Piezoelectricity

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

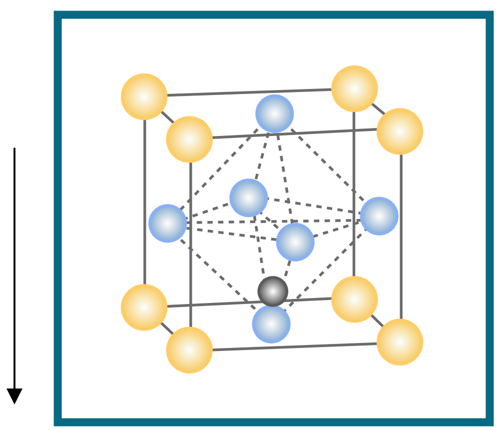
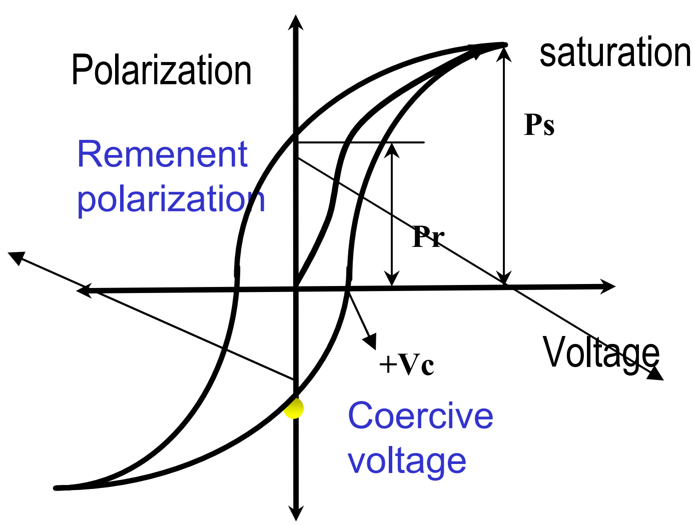


Figure by MIT OCW



FRAM utilize two stable positions.

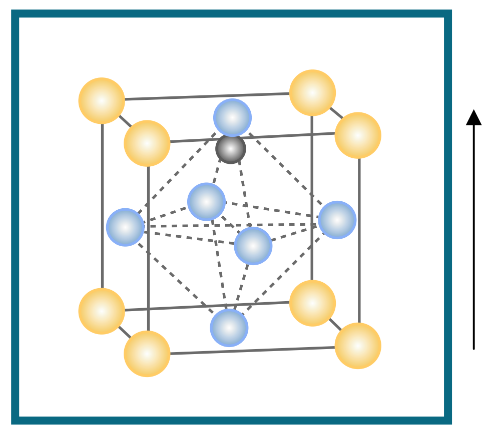
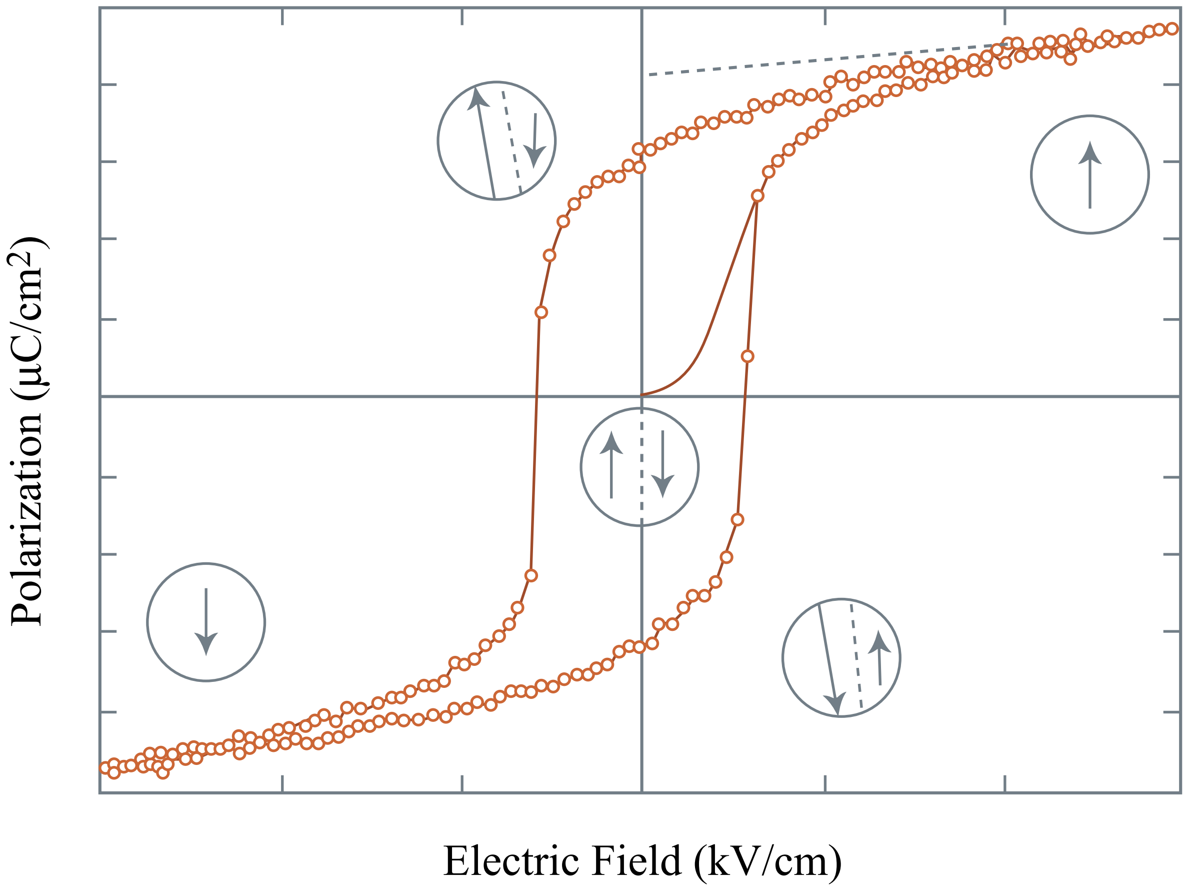


Figure by MIT OCW

Sang-Gook Kim, MIT

Hysterisis



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

Figure by MIT OCW.

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

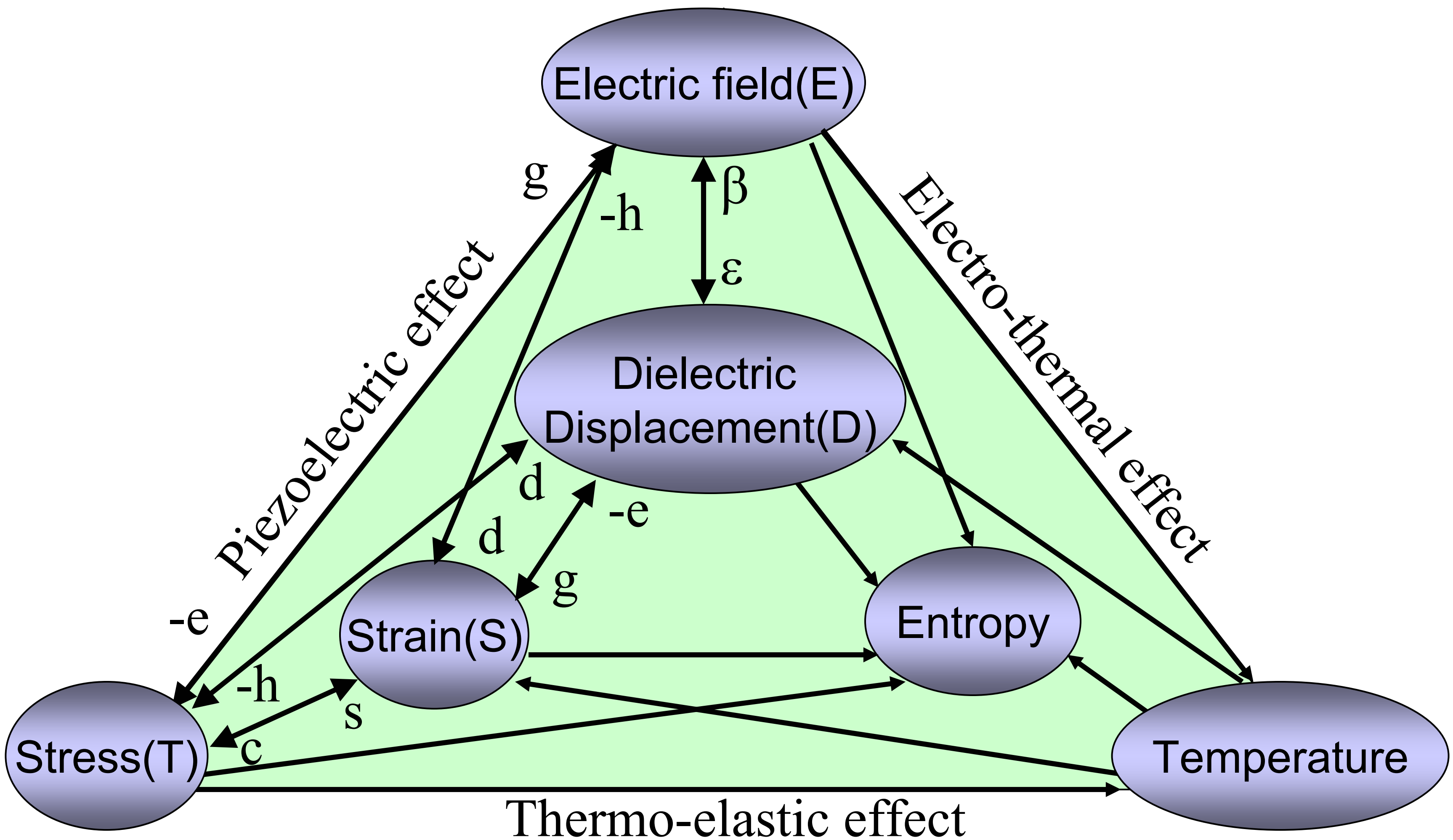
$$d = (\partial S/\partial E)_T = (\partial D/\partial T)_E$$

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

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

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

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

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

$c^{E} = 1/s^{E}$

$e = dc^{E}$

$\varepsilon^{E} = \varepsilon^{T}-dc^{E}d_t$

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

$g = d/\varepsilon^{T}$

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

$D = Q/A$

$S = F/A$

Equation of states

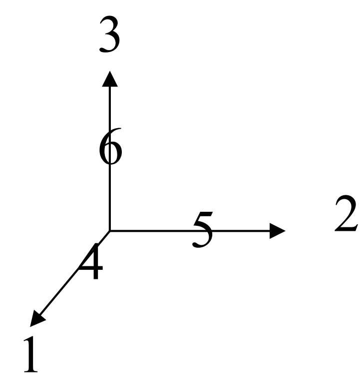
$$D = dT + \varepsilon^T E$$
direct

$$S = s^E T + dE$$
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})

Diagram removed for copyright reasons.
Source: Piezo Systems, Inc.
"Introduction to Piezo Transducers."
http://www.piezo.com/bendedu.html

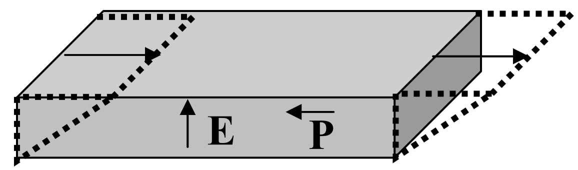
$$\Delta T/T = d_{33} \cdot E$$

Transverse (d_{31})

Diagram removed for copyright reasons.
Source: Piezo Systems, Inc.
"Introduction to Piezo Transducers."
http://www.piezo.com/bendedu.html

$$\Delta L/L = d_{31} \cdot E$$

Shear (d_{15})



Shear strain $= d_{15} E$

Piezoelectric Charge Constants

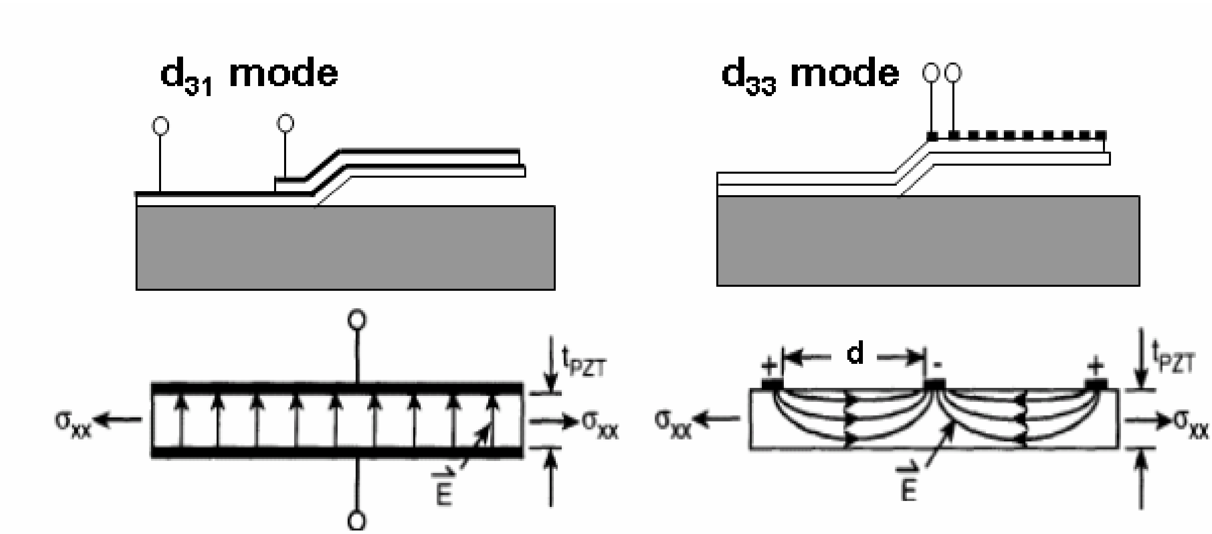
Mechanical energy → **Sensor** → **Electrical energy**

Longitudinal (d_{33})	**Transverse (d_{31})**	**Multi-layer (d_{33})**
Diagram removed for copyright reasons. Source: Piezo Systems, Inc. "Introduction to Piezo Transducers." http://www.piezo.com/bendedu.html	Diagram removed for copyright reasons. Source: Piezo Systems, Inc. "Introduction to Piezo Transducers." http://www.piezo.com/bendedu.html	Diagram removed for copyright reasons. Source: Piezo Systems, Inc. "Introduction to Piezo Transducers" http://www.piezo.com/bendedu.html
$Q = d_{33} \cdot F_{in}$ $V_{out}/T = g_{33} \cdot F_{in} /(L \cdot W)$	$Q = d_{31} \cdot F_{in}$ $V_{out}/T = g_{31} \cdot F_{in}/(T \cdot W)$	$Q = n \cdot d_{33} \cdot F_{in}$ $V_{out}/T = t/n \cdot g_{33} \cdot F_{in} /(LW)$

Sang-Gook Kim, MIT

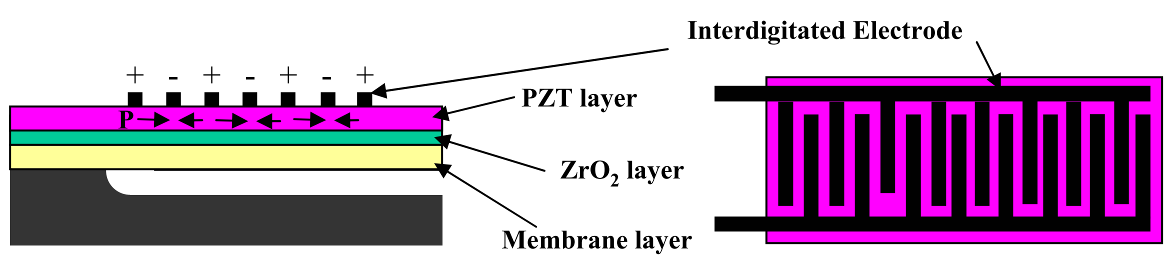
d_{31} vs d_{33}

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

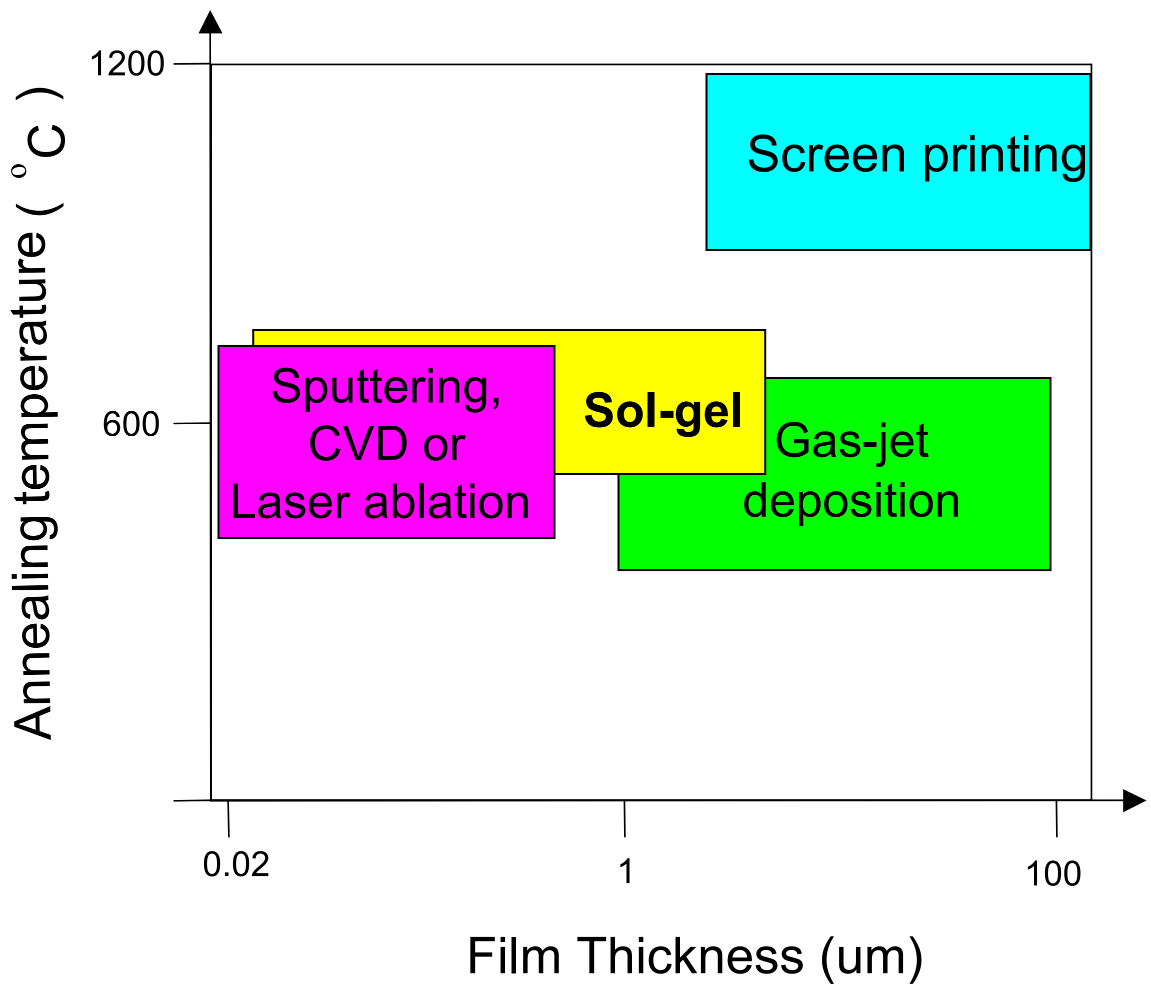


Design of a Z-positioner

Component schematic removed for copyright reasons.
Physik Instrumente Z-positioner P-882.10, in
http://www.pi-usa.us/pdf/2004_PICatLowRes_www.pdf, page 1-45.

Ordering Number*	Dimensions A x B x L [mm]	Nominal Displaceme nt [µm @ 100 V] (±10%)	Max. Displaceme nt [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

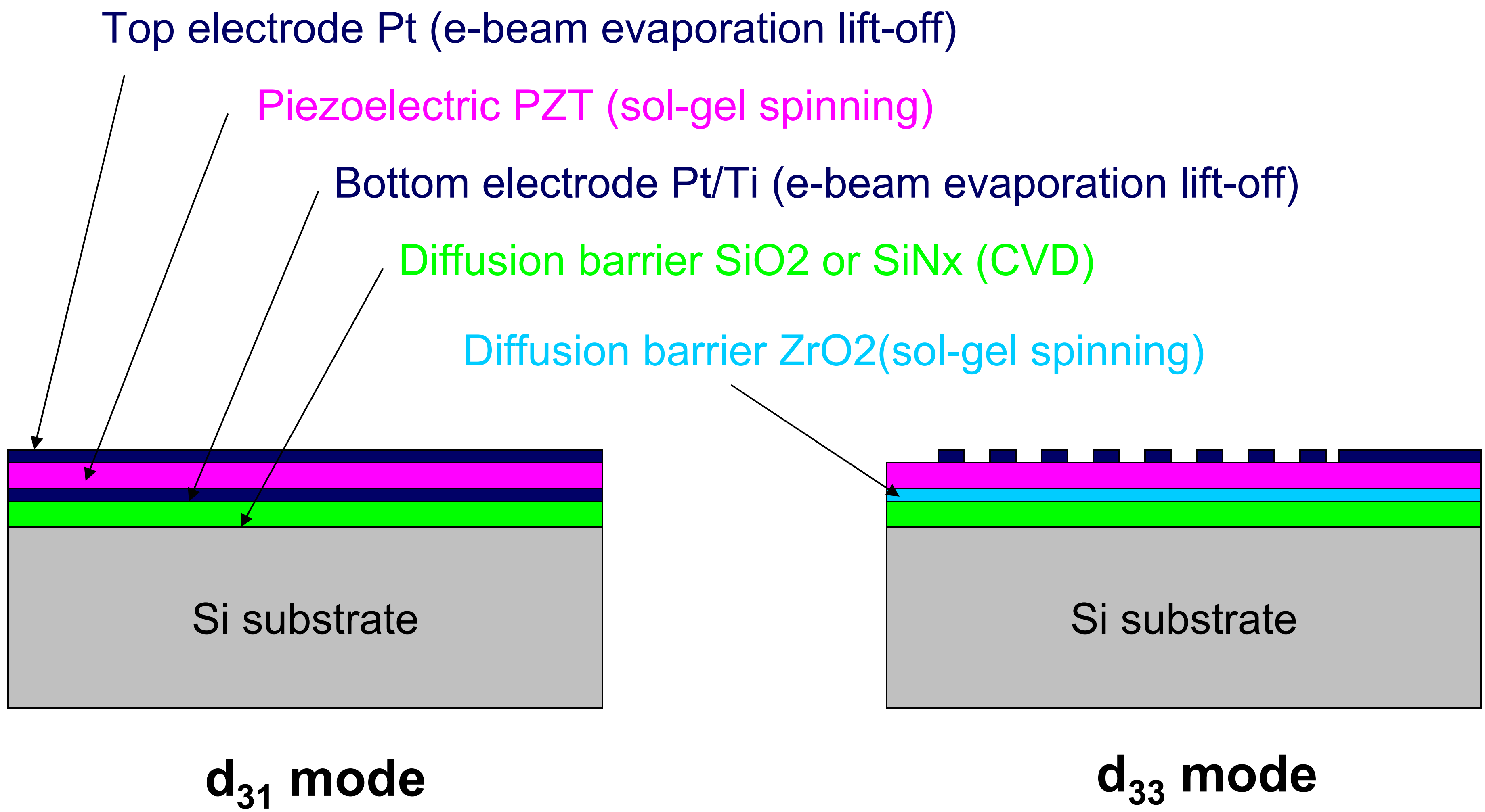
Disadvantages

- 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



Thermal Oxide Growth and Bottom Electrode Evaporation

Tubes for growing of device diffusion barrier

Evaporation of device electrodes

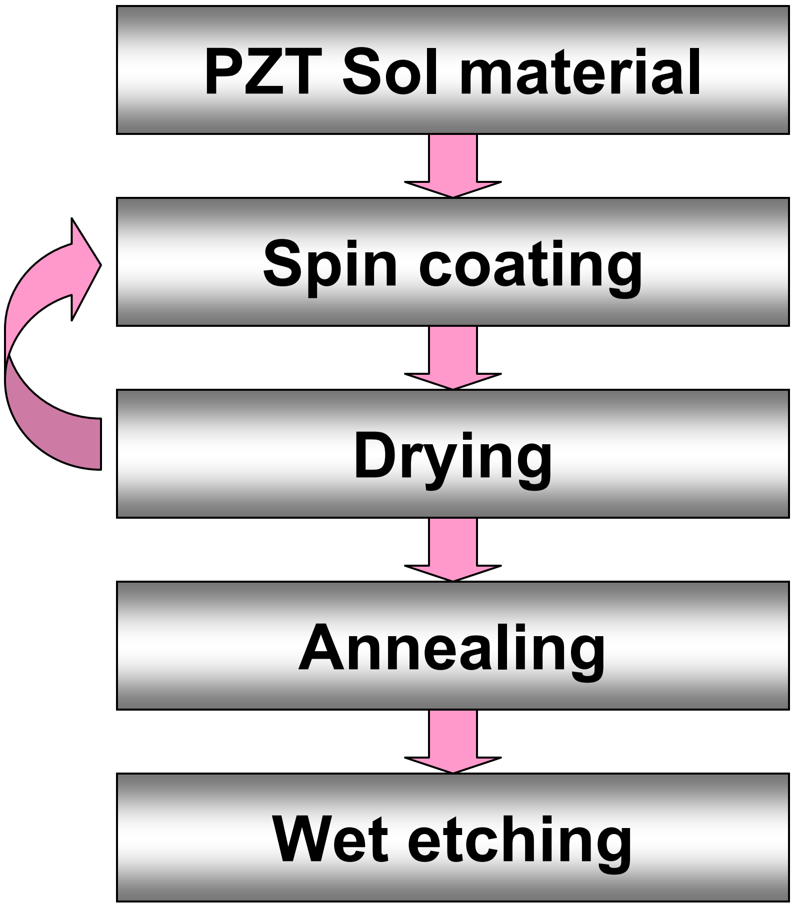
Photos: MIT Microsystems Technologies Laboratory

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



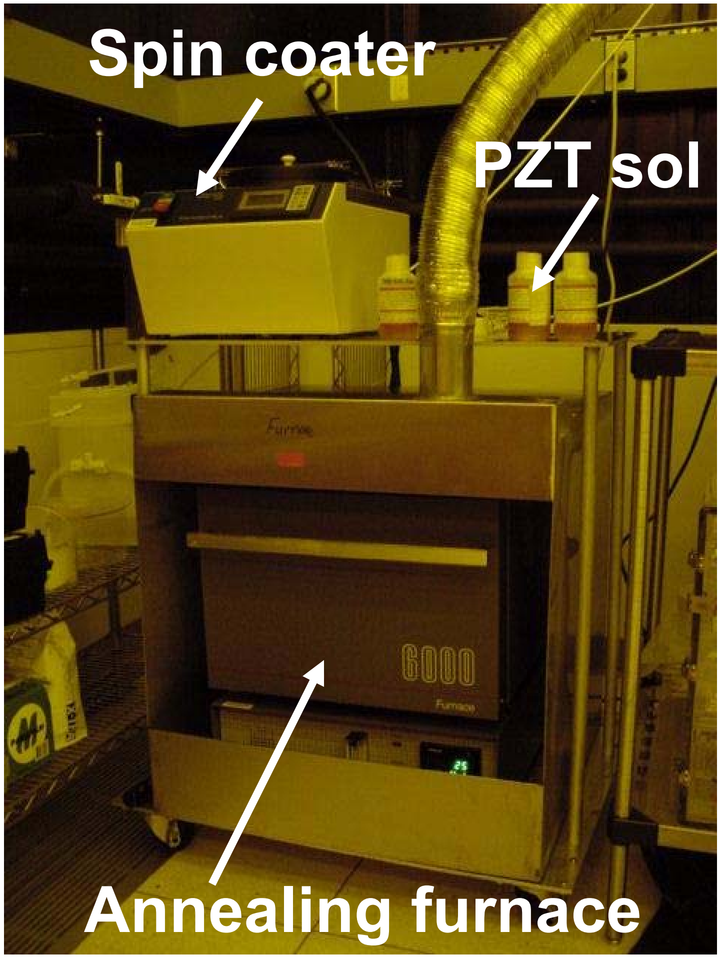
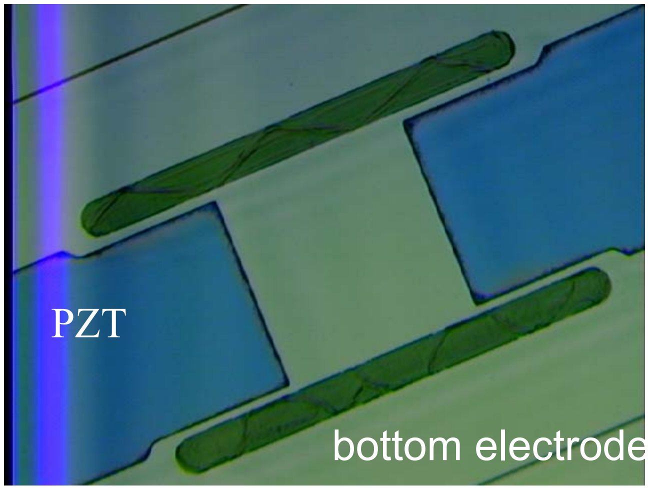
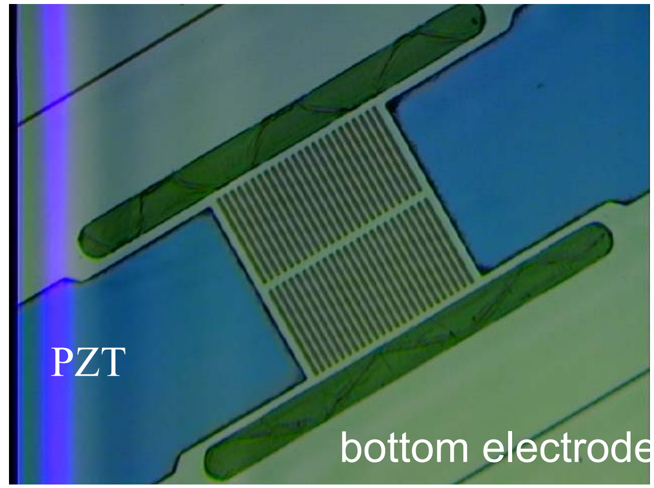


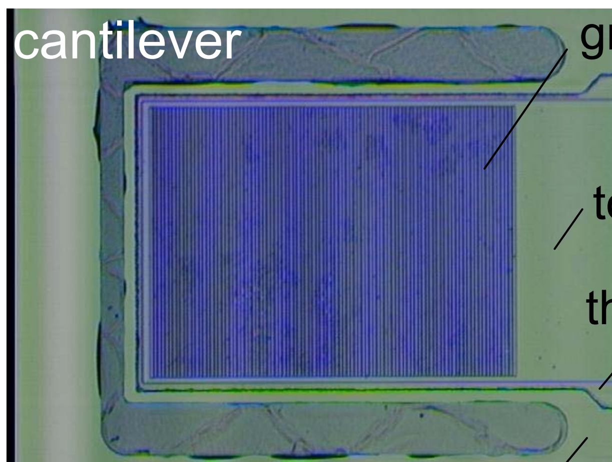
Photo: MIT Microsystems Technologies Laboratory

PZT Patterning

Patterned PZT on device







gratings

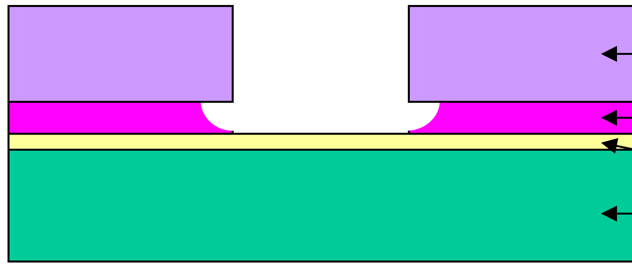
top electrode

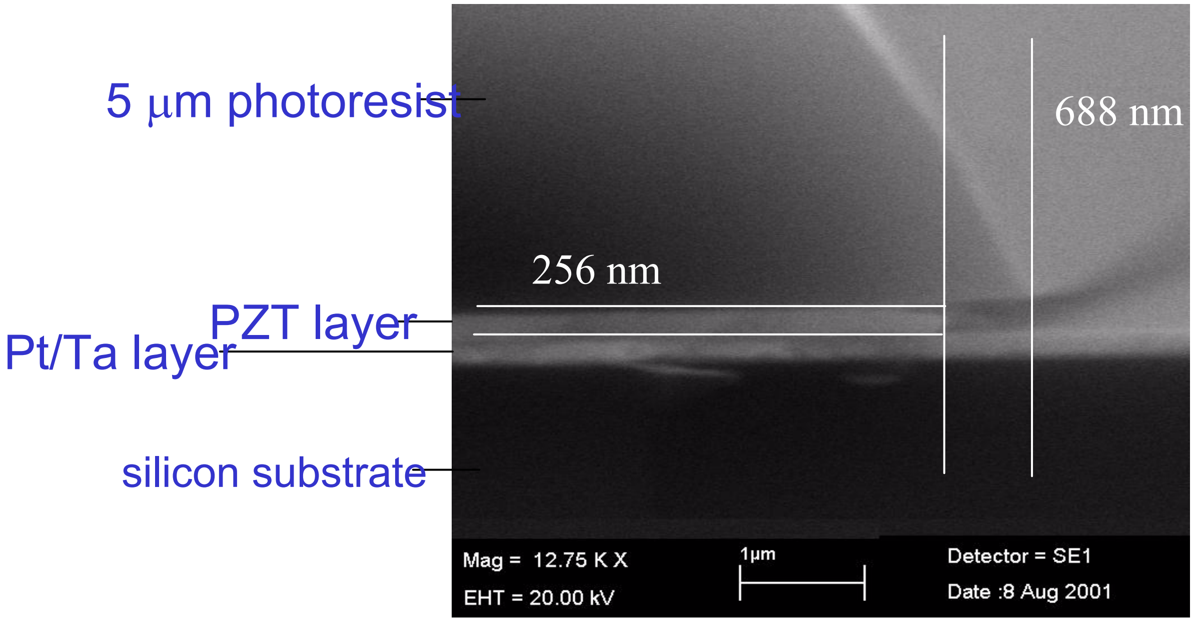
thin-film PZT

bottom electrode

PZT Patterning (Wet ethcing)

PZT wet-etching with thick photoresist

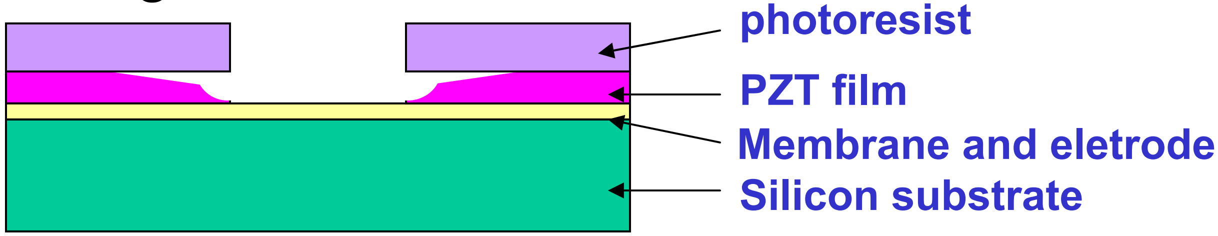


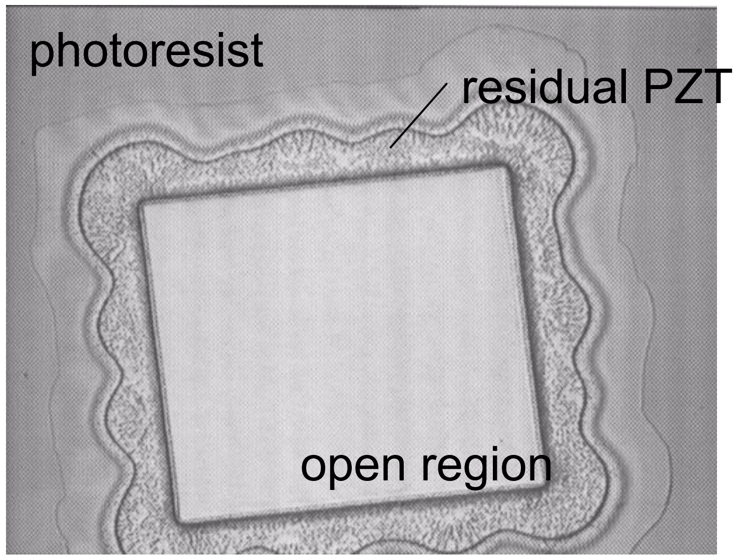


HCl(64%)+BOE(31%)+DI (5%)
(etch rate: 0.25 μm/min)

PZT Patterning (Wet ethcing)

PZT wet-etching with thin resist





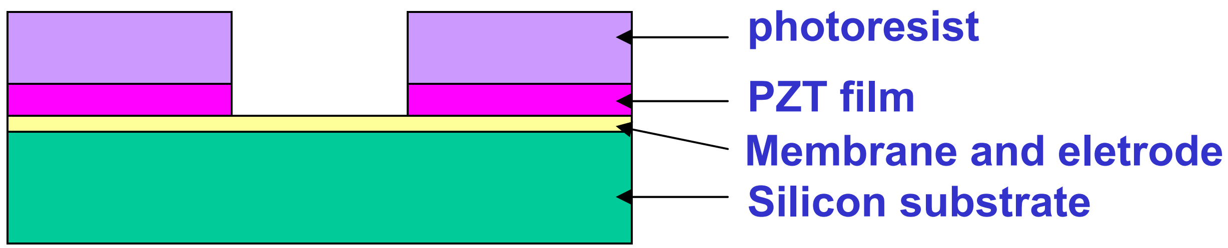
• large undercuts with thin (1 μm) photoresist material

[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

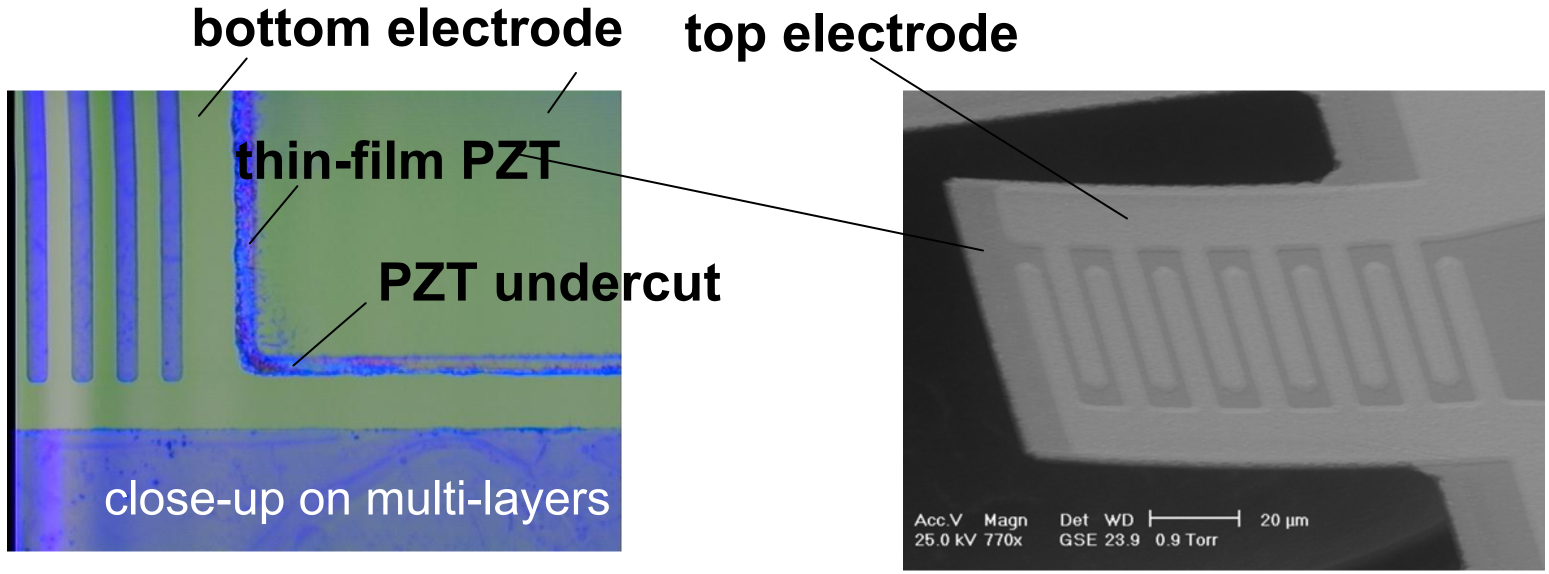


using RIE, Plamaquest (in TRL) or Plasmatherm (in EML) with BCl_3:Cl_2 (30:10)

• stiff sidewall with thick (10 μm) photoresist material

Top Electrode Lift-Off

d33 mode interdigitated structure

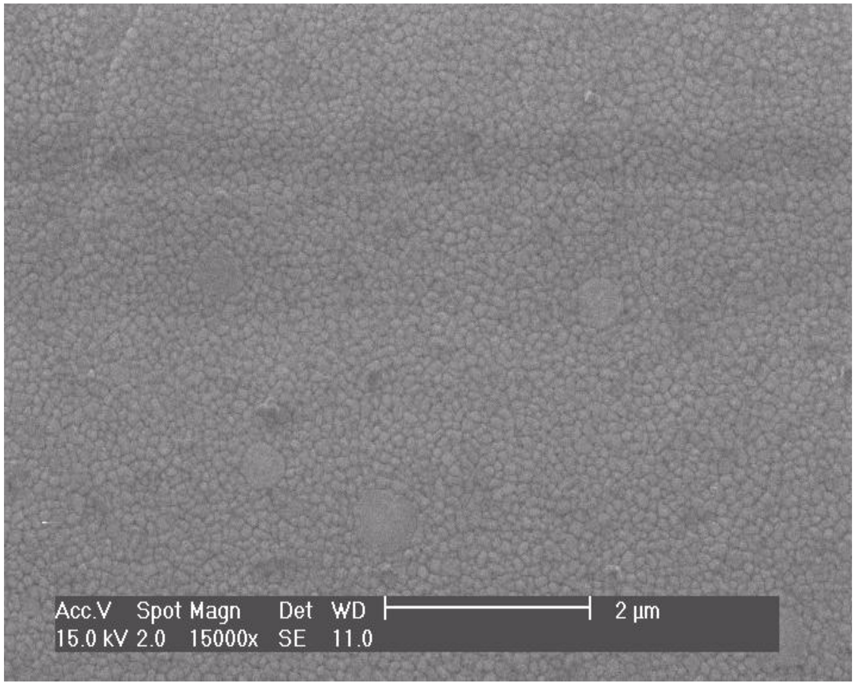


d31 mode sandwich structure

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

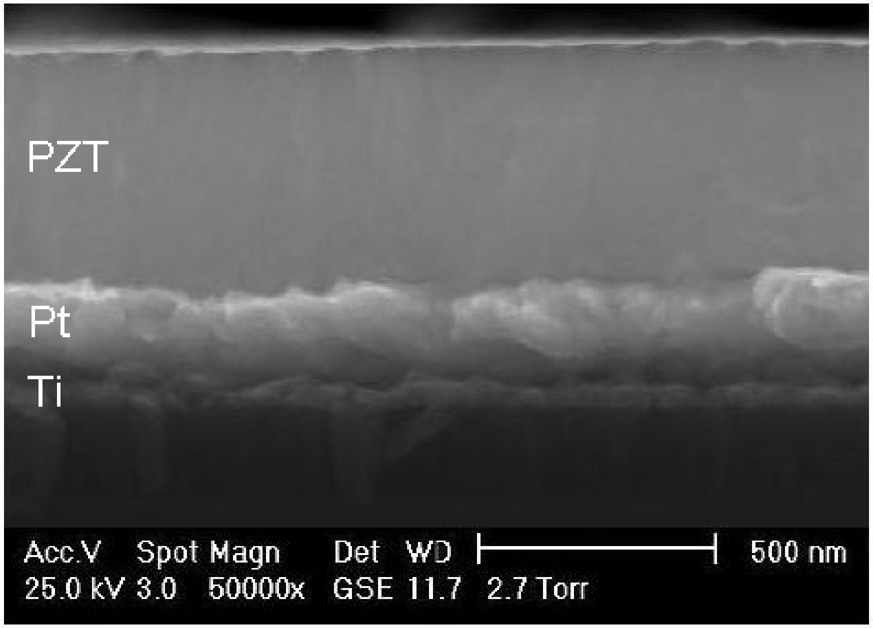
Micro-structure of PZT Thin Film

SEM of PZT film surface



Average grain size : 0.1µm

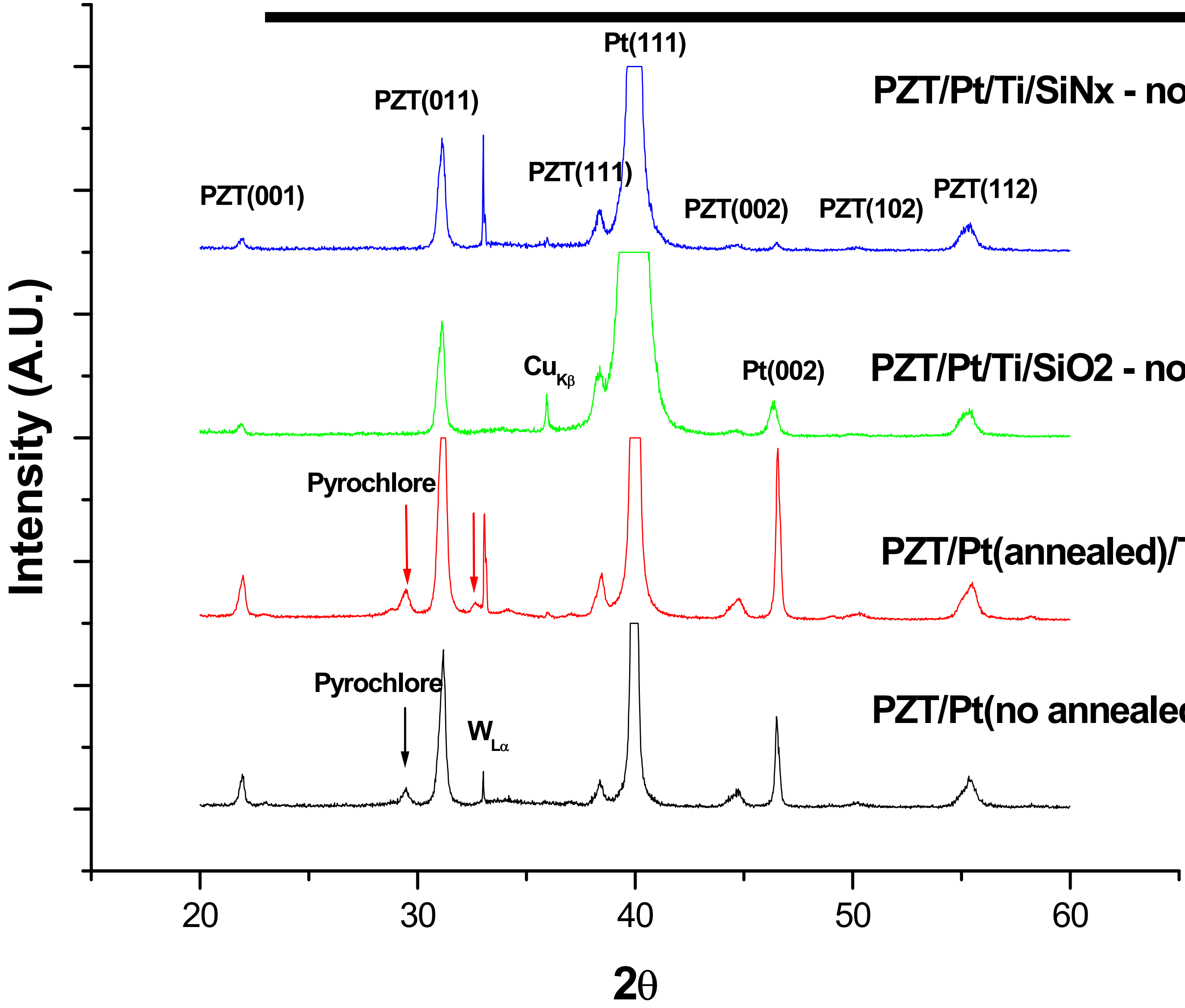
Cross sectional image of PZT film



PZT thickness = 510 ± 40 nm;
Pt thickness = 200 nm.

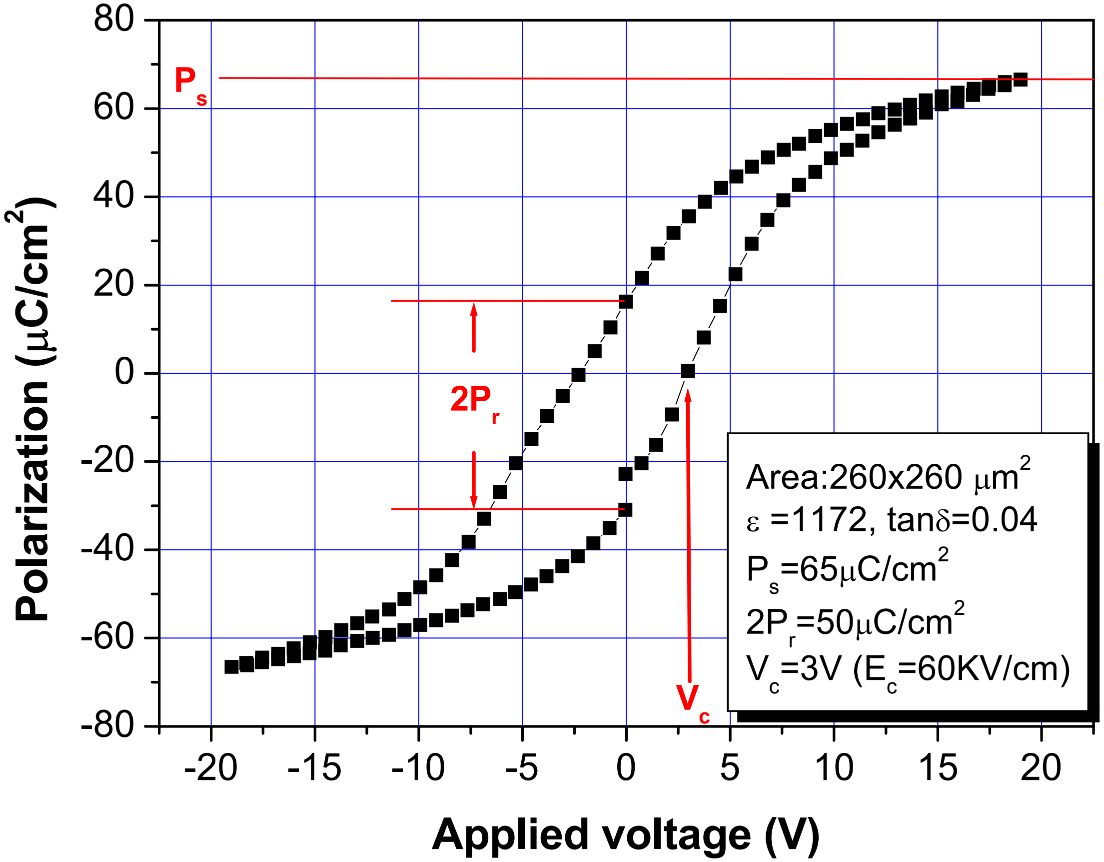
Using SEM

PZT XRD On Various Bottom Electrode Combinations



Using XRD

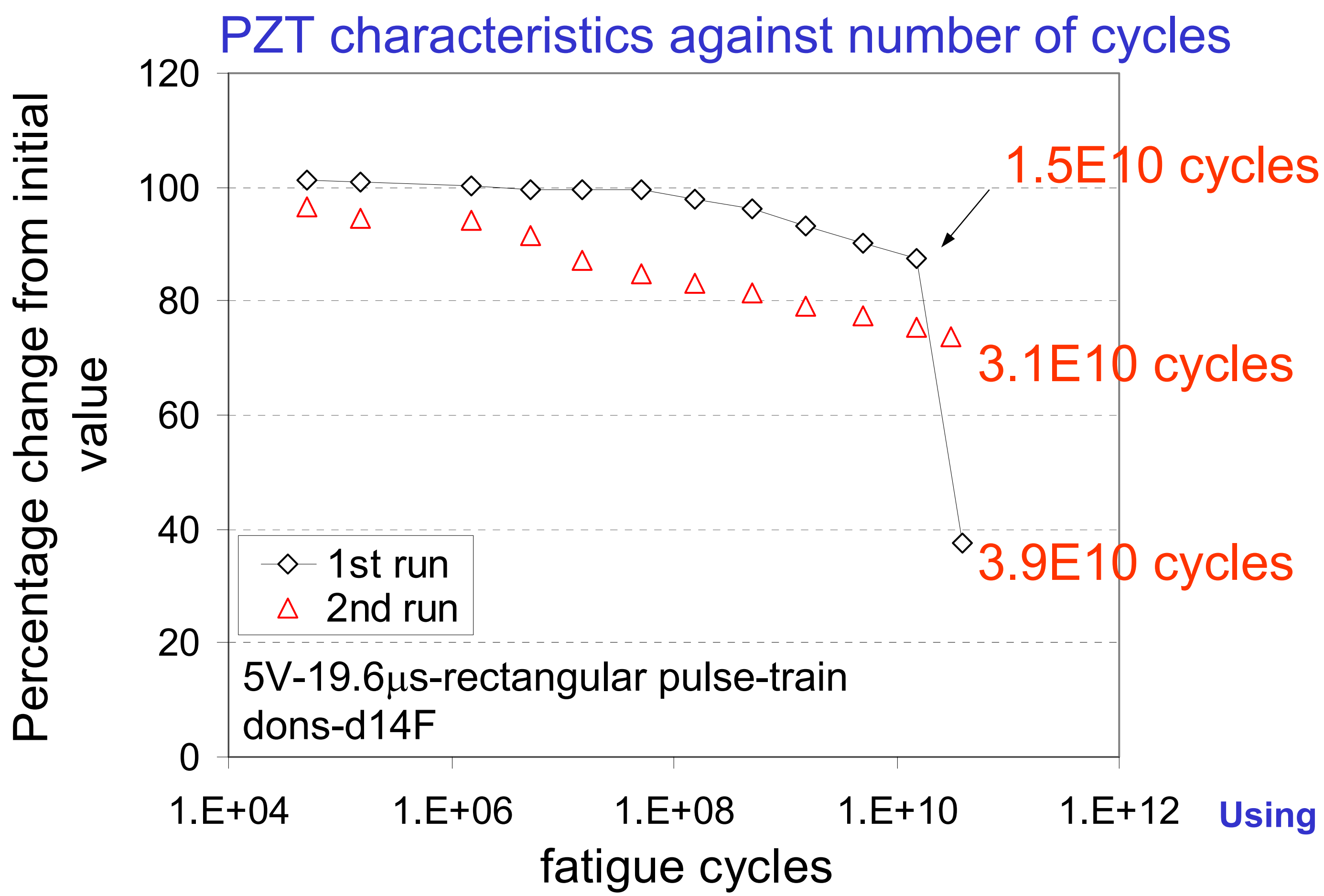
Electrical Measurements - PZT Ferroelectric Characterization



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

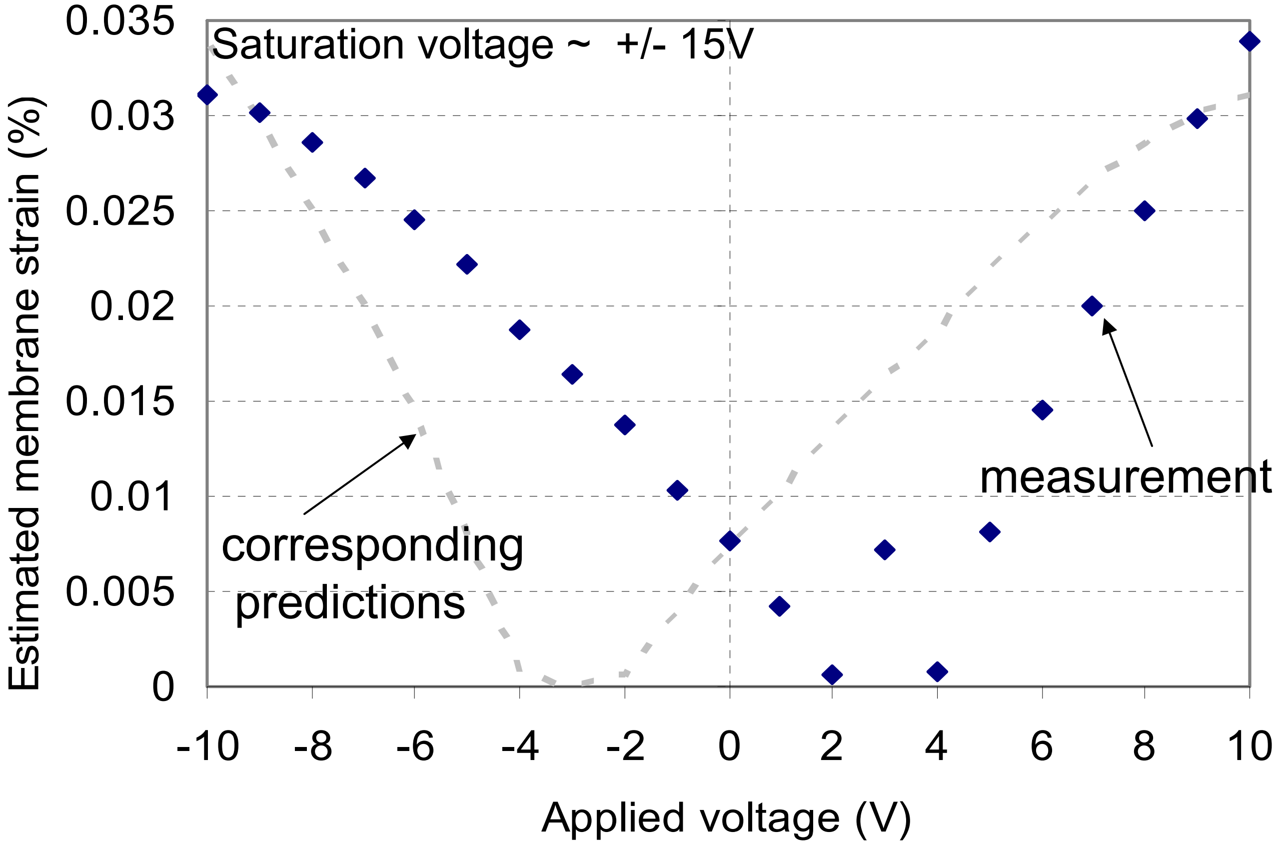
Piezoelectric Fatigue Analysis



Using RT-66A

- PZT electrical fatigue up to more than 1E10 cycles
- characteristics recovered on 2nd 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