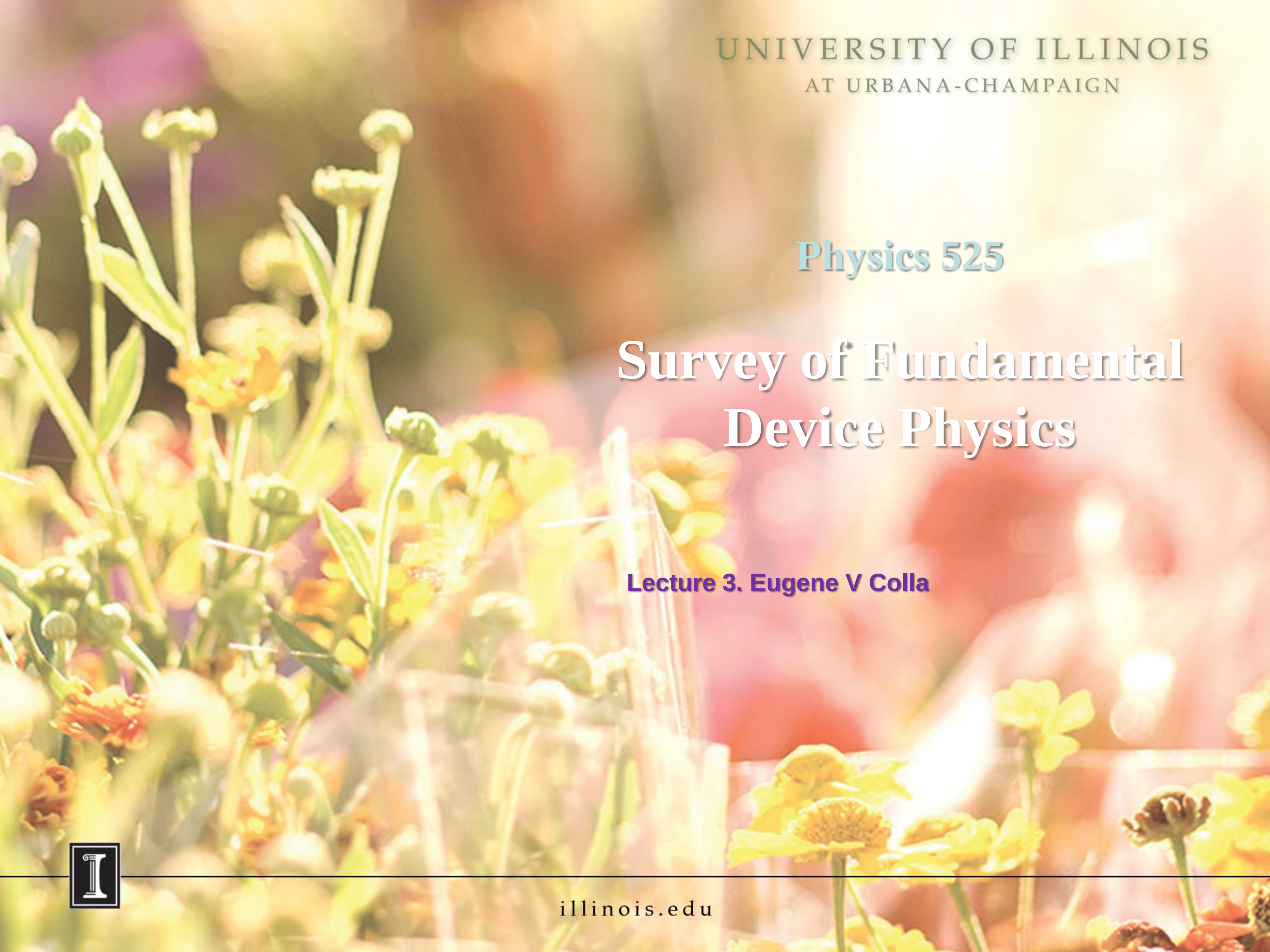


UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

Physics 525

Survey of Fundamental Device Physics

Lecture 3. Eugene V Colla

Agenda of the lecture:

- Dielectrics
- Ferroelectrics
- Main properties
- Relaxors
- Applications

Electric Displacement Field. Dielectric Susceptibility

Electric field E in material causes appearance of local electrical dipole moment and electrical displacement field D could be define as:

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$$

ε_0 – vacuum permittivity; $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m. Polarization P depends on applied electrical field *as:* $P = \chi E$ where χ is dielectric susceptibility. χ is the property on the material.

Finally:

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} = \varepsilon_0 \vec{E} + \chi E = \varepsilon_0 (1 + \chi) E = \varepsilon_0 \varepsilon_r E$$

ε_r – relative permittivity; $\varepsilon_r = 1 + \chi$

Dielectric Susceptibility. Nonlinear Properties.

In general, χ could depend on the electrical field and equation for the nonlinear dependence of P on E can be presented as:

$$P(E) = P_0 + \varepsilon_0 \chi^1 E + \varepsilon_0 \chi^2 E^2 + \varepsilon_0 \chi^3 E^3 + \ldots$$

For non ferroelectric materials the built-in polarization $P_0 = 0$

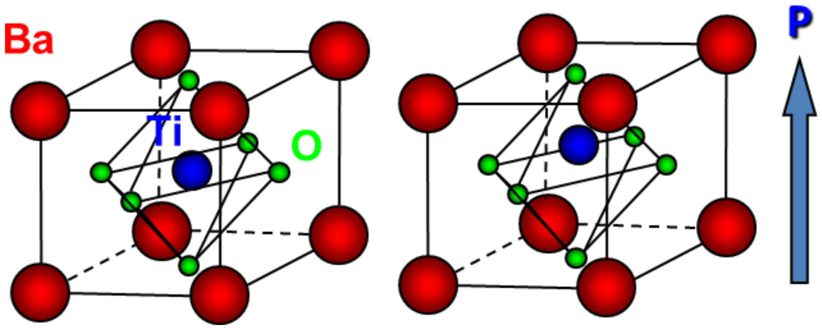
χ^2, χ^3 … are the nonlinear susceptibility terms of Tylor expansion. The nonlinear properties of dielectrics and especially of ferroelectrics are widely used in optics.

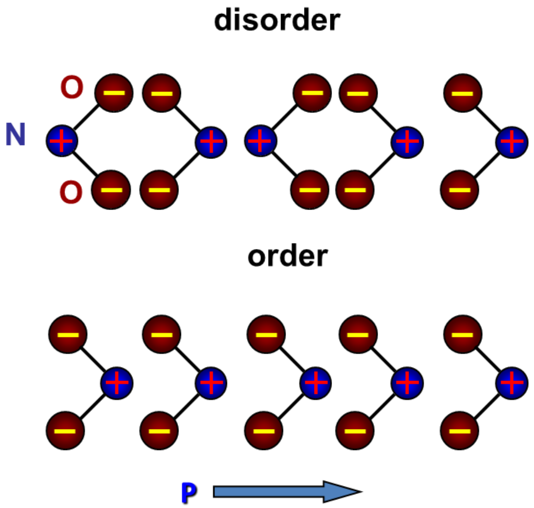
Ferroelectric Phase Transition.

Ferroelectric is a class of dielectric materials exhibiting the spontaneous electric polarization and this polarization can be reversed by applying of the electrical field.

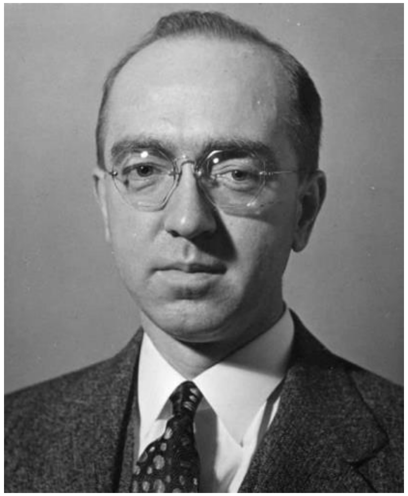
Appearance of the spontaneous polarization is associated with phase transition usually related to changes of the crystallography structure of the material. Usually, this phase transitions are of the first order.

Two main classes of ferroelectrics could be revealed: displacive and order-disorder



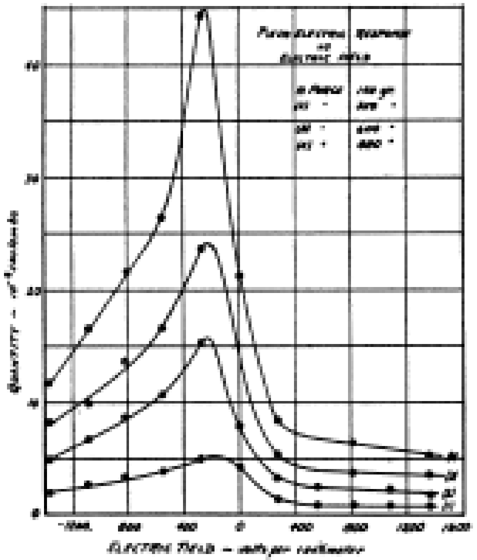


Ferroelectricity. Discovery.

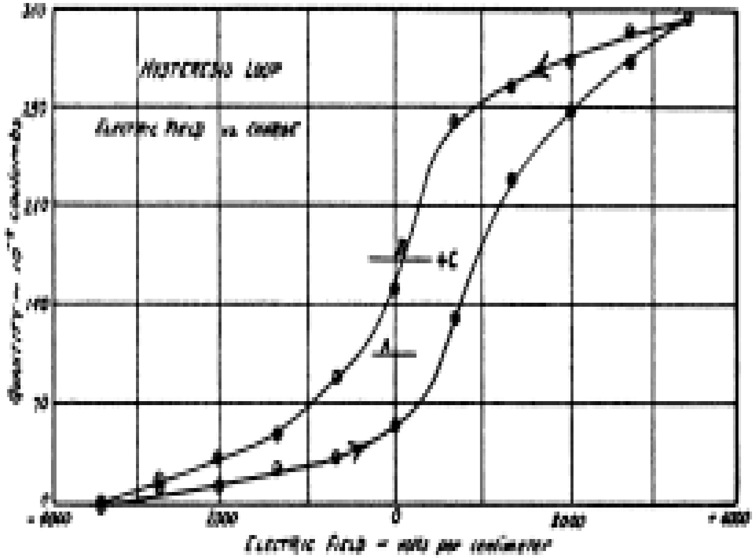


Joseph Valasek
(1897–1993)

PIEZO-ELECTRIC AND ALLIED PHENOMENA IN ROCHELLE SALT.[1]

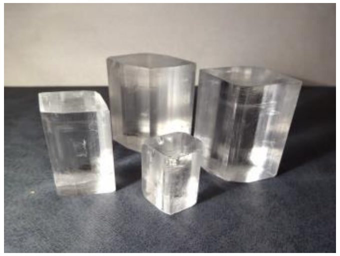


Temperature dependency
of dielectric susceptibility
of Rachelle salt



P- E hysteresis loops

In 1920 J Valasek (University of Minnesota) demonstrated the ferroelectric properties observe on Rachelle salt ($KNaC_4H_4O_6 \cdot 4H_2O$). This gave a start of the intensive research in this area.



Phys.Rev, **17**, 475, 1921;

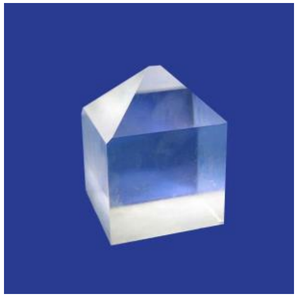
Ferroelectricity. Materials. Potassium Dihydrogen Phosphate. KDP.

Georg Bush
(1908-2000)

Paul Scherrer
(1890-1969)

G. Busch and P. Scherrer, Naturwissenschaften 23, 737 (1935)
Eine neue seignette-elektrische Substanz

KH_2PO_4



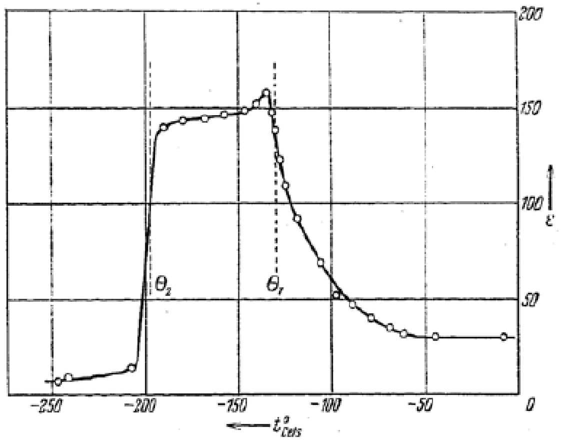
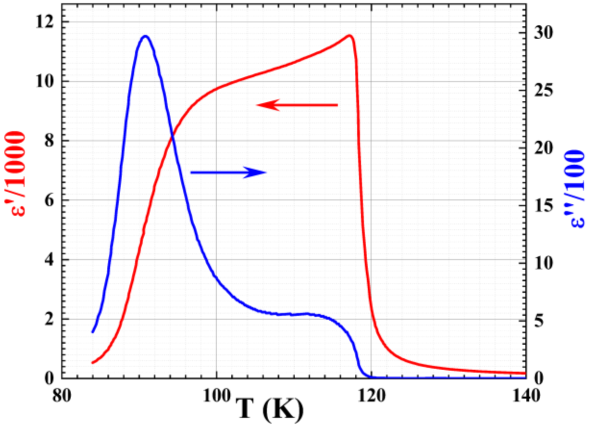
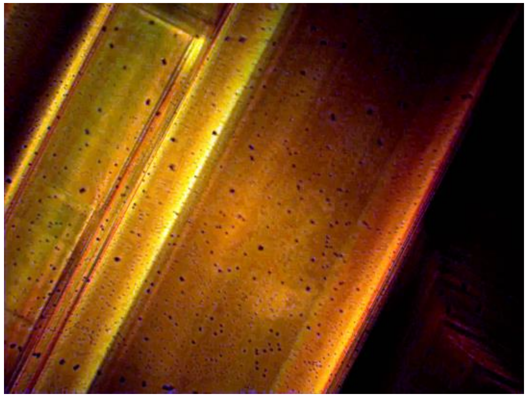


Fig. 1. Temperaturverlauf der Dielektrizitätskonstanten ε_{33} an KH_2PO_4.

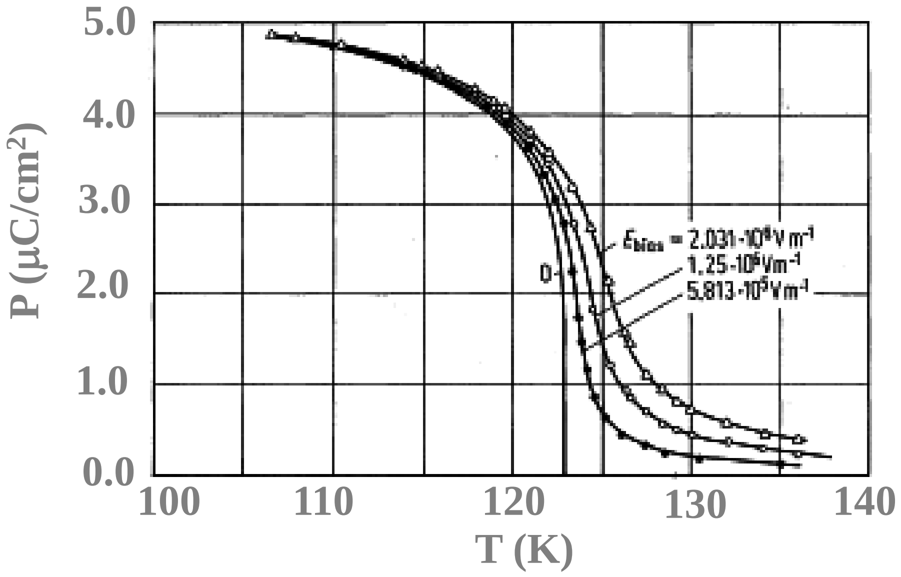




Dielectric susceptibility and the domain structure (T<110K). Courtesy of Physics 403 Lab

Ferroelectricity. Materials. KDP family.

		T_C(K)	Ps (μC/cm^2)
KDP type	**KH_2PO_4**	**123**	**4.75**
	KD_2PO_4	**213**	**4.83**
	RbH_2PO_4	**147**	**5.6**



c axis polarization of KDP measured under different DC biases (Chabin, M., Gilletta, F.: Ferroelectrics 15 (1977) 149.)

Applications of KDP:

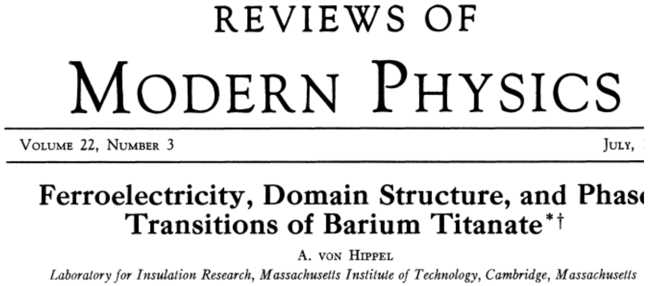
2 Bags 40g Flower Vegetable Planting Potassium Dihydrogen Phosphate Fertilizer $7.98

Developing KH_2PO_4 and KD_2PO_4 Crystals for the World's Most Power Laser

(International Materials Reviews, 47:3, 113-152, 2002)

Ferroelectricity. Materials. Barium Titanate. Perovskites.

Arthur R. von Hippel
1898-2003



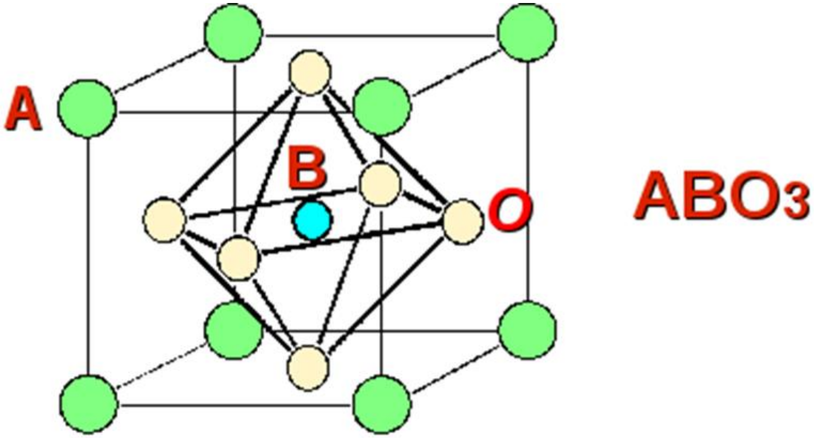
REVIEWS OF
MODERN PHYSICS

VOLUME 22, NUMBER 3 JULY,

**Ferroelectricity, Domain Structure, and Phas
Transitions of Barium Titanate*†**

A. VON HIPPEL

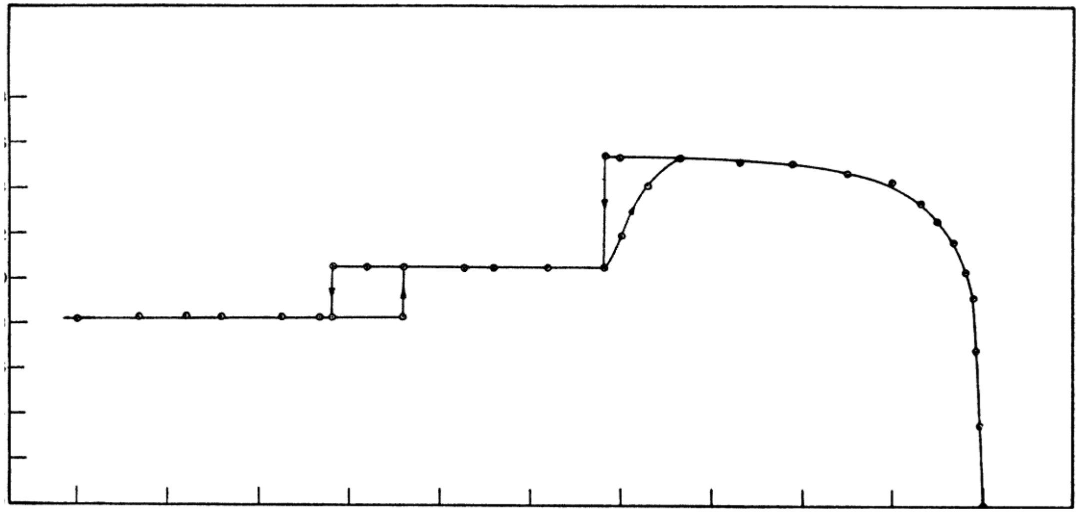
Laboratory for Insulation Research, Massachusetts Institute of Technology, Cambridge, Massachusetts

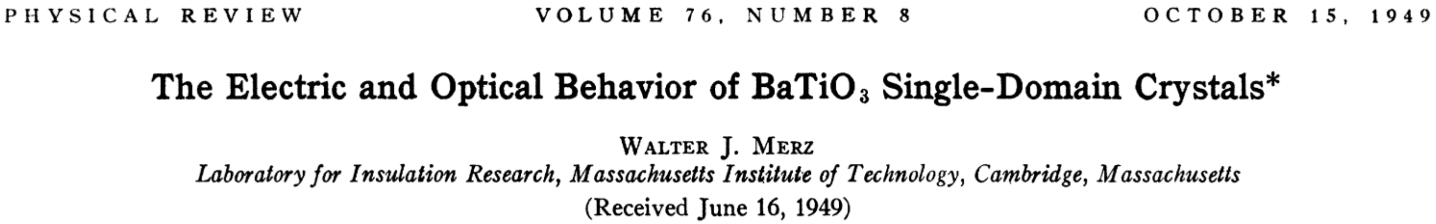


		T_C(K)	Ps (μC/cm²)
Perovskites	$BaTiO_3$	408	26
	KNbO3	708	30
	$PbTiO_3$	765	>50
	$LiTiO_3$	938	50
	$LiNbO_3$	1480	71

Perovskite structure
Barium Titanate:
A – Ba
B – Ti

Ferroelectricity. Materials. Barium Titanate.





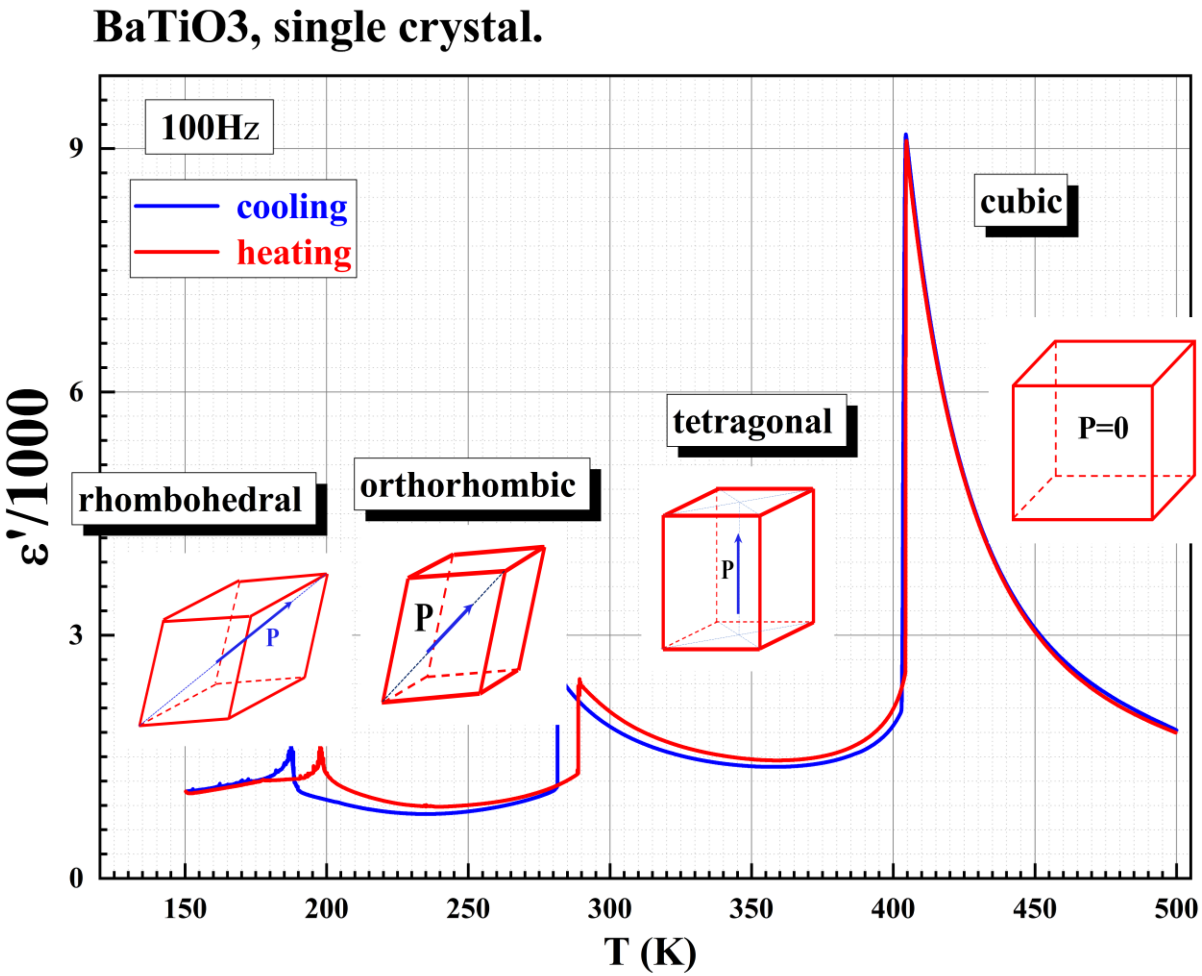
PHYSICAL REVIEW VOLUME 76, NUMBER 8 OCTOBER 15, 1949

The Electric and Optical Behavior of $BaTiO_3$ Single-Domain Crystals*

WALTER J. MERZ
Laboratory for Insulation Research, Massachusetts Institute of Technology, Cambridge, Massachusetts

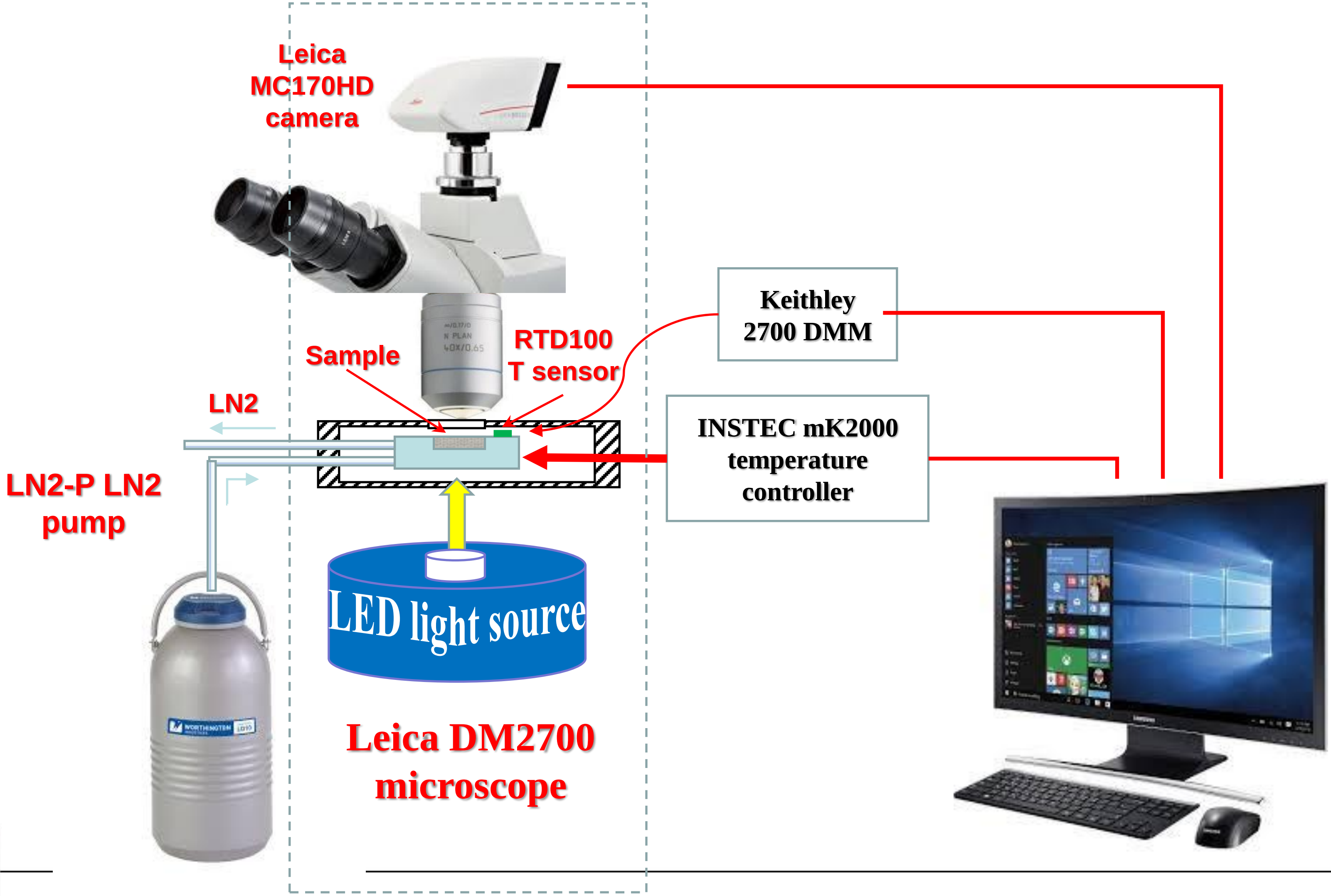
(Received June 16, 1949)

Ferroelectricity. Materials. Barium Titanate.



Courtesy of P403 course

Ferroelectricity. Domains. Polarizing Microscopy.



Leica MC170HD camera

Sample

RTD100 T sensor

LN2

LN2-P LN2 pump

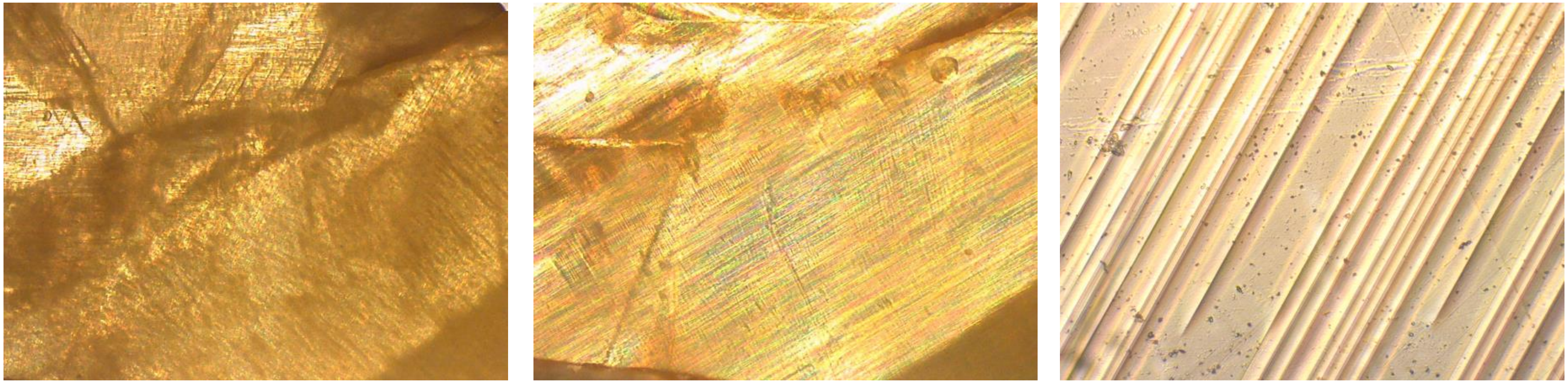
Keithley 2700 DMM

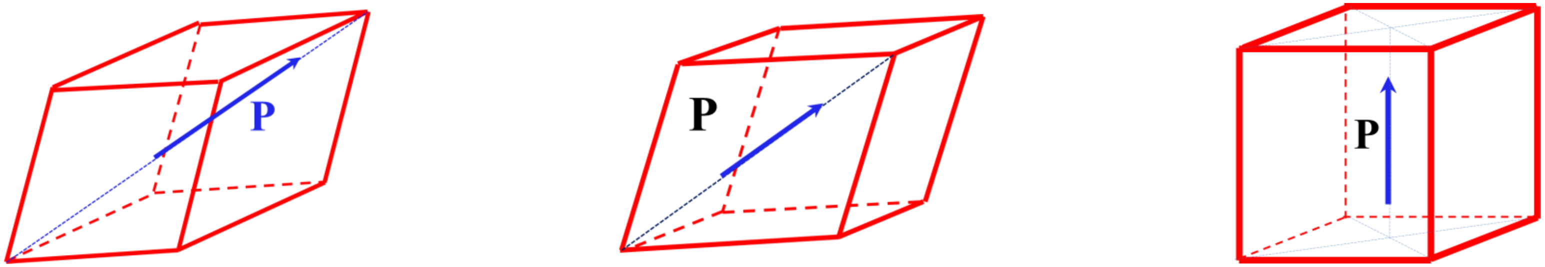
INSTEC mK2000 temperature controller

LED light source

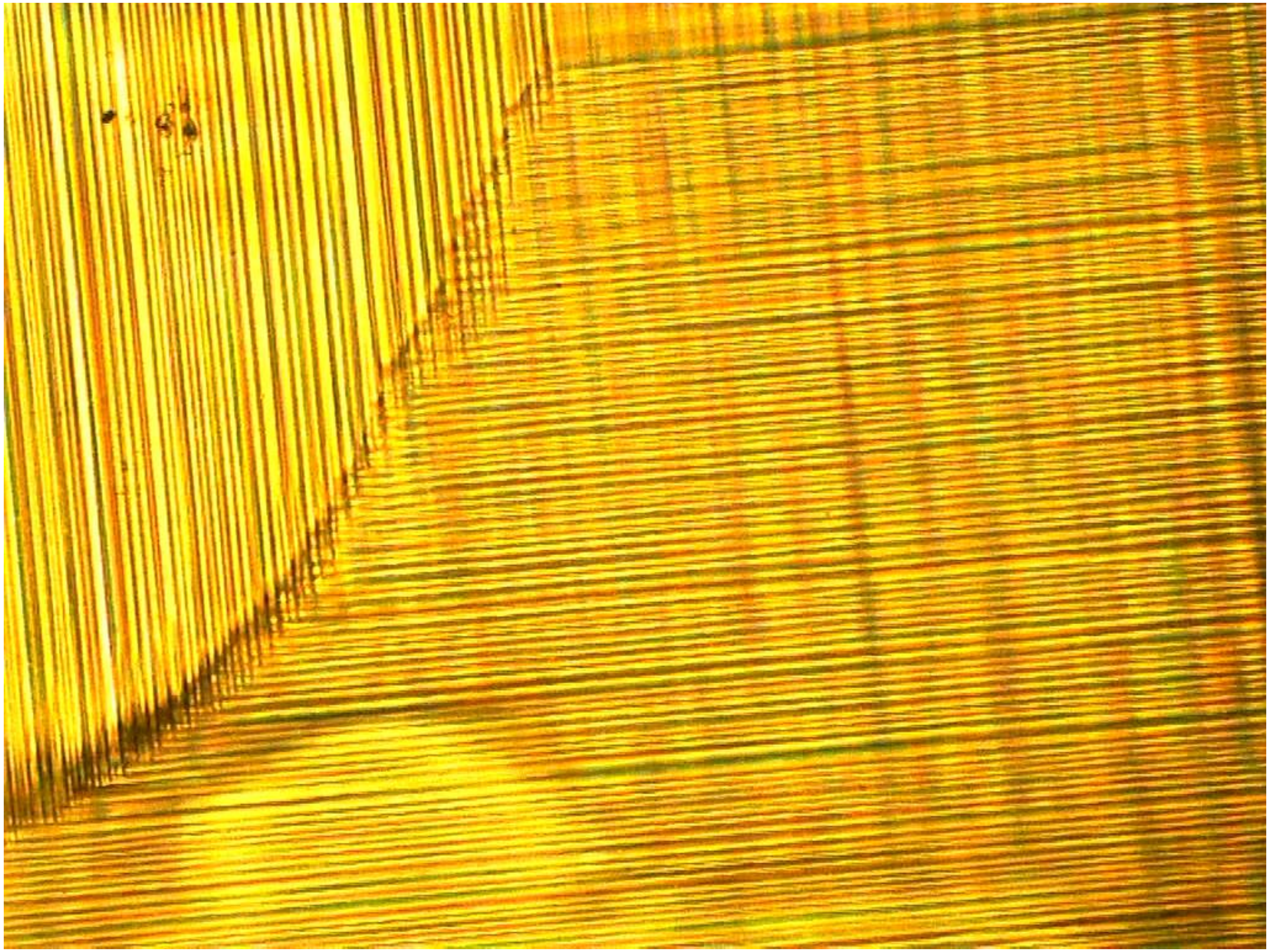
Leica DM2700 microscope

Ferroelectricity. Materials. Barium Titanate. Domains. Different Phases.

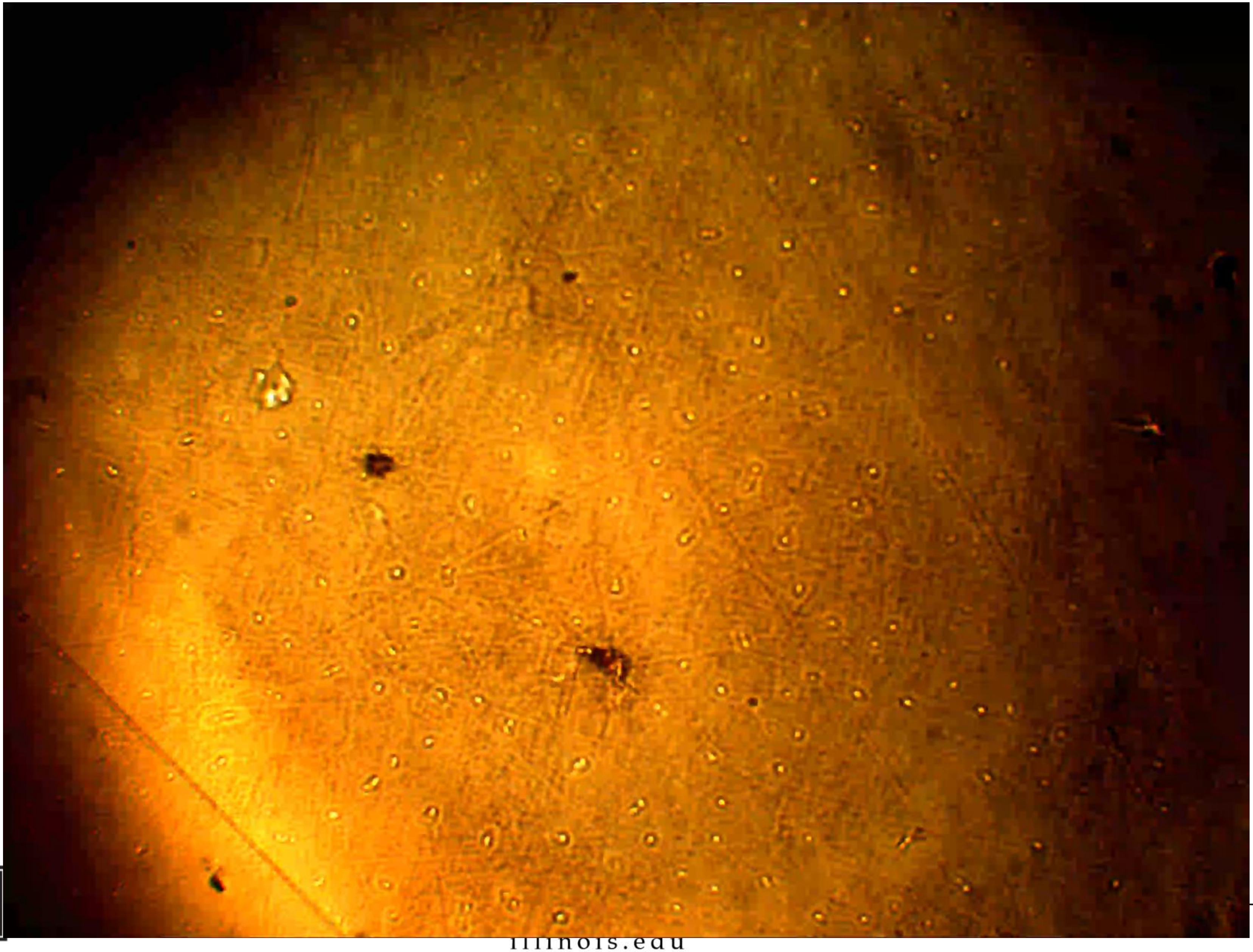




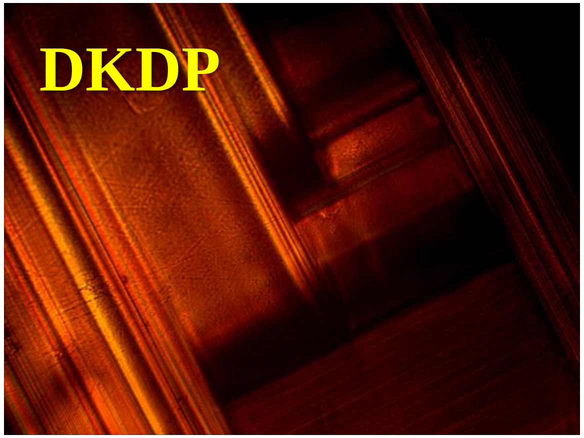
Ferroelectricity. Materials. Barium Titanate. Tetragonal to Cubic Phase Transition.



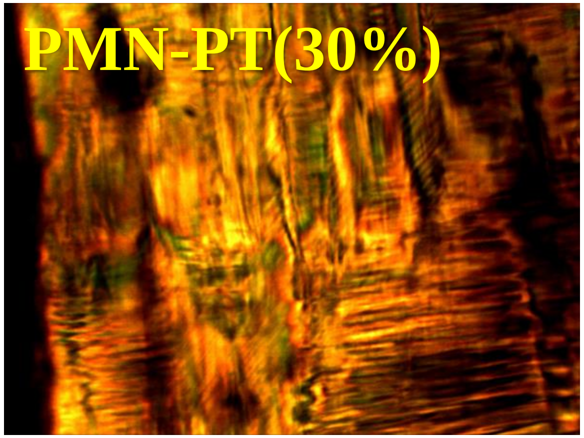
Ferroelectricity. Materials. DKDP.

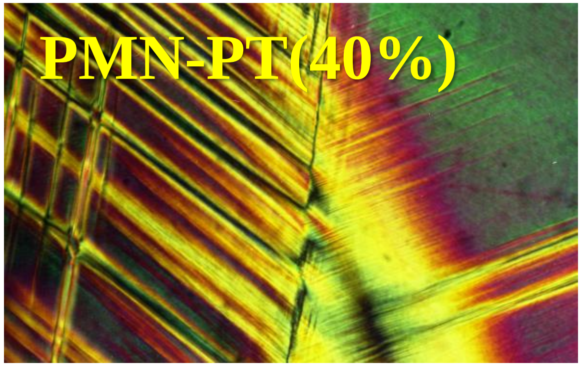


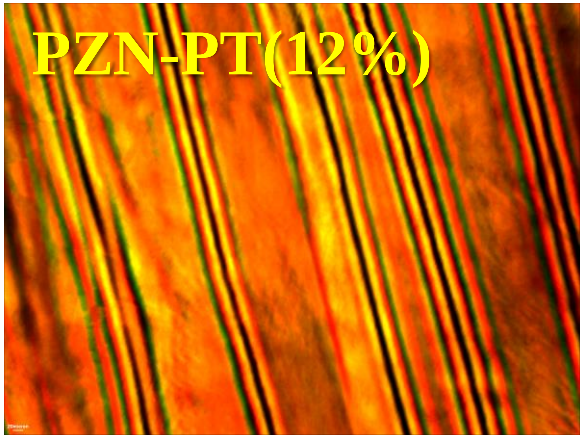
Ferroelectric Domains. The Case of Art.

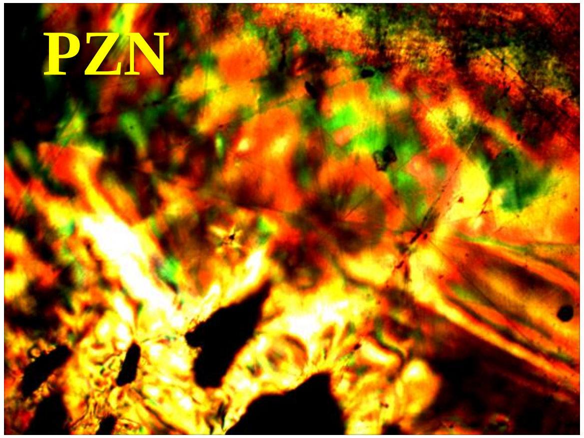

DKDP


$BaTiO_3$

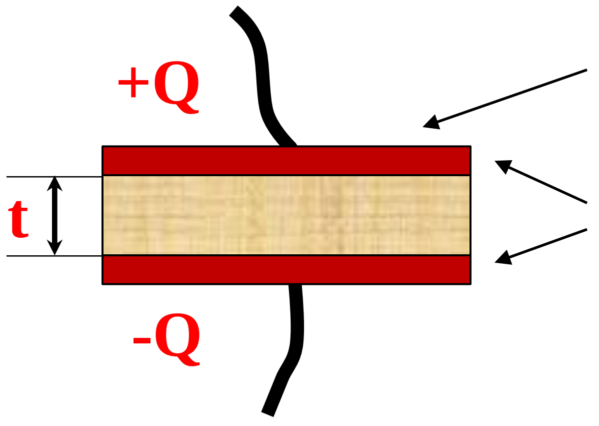

PMN-PT(30%)


PMN-PT(40%)


PZN-PT(12%)


PZN

Ferroelectricity. Switching the Polarization. P-E Hysteresis.



Sample as a flat capacitor

$$P = Q \bullet t$$

$$p = \frac{P}{V} = \frac{Q * t}{A * t} = \frac{Q}{A};$$

p – polarization per unit volume (C/m^2; convenient units - μC/cm^2)

Ferroelectricity. P-E Hysteresis. Measuring Technique.

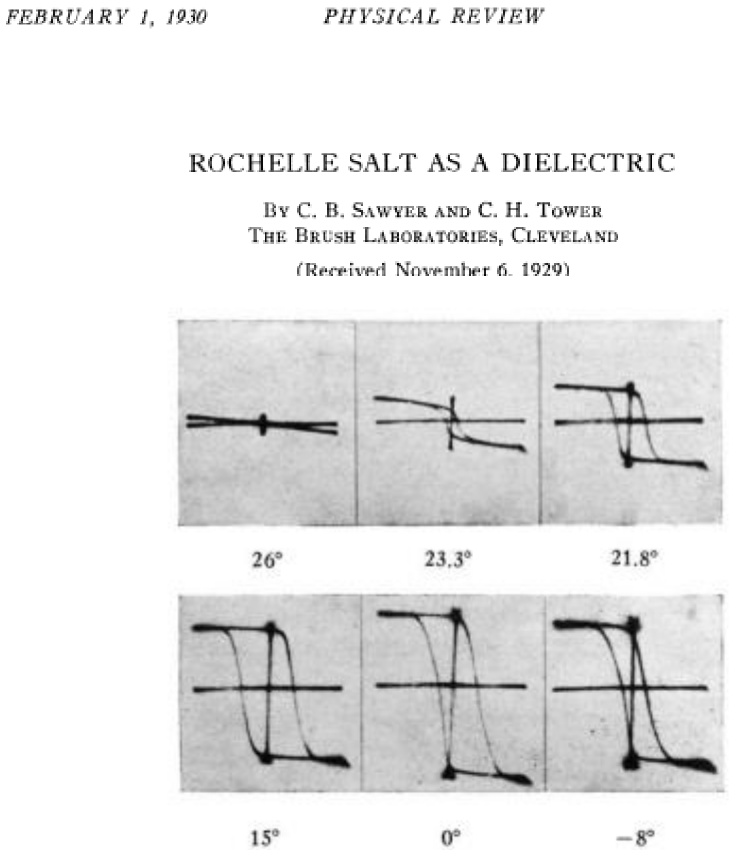
Crossing the critical temperature point ferroelectric exhibits the polarization – separation the charges and this causes the appearance of polarization current *Ip*

$$Ip = \frac{dQ}{dt}$$

Polarization can be calculated as:

$$p = \frac{P}{V} = \frac{1}{A}\int I_p dt$$

Ferroelectricity. P-E Hysteresis. Measuring Technique.



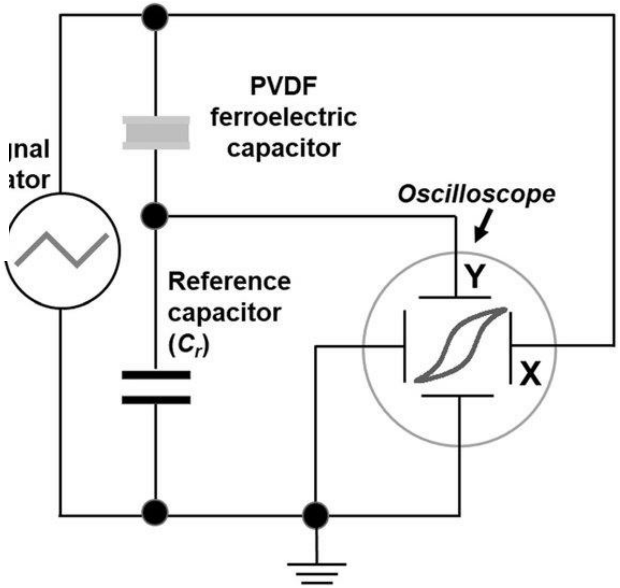
FEBRUARY 1, 1930 PHYSICAL REVIEW VOLUME 35

ROCHELLE SALT AS A DIELECTRIC

By C. B. Sawyer and C. H. Tower
The Brush Laboratories, Cleveland

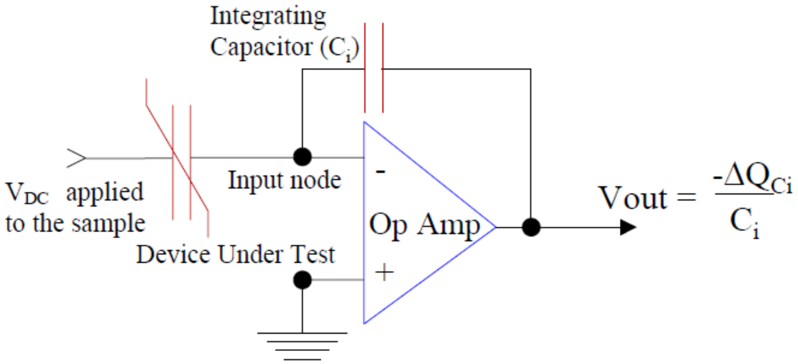
(Received November 6, 1929)

Hysteresis and saturation of Rochelle salt plate

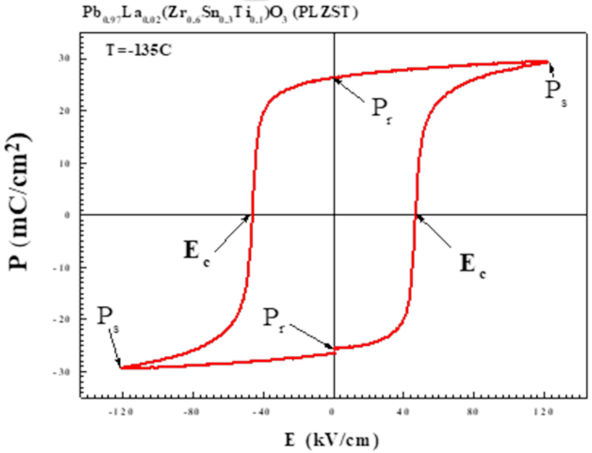


Sawyer-Tower measuring technique

Ferroelectricity. P-E Hysteresis. Measuring Technique.

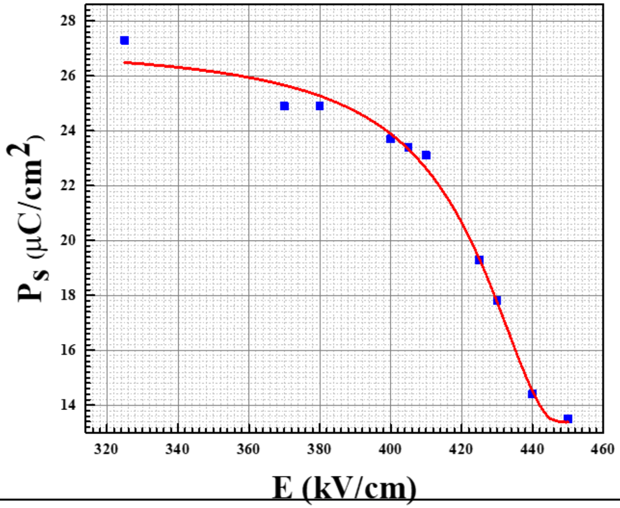


Measuring idea realized in RT66B tester. (courtesy of Radiant Technology Inc.)



Saturation polarization vs temperature measured on BaTiO3 single crystal. (courtesy Physics 403)

Saturation polarization vs temperature. BaTiO3, single crystal. (courtesy Physics 403)



Ferroelectricity. Materials. Relaxors.

B-site complex	**Lead magnesium niobate (PMN)**	$PbMg_{l/3}Nb_{2/3}0_3$
	Lead scandium tantalate (PST)	$PbSc_{1/2}Ta_{1/2}0_3$
	Lead zinc niobate (PZN)	$PbZn_{l/2}Nb_{1/2}0_3$
	Lead indium niobate (PIN)	$PbIn_{1/2}Nb_{1/2}0_3$
A-site complex	**Lead lanthanum titanate (PLT)**	$Pb_{1-x}La_xTiO_3$
Both sites complex	**Lead lanthanum zirconate titanate (PLZT)**	$Pb_{1-x}La_xZr_yTi_{1-y}O_3$
	Potassium lead zinc niobate	$K_{1/3}Pb_{2/3}Zn_{2/9}Nb_{7/9}0_3$

L. Eric Cross[1]
(1923-2016)

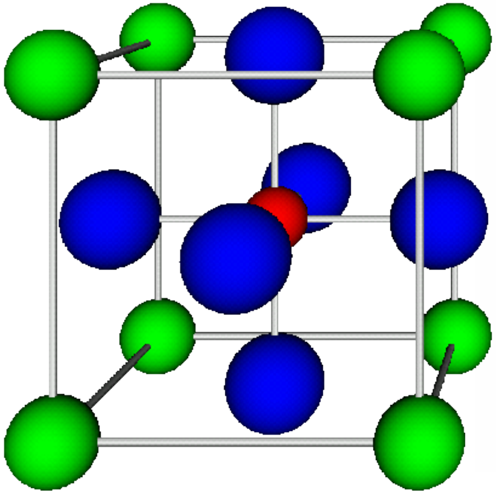
Smolenskii G.A.[2]
(1910 – 1986)

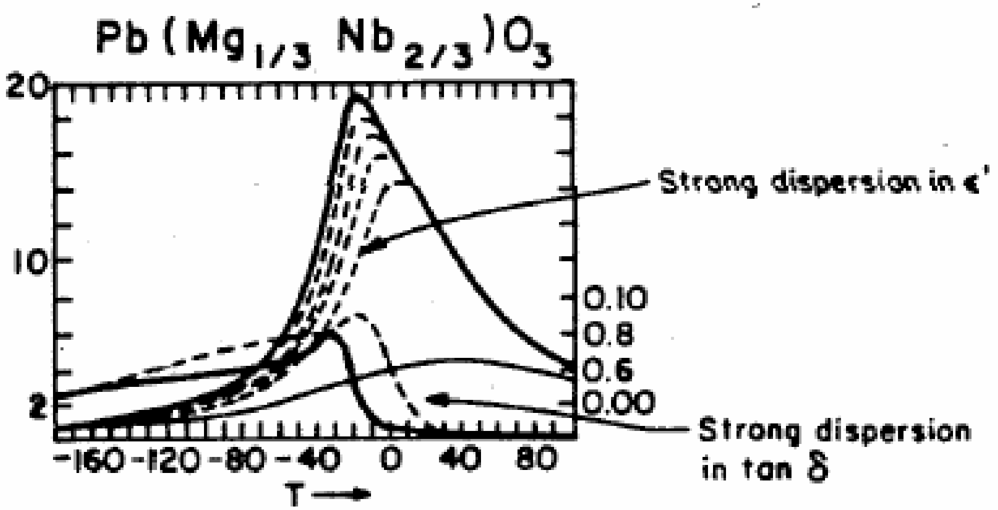
1. **Pennsylvania State University, USA**
2. **A.F. Ioffe Institute, USSR**

$AB1_{(1-x)}B2_xO_3$ $A1_{(1-x)}A2_xBO_3$ $A1_{(1-x)}A2_xB1_{(1-y)}B2_yO_3$ **typical complex oxides with perovskite structure**

Ferroelectricity. Materials. Relaxors.

Lead magnesium niobate (PMN)	$PbMg_{1/3}Nb_{2/3}0_3$



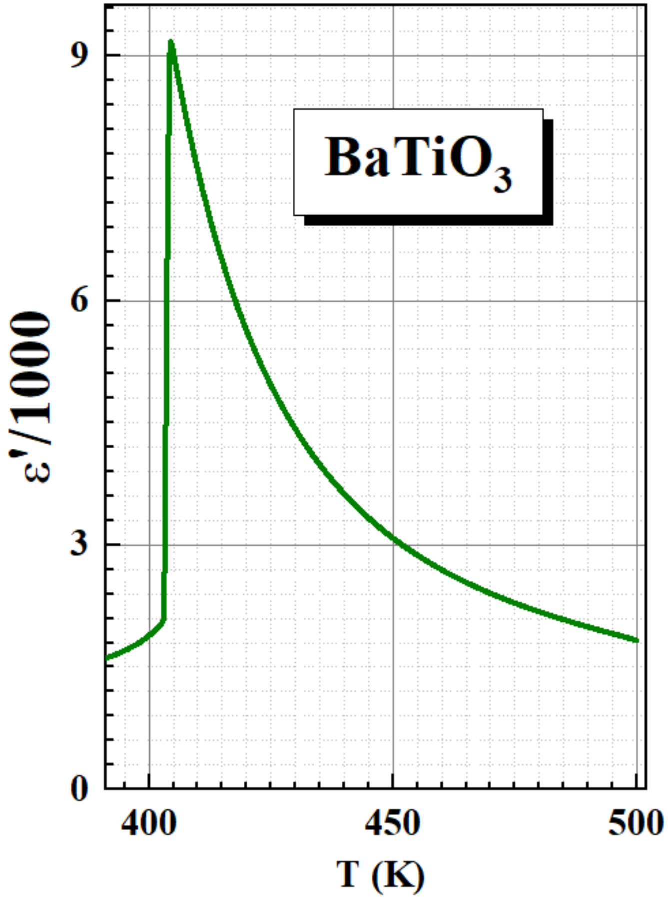


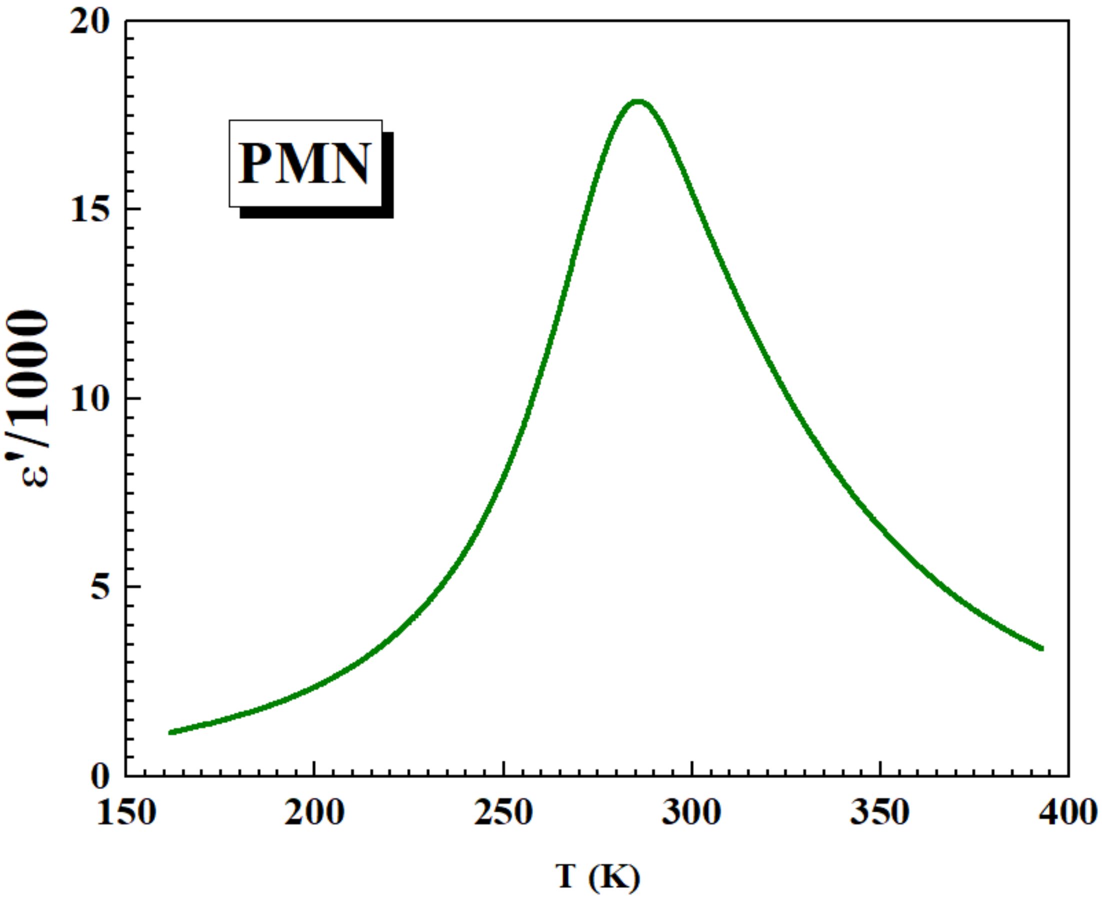
G. A. Smolenskii and A. I. Agranovskaya, “Dielectric Polarization of a Number of Complex Compounds,” Soviet Physics Solid State, Vol. 1, 1960, pp. 1429-1437.

● **Pb** ● **O** ● **Mg^{+2} or Nb^{+5}**

Ferroelectricity. Materials. Relaxors. Main Properties.

Broad peak of dielectric permittivity



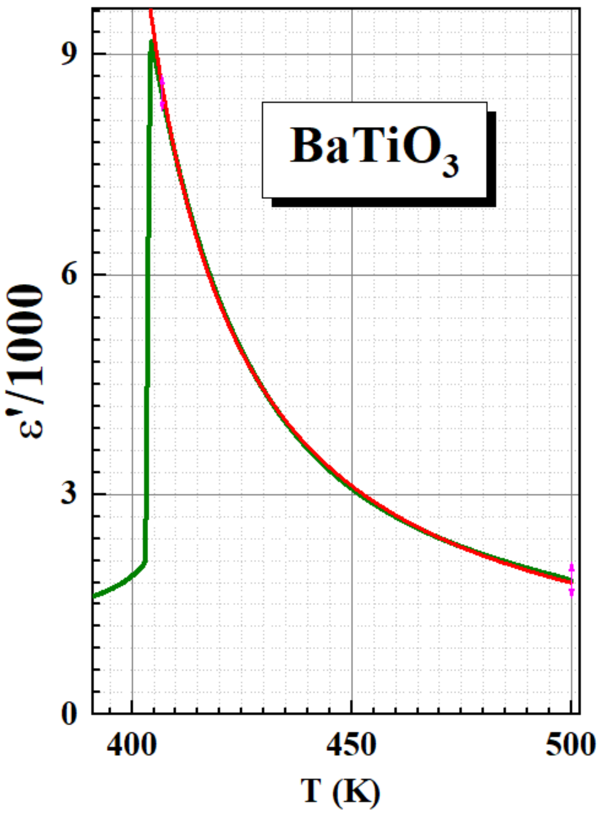


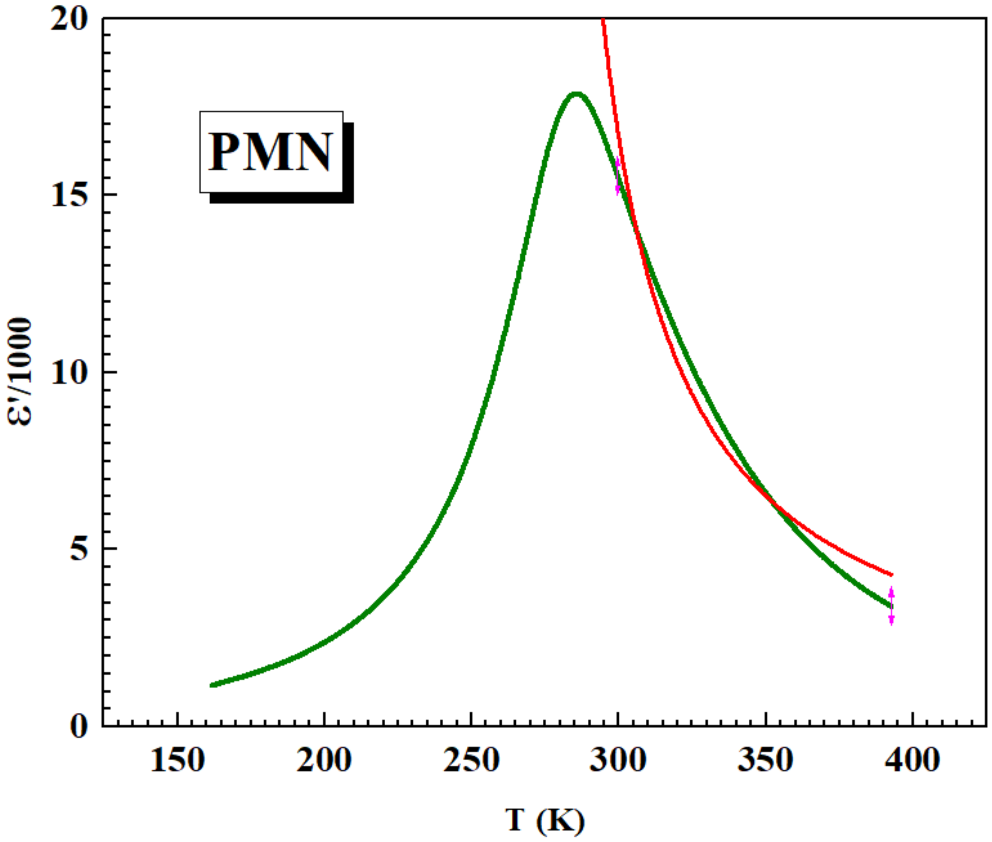
Courtesy of P403 Lab

Ferroelectricity. Materials. Relaxors. Main Properties.

$$\chi' = \frac{C}{T - T_{CW}}; \varepsilon' = \chi' + 1; \chi'$$

Relaxors do not obey the Curie-Weiss Law

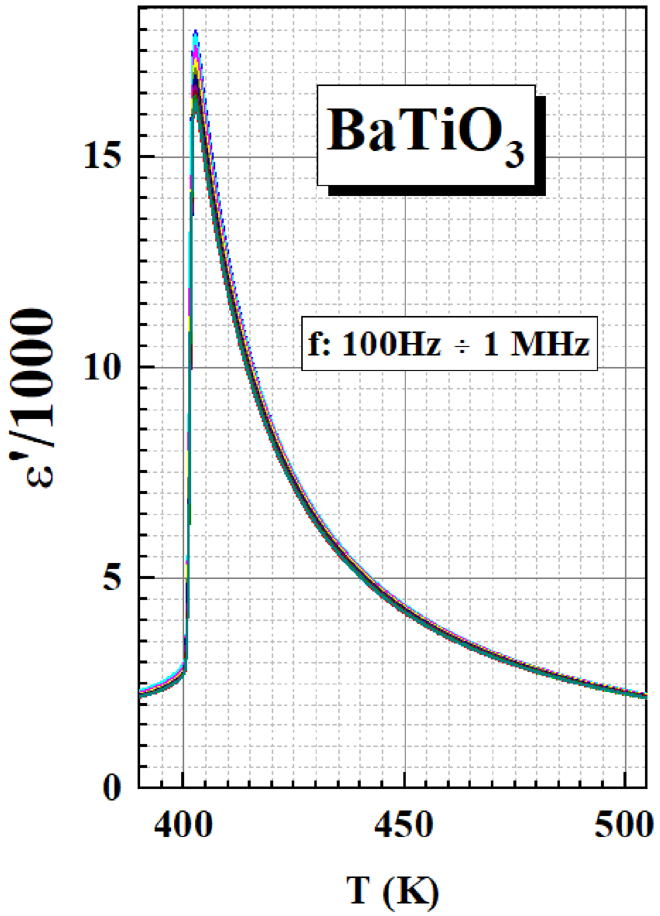


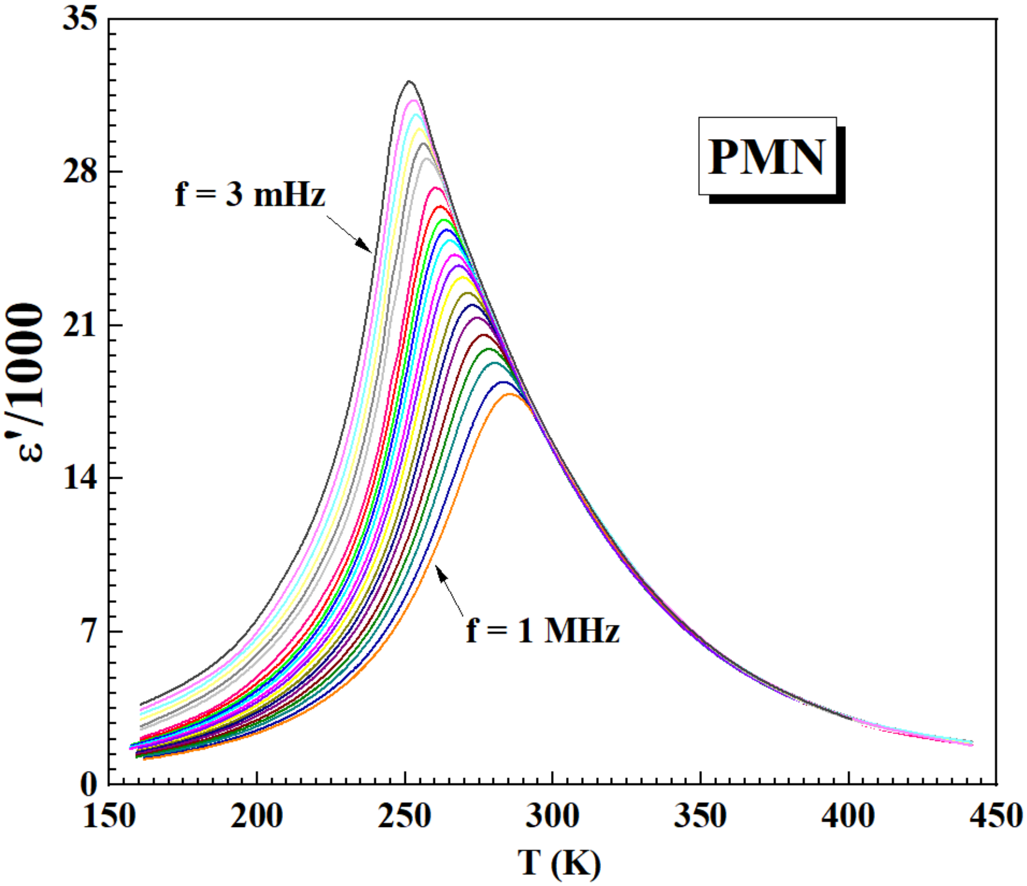


Courtesy of P403 Lab

Ferroelectricity. Materials. Relaxors. Main Properties.

Frequency dispersion of the permittivity peak position

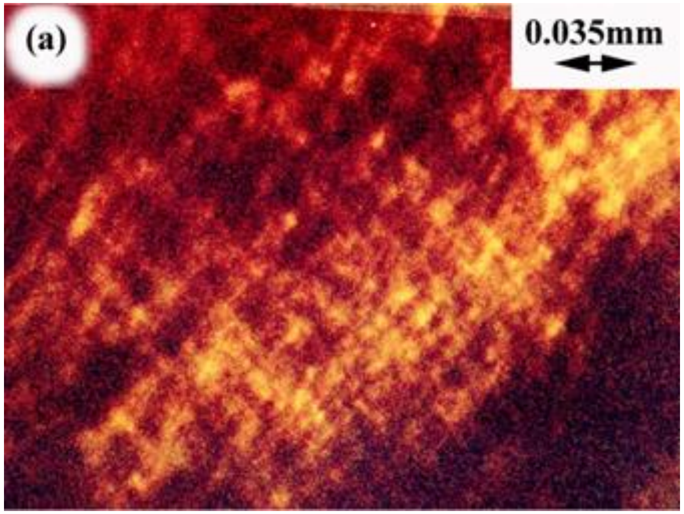


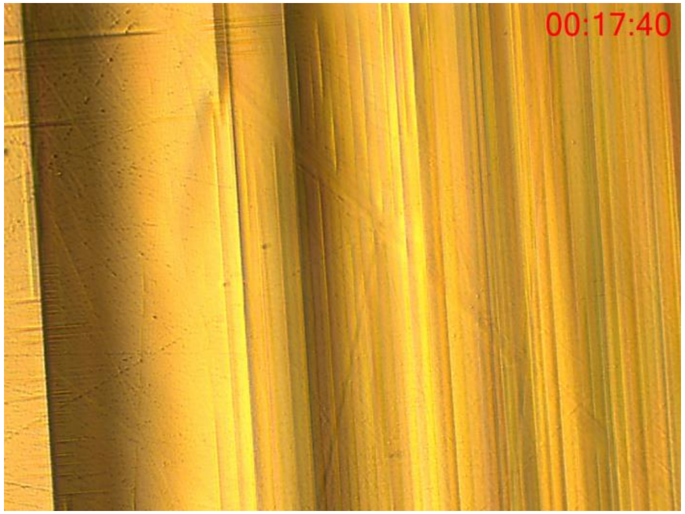


Courtesy of P403 Lab

Ferroelectricity. Materials. Relaxors. Main Properties.

Long range ferroelectric order. Ferroelectric domains.





Relaxor (PMN-PT10%)

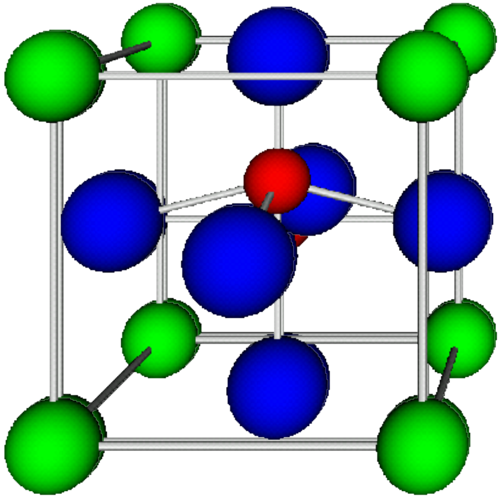
$BaTiO_3$

Courtesy of P403 Lab

Ferroelectricity. Materials. Relaxors. Main Properties. Structure.

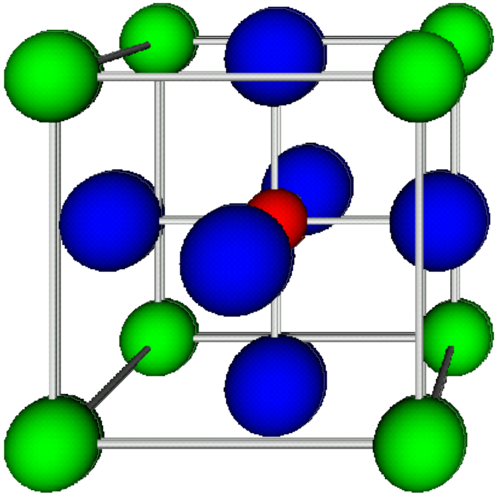
Regular ferroelectric $BaTiO_3$

Relaxor - PMN $Pb(Mg_{1/3}\ Nb_{2/3})O_3$



$T \lessgtr T_c$ **(cubic) (tetragonal)**

● Ba ● O ● Ti



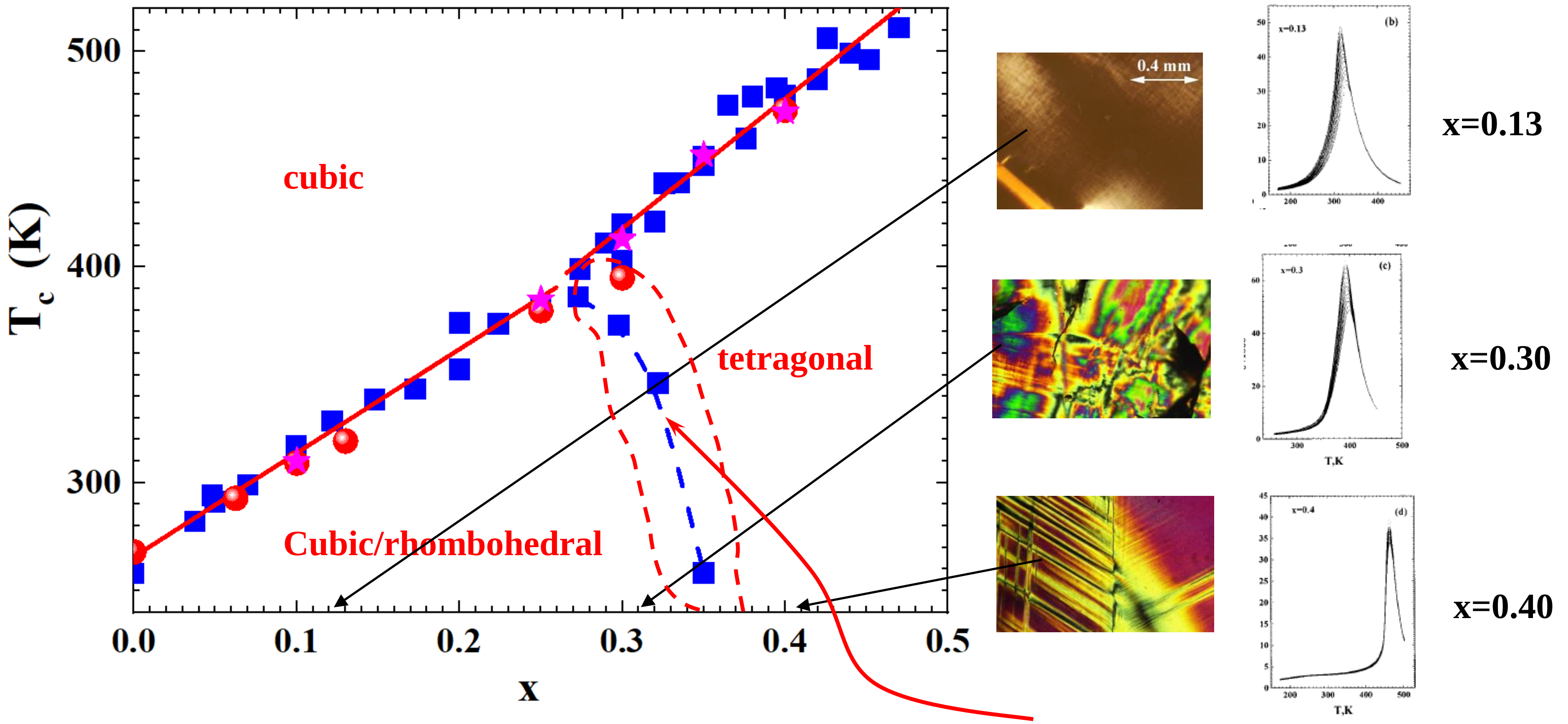
(cubic)

● Pb ● O ● Mg^{+2} or Nb^{+5}

Courtesy of P403 Lab

Ferroelectricity. Materials. Relaxors. Main Properties. PMN-PT Solid Solution.

PbTiO$_3$: T$_c$=763 K



Eugene V Colla at all, JAP, 83, 3298, (1998)

Morphotropic phase boundary

Piezoelectricity.

Piezoelectric materials are a class of materials which can be polarized, in addition to an electric field, also by application of a mechanical stress*

Direct piezoelectric effect: stress X_{jk} applied to piezoelectric material results in charge density D_i

$$D_i = d_{ijk} X_{jk} \qquad (1)$$

d_{ijk} **– third rank tensor of piezoelectric coefficients. Units -** $\frac{C}{N} \equiv \frac{A \bullet s^3}{kg \bullet m}$

Converse piezoelectric effect: piezoelectric material changes the dimensions by application of the electrical field E

$$x_{ij} = d_{kij} E_k = d^t_{ijk} E_k$$

x_{ij} **– strain,** d^t_{ijk} **– transposed matrix. Units -** $\frac{m}{V} \equiv \frac{A \bullet s^3}{kg \bullet m}$

direct and converse piezoelectric effects are thermodynamically identical i.e.

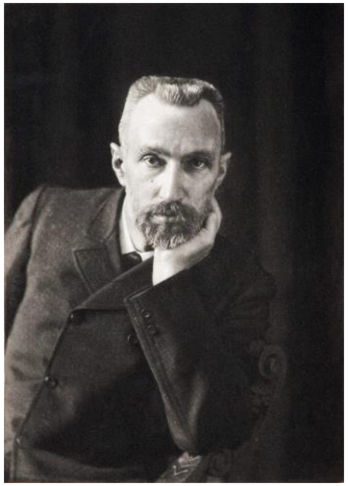
$d_{direct} = d_{converse}$

---

* D. Damjanovic, Rep. Prog. Phys. 61, 1267-1324 (1998)

Ferroelectricity. Main Properties. Piezoelectricity.

Paul-Jacques Curie
(1855-1941)



Pierre Curie
(1850-1906)

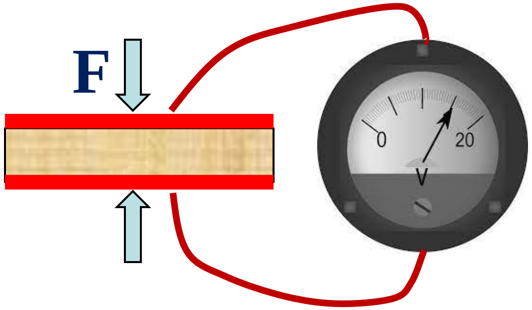
Natural Piezoelectric' s:

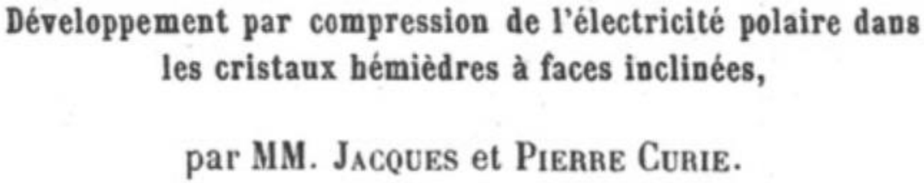
Quartz
Cane sugar,
Rochelle salt
Topaz
Tourmaline

Some manmade materials:

Barium Titanate
Lead Zirconate Titanate
Lead Titanate
(Ferroelectrics in red)

Bulletin de la Société minéralogique de France, volume 3, 4, 1880.





Développement par compression de l'électricité polaire dans
les cristaux hémièdres à faces inclinées,

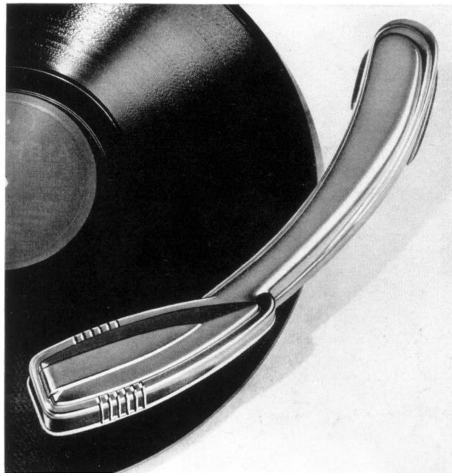
par MM. Jacques et Pierre Curie.

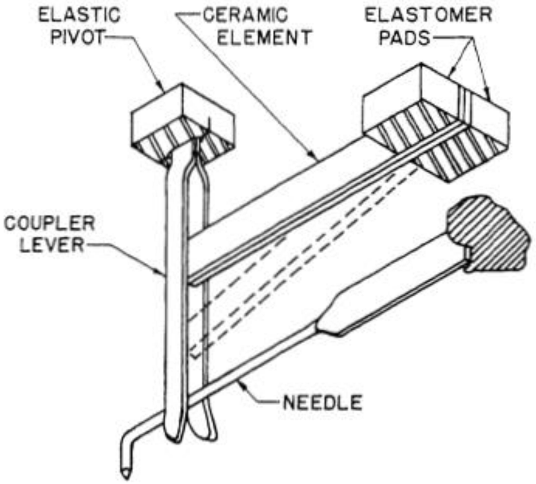
Piezoelectricity. Materials

Material	Orientation	Piezoelectric coefficient d (pC/N)
$BaTiO_3$	111	$d_{33}=289$
PMN-PT (33%)		$d_{33}=2820$
PZN-PT (8%)		$d_{33}=2500$
Rochelle salt		27
PZT		$d_{31}=110$
Quartz		2.3

Ferroelectricity. Materials. Piezoelectricity. Applications.

Piezoelectric tone-arm.





Astatic B-1 or B-2 Hermetically Sealed Crystal Turntable Cartridge

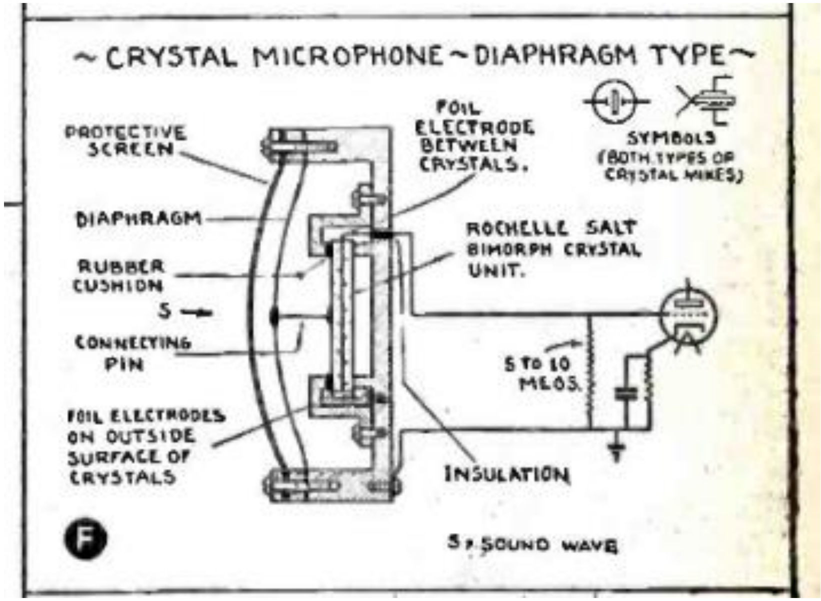
Piezo Electric Pick-up

Quartz Replaced By Salt Crystals

the needle which follows the
along the record twists the
Fig. 2A shows the crystal
needle armature and needle,
the moulded cases removed.
crystal element is held in the
by the two rubber supports,
the needle tracking the record
the crystal and produces a
on the faces BB proportional

Ferroelectricity. Materials. Piezoelectricity. Applications.

Piezoelectric Microphones



Crystal
HAND MICROPHONES

SHURE MODEL 71AS

"CLOSE-TALKING" MODELS

The Shure Model 71AS Crystal Hand Microphone makes available the fine performance of Shure Crystal Microphones in the hand mounting so essential for many applications. The instrument is of the "close-talking" type and is specially designed to minimize crowd noise. The crystal unit is mounted in a beautiful chromium-plated cast case with rubber-black-japan handle. A conveniently located "push-to-talk" switch is built into the handle.

Specifications: Diameter of case, 3-1/16 inches (7.77 cm.) Case Thickness: 1-5/16 inches (3.33 cm.) Overall Length: 9 inches (22.86 cm.) Net Weight, including cable: 1¼ lbs. (5.67 kg.) Shipping Weight: 1¾ lbs. (7.94 kg.)

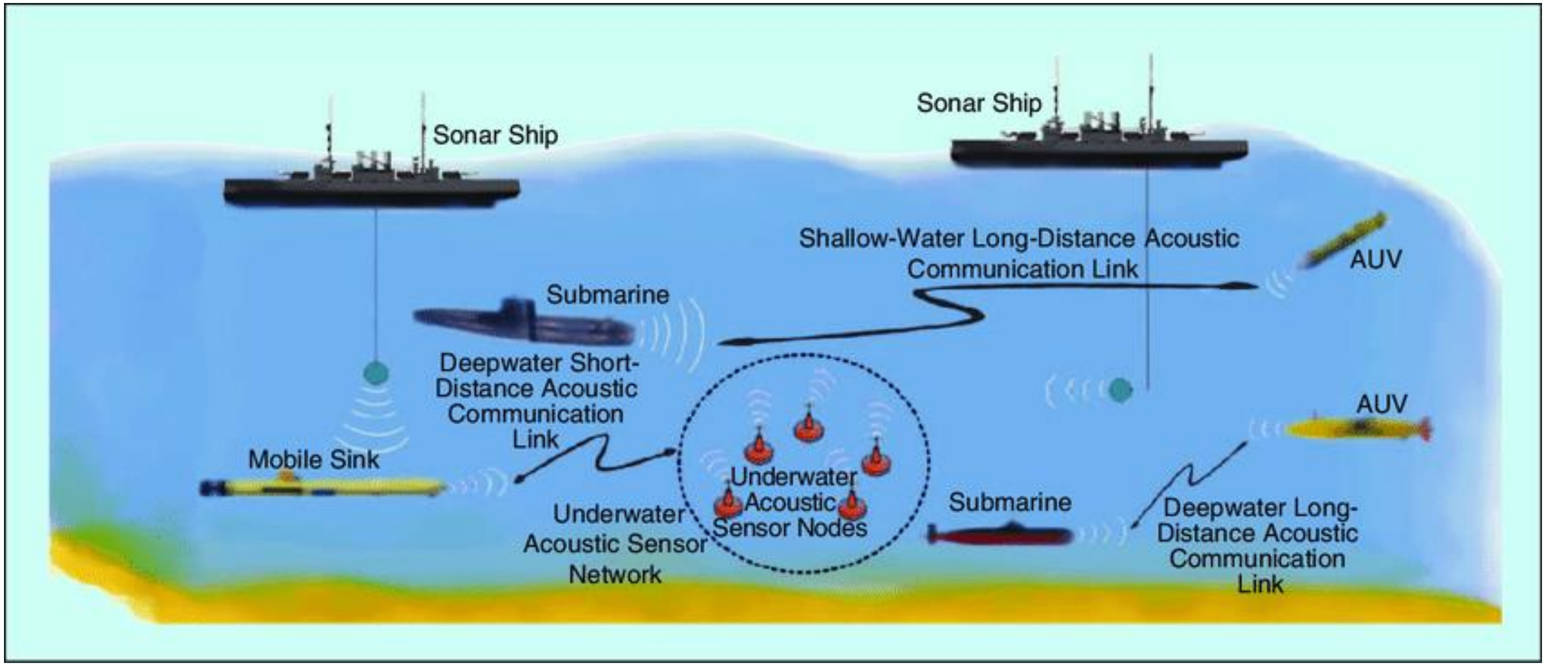
Model 71AS. Crystal Hand Microphone, "close-talking" type. Complete with 7 feet of special rubber-jacketed, shielded, single-conductor cable. Complete instructions. Code: **Rurec.**
List Price **$26.50**

Courtesy

Ferroelectricity. Materials. Piezoelectricity. Applications.

Underwater Sonars

(**sound navigation and ranging** or **sonic navigation and ranging**)

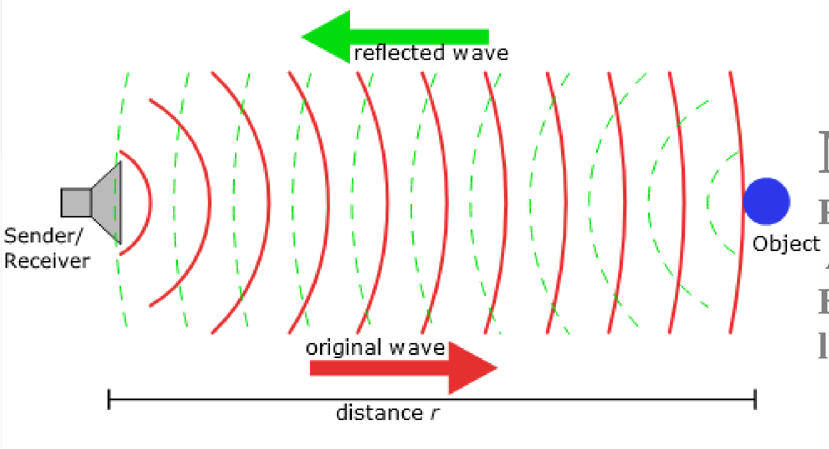


Underwater communication

JUNE 2012 | IEEE VEHICULAR TECHNOLOGY MAGAZINE

Ferroelectricity. Materials. Relaxors. Piezoelectricity. Applications.

Underwater Sonars



Materials:

Rochelle salt (1940),
Ammonium dihydrogen phosphate (ADP) (WWII),
Barium titanate (~1950)
lead zirconate titanate (PZT) (now),

Ferroelectricity. Materials. Piezoelectricity. Transducers.

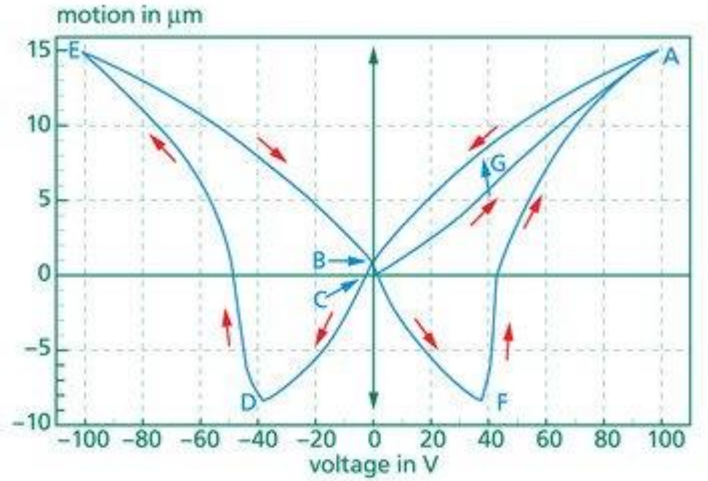
piezosystemjena
incredibly precise

- PZT multilayer stack without housing
- Without pre-load
- Motion up to 123 µm

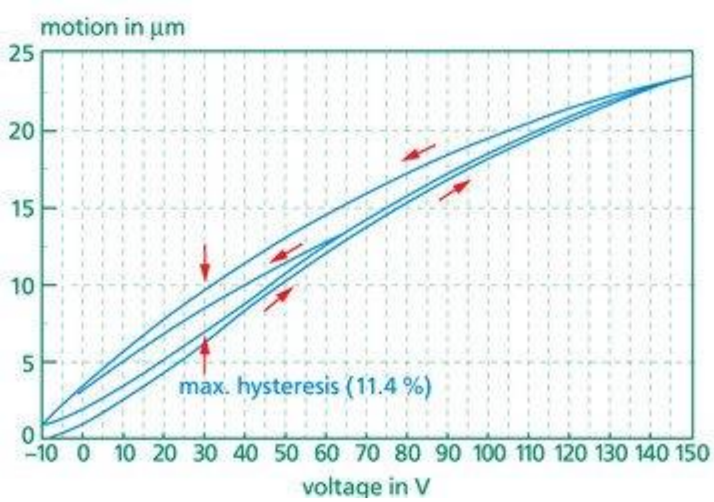
Electrical field

$$\frac{\Delta l}{L_0} = d \bullet E$$

Piezoelectric coefficient (in general it is nonlinear for E)



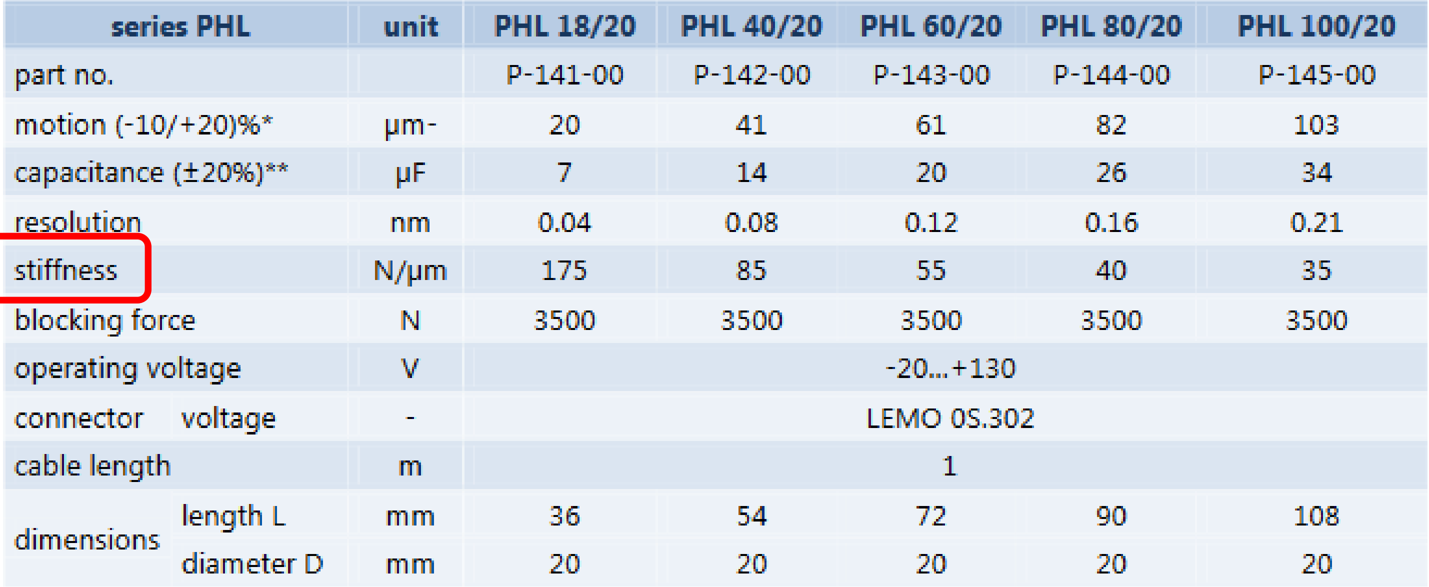
Typical hysteretic behavior of the transducer in respect of bipolar applied field



Typical hysteresis curve of a multilayer piezostack under unipolar bias

Ferroelectricity. Materials. Piezoelectricity. Transducers.

piezosystemjena
incredibly precise

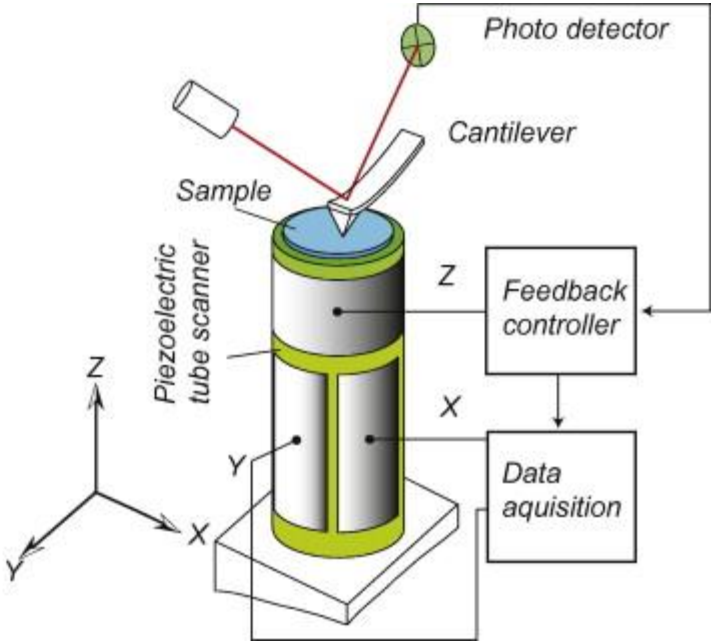


series PHL		unit	PHL 18/20	PHL 40/20	PHL 60/20	PHL 80/20	PHL 100/20
part no.			P-141-00	P-142-00	P-143-00	P-144-00	P-145-00
motion (-10/+20)%*		µm-	20	41	61	82	103
capacitance (±20%)**		µF	7	14	20	26	34
resolution		nm	0.04	0.08	0.12	0.16	0.21
stiffness		N/µm	175	85	55	40	35
blocking force		N	3500	3500	3500	3500	3500
operating voltage		V	-20...+130				
connector	voltage	-	LEMO 0S.302				
cable length		m	1				
dimensions	length L	mm	36	54	72	90	108
	diameter D	mm	20	20	20	20	20

The maximum force generated by transducer could be estimated as $F_{max} \approx k_t \bullet \Delta l$

k_t **– piezo actuator stiffness**

Ferroelectricity. Piezoelectricity. Transducers. Scanning Probe Microscopy



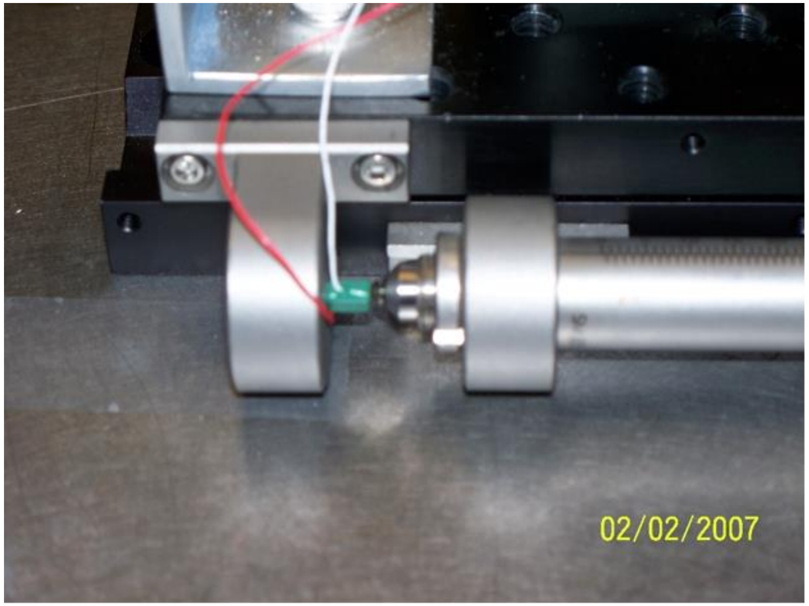
Schematic of an Atomic Force Microscope with a piezoelectric tube scanner for the positioning of the sample.

S. Kuiper, G. Schitter, Mechatronics v20, 656-665 (2010)

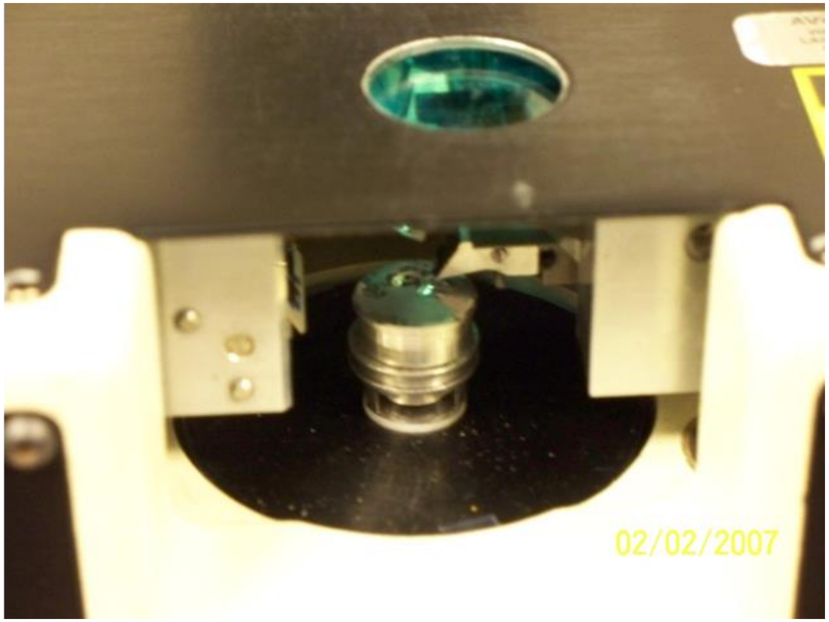
standa

Specifications	
XY travel range, µm	40 x 40
Z range, µm	5
Resonant frequency XY, kHz	5
Resonant frequency Z, kHz	50
Resolution (closed loop), nm	1
Resolution (open loop), nm	0.1

Ferroelectricity. Piezoelectricity. Transducers. Applications in P403 Lab.



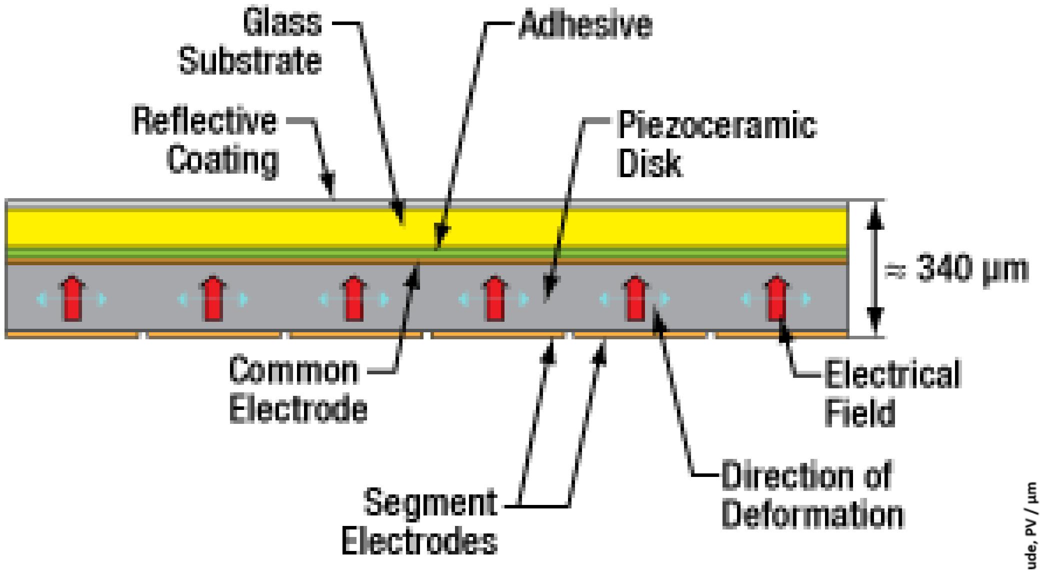
Quantum Optics

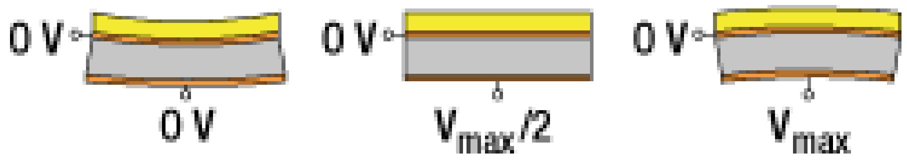


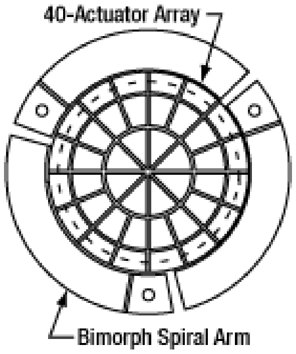
AFM experiment

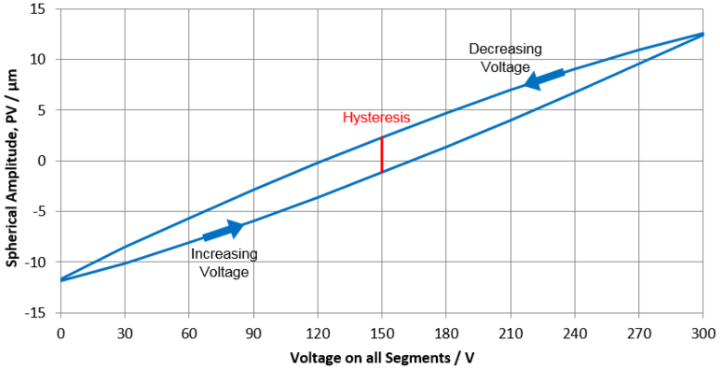
Ferroelectricity. Piezoelectricity. Transducers. Adaptive Optics.

THORLABS





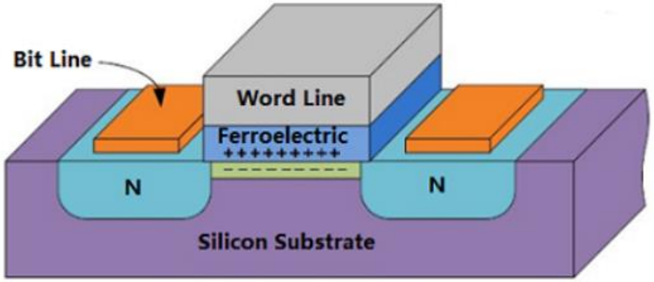




DMH40 Hysteresis Curve

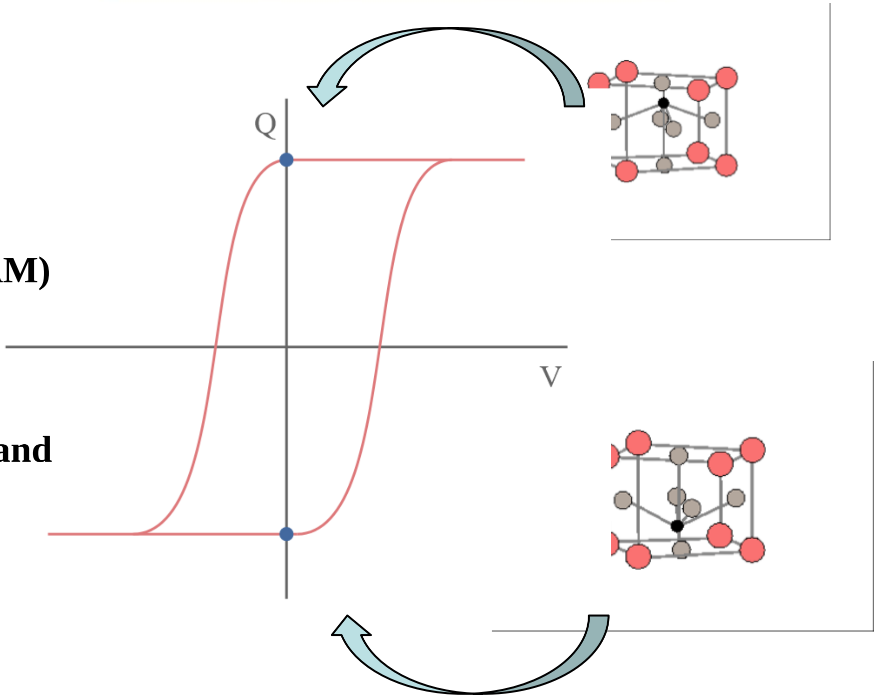
Active elements: PZT (lead zirconate titanate)

Ferroelectricity. Non-volatile Memory.

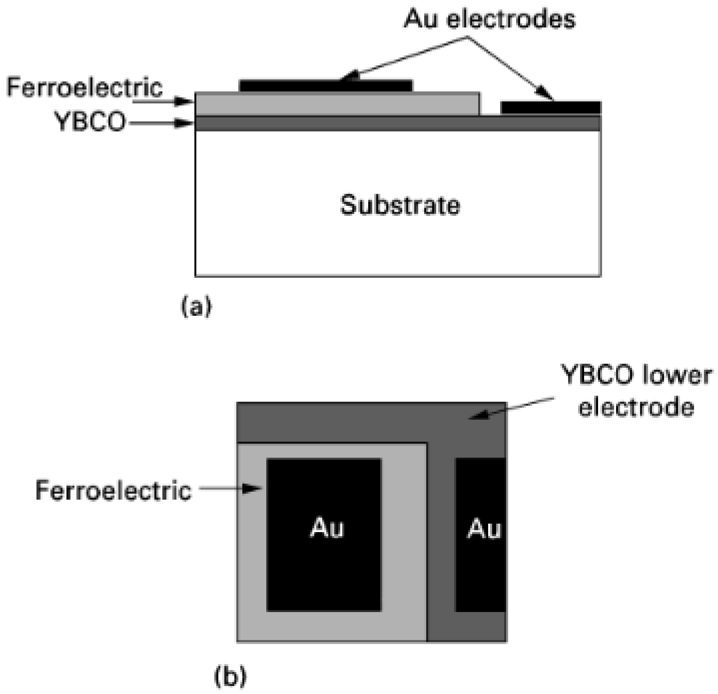


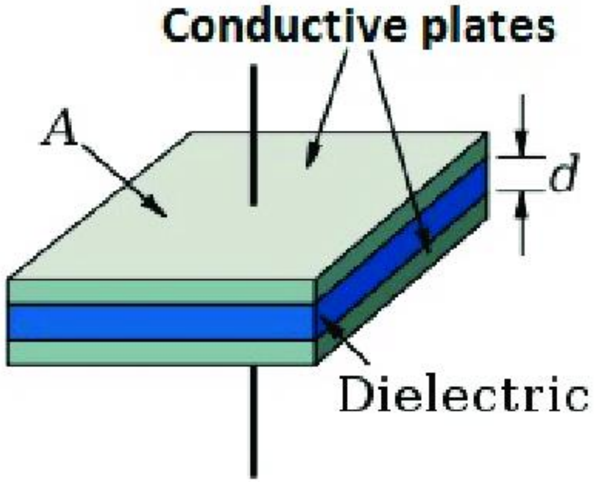
4-Kbit ferroelectric random access memory (F-RAM) logically organized as 8 K × 8

- ❒ **High-endurance** **100 trillion (10^{14})** **read/writes**
- ❒ ***151-year data retention*** **(see the Data Retention and Endurance table)**
- ❒ **NoDelay™ writes**
- ❒ **Advanced high-reliability ferroelectric process**
- ❒ **70-ns access time, 130-ns cycle time**



Ferroelectricity. Capacitors.





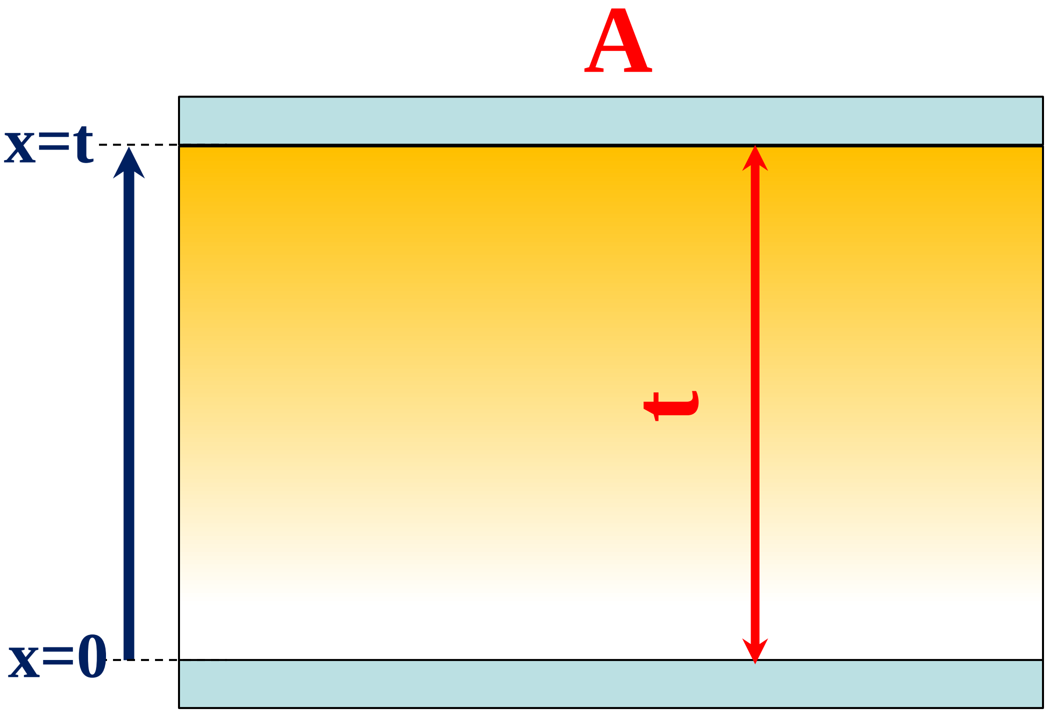
Advantages and disadvantages of the capacitors with ferroelectrics:

1. **Huge dielectric constant (e>10,000)**
2. **Temperature dependence of e**
3. **Nonlinearity C(V) – can be used for tuning the capacitor**

D O'Neill at all;J. Of Materials. Science: Materials in Electronics v9 199 (1998); "Thin film ferroelectrics for capacitor applications"

Homework

The flat capacitor is filled by dielectric with dielectric permittivity is distributed along the x axis as $\varepsilon = \varepsilon_1 + \varepsilon_2 * x$
Thickness of the dielectric is t and electrodes area A.
Derive the equation of this capacitance of this capacitor



Reference materials:

Equation for flat capacitor:

$$C = \frac{\varepsilon_0 \varepsilon A}{t}$$

$$\int \frac{1}{ax+b}dx = \frac{1}{a}\ln(ax+b)$$

$$\ln x - \ln y = \ln\left(\frac{x}{y}\right)$$

$$\varepsilon_0 = 8.854 \times 10^{-12}\frac{F}{m}$$