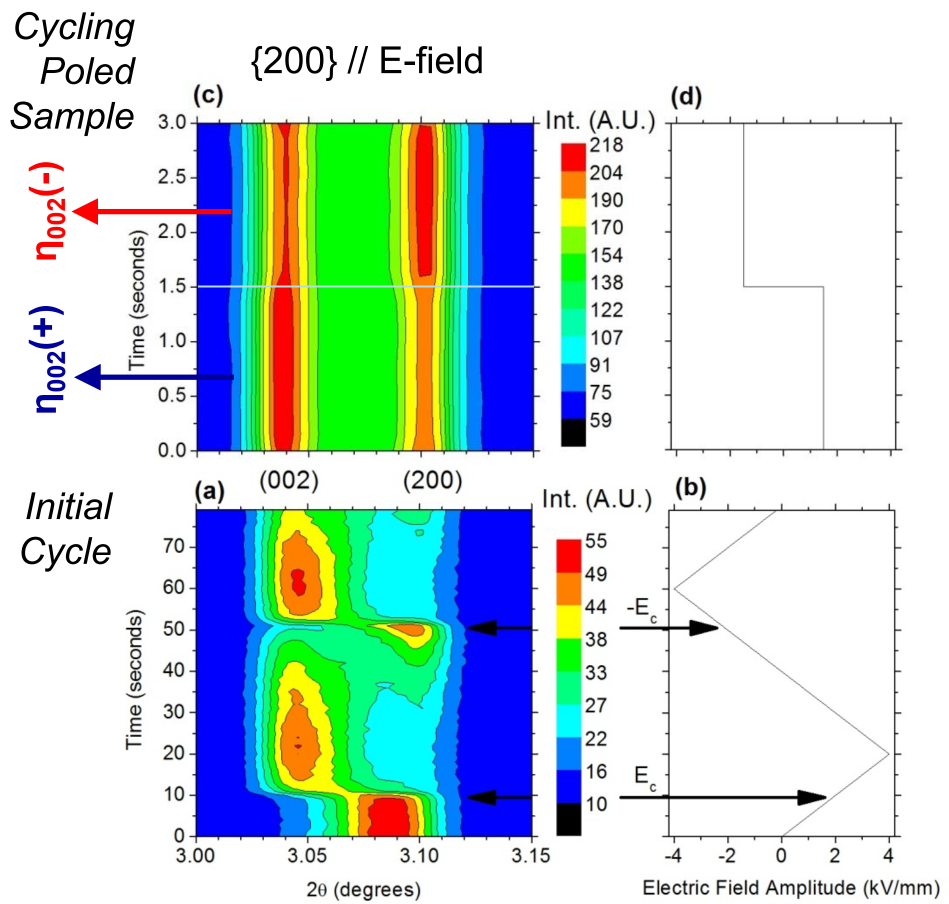
Eitel et al., J. Appl. Phys., 96, 5, 2828+ (2004).

[*]Kim et al., J. Appl. Phys. 105, 114101 (2009).

High-Temperature .36$BiScO_3$-.64$PbTiO_3$

Domain wall motion in tetragonal phase



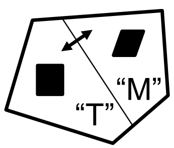


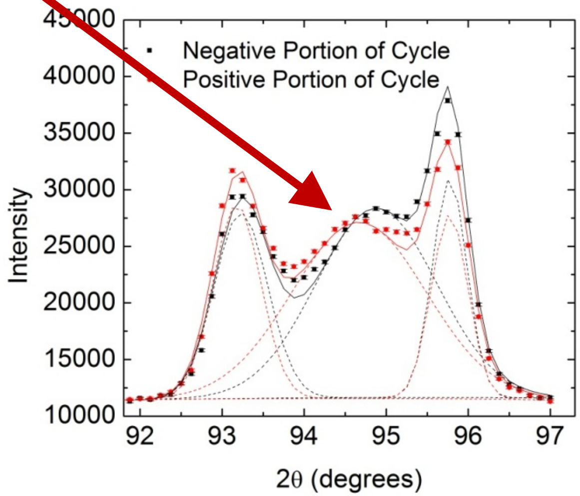
Tutuncu et al., Phys. Rev. Lett. 108, 177601 (2012).

High-Temperature .36$BiScO_3$-.64$PbTiO_3$

In related work,* we also showed:

- **Domain wall motion in monoclinic phase** of this two-phase mixture is ***high***,
- Extent of **interphase boundary motion** (i.e., phase switching between M and T phases) is ***low***, and
- Electric-field-induced **piezoelectric strains** are ***frequency independent*** and correlate with single crystal piezoelectric coefficients.

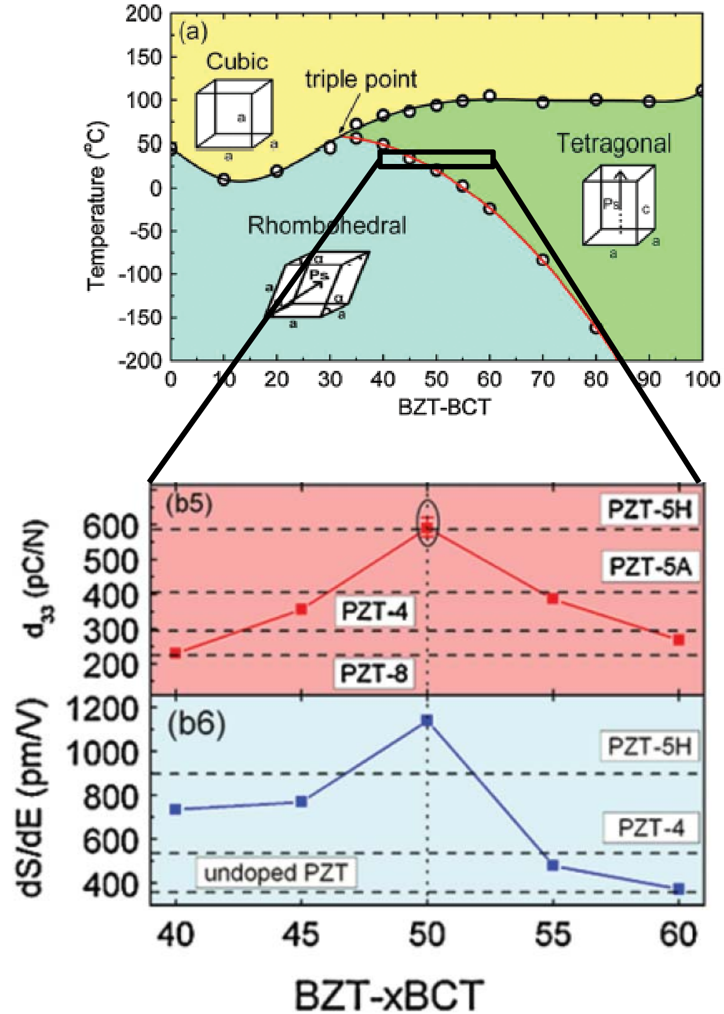




Jones et al., Phys. Rev. B, 86, 024104 (2012).

$Ba(Zr_{0.2}Ti_{0.8})O_3–x(Ba_{0.7}Ca_{0.3})TiO_3$

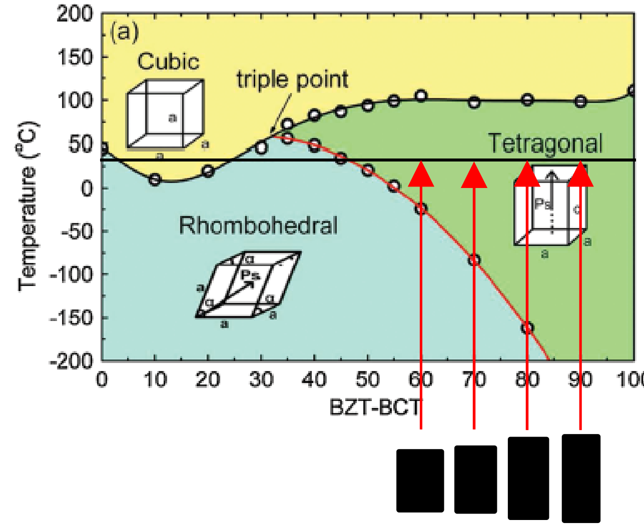
- Pb-free, with d_{33} up to **<u>620 pC/N</u>** at room temperature
- (albeit with T_c of 93°C)



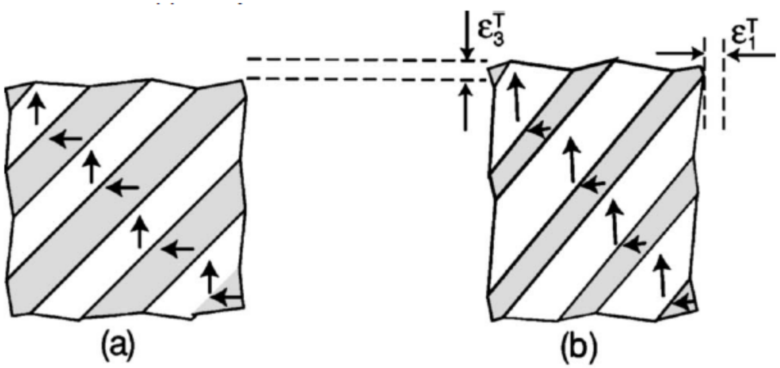
Figures from Liu and Ren, Physical Review Letters, 103, 257602 (2009).

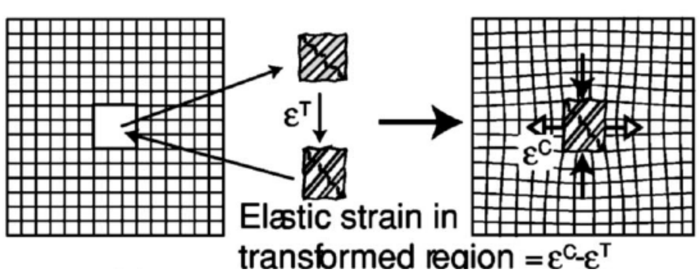
$Ba(Zr_{0.2}Ti_{0.8})O_3–x(Ba_{0.7}Ca_{0.3})TiO_3$

- Lattice aspect ratio decreases towards MPB
- **<u>Test the developing hypothesis that</u> domain wall motion *increases* with *decreasing* lattice aspect ratio due to *less strain incompatibility (grain-grain interactions)*.**



	60BCT	70BCT	80BCT	90BCT
c/a	1.0054	1.0067	1.0075	1.0079





Schematic from David Hall et al., J. Appl. Phys. (2004).

Phase diagram from Liu and Ren, Physical Review Letters, 103, 257602 (2009).

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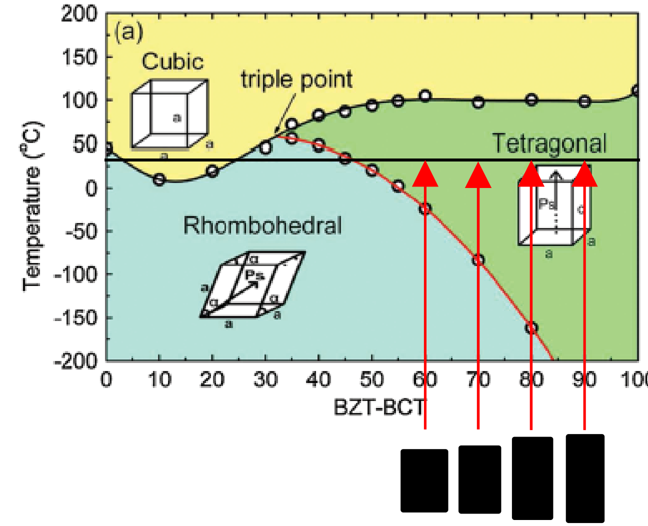

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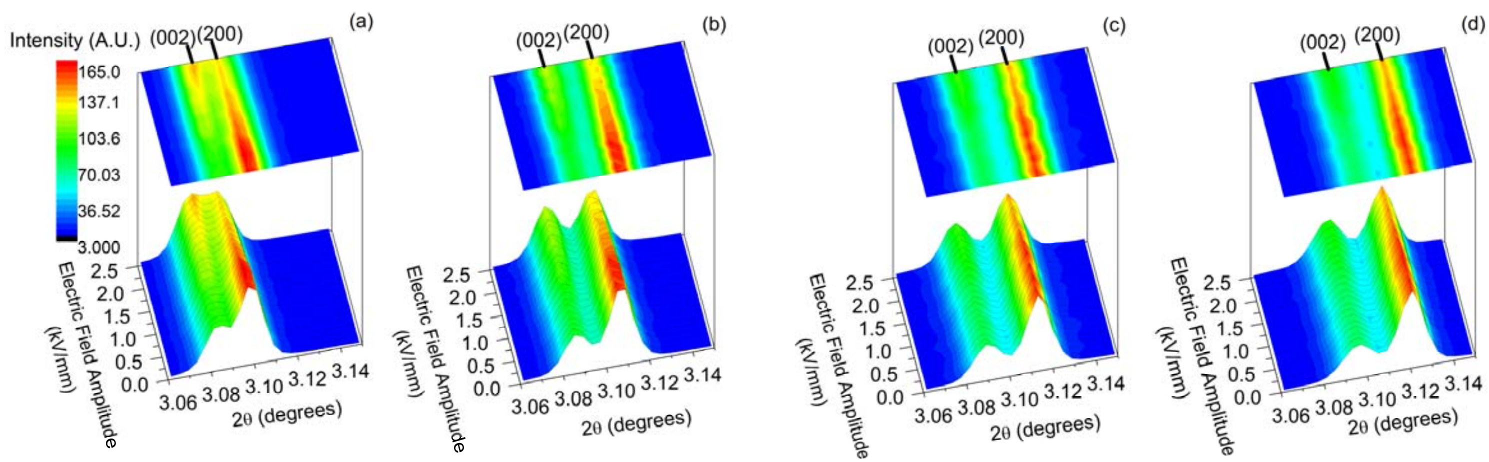

Phase diagram from Liu and Ren, Physical Review Letters, 103, 257602 (2009).

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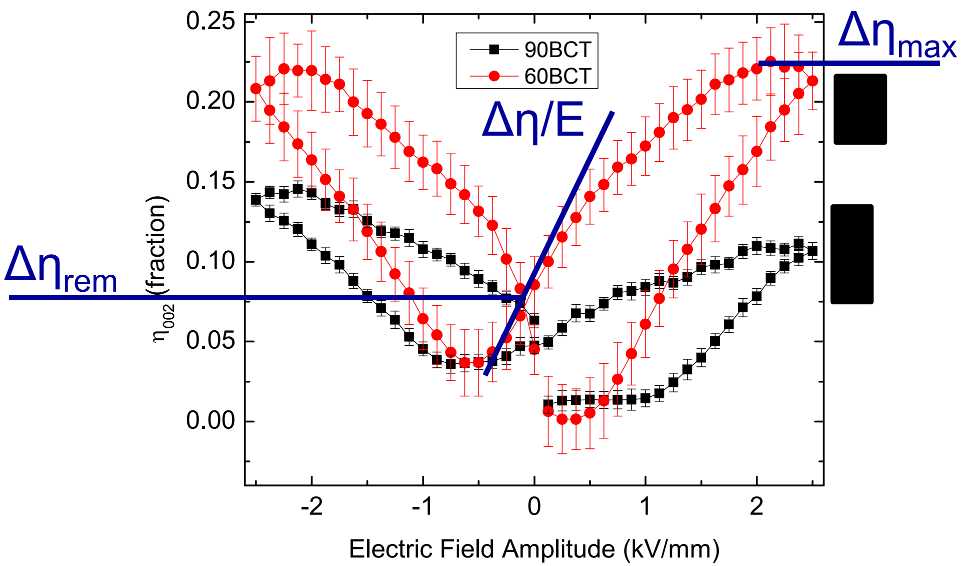

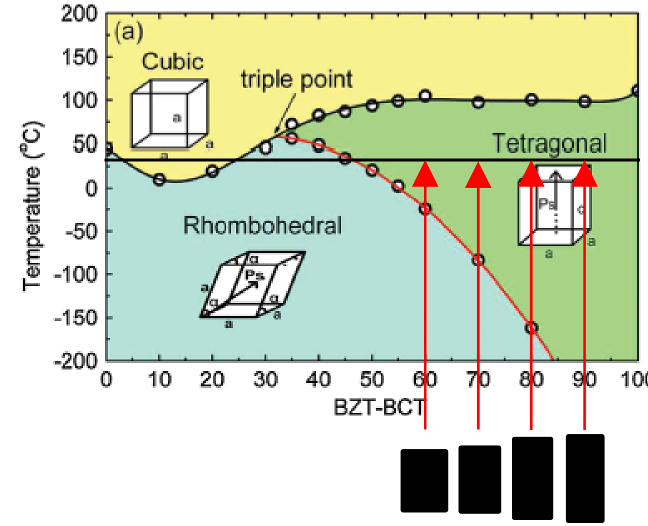

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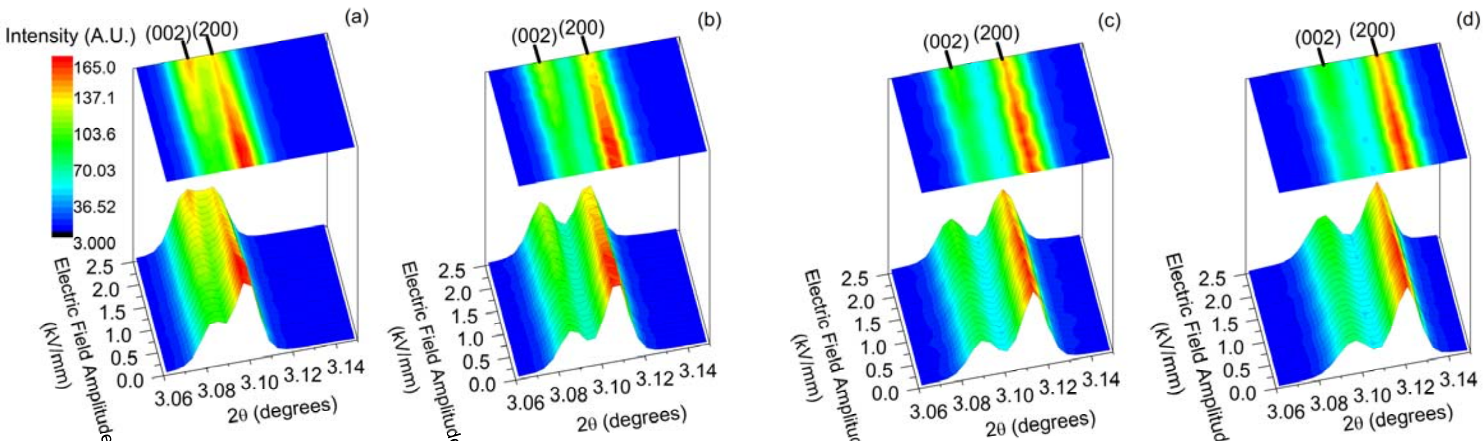

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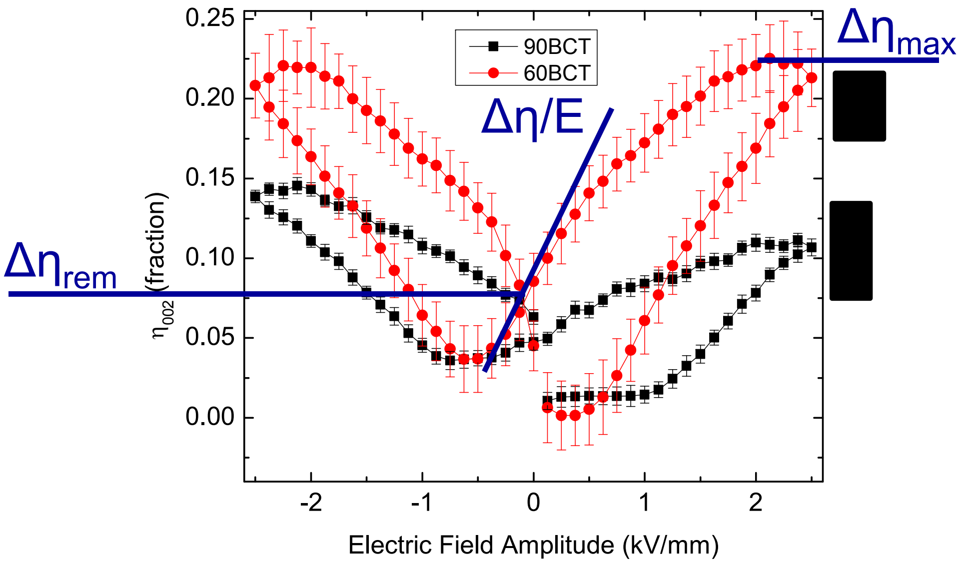
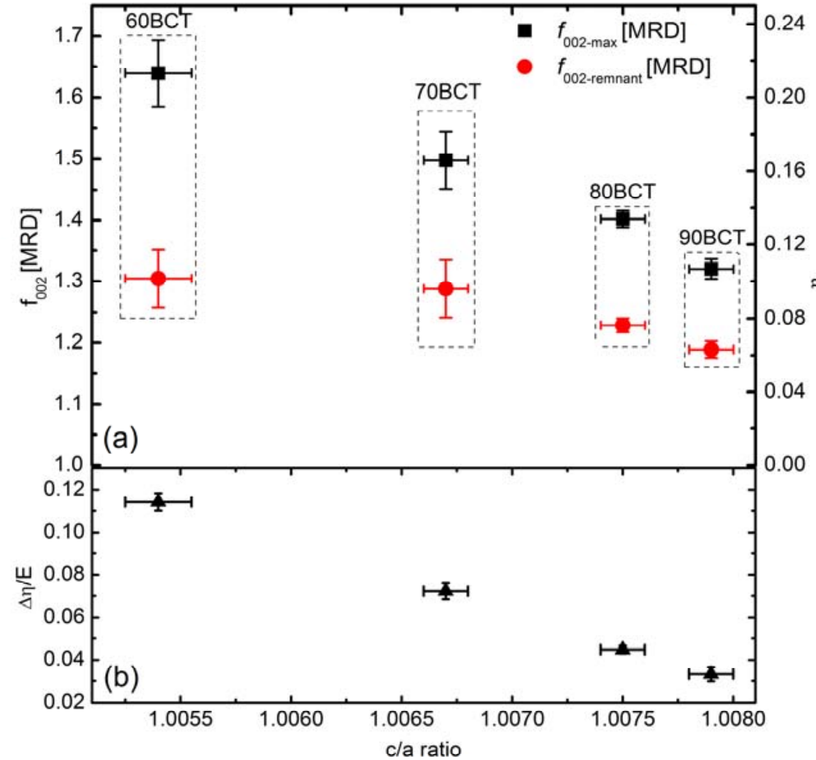




Take-home Message:

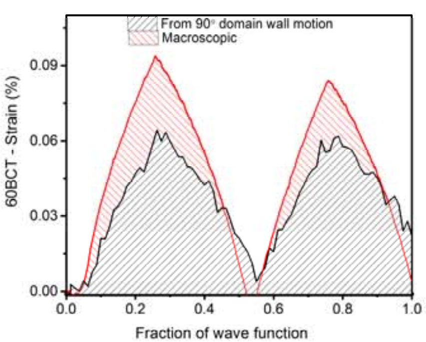
- ***Extent of domain wall motion inversely related to c/a.***

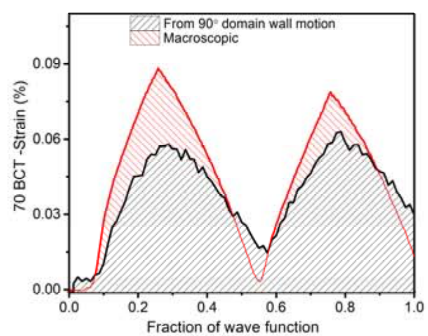
$Ba(Zr_{0.2}Ti_{0.8})O_3–x(Ba_{0.7}Ca_{0.3})TiO_3$

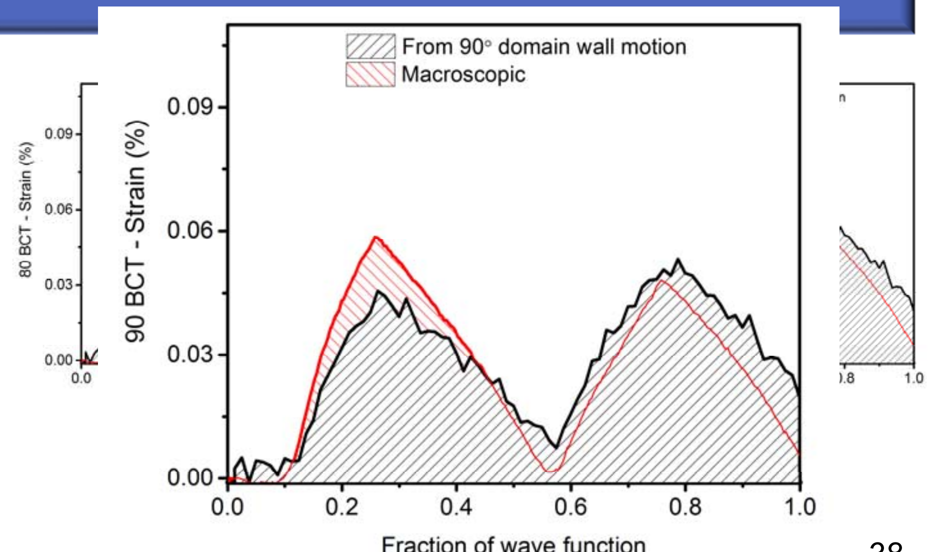
- Measured at all angles to the field direction, enabling a calculation of contribution of non-180° DW motion to macroscopic strain

Take-home Message:

- ***Non-180° domain wall motion constitutes majority of macroscopic response.***
- ***Absolute contribution from non-180° DW motion increases as MPB is approached.***
- ***Additional contributions from other effects also increase as MPB is approached.***







Grain size effects in $BaTiO_3$

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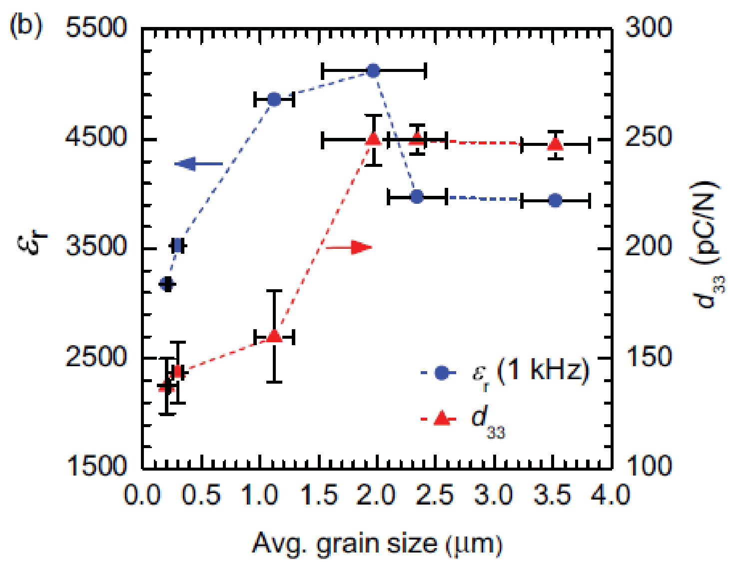
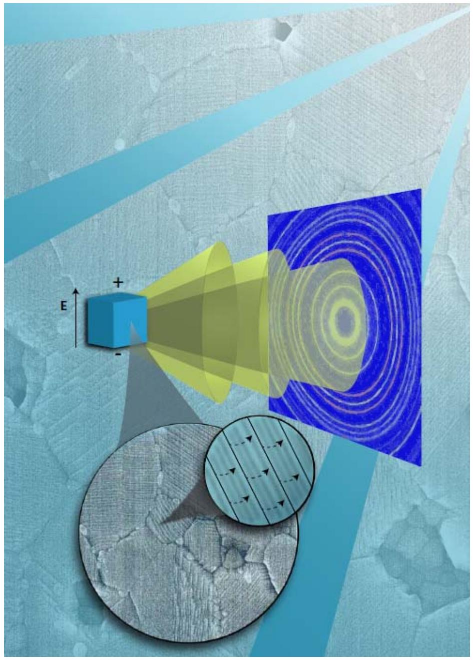
FULL PAPER

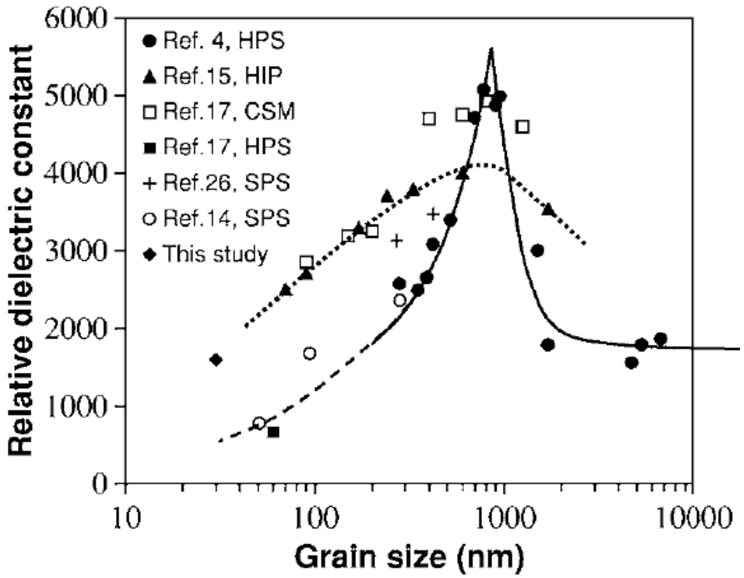
Domain Wall Displacement is the Origin of Superior Permittivity and Piezoelectricity in $BaTiO_3$ at Intermediate Grain Sizes

*Dipankar Ghosh, Akito Sakata, Jared Carter, Pam A. Thomas, Hyuksu Han, Juan C. Nino, and Jacob L. Jones**

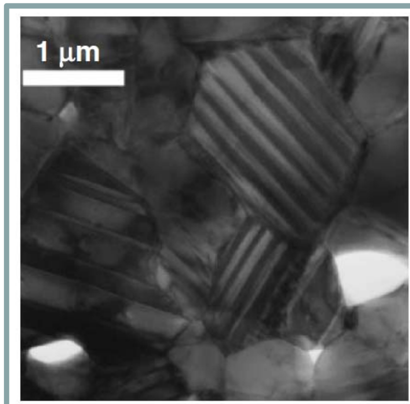




Grain size effects in $BaTiO_3$



Buscaglia et al., Physical Review B, 73, 064114 (2006).

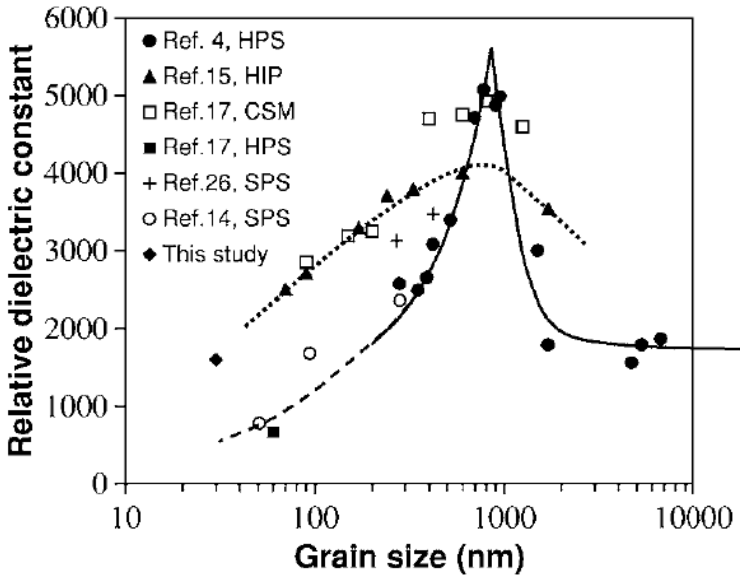


Hoshina and Tsurumi et al., Jap. J. Appl. Phys., 47, 7607 (2008).

- Known since 1960's:
  - Peak in permittivity at ~1 μm
  - 90° domain sizes decrease down to ~1 μm, then single domain below ~1 μm.
- Competing theories:
  - Near ~1 μm, grains become single ferroelastic domain. This increases internal **residual stress** and pushes the structures towards the paraelectric phase with a commensurate increase in ε_r (Buessem *et al.*, 1966)
  - **Domain walls** exhibit greatest mobility at ~1 μm, leading to the large extrinsic contribution to ε_r (Arlt *et al.*, 1985)

Ghosh, Jones *et al., Adv. Funct. Mater.*, in press (2013).

Grain size effects in $BaTiO_3$



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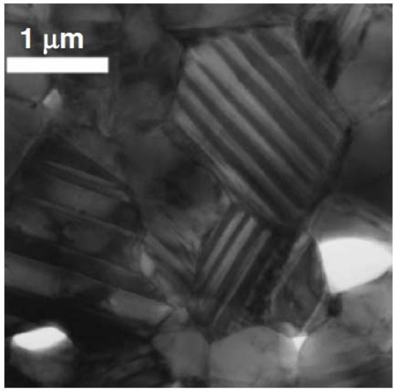
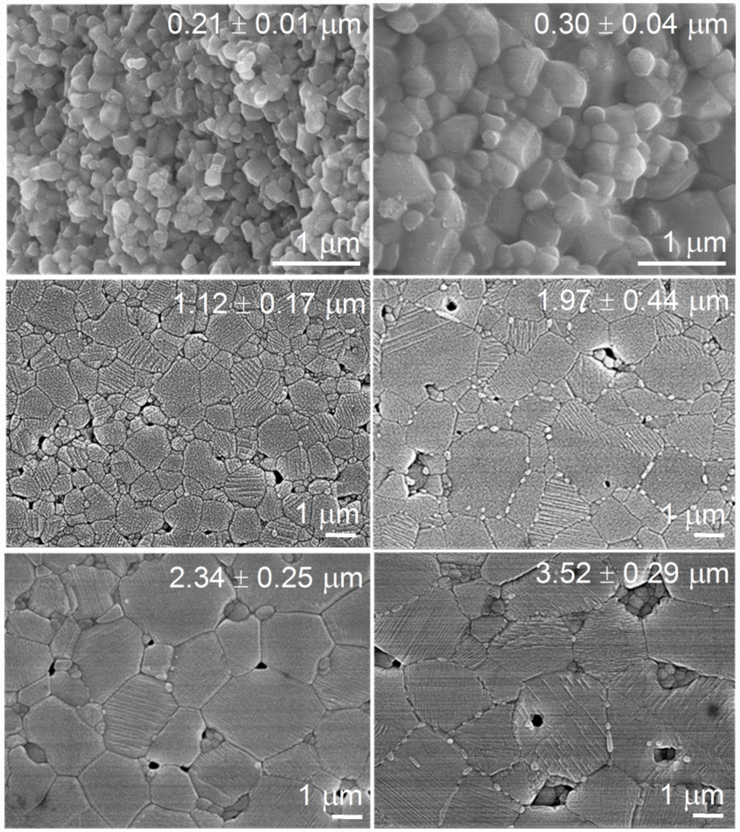


Hoshina and Tsurumi et al., Jap. J. Appl. Phys., 47, 7607 (2008).

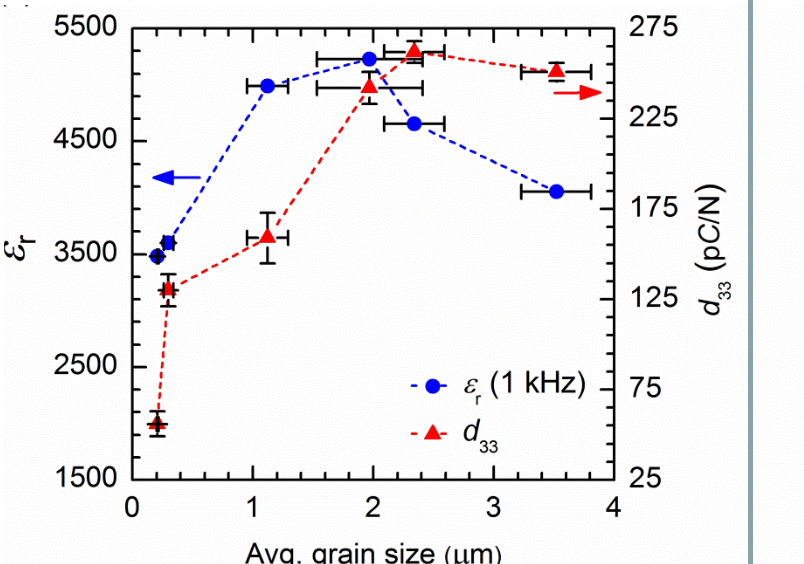
Synthesis using both spark plasma sintering and conventional sintering



Ghosh et al., unpublished (2012).

Ghosh, Jones *et al., Adv. Funct. Mater.*, in press (2013).

Grain size effects in $BaTiO_3$



Ghosh, Jones et al., unpublished (2012).

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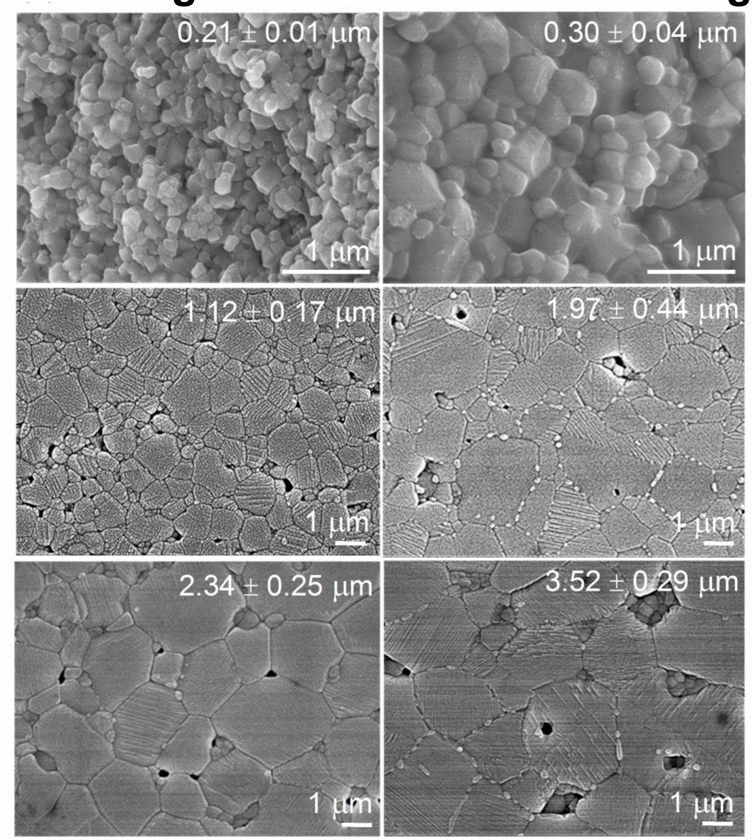
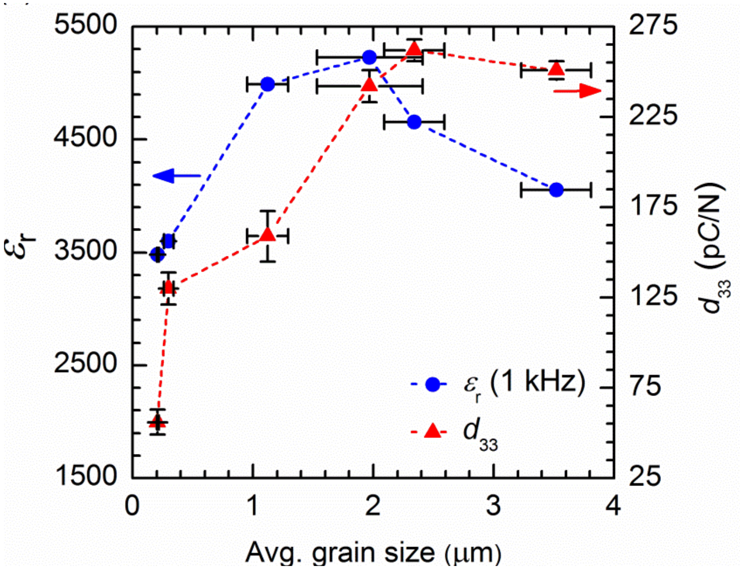


Ghosh et al., unpublished (2012).

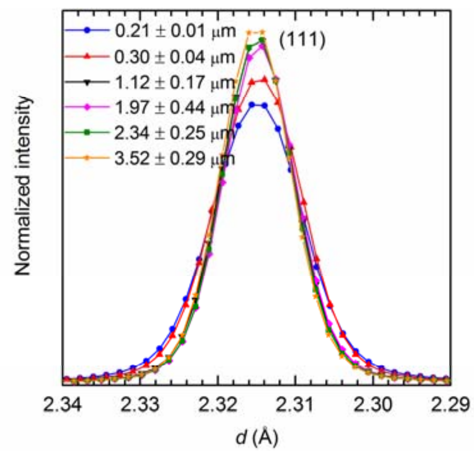
Ghosh, Jones *et al., Adv. Funct. Mater.*, in press (2013).

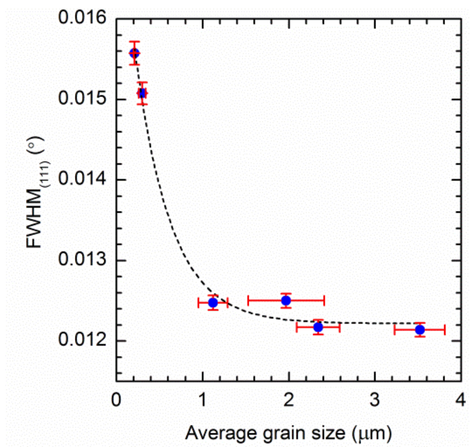
Grain size effects in $BaTiO_3$



Ghosh, Jones et al., unpublished (2012).

Residual strain and crystallite size effects

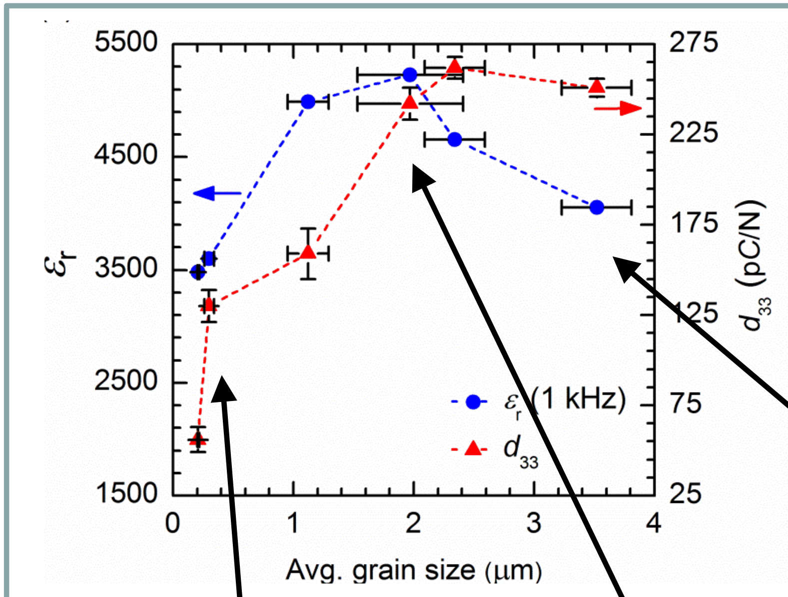




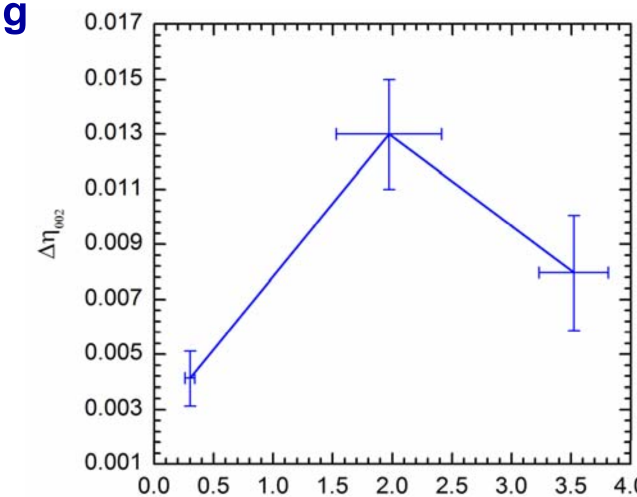
- **No macrostrain (i.e., residual stress)**
- **Either microstrain (i.e., distribution of lattice spacings) or crystallite broadening.**

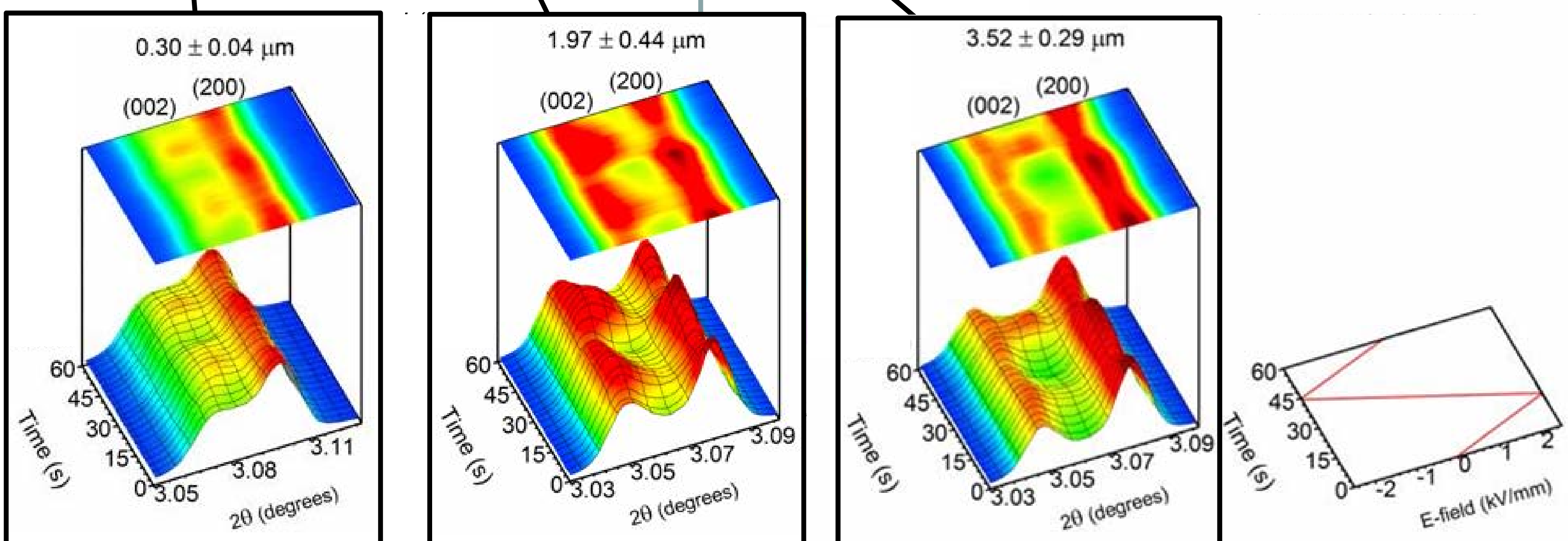
Ghosh, Jones *et al., Adv. Funct. Mater.*, in press (2013).

Grain size effects in $BaTiO_3$

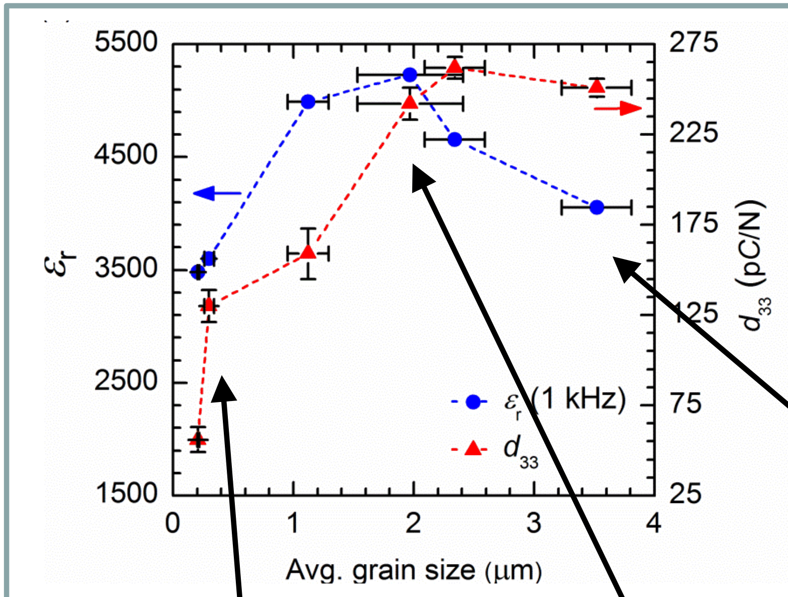


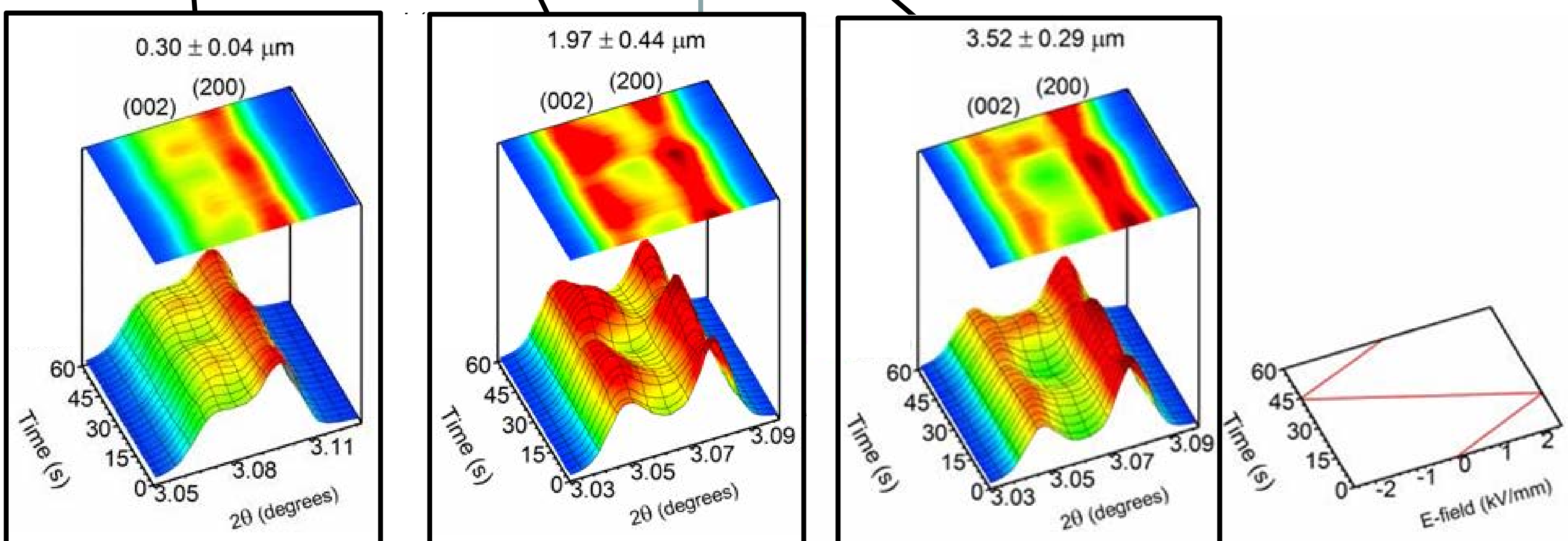
- **Domain wall motion during *weak field* cycling**





Grain size effects in $BaTiO_3$

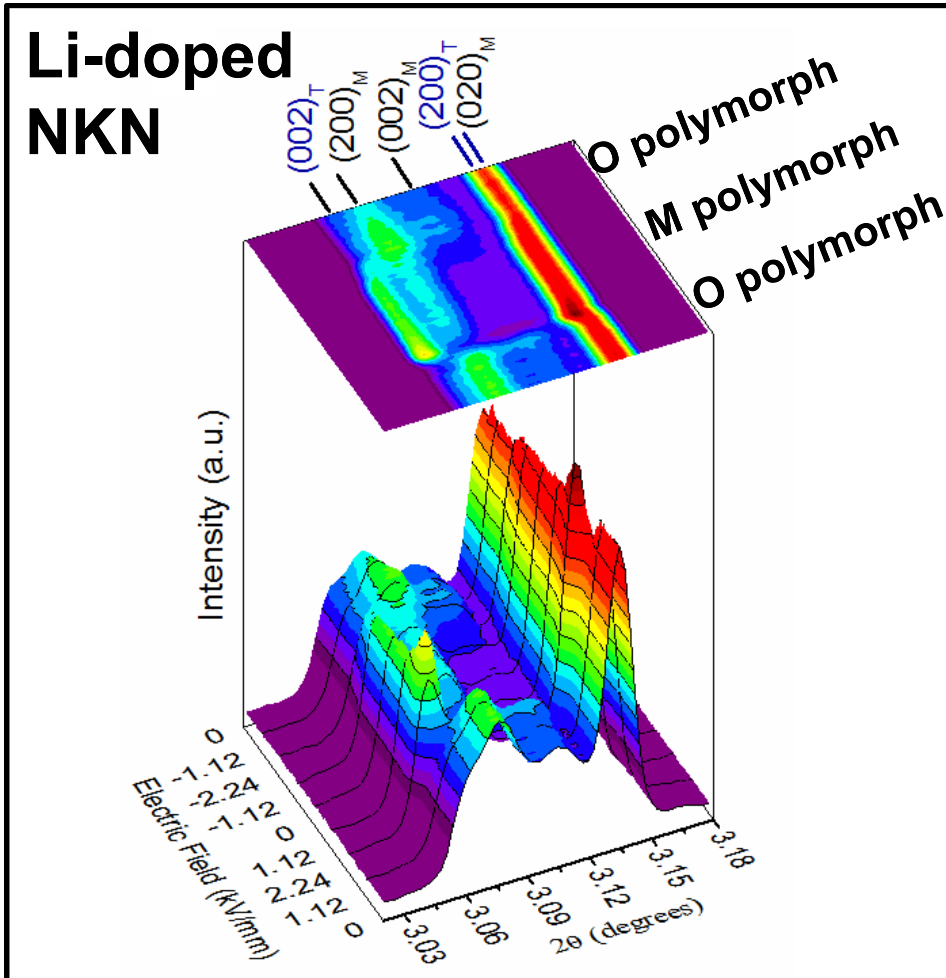




Take-home Message:

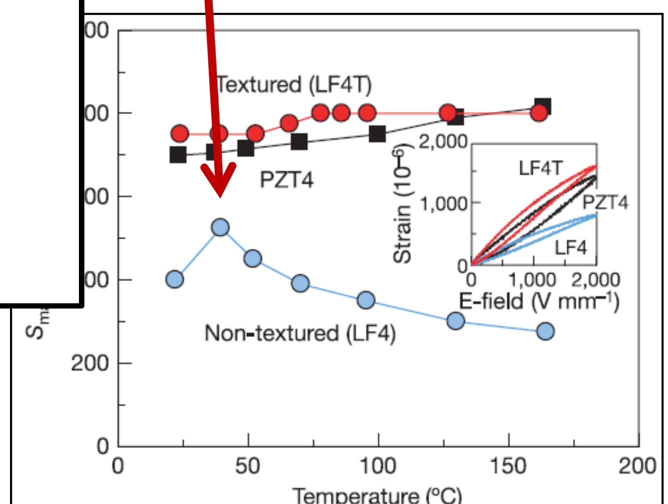
- Domain wall motion correlated with enhanced properties.
- Confirms **domain wall motion theory** is dominant origin of d_{33} and ε_r peaks at ~1 μm grain size in $BaTiO_3$ (theory of Arlt *et al.*, 1985)

Phase transitions in $Na_{0.5}K_{0.5}NbO_3$



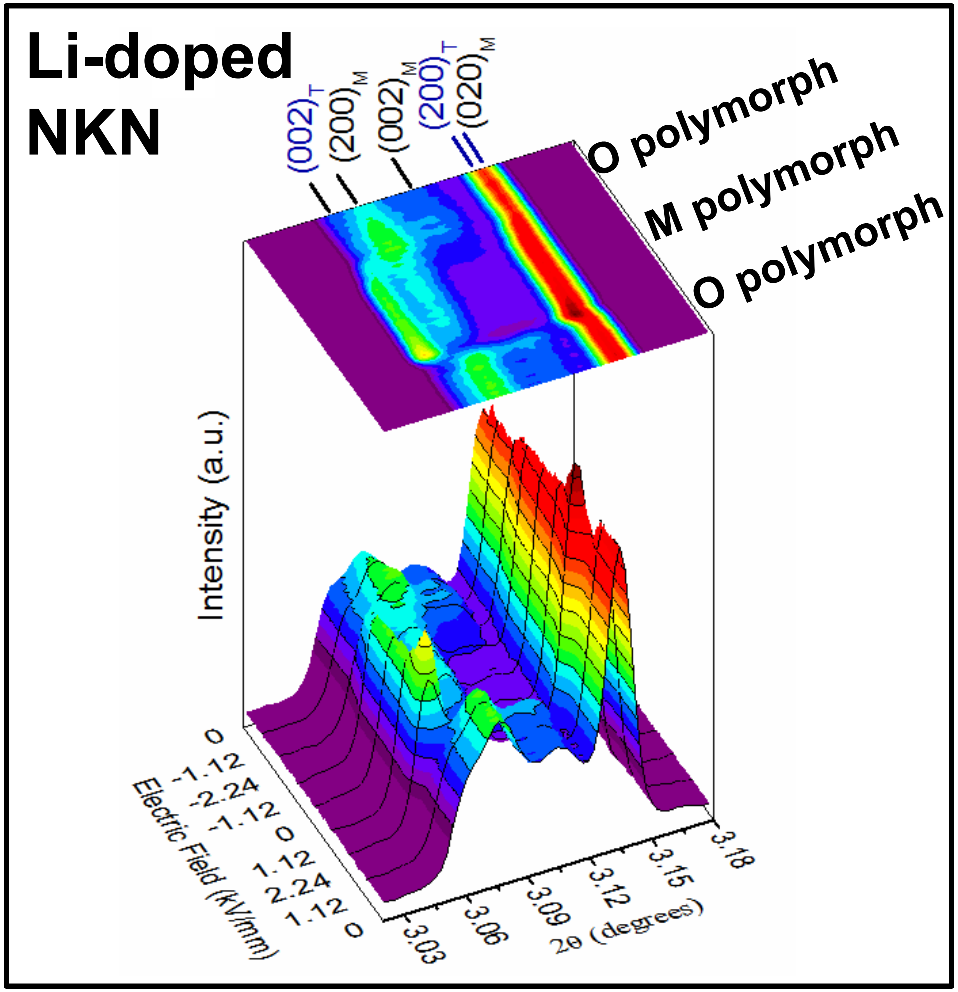
"It is considered that this anomaly is related to the **electric-field-induced tetragonal-to orthorhombic** phase transformation, shifting the phase transformation temperature from below 25°C in the unpoled specimen to 40°C under a high electric field. In order to clarify the origin of this anomaly, morphotropic phases need to be determined under high electric-field driving."

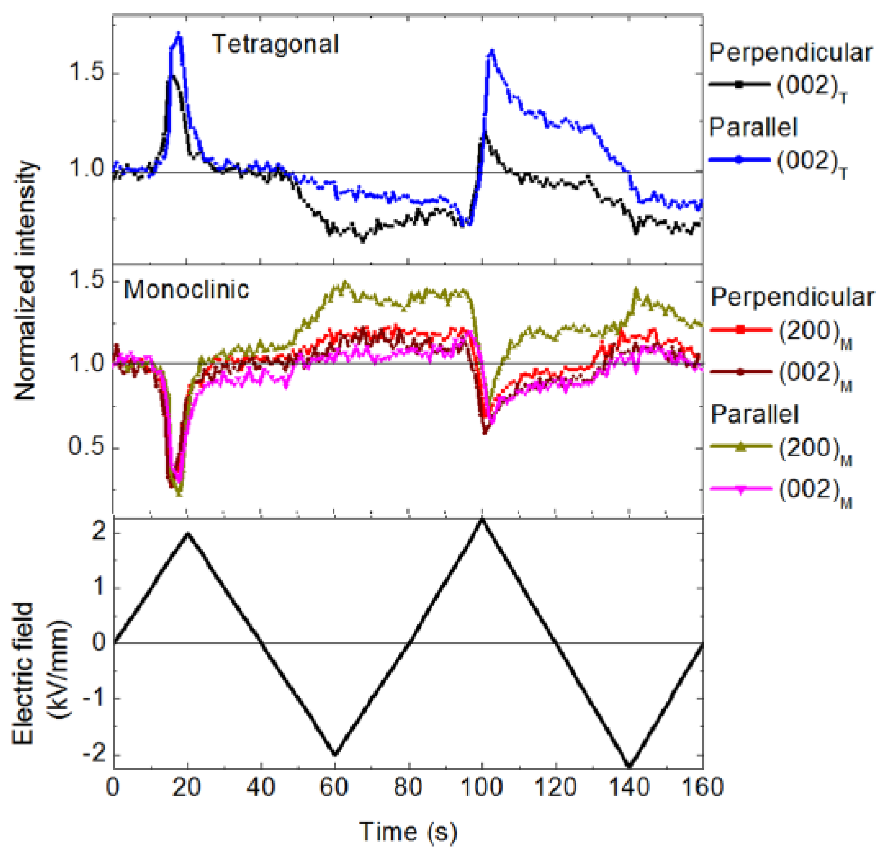
- Saito et al., Nature (2004)



Iamsasri, Jones et al., J. Appl. Phys., 117, 024101 (2015).

Phase transitions in $Na_{0.5}K_{0.5}NbO_3$





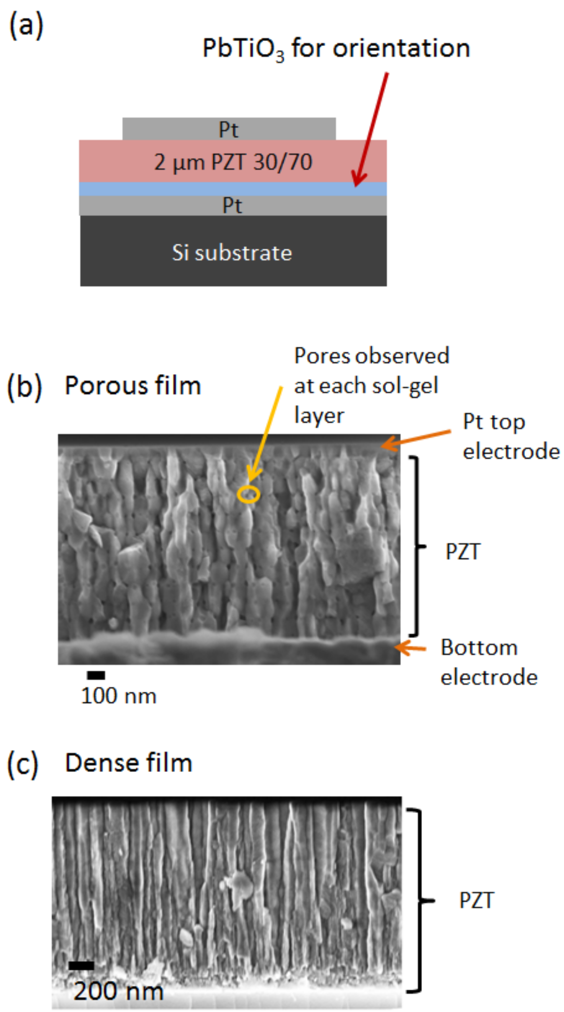
Take-home Message:

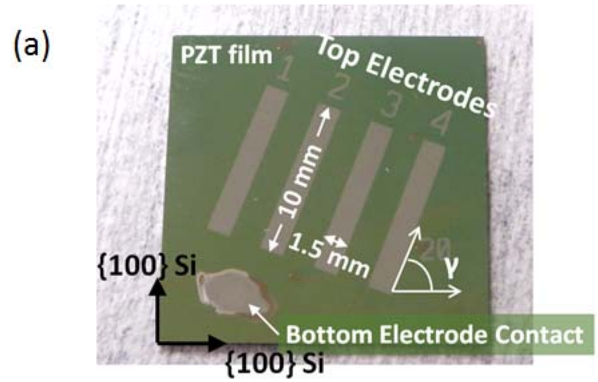
- Dramatic phase switching present, and field-dependent.

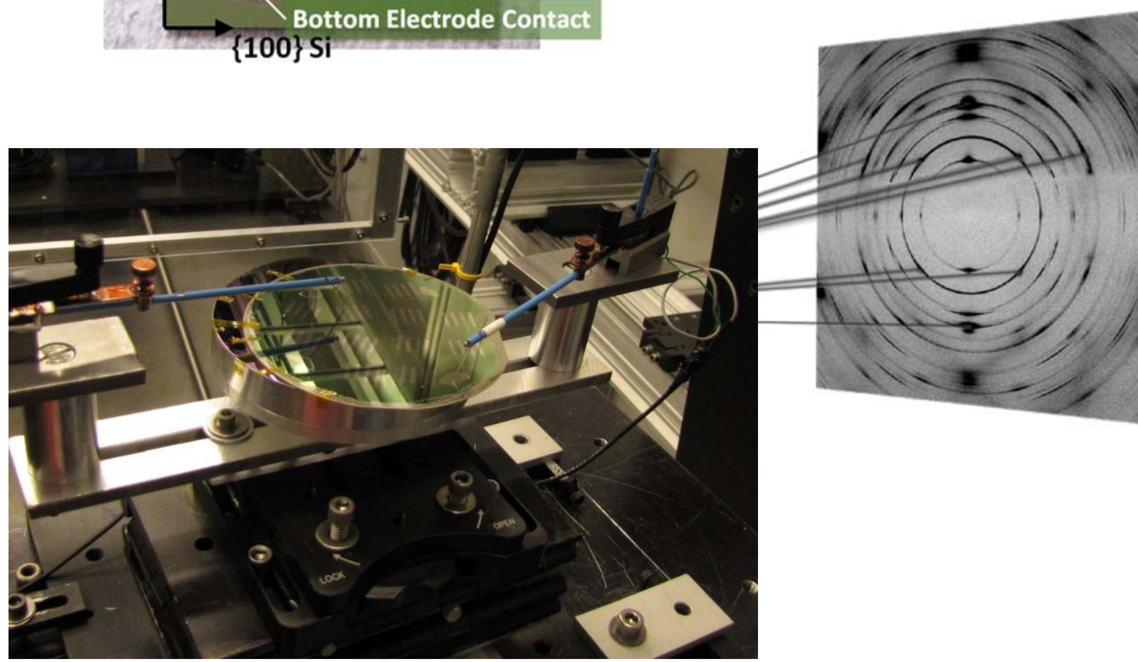
Iamsasri, Jones et al., J. Appl. Phys., 117, 024101 (2015).

$PbZr_{0.3}Ti_{0.7}O_3$ Thin Films

001-oriented, solution deposition from 2-MOE.

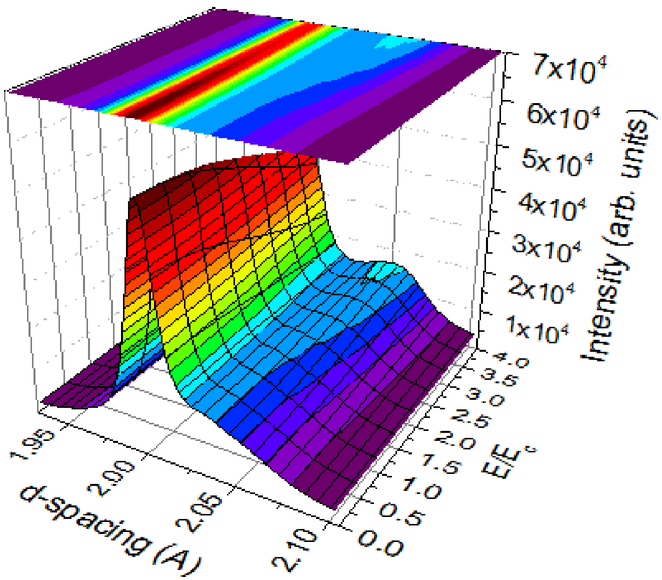






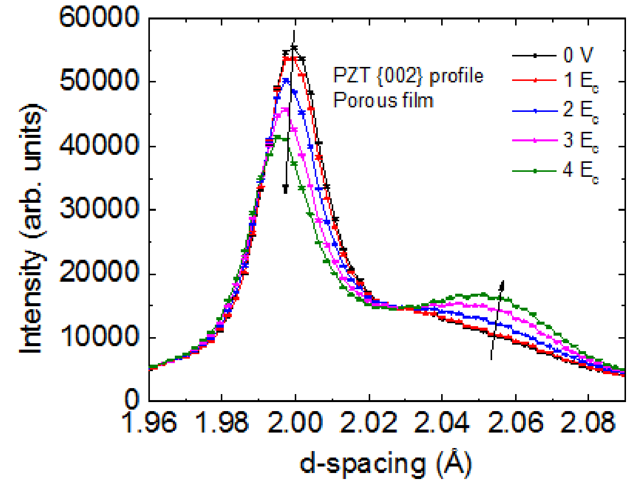
Trolier-McKinstry, Johnson, Wilke, Jones et al., IEEE TUFFC, 62, 46-55 (2015).

$PbZr_{0.3}Ti_{0.7}O_3$ Thin Films



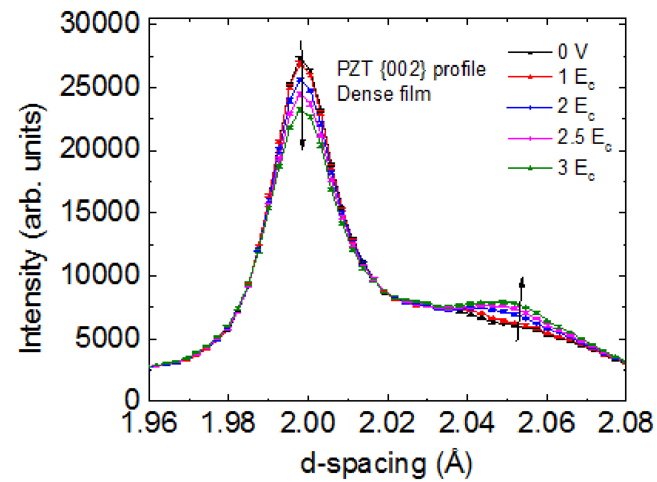
Porous:

More **90° domain wall motion and (002) lattice strain**



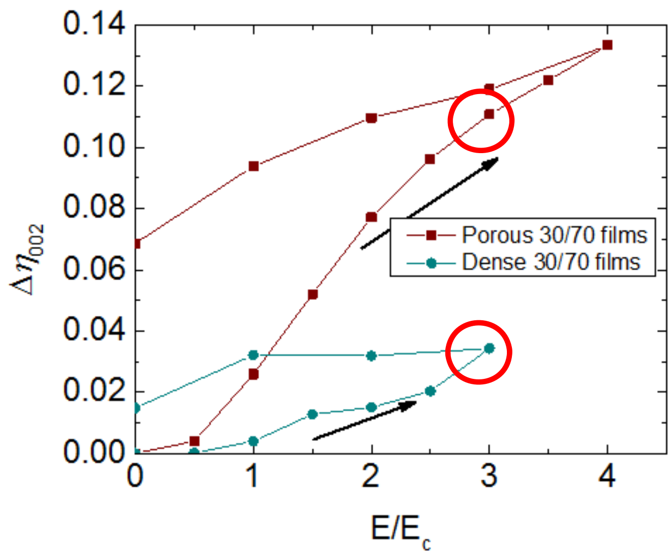
Dense:

Less **90° domain wall motion and (002) lattice strain**



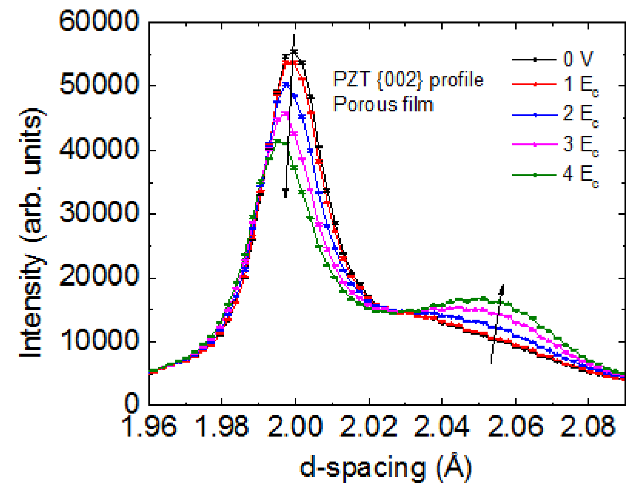
Trolier-McKinstry, Johnson, Wilke, Jones et al., IEEE TUFFC, 62, 46-55 (2015).

$PbZr_{0.3}Ti_{0.7}O_3$ Thin Films



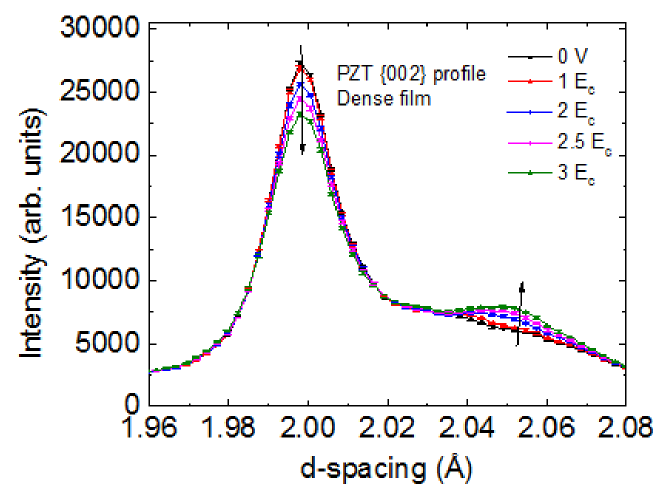
Porous:

More **90° domain wall motion and (002) lattice strain**



Dense:

Less **90° domain wall motion and (002) lattice strain**

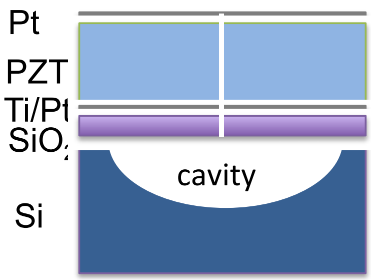


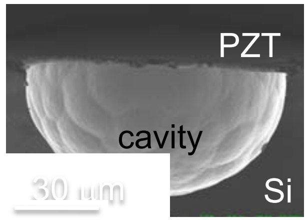
Take-home Message:

- Porous films have ***~threefold*** increase in DW motion relative to dense films.

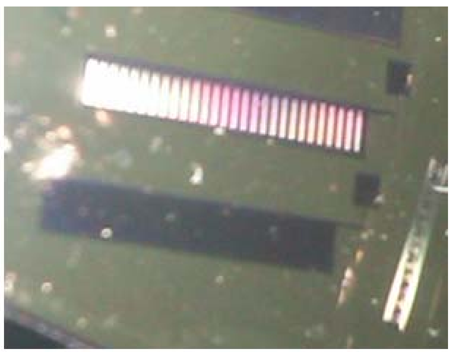
Trolier-McKinstry, Johnson, Wilke, Jones et al., IEEE TUFFC, 62, 46-55 (2015).

$PbZr_{0.3}Ti_{0.7}O_3$ Thin Films



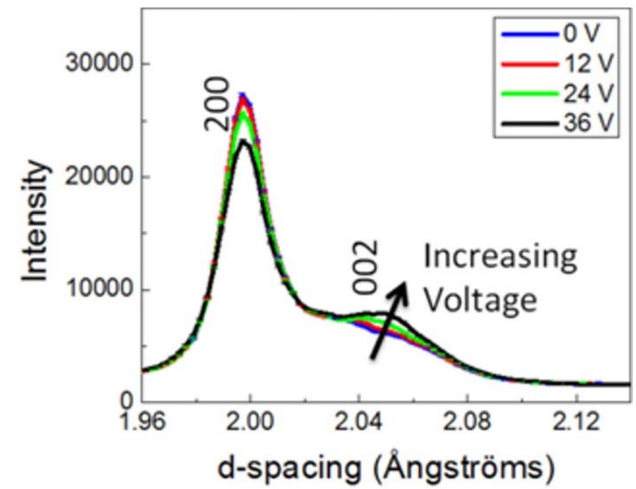


Cross-section of released PZT diaphragm



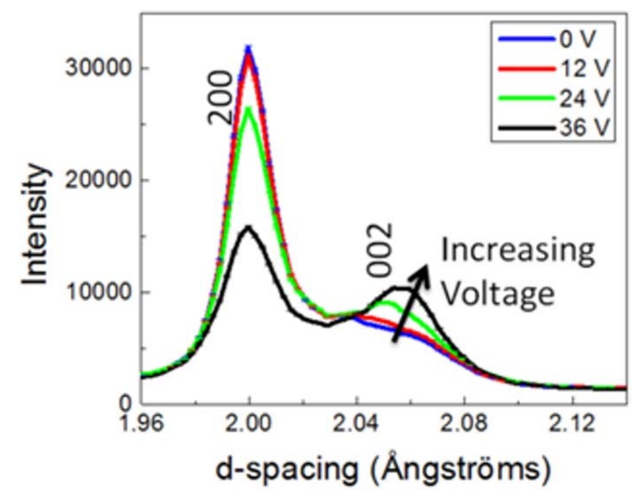
<u>Clamped (control):</u>

<u>*Less*</u> 90° domain wall motion and (002) lattice strain



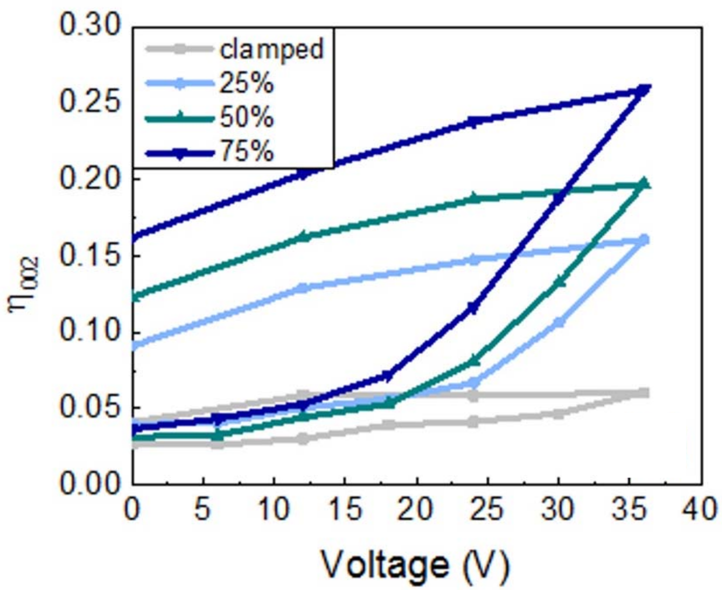
<u>75% released:</u>

<u>*More*</u> 90° domain wall motion and (002) lattice strain



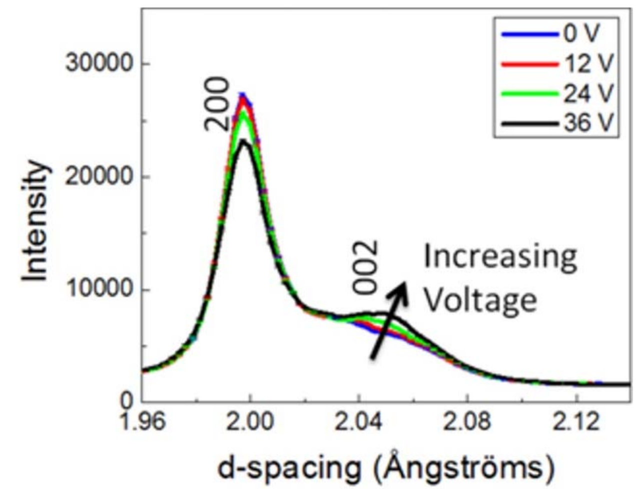
Wallace, Jones, Trolier-McKinstry et al., J. Appl. Phys., in press (2015).

$PbZr_{0.3}Ti_{0.7}O_3$ Thin Films



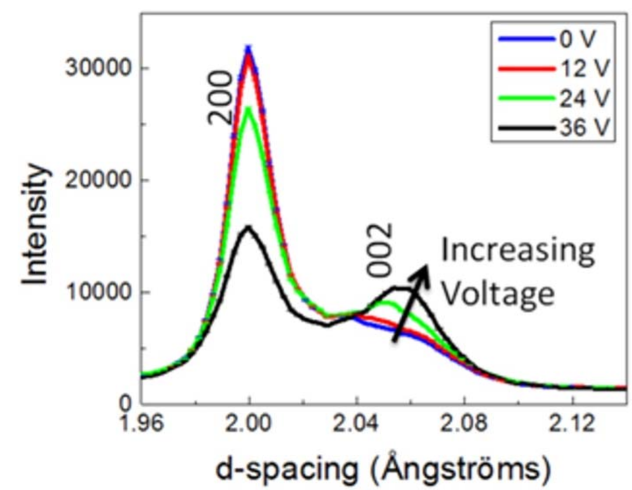
Clamped (control):

Less 90° domain wall motion and (002) lattice strain



75% released:

More 90° domain wall motion and (002) lattice strain



Take-home Message:

- Domain wall motion can be increased ***~fivefold*** if released from substrate.

Wallace, Jones, Trolier-McKinstry et al., J. Appl. Phys., in press (2015).

Other experiments in this area (not shown today)

- *Much more* on polycrystalline *PZT*
- DW motion in *orthorhombic* $Na_{0.5}K_{0.5}NbO_3$
- $Na_{0.5}Bi_{0.5}TiO_3$-$xBaTiO_3$ as a function of *x*
- *Frequency dispersion* of DW motion in $(1-x)BaTiO_3$-$xBi(Zn_{1/2}Ti_{1/2})O_3$ and PZT
- *Time-dependence* of domain switching and intermediate ferroelastic states during polarization reversal in *PZT*
- *Stress-dependence* of domain reorientation during stress and near crack tips in *PZT*

North Carolina State University

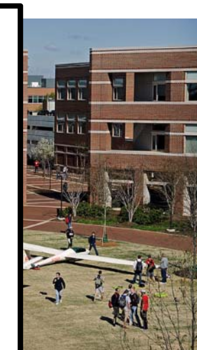
Main Campus

- *Raleigh, NC*
- *NC's main institution for Engineering*
- *Established **1887***
- ***~35,000** students*

Centennial Campus

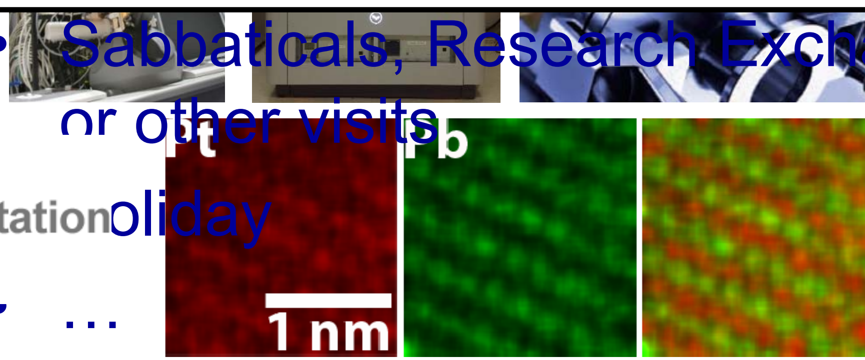
- *Built mostly within last 5-10 years*
- ***1,227** acres*
- ***65** Partners*
- ***72** academic units*
- ***34** buildings*

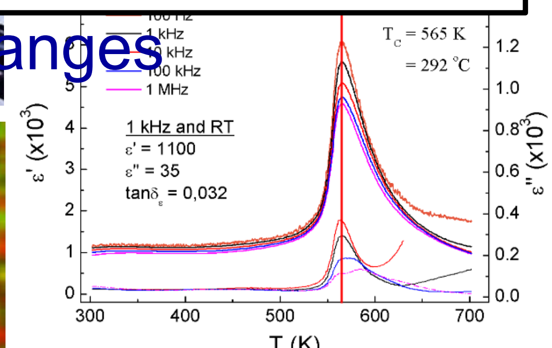
North Carolina State University



Consider Raleigh / NC State for:

- Conferences
- Sabbaticals, Research Exchanges or other visits
- Holiday
- …





AIF analytical instrumentation facility

Origins of Electromechanical Strain Ascertained from *in situ* X-ray and Neutron Diffraction

Jacob L. Jones

Department of Materials Science and Engineering
North Carolina State University