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Misconceptions in Piezoelectric Energy Harvesting System Development

Kenji Uchino

International Center for Actuators and Transducers
The Pennsylvania State University, University Park, PA 16801

* Corresponding author: kenjiuchino@psu.edu

PennState

Bio-History of Kenji Uchino

- **University professor = 46 years**

  Tokyo Tech–10 yrs Sophia Univ–8 yrs Penn State–30 yrs

- **Company executive = 21 years**

  NF Electronics – 7 yrs Micromechatronics – 7 yrs

- **Government Officer = 7 years**

  NASDA (JAXA) – 3 yrs US ONR – 4 yrs

- **"Discover/Inventor"**

  Pioneer of "**Piezoelectric Actuators**"
  Relaxor single crystals (PZN-PT, PMN-PT)

- **"Educator"**

  Engineering – Ferroelectric Devices, Micromecha-tronics, Application of FEM, "**Business Ethics**"
  Business – **Entrepreneurship for Engineers**
  Politico-Engineering – Global Crisis Technologies

- **Buddhist = "Zen" Practitioner**


Series Editor: Harry L. Tuller
HIGH-POWER PIEZOELECTRICS AND LOSS MECHANISMS
KENJI UCHINO
CRC Press
圧電/電歪アクチュエータ
基礎から応用まで
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Misconceptions in Piezoelectric Energy Harvesting System Development

Kenji Uchino

Int'l Center for Actuators & Transducers
The Pennsylvania State University, PA

1. **Background of Piezo-Energy Harvesting**
   Piezo-Dampers, Research Trends
2. **Figures of Merit in Energy Harvesting**
   d·g, EM Coupling factor, Energy transmission coefficient
3. **Mechanical Impedance Matching**
4. **Mechano-Electric Energy Transduction**
5. **Electrical Impedance Matching**
6. **Summary and Future**

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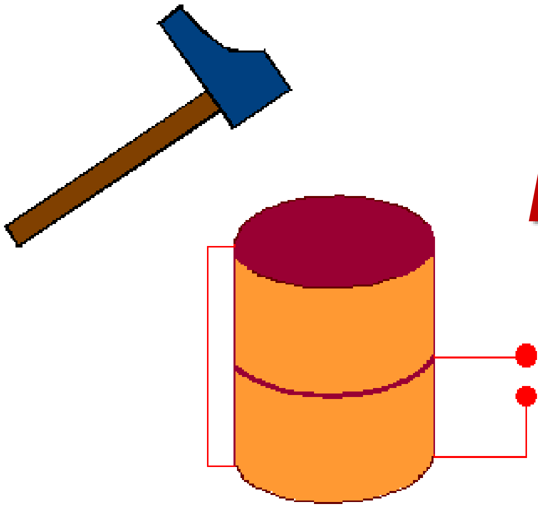
What's "Piezoelectric Effect"?

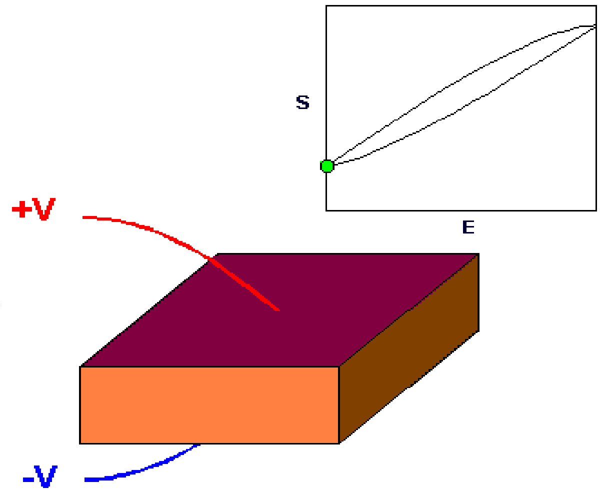
DIRECT PIEZOELECTRIC EFFECT



$$P = d X$$

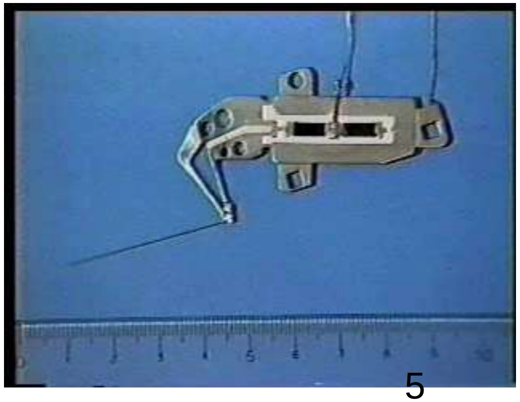
CONVERSE PIEZOELECTRIC EFFECT

$$x = d E$$



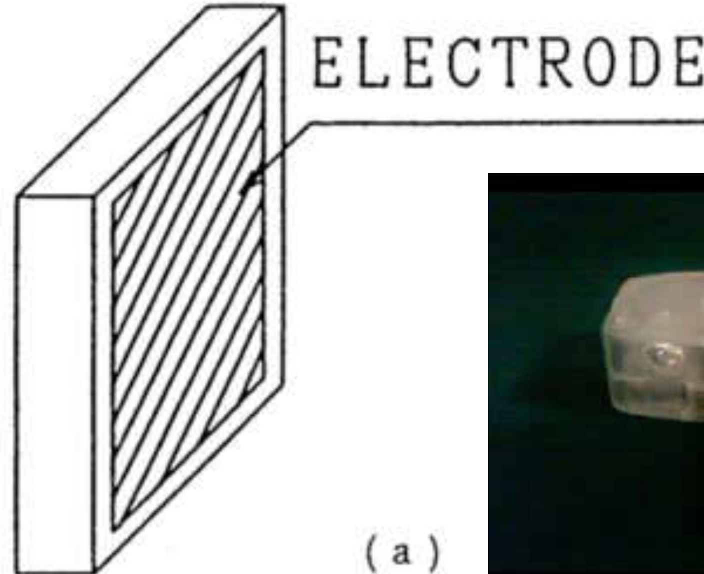
Igniter
Microphone
Pressure Sensor
Energy Harvest

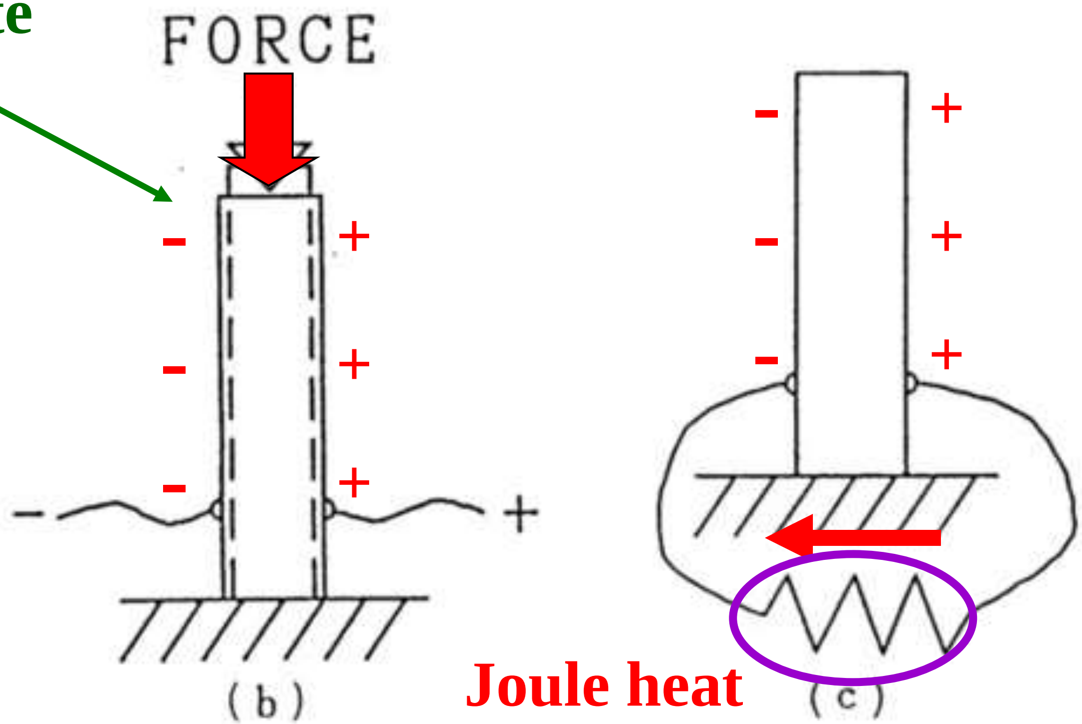
Clock
Speaker
Actuator



Piezoelectric Damper
1980s

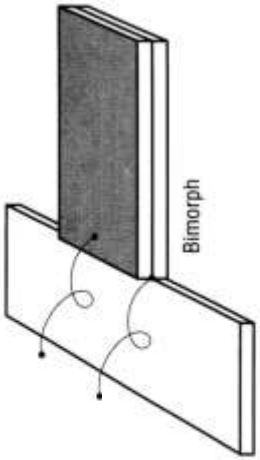
Piezoelectric plate

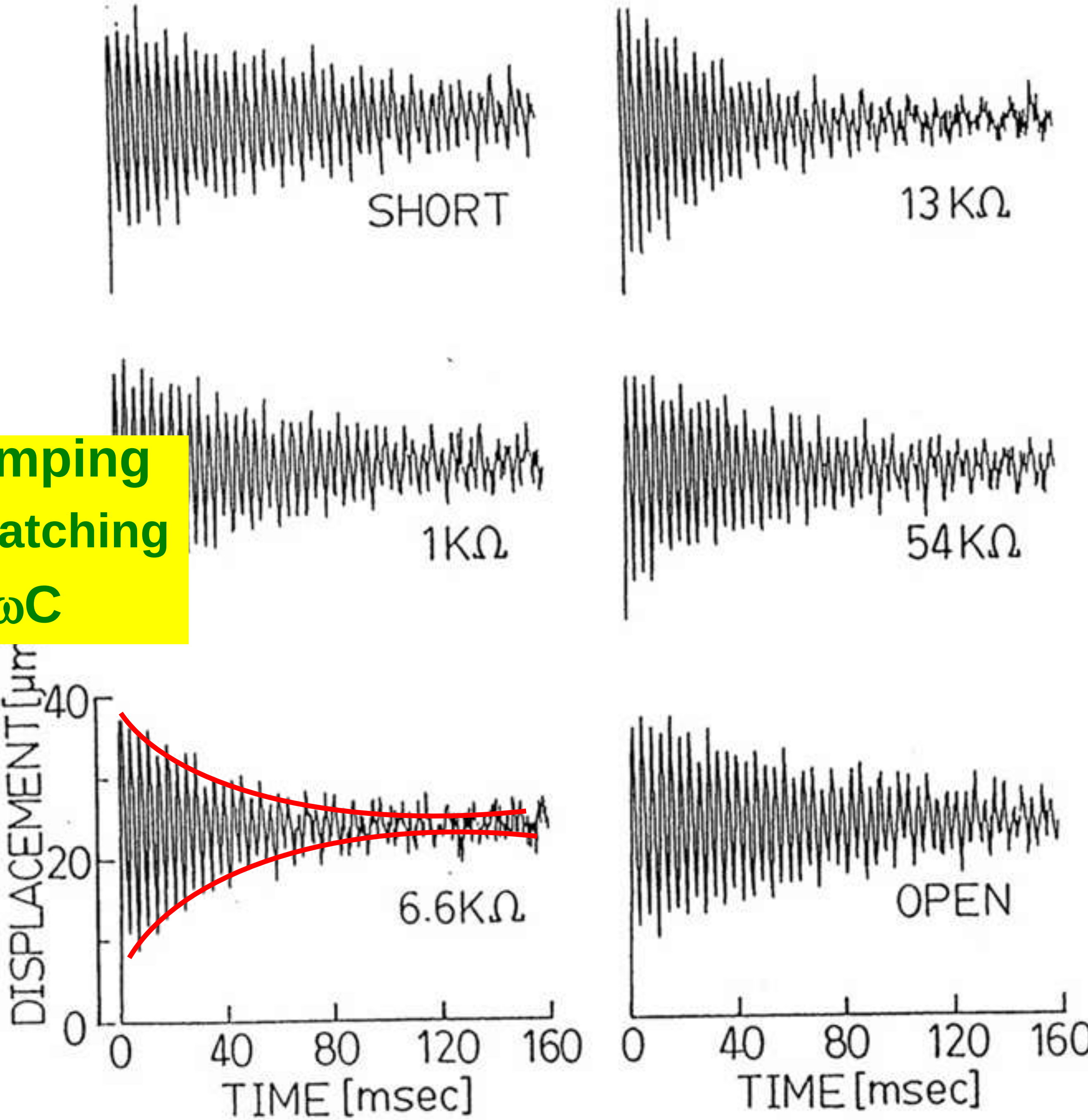




K.Uchino, T.Ishii: J. Ceram.Soc.Jpn. Vol.96, 863 (1988)

Background





Quickest Damping

Impedance matching

R = 1/ωC

K.Uchino, T.Ishii: J. Ceram.Soc.Jpn. Vol.96, 863 (1988)

Piezoelectric Damping Principle

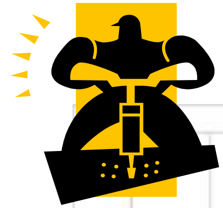
Induced Electrical Energy

$$U_E = U_M \times k^2$$

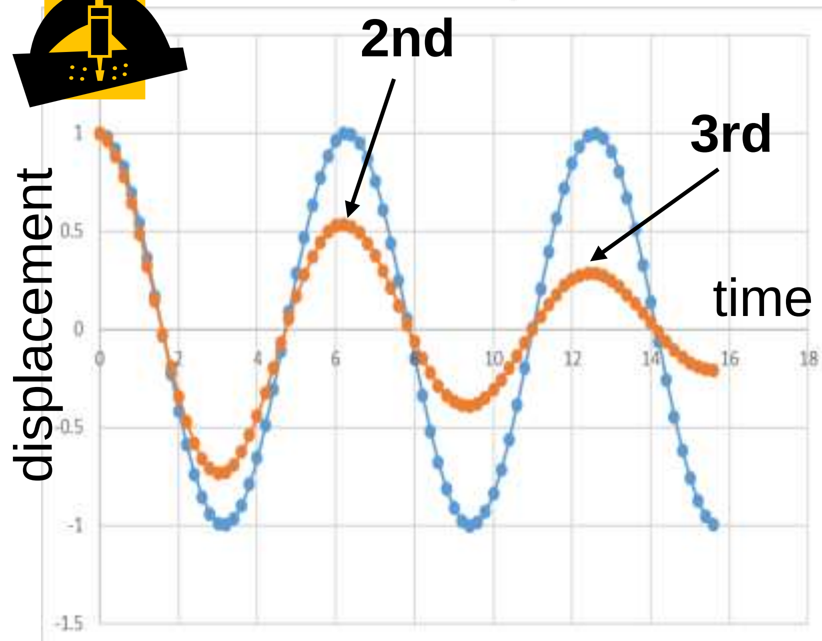
Suppose that 1/2 of U_E is consumed as Joule heat per vibration cycle, the vibration amplitude decreases at a rate

$$\sqrt{(1-(1/2)k^2)}$$

per vibration cycle:



$$\sqrt{(1-(1/2)k^2)}$$



Damping factor τ vs. the electromechanical coupling k:

$$(1-\frac{1}{2}k^2)^{t/T_0} = \exp(-\frac{t}{\tau}) \qquad \tau = -T_0 ln(1-\frac{1}{2}k^2)$$

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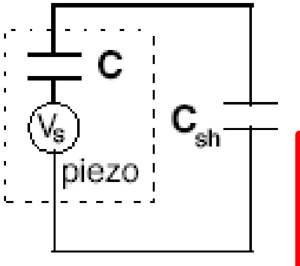
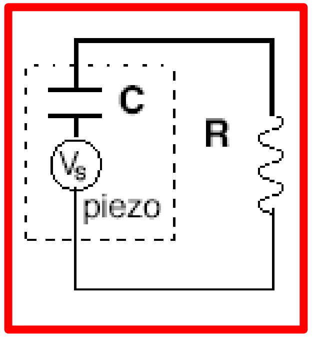
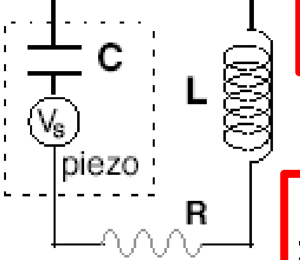
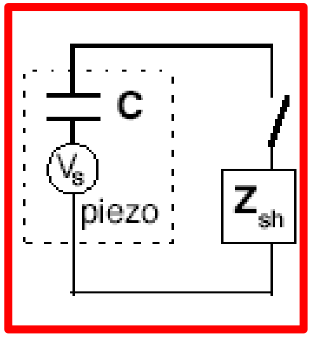
Piezo Shunting

- Mechanical structure interacts with electrical circuit via piezo transducer
  - Capacitive shunting yields frequency-dependent stiffness
  - Resistive shunting yields frequency-dependent damping
  - Inductive shunting yields electrical resonant absorber
  - Switch-shunting could provide broadband damping, energy harvesting







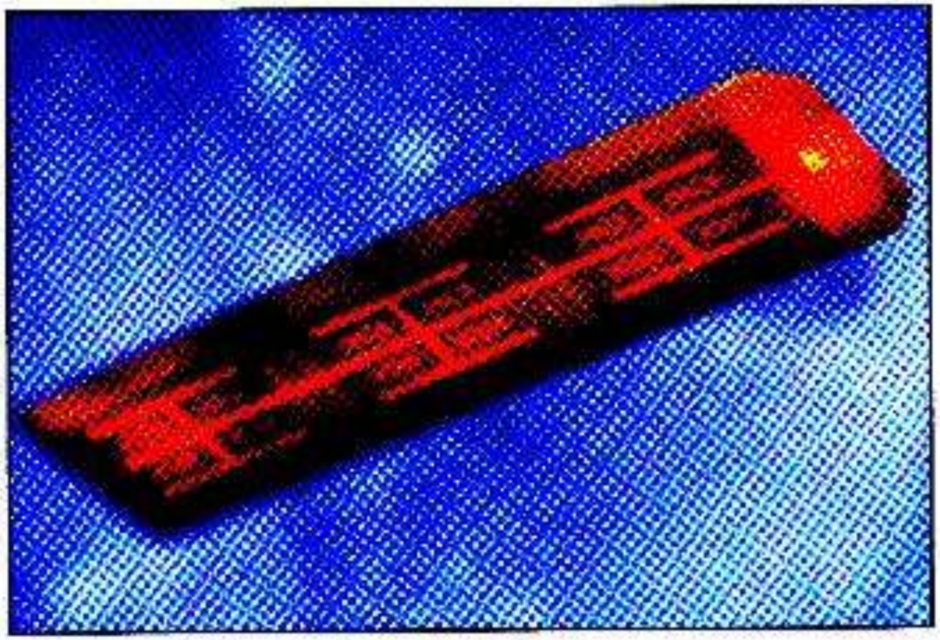


Background

K2 & ACX

Piezoelectric damper hones ski performance

Module integrates piezoelectric material and electronics in ruggedized package



Integrated damping module measures approximately 6.62 × 1.66 × 0.07 inches and includes piezoelectric wafers, energy-dissipating resistive shunt, and an LED function indicator.

: Technical Editor

—In what's called the first
plication of "smart structures"
K2 Four ski from K2 Corp.,
WA, incorporates a piezoelec-
from Active Control eXperts
dge, MA. The damper selec-
on to improve edge control for
icker runs.
kiing involves the reaction
d the snow. Uneven snow sur-
rate, lessening the contact area
of edge to ice and reduc-
ing the ability of the skier
to control turning forces.
' says Kenneth Lazarus, presi-
of techniques have been tried,
lamper is the first that's unob-
unaffected by temperature."
al dampers, the ACX device
l energy as heat by first con-
ty then passing it through a
uring approximately 6.62 ×
it delivers better than 30%
t makes it "smart"?
ce (the piezoelectric
eract vibration), its
o damp only those
affect ski performan
. director of alpine
xplains that identify
modes required a
esearch effort in co
with ACX and with
ists at Boeing. For
... developing fi
hold the ski for vi
esting so as to corre
-snow data took
Fully a year went b
mize the Four's desi
Nevertheless, th
electric damper wer

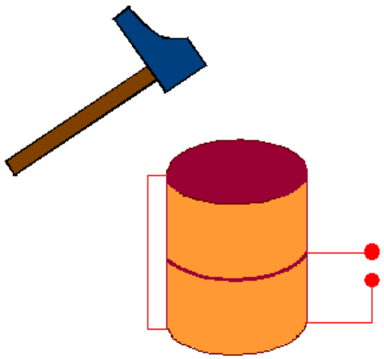
K2's model Four ski exhibits tighter turning and better edge control without the disadvantages of viscoelastic or tuned mass dampers.

only a few iterations, says Adam Bogue, director of marketing at ACX. One attempt delivered too much damping; ski testers called it unresponsive. Later

minimal changes to K2's conventional tooling.

From Passive Dampers to Adaptive Dampers with Energy Harvesting

Mechanical Noise Vibration



Piezoelectric Material

Electrical Energy

Spend → **Passive Damping** 1980s

Accumulate → **Energy Harvesting** 1990s

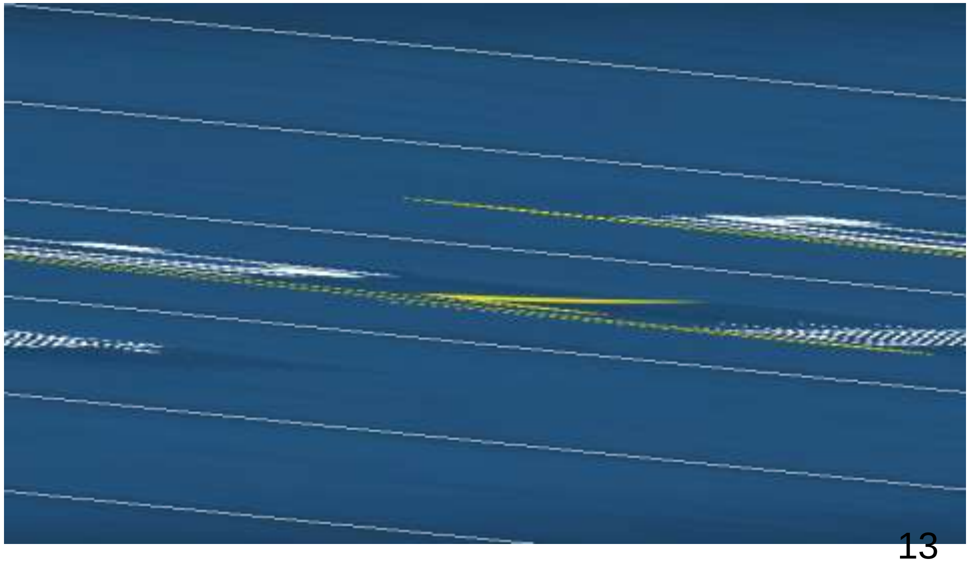
- K. Uchino and K. Ohnishi: Shock Preventing Apparatus, US patent (#4883248)
- M. Sumita and K. Uchino: Damping Materials, Jpn. Patent (3-205293)

Piezoelectric Energy Harvesting - Research Trends -

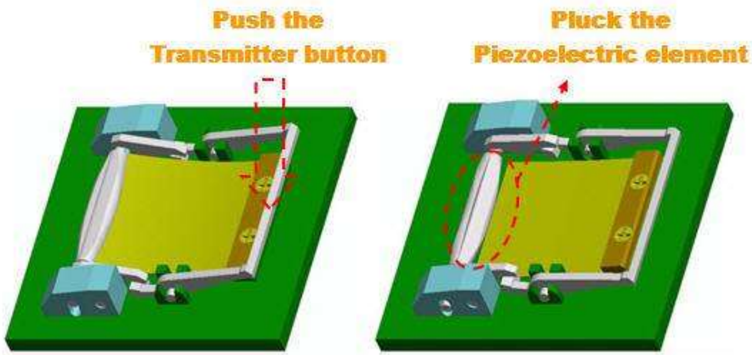
After 2000s

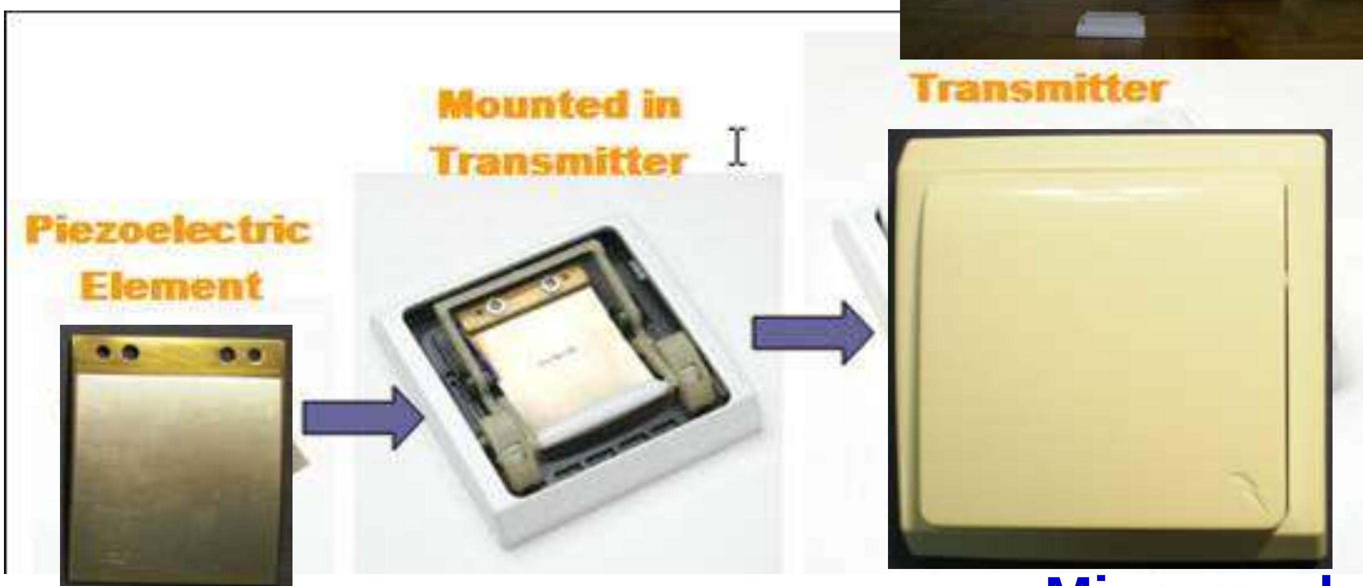
- Machinery Vibration (Resonance Usage)
  - Machine health monitoring
- Human Motion
  - Small energy harvesting
- Electrical Engineers' Approach
  - DC/DC converter
- MEMS Engineers' Approach
  - Thin film, Nano fiber
- Military Application
  - Programable Air-Burst Munition

Smart Diagnostics
(KCF Technologies, PA)



Lightening Switch – Face Electronics





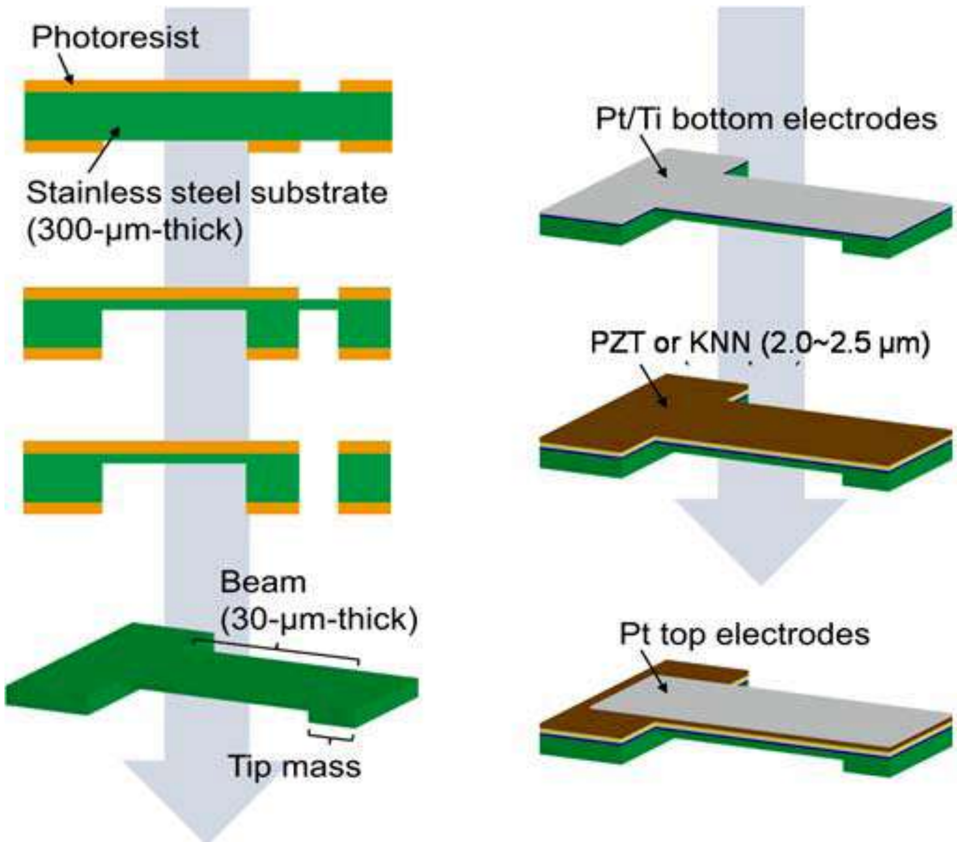
Energy Harvesting with Thunder

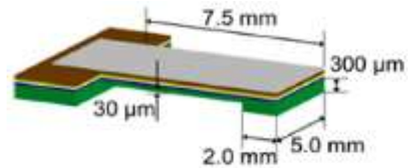
**Micromechatronics Inc.
(State College, PA)**

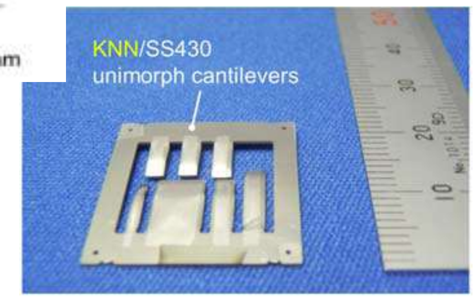
Piezoelectric Carpet (Keio University)

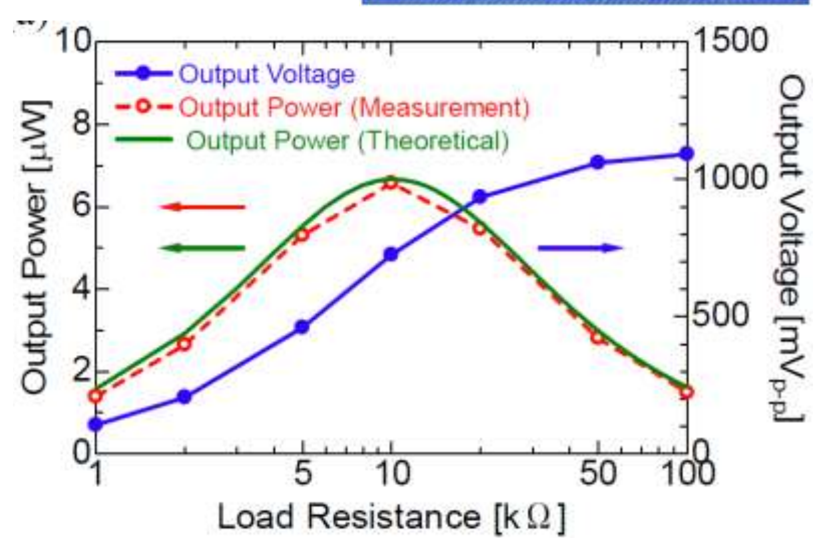
(https://www.youtube.com/watch?v=RCOBA3Yfm1k)

Piezoelectric MEMS for Energy Harvesting





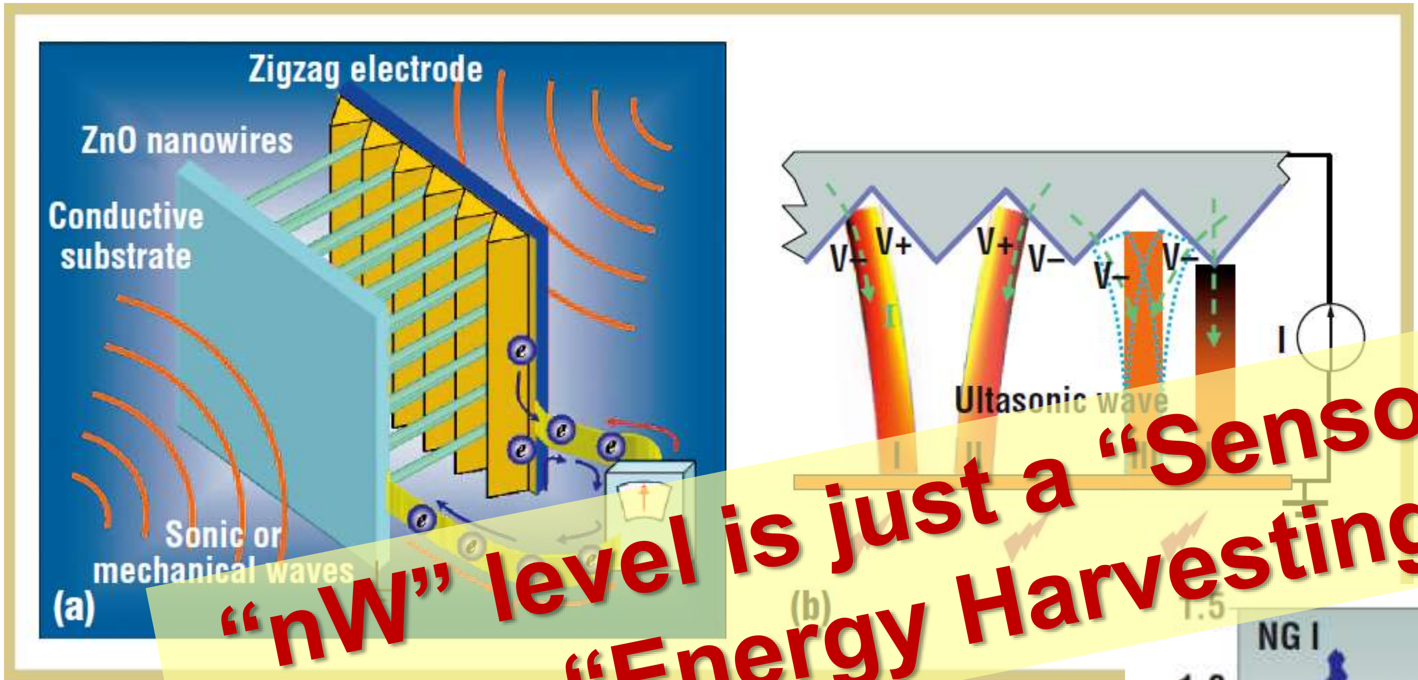




Fabrication process of piezoelectric MEMS energy harvesters of PZT- or KNN-thin films on stainless steel cantilevers.

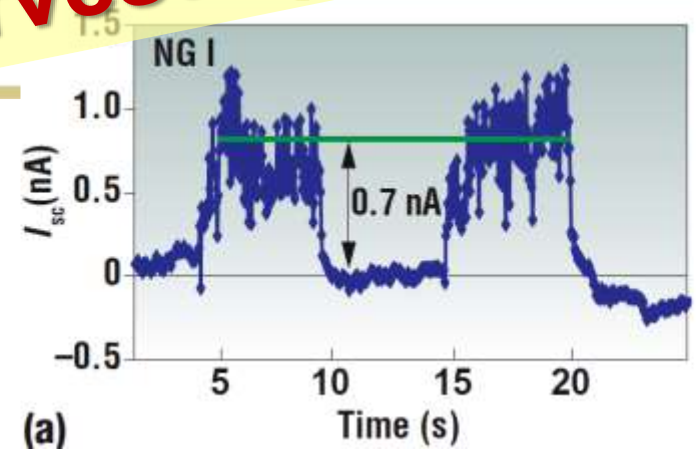
I. Kanno: J. Physics, Conf. Series 660 (2015) 012001

Piezo Nano Generator with ZnO Nanowires



“nW” level is just a “Sensor”, not an “Energy Harvesting” !

(a) Direct current generator using aligned ZnO NW arrays with a zigzag top electrode. Mechanical vibration drives the generator, and the output current is continuous. (b) Zigzag electrode and its contact with the NWs and the resulting current.

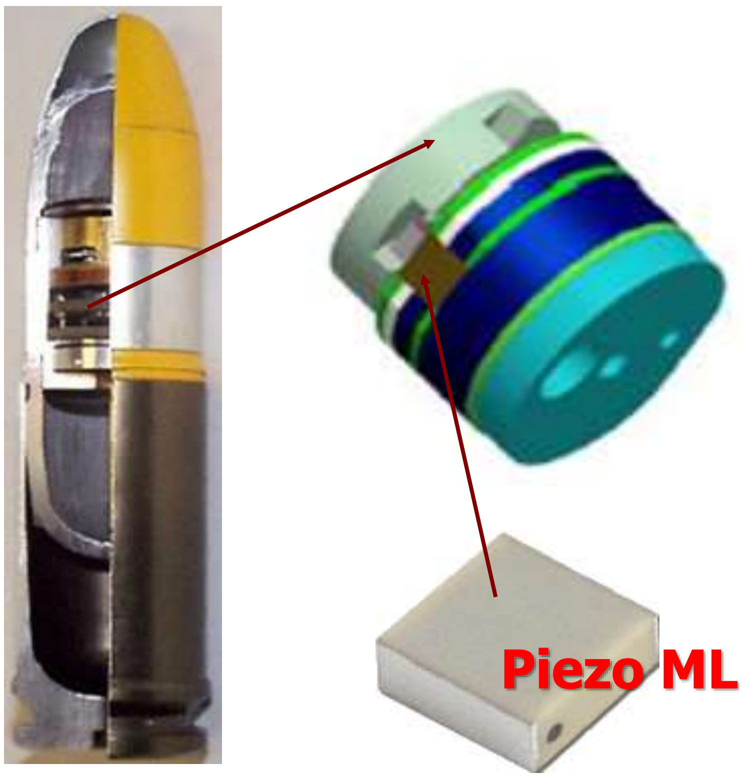


Z. L. Wang: IEEE Perv. Comp. Vol 7, p.49 (2008)

Piezo Generators for Ammunitions

Programmable Air Burst Munition (PABM) – Revenge after the World Trade Center Attack in 2001. Killing terrorists without collapsing buildings.

Million-Selling Device !



Impact force generates electricity.

ATK & Micromechatronics Inc. (State College, PA)

Piezoelectric Energy Harvesting
- Uchino's Frustration-

(1) Though the electromechanical coupling factor k is the smallest among various device configurations, the majority of researchers primarily use the '**unimorph**' design. Why?

(2) Though the typical noise vibration is in a much lower frequency range, the researchers measure the amplified **resonance response** and report these unrealistically harvested energy. Why?

(3) Though the harvested energy is **lower than 1 mW**, which is lower than the required electric energy to operate a typical energy harvesting electric circuit with a DC/DC converter, the researchers report the result as an energy 'harvesting' system. Why?

(4) Few papers have reported **energy flow or exact efficiency** from the input mechanical noise energy to the final electric energy in a rechargeable battery via the piezoelectric transducer step by step. Why?

The unanimous answer to my questions 'why' is
"**because the previous researchers did so !**".

Development Misconception
Case I (Design Problem)

In order to damp vibration in an aluminum cantilever beam, a mechanical engineer uses a shunted soft-piezoelectric composite (Macro Fiber Composite) bonded on the beam. This is NOT an ideal design from the two viewpoints:

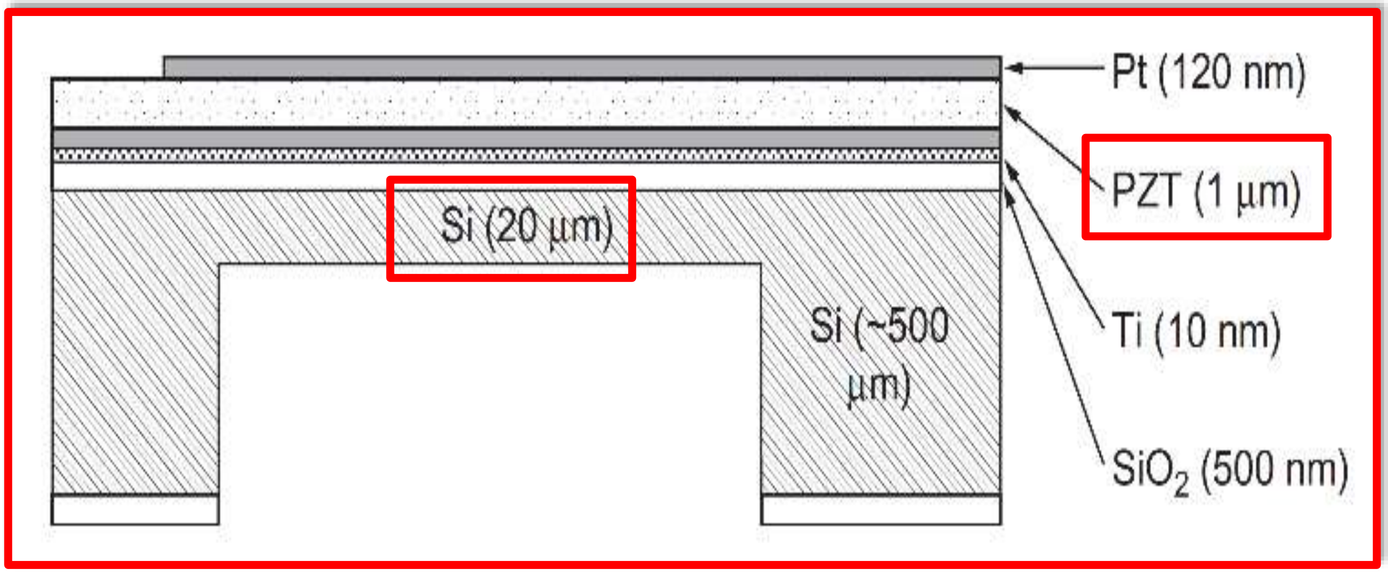
(1) *Mechanical/acoustic impedance matching Z*, and

(2) *Electromechanical coupling factor k*

Vibration damping of an aluminum cantilever beam using a piezoelectric composite bonded on the beam.

Development Misconception
Case II (Volume Problem)

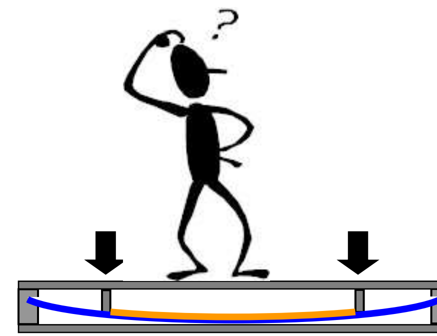
Piezoelectric MEMS is researched popularly with the PZT thin film thickness around 1 μm for the actuators and piezo-energy harvesting applications. What are the three major problems to be solved on a popular design shown in Figure?



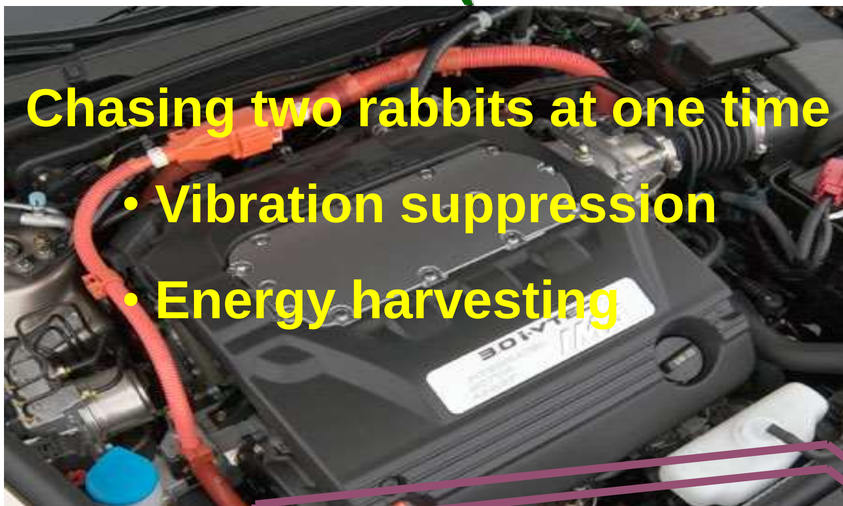
Piezoelectric MEMS structure with the PZT thin film thickness around 1 μm for the actuators.

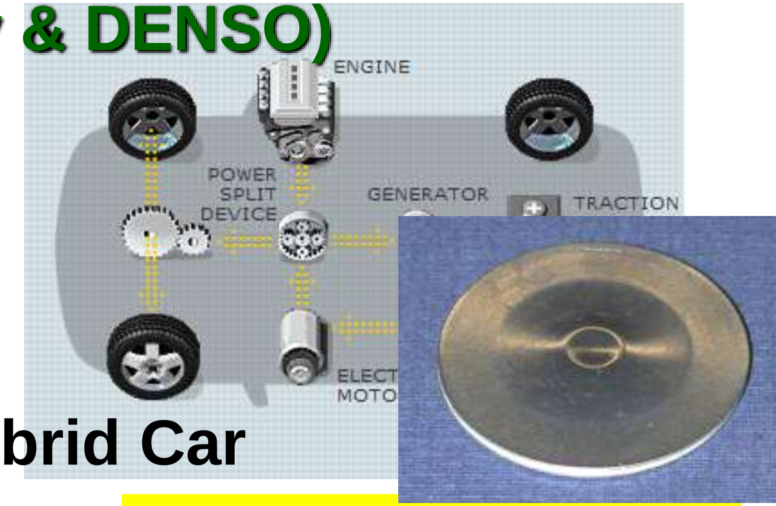
Development Misconception
Case III (Application Problem)

- Grand Central Station: 750,000 visitors per day, average of 31,250 visitors per hour
- *Assumptions*:
  - **<u>Potential Energy</u>** of a person of **75kg** stepping on a tile which gives in about **10mm** to convert into a bending/strain motion ~ 7.4J per step
  - Tile is 50cm by 50cm
  - Person does on average 500 steps in one hour in the station, one step per tile (all tiles are the same)
- This converts to 19.2 kWh **raw potential energy!**
- **Typical efficiency of harvester**, minus energy being stored in the tile spring to bend back the tile, about **2%** (actually measured)
- Total harvested **energy ~ 384 Wh,** it would power just **4 bulbs of the ~4,000 bulbs** at Grand Station but at what costs!



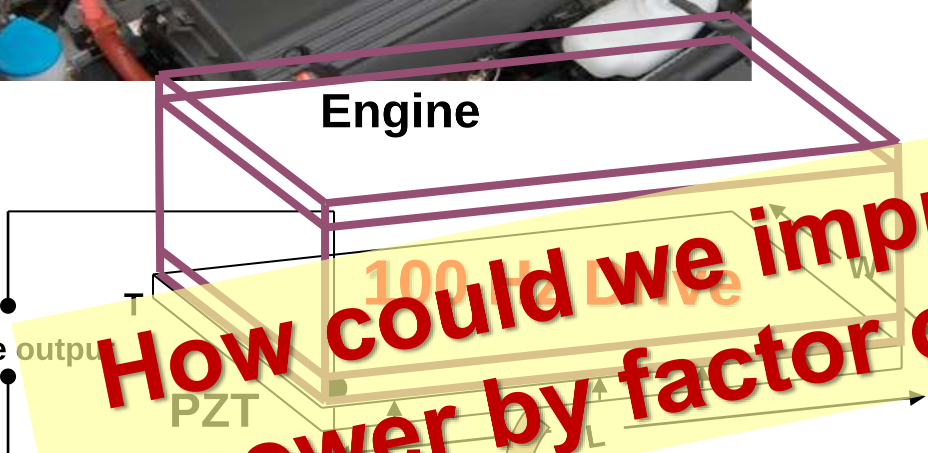
Development Model I
(Penn State Univ & DENSO)



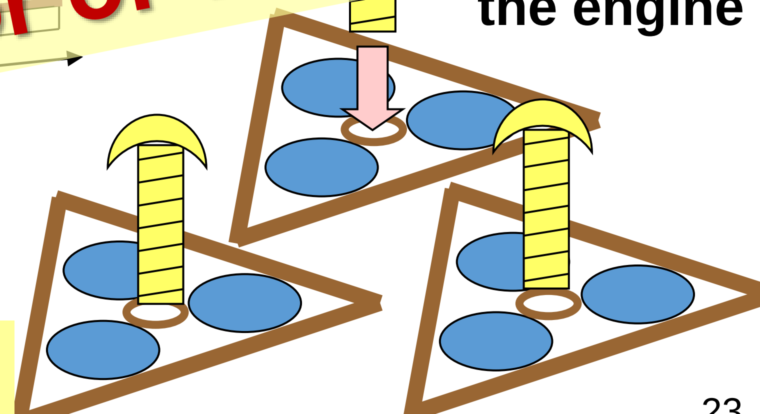


Hybrid Car

Composite Sheet with Cymbals



How could we improve the power by factor of 10^3 ?

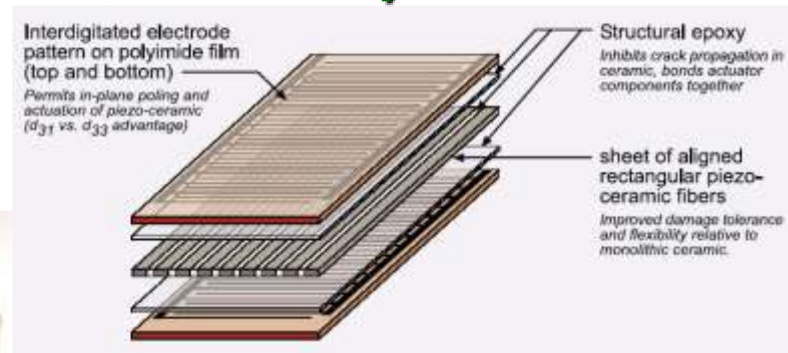


Bolt to support the engine

1 mW → 1 W

Development Model II

(Penn State Univ & Smart Materials)



Intelligent Clothing (IC)

1-5 mW

Charging the electronic devices

Flexible piezoelectric textile

Flexible energy harvest circuit

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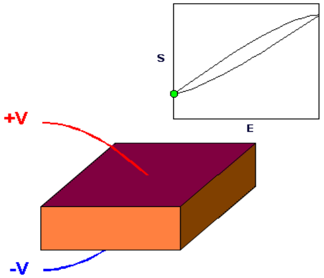
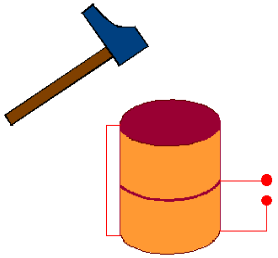
Figures of Merit in Piezoelectrics



a) Piezoelectric Strain Constant d

Electric Field → Strain (For Actuation): $x = d\,E$

Stress → Polarization: $P = d\,X$



b) Piezoelectric Voltage Constant g

Stress → Electric Field (For Sensing): $E = g\,X$

Related with d by $g = d/\varepsilon_0\varepsilon_r$ (ε_r: permittivity)

c) Electromechanical Coupling

Electromechanical Coupling Factor k
Energy Transmission Coefficient λ
Efficiency η

k^2 = (Mech.Stored Energy/Electr.Input Energy) = $d^2/\varepsilon_0\varepsilon_r s$
(s: elastic compliance)

λ = (Mech. Output Energy / Electr. Input Energy) = $(1/4 \sim 1/2)\,k^2$

η = (Mech. Output Energy / Electr. Consumed Energy) ≈ 98%

d) Acoustic Impedance Z

Mechanical → Mechanical (Acoustic Energy Transfer)

$Z^2 = \rho\,c$ (ρ: density, c: elastic stiffness)

FOM

Figures of Merit in Energy Harvesting

1. Constant Stress Input

P = d X

$$Electric\ Energy = \left(\frac{1}{2\varepsilon_0\varepsilon}\right)P^2$$

$$= \left(\frac{1}{2}\right)\boxed{d\cdot g}X^2$$

- Input mechanical energy is not constant → Elastic compliance changes with electric load.

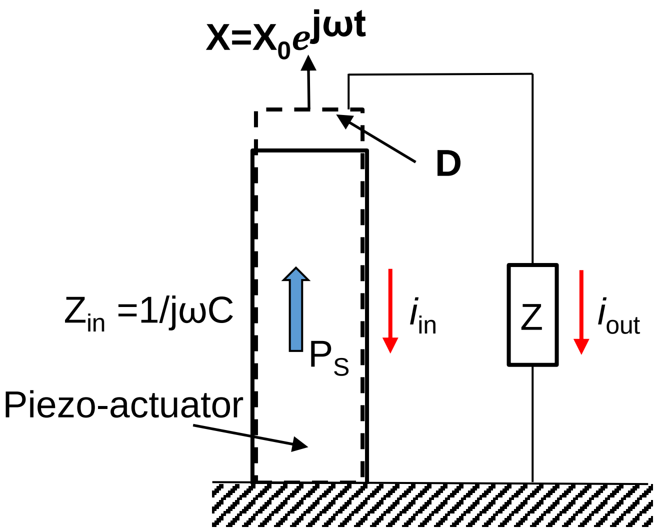
2. Constant Mechanical Energy Input

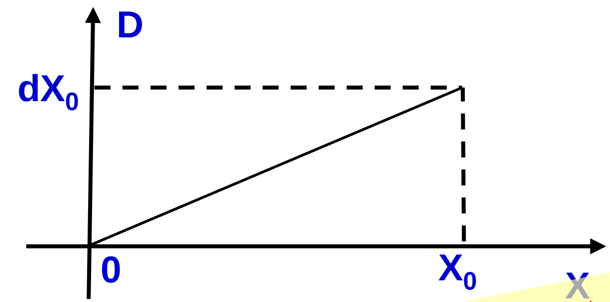
$$Electric\ Energy\ U_E = k^2\ U_M$$

$$k^2 = \left(\frac{d^2}{s^E\varepsilon_0\varepsilon}\right) = \boxed{d\cdot g/s^E}$$

FOM

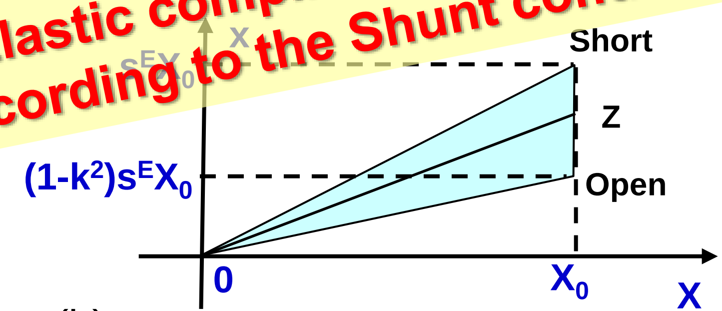
Energy Calculation in a Piezoelectric



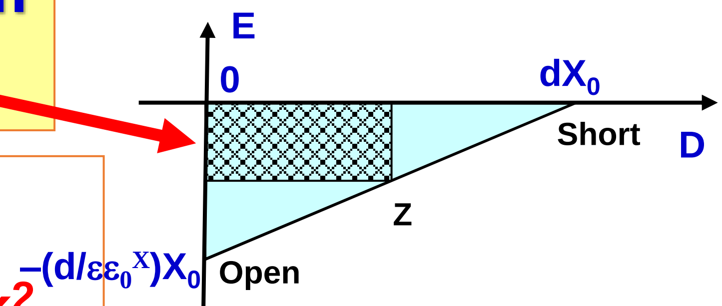


(a) Stress vs Electric Displacement

Elastic compliance is different according to the Shunt condition !



(b) Stress vs Strain



(c) Electric Displacement vs Field

Output electric. energy maximum

$$Z = |Z_{in}| = 1/\omega C$$

Energy transmission coefficient

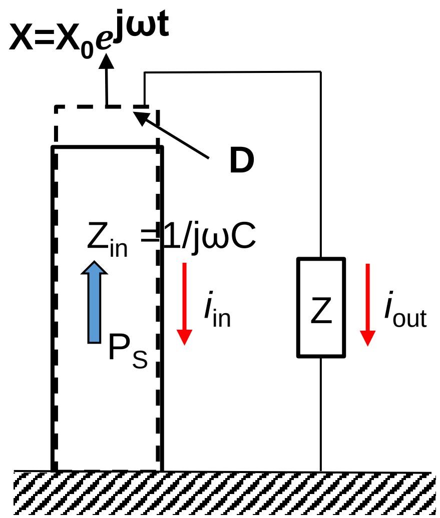
$$\lambda_{max} = [(1/k) - \sqrt{(1/k^2) - 1}\,]^2 = (1/4 \sim 1/2)\, k^2$$

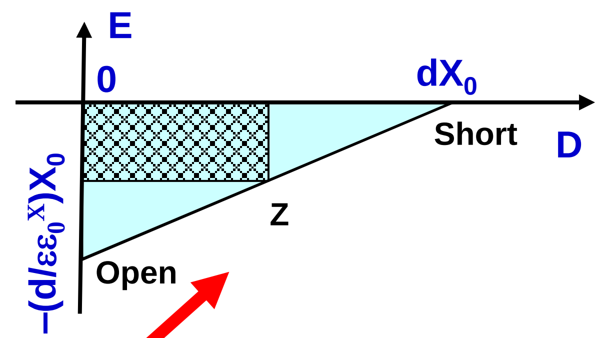
λ = (Elec. Output Energy / Mech. Input Energy)

Supposition 'Infinite mechanical energy pool' !

Optimization of Load on the Piezo-Device

$$D = \varepsilon_0 \varepsilon^X E + dX$$
$$x = dE + s^E X$$





Electric Displacement vs Field

- **Open circuit:**

  D=0, E_{rev}= $-(d/\varepsilon\varepsilon_0^X)X$

  $$x = (1 - k^2) s^E X$$

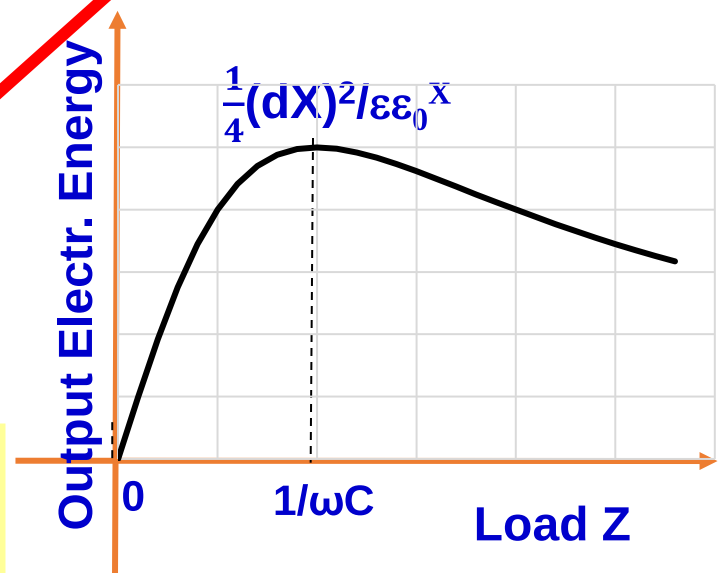
- **Short circuit:**

  E=0, D= dX $\quad x = s^E X$

- **Z connection:**

  $$|P| = \frac{1}{2} Z i_{out}^2 = \frac{1}{2} Z \frac{(\omega d X_0)^2}{(1 + (\omega C Z)^2)}; \; When$$

  $$Z = 1/\omega C, \; |P| = \frac{1}{4} \frac{\omega d^2 X_0^2}{C}$$



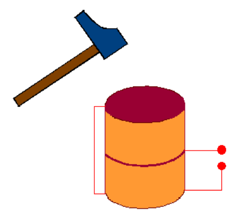
Load should be impedance-matched with the actuator capacitance.

FOM

Energy Flow of the Piezoelectric Generator

Phase I Mechanical Energy Transfer	Phase II Mechanical-Electrical Energy Transduction	Phase III Electrical Energy Transfer

Environment Excitation Energy → Mechanical Vibration Energy → Electrical Energy Generated → Electrical Energy Output



Mechanical Loss
- Mechanical strength
- **Mechanical impedance**
- Damping factor

Mechanical-Electrical Transduction Loss
- **Coupling factor (k)**
- Piezoelectric coeff. (d, g)

Electrical Loss
- **Electrical impedance**
- Circuit loss

Misconceptions in Piezoelectric Energy Harvesting System Development

Kenji Uchino
Int'l Center for Actuators & Transducers
The Pennsylvania State University, PA

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   Piezo-Dampers, Research Trends
2. **Figures of Merit in Energy Harvesting**
   d·g, EM Coupling factor, Energy transmission coefficient
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6. **Summary and Future**

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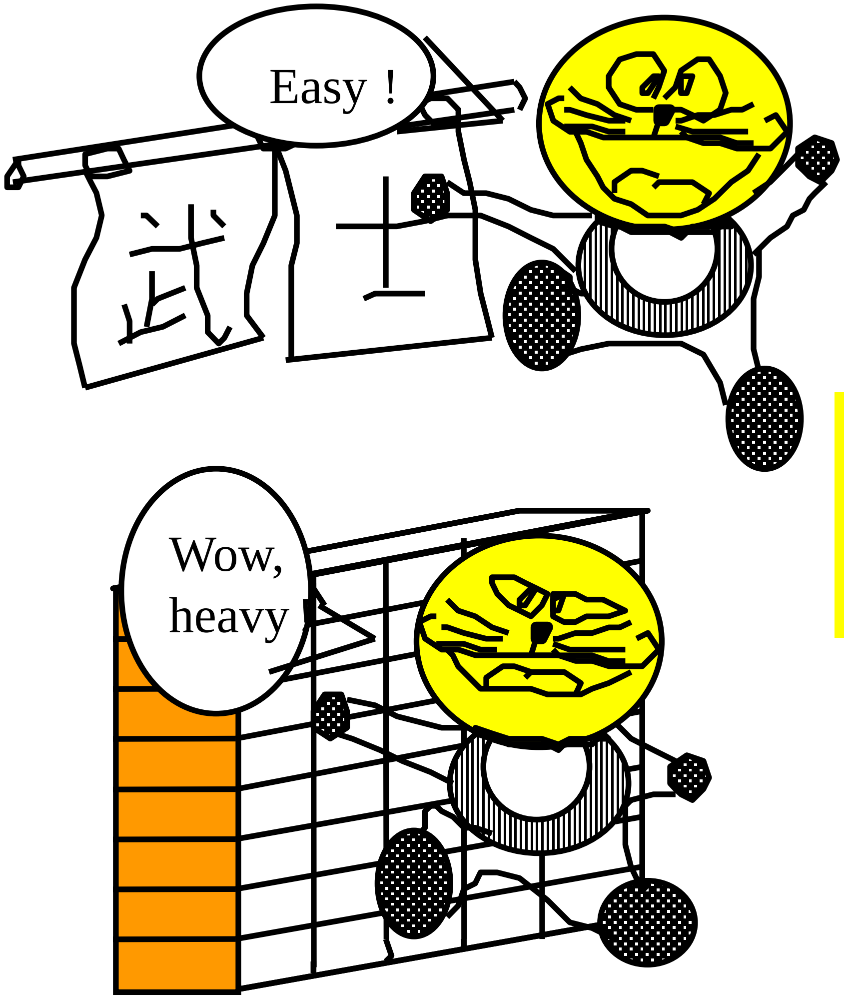
Mechanical Impedance Matching



Work W = F x Δ L

F = 0

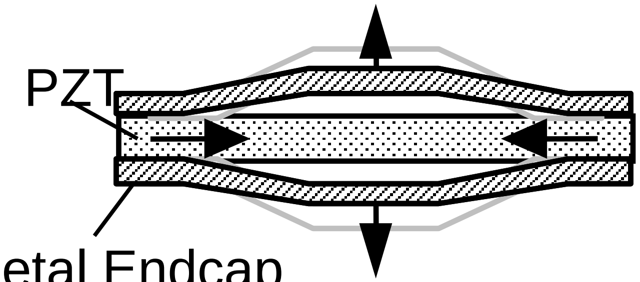
"Pushing a curtain, and pushing a wall"
(Japanese proverb)

ΔL = 0

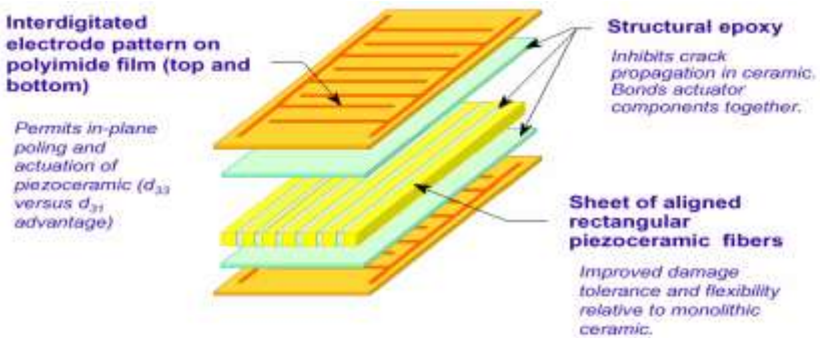
Phase I : Mechanical Energy Transfer

Solutions for Mechanical Matching

- **For a high force mechanical source**
  - High stiffness and rigid
  - High coupling factor

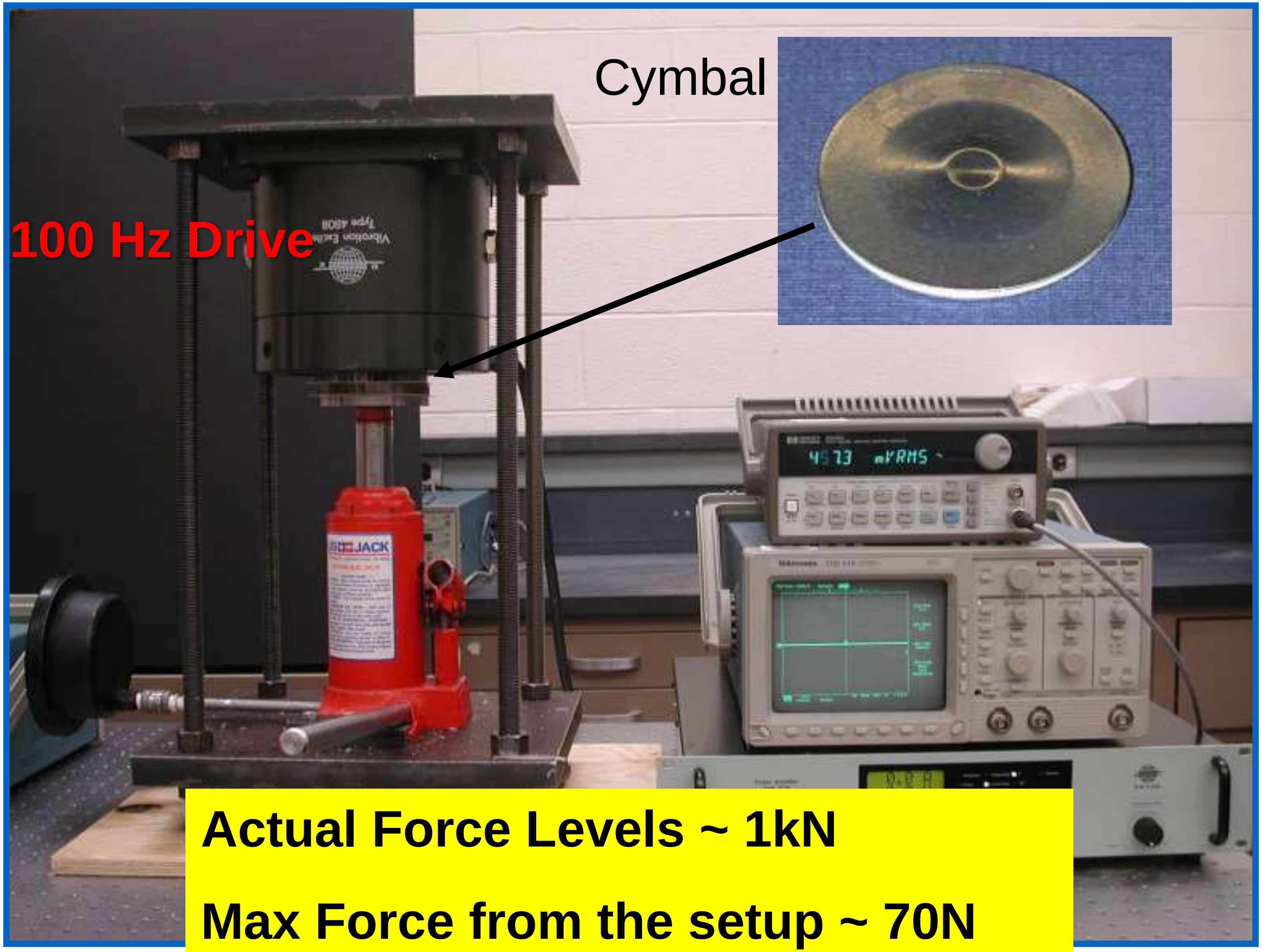


- **For a small force mechanical source**
  - High flexibility and soft
  - High coupling factor



Smart Material

Experimental Setup

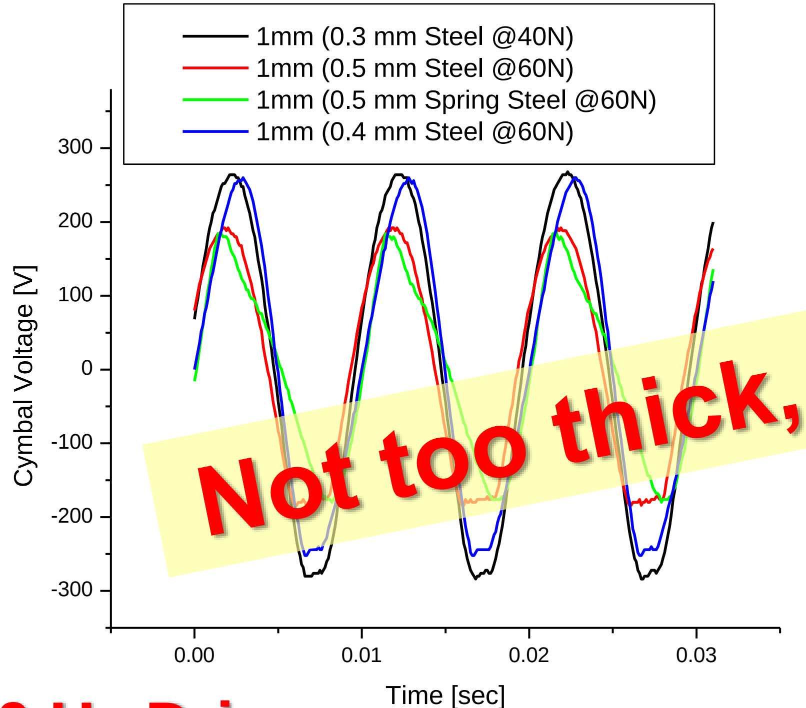


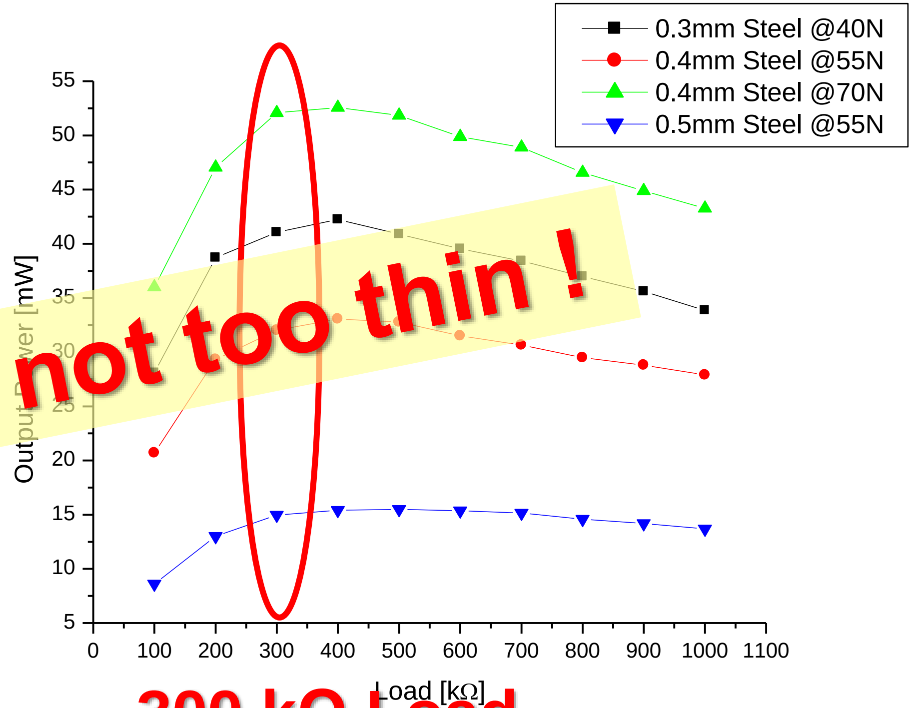
Actual Force Levels ~ 1kN

Max Force from the setup ~ 70N

Endcap Materials/Thickness

- Elastic constant, Thickness, Cavity of the metal endcap.
- Mechanical impedance increases with thickness. (The Softer is the better)





100 Hz Drive

300 kΩ Load

LOAD DEPENDENCE

- Pre-stress (66 N) and Applied Force (55 & 70N) at 100Hz
- Max power : 53mW at 400 kΩ with a 0.4mm steel endcap at 70N
- 0.3 mm Steel does not endure for 70 N.

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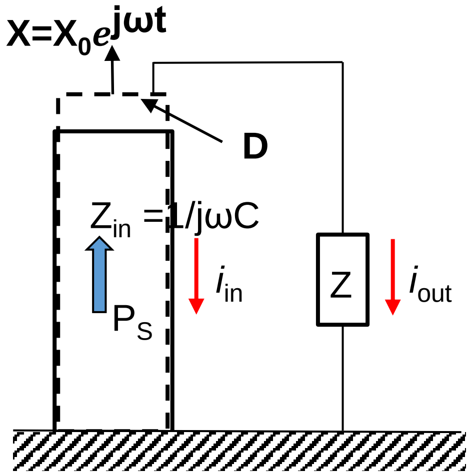
Phase II: Mech. to Elec. Energy Transduction

Operation Principle



- **Sinusoidal Drive**
  - **Engine 100 Hz**
  - **EM Motor 50 Hz**
  - **Water/wind flow 10 Hz**
  - **Building 1 Hz**

$$P \propto g \cdot d$$

$$|P| = \frac{1}{2} Z i_{out}^2 = \frac{1}{2} Z \frac{(\omega d X_0)^2}{(1+(\omega C Z)^2)};$$

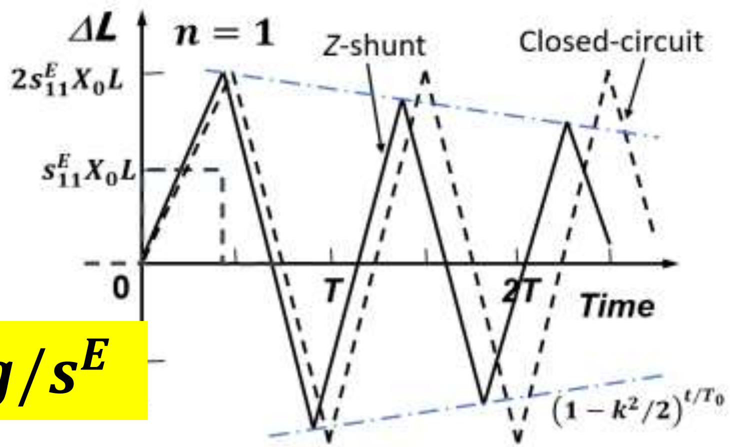
$$When\ Z = 1/\omega C,\ |P| = \frac{1}{4} \frac{\omega d^2 X_0^2}{C}$$

- **Pulse Drive**

$$\frac{1}{2} k^2 U_M \sum_{n=0}^{n} \left[\left(1 - \frac{1}{2} k^2\right) e^{-\frac{\pi}{2Q_M}} \right]^n$$

$$= \frac{1}{2} k^2 U_M \frac{1 - \left[\left(1 - \frac{1}{2} k^2\right) e^{-\frac{\pi}{2Q_M}}\right]^n}{1 - \left(1 - \frac{1}{2} k^2\right) e^{-\frac{\pi}{2Q_M}}}$$

$$k^2 = d \cdot g / s^E$$



Total energy reaches input mechanical energy U_M for high Q_m, $(1/2)k^2 U_M$ for low Q_m.

Piezoelectric Energy Harvesting
- Uchino's Frustration-

(2) Though the typical noise vibration is in a much lower frequency range, the researchers measure the amplified **resonance response** (> 1 kHz) and report these unrealistically harvested energy. Why?

↓

Forget this approach
"because the previous researchers did so !".

Phase II: Mech. to Elec. Energy Transduction

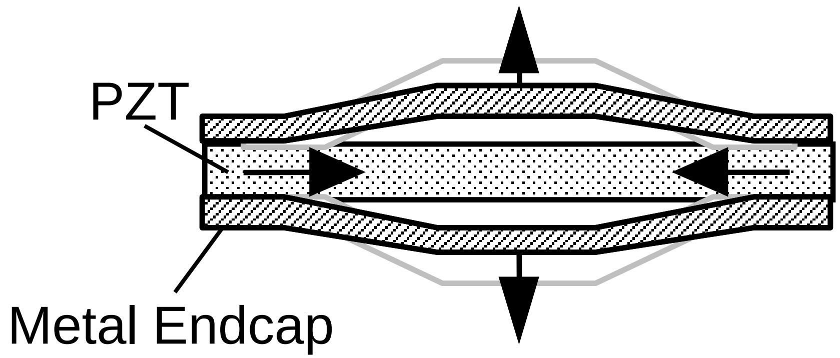
Piezoelectric Selection

	Hard (APC 841)	Soft (APC 850)	high g (D210)
ε_r	1350	1750	681
k_p(%)	0.60	0.63	0.58
d_{31} (10^{-12} C/N)	109	175	120
g_{31} (10^{-3}Vm/N)	10.5	12.4	20
Q_m	1400	80	89.7
T_c (^oC)	320	360	340
$g_{31} \cdot d_{31}$	0.99E-12	1.97E-12	2.4E-12

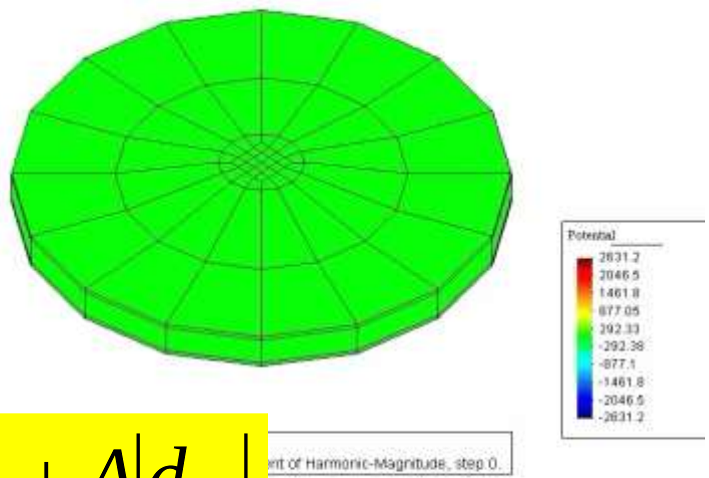
$$P = \frac{1}{2}CV^2 \cdot f$$
$$= \frac{1}{2} \cdot g_{33} \cdot d_{33} \cdot F^2 \cdot \frac{t}{A} \cdot f$$

Phase II : Mech. to Elec. Energy Transduction

❑Ceramic-Metal Composite Transducer "Cymbal"



Cymbal



$$d_{eff} = d_{33} + A|d_{31}|$$

$$A \propto \frac{1}{2}\frac{\text{CavityDiameter}}{\text{CavityDepth}}$$

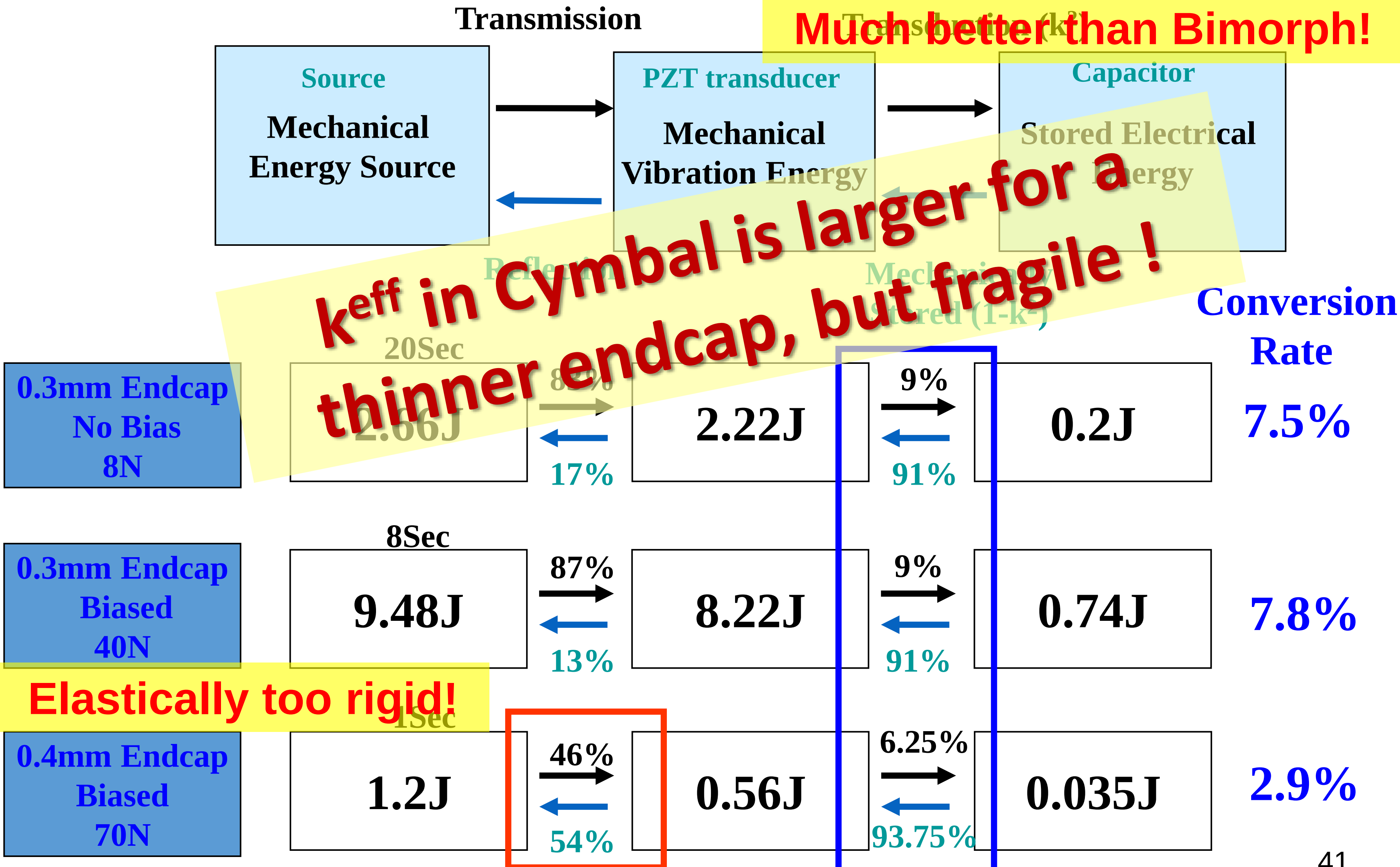
- Larger displacement
- Larger generative electric field
- Higher piezoelectric coefficient, d_{33}

  (roughly 40 times higher)

Energy Flow (Transmission & Conversion)

k^{eff} in Cymbal = 0.25-0.30

Much better than Bimorph!



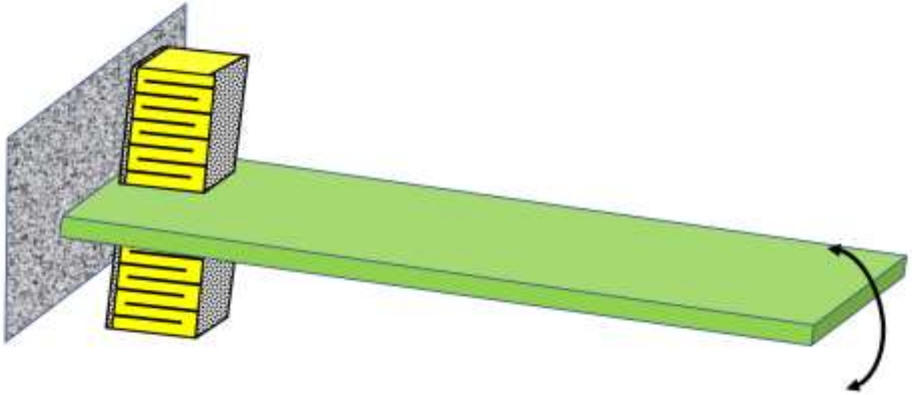
k^{eff} in Cymbal is larger for a thinner endcap, but fragile !

Elastically too rigid!

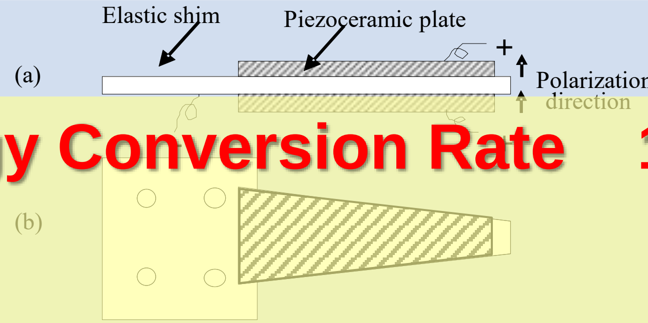
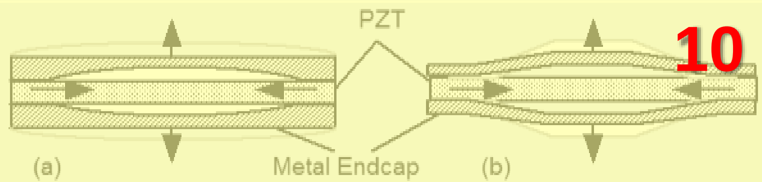
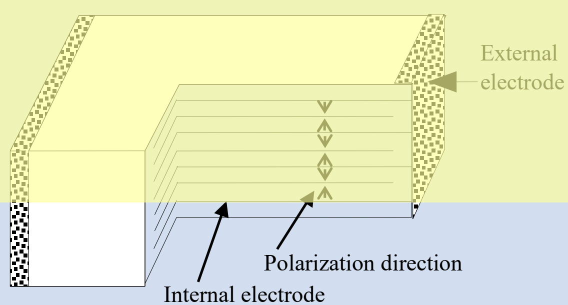
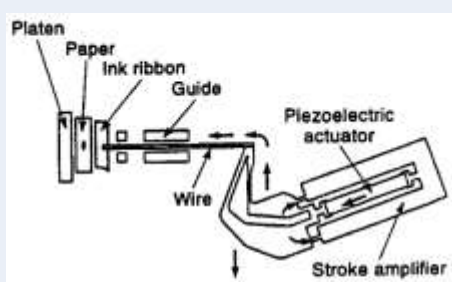
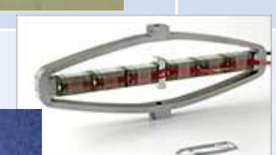
Piezoelectric Energy Harvesting
- Uchino's Frustration-

(1) Though the electromechanical coupling factor k is the smallest among various device configurations, the majority of researchers primarily use the 'unimorph' design. Why?

- Mechanical impedance matching
  → Use stiff actuator
- Electromechanical coupling factor
  → Use k_{33} actuator



Energy Transduce

Device Design		keff (%)	Response
Unimorph/ Bimorph		10%	0.5 – 2 kHz
Moonie/ Cymbal		30%	10 – 40 kHz
Multilayer	 	70%	50 – 300 kHz
Multilayer + Hinge Lever	  	70%?	1 – 20 kHz

Energy Conversion Rate 1 %

10 %

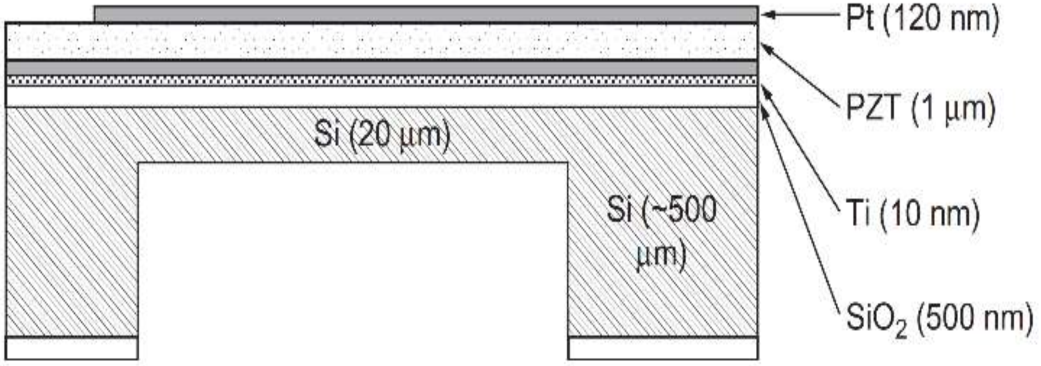
50 %

Piezoelectric Energy Harvesting

- Uchino's Frustration-

(3) Though the harvested energy is lower than 1 mW, which is lower than the required electric energy to operate a typical energy harvesting electric circuit with a DC/DC converter, the researchers report the result as an energy 'harvesting' system. Why?

- Volume Problem
- Thickness Ratio
- Electromechanical Coupling Factor



Piezoelectric Energy Harvesting

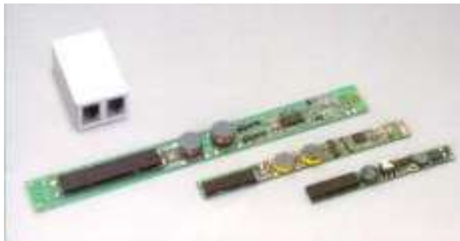
- Uchino's Frustration-

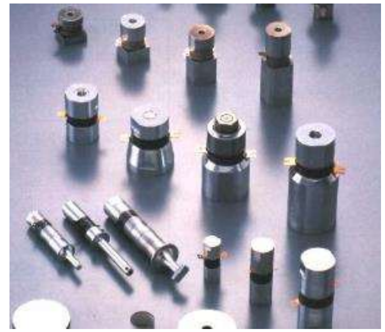
Required Energy for Practical Applications

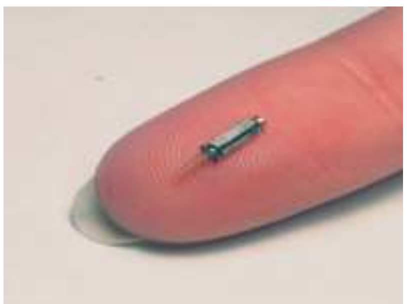
- Charging electricity into a battery: **30 – 100 mW**
- Soaking blood from a human vessel: **10 – 20 mW**
- DC-DC converter spends **2 – 3 mW**
- Sending electronic signal: **1 – 3 mW**

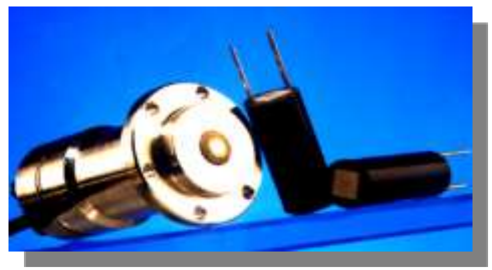
- **Minimum 1 mW is required for the energy harvesting devices.**
- **Less than 1 mW is called "*sensor devices*".**

Power Density in Piezoelectrics





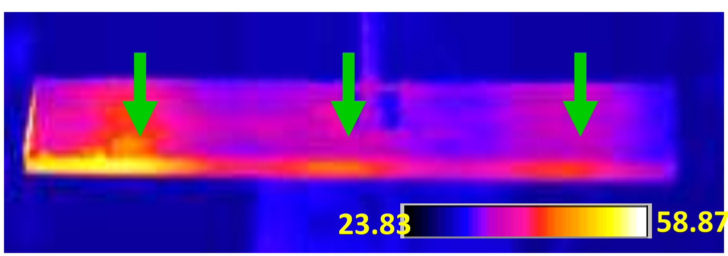


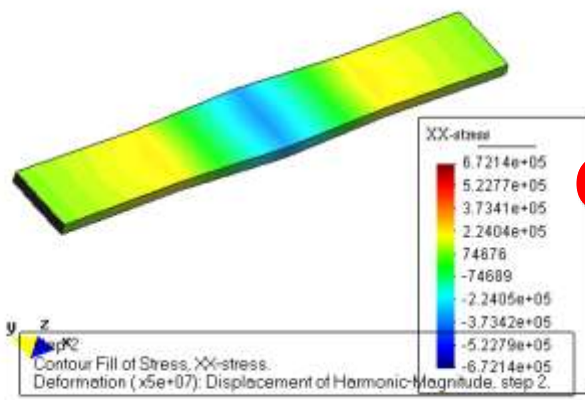


Piezoelectric Devices

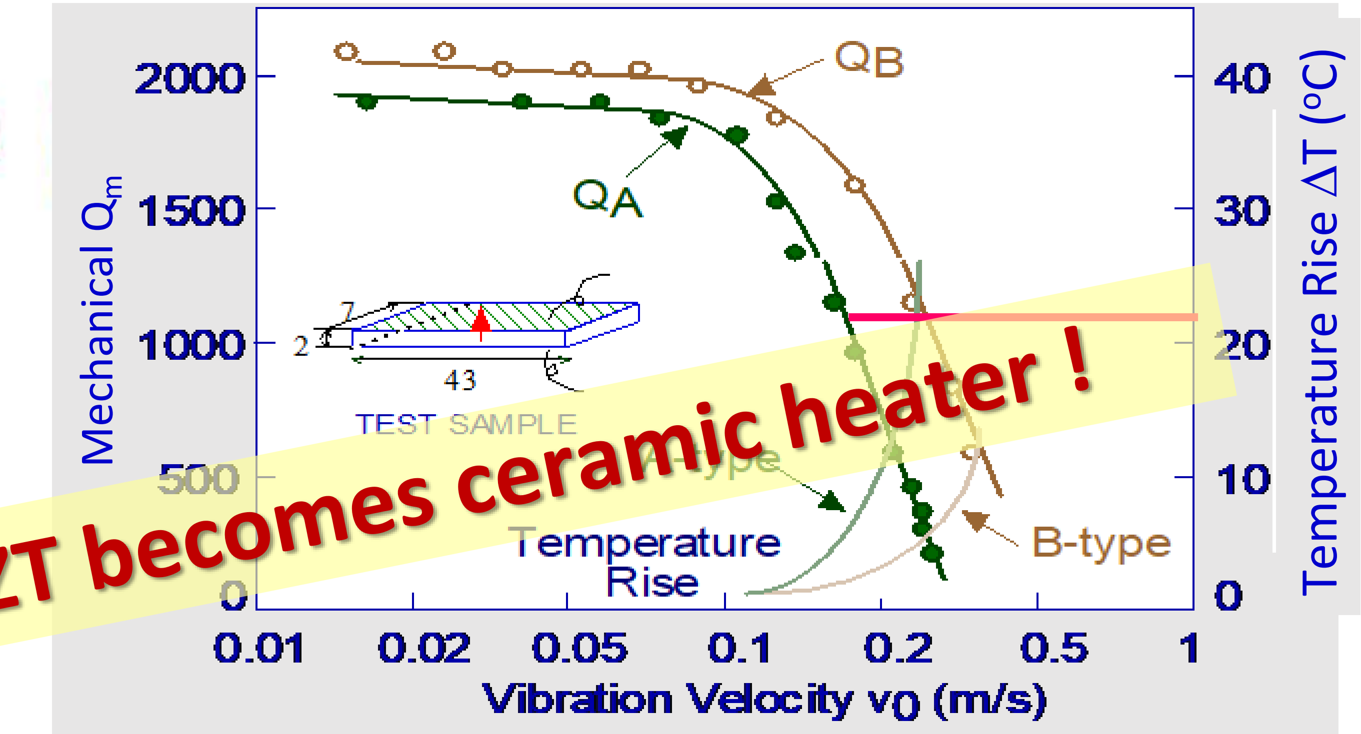
↓

Heat Generation



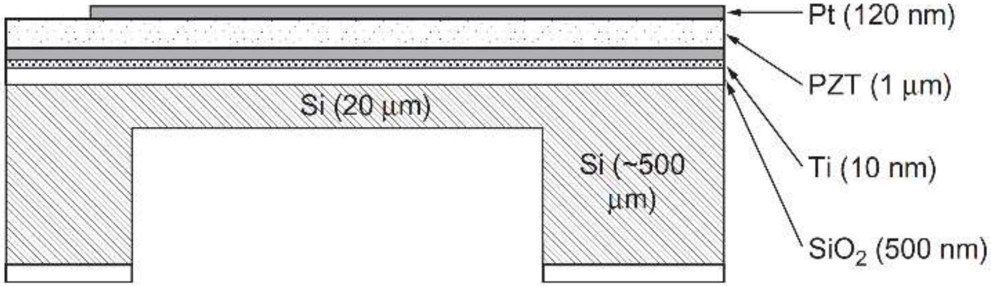


Power Density in Piezoelectrics



- Maximum Vibration Velocity 0.6 m/s (rms)
- Power density 30 W/cm^3 in PZT
- Minimum PZT volume 0.1 mm^3 for 1 mW
- 30 μm thick films with 3 × 3 mm^2 device area
- MEMS devices with less than 1 μm thin PZT films are useless for energy harvesting

MEMS Energy Harvesting



- **Thickness Ratio**

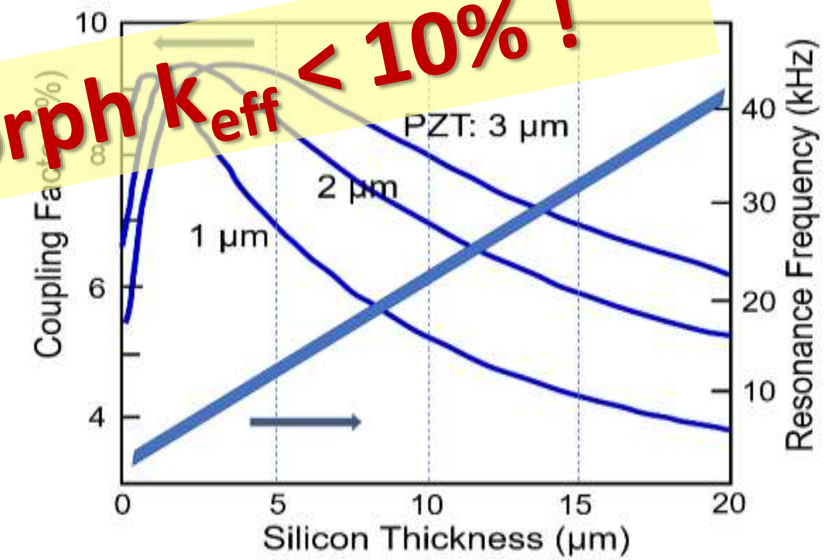
$$\delta = \frac{d_{31} E l^2 Y_c t_c}{\left(Y_m \left[t_o^2 - (t_o - t_m)^2\right] + Y_c \left[(t_o + t_c)^2 - t_o^2\right]\right)}$$

$$t_o = \frac{t_c t_m^2 (3 t_c + 4 t_m) Y_m + t_c^4 Y_c}{6 t_c t_m (t_c + t_m) Y_m}$$

Displacement is max at $t_c \approx t_m$

- **Electromechanical Coupling Factor shows max at $t_c \approx t_m$**

PZT MEMS unimorph k_{eff} < 10% !



P. Muralt, Integrated Ferroelectrics, Vol. **17**: 297 – 307 (1997).

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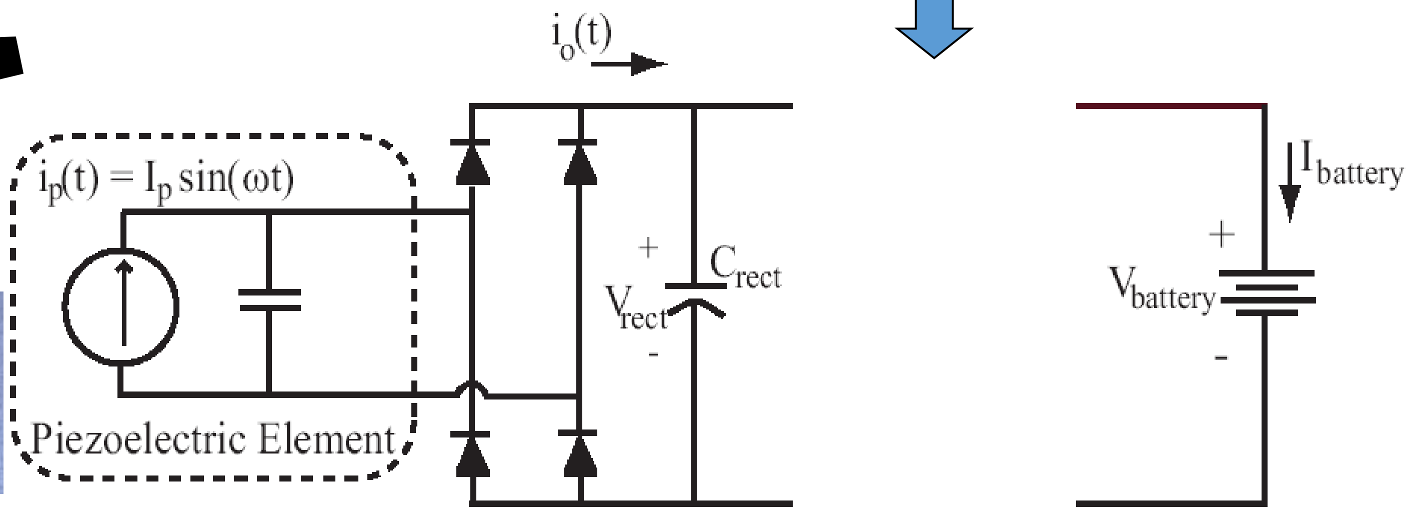
Phase III : Electrical Energy Transfer

High voltage
Low current

Low voltage
High current



(1) Mechanical Impedance Matching
(2) Mechanical-Electrical Energy Conversion
(3) Electrical Impedance Matching

- Various converter topologies can step down the voltage: Forward converter, Buck Converter, Buck-Boost Converter, Flyback Converter etc.

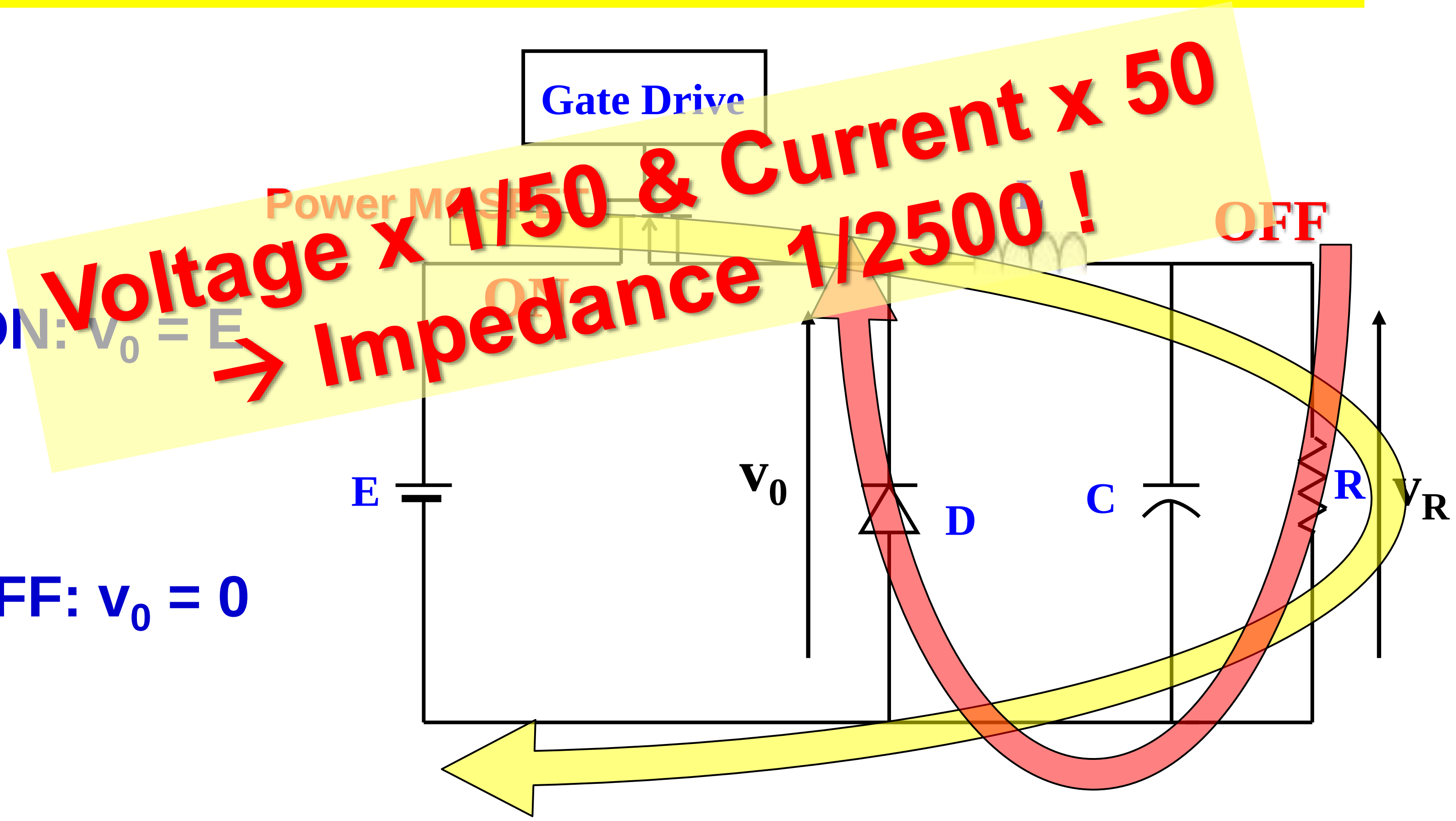
Switching Regulator: Step-down buck chopper

Average: $v_0 = dE = \frac{T_{on}}{T_{on}+T_{off}} E$, d: Duty Factor (2%)

If the loss is zero, Input power = Output power

ON: $v_0 = E$

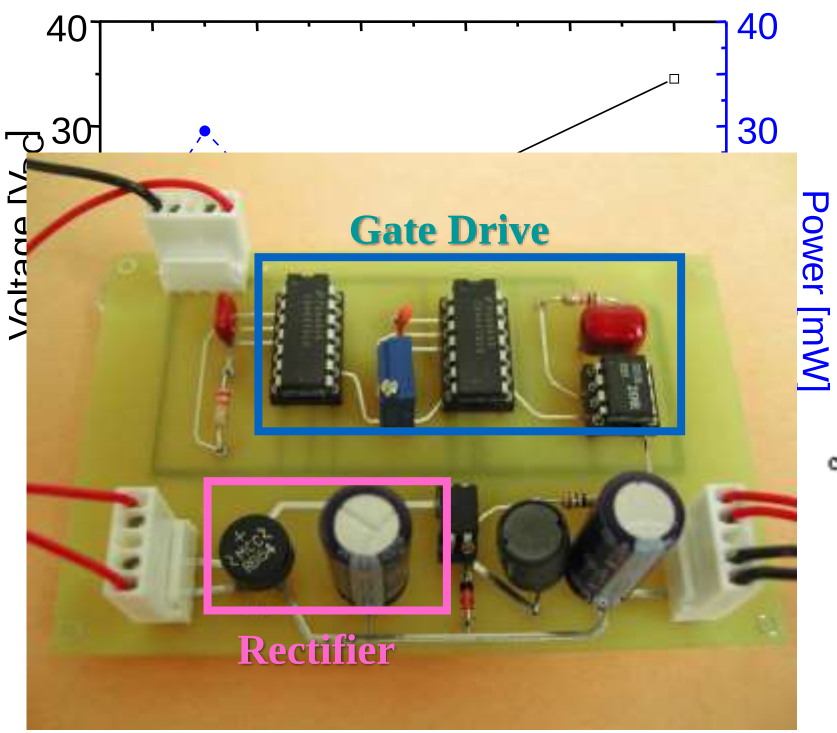
OFF: $v_0 = 0$



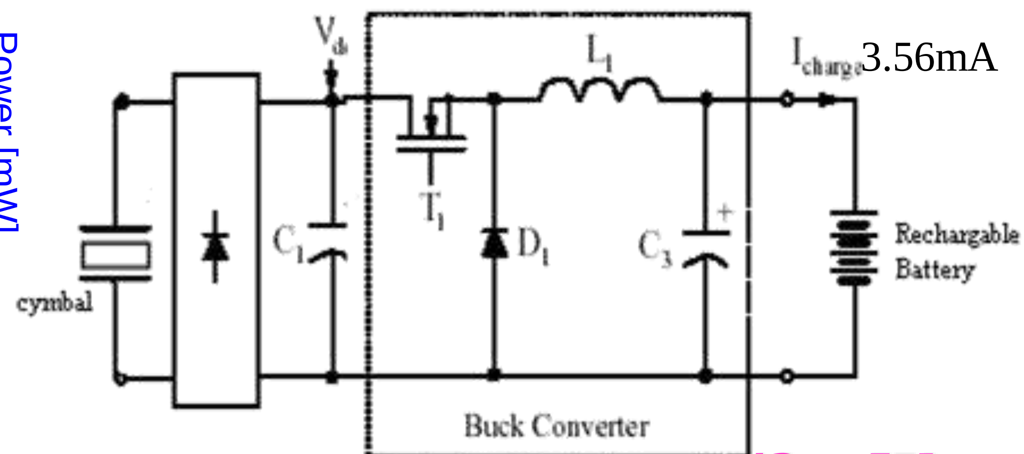
DC-DC Buck Converter with 12V Battery

- Shifting of matching impedance, **300kΩ to 5kΩ**.

- The Buck Converter increased the charging by 10 times.
- The power loss in the Gate Drive Circuit of Buck Converter is only **~5mW**.
- Buck DC-DC Converter harvests at the optimal duty cycle $D_{optimal}$ (**2% → 50^2 impedance change**) for a given mechanical excitation.



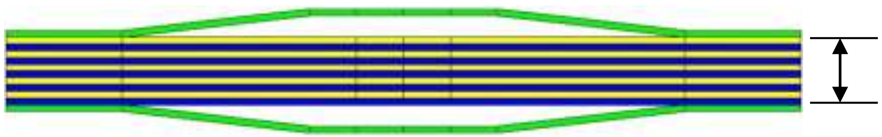
$$\eta_{converter} = 42.75\text{mW}/53\text{mW} \sim 81\%$$



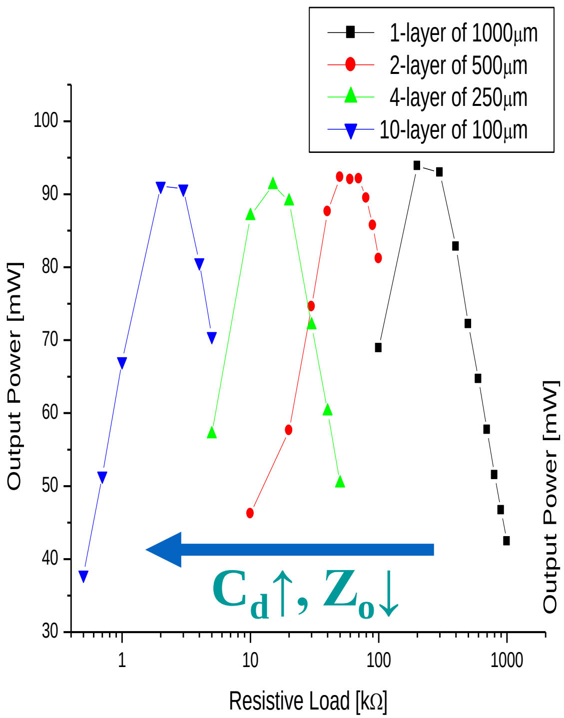
53 mW **43 mW**

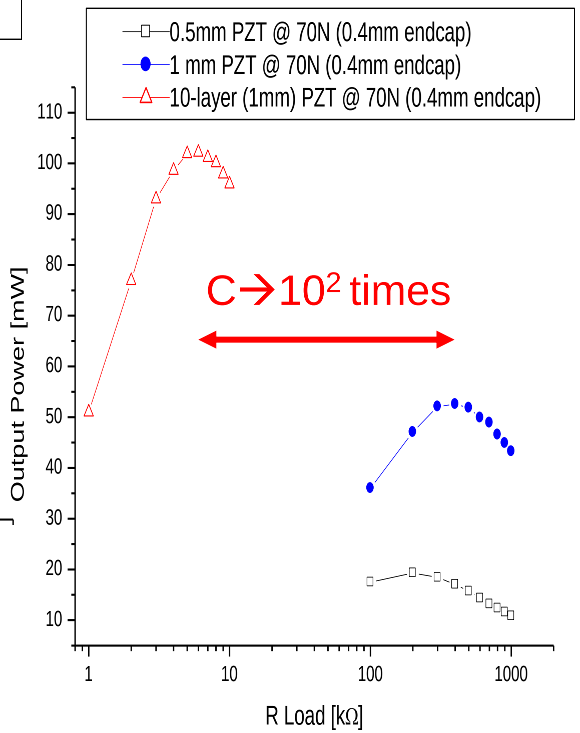
Output from Multilayered PZT Cymbals

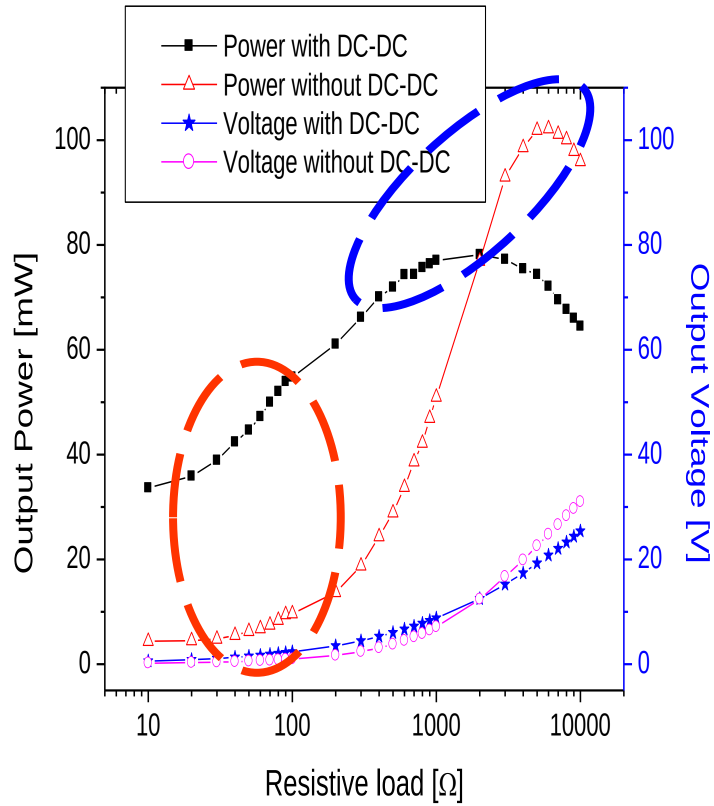
- Single layer (1mm and 0.5mm) and Multilayer (100 µm 10-layer)
- Output current of multilayer is 10 times higher at lower impedance



$$Z_o \propto {}^{1}\!/_{C}$$

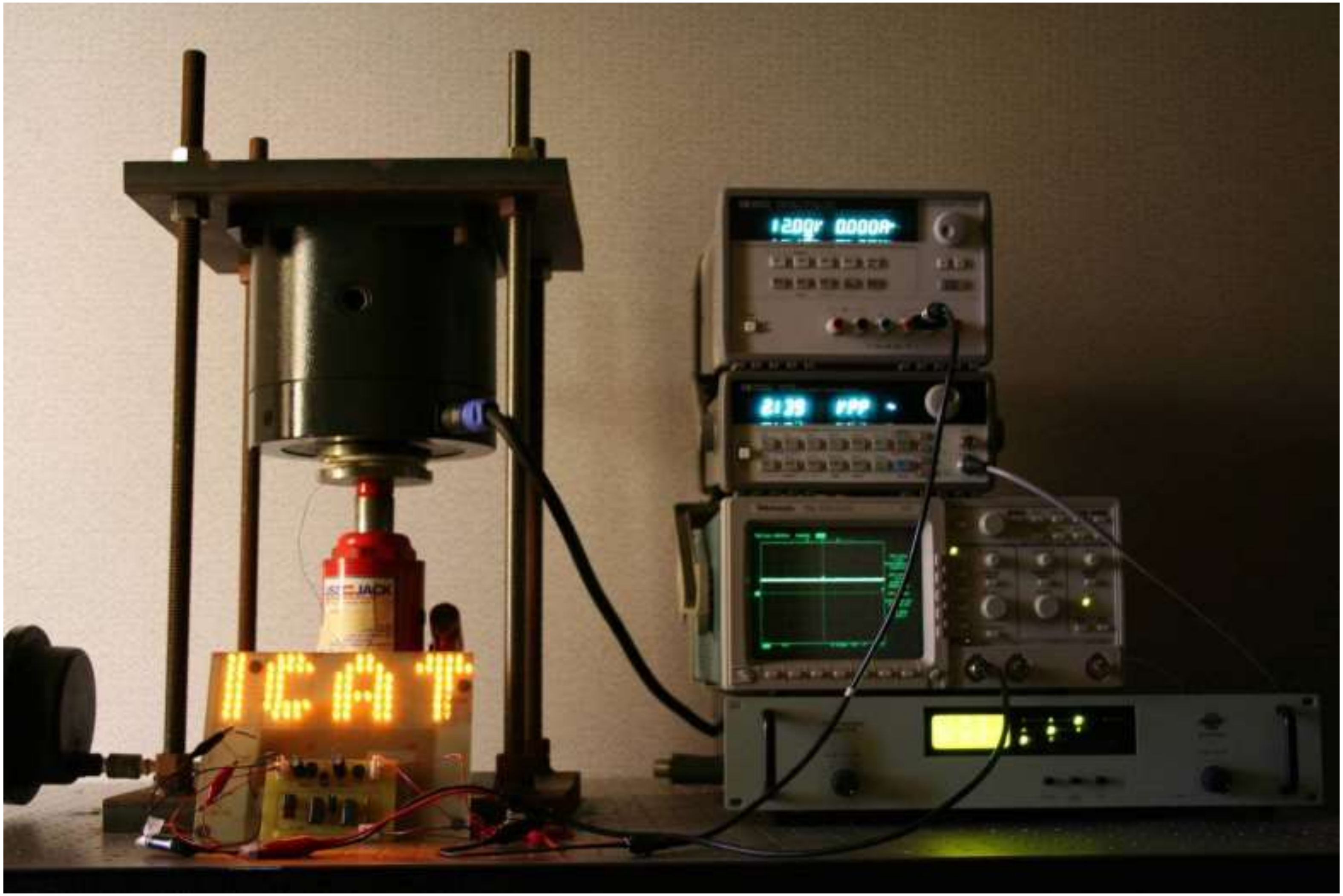






LED Lighting

- 5.3V, 10mA, 53mW, 500Ω



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Piezoelectric Energy Harvesting
- Uchino's Frustration-

(4) Few papers have reported energy flow or exact efficiency from the input mechanical noise energy to the final electric energy in a rechargeable battery via the piezoelectric transducer step by step. Why?

↓

You should learn how to measure the energy flow.

Future

Energy Flow (Transmission & Conversion)

Table 4 Energy flow/conversion analysis in the cymbal energy harvesting process.

Source Mechanical Energy	⇄	Transducer Mechanical Energy	⇄	Transducer Electrical Energy	⇄	Circuit-in Electrical Energy	⇄	Battery Electrical Energy
9.48 J		8.22 J		0.74 J		0.42 J		0.34 J

87 %

9 %

Rectifier- 57%

Converter- 81%

Efficiency 3.6 %

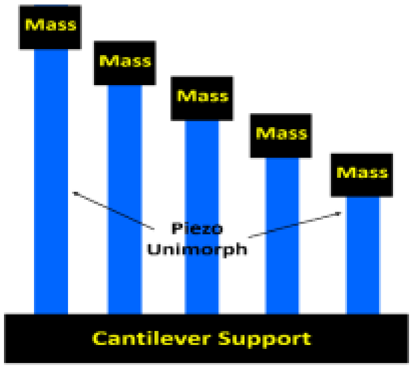
Amorphous Si solar cell 6%

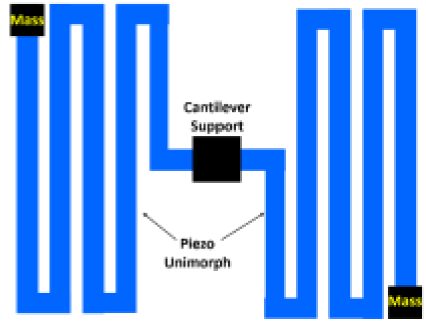
Higher electromechanical coupling k design is the key !

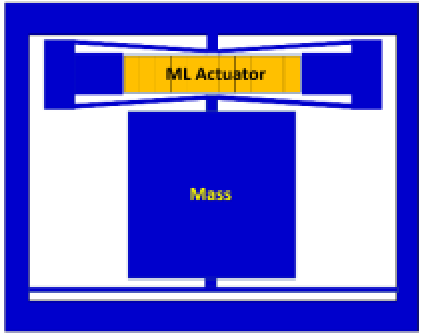
Summary

- Keys for piezoelectric energy harvesting: (1) Mechanical impedance matching, (2) Electromechanical transduction, and (3) Electrical impedance matching.
- The Cymbal is employed for the energy harvesting from a high-power mechanical vibration, while the MFC or PVDF is suitable for a small flexible energy vibration.
- A **Buck-Converter** is effectively used for the DC/DC converter for realizing the electrical impedance matching.
- Key to dramatic enhancement in the efficiency is to use a **high k mode**, such as k_{33}, k_t, or k_{15}, rather than flex-tensional modes.

Piezoelectric Energy Harvesting
- MEMS High k Design Proposals -



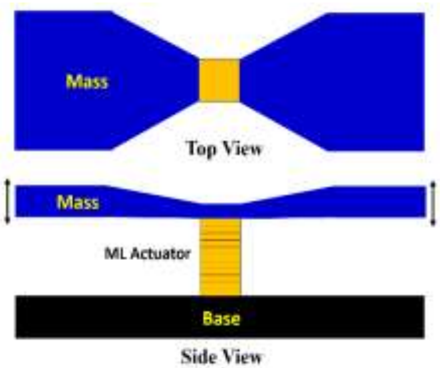


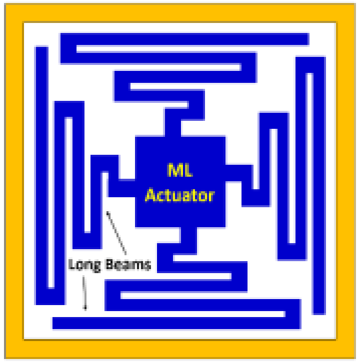


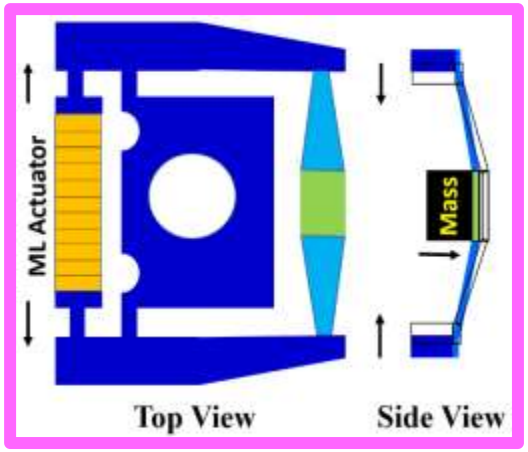
(a) Unimorph array with wide-frequency-range coverage

(b) Unimorph long-beam design with low resonance frequency

(c) ML & a hinge lever for in-plane vibration







(d) ML & wings for out-of-plane vibration

(e) ML & long-wing design with low resonance frequency

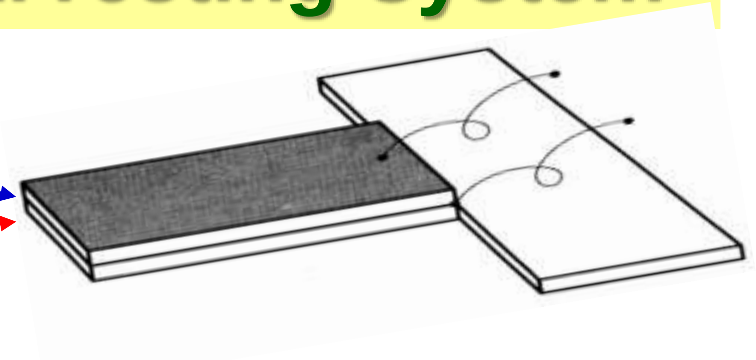
(f) ML & hinge lever for out-of-plane vibration

Future

Hybrid Energy Harvesting System

Piezoelectric Plate

Elastic Plate

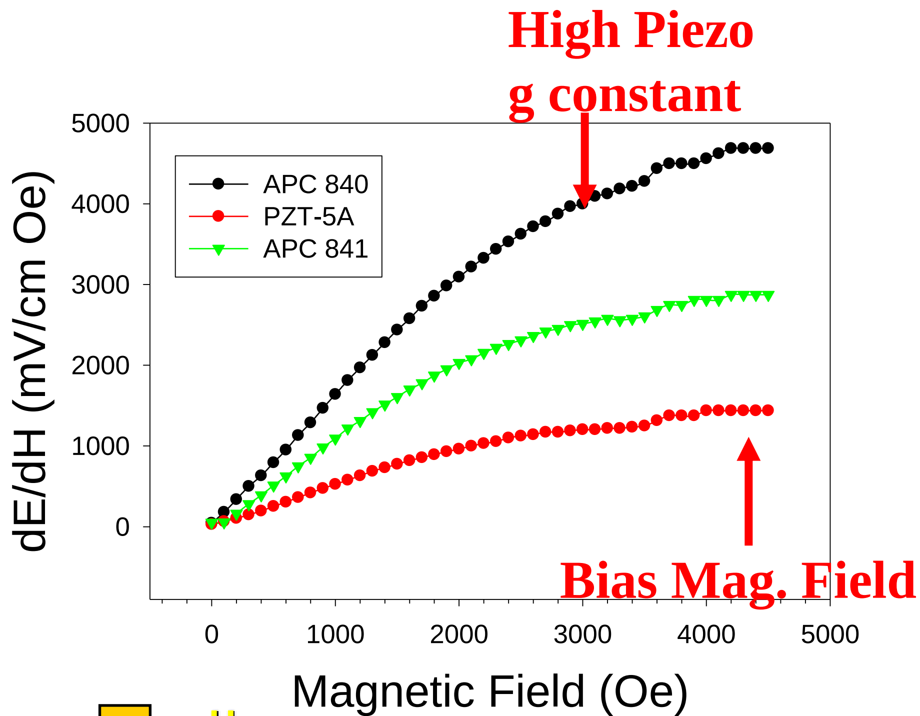


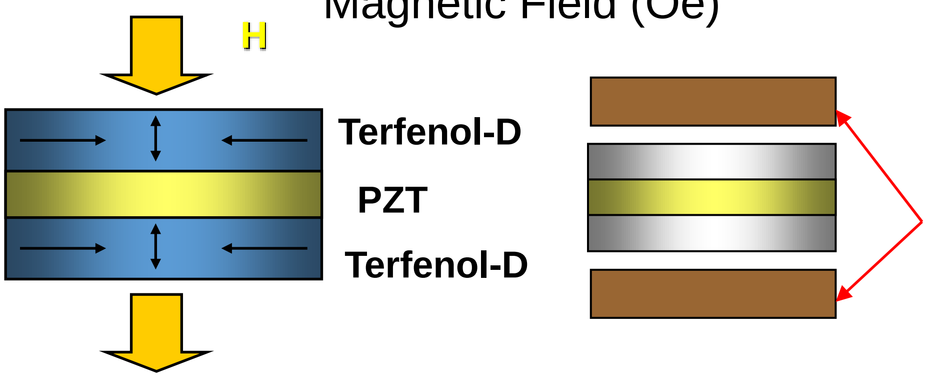
- Vibration Noise → Elastic material → Piezoelectric effect
- Magnetic Noise → Magnetostrictive material → Magnetoelectric effect
- Photo Illumination
  - Pure light → Elastic material → Photovoltaic effect
  - Photothermal heat → Elastic material → Pyroelectric effect

Future

Magneto-electric Sensor

Penn State Univ & Seoul National Univ





Can detect low frequency magnetic field!

Ryu, J., A. Vazquez Carazo, K. Uchino and H. E. Kim, J. Electroceramics, 7, 17-24 (2001).

Seoul National University
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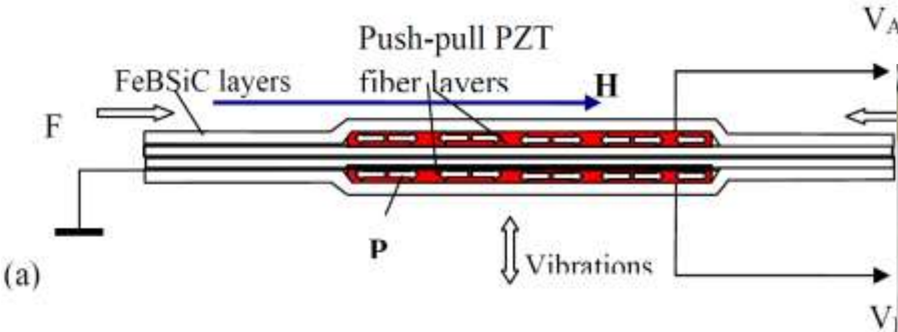
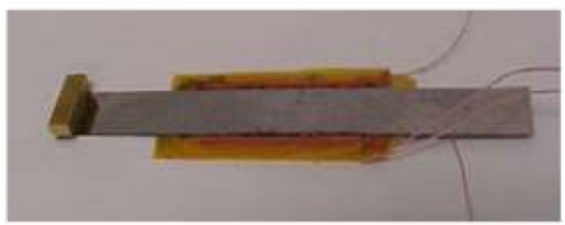
Future

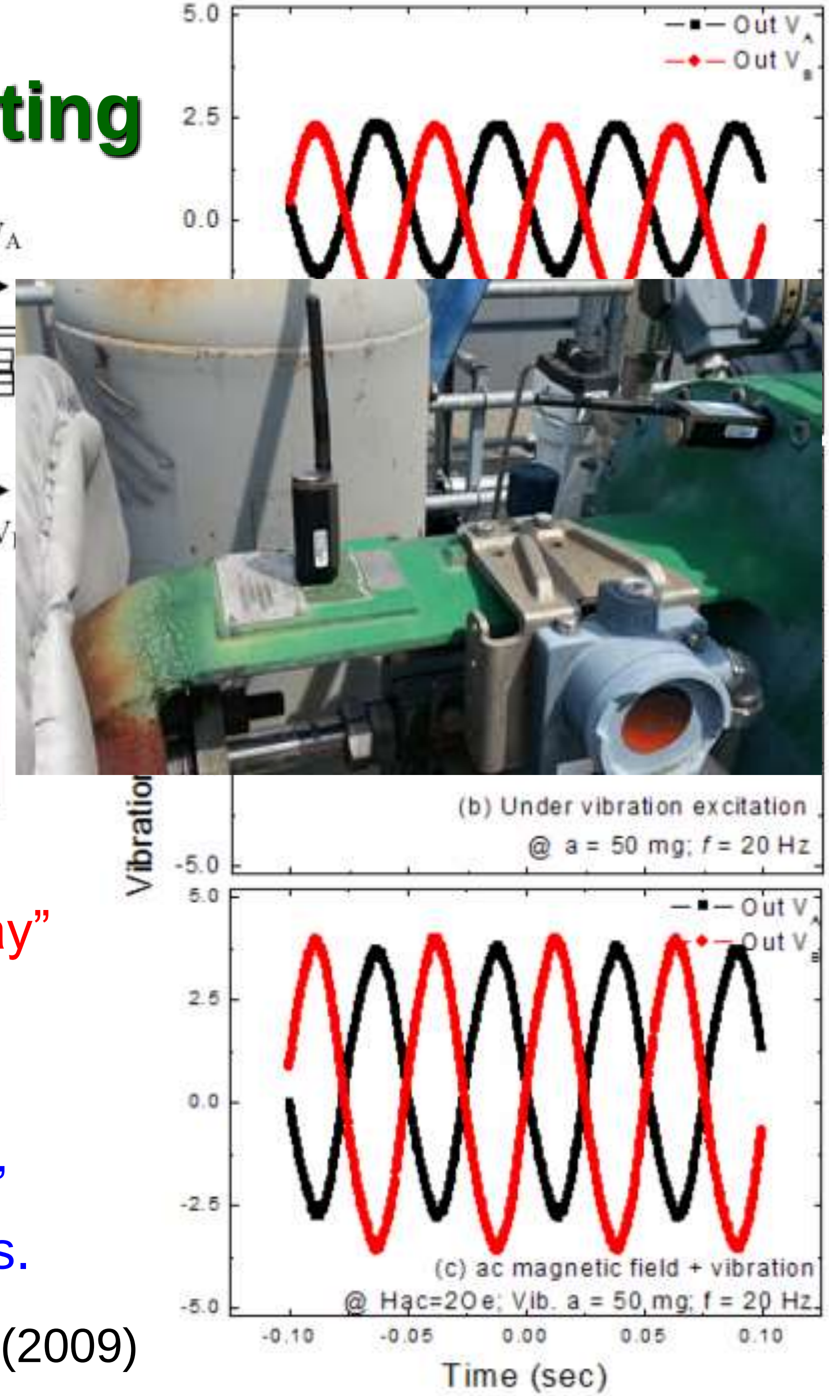
Hybrid Energy Harvesting



(a)



(b)



Experimental: (a) under only a "stray" magnetic excitation of H^{ac}=2Oe (f=20Hz), (b) under only a "stray" vibrational excitation of a=50mg (f=20Hz), and (c) under both "stray" magnetic and vibrational excitations.

Junyi Zhai: Ph. D. Thesis, Virginia Tech (2009)

Piezoelectric Energy Harvesting
- Personal Perspectives-

(1) A hybrid energy harvesting device which operates under either magnetic and/or mechanical noises was introduced, by coupling magnetostrictive and piezoelectric materials.

(2) Two development directions:

(a) Remote signal transmission (such as structure health monitoring) in [mW] power level, and

(b) Energy accumulation in rechargeable batteries in [W] power level for home appliance and automobile applications.

(3) MEMS/NEMS and 'nano harvesting' devices:

(a) Present energy level pW ~ nW is NOT useful.

→ Thick film (> 30 μm), k_{33} mode design

(b) A genius idea is required on how to combine thousands of these nano-devices in parallel and synchronously in phase.

Misconceptions in Piezoelectric Energy Harvesting System Development

Kenji Uchino
Int'l Center for Actuators & Transducers
The Pennsylvania State University, PA

END

Thank you!

Contact: Kenji Uchino, Director
E-mail: kenjiuchino@psu.edu; Phone: 814-863-8035