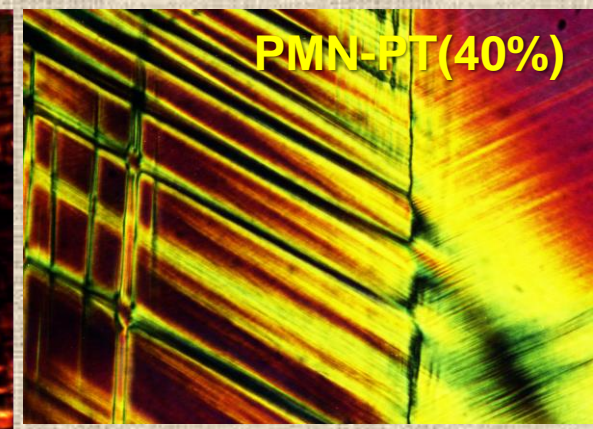
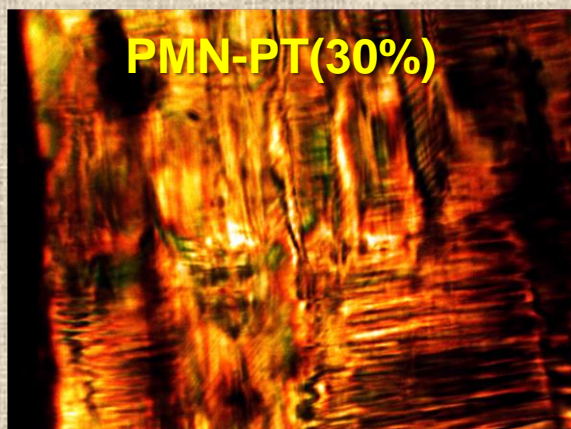
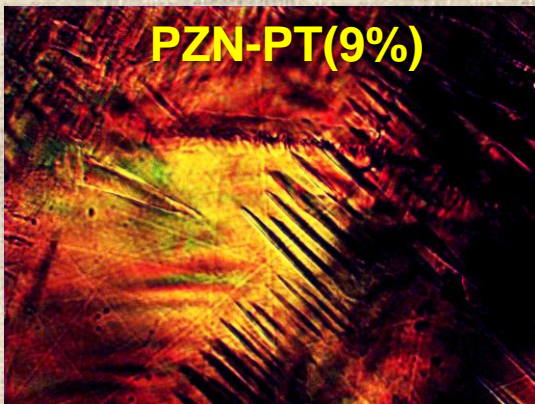
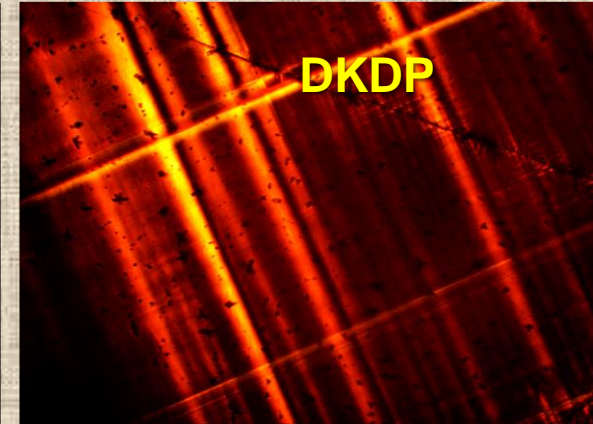
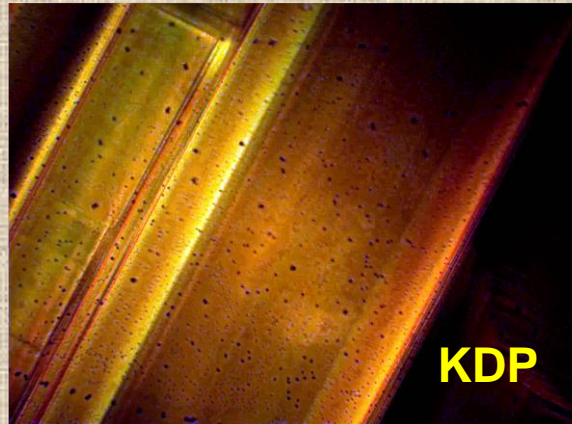
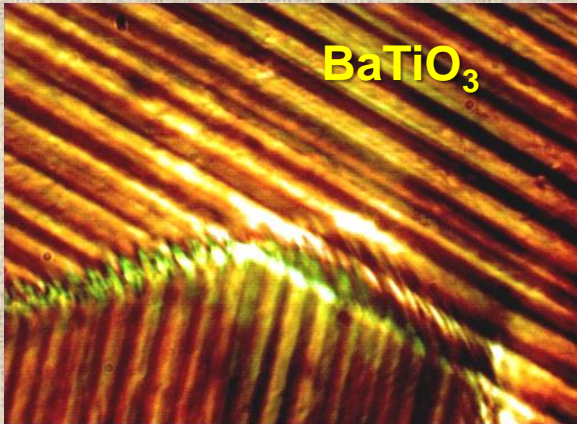


Ferroelectricity. Phase transition. Material properties



Ferroelectricity. outline

- **Ferroelectricity. Definition**
- **Discovery**
- **Main properties**
- **Phenomenological theory**
- **Some materials**
- **Relaxors**
- **Applications**

Ferroelectricity. Definitions.

Ferroelectric Materials. A ferroelectric material is a material that exhibits, over some range of temperature, a spontaneous electric polarization that can be reversed or reoriented by application of an electric field.

***An American National Standard
IEEE Standard Definitions of
Primary Ferroelectric Terms***

Ferroelectricity: Discovery

Rochelle Salt $\text{KNaC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$

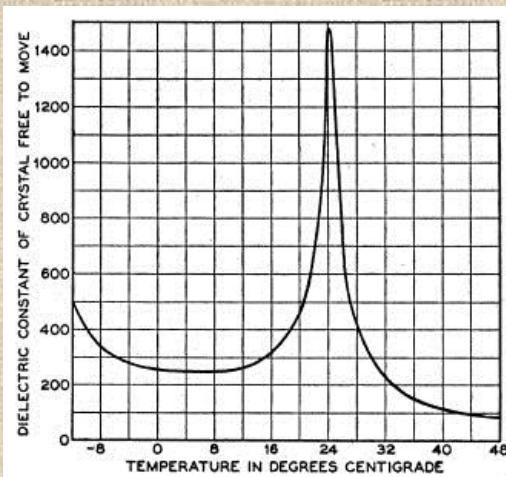
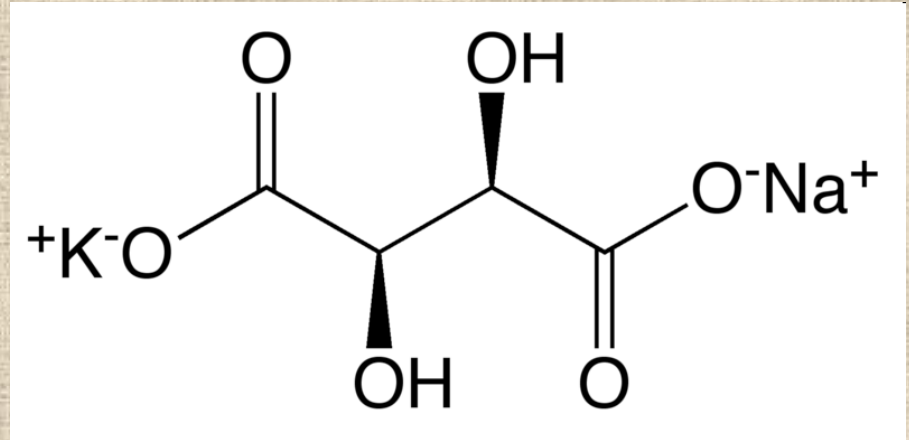


FIG. 3. Dielectric constant of an X cut Rochelle salt crystal free to move plotted as a function of the temperature.



Ferroelectricity: Discovery

Rochelle Salt $\text{KNaC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$

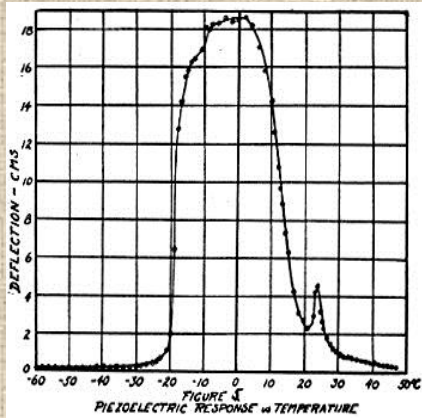


Fig.3. Piezoelectric response as a function of temperature [2]

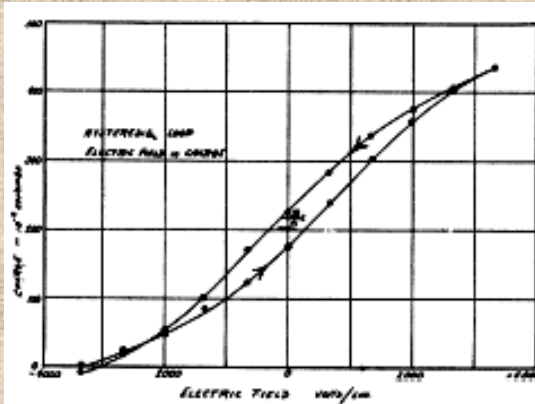
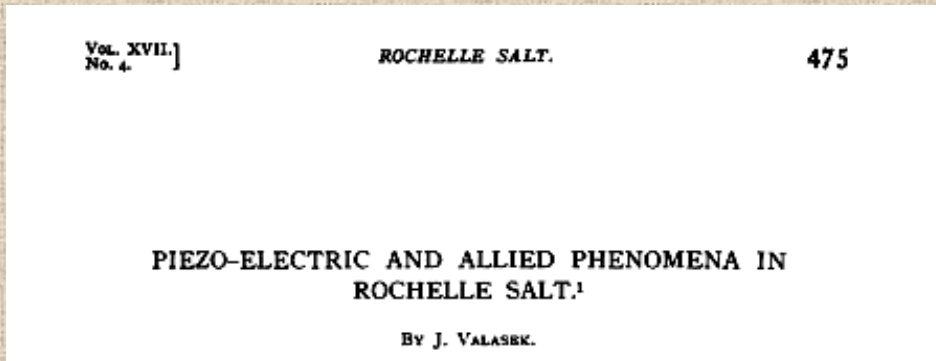


Fig.1. The first published hysteresis loop [1]



Joseph Valasek (1897-1993)
University of Minnesota

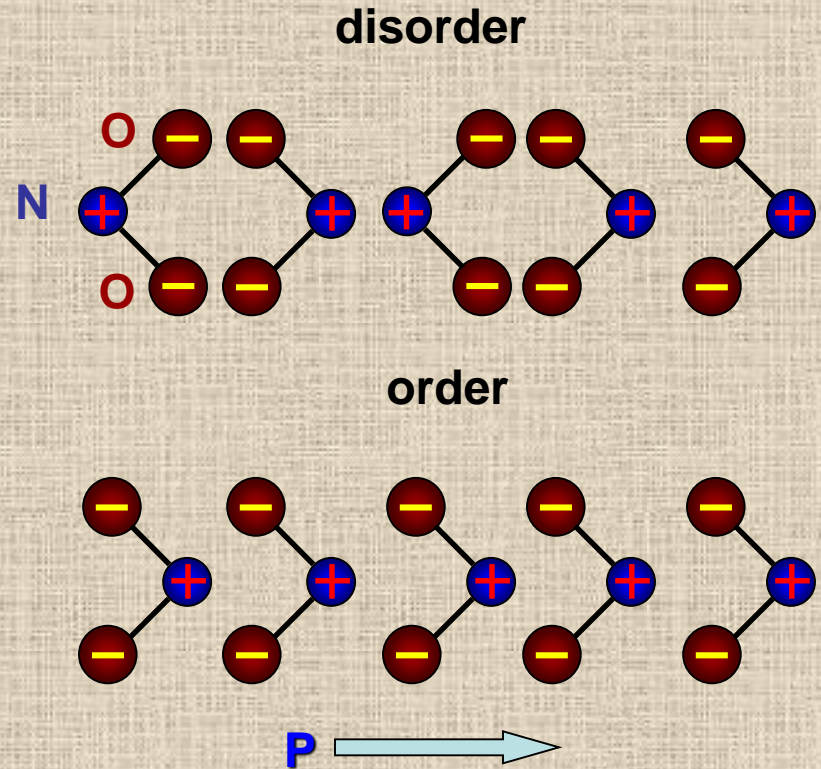
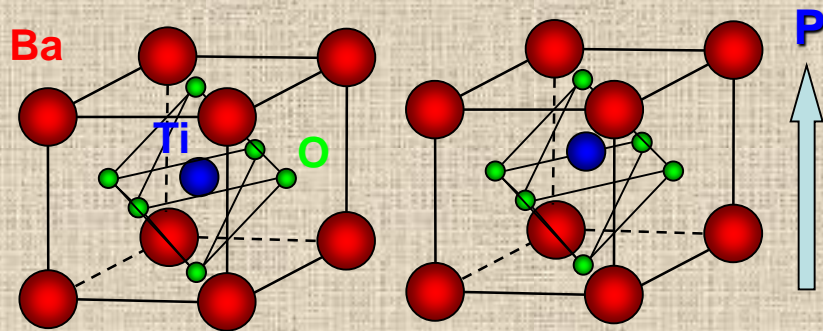
1. J. Valasek, Phys. Rev. 17, 475 (1921)
2. J. Valasek, Phys. Rev. 19, 478 (1922)



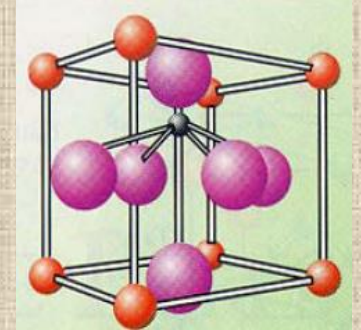
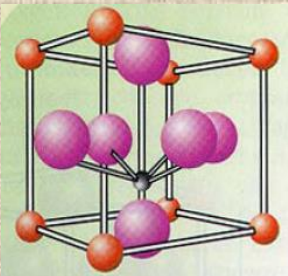
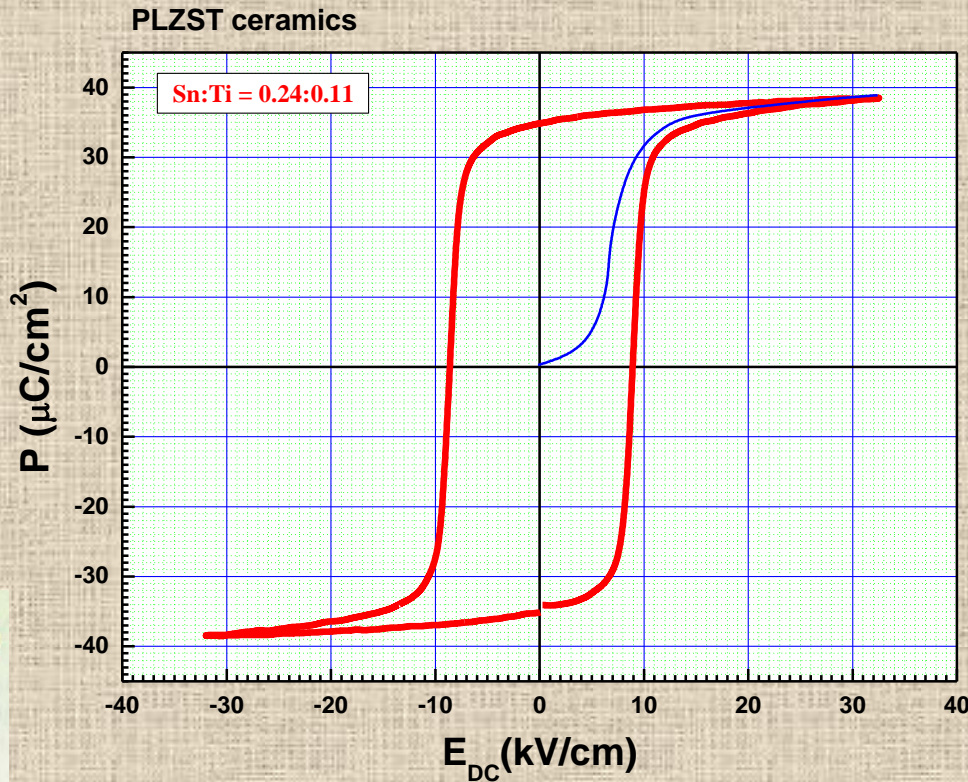
Ferroelectricity: Two classes of ferroelectrics

Order-Disorder

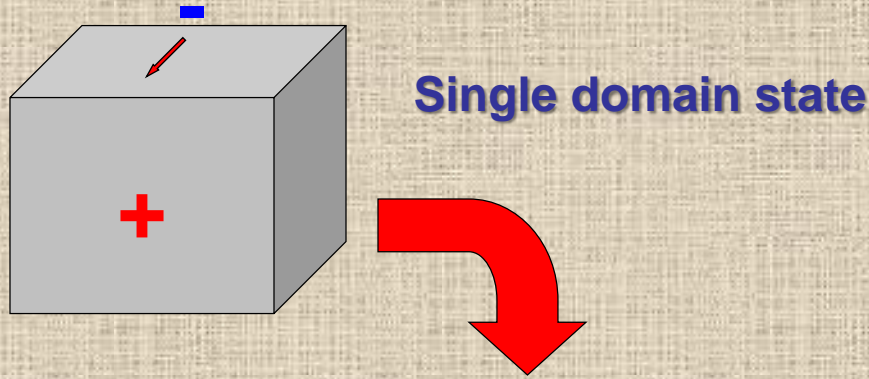
Displacement type



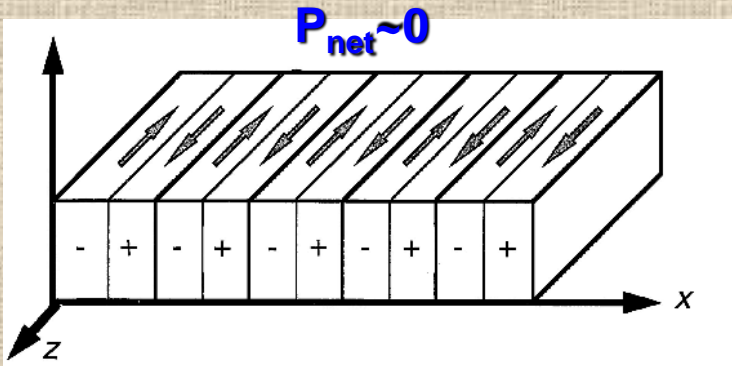
Ferroelectricity: Polarization reversible (P-E hysteresis)



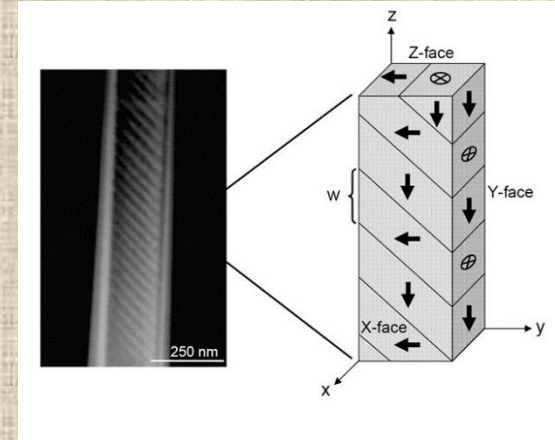
Ferroelectricity: Domains



Multi domain state

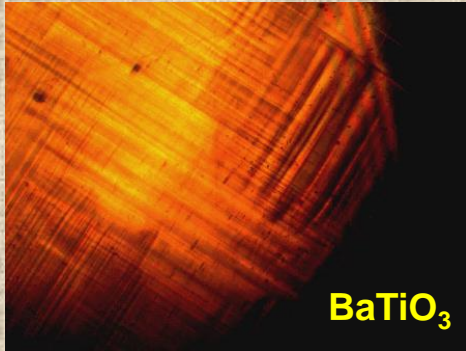


Y Lu et al. Science 1997;276:2004-2006

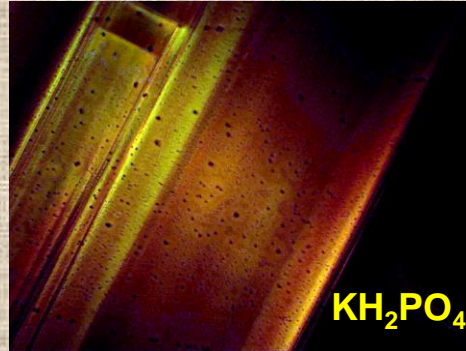


Courtesy of Igor Lukyanchuk
<http://www.lukyanc.net/stories/nano-worldofdomains>

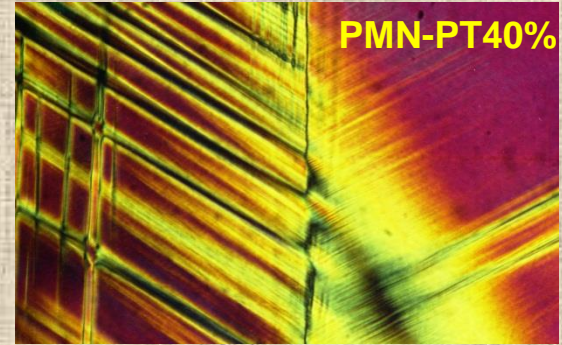
Ferroelectricity: Domains



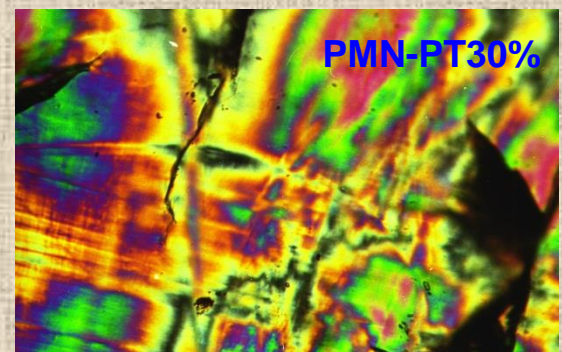
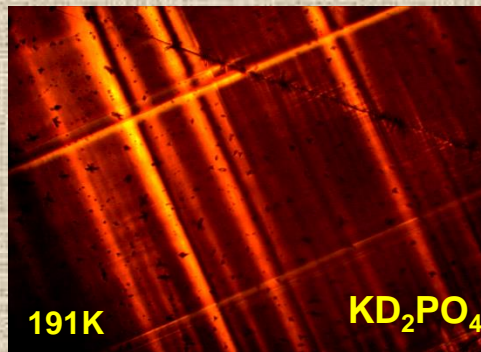
Courtesy of Benjamin Vega-Westhoff and Scott Scharfenberg, P403, Fall2009



Courtesy of Allison Pohl, P403, Fall2009



Crystal from Forschungsinstitut für mineralische und metallische Werkstoffe -Edelsteine/Edelmetalle



Ferroelectricity: Landau-Ginzburg phenomenological theory

Free energy Order parameter (polarization) Electric field

$$F_P = \frac{1}{2}aP^2 + \frac{1}{4}bP^4 + \frac{1}{6}cP^6 + \dots - EP$$

To find the equilibrium solution we need to find the minima of FP by solving the equation: $\frac{\partial F}{\partial P} = 0$

Ignoring higher terms we can get the linear solution:

$$\frac{\partial F}{\partial P} = aP - E = 0 \qquad \chi = \frac{\partial P}{\partial E} = \frac{1}{a}$$

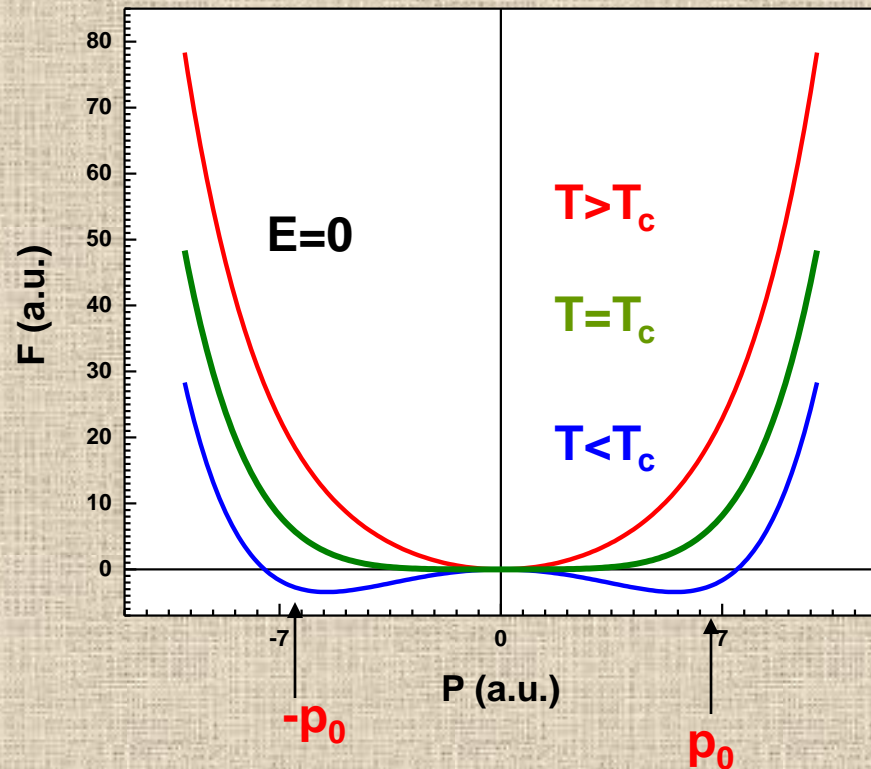
Assuming linear dependence of **a** on temperature we will have:

$\alpha = \frac{1}{C}(T - T_c)$ and finally we will have Curie-Weiss law

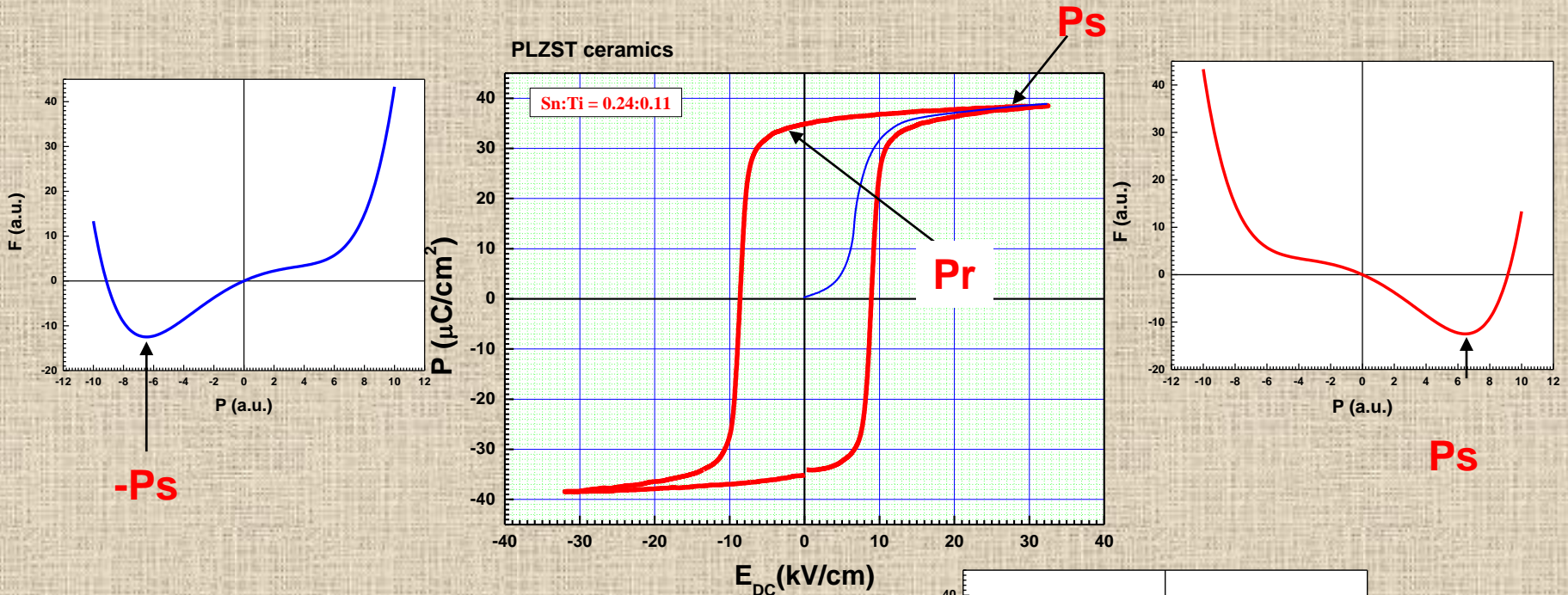
$$\chi = \frac{C}{(T - T_c)}$$

Ferroelectricity: Landau-Ginzburg phenomenological theory

In case of $b > 0$ ($C > 0$ also) We will have the solution for second order phase transition with two equilibrium points $-p_0$ and p_0 . Both these states are equivalent

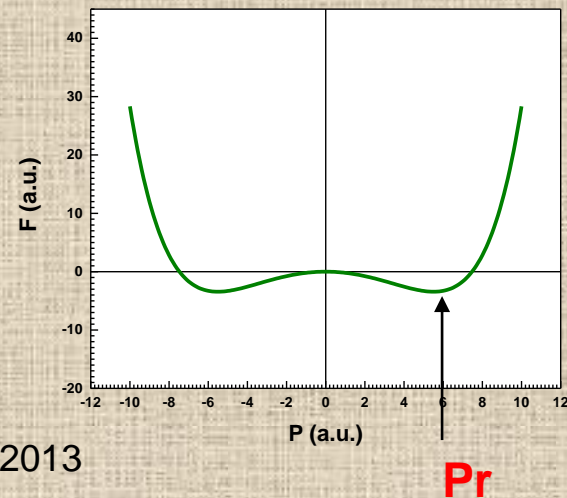


Ferroelectricity: Landau-Ginzburg phenomenological theory



Including EP term can illustrate the P-E hysteretic behavior

$$F_P = \frac{1}{2}aP^2 + \frac{1}{4}bP^4 + \frac{1}{6}cP^6 + \dots - EP$$

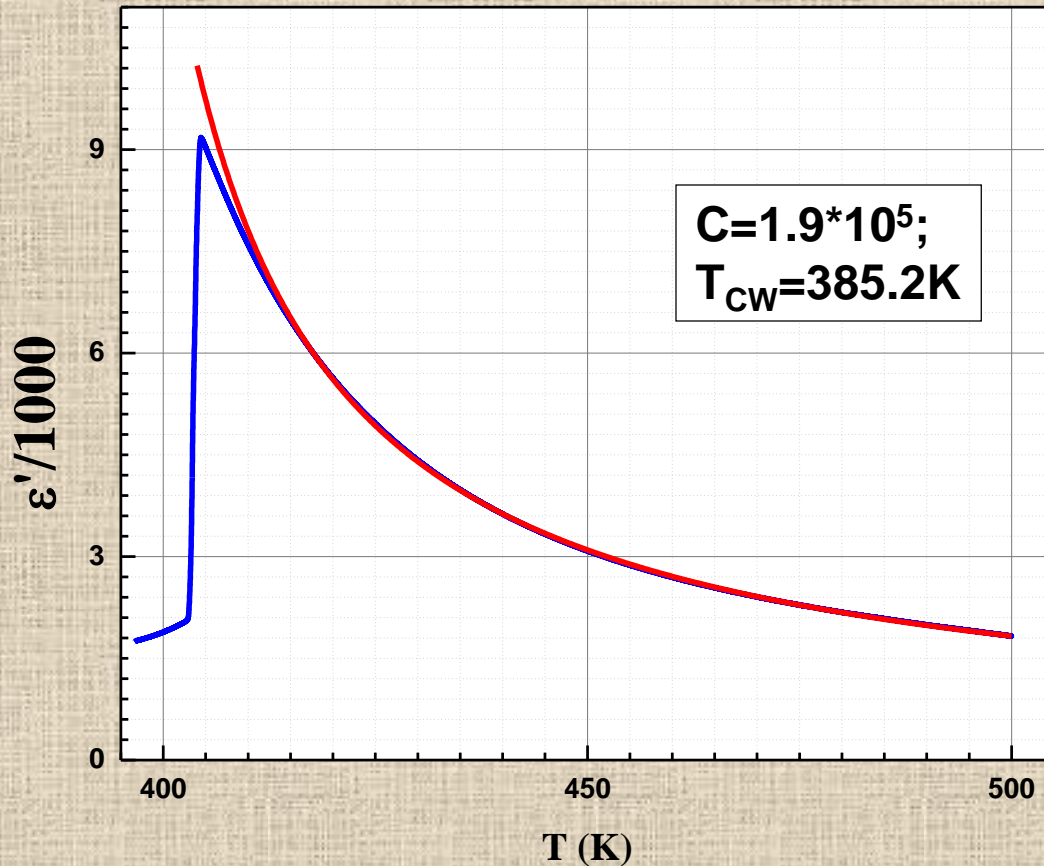


Ferroelectricity: Susceptibility

$$\vec{P} = \epsilon_0 \chi \vec{E}$$

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P} = \epsilon_0 \vec{E} + \epsilon_0 \chi \vec{E} = \epsilon_0 (1 + \chi) \vec{E} = \epsilon_0 \epsilon \vec{E}$$

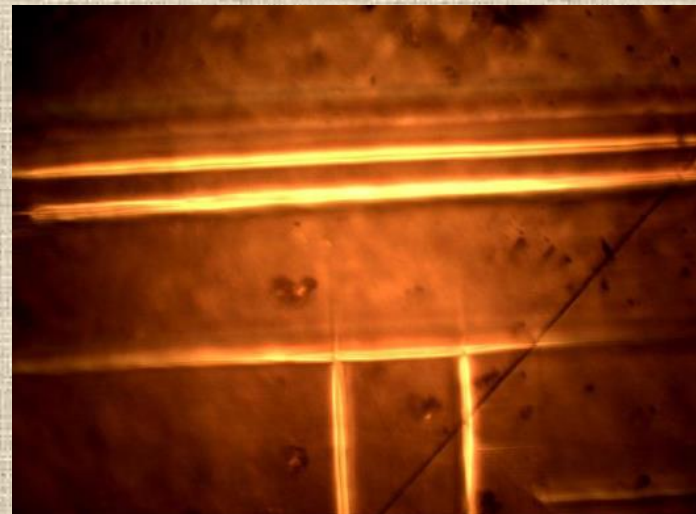
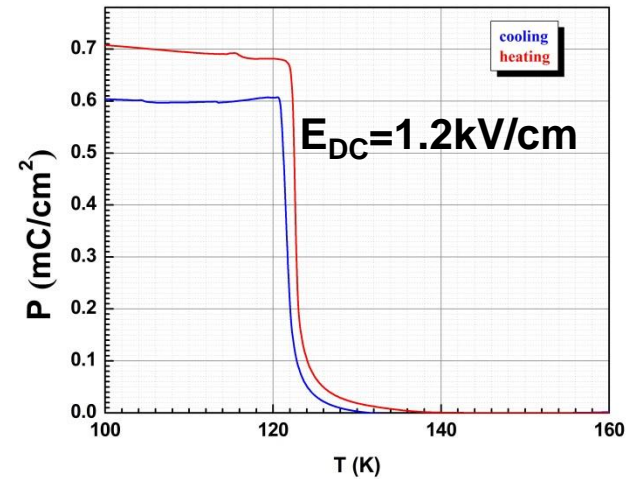
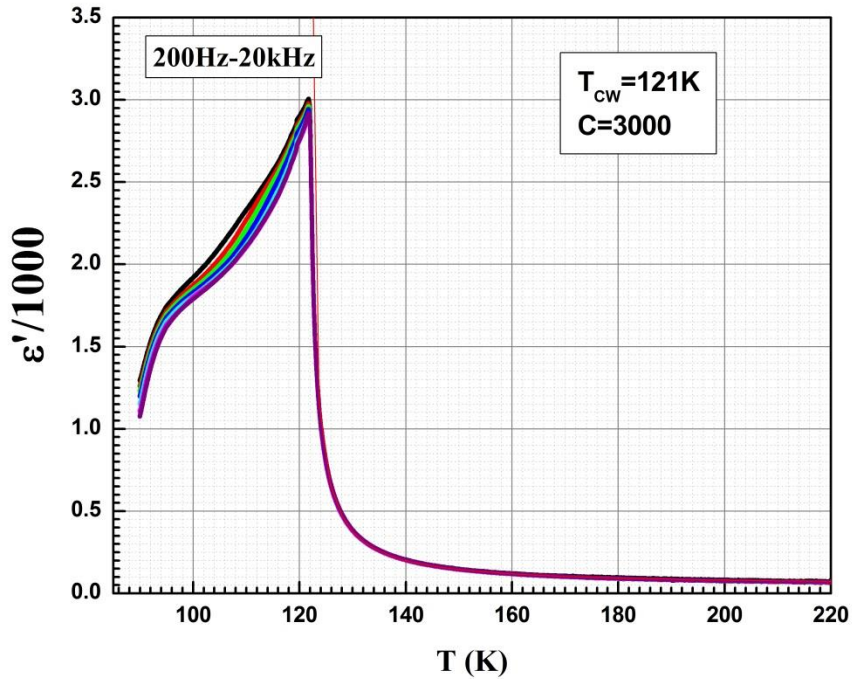
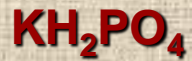
For ferroelectrics $\epsilon \gg 1$ and $\epsilon \approx \chi$



Curie-Weiss law:

$$\epsilon = \frac{C}{(T - T_{CW})} + \epsilon_{00}$$

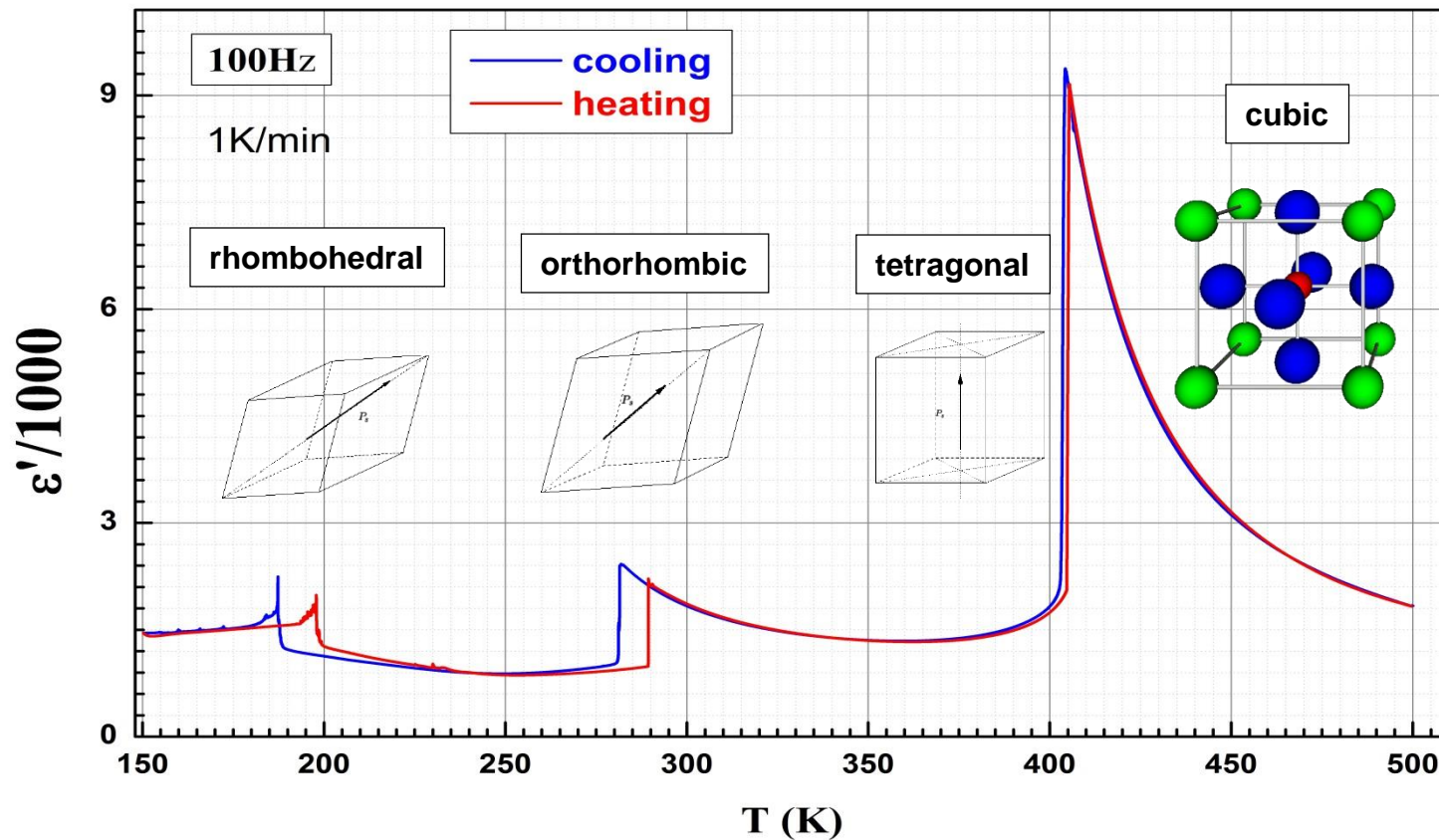
Ferroelectricity: Typical ferroelectric materials



Courtesy Max Candocia, P403 Spring 2011

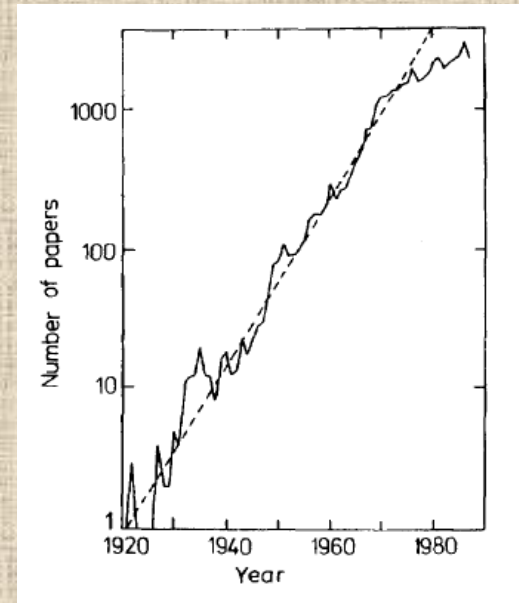
Ferroelectricity: Typical ferroelectric materials

BaTiO_3



Ferroelectricity: Typical ferroelectric materials

		T_c (K)	P_s ($\mu\text{C}/\text{cm}^2$)
KDP type	KH_2PO_4	123	4.75
	KD_2PO_4	213	4.83
	RbH_2PO_4	147	5.6
Perovskites	BaTiO_3	408	26
	KNbO_3	708	30
	PbTiO_3	765	>50
	LiTiO_3	938	50
	LiNbO_3	1480	71

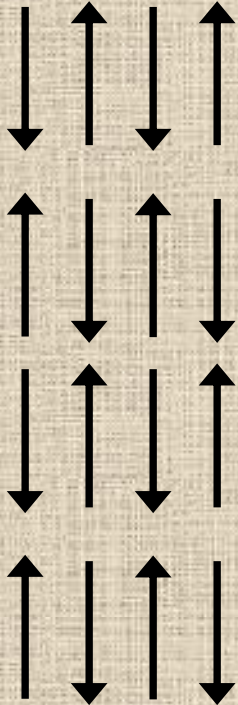


Number of publications concerning ferroelectricity.
From Jan Fousek "*Joseph Valasek and the Discovery of Ferroelectricity*"

Number of ferroelectric substances discovered in each year.
Springer Handbook of Condensed Matter and Materials Data

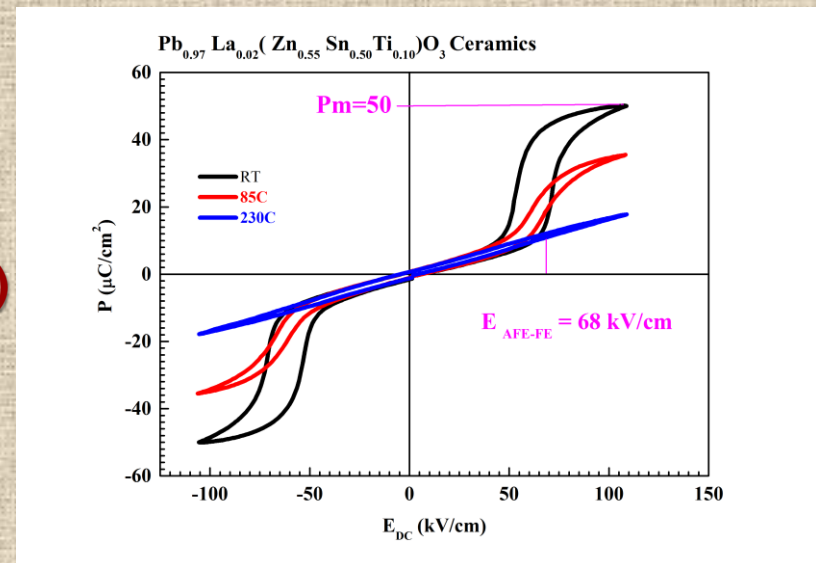
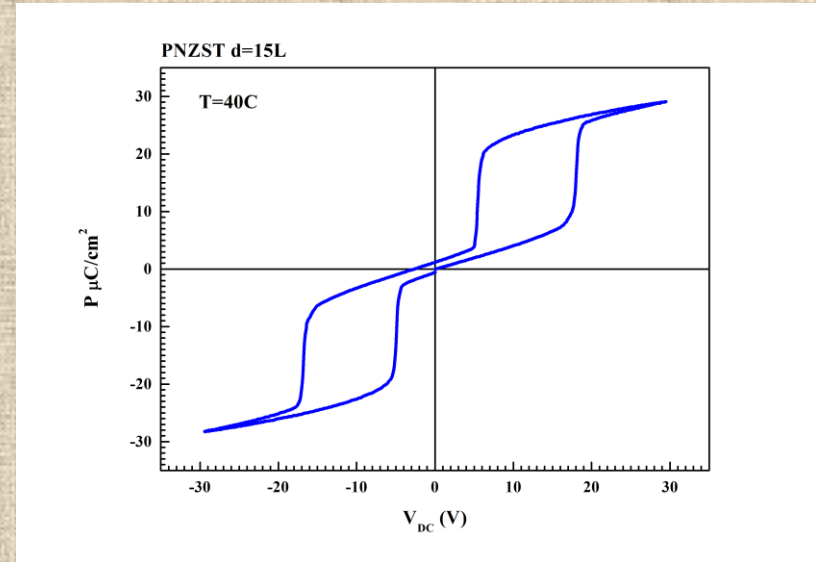
Antiferroelectrics

$$\langle P \rangle \sim 0$$



PNZST (film)

PLZST (ceramic)



Antiferroelectricity in BaTiO₃

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 23, No. 2, AUGUST, 1967

Ferroelectricity and Antiferroelectricity in BaTiO₃*

W. N. LAWLESS**

*Interdisciplinary Materials Research Center, Rensselaer
Polytechnic Institute, Troy, New York*

*and
Corning Research Laboratory, Corning, New York*

(Received April 19, 1967)

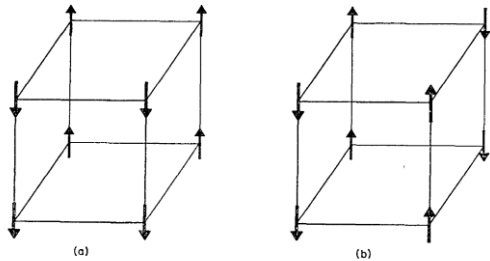
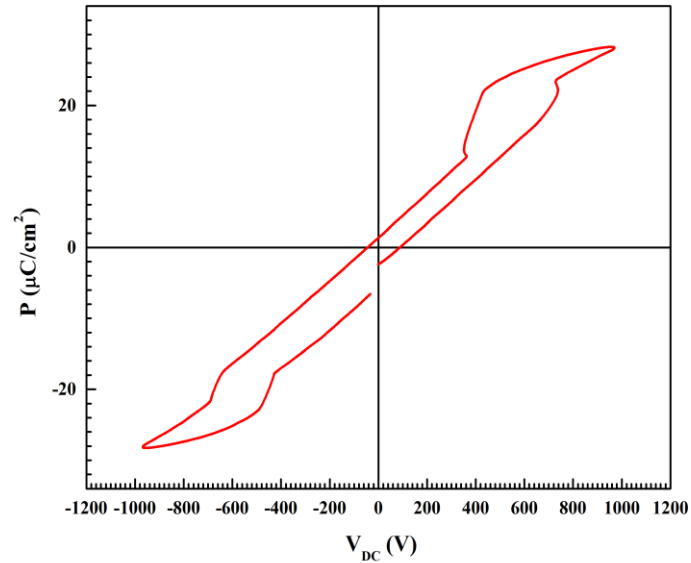
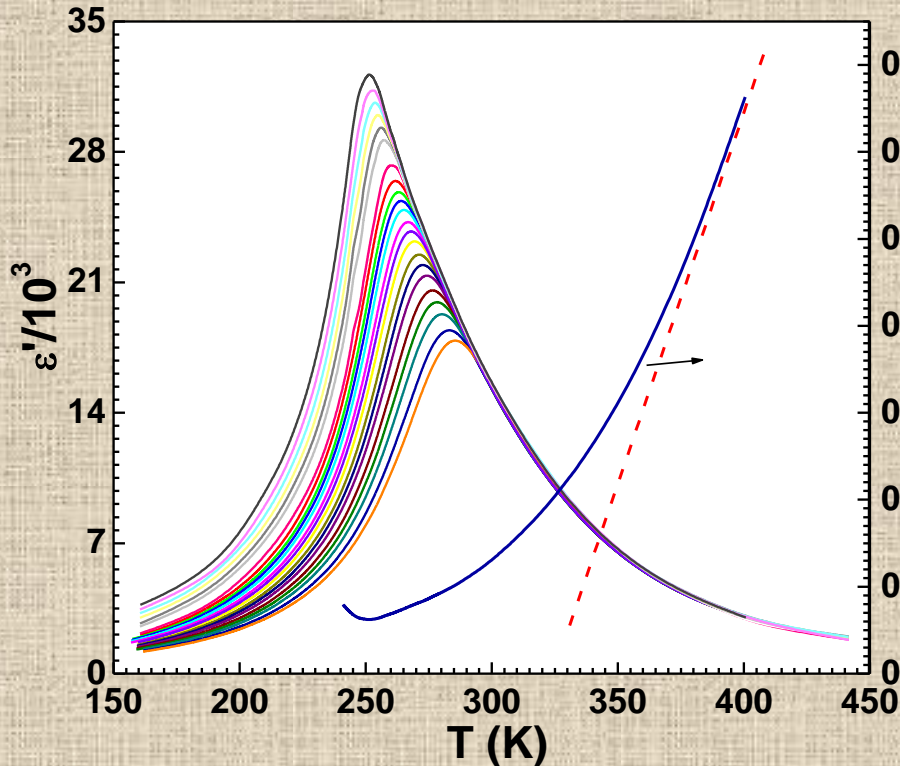


Fig. 2. Antiferroelectric arrays on a simple-cubic lattice: (a), alternating planes, AP(100); (b) alternating-rows, AP(110).

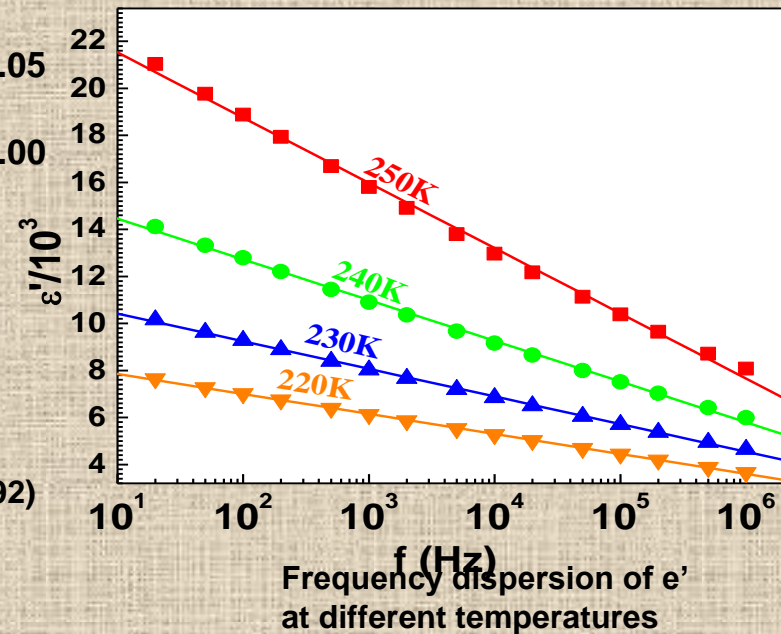
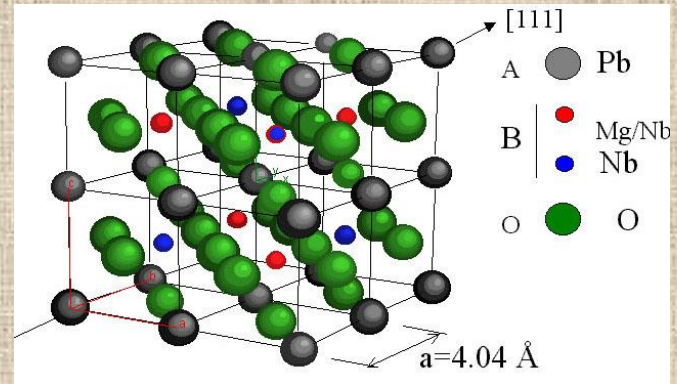


Courtesy of Alan Selewa and
Nathaniel Scheidler (2014,
unpublished)

Ferroelectricity: Relaxors - PMN $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$

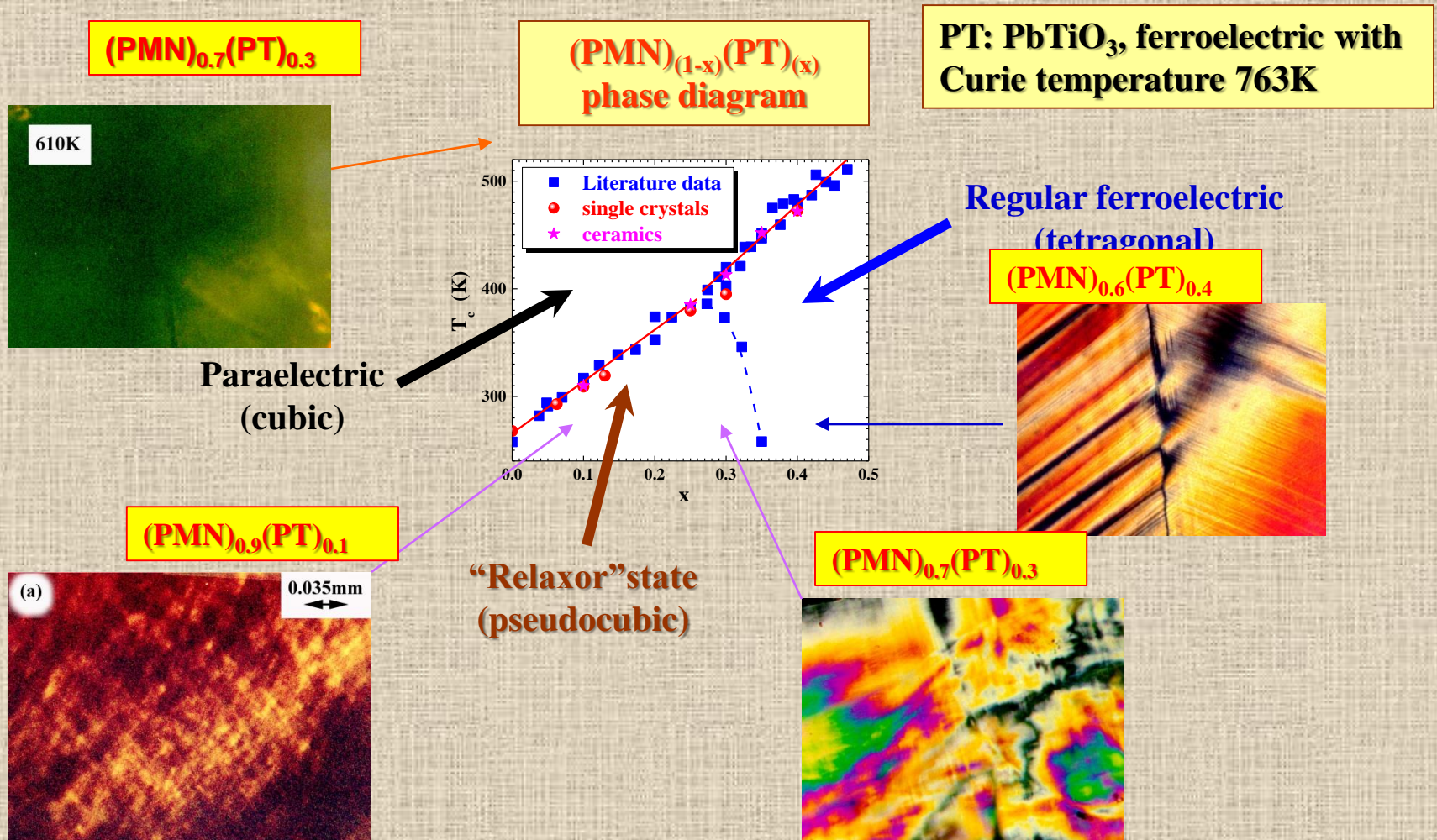


Temperature dependencies of the real part of the dielectric constant measured in a broad frequency range: $3 \cdot 10^{-3} - 10^6$ Hz [1,2]

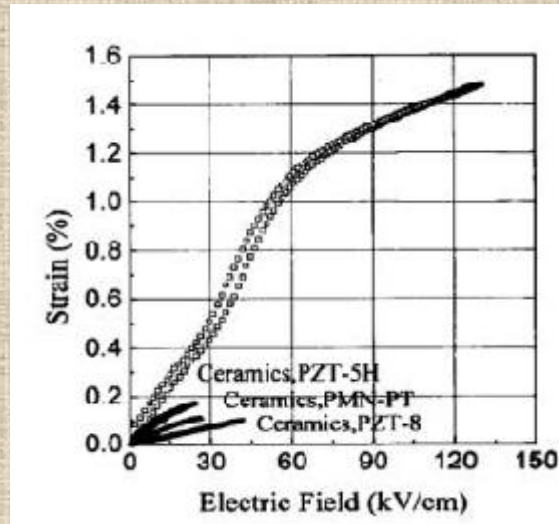


1. E.V. Colla et al., J. Phys.: Cond. Matter, 4,3671, (1992)
2. E.V. Colla et al. J. Appl. Phys., 83, 3298, (1998)

Ferroelectricity: Solid solution relaxor-regular ferroelectric.



Ferroelectricity: Relaxors - some applications



Actuators
 Transducers
 Adaptive optics
 Capacitors
 Line motors for SFM



Transducer stack for ultrasonic sonar application (TRS Ceramics)

Material	Dielectric constant	Piezoelectric coefficient, (pC/n)	Electromechanical coupling factor
Quartz	4.5	2.3	0.1
Rochelle salt (30C)	9.2	27	0.3
Barium titanate ceramic	1700	190	0.52
Lead zirconate titanate PZT 45/55	450	140	0.60
PMN-PT (sc)	4200	2200	0.92-0.94
PZN-PT (sc)	2500	2400	0.91-0.93

Piezoelectric properties of different materials