DIELECTRIC TUNABILITY IN PEROVSKITE OXIDES

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MATRL 286G

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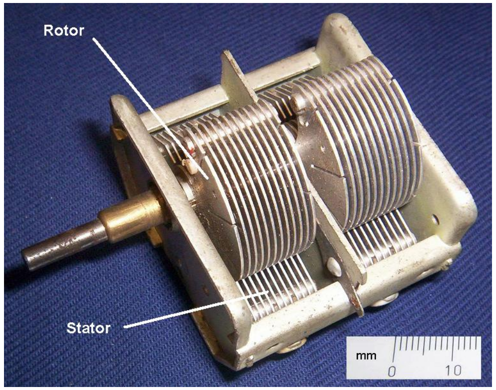
Motivation: Variable Capacitors

- Several ways to vary capacitance:
  - mechanically
    (e.g. rotary, vacuum)
  - electrically
    (e.g. diode, ferroelectric)
- Important for wireless communications and radar systems

$$C = \varepsilon_0 \frac{\varepsilon_r A}{d}$$



http://en.wikipedia.org/wiki/File:Variable_Capacitor.jpg

http://www.gizmag.com/smartphone-comparison-2012/24901/

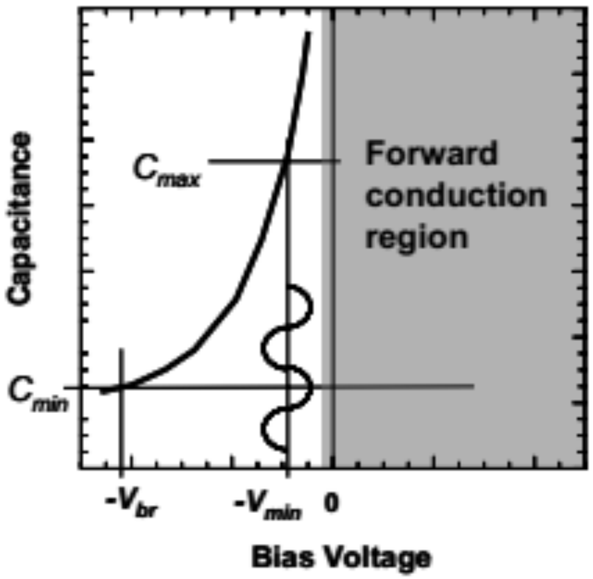
Variable capacitor diodes

- p-n, Schottky, or MOS diode operated in reverse-bias regime

$$d \propto (V_{bi} - V)^{1/2}$$

- vary capacitance by changing charge depletion region width

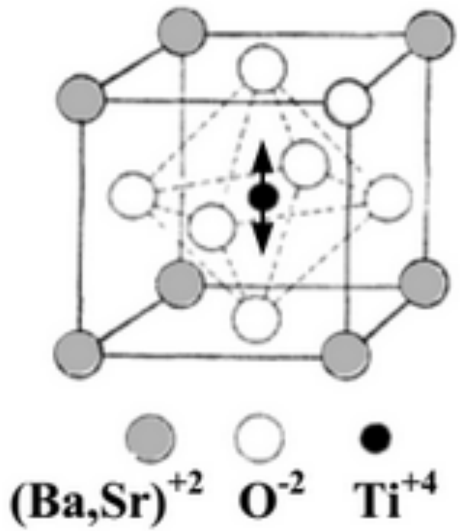
- not suitable for large-amplitude signals at zero DC bias

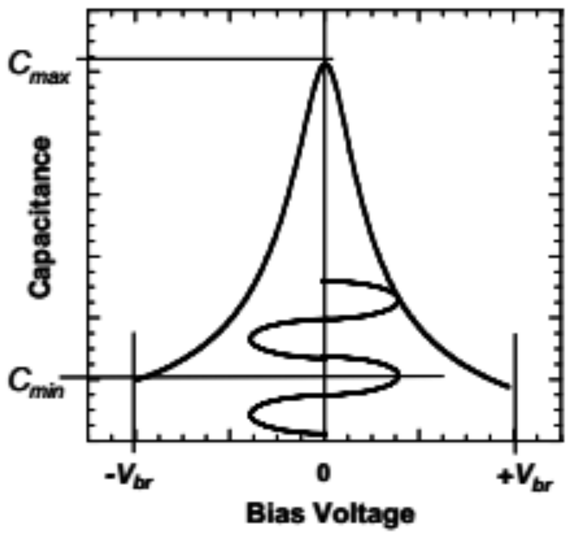


R. A. York. "Tunable Dielectrics for RF Circuits," in *Multifunctional Adaptive Microwave Circuits and Systems*. M. Steer, ed. Johnson City, NY. Scitech Pub. 2009, ch. 6,

Ferroelectric capacitors

- ferroelectric perovskites (e.g. $Ba_xSr_{1-x}TiO_3$) in their paraelectric phase
- vary capacitance by changing the relative permittivity ε_r

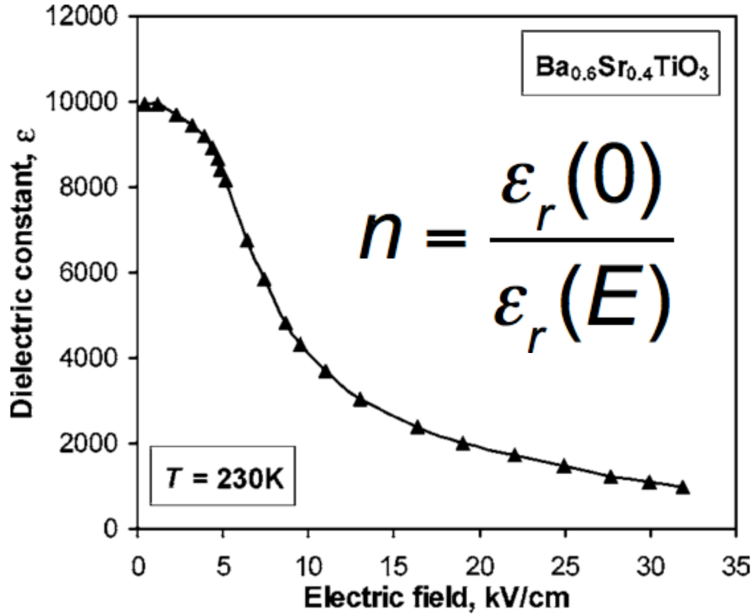




- no forward conduction region
- lower cost of processing

R. A. York. "Tunable Dielectrics for RF Circuits," in *Multifunctional Adaptive Microwave Circuits and Systems*. M. Steer, ed. Johnson City, NY. Scitech Pub. 2009, ch. 6,

Dielectric tunability



$$n = \frac{\varepsilon_r(0)}{\varepsilon_r(E)}$$

- the extent to which the relative permittivity is suppressed by an electric field
- scales with zero-field permittivity $\varepsilon_r(0)$
- high tunability usually results in higher dielectric loss

at low fields:

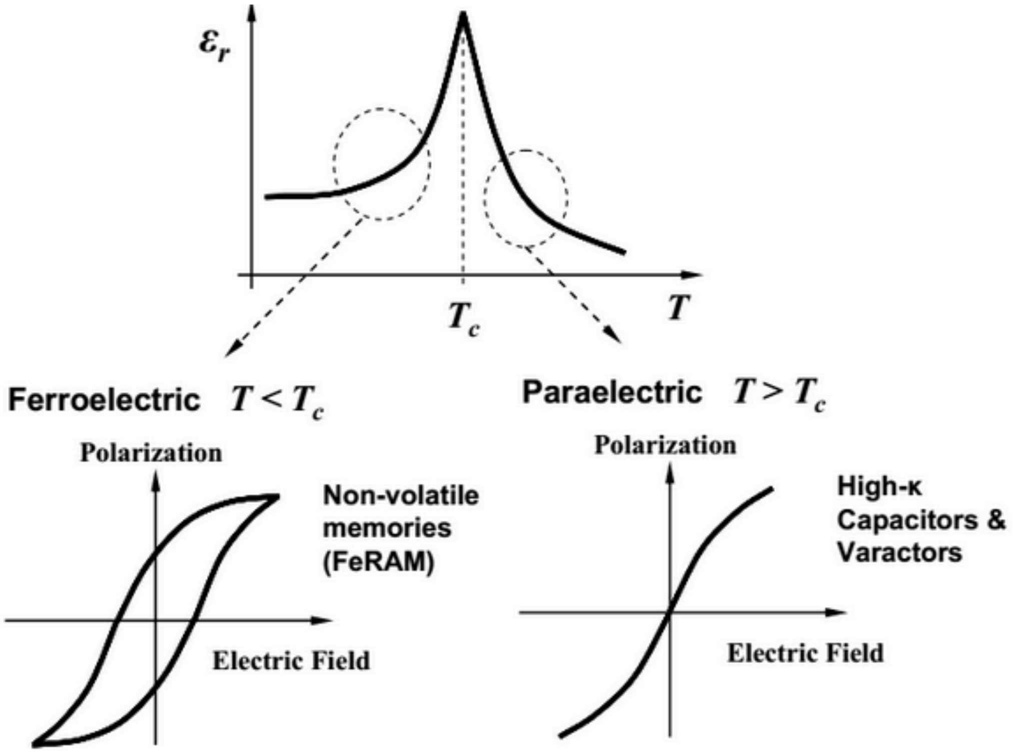
$$n \propto \varepsilon_r(0)^3$$

at high fields:

$$n \propto \varepsilon_r(0)$$

A. Tagantsev and V. Sherman, "Ferroelectric materials for microwave tunable applications," Journal of Electroceramics, vol. 11, pp. 5–66, 2003.

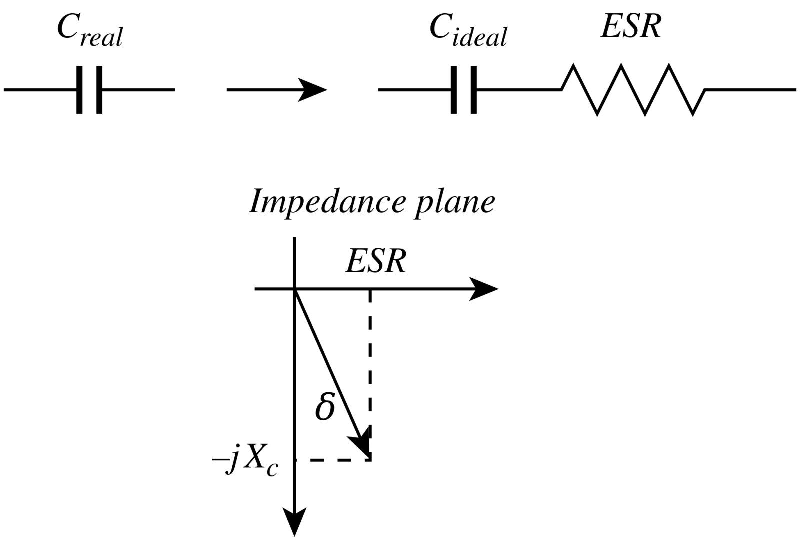
Dielectric tunability



- ε_r is more tunable in the ferroelectric phase than in paraelectric phase near the phase transition
- less dielectric loss in the paraelectric phase

R. A. York. "Tunable Dielectrics for RF Circuits," in *Multifunctional Adaptive Microwave Circuits and Systems*. M. Steer, ed. Johnson City, NY. Scitech Pub. 2009, ch. 6,

Dielectric loss



http://en.wikipedia.org/wiki/File:Loss_tangent_phasors_1.svg

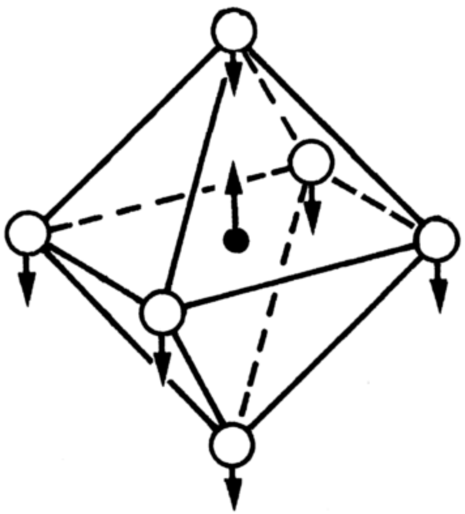
- dissipation of electrical energy resulting in deviation from ideal capacitor behavior
- quantified as loss tangent tanδ or Q = 1/tanδ

$$\tan\delta \propto \varepsilon^n$$

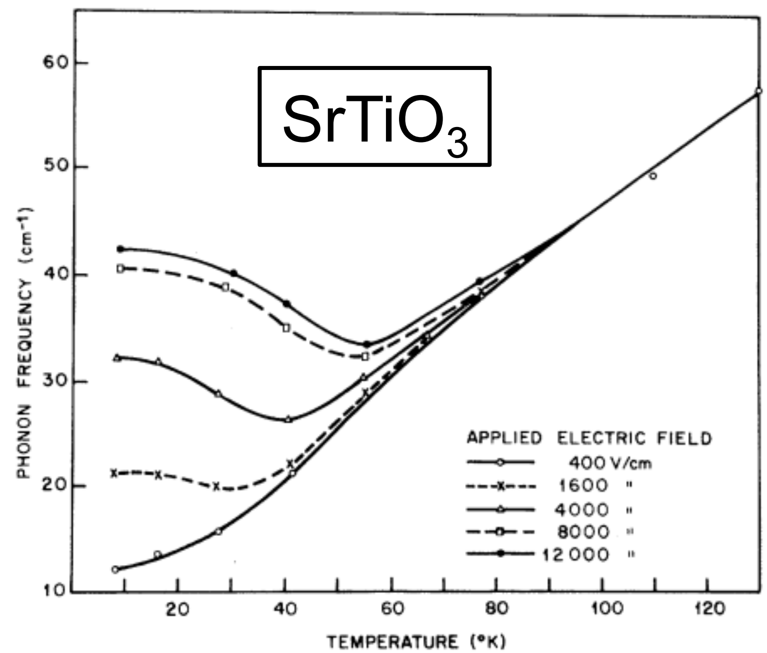
- **n = -1 ➔** DC leakage, Quasi-Debye
- **n = 1 ➔** charged defects
- **n = 1.5 ➔** intrinsic phonon scattering
- **n = 2.5-4 ➔** polar regions

A. Tagantsev and V. Sherman, "Ferroelectric materials for microwave tunable applications," Journal of Electroceramics, vol. 11, pp. 5–66, 2003.

Dielectric tunability in the paraelectric phase



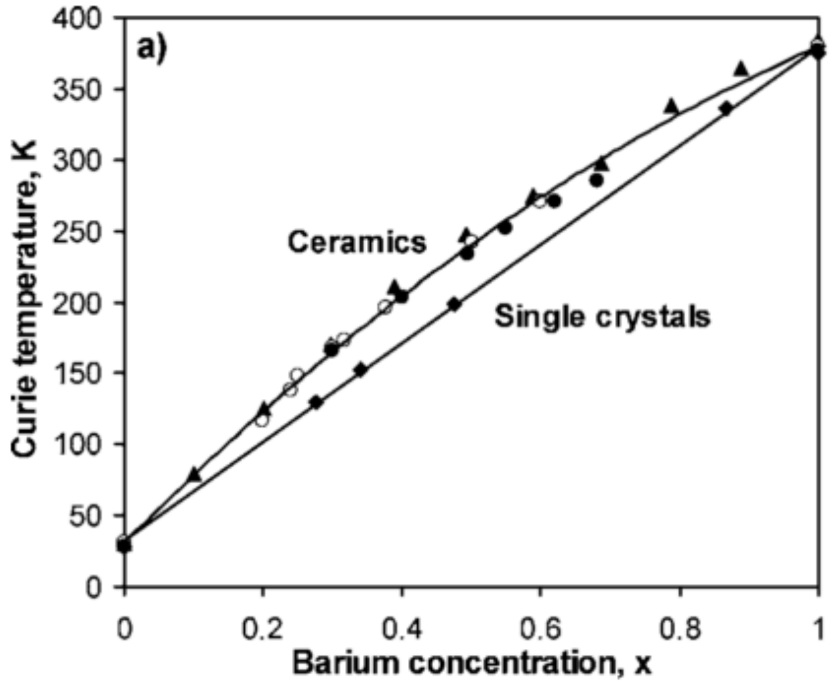
$$\frac{\varepsilon}{\varepsilon_\infty} = \frac{\omega_{LO}^2}{\omega_{TO}^2}$$

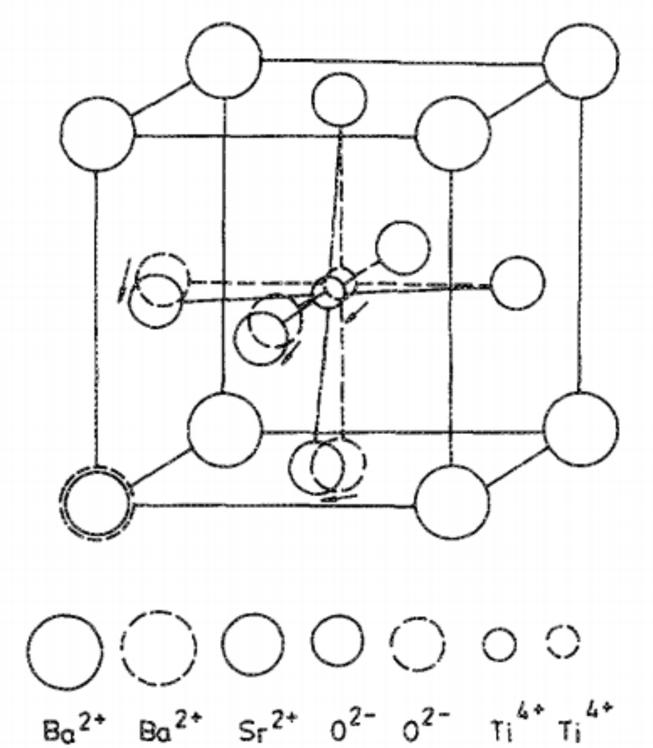


- ω_{TO} approaches zero at ferroelectric T_C
- applying electric field hardens the phonon mode (increases ω_{TO})
- permittivity varies with tuning of phonon mode

- X. Xi, H. Li, W. Si, A. Sirenko, I.A. Akimov, J.R. Fox, A.R. Clark, and J. Hao “Oxide thin films for tunable microwave devices,” *J. of Electroceramics 4:2/3,* pp. 393–405, 2000.
- J. Worlock and P. Fleury, “Electric Field Dependence of Optical-Phonon Frequencies,” *Phys. Rev. Lett.*, vol. 19, no. 20, 1967.

Phase transition and composition

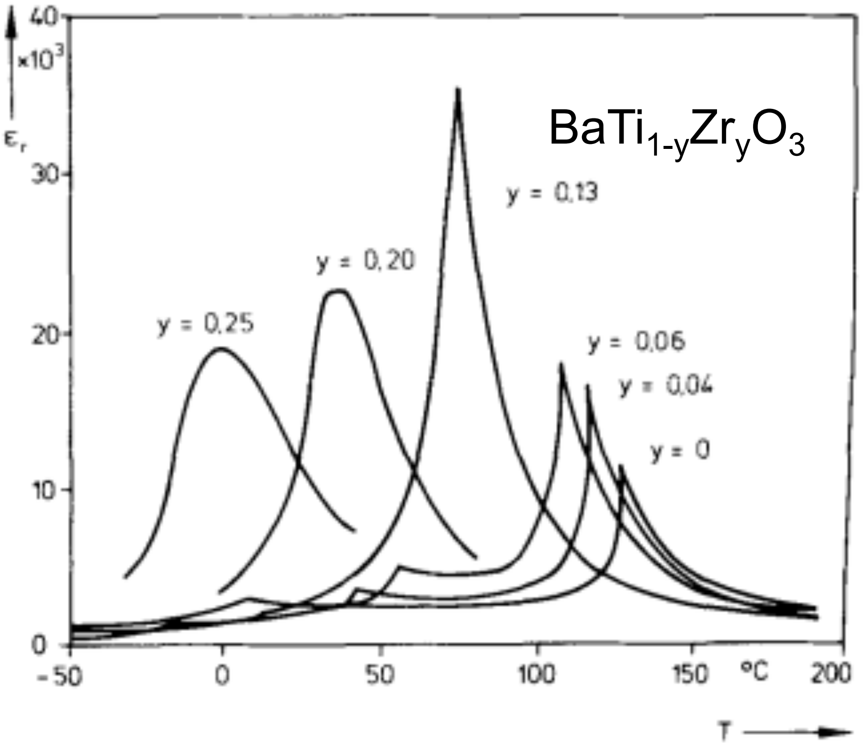


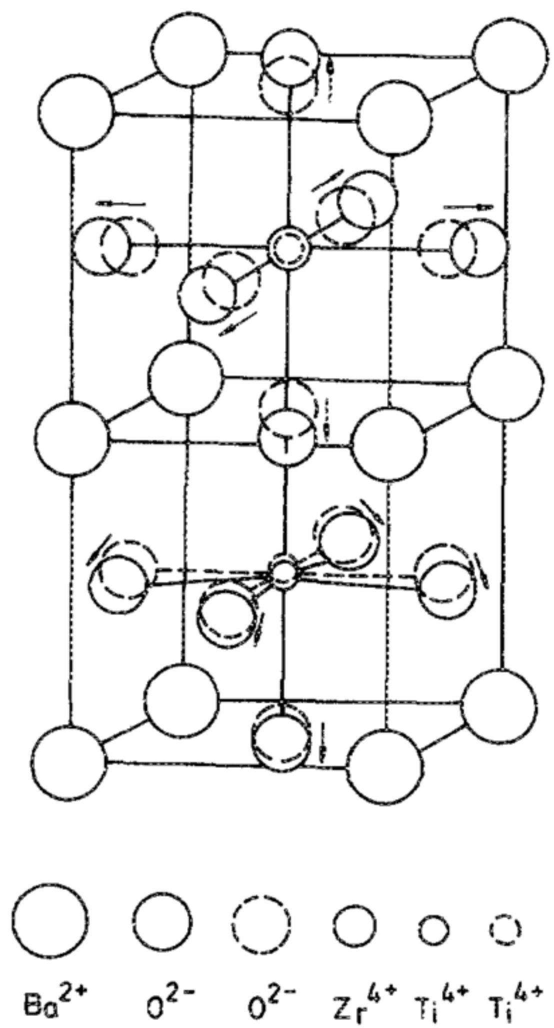


- T_C of **$Ba_xSr_{1-x}TiO_3$** varies between T_C of each end member
- substitution on A-sites affects oxygen packing and phonon mode damping

- A. Tagantsev and V. Sherman, “Ferroelectric materials for microwave tunable applications,” Journal of Electroceramics, vol. 11, pp. 5–66, 2003.
- J. N. Lin and T. B. Wu, “Effects of isovalent substitutions on lattice softening and transition character of BaTiO3 solid solutions,” *J. Appl. Phys.*, vol. 68, no. 3, p. 985, 1990.

Phase transition and composition

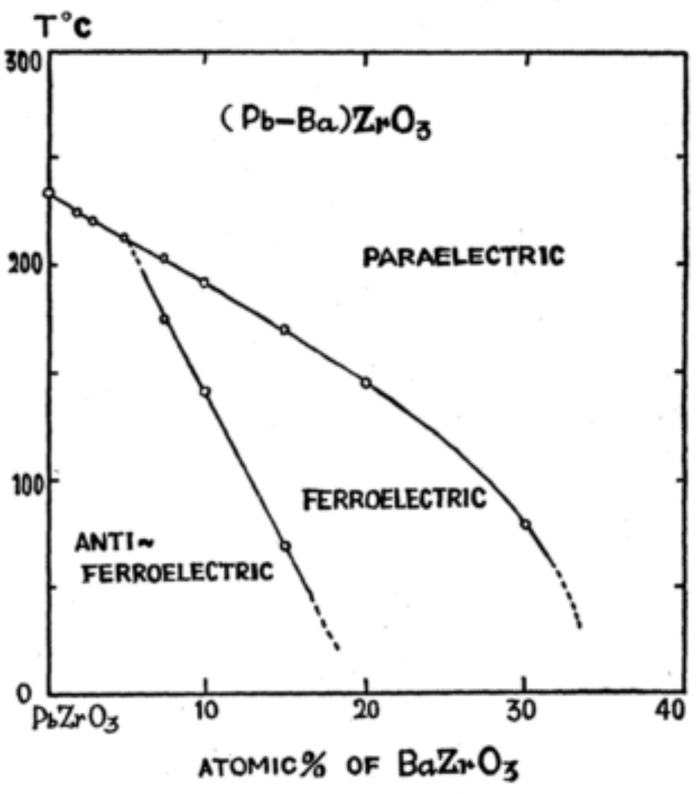


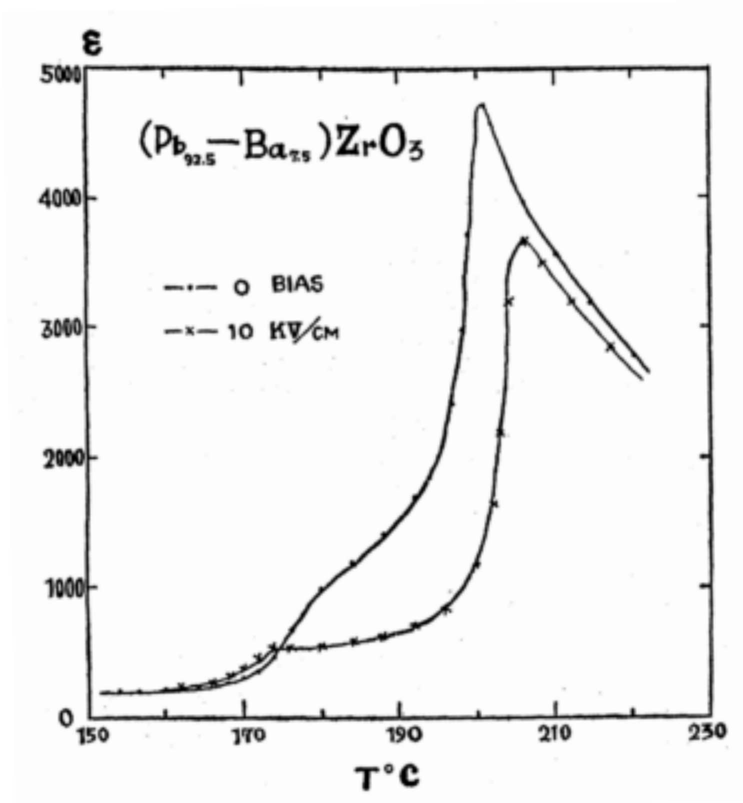


- substituting Zr on B-sites in $BaTiO_3$ leads to a single ferroelectric transition
- coexistence of multiple transitions over a narrow temperature range

- D. Hennings, A. Schnell, and G. Simon, "Diffuse Ferroelectric Phase Transitions in Ba (Ti1-yZry) O3 Ceramics," *J. of Amer. Ceram. Soc.*November, pp. 539–544, 1982.
- J. N. Lin and T. B. Wu, "Effects of isovalent substitutions on lattice softening and transition character of BaTiO3 solid solutions," *J. Appl. Phys.*, vol. 68, no. 3, p. 985, 1990.

Phase transition and composition





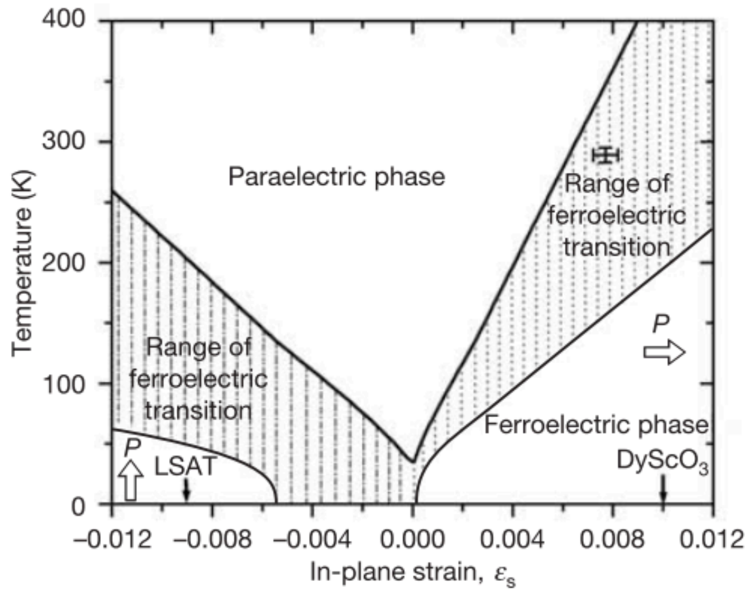
- tunable ferroelectric phase in a solid solution of antiferroelectric $PbZrO_3$ and paraelectric BaZrO

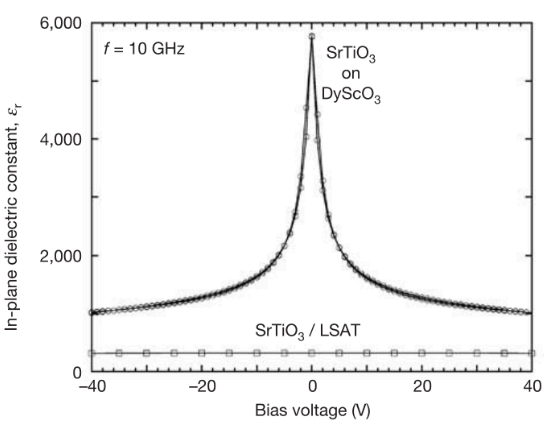
G. Shirane, “Ferroelectricity and Antiferroelectricity in Ceramic PbZr O 3 Containing Ba or Sr,” *Phys. Rev.*, vol. 86, no. 2, 1952.

Phase transition and epitaxial strain

- T_C of $SrTiO_3$ can be brought close to room temperature with appropriate strain

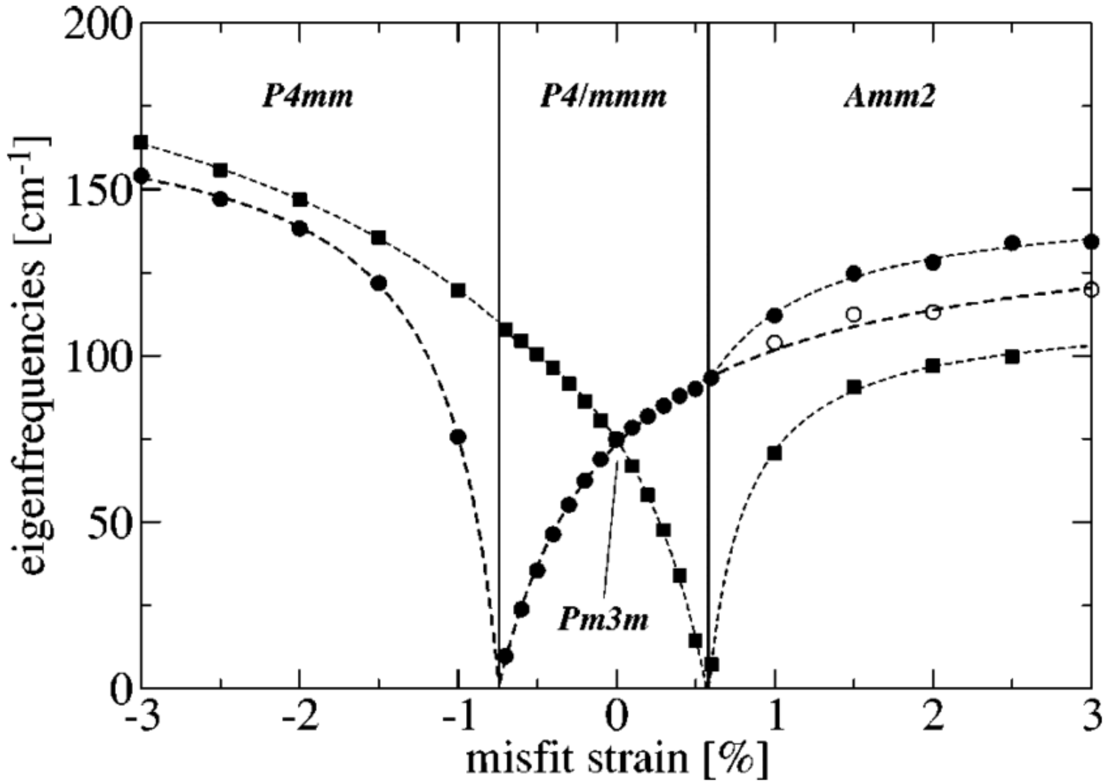
- polarization dependent on strain sense





- J. Haeni, P. Irvin, W. Chang, R. Uecker, and P. Reiche, "Room-temperature ferroelectricity in strained SrTiO3," *Nature*, vol. 430, 12 August, pp. 583–586, 2004.
- N. Pertsev, A. Tagantsev, and N. Setter, "Phase transitions and strain-induced ferroelectricity in SrTiO3 epitaxial thin films," *Phys. Rev. B*, vol. 61, no. 2, pp. 1–5, 2000.

Phase transition and epitaxial strain



- strain modifies phonon modes of different orientation depending on sense

- J. Haeni, P. Irvin, W. Chang, R. Uecker, and P. Reiche, “Room-temperature ferroelectricity in strained SrTiO3,” *Nature*, vol. 430, 12 August, pp. 583–586, 2004.
- N. Pertsev, A. Tagantsev, and N. Setter, “Phase transitions and strain-induced ferroelectricity in SrTiO3 epitaxial thin films,” *Phys. Rev. B*, vol. 61, no. 2, pp. 1–5, 2000.
- A. Antons, J. Neaton, K. Rabe, and D. Vanderbilt, “Tunability of the dielectric response of epitaxially strained SrTiO3 from first principles,” *Phys. Rev. B*, vol. 71, no. 2, p. 024102, Jan. 2005.

Summary

- the permittivity of ferroelectric perovskite oxides is highly electric-field-tunable in the ferroelectric phase or paraelectric phase near T_C
- tunability in the paraelectric phase arises due to the electric-field dependence of ω_{TO}
- the temperature range of field-dependent permittivity can be adjusted with both chemical substitution and strain

Questions?