2.76/2.760 Multiscale Systems Design & Manufacturing

Fall 2004

Piezoelectric Transducers

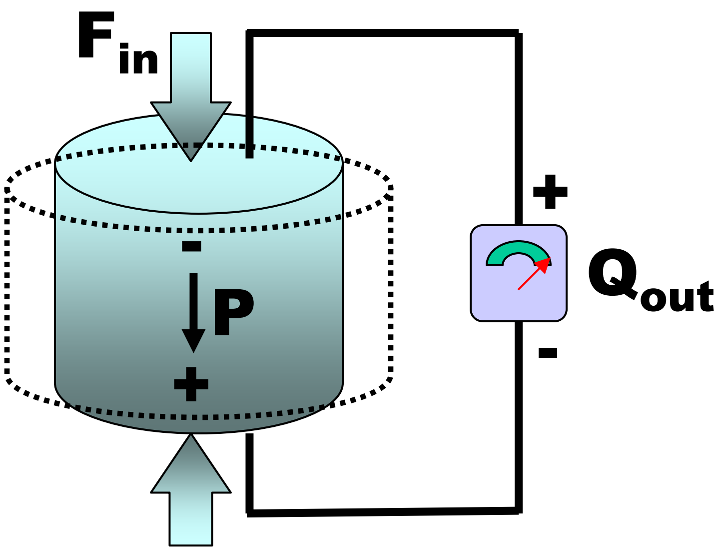
Sang-Gook Kim, MIT

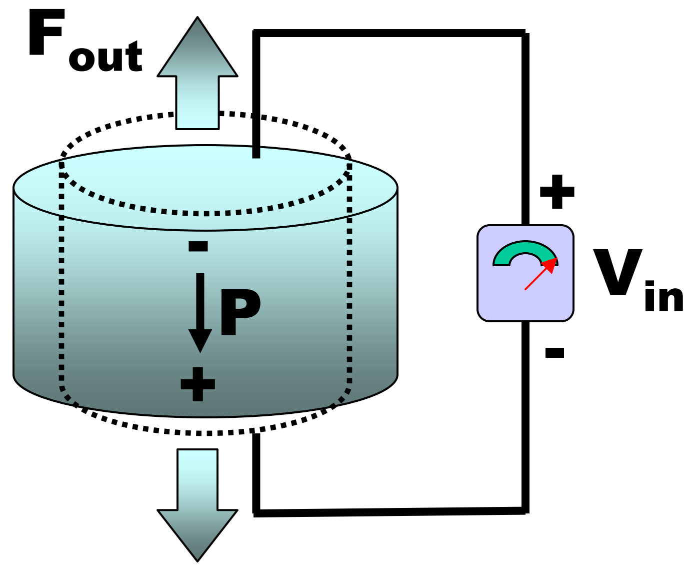
What is Piezoelectricity ?

Jacques & Pierre Curie (1880)

Lippmann (1881)

Electrical Energy ⟷ **Mechanical Energy**

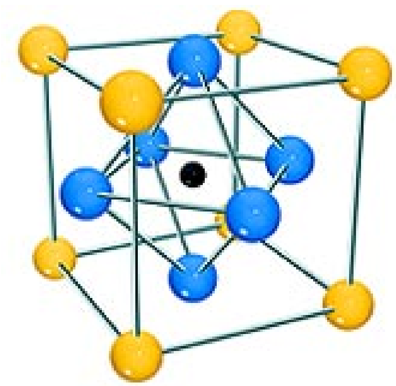




Piezoelectricity

- **Piezoelectric Ceramics**
- **Thin film fabrication**

- **Piezoelectric Transducers**

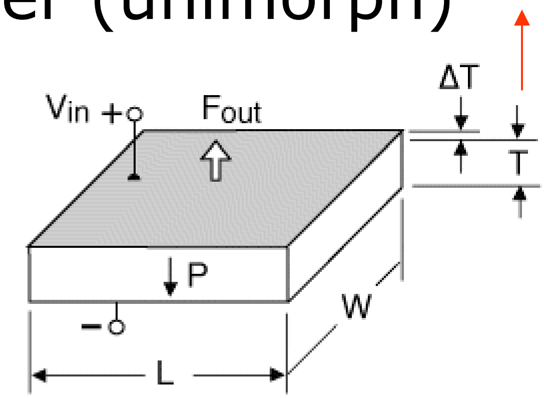


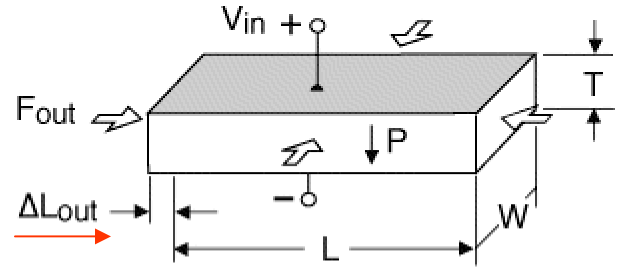
G. Binnig & H. Rohrer, Nobel Prize, 1986

Photos removed for copyright reasons.
Medical ultrasound, disk drive heads, naval submarine.

Piezoelectric Transducers

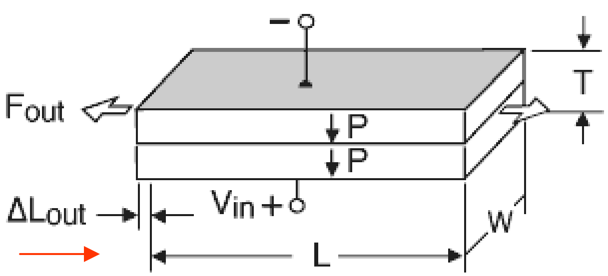
1-layer (unimorph)





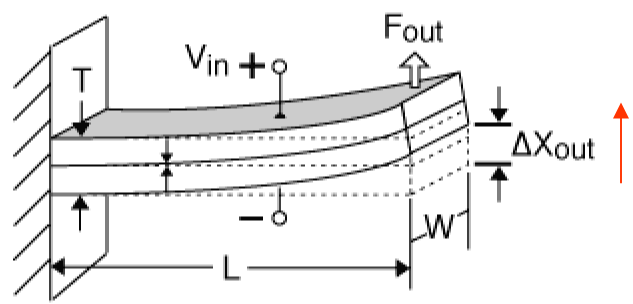
2-layer

extender



Y-poled

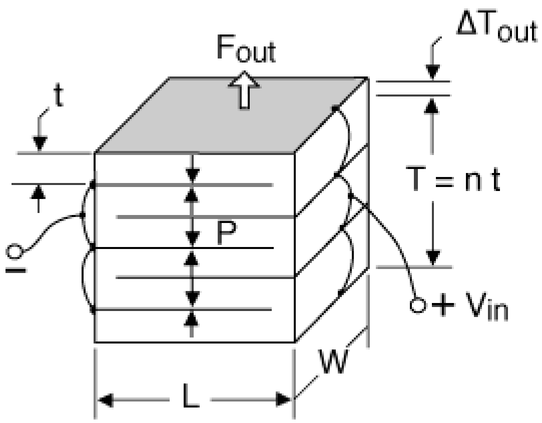
bender (bimorph)

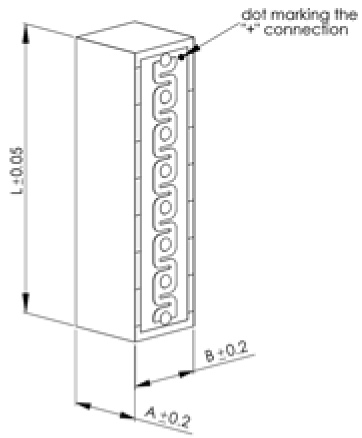


x-poled

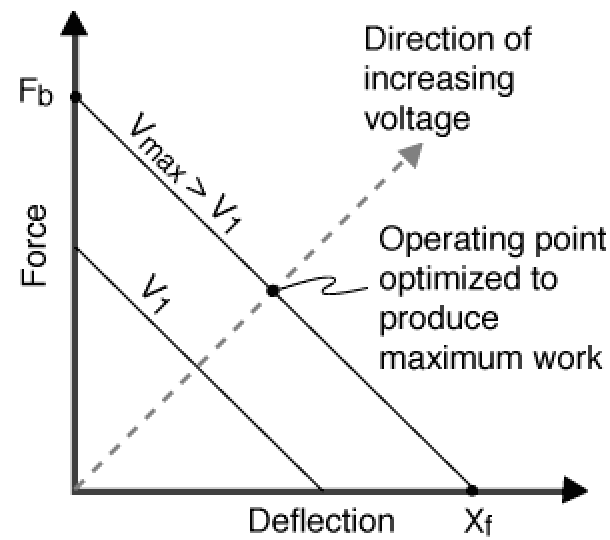
Transducers

multi-layer (multimorph)





blocked force



free deflection

Dielectric Constant

- Dielectric materials, atoms are ionized, + and – charged, causing electric dipoles. – electric polarization

- Polarization, quantitatively,

  electric dipoles/unit volume, C/m^2

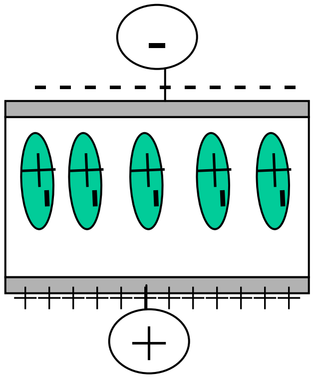
- Dielectric Displacement, D,

  stored electric charge/unit area

$$D = \varepsilon_o + P = \varepsilon E = K\varepsilon_o E$$

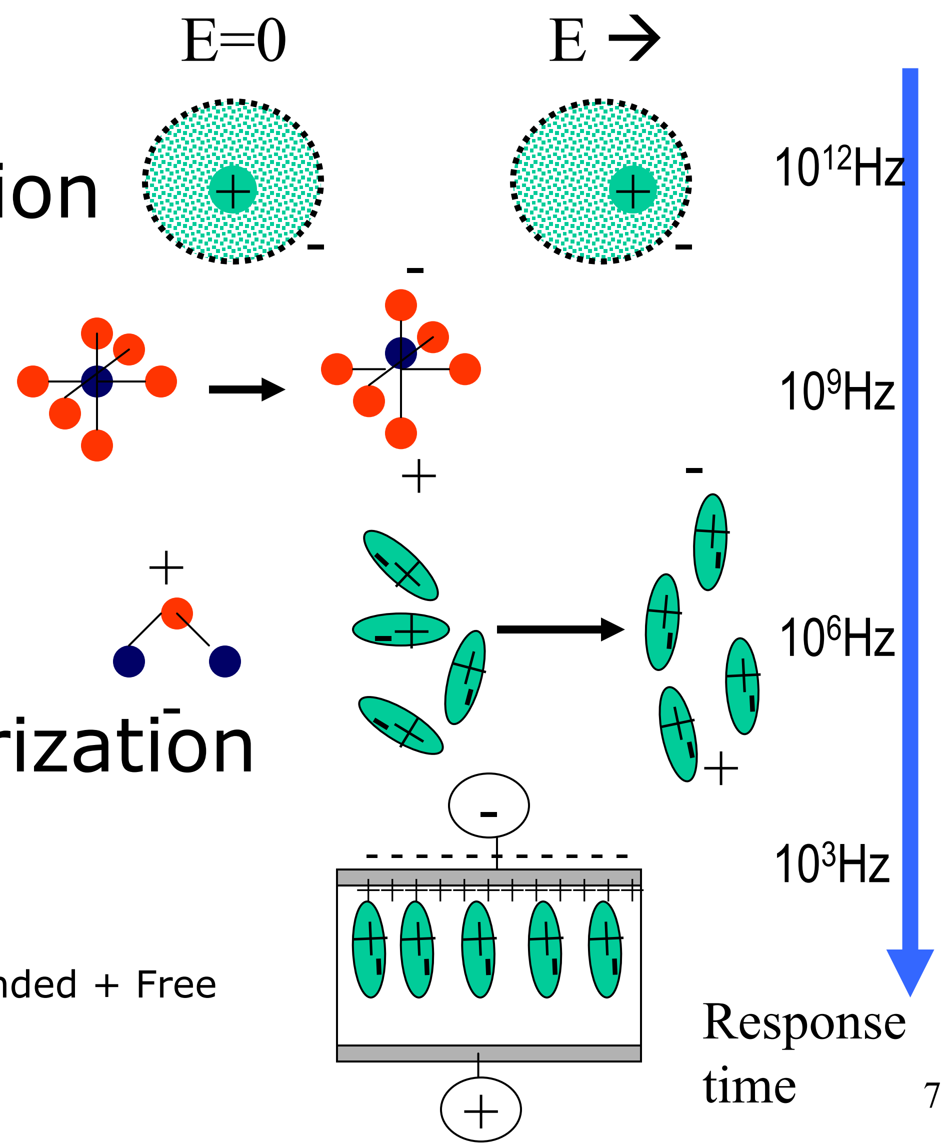
ε_o :Vacuum permittivity (8.854×10^{-12} F/m)

K :Relative Permittivity or dielectric constant



Origins of Polarization

- Electronic Polarization
- Ionic Polarization
  - Ionic crystals, NaCl..
- Dipolar Polarization
  - HCl
- Space Charge Polarization



Total Charge= bounded + Free

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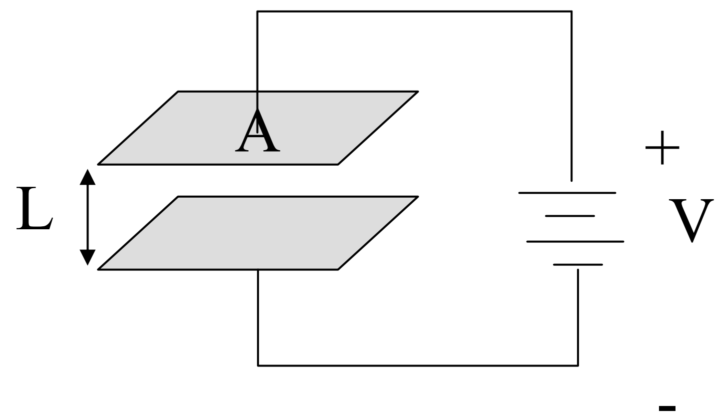
Capacitance

$$C = \frac{q}{V}$$

Capacitance of a parallel plate capacitor

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



Relative Dielectric Constant (K), or permittivity

$$\varepsilon = \frac{C}{C_{Vac}}$$

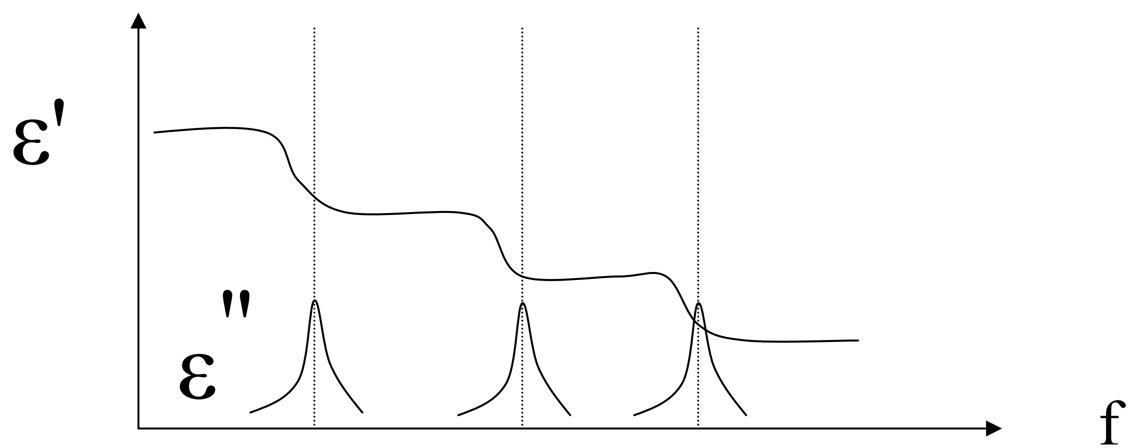
Dielectric Constants

- Water 81.1
- Silicon 11.8
- Glass 6.9
- Epoxy 4.0
- Ice 3.0
- Polyethylene 2.3
- Air 1.000576

- $BaTiO_3$ 6000
- $KNbO_3$ 700
- Rochelle salt 170
- PZT 1200

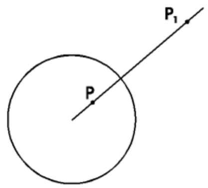
Dielectric Loss

- Frequency dependency of polarization
- When τ and f are in the same order, energy absorbed and phase lag occurs.
- Dielectric Loss, $\tan\delta = \varepsilon'' / \varepsilon'$
- Dielectric breakdown: 60kV/cm for PZT



Ferroelectricity

- Ionic and electronic polarization
- S^2P or d^0 cations
- Crystal structure with no inversion center



- Ferroelectricity;
  - Spontaneous polarization wrt external electric field
  - Reversible, Remanent polarization, hysterisis
- Pyroelectricity; strong variation in polarization with temperature
- Piezoelectricity; large mechanical strain response to applied electrical field

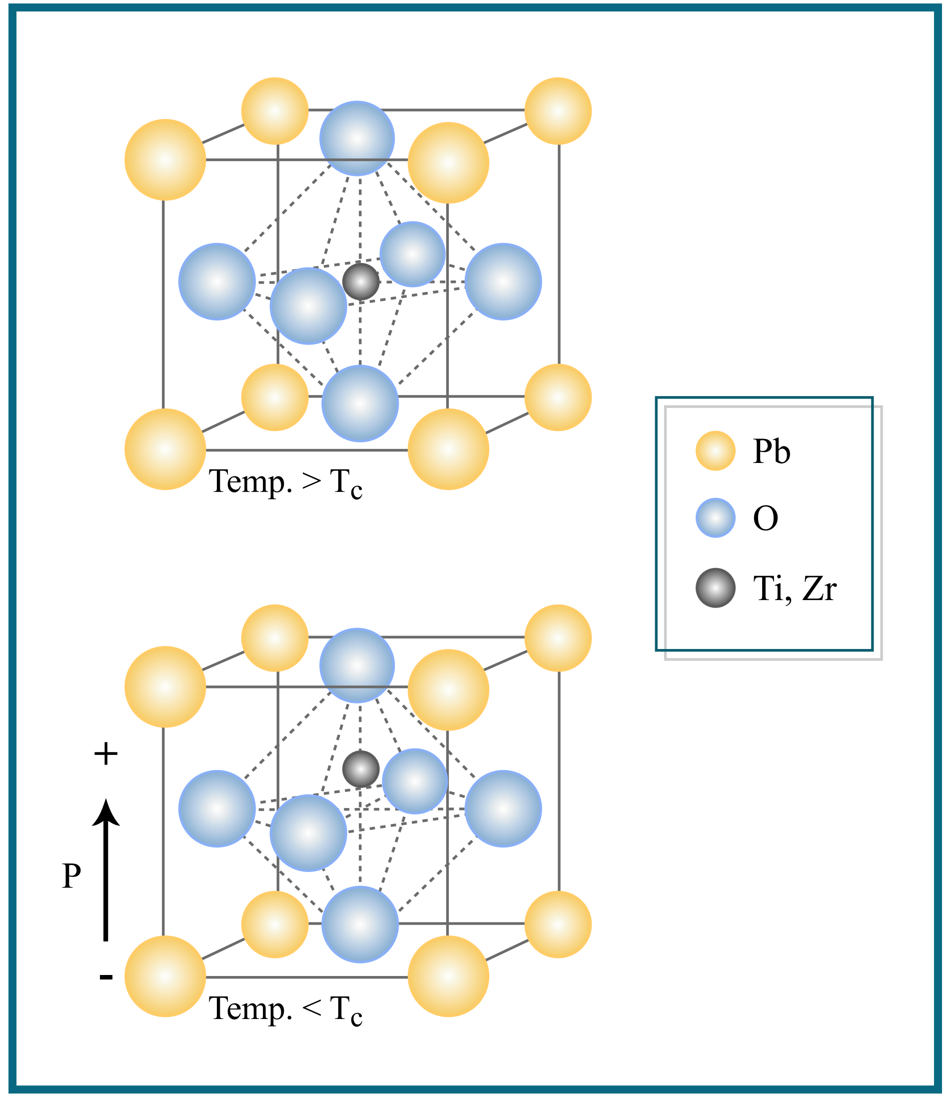
Perovskite Phase

- PZT, (Pb(Zr_{1-x} Ti_x)O3, the most important piezoelecric material.

  PbZrO3:PbTiO3 → 52:48

  rhombohedral →cubic→tetrahedral

- Curie Temperature
- Pyrochlore phase

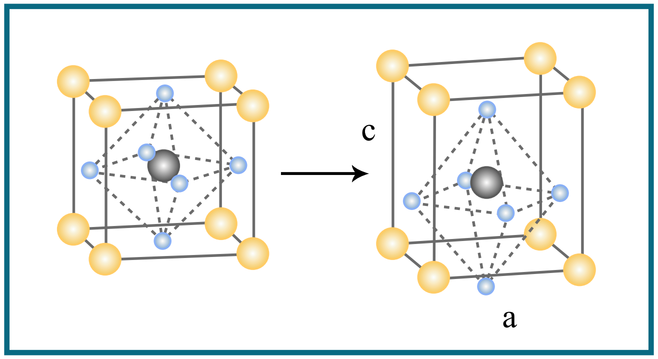


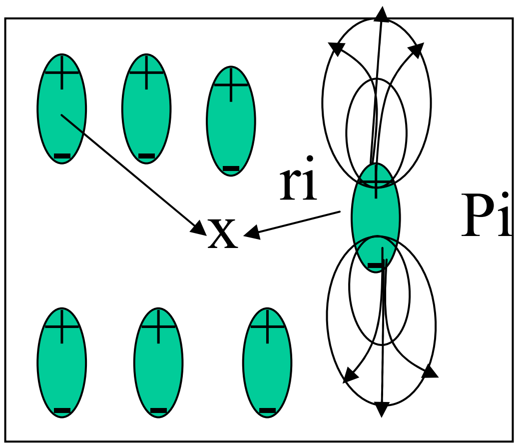
ex) Pb(TixZr1-x)O3(PZT)

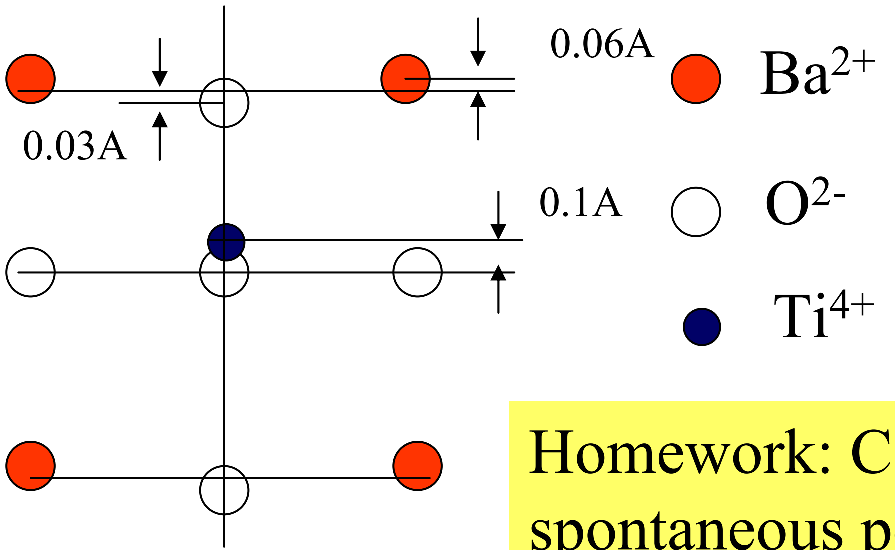
Spontaneous polarization

$$\Delta\vec{P} = \vec{P}(\text{polar}) - \vec{P}(\text{nonpolar}) \,/\, a^2c$$

: Polarization per unit cell volume







Homework: Calculate the magnitude of spontaneous polarization. a=3.992 A, c=4.036a
$1e=1.602\times10^{-19}$ C

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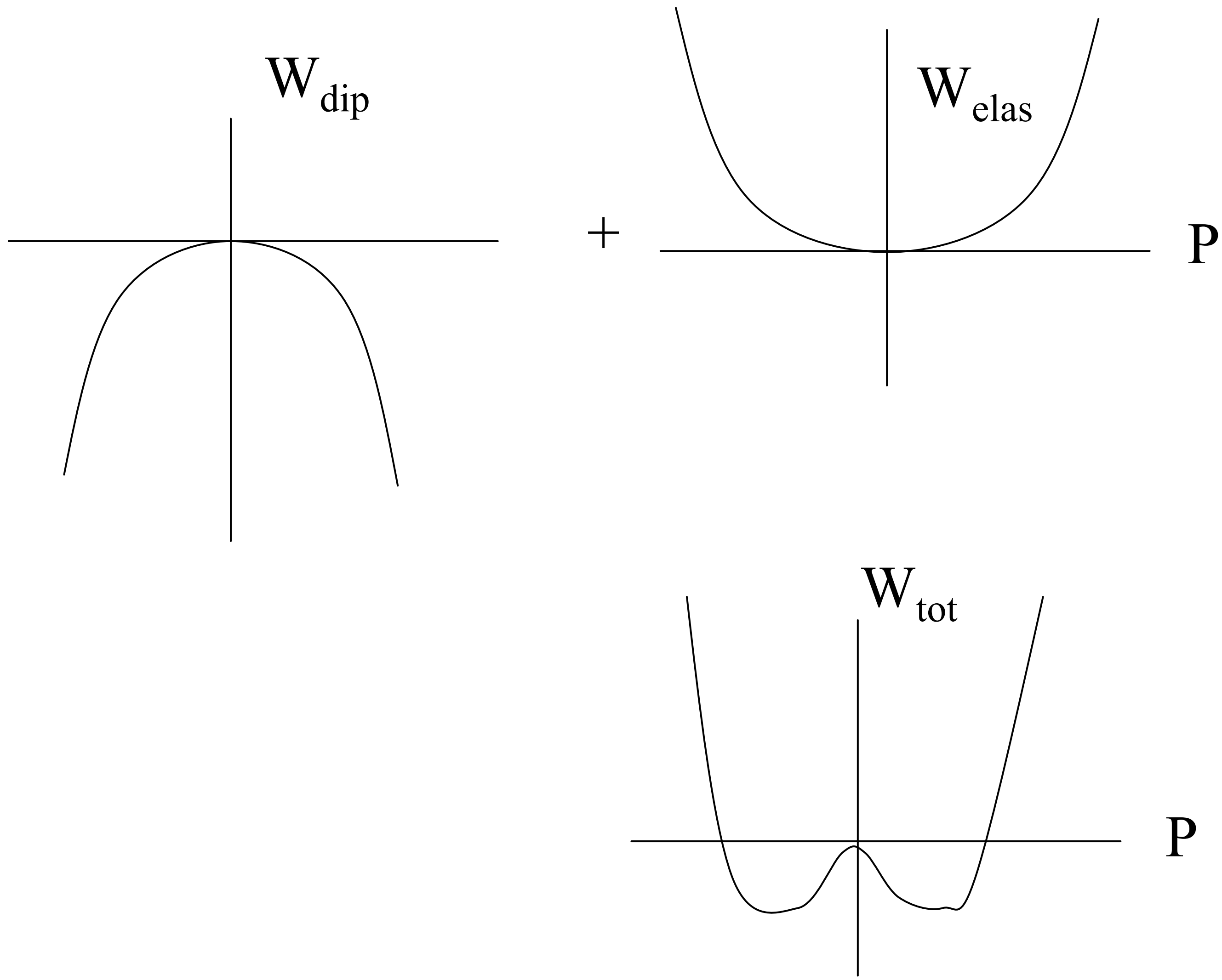
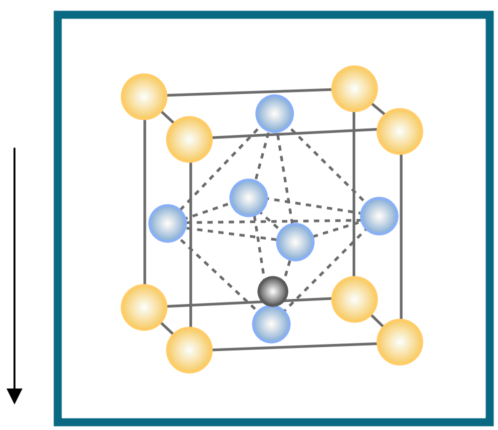
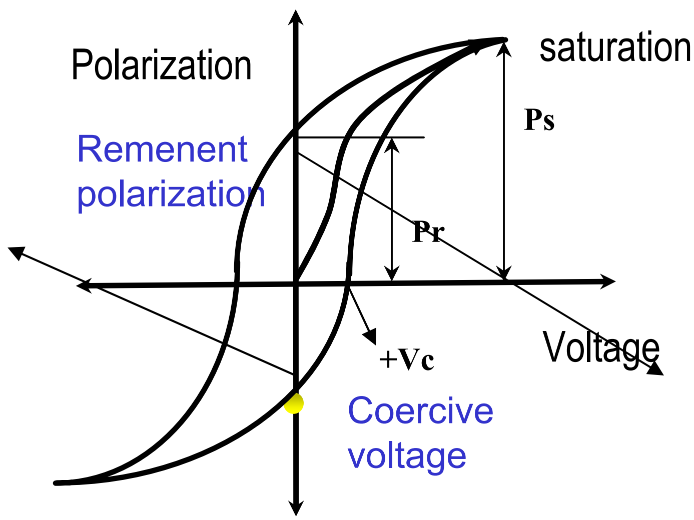
Energy of polarization

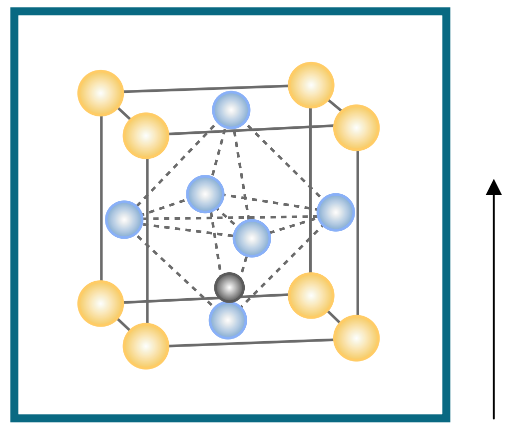


Piezoelectricity

- Polarization does not disappear when the electric field removed.
- The direction of polarization is reversible.

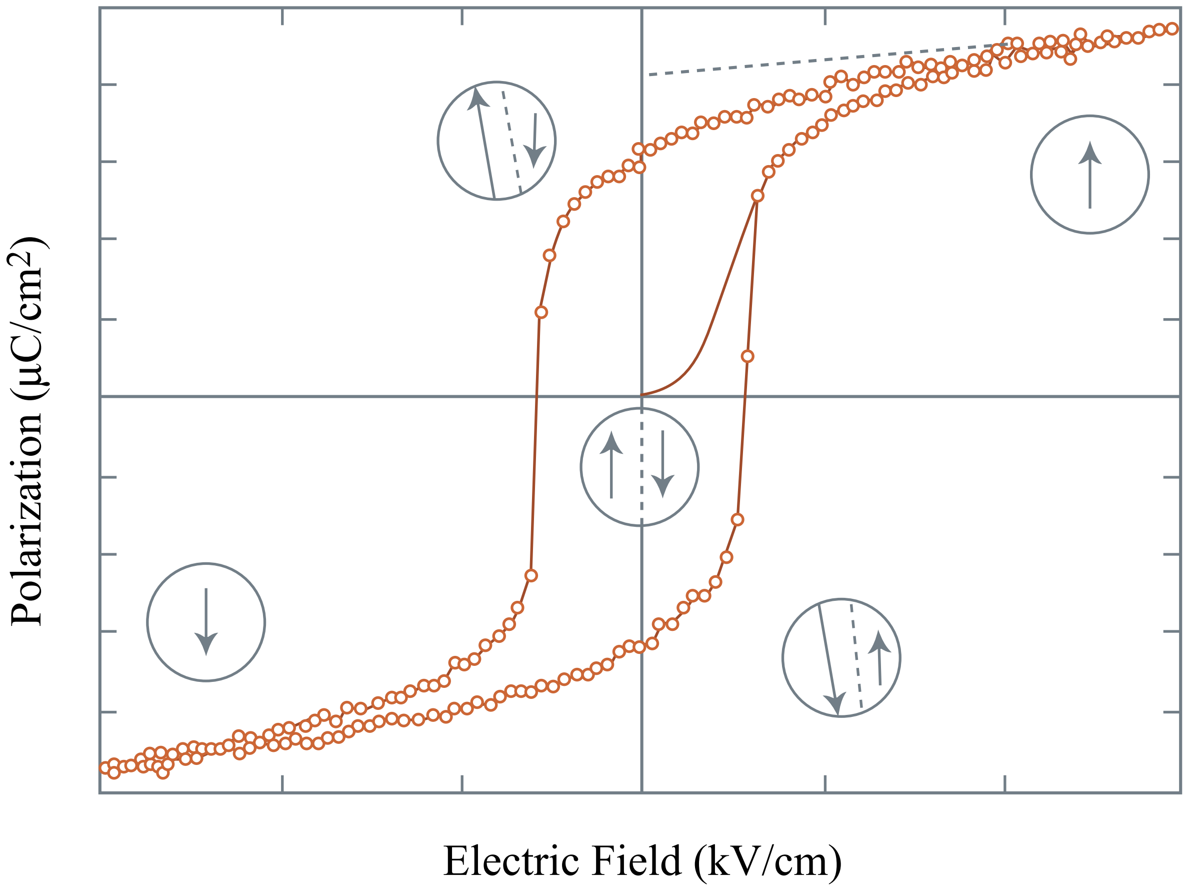






FRAM utilize two stable positions.

Hysterisis



Ferroelectric (P-E) hysteresis loop. The circles with arrows indicate the polarization state of the material for different fields.

Domain Polarization

- Poling: 100 C, 60kV/cm, PZT
- Breakdown: 600kV/cm, PZT
- Unimorph cantilever

Piezoelectricity

Direct effect

$$D = Q/A = dT$$

Converse effect

$$S = dE$$

$$E = -gT \qquad T = -eE$$

$$g = d/\varepsilon = d/K\varepsilon_o \qquad E = -hS$$

- D: dielectric displacement, electric flux density/unit area
- T: stress, S: strain, E: electric field
- d: Piezoelectric constant, [Coulomb/Newton]

Boundary Conditions

- Free → T
- Short circuit → E
- Open circuit → D
- Clamped → S

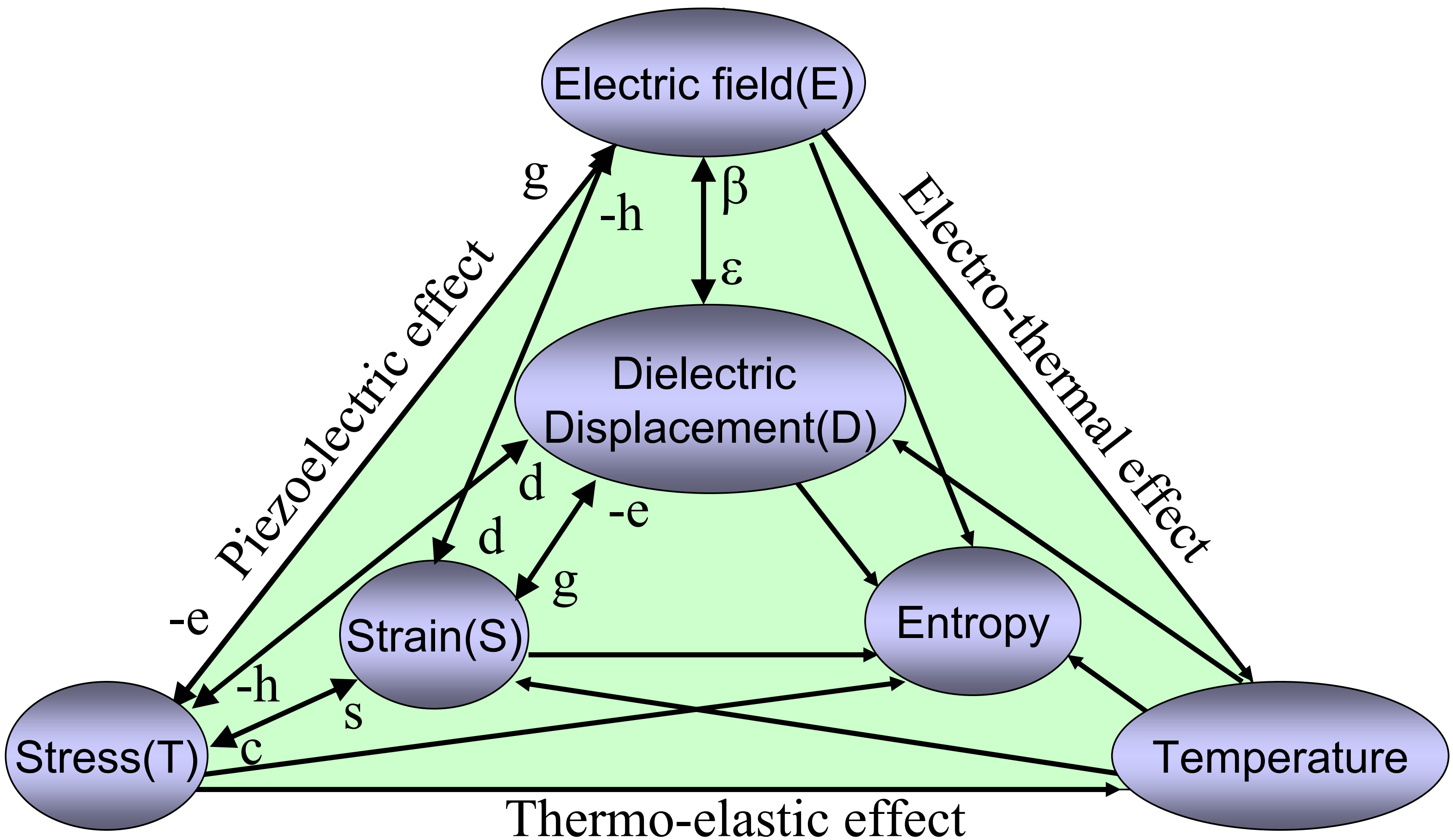
$$d = (\partial S/\partial E)_T = (\partial D/\partial T)_E$$

$$g = (-\partial E/\partial T)_D = (\partial S/\partial D)_T$$

$$e = (-\partial T/\partial E)_S = (\partial D/\partial S)_E$$

$$h = (-\partial T/\partial D)_S = (-\partial E/\partial S)_D$$

Principles of piezoelectric



Equation of State

Basic equation

d-form $S_{ij} = s_{ijkl}{}^{E}T_{kl}+d_{kij}E_k$

$D_i = d_{ikl}T_{kl}+ \varepsilon_{ik}{}^{T}E_k$

g-form $S = s^{D}T+gD$

$E = -gT+ \beta^{T}D$

e-form $T_{ij} = c_{ijkl}{}^{E}S_{kl}-e_{kij}E_k$

$D_i = e_{kij}S_{kl}+ \varepsilon_{ik}{}^{S}E_k$

h-form $T = c^{D}S-hD$

$E = -hS+\beta^{S}D$

$c^E = 1/s^E$

$e = dc^E$

$\varepsilon^E = \varepsilon^T-dc^Ed_t$

$\beta^T = 1/\varepsilon^T$

$g = d/\varepsilon^T$

$s^D = s^E-d_t(\varepsilon^T)^{-1}d$

$D = Q/A$

$S = F/A$

Equation of states

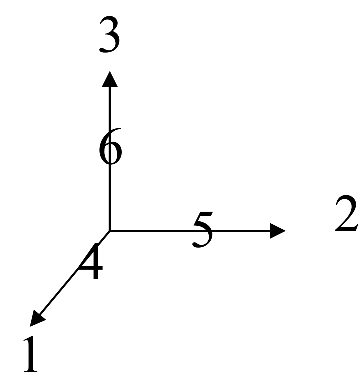
$$D = dT + \varepsilon^{T} E$$
direct

$$S = s^{E} T + dE$$
converse

Tensor to Matrix notation

For cylindrical symmetry, and poling in axis 3,

$$D_1 = \varepsilon_1 E_1 + d_{15} T_5$$
$$D_2 = \varepsilon_1 E_2 + d_{15} T_4$$
$$D_3 = \varepsilon_3 E_3 + d_{31}(T_1 + T_2) + d_{33} T_3$$
$$S_1 = s_{11} T_1 + s_{12} T_2 + s_{13} T_3 + d_{31} E_3$$
$$S_2 = s_{11} T_2 + s_{12} T_1 + s_{13} T_3 + d_{31} E_3$$
$$S_3 = s_{13}(T_1 + T_2) + s_{33} T_3 + d_{33} E_3$$
$$S_4 = s_{44} T_4 + d_{15} E_2$$
$$S_5 = s_{44} T_5 + d_{15} E_1$$
$$S_6 = s_{66} T_6$$



Applications of piezoelectric

Sensors

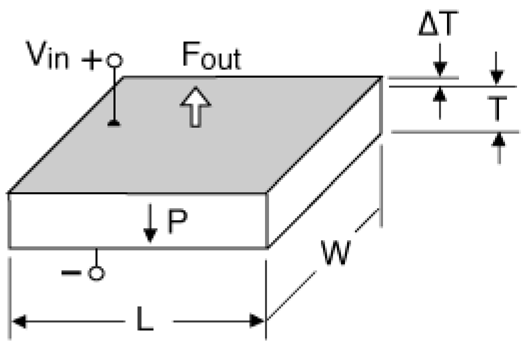
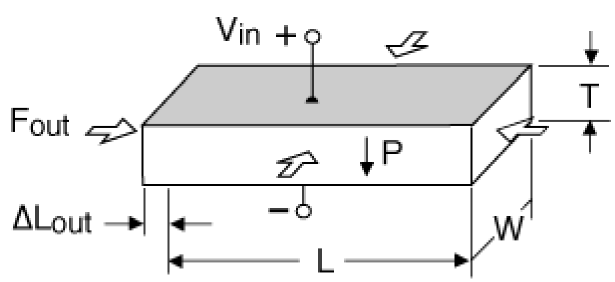
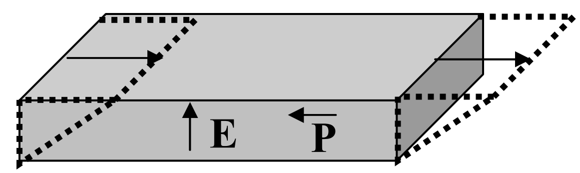
Pressure sensors
Accelerometers
Gyroscopes
Power generators

Actuators

Vibrators
Ultrasonic transducers
Resonators / Filters / Switches
Surface Acoustic wave(SAW) devices
Transformers
Actuators
Ultrasonic motors

Piezoelectric Charge Constants

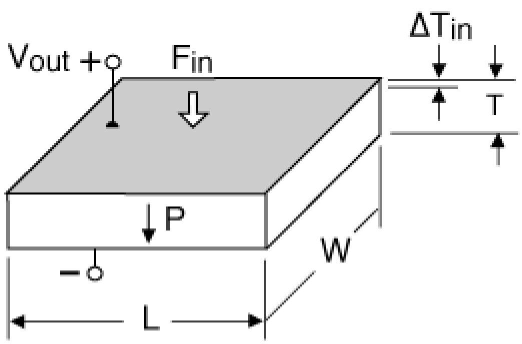
Electrical energy → **Actuator** → **Mechanical energy**

Longitudinal (d_{33})	**Transverse (d_{31})**	**Shear (d_{15})**
		
$\Delta T/T = d_{33} \cdot E$	$\Delta L/L = d_{31} \cdot E$	Shear strain $= d_{15}$ E

Piezoelectric Charge Constants

Mechanical energy **Sensor** → **Electrical energy**

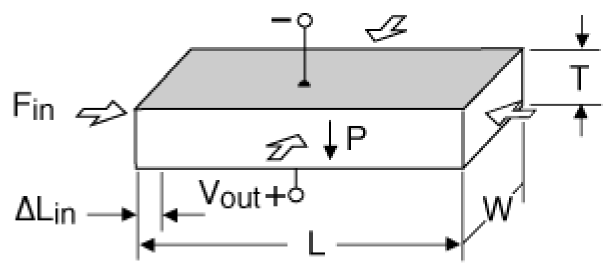
Longitudinal (d_{33})



$Q = d_{33} \cdot F_{in}$

$V_{out}/T = g_{33} \cdot F_{in} /(L \cdot W)$

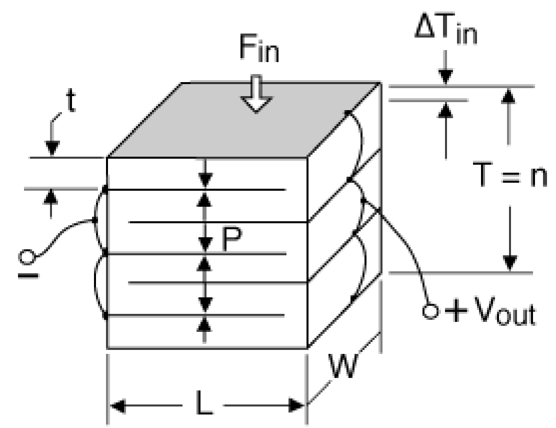
Transverse (d_{31})



$Q = d_{31} \cdot F_{in}$

$V_{out} /T= g_{31} \cdot F_{in}/(T \cdot W)$

Multi-layer (d_{33})



$Q = n \cdot d_{33} \cdot F_{in}$

$V_{out} /T= t/n \cdot g_{33} \cdot F_{in} /(LW)$

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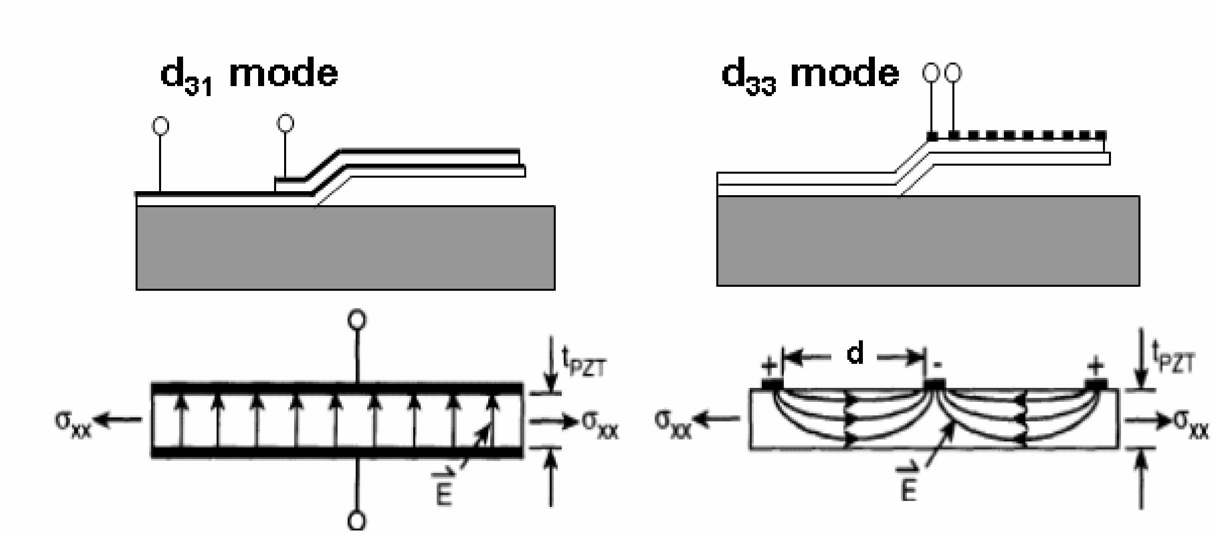
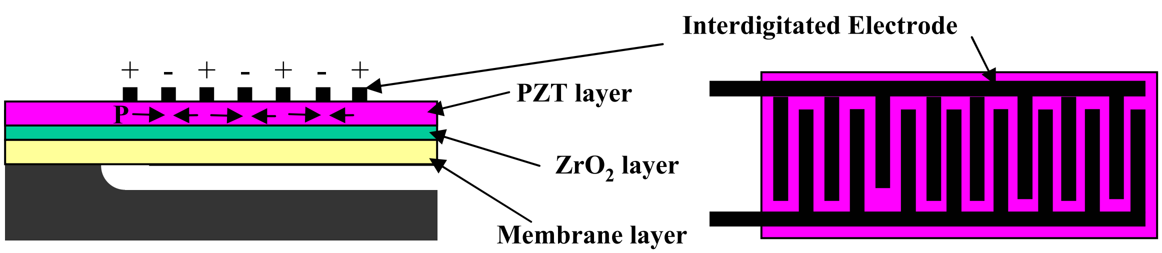
d_{31} vs d_{33}

Homework 2:
Compare generated voltages V31 (from d31mode), V33 (d33mode). Both have same cantilever dimension, but different electrodes.

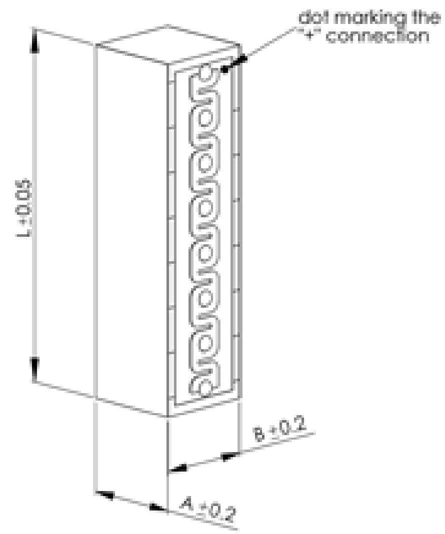


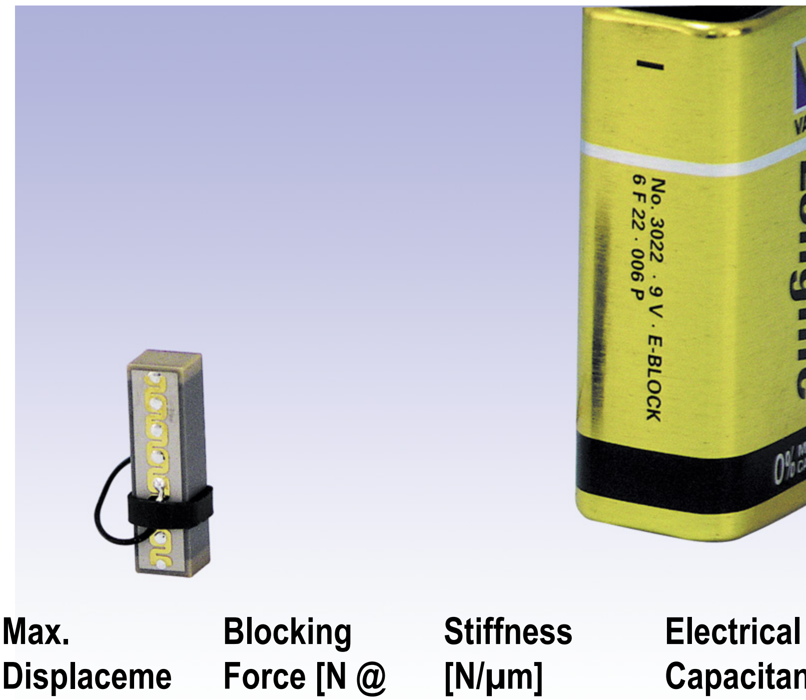
Assume, g33=2g31
tpzt=o.5 μ
d=5 μ
length=100 μ, width=50 μ
Young's modulus of the beam= 65 Gpa, max. strain = 0.1%

d33=200 pC/n
K=1000



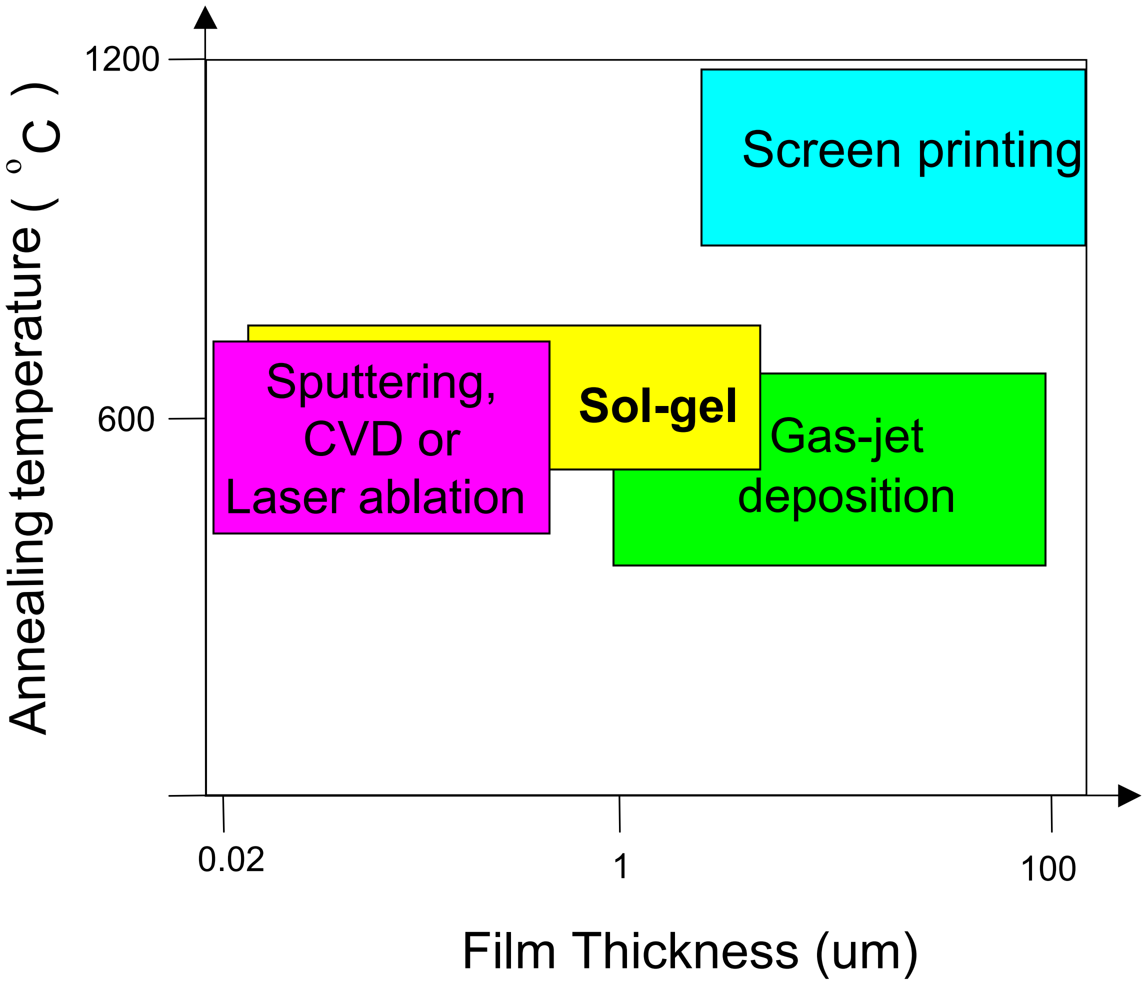
Design of a Z-positioner





Ordering Number*	Dimensions A x B x L [mm]	Nominal Displacement [µm @ 100 V] (±10%)	Max. Displacement [µm @ 120 V] (±10%)	Blocking Force [N @ 120 V]	Stiffness [N/µm]	Electrical Capacitance [µF] (±20%)	Resonant Frequency [kHz]
P-882.10	2 x 3 x 9	7	9	215	26	0.13	135

Fabrication Methods for PZT thin Films



Sol-Gel spin coating

Advantages

- Vacuum chamber not necessary (simple)
- Easy composition control
- Deposition on large flat substrate

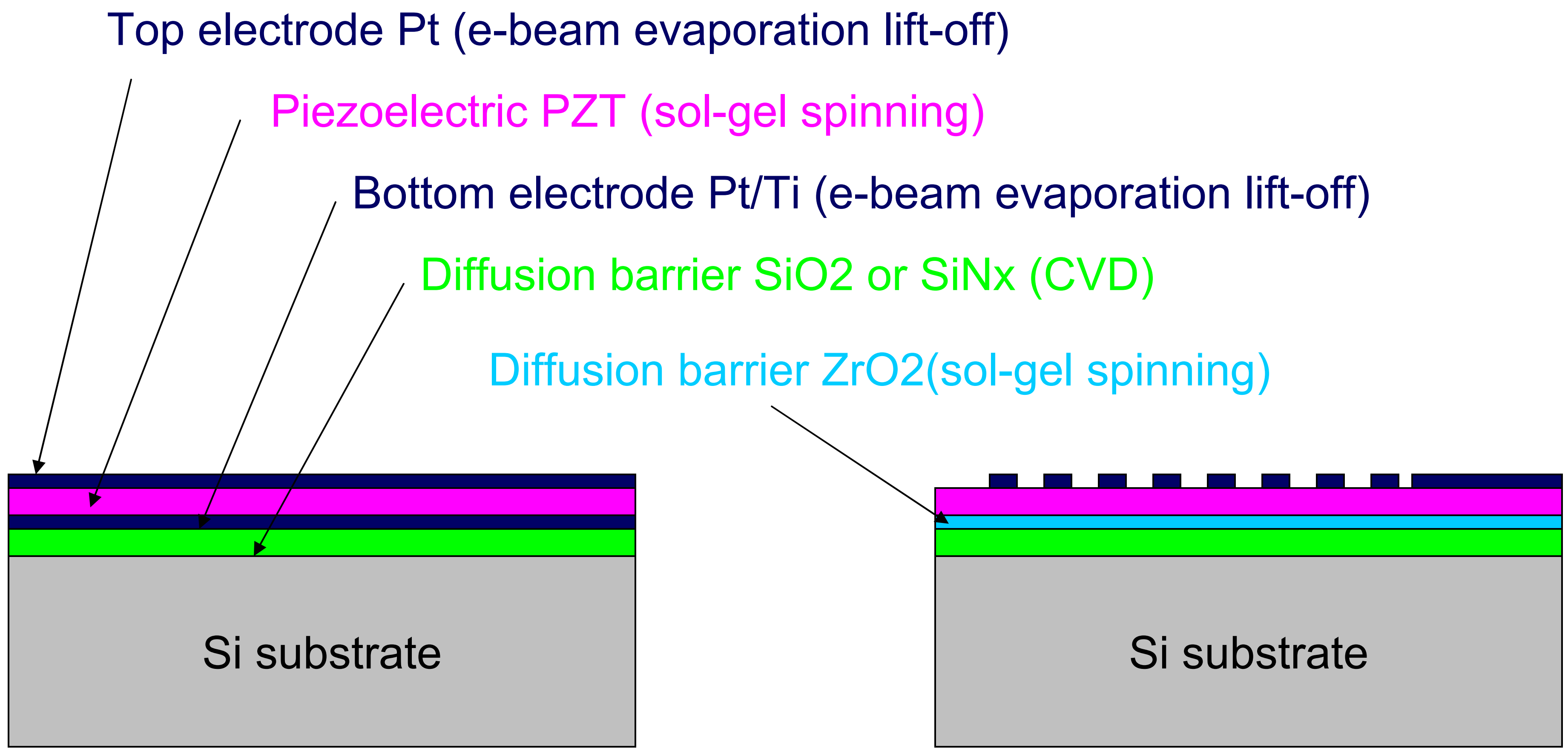
Disadvantages

- Difficult to deposit on deep trenched surface
- Higher raw material consumption

Advantage and disadvantage of PZT film

Advantage	Disadvantage
Unlimited resolution Large force generation Fast expansion No magnetic fields (low cross talk) Low power consumption No wear and tear for actuation Vacuum and clean room compatible Operation at cryogenic temperature	Complex fabrication Hysteresis Life cycle (10^{12} cycles) ; Fatigue, retention…

Typical Layer Structures for Sol-Gel PZT



d_{31} mode

d_{33} mode

Thermal Oxide Growth and Bottom Electrode Evaporation

Tubes for growing of
device diffusion barrier

Evaporation of
device electrodes

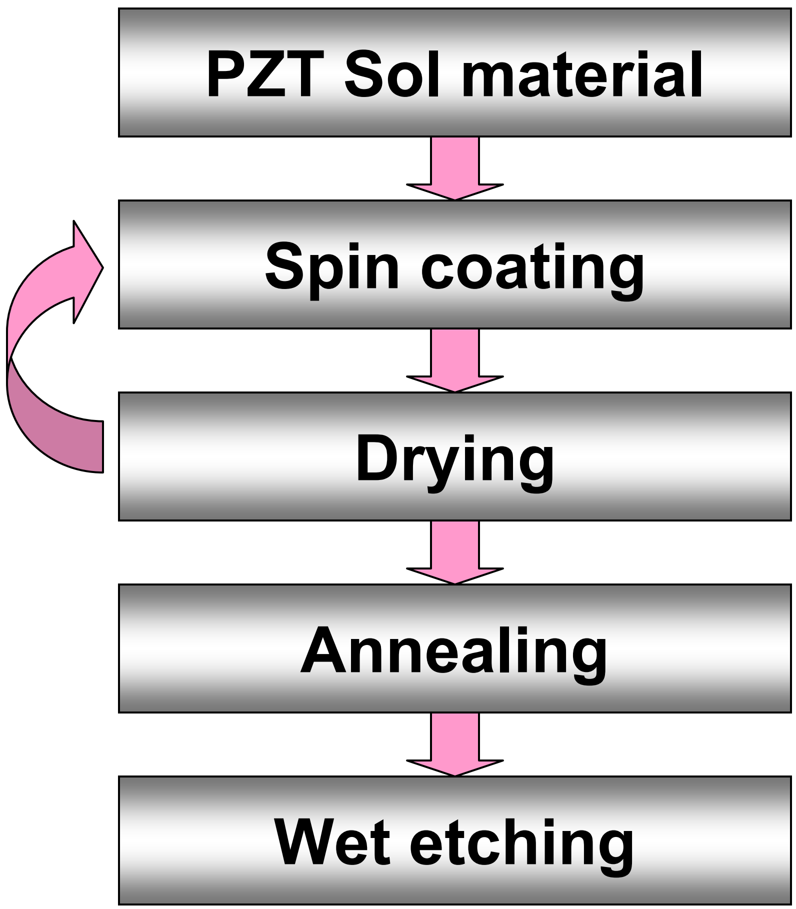
Photos: MIT Microsystems Technologies Laboratory

Fabrication of the PZT Film

PZT Sol material	18% PbO excess PZT (52/48)
Spin coating	At 500 rpm for 3sec and at 3000 rpm for 30sec
Drying	At 350°C for 5 min. (hot plate)
Annealing	At 650°C for 15 min. (box furnace)
Wet etching	HCl(64%)+BOE(31%)+DI (5%) (0.25 μm/min)

Spin-coat Mitsubishi PZT sol-gel: 15% PZT(118/52/48) A6 Type

Fabrication of the PZT Film



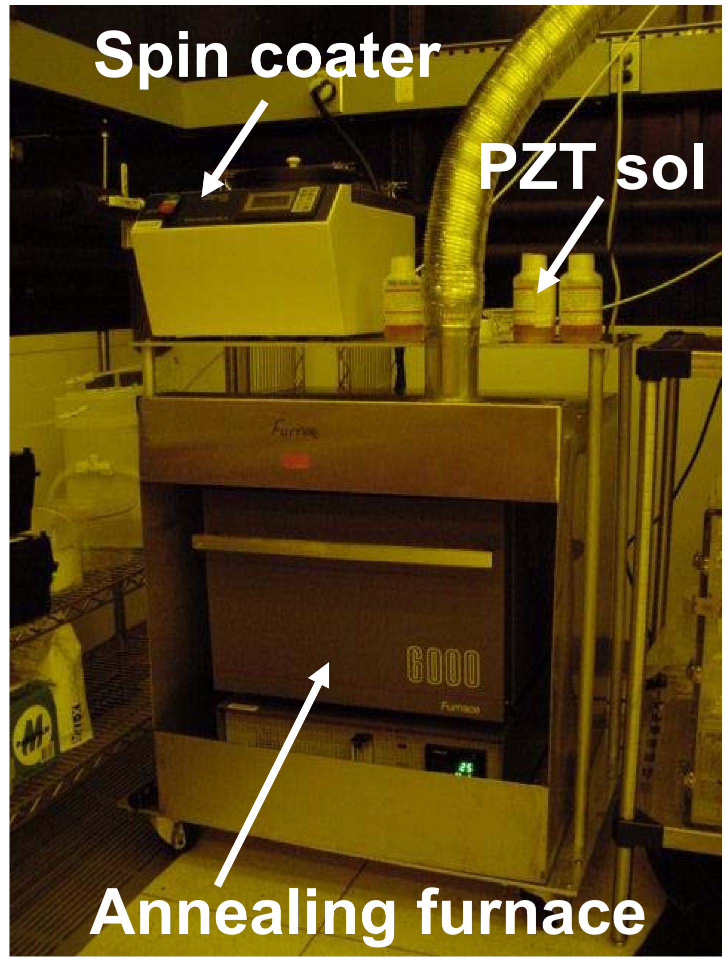
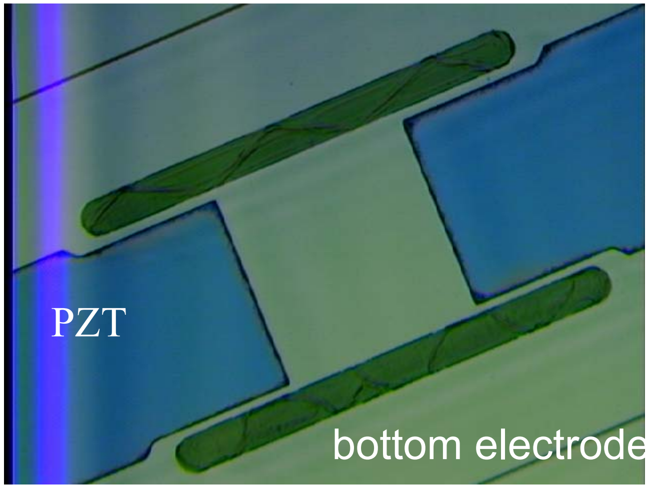
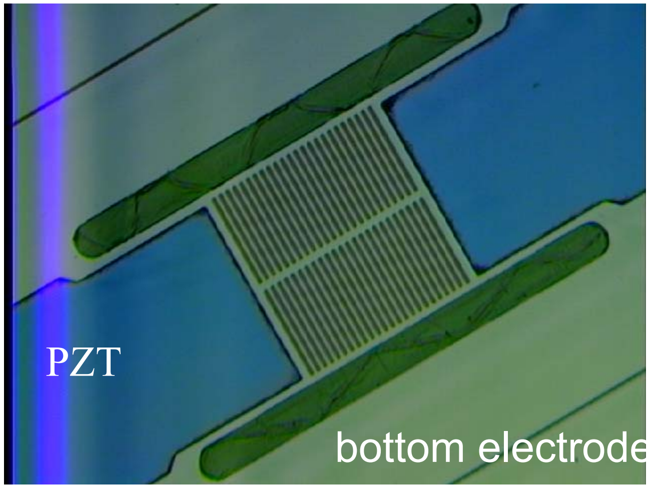


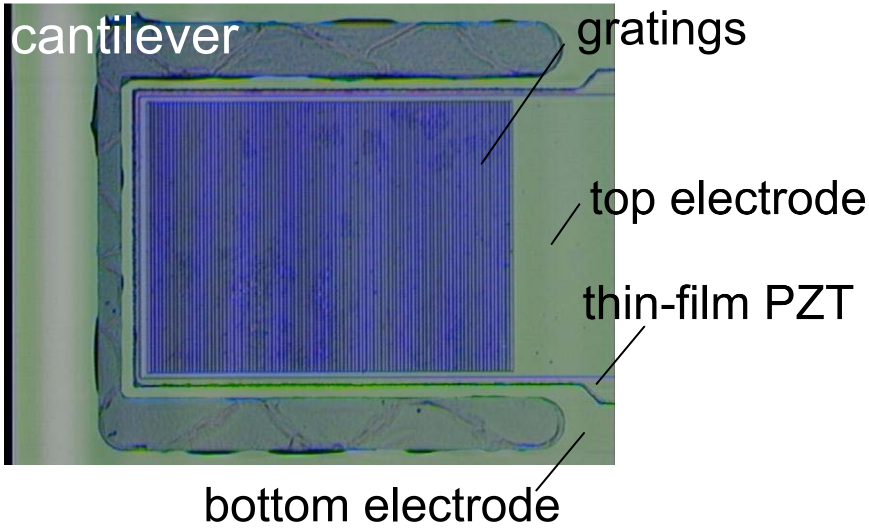
Photo: MIT Microsystems Technologies Laboratory

PZT Patterning

Patterned PZT on device

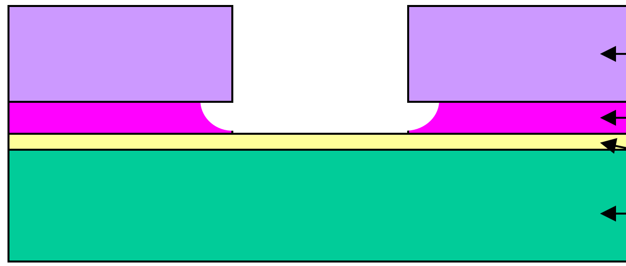


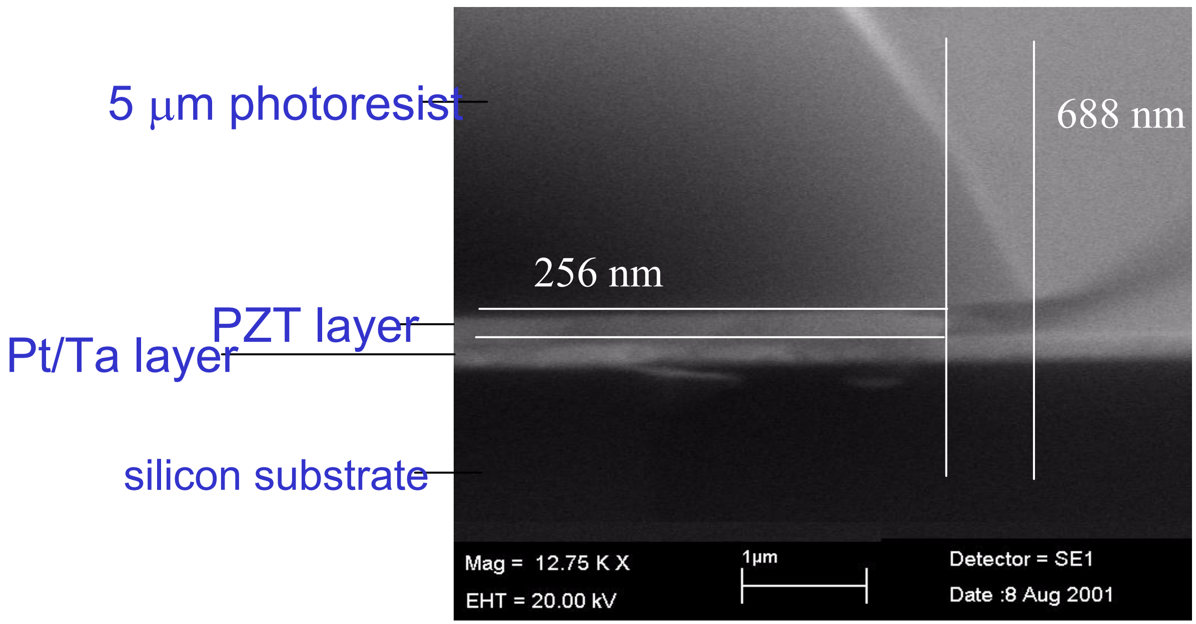




PZT Patterning (Wet ethcing)

PZT wet-etching with thick photoresist

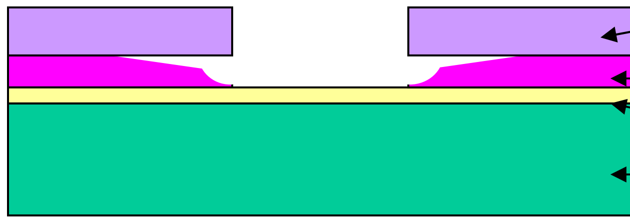


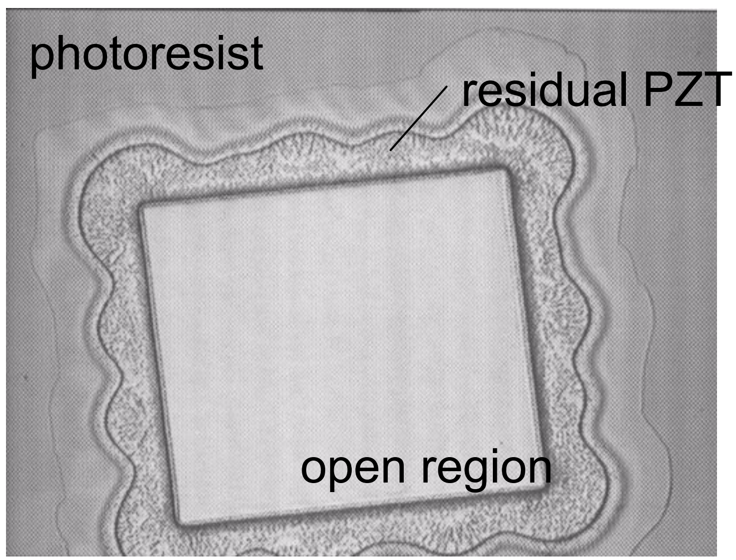


HCl(64%)+BOE(31%)+DI (5%)
(etch rate: 0.25 μm/min)

PZT Patterning (Wet ethcing)

PZT wet-etching with thin resist





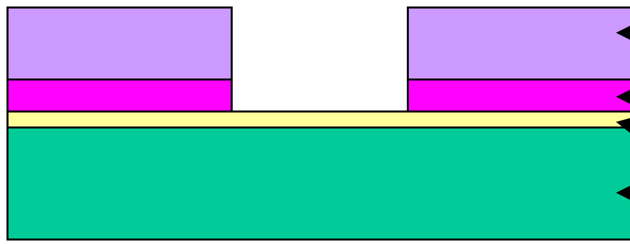
- large undercuts with thin (1 μm) photoresist material

[1] W. Liu *et al, Thin Solid Films*, 2000.

[2] K. Yamashita *et al,Transducers '01*, Munich.

PZT Patterning (Dry etching)

PZT dry-etching with thick resist

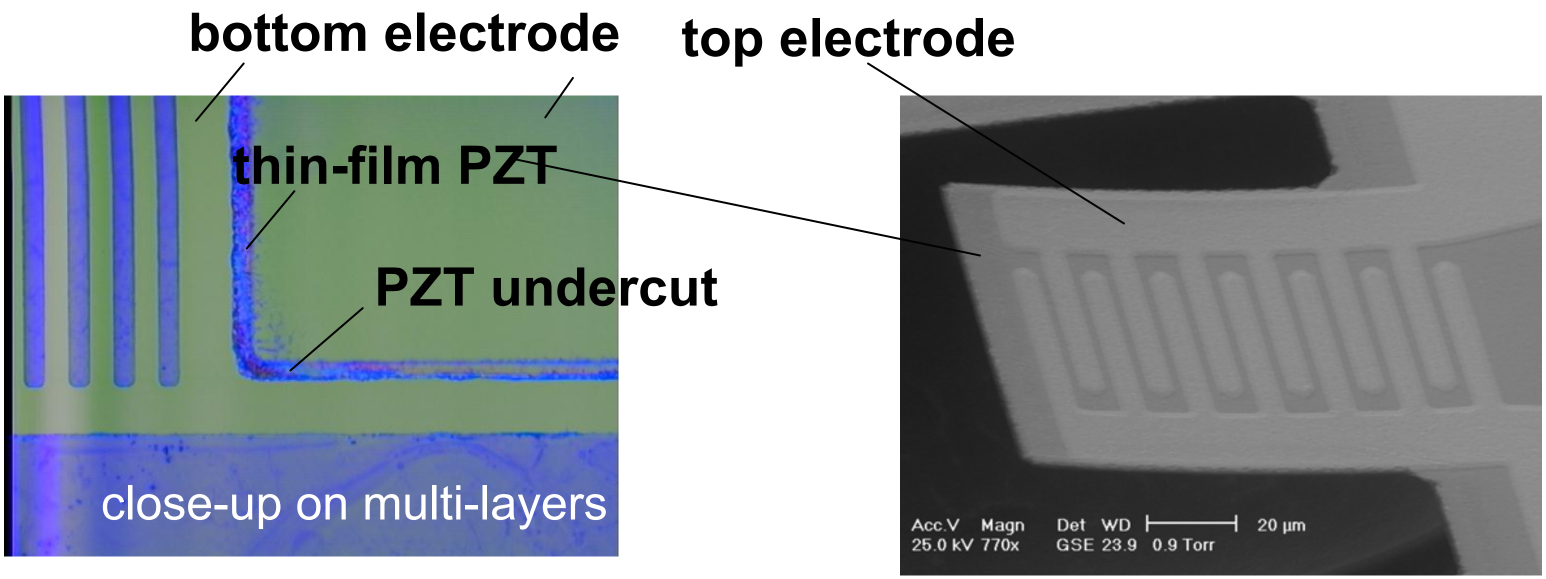


using RIE, Plamaquest (in TRL) or Plasmatherm (in EML) with BCl_3:Cl_2 (30:10)

- stiff sidewall with thick (10 μm) photoresist material

Top Electrode Lift-Off

d33 mode interdigitated structure

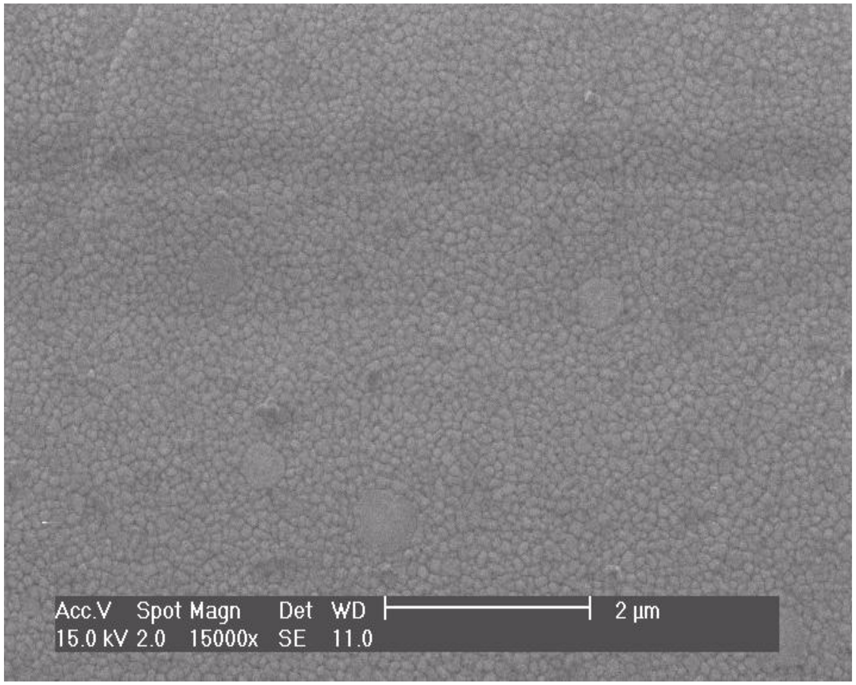


d31 mode sandwich structure

Pt/Ti top electrode pattern by lift-off, 220 nm thick.

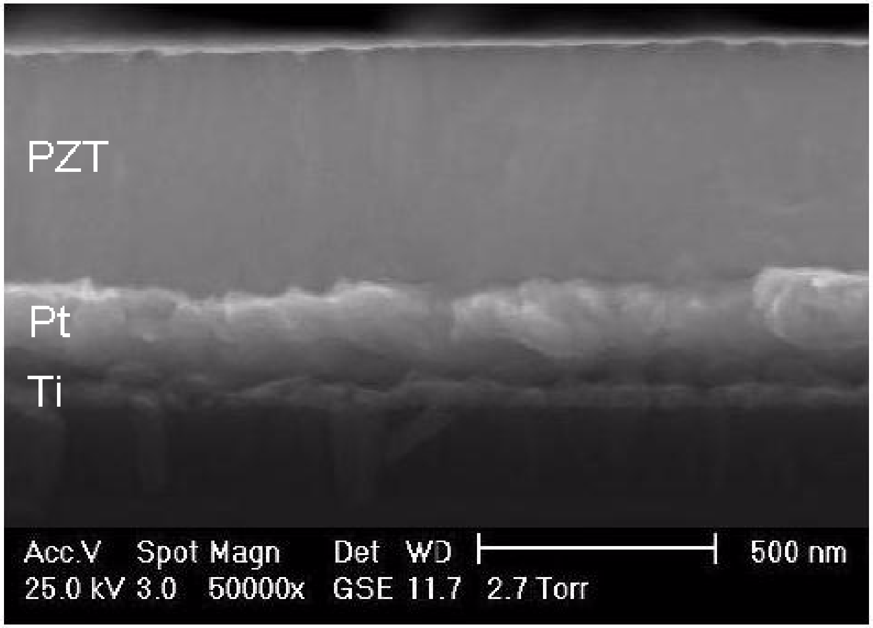
Micro-structure of PZT Thin Film

SEM of PZT film surface



Average grain size : 0.1μm

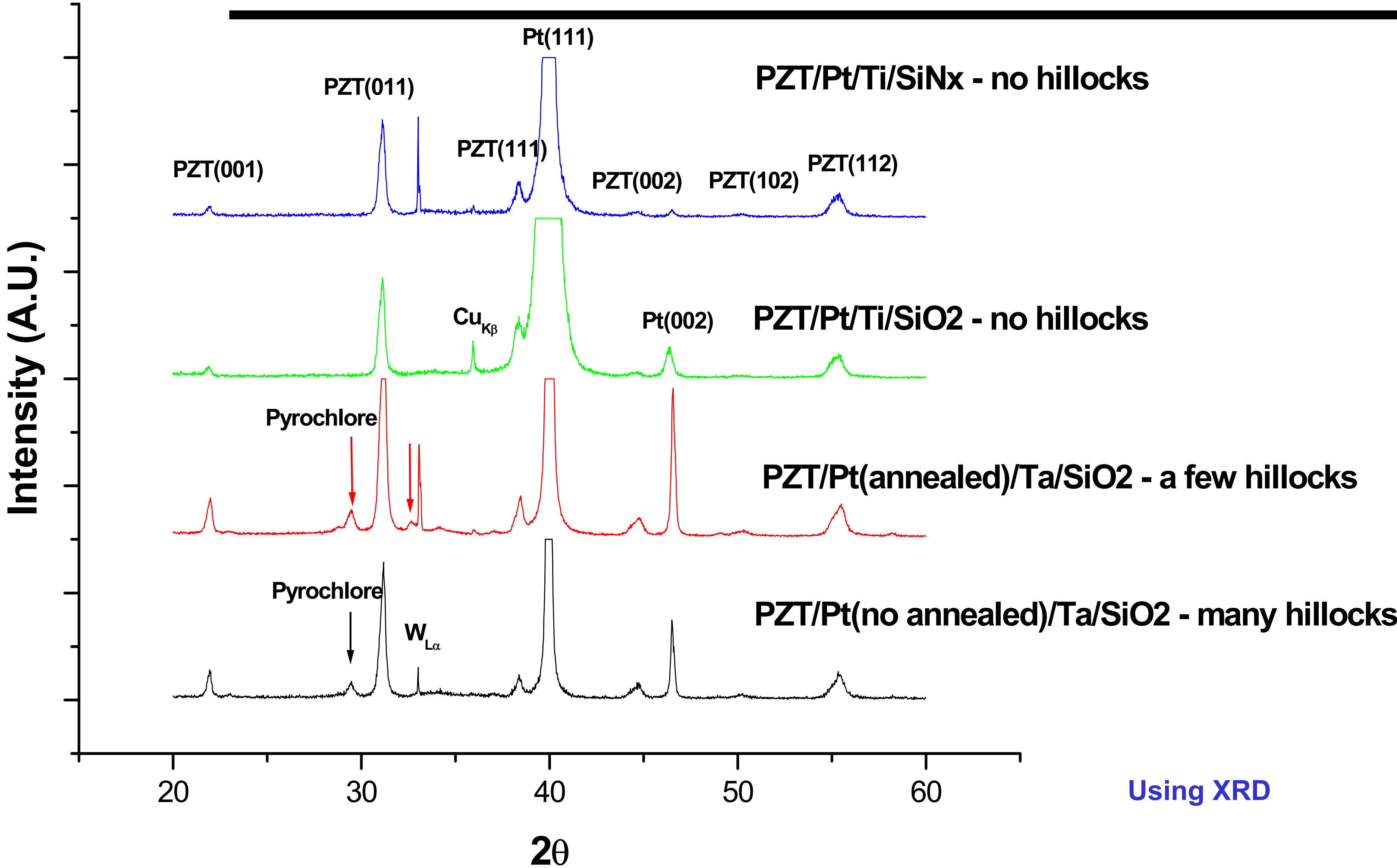
Cross sectional image of PZT film



PZT thickness = 510 $\pm$ 40 nm;
Pt thickness = 200 nm.

Using SEM

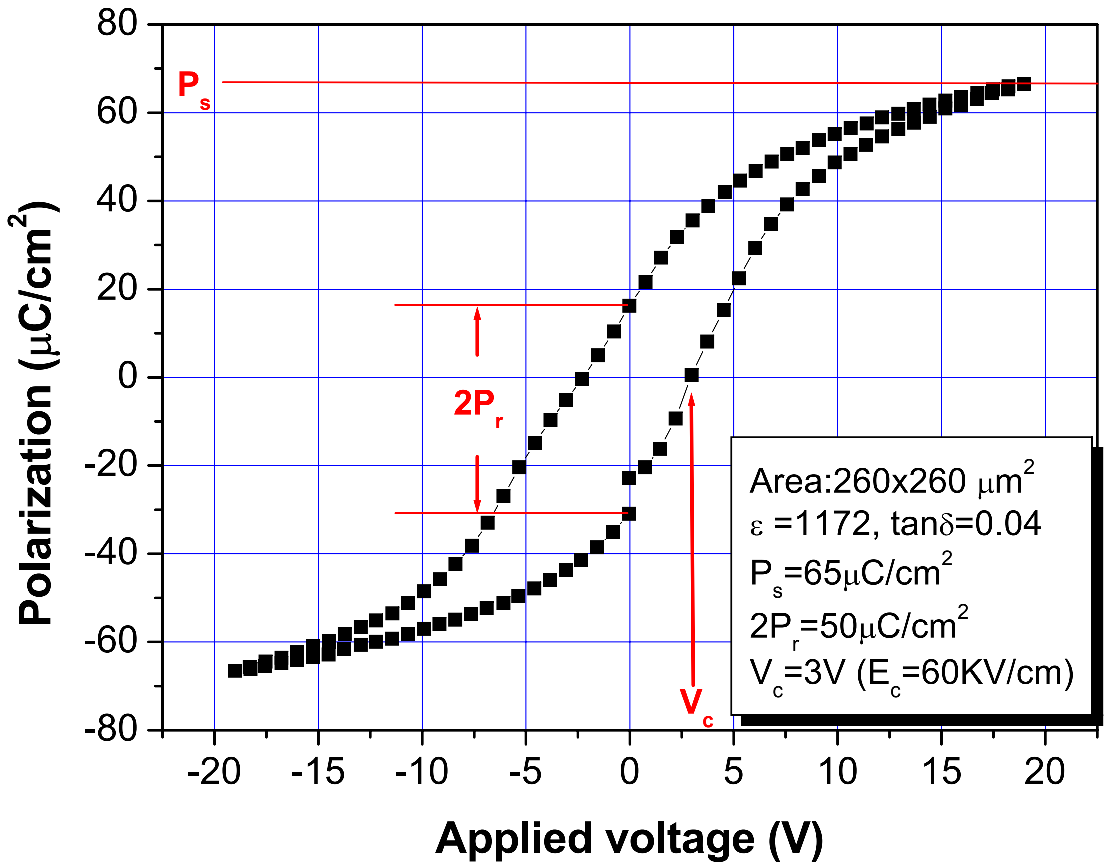
PZT XRD On Various Bottom Electrode Combinations



Using XRD

Sang-Gook Kim, MIT

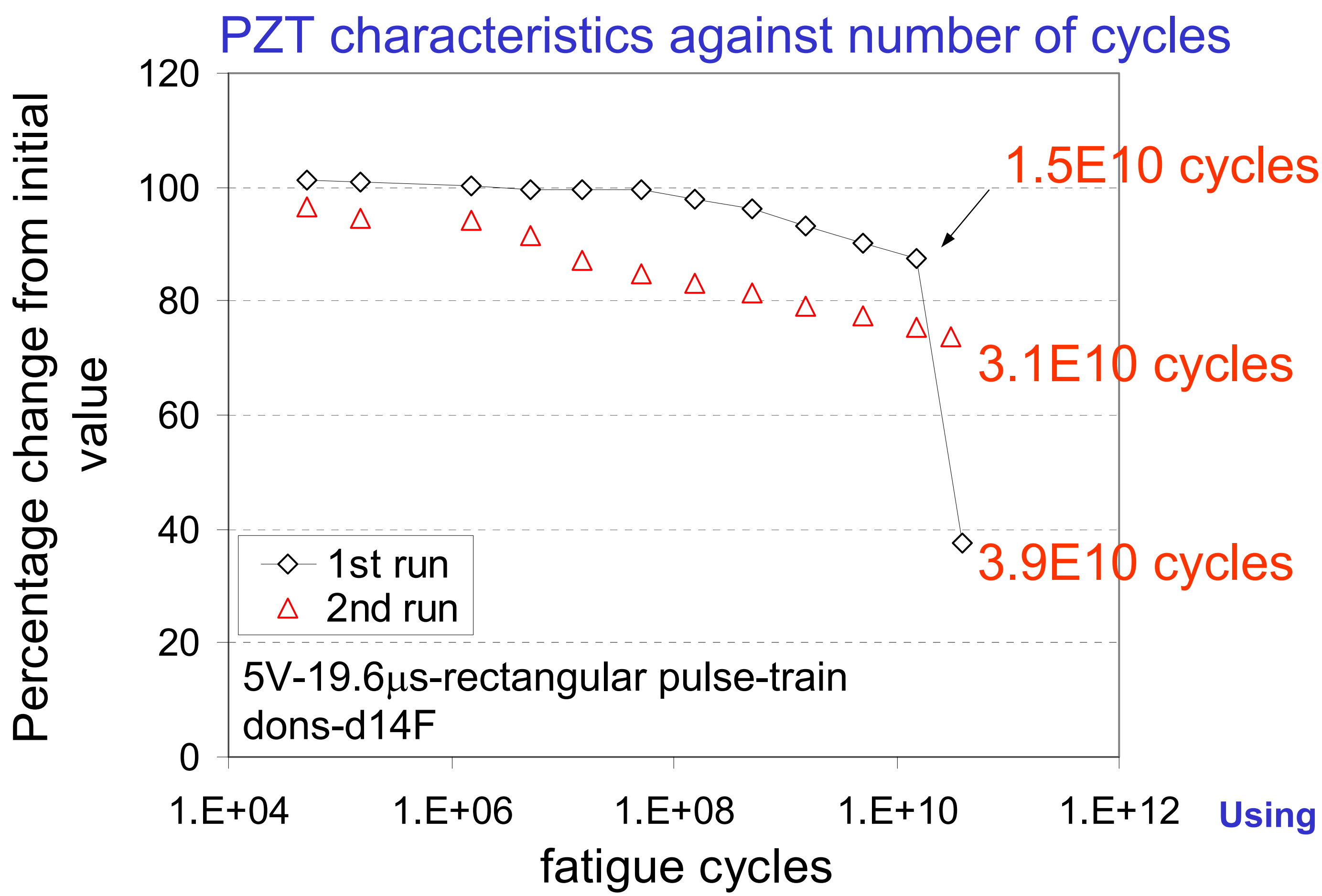
Electrical Measurements - PZT Ferroelectric Characterization



Using RT-66A

- hysteresis due to domain reorientation - growth, merging and shrinkage
- saturation polarization, P_s at 65 $\mu C/cm^2$
- remnant polarization, $2P_r$ at 50 μ C/cm^2

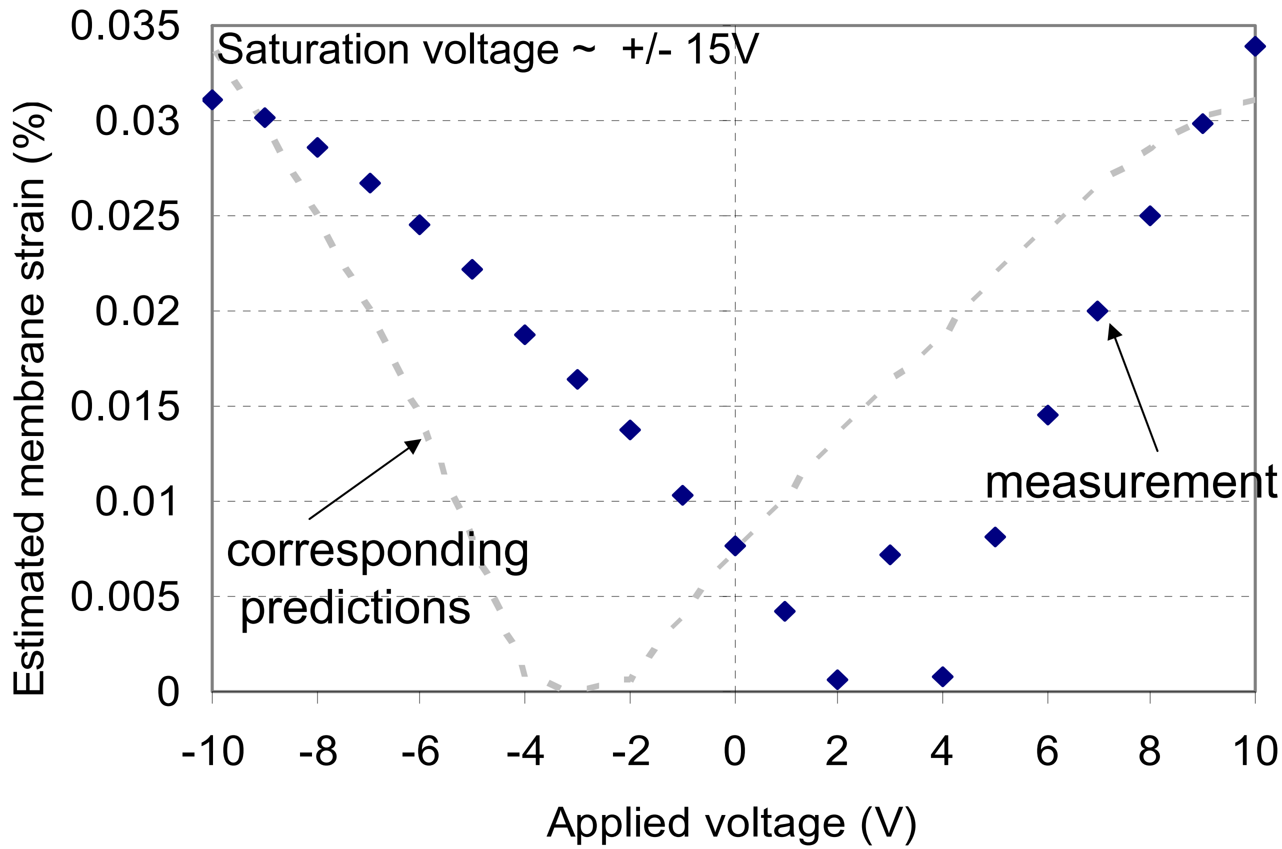
Piezoelectric Fatigue Analysis



Using RT-66A

- PZT electrical fatigue up to more than 1E10 cycles
- characteristics recovered on 2^{nd} run with same device

Piezoelectric Displacement Analysis



strain = $d_{31}V/t$ (d_{33}=275pC/N [1], d_{31}=-115pC/N [2])

[1] direct measurement [2] inferred from mechanical motion

Using computer microvision system