2.76/2.760 Multiscale Systems Design & Manufacturing

Fall 2004

Piezoelectricity–2

Sang-Gook Kim, MIT

Spontaneous polarization

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

: Polarization per unit cell volume

Ba^{2+}

O^{2-}

Ti^{4+}

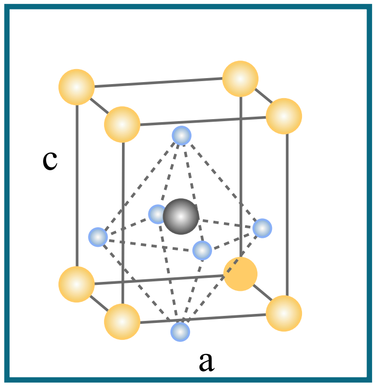
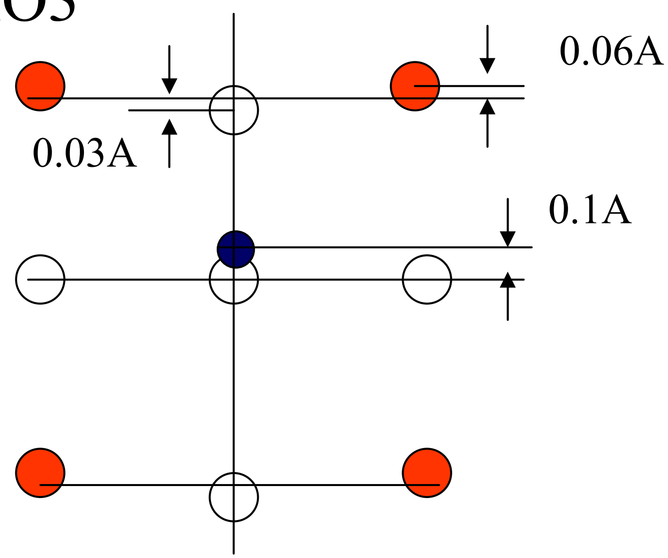


Figure by MIT OCW.

HW1: Calculate the magnitude of spontaneous Polarization. a=3.992 A, c=4.036a
1e=$1.602\text{x}10^{-19}$ C

BaTiO3



Dipole moment=Σ charge x position shift
= 8(2e/8)(0.06 x 10^{-10} m) + 4e(0.1 x 10-10 m)
+ 2(-2e/2)(-0.03 x 10-10 m)

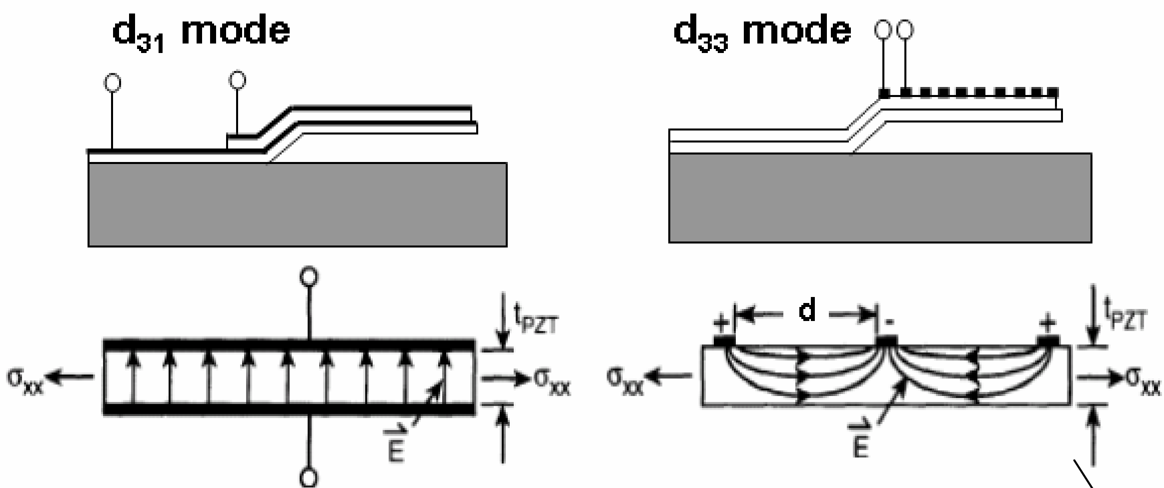
=0.9292 x 10^{-29}C m

Volume=a x a x c=64.3 x 10^{-30} m^3

Spontaneous Polarization = 0.145 C/ m^2

Sang-Gook Kim, MIT

d_{31} vs d_{33}



$V_{31} = \sigma_{xx} \bullet t_{pzt} \bullet g_{31}$

$V_{33} = \sigma_{xx} \bullet d \bullet g_{33}$

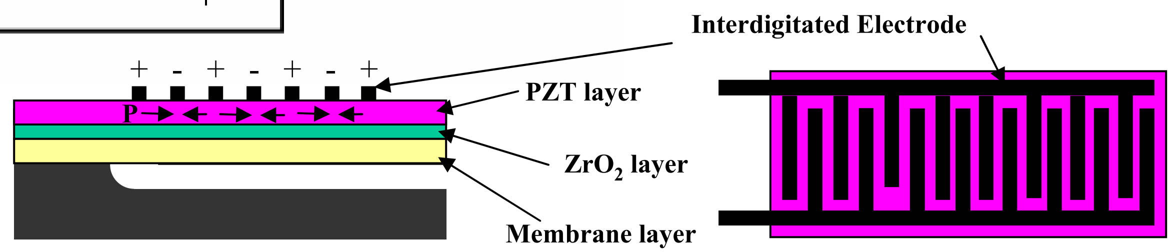
$V_{33} = 2d / t_{pzt} \bullet V_{31} \cong 20 \bullet V_{31}$

$(\text{if } g_{33} > 2g_{31}, \quad d \cong 10\, t_{pzt})$

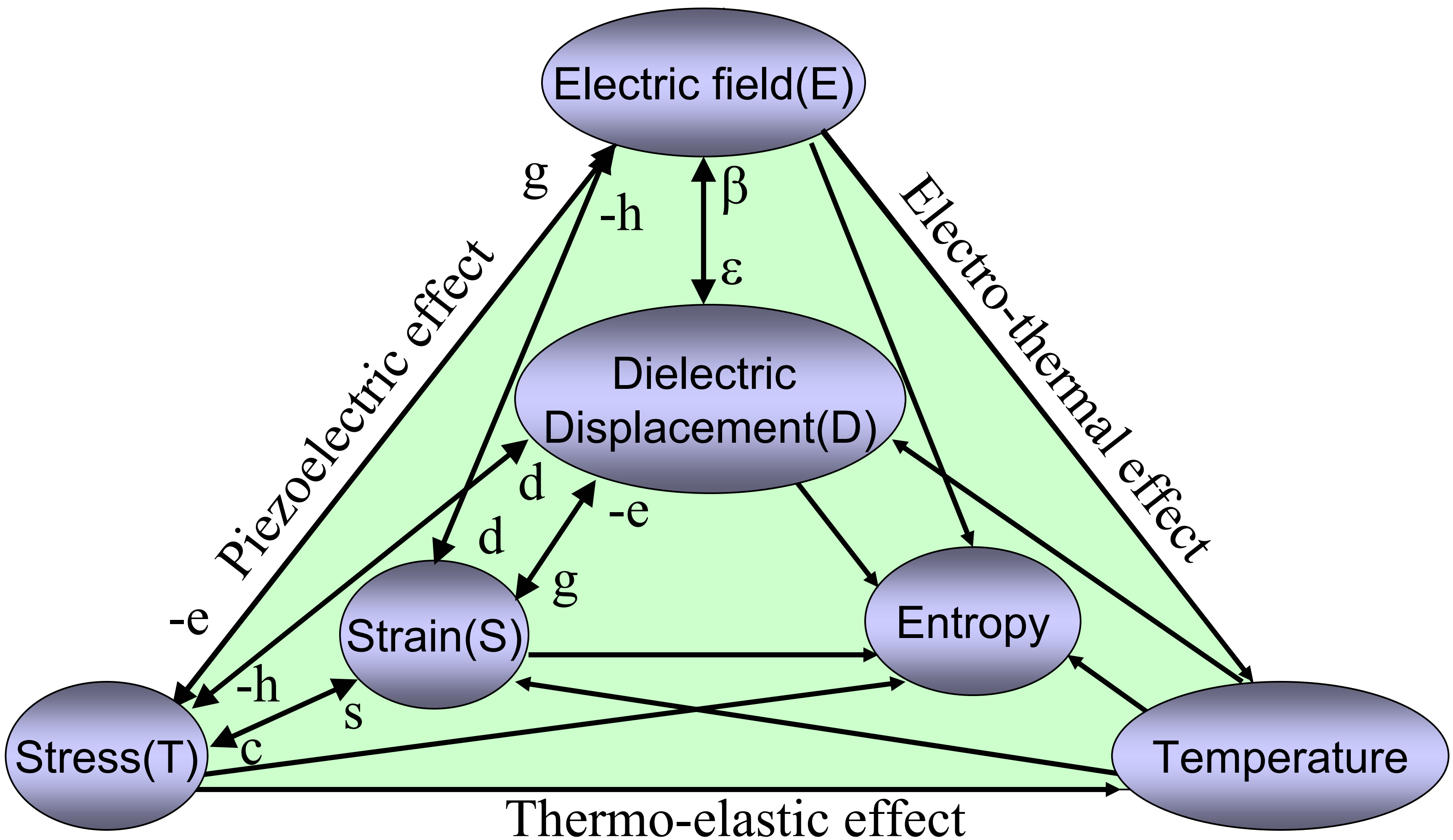
HW2: Compare generated voltages V31 (from d31mode), V33 (d33mode). Both have same cantilever dimension, but different electrodes.

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



Principles of piezoelectric



Piezoelectricity

Direct effect

$$D = Q/A = dT$$

$$E = -gT$$

Converse effect

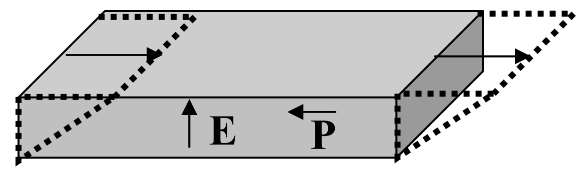
$$S = dE$$

$$g = d/\varepsilon = d/K\varepsilon_o$$

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

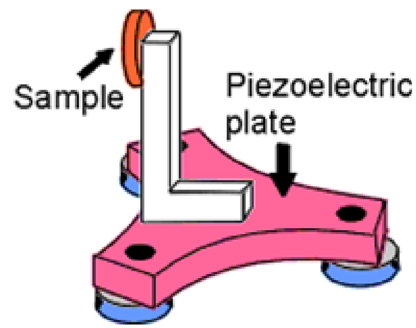
Piezoelectric Charge Constants

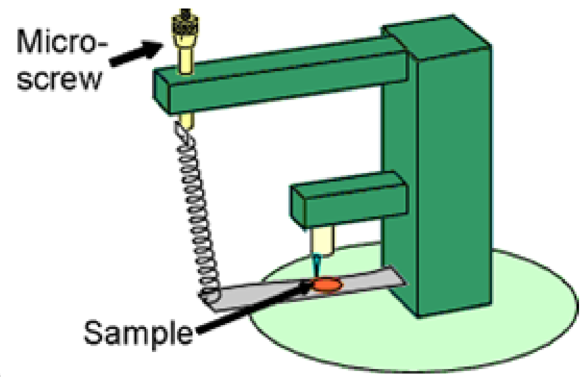
Electrical energy — **Actuator** → **Mechanical energy**

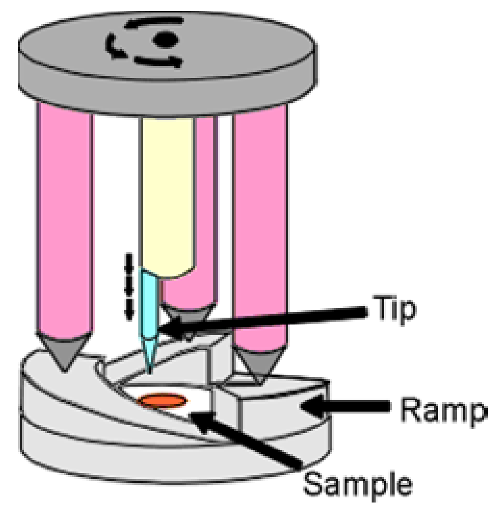
Longitudinal (d_{33})	**Transverse (d_{31})**	**Shear (d_{15})**
Diagram removed for copyright reasons. Source: Piezo Systems, Inc. "Introduction to Piezo Transducers." http://www.piezo.com/bendedu.html	Diagram removed for copyright reasons. Source: Piezo Systems, Inc. "Introduction to Piezo Transducers." http://www.piezo.com/bendedu.html	
$\Delta T/T = d_{33} \cdot E$	$\Delta L/L = d_{31} \cdot E$	Shear strain $= d_{15}\, E$

Coarse Positioning

- Screw
- Louse
- Beetle



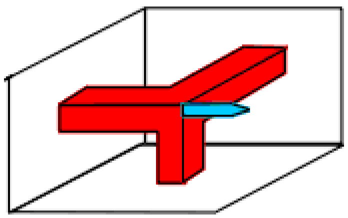




Courtesy of Friedrich-Alexander University. Used with permission.
Source: "Scanning Tunneling Microscopy"
http://www.fkp.uni-erlangen.de/methoden/stmtutor/stmtech.html

STM tip scanning

- Tripod



$$\Delta x = d_{31} V \frac{L}{h} \qquad \frac{\Delta x}{V} = d_{31} \frac{L}{h}$$

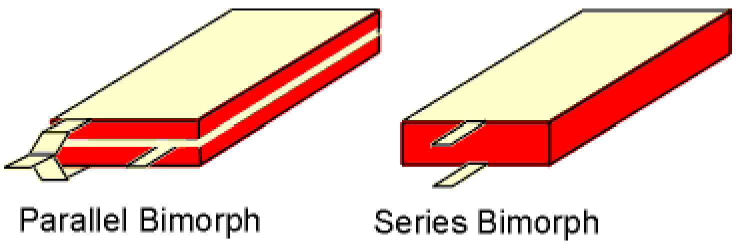
For L=20mm, h=2mm, PZT-5H

$$\frac{\Delta x}{V} = ?$$

Resonant frequency=?

PZT-5H
d31: -2.74 Angstrom/V
d33: 5.93 A/V
E: 6.1 10^{10}N/m2
Tc: 195 C
Q: 65
ρ: 7.5g/cm3
C: 2.8 km/sec

Bimorph bender



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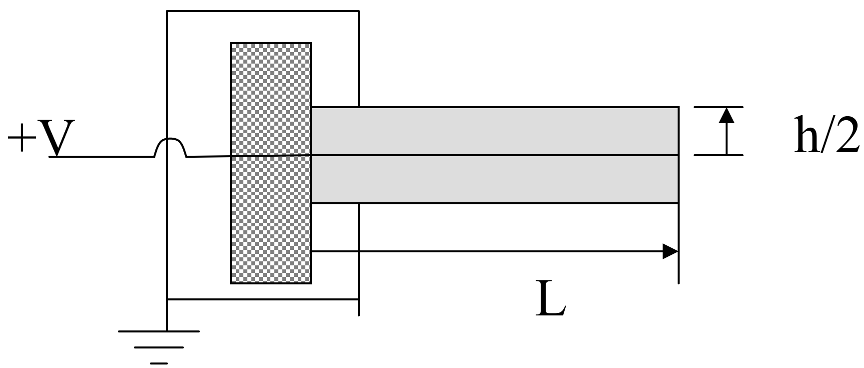
Source: "Scanning Tunneling Microscopy" http://www.fkp.uni-erlangen.de/methoden/stmtutor/stmtech.html



$$\sigma_1 = \pm E d_{31} V \frac{1}{h/2}$$

$$\sigma(z) = \sigma_1 - \alpha z$$

$$M = 0 = \int z\sigma(z)dz$$

$$\alpha = \frac{3\sigma_1}{h}$$

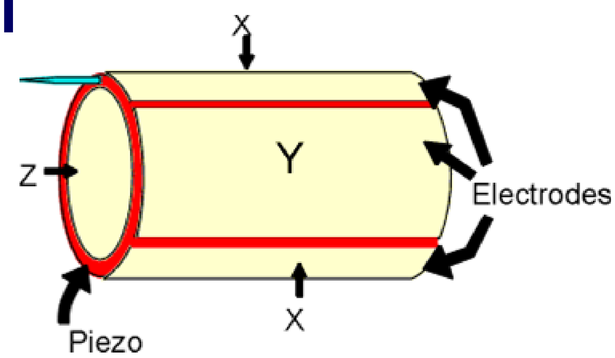
$$radius : \rho = \frac{h^2}{6d_{31}V}$$

$$\Delta z = 3d_{31}V\frac{L^2}{h^2}$$

Sang-Gook Kim, MIT

Tube scanner

- Piezo Tube with ¼ electrodes



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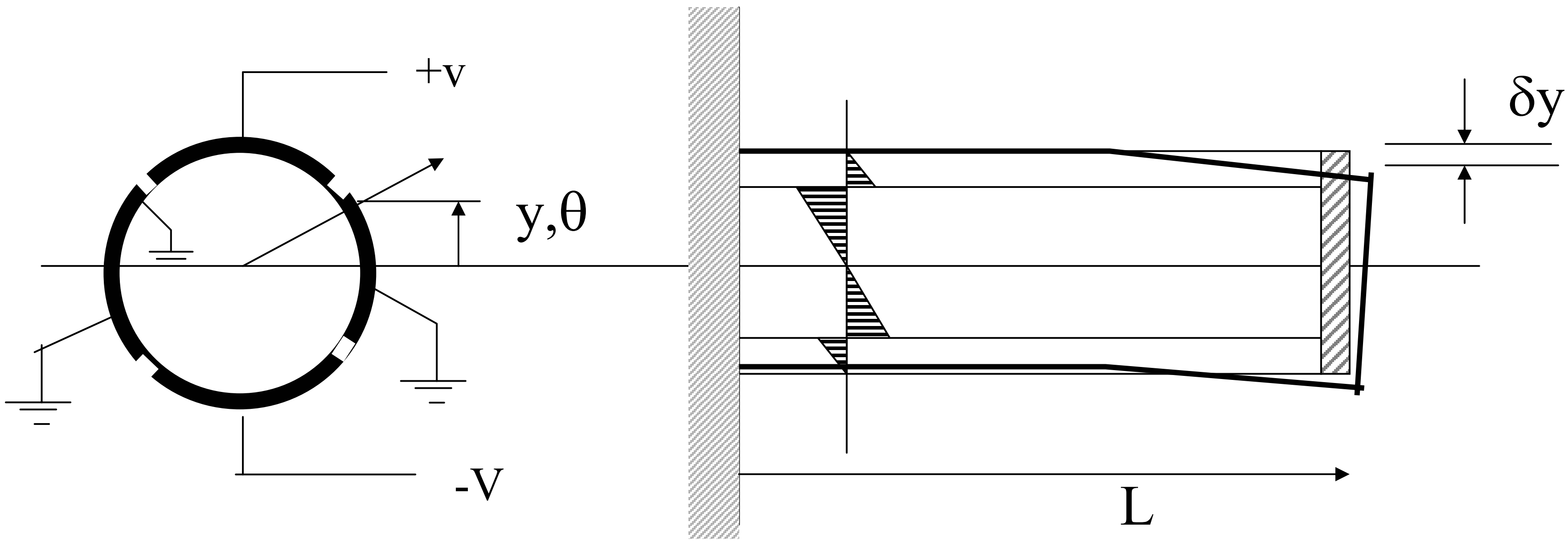

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Tube scanner, deflection

Curvature

$$R = \frac{\pi D h}{4\sqrt{2} d_{31} V}$$

$$\delta y = \frac{2\sqrt{2} d_{31} V L^2}{\pi D h}$$

Resonant frequency 40KHz (z), 8 KHz(x,y),
For a tube of 12.7mm L, 6.35 mm diameter, 0.51mm thick

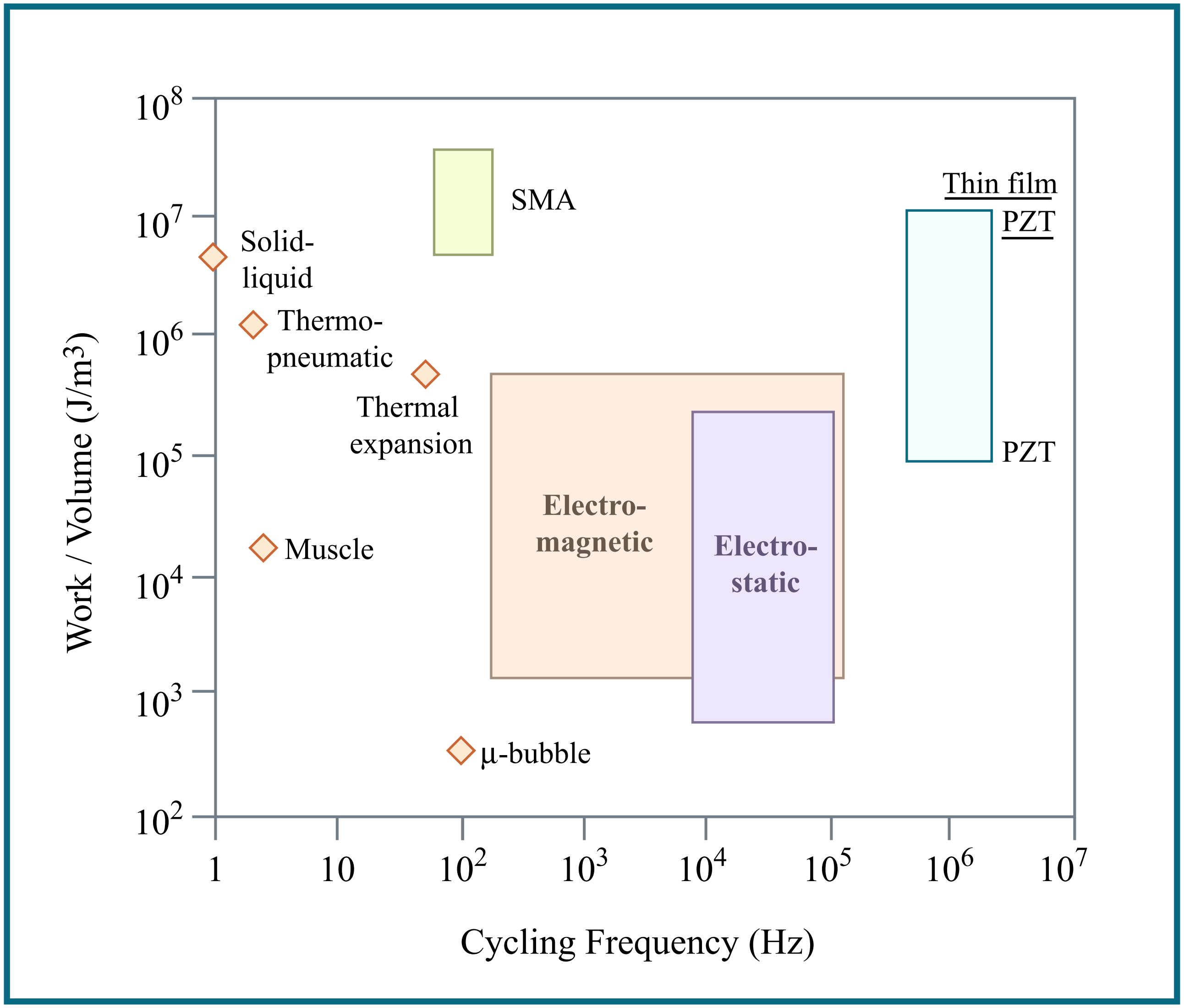
Design of a Z-axis scanner

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 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

Sang-Gook Kim, MIT

Case 1: Piezoelectric micro-actuators



<u>Positives</u>

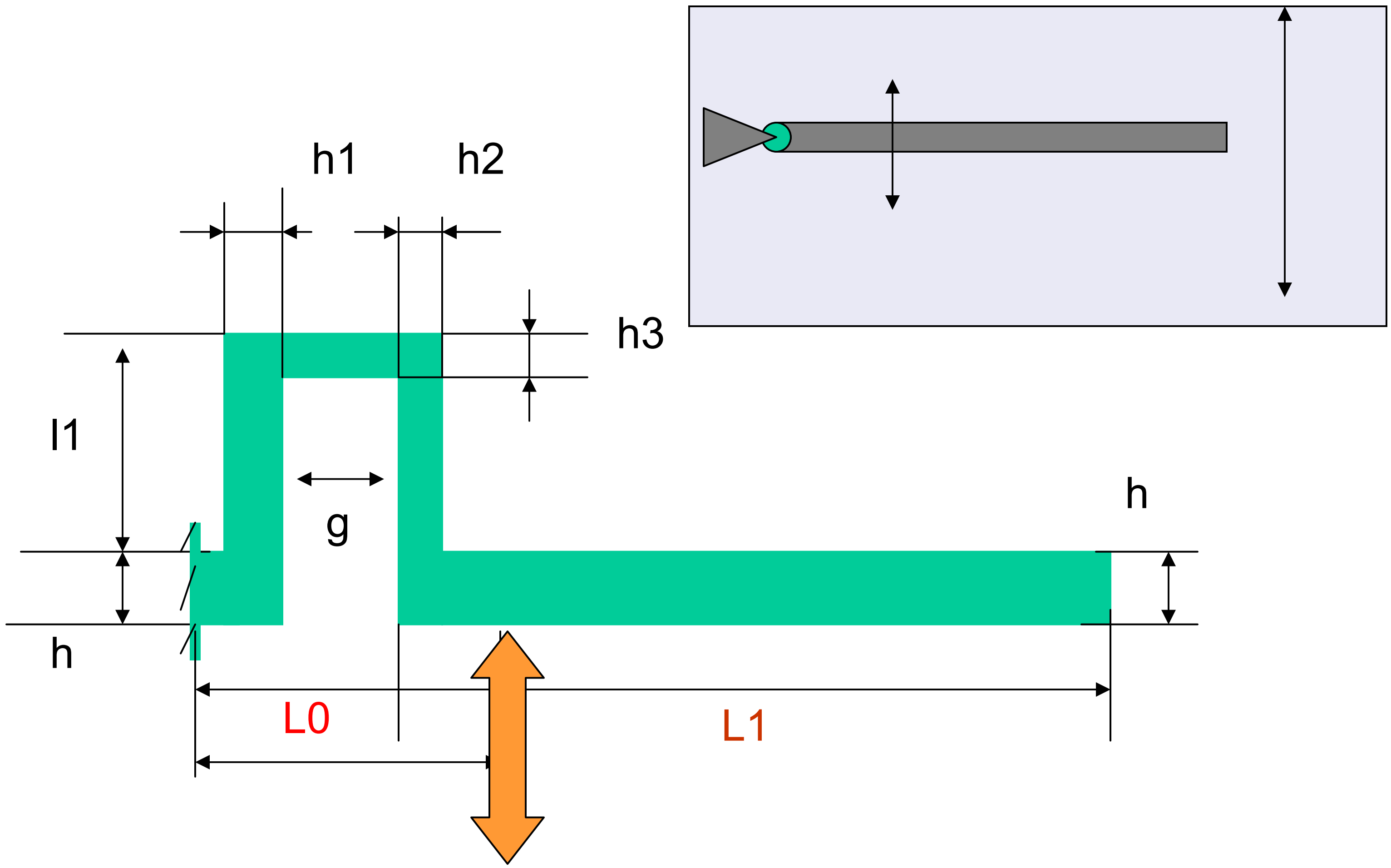
1. Low power and voltage for thin films
2. High force
3. Compact

Modified from P. Krulevitchet al, "Thin Film Shape Memory Alloy Microactuators," JMEMS Vol. 5, No. 4. 1996 pp 270-282.

Sang-Gook Kim, MIT

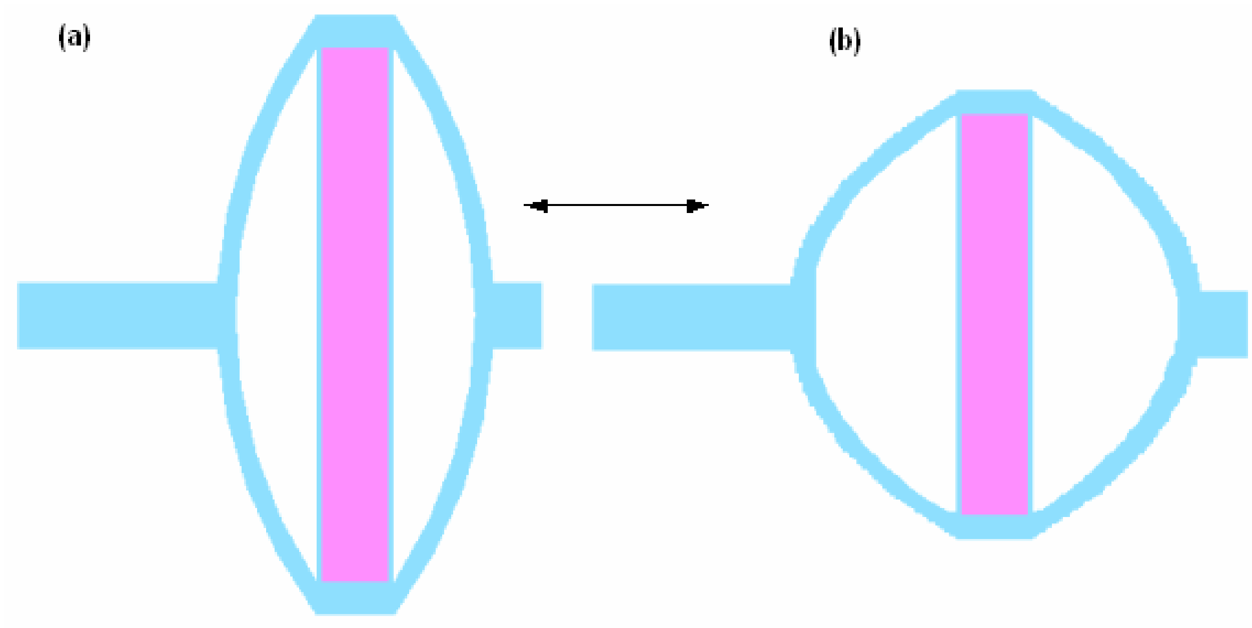
Figure by MIT OCW

Leveraged Amplification



Sang-Gook Kim, MIT

Bow Strain Amplifier



US Patent pending, N. Conway, S. Kim

Amplification depends on 2 factors

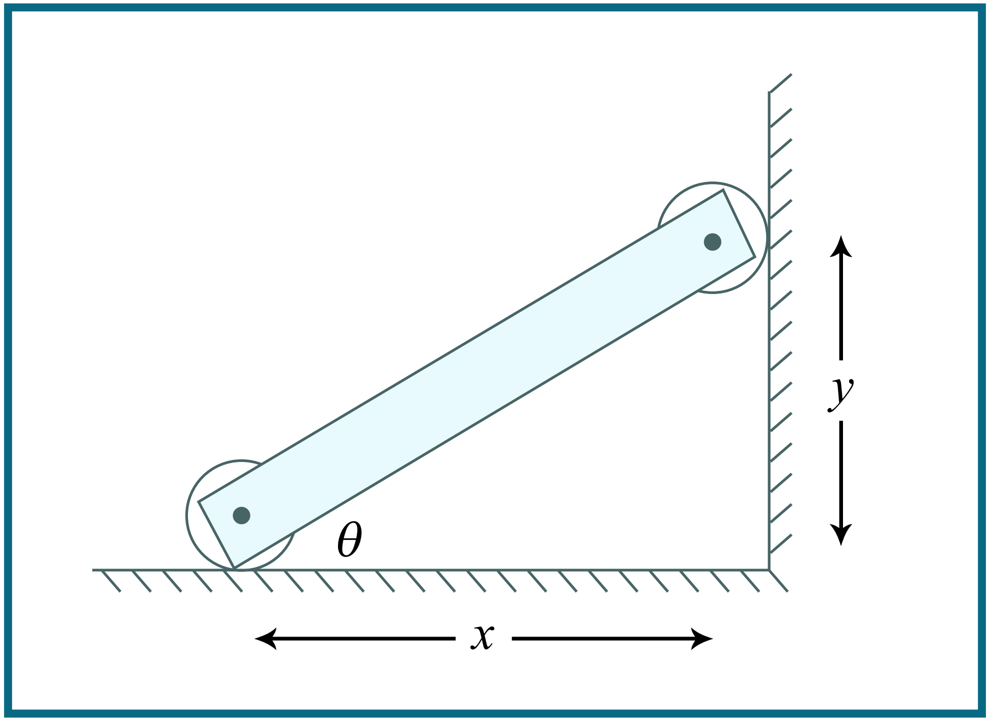
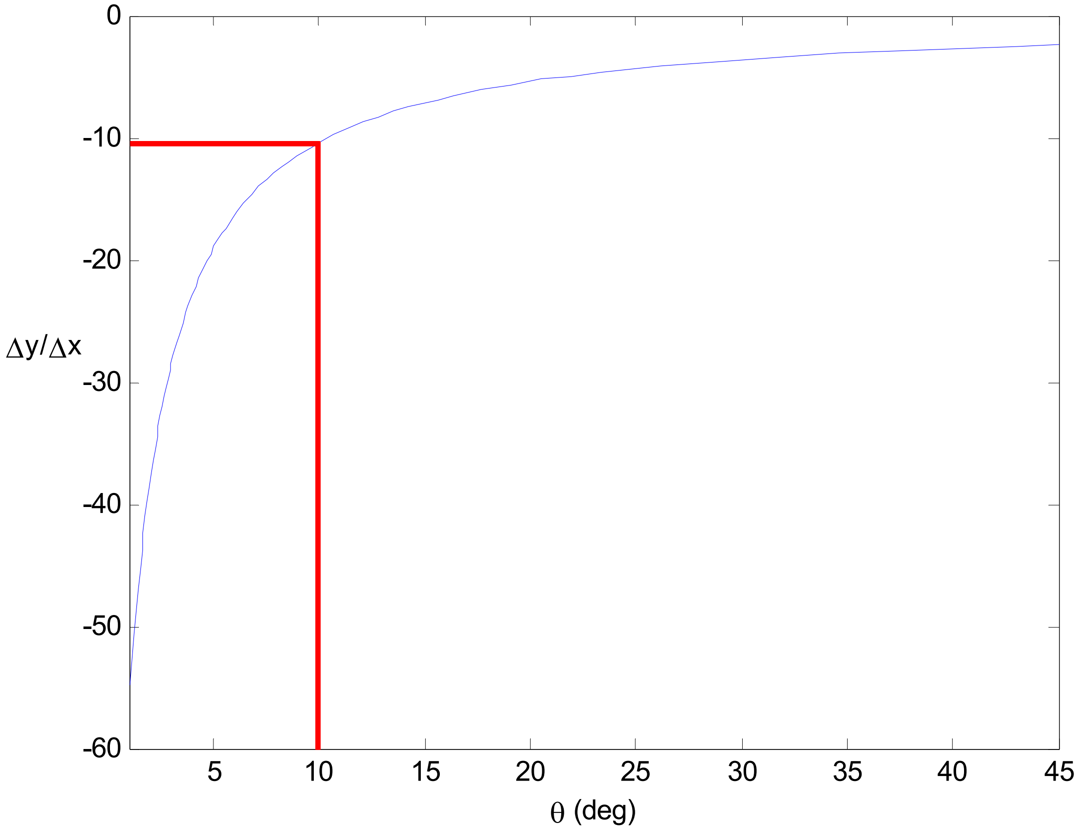


Figure by MIT OCW.

θ_0 = initial angle

$$\frac{\Delta y}{\Delta x} = \frac{\sin\theta - \sin\theta_0}{\cos\theta - \cos\theta} = -^{0}\cot\left(\frac{1}{2}\left(\theta + \theta_0\right)\right)$$

Small angles yield enormous amplification



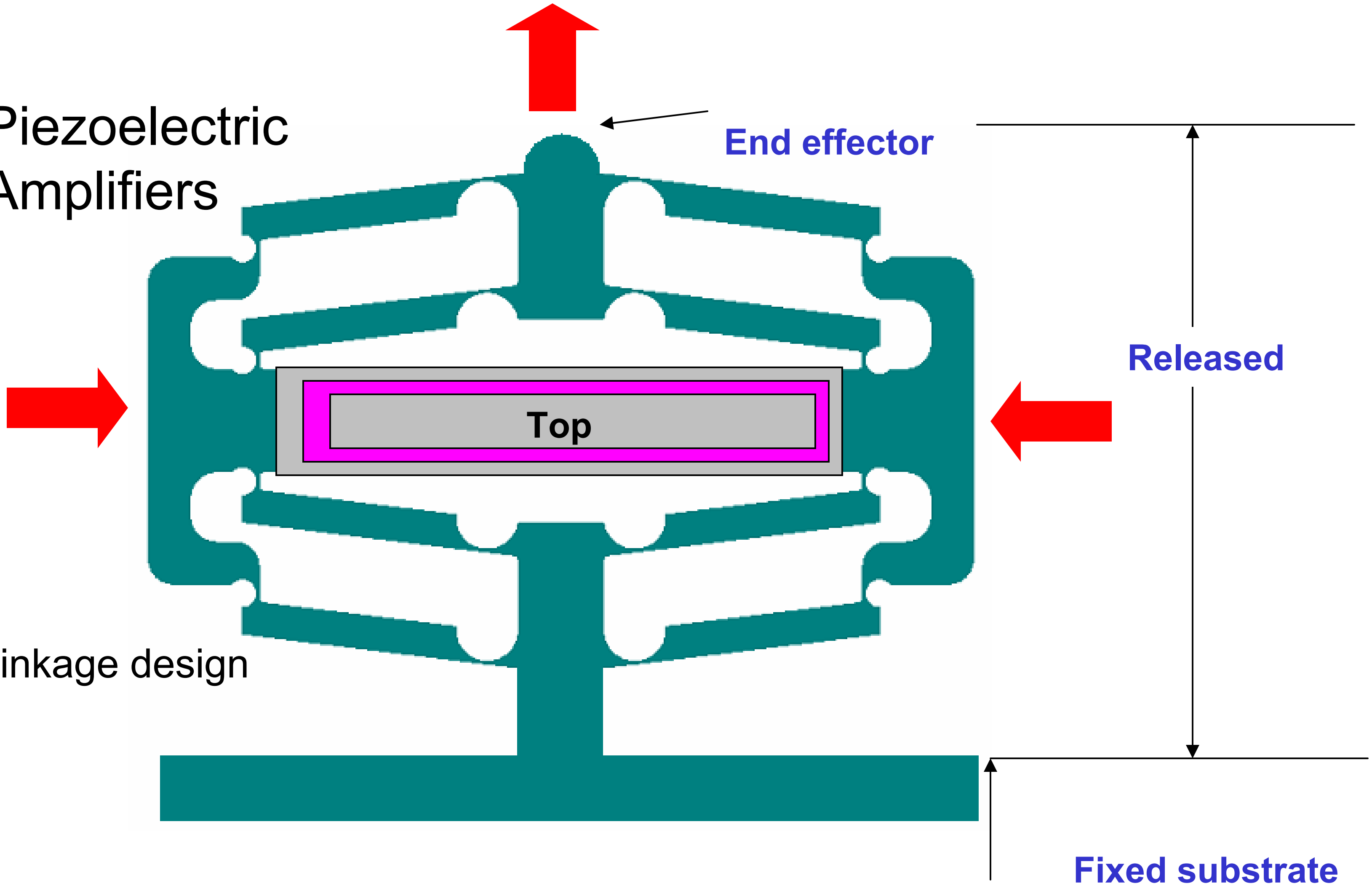
amplification

$\theta_0 = 1°$

MIT Bow-actuator

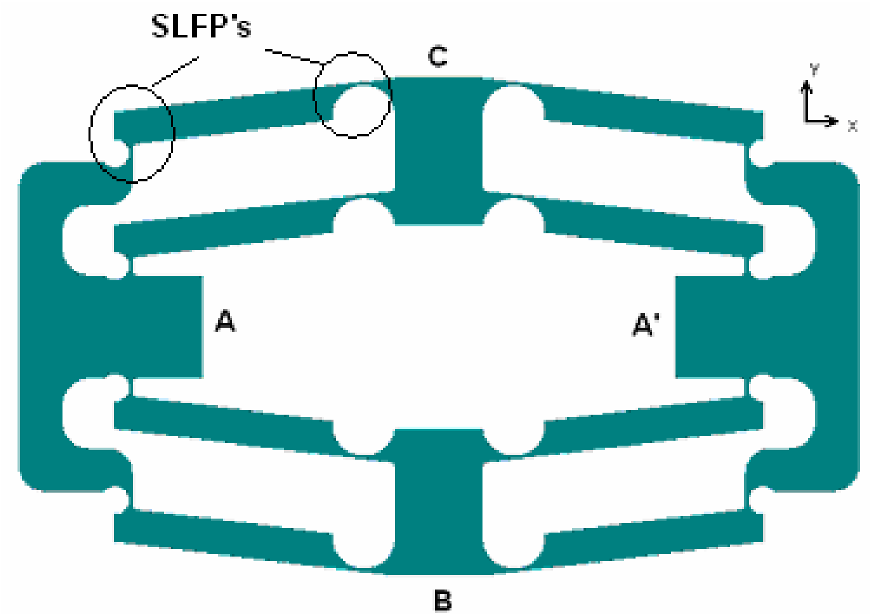
Nick Conway, MS 2003

Piezoelectric Amplifiers

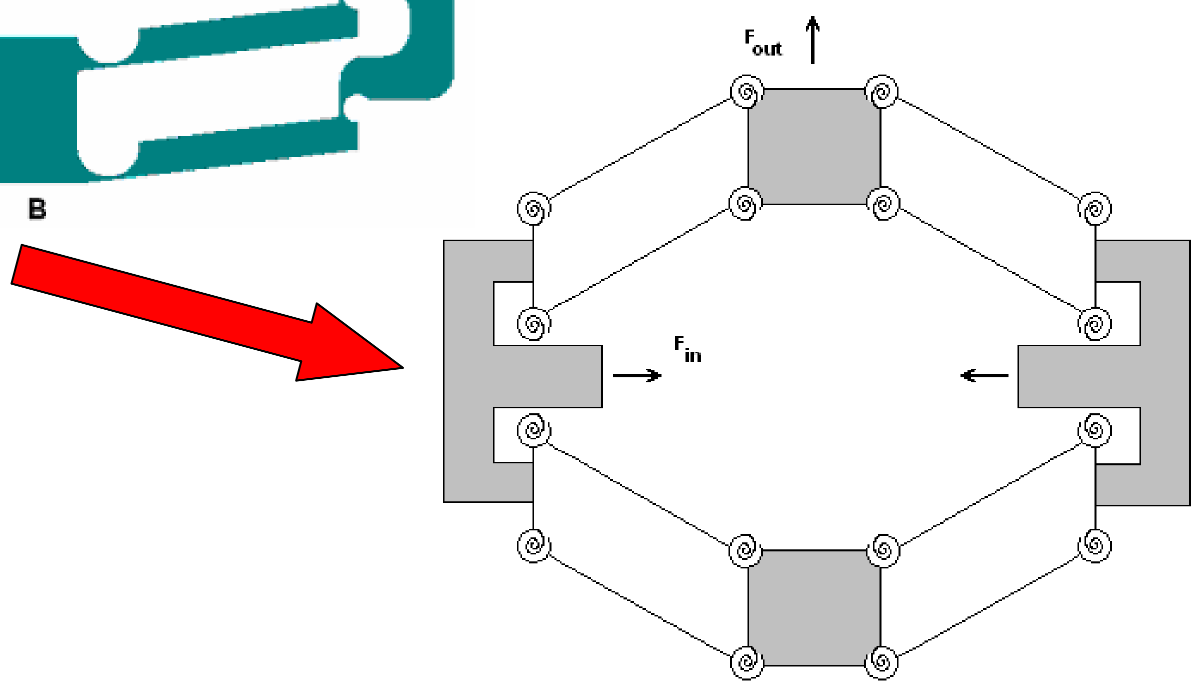


4-bar linkage design

Flexural pivots enable a parallel guiding linkage in a high aspect ratio structure.



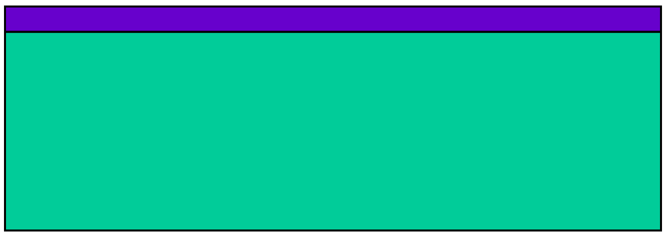
$$k_\theta \approx \frac{YI}{L}$$



Sang-Gook Kim, MIT

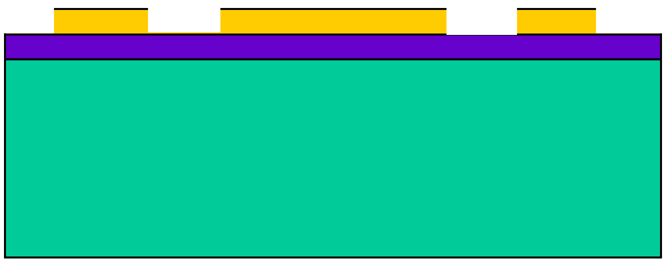
Process Flow 1- 4 mask process

1



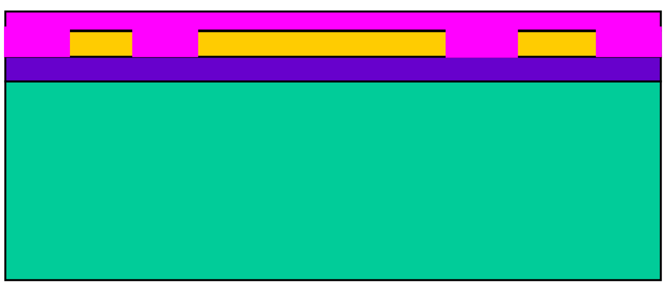
Deposit oxide (SiO_2) layer on Si substrate

2



Deposit and pattern Pt/Ti bottom electrode layer (#1)

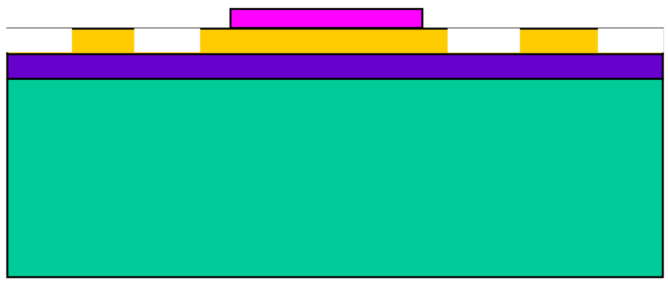
3



Spin-on PZT

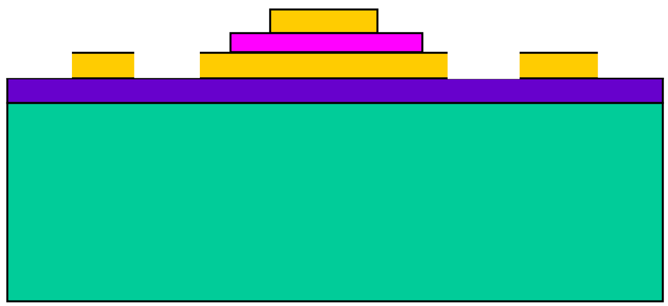
Process Flow 2

4



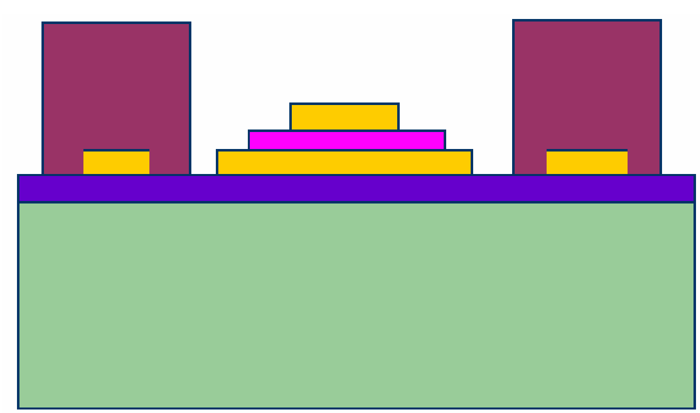
Pattern then anneal PZT (#2)

5



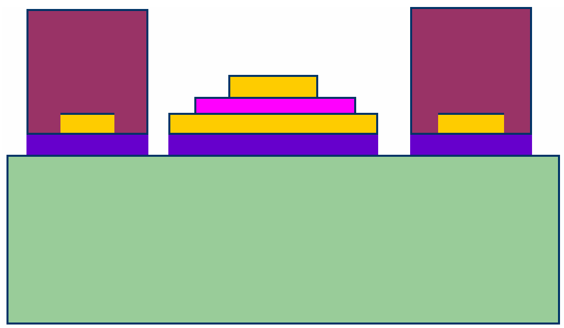
Deposit top electrode (platinum) (#3)

6

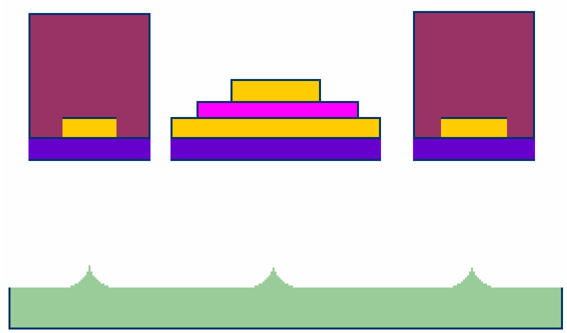


Spin-on SU-8 (30 μm) and cure, expose, and develop (#4)

Process Flow 3

7 

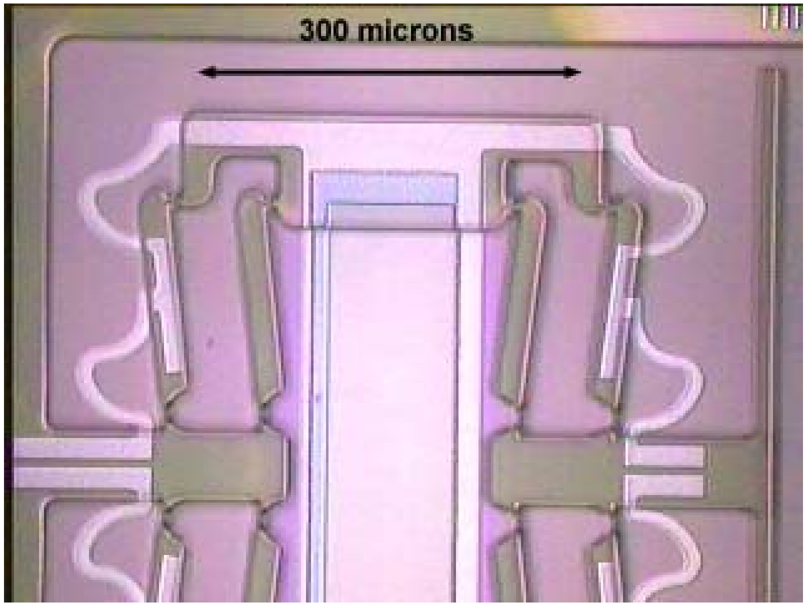
RIE oxide

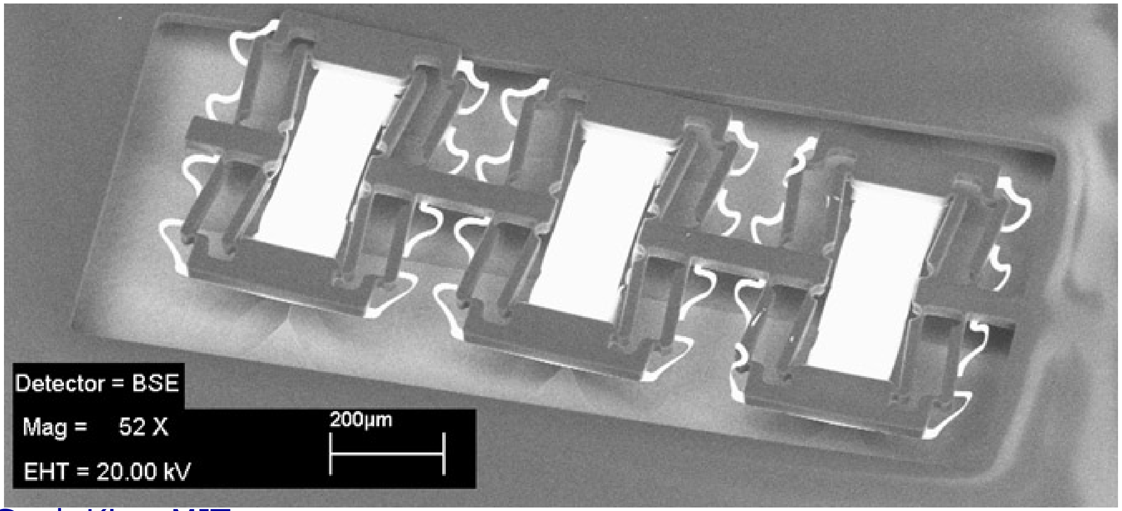
8 

XeF_2 etch away Si to release actuator

Finished

Note: SU-8 non-conducting.





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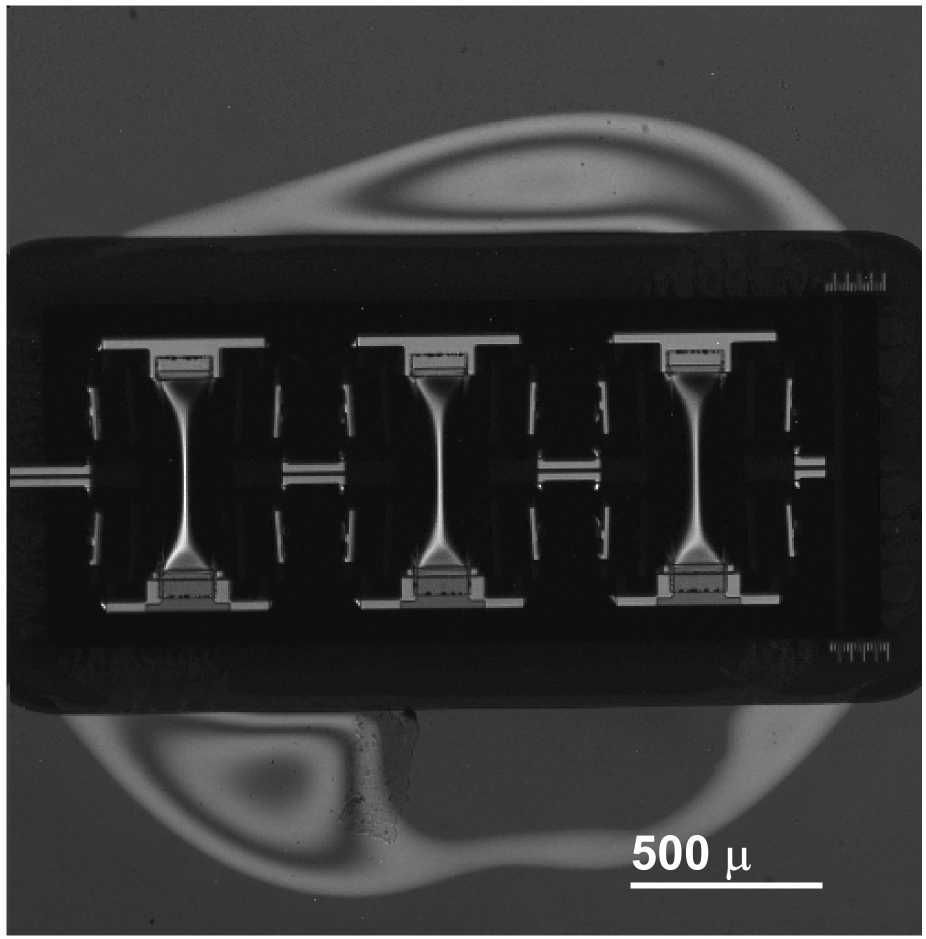
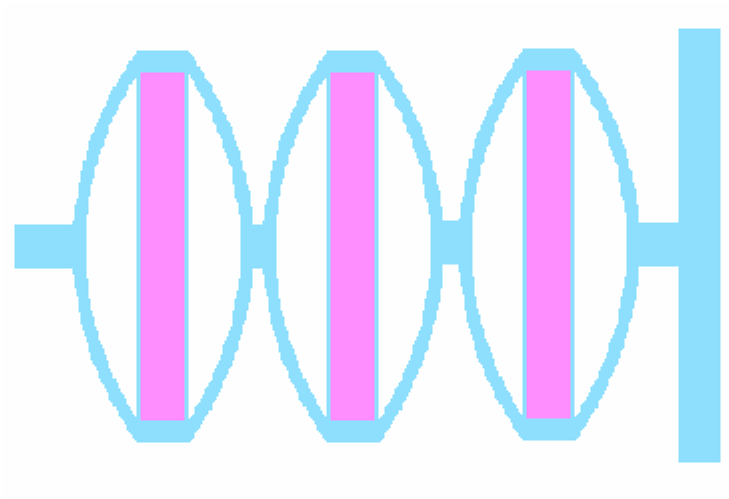
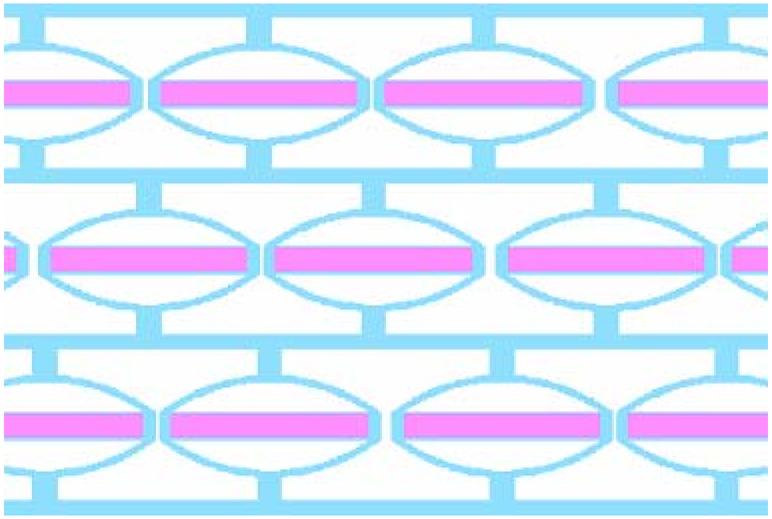
MEMS-Strain-Amplifier

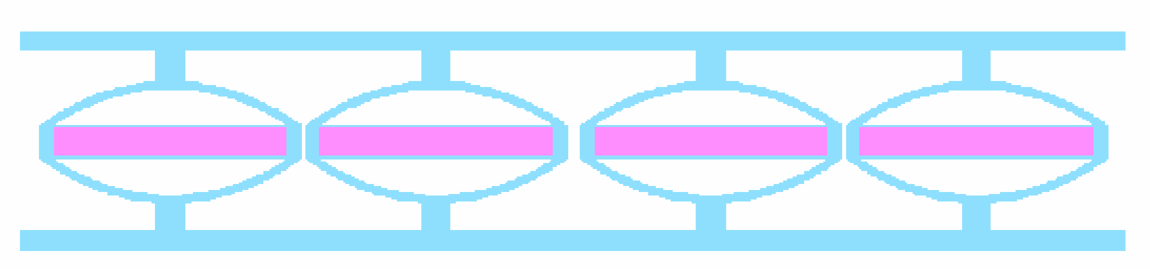


Nick Conway, Micronanosystems Laboratory, MIT

Arrayed configurations – Cellular analog digital actuation

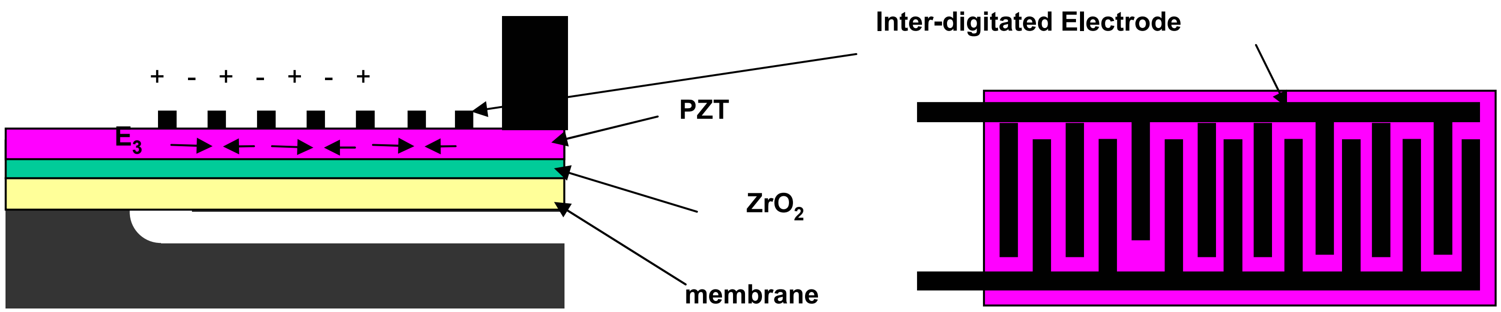


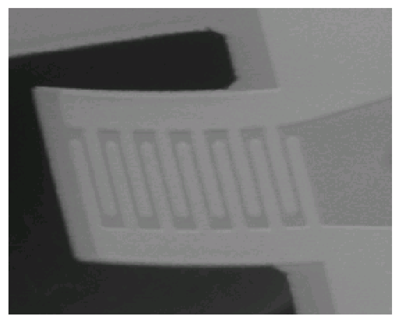




Sang-Gook Kim, MIT

Case: Piezoelectric Micro Power Generator





MIT Media Lab, Shoe Power

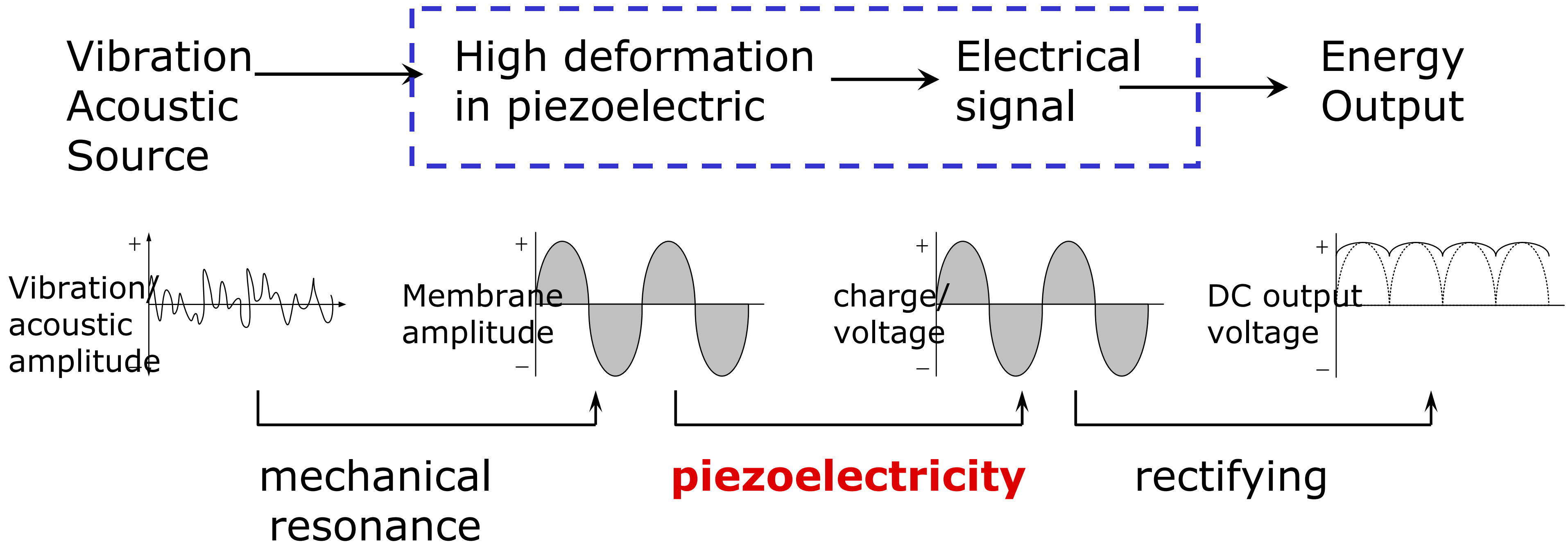
MIT EECS, Chandrakasan Energy Amplifier

Comparison of Energy Scavenging

Energy Source	Power Density for 10 Years
Solar (outdoor)	15,000 $\mu W/cm^3$
Solar (indoor)	6 $\mu W/cm^3$
Vibrations (piezoelectric)	250 $\mu W/cm^3$
Vibrations (electrostatic)	50 $\mu W/cm^3$
Acoustic noise	0.003 $\mu W/cm^3$(at 75 dB)
Temperature gradient	15 $\mu W/cm^3$(at 10 ^oC gradient)
Batteries (non-rechargeable)	3.5 $\mu W/cm^3$ (45 $\mu W/cm^3$ one year life)
Batteries (rechargeable)	0 $\mu W/cm^3$ (7 $\mu W/cm^3$ one year life)
Hydrocarbon fuel (micro heat engine)	33 $\mu W/cm^3$ (330 $\mu W/cm^3$ one year life)
Fuel cells (methanol)	28 $\mu W/cm^3$ (280 $\mu W/cm^3$ one year life)

Shad Roundy, Paul K. Wright, Jan Rabaey, Computer Communications xx(2003) 1-14

Energy Harvesting Concept with Piezoelectricity

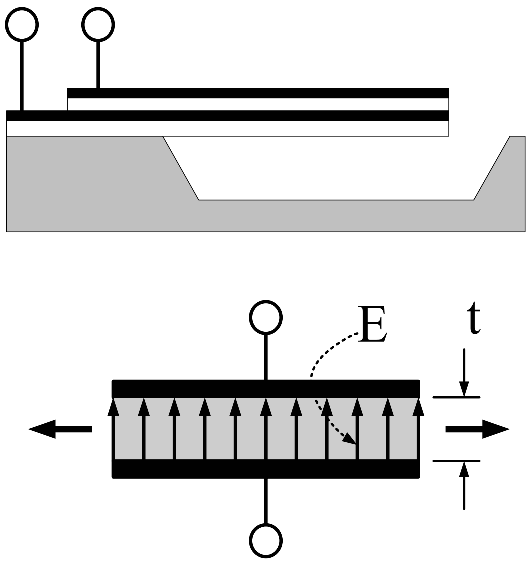


- Energy conversion efficiency (η_p)
  η_p = generated energy/input energy
  ≈ 65 to 78 % → JMM, 14, 717
- No voltage source needed
- Open circuit voltage: 3~15V

Sang-Gook Kim, MIT

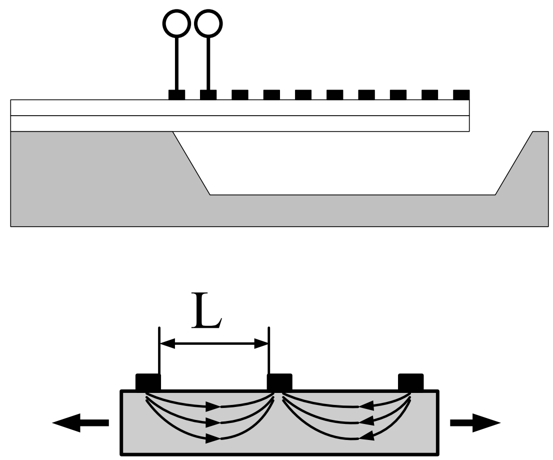
Piezoelectrics

d mode



V = t g

d mode



V = Lg

$V_{33} = 2L / t_{pzt} \bullet V_{31} \cong 20 \bullet V_{31} \cong 3\ V$

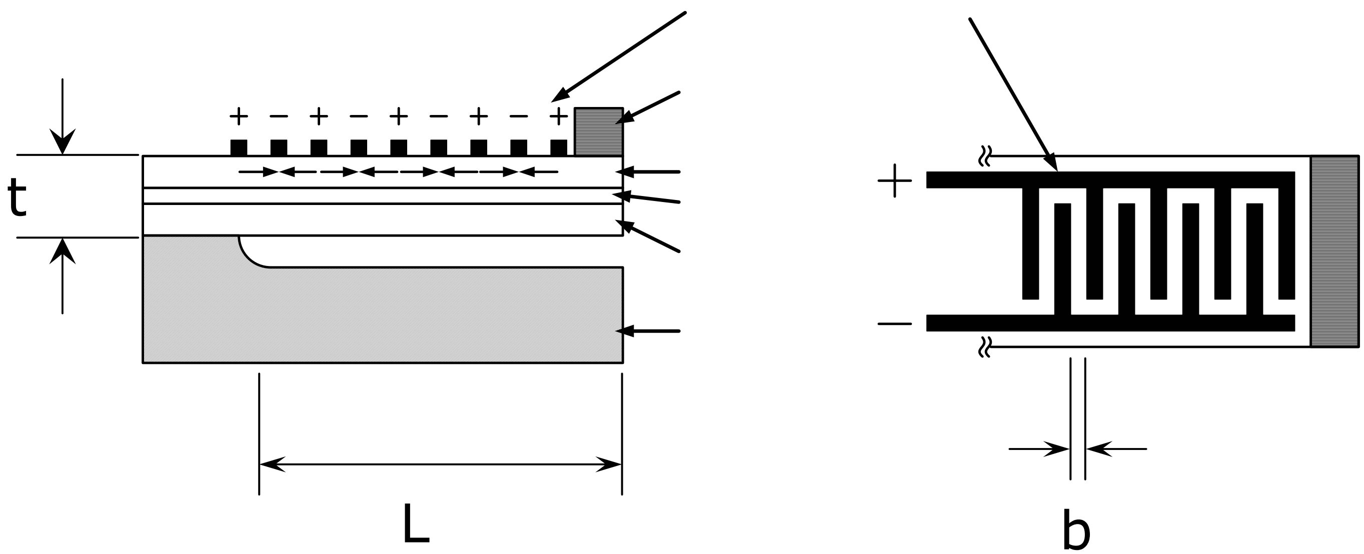
$g_{33} > 2g_{31}$

$L \sim 10t_{pzt}$

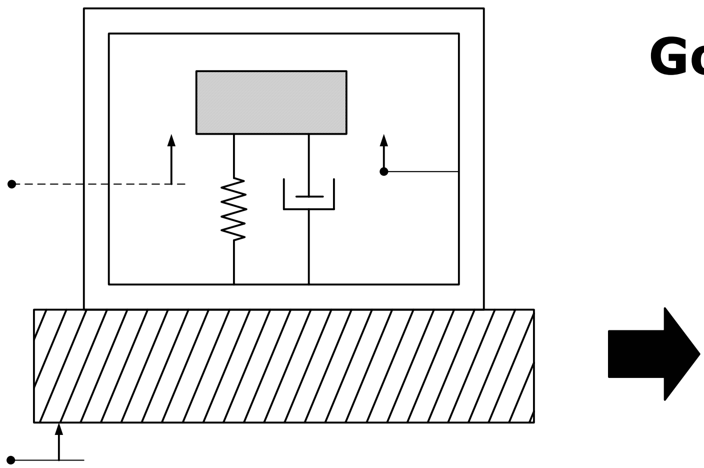
Sang-Gook Kim, MIT

Device Design

- High strain: cantilever beam, proof mass
- High open-circuit voltage:
  d_{33} interdigitated electrodes



Device Modeling



Governing equation for seismic excitation

$$m\ddot{z}_o = -b_m\dot{z}_o - kz_o + (EMC) - m\ddot{z}_i$$

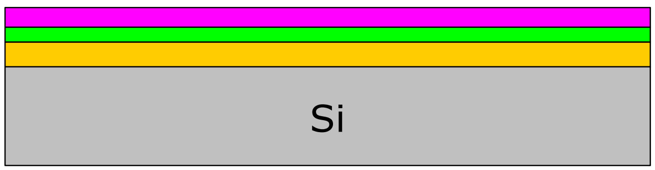
$$m\ddot{\delta} + b_m\dot{\delta} + k\delta - k\frac{d_{33}V_L}{b} = \frac{3t}{4L^2}m\ddot{z}_i$$

Open Circuit Voltage of PMPG

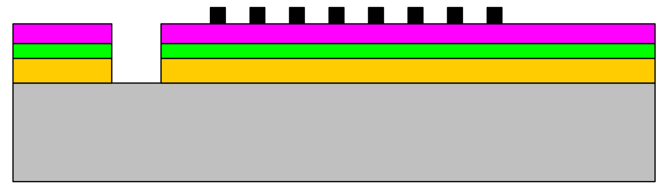
$$V_s = bE = -\frac{bd_{33}Y}{\varepsilon\left(1 - k_{33}{}^2\right)}\delta$$

Y: Young's modulus
δ: strain
d: piezoelectric coeff.
K_{33}: coupling constant

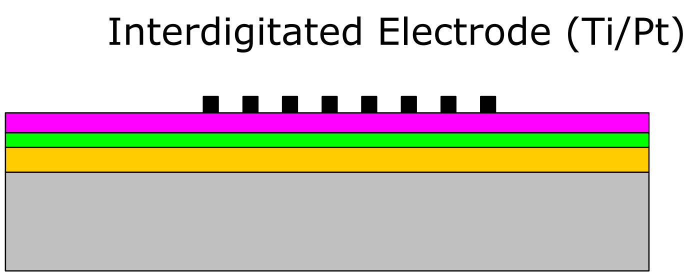
Device Fabrication



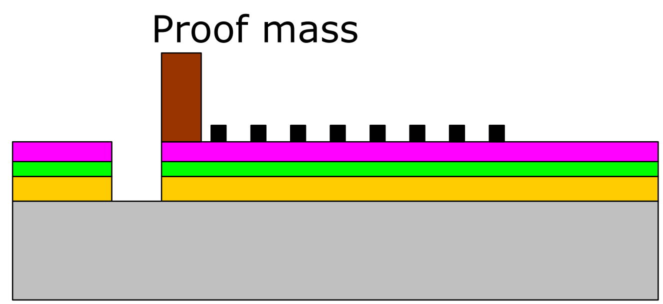
(a) Films deposition (CVD, spinning)



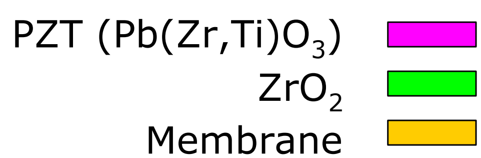
(c) Films patterning (RIE)



(b) Top electrode deposition (e-beam) and then lift-off

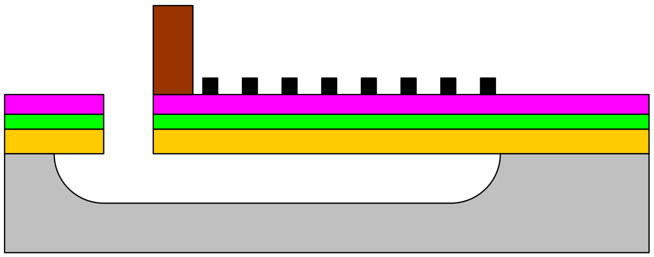


(d) Proof mass (SU-8, spinning)

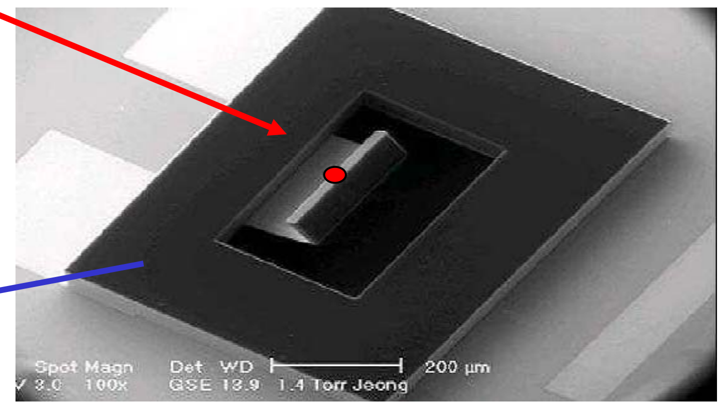


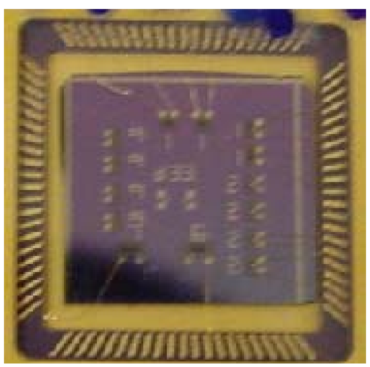
Sang-Gook Kim, MIT

Device Fabrication (II)



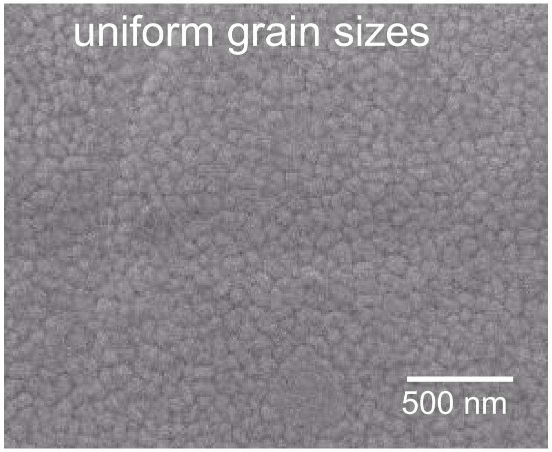
(e) Cantilever release (XeF_2 etcher)

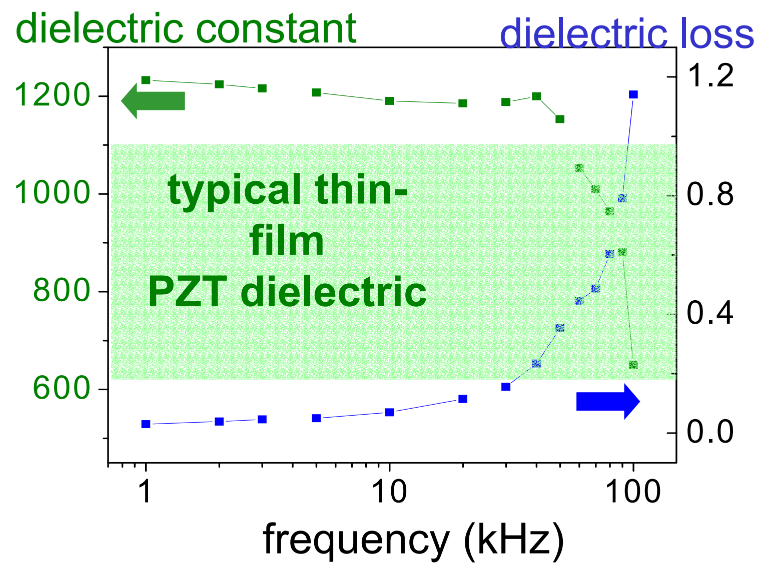




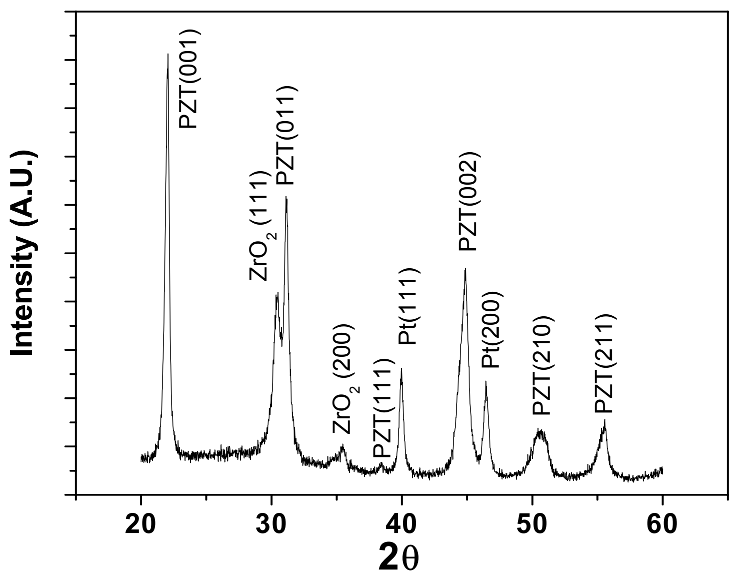
(f) Packaging & PZT poling

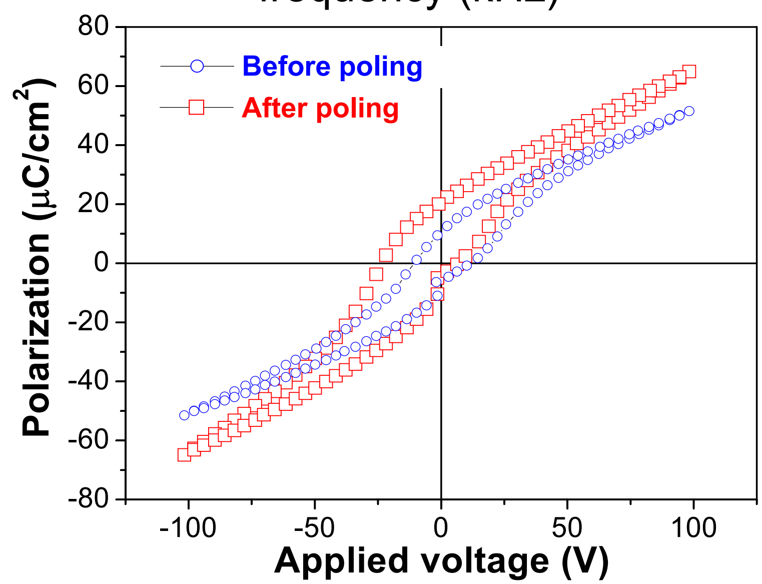
Characterization of PZT films





XRD peaks of PZT film





Sang-Gook Kim, MIT

PZT characterization

High performance PZT thin film

-d_{33}=200 pC/N, d_{31}=-100 pC/N,

-ε=1200,

-$\tan\delta$=0.02 at 15 kHz

Cantilever Bow Control

Photos removed for copyright reasons.
Source: Jeon, Y.B., R. Sood, J.H. Joeng and S.G. Kim. "Piezoelectric Micro Power Generator for Energy Harvesting." Sensors and Actuators A: Physical, accepted for publication, 2005.

ZrO_2(0.05um)/
thermal oxide(0.4um)

(A)

→ Towards Tensile stress

ZrO_2(0.05um)/
PECVD oxide(0.4 um)

(B)

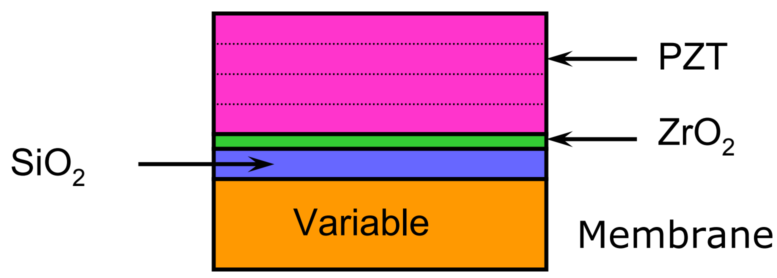
→ Towards High elastic modulus

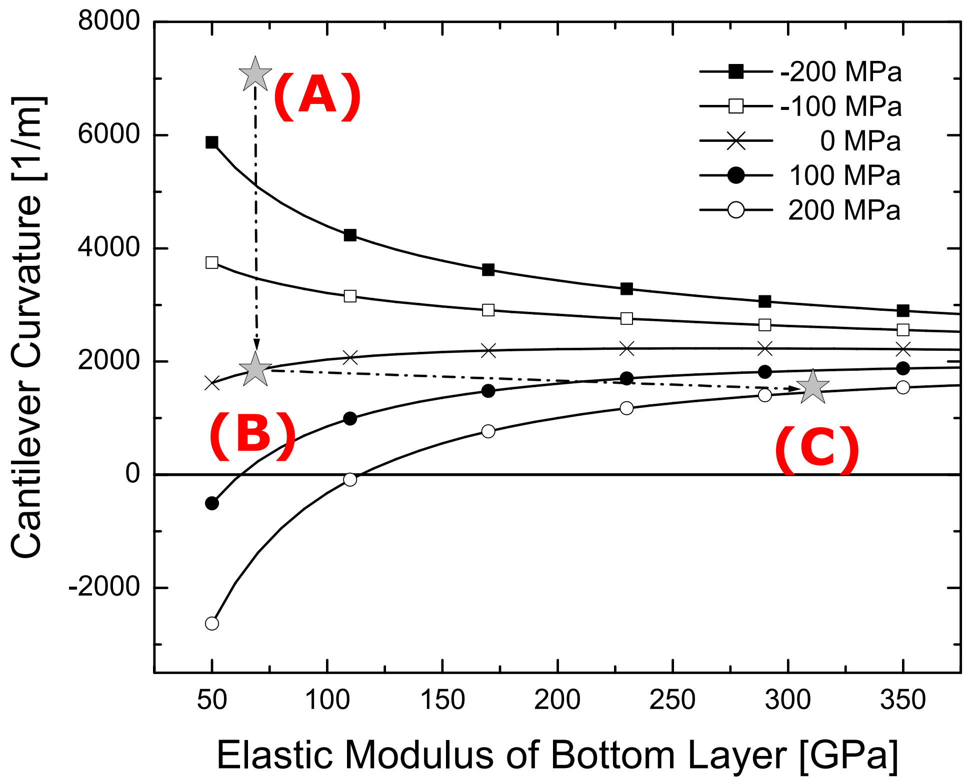
ZrO_2(0.05um)/
PECVD oxide(0.1um)/
LPCVD nitride(0.4um)

(C)

Cantilever Bow Control (II)

Cantilever Beam Structure





Sang-Gook Kim, MIT

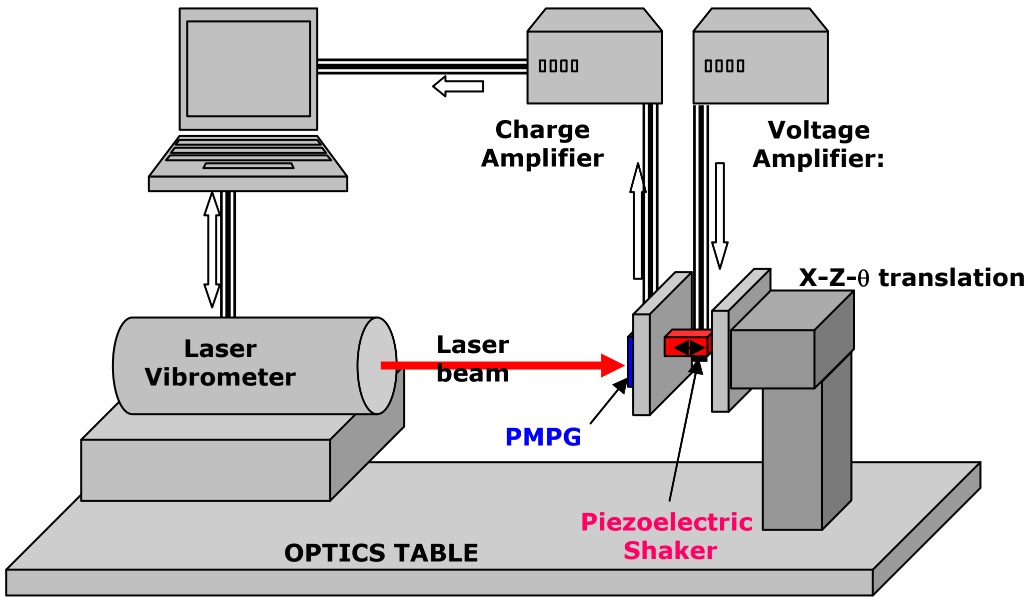
Fabricated PMPG devices

Photos removed for copyright reasons.
Source: Jeon, Y.B., R. Sood, J.H. Joeng and S.G. Kim. "Piezoelectric Micro Power Generator for Energy Harvesting." Sensors and Actuators A: Physical, accepted for publication, 2005.

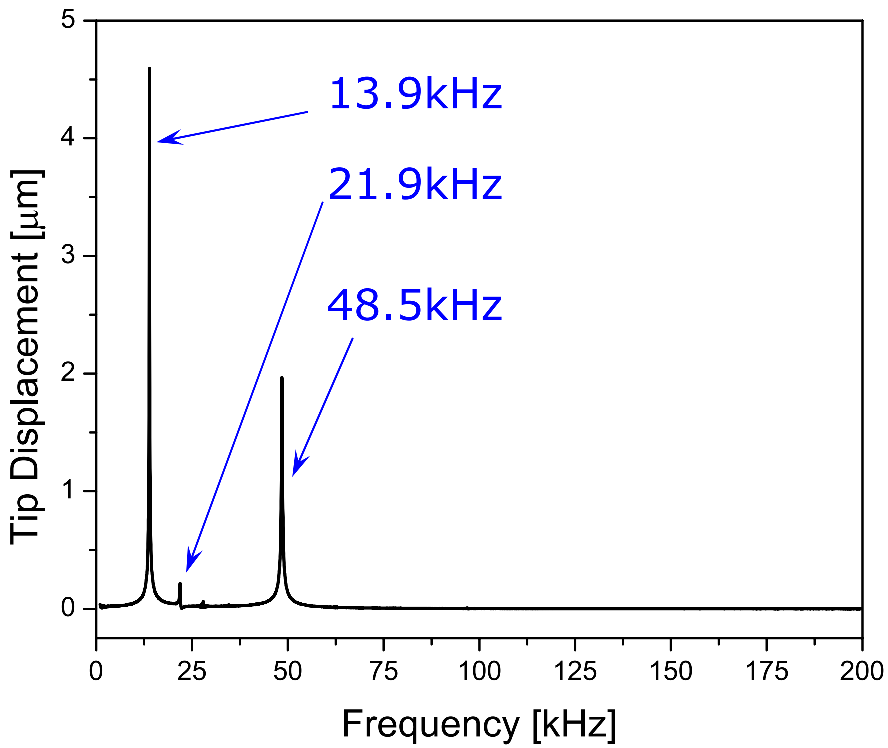
Top view of PMPG **SEM image of PMPG**

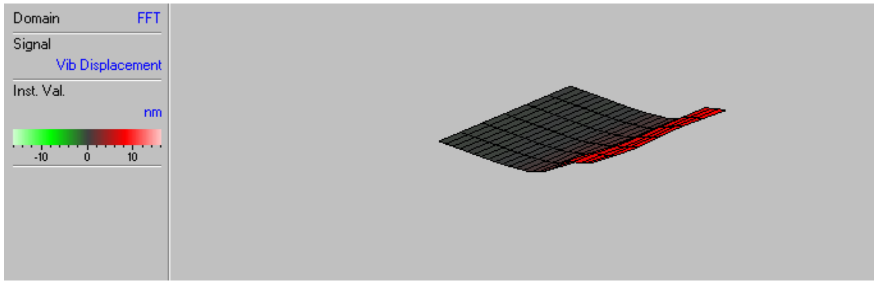
Multiple cantilever device **SEM image of PMPG**

Set-up for measurement

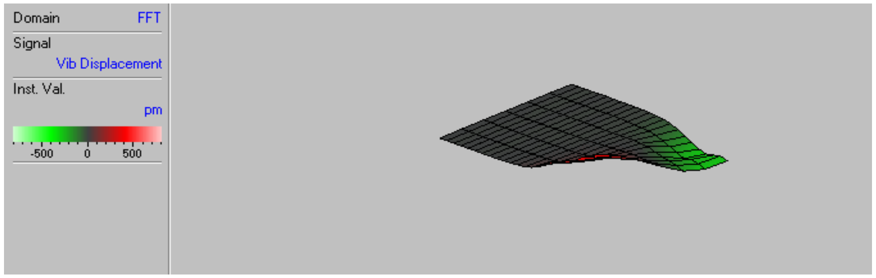


Resonant Response of Cantilever Tip

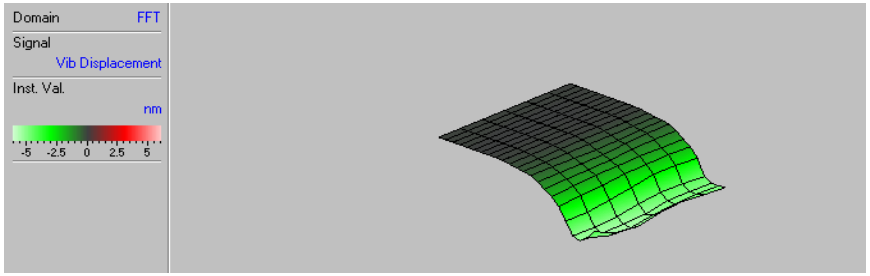




1st mode at 13.9 kHz



2nd mode at 21.9 kHz

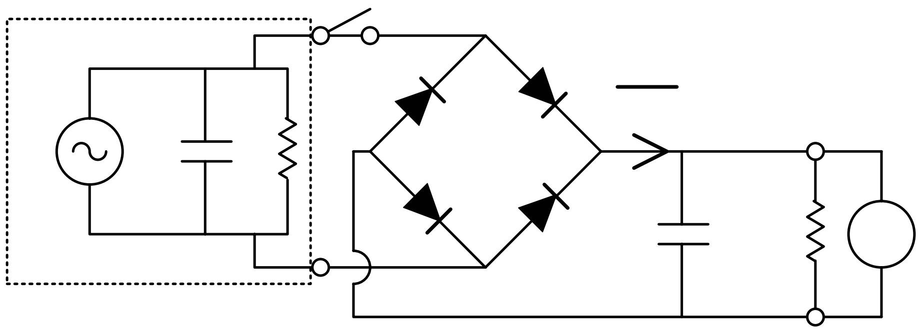


3rd mode at 48.5 kHz

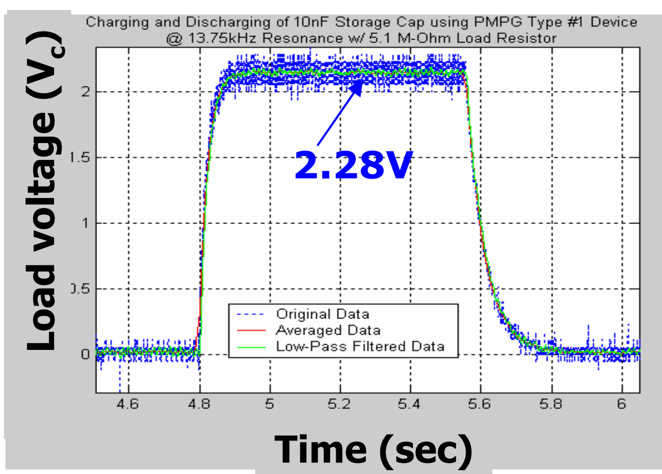
Sang-Gook Kim, MIT

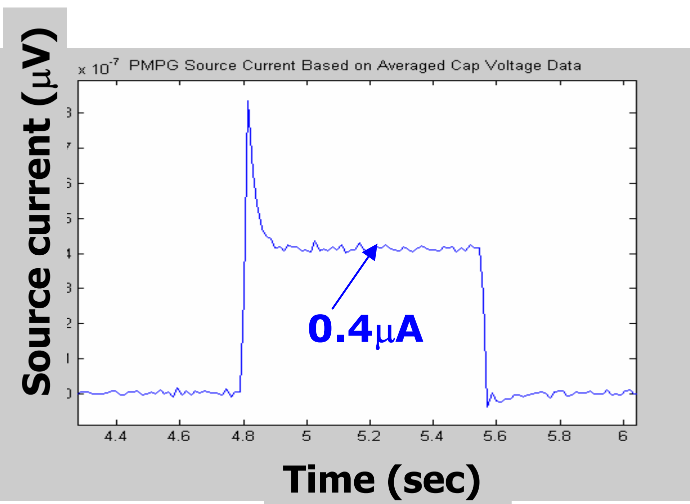
Power Generation

- First mode of resonance at 13.9 kHz with 14 nm amplitude
- Rectifying the AC signal, then store the charge
- Variation of load resistance

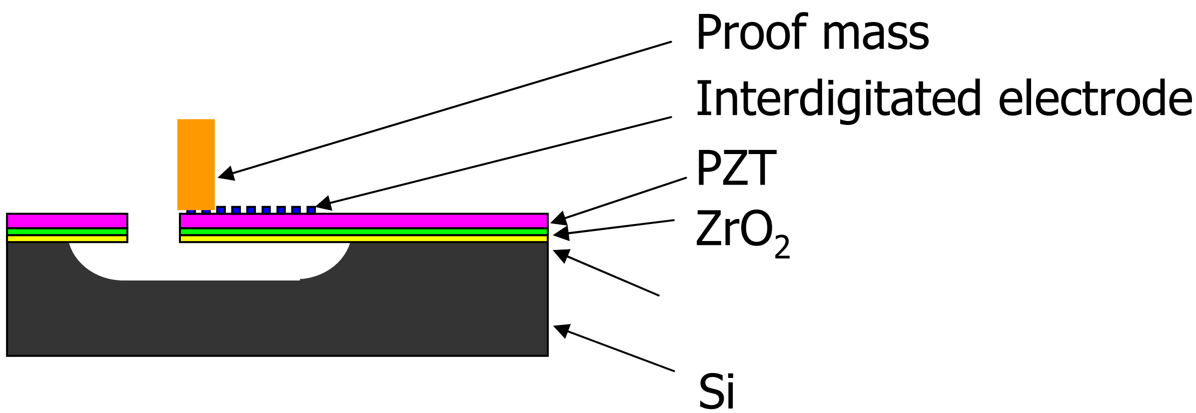


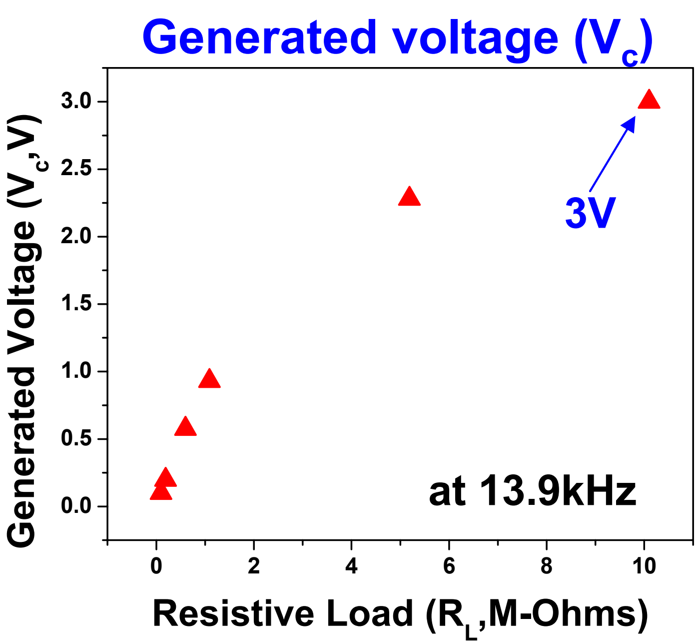
Schottky diodes: smallest forward voltage drop
10 nF mylar cap: low leakage current

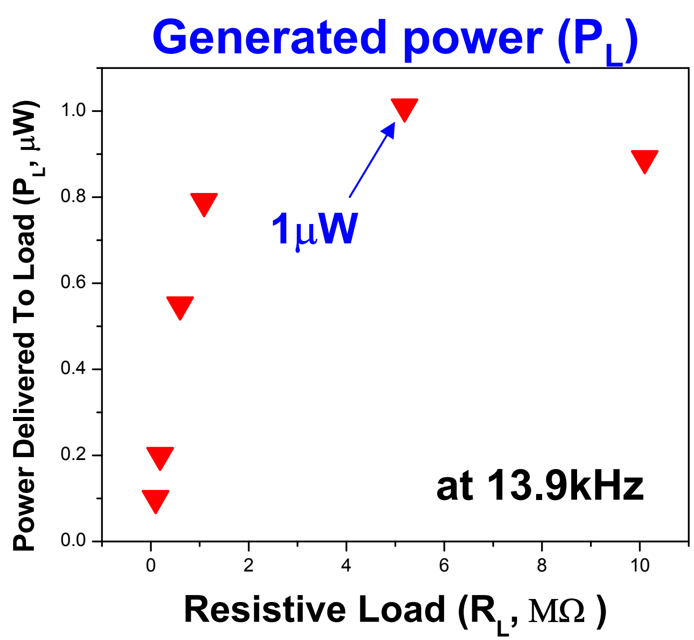




Measurement of generated power







Y. Jeon, R. Sood, and S.G. Kim, Hilton Head Conference 2004

Summary

Characteristic	Li/MnO_2	$Li/LiCoO_2$	PMPG
Nominal OCV	3.1 V	4 V	3V
Internal Construction	Spiral	Thin Film	MEMS Packaging
Hermeticity	Nonhermetic	Nonhermetic	Excellent
Energy Density	637 Wh/L	0.8 mWh/cm^2	0.74 mWh/cm^2
Operating Temperature	-20~60°C	-50~180°C	-20~80°C
Storage Conditions	10 years	60,000 cycles (charge/discharge)	Infinite

- Energy conversion efficiency (η_p)
  η_p = generated energy/input energy
  $\approx$ 65 to 78 %
- No voltage source needed
- Open circuit voltage: 3V

Sang-Gook Kim, MIT

Power depends on

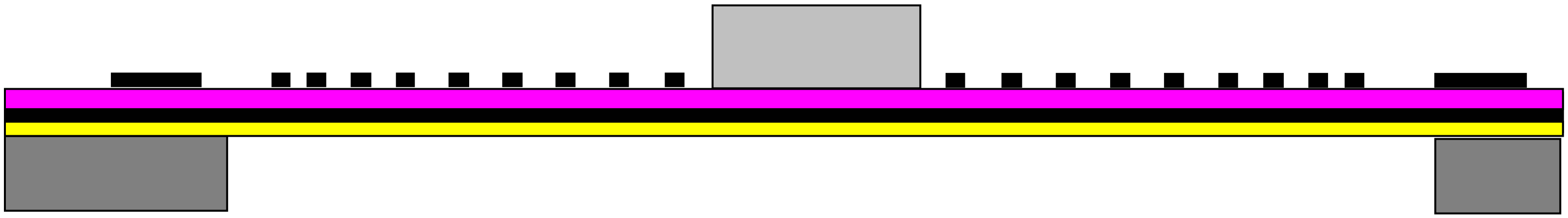
- Resonant Frequency
- Internal Capacitance and Resistance
- External Capacitance and Load Resistance
- Mechanical damping
- Membrane structure
- Electrode shape

- Bow control?
- Multi-cantilever → Multiple bridges?

New Design for
Efficient Power Harvesting

Sang-Gook Kim, MIT

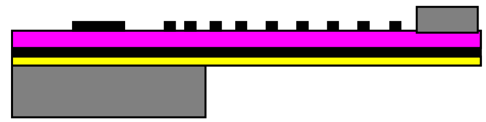
In progress,



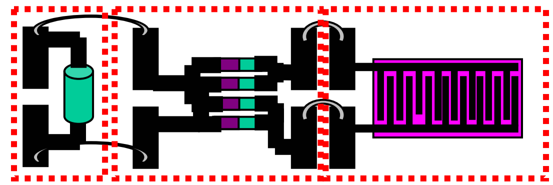
- High resonant frequency products
  - Bridge Structures vs. Cantilevers
  - Smart bearings
- Low resonant frequency structures
  - Scavengers
- Monolithic Device Design
  - Mechanical Rectifiers

Self-supportive Wireless Sensors

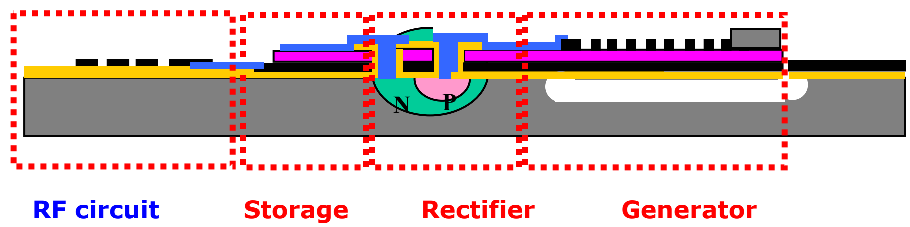
Design and fabrication



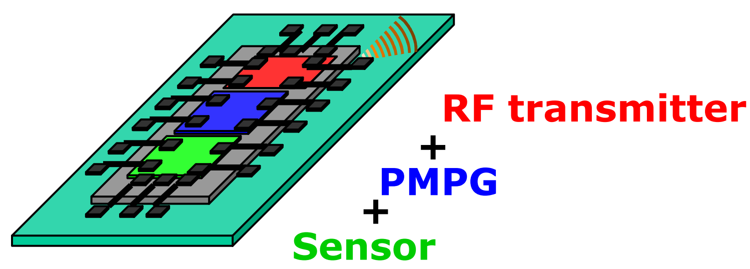
Concept prove



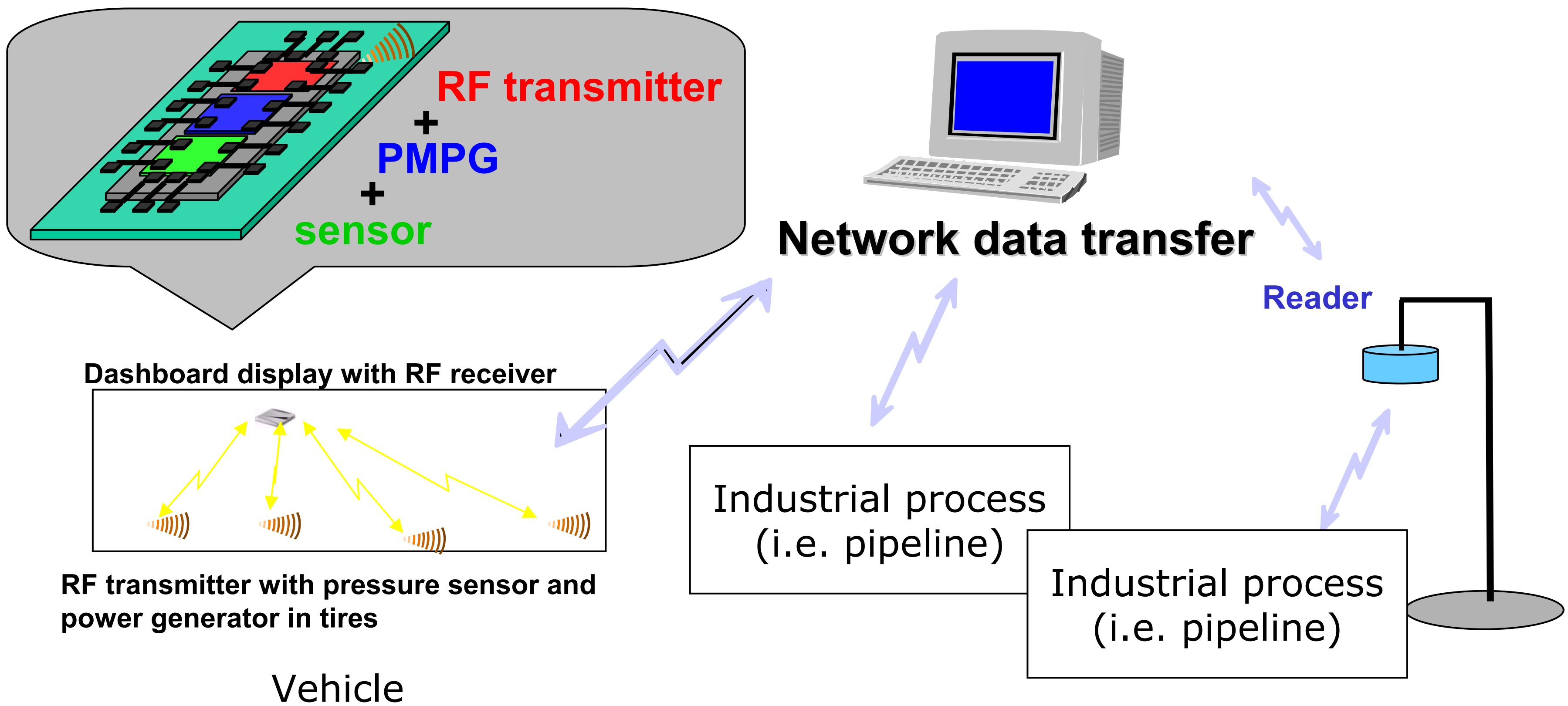
New Design & PMPG integration



On chip RFID with PMPG and Sensor



Wireless Sensing Applications



Self-supportive Sensors

Sang-Gook Kim, MIT

Can we avoid disasters?

Belgian gas pipe blast kills 15, destroys plants

Photo removed for copyright reasons

GHISLENGHIEN (Belgium) July 30 - A huge blast on a leaking gas pipeline in Belgium on Friday sent giant fireballs in the air and catapulted bodies hundreds of metres in the biggest industrial disaster in the country's recent history.

At least 15 people were killed and more than 100 injured when the explosion ripped through the underground pipeline in the industrial zone of Ghislenghien, near the town of Ath, 40 km (25 miles) southwest of Brussels.

PICTURE shows the cut gas pipeline which exploded at an industrial estate in Ghislenghien, southern Belgium, July 30. - AFPpix.