Piezoelectric MEMS Energy Harvesters

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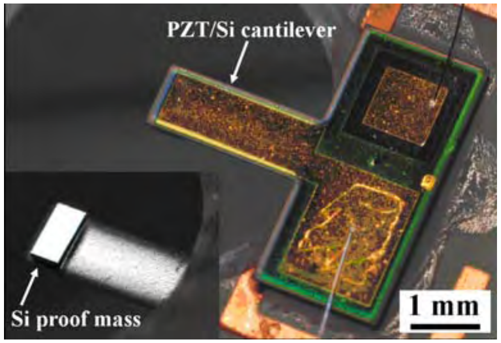
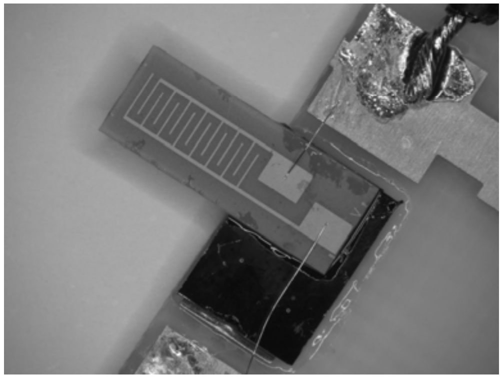
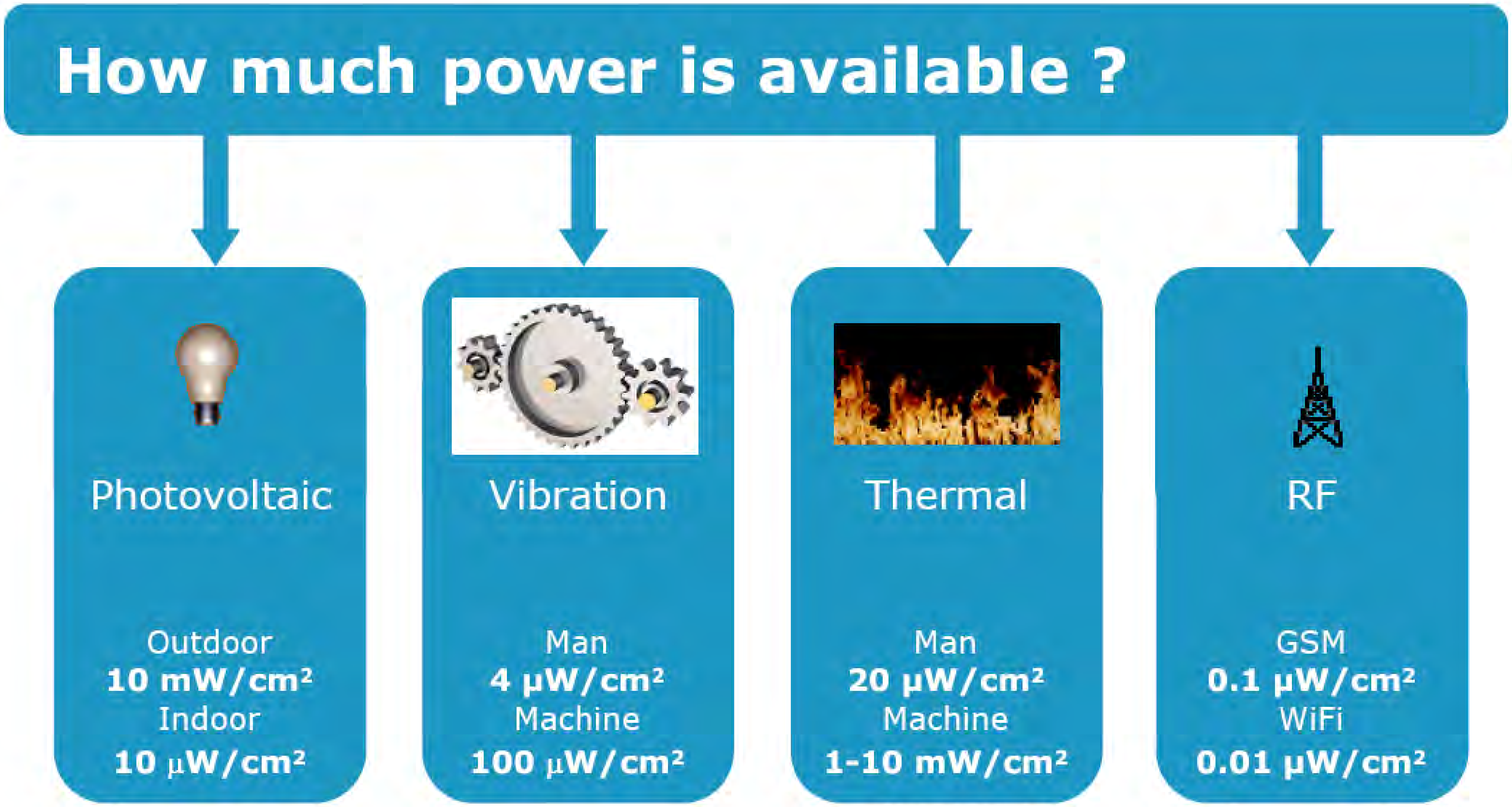


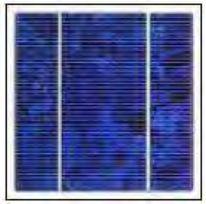


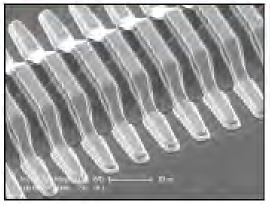
Sources of energy and harvesting approaches



How much power is available ?

Photovoltaic	Vibration	Thermal	RF
Outdoor	Man	Man	GSM
$10\ \mathrm{mW/cm^2}$	**$4\ \mu\mathrm{W/cm^2}$**	**$20\ \mu\mathrm{W/cm^2}$**	**$0.1\ \mu\mathrm{W/cm^2}$**
Indoor	Machine	Machine	WiFi
$10\ \mu\mathrm{W/cm^2}$	**$100\ \mu\mathrm{W/cm^2}$**	**$1\text{-}10\ \mathrm{mW/cm^2}$**	**$0.01\ \mu\mathrm{W/cm^2}$**

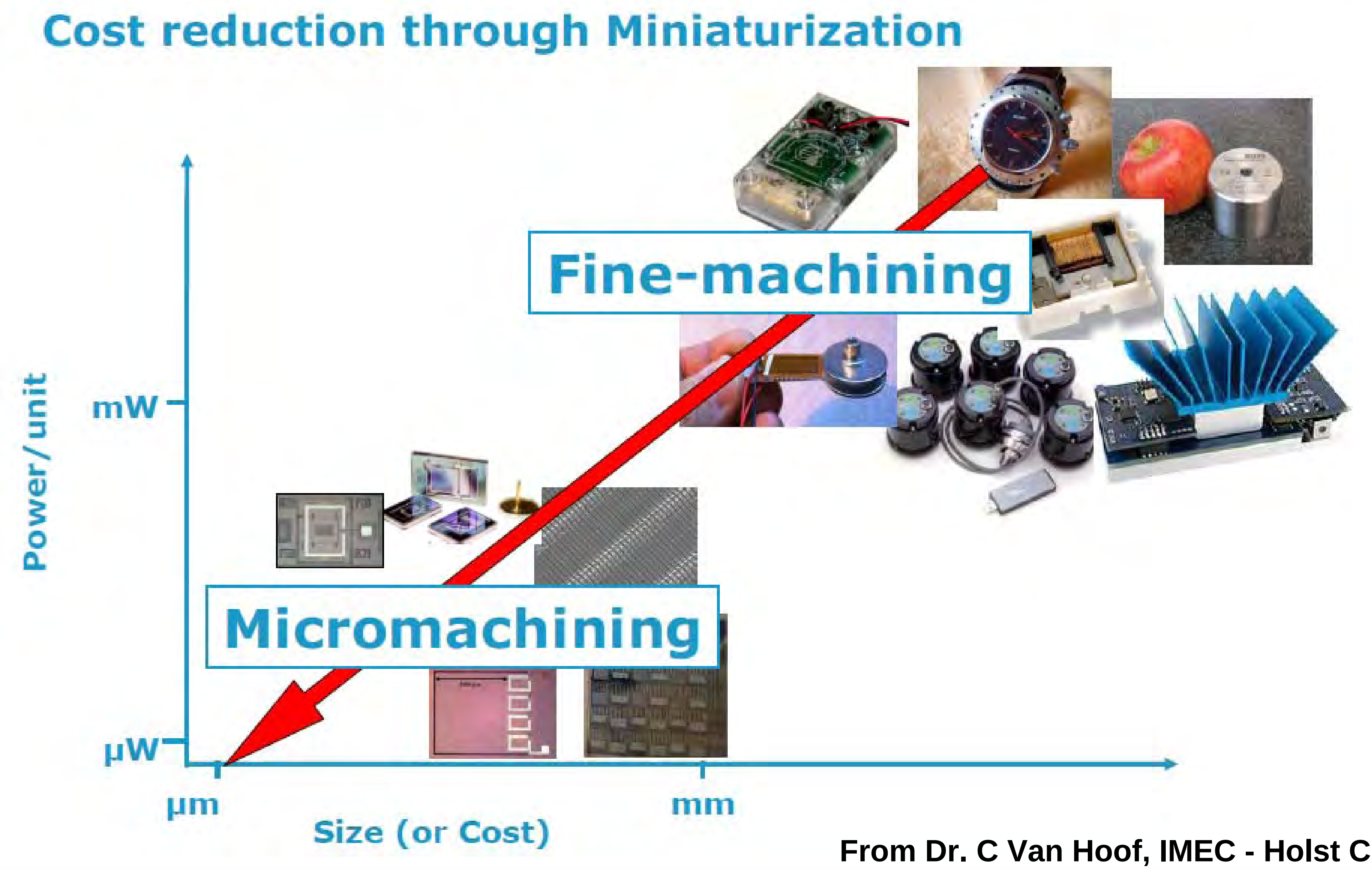




*Vullers et al, Micropower Energy Harvesting, Solid-State Electronics 53 (7) Pgs 684-693, DOI: 10.1016/j.sse.2008.12.011

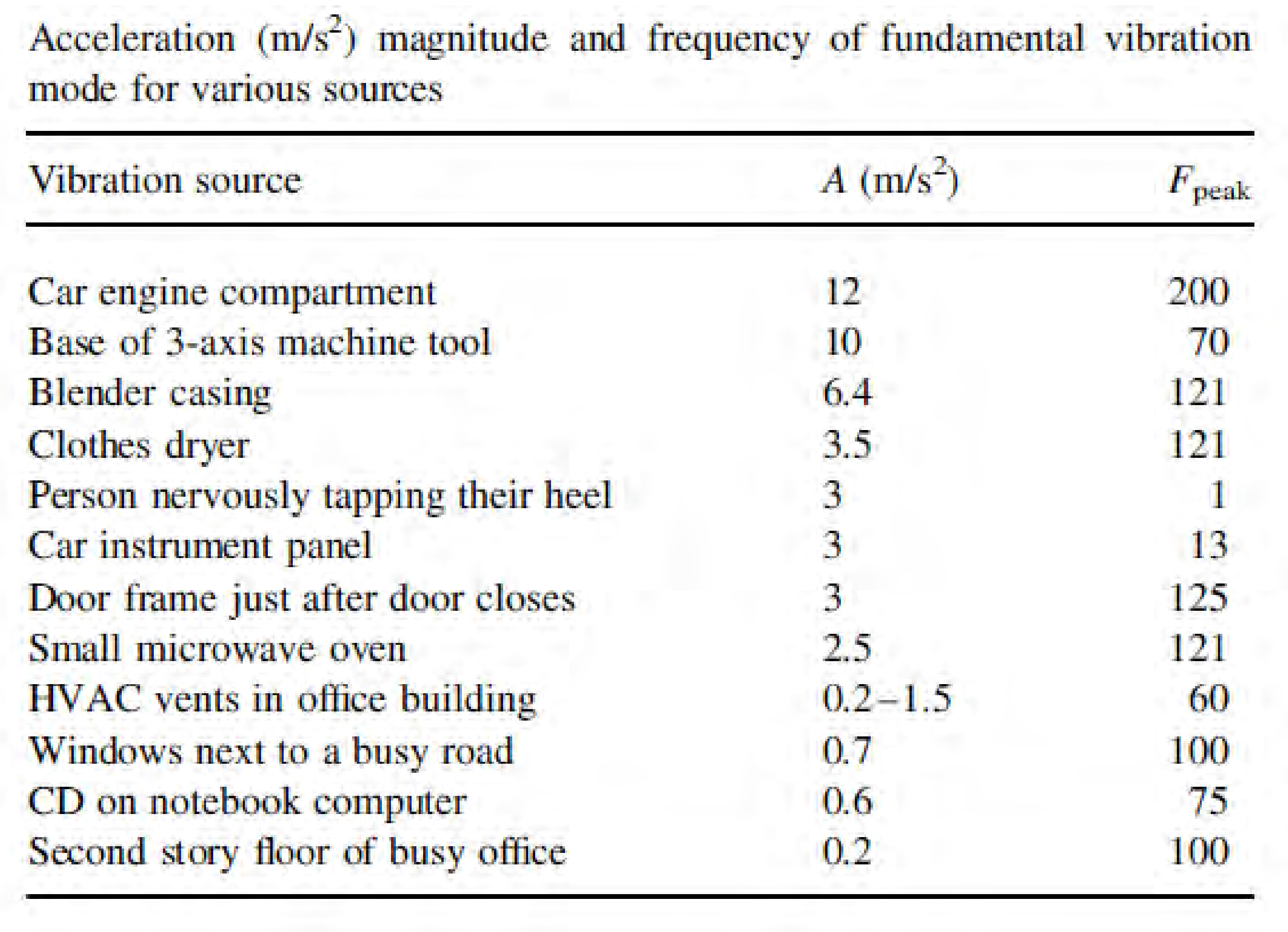
From Dr. C Van Hoof, IMEC - Holst Center

Towards miniaturization



From Dr. C Van Hoof, IMEC - Holst Center

Vibration sources

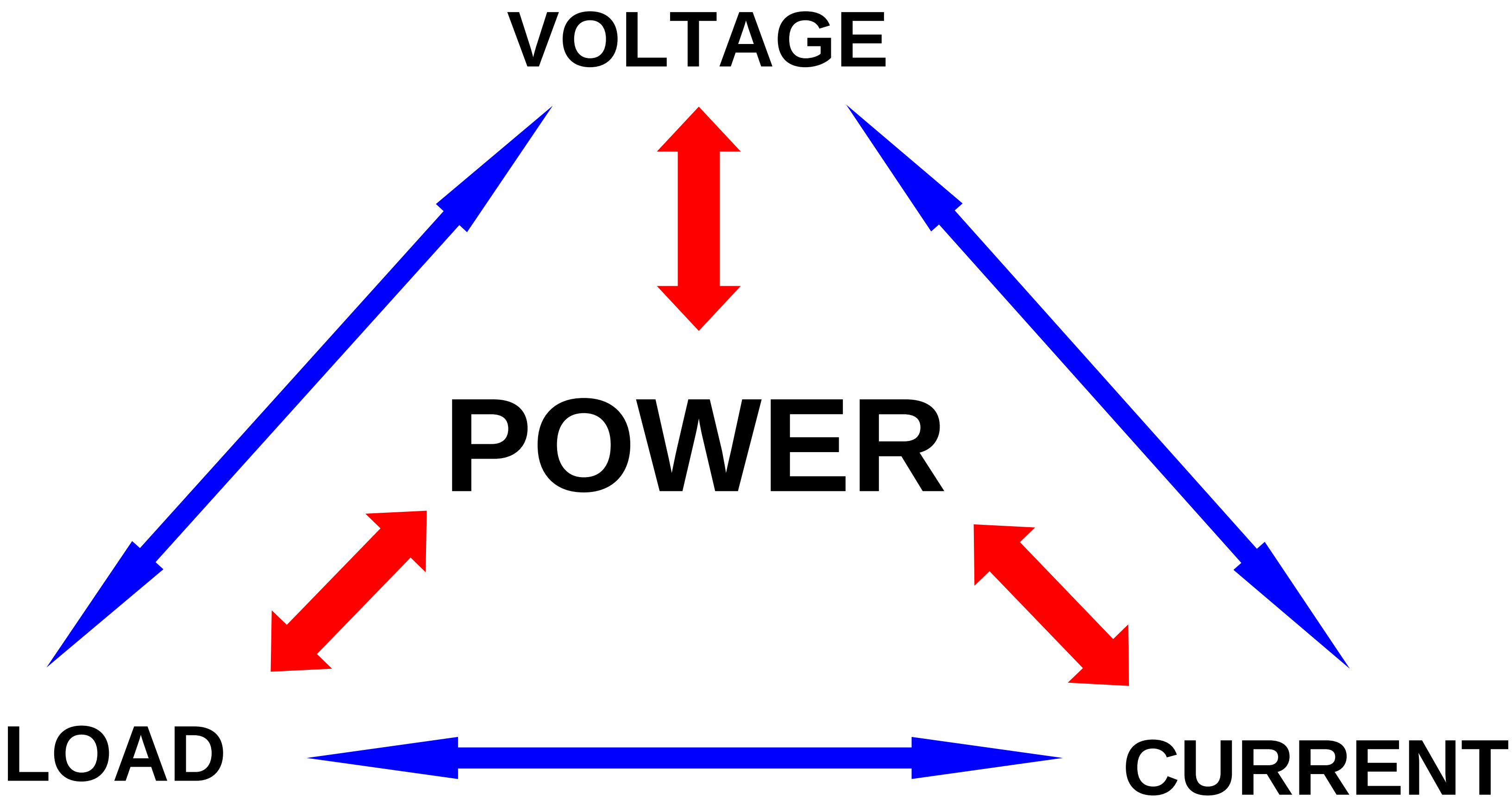


Acceleration (m/s^2) magnitude and frequency of fundamental vibration mode for various sources

Vibration source	A (m/s^2)	F_{peak}
Car engine compartment	12	200
Base of 3-axis machine tool	10	70
Blender casing	6.4	121
Clothes dryer	3.5	121
Person nervously tapping their heel	3	1
Car instrument panel	3	13
Door frame just after door closes	3	125
Small microwave oven	2.5	121
HVAC vents in office building	0.2–1.5	60
Windows next to a busy road	0.7	100
CD on notebook computer	0.6	75
Second story floor of busy office	0.2	100

S. Roundy et al., Computer Communications 26 (2003) 1131–1144

Electrical parameters of energy harvesters



VOLTAGE

POWER

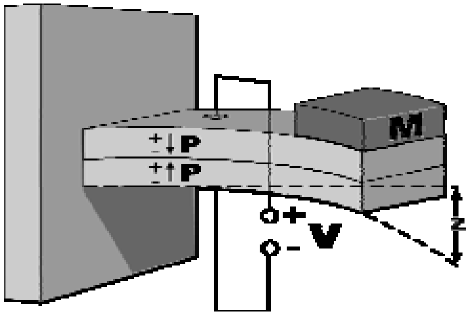
LOAD

CURRENT

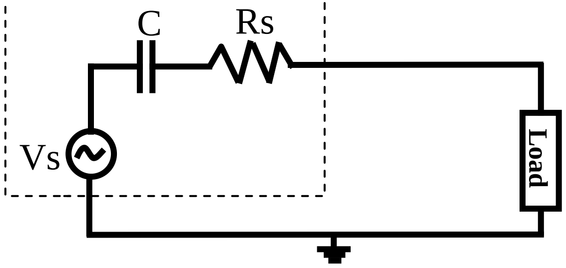
Three ways to convert vibrations

Piezoelectric

Strain in piezoelectric material causes a charge separation (voltage across capacitor)

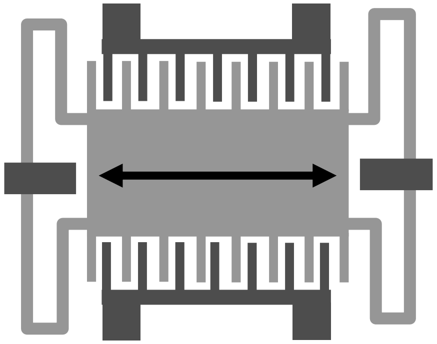


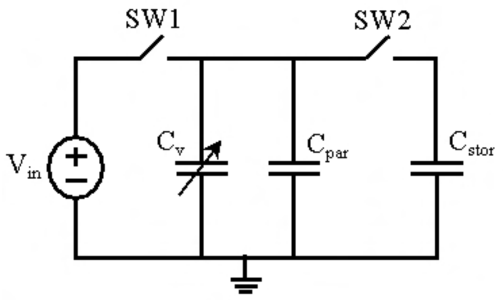
Piezoelectric generator



Capacitive

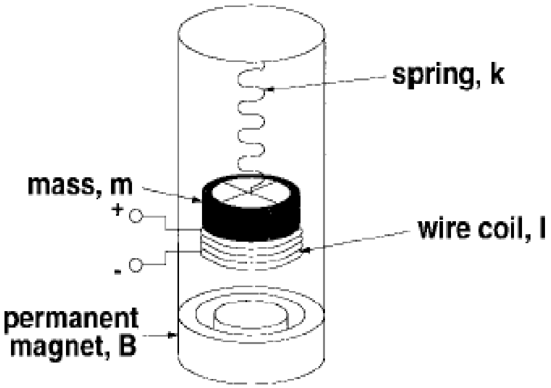
Change in capacitance causes either voltage or charge increase.





Inductive

Coil moves through magnetic field causing current in wire.

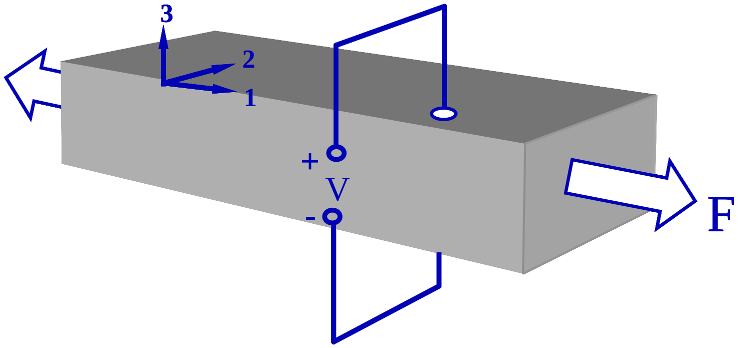


Amirtharajah et. al., 1998

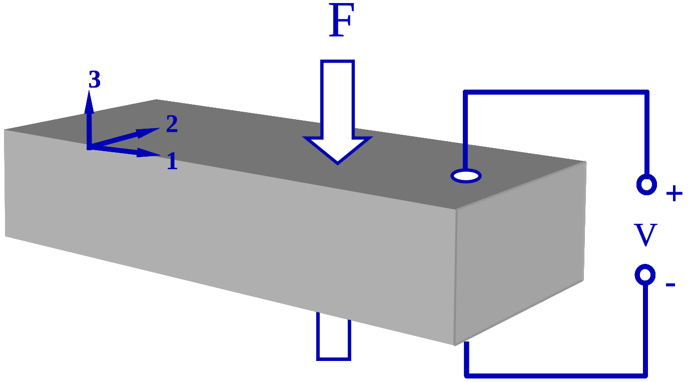
Piezoelectric scavengers on silicon

- Resonant type and impact type harvesters
- d31 or d33

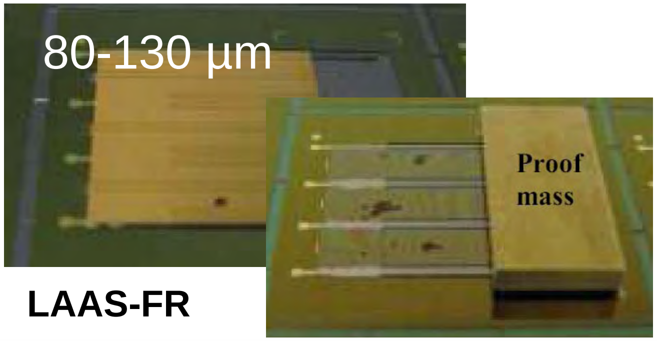
31 Mode (transverse)



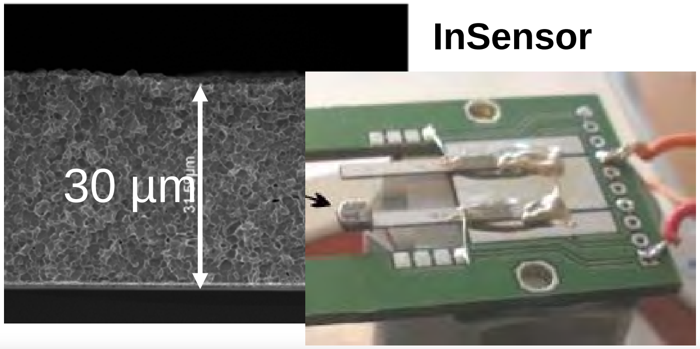
33 Mode (longitudinal)



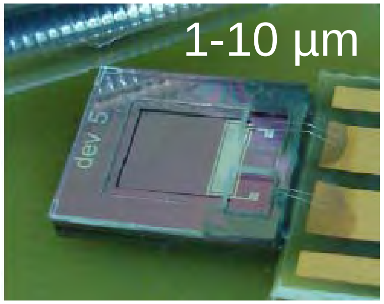
- Thick PZT sheet - Thick PZT films - Thin films (AlN, PZT)



LAAS-FR



InSensor



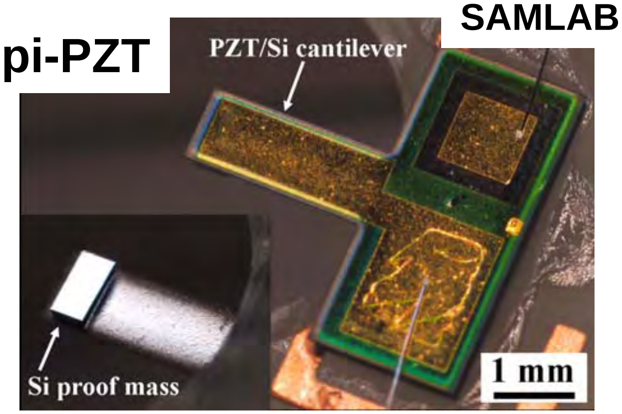
IMEC

Piezoelectric micro energy harvesters

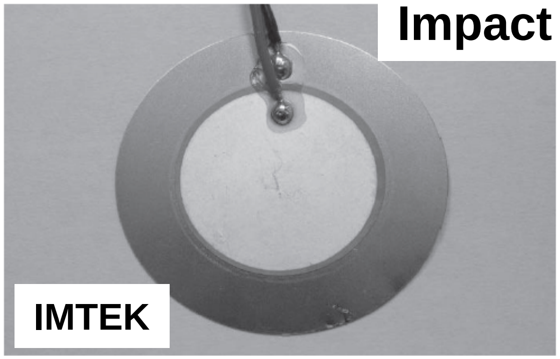
1. Impact generators
2. Resonant generators
   - d_{31} mode (transverse)
   - d_{33} mode (longitudinal)
   - AlN
   - Epitaxial films

Epi-PZT

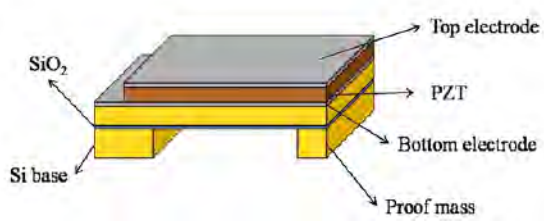
SAMLAB

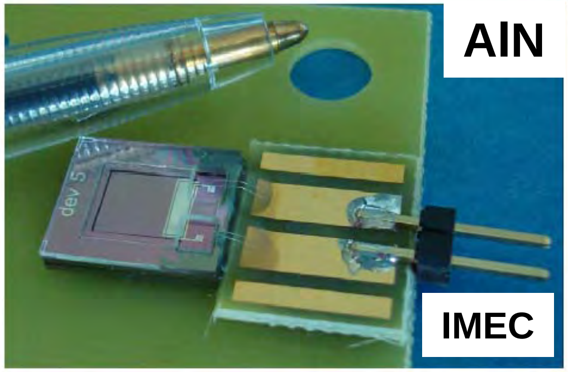


Impact



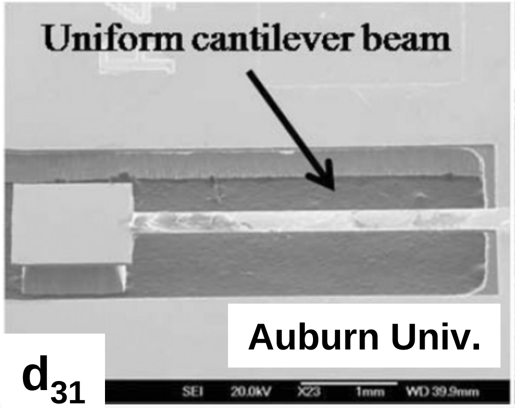
IMTEK





AlN

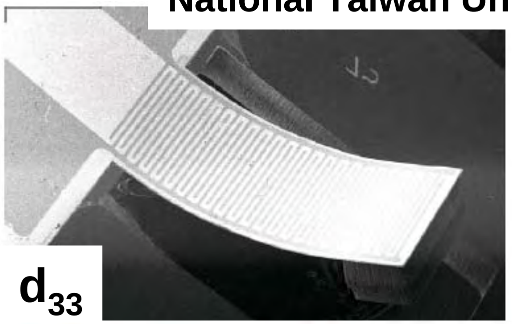
IMEC



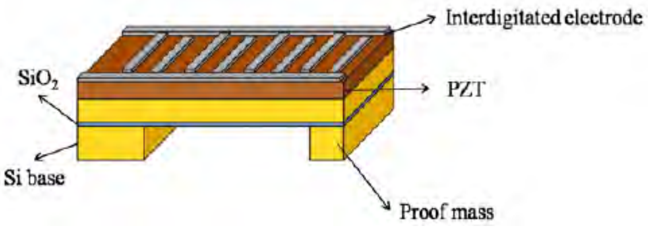
d_{31}

Auburn Univ.

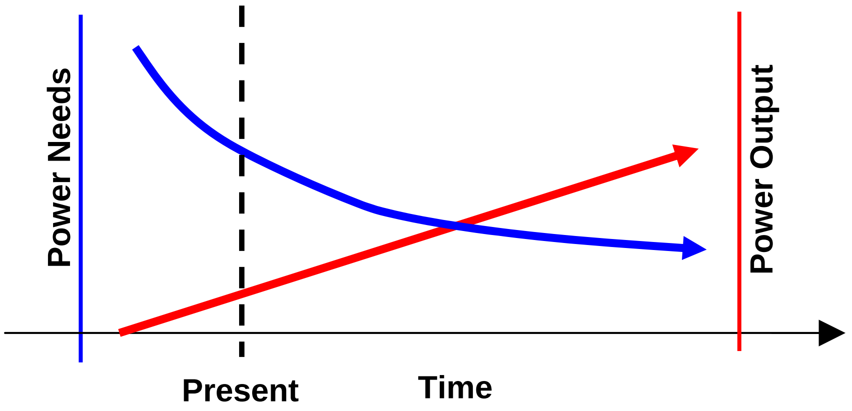
National Taiwan Univ.



d_{33}



MEMS power generator

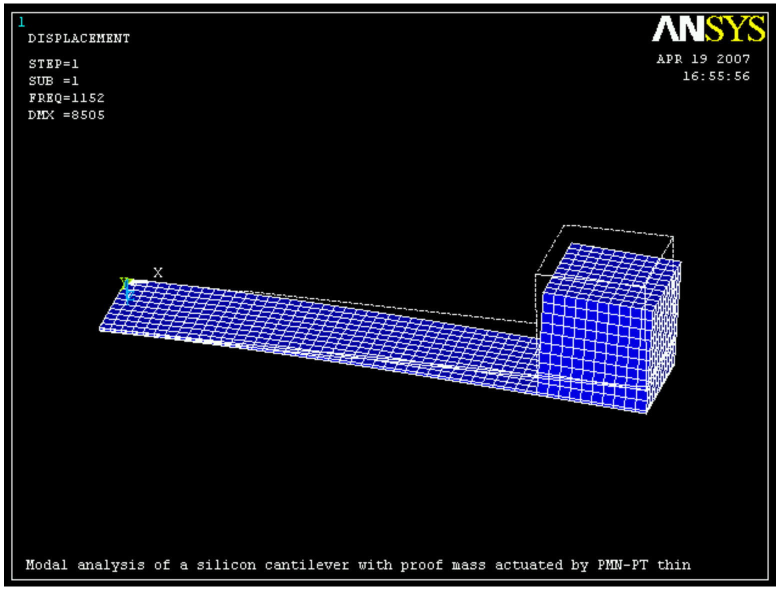


Project description

- Optimize the structure and load impedance to maximize the efficiency of the vibration-to-electricity conversion
- Develop microfabrication processes
- Study the effect of viscous air damping on the power generation
- Design a piezoelectric converter circuit
- Develop an experiment set-up for power generating test

Objective

Design and fabricate a MEMS-based piezoelectric power generator for the vibrational energy harvesting



```
1
DISPLACEMENT
STEP=1
SUB =1
FREQ=1152
DMX =8505
```

Modal analysis of a silicon cantilever with proof mass actuated by PMN-PT thin

Resonant type harvester

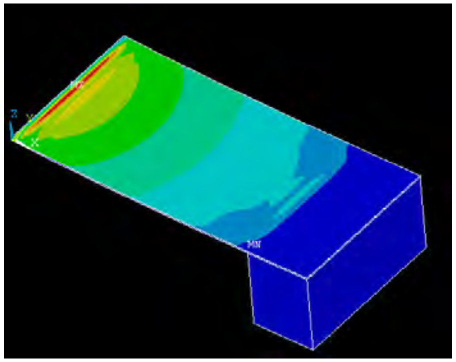
Structure design requirements

Low resonant frequency

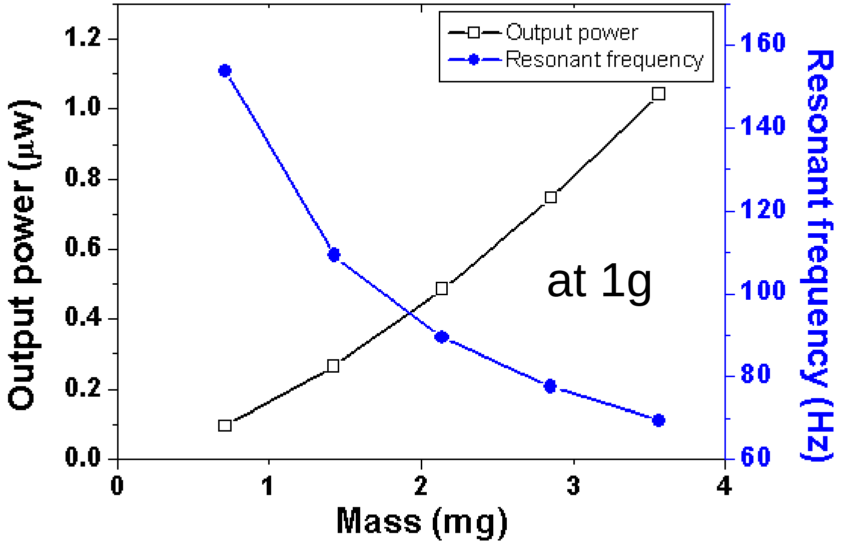
The frequency range of the ambient vibrations → 60-200 Hz

High power generation

Large stress in the PZT film → Large deflection



Modelling of PZT cantilever with a proof mass ***(1000um x 2000um)***



Cantilever with a proof mass

- Heavy proof mass: low resonant frequency and high power generation
- Low damping effect
- Compactness

Analytical power model (Roundy)

$$P = \frac{1}{2\omega^2} \frac{RC_b^2 \left(\frac{1.5 E_P d_{31} t_p \left(t_p + t_s \right)}{l_b^2 \varepsilon} \right)^2 A_{in}^2}{\left(4\zeta^2 + k_{31}^2 \right) \left(RC_b \omega \right)^2 + 4\zeta k_{31}^2 \left(RC_b \omega \right) + 4\zeta^2}$$

Measured parameters
-Frequency
-Damping ratio
-Coupling factor
-Dielectric constant
-Piezo coefficient d_{31}

P: output power (bimorph)
R: resistive load
C_b: PZT capacitance
E_p: PZT Young's modulus
d_{31}: piezoelectric coeff.
ε: dielectric constant
t_p: PZT thickness
t_s: silicon thickness
l_b: cantilever length
A_{in}: acceleration
ζ: damping ratio
k: coupling coeff.
ω: angular frequency

Piezoelectric films for energy harvesters

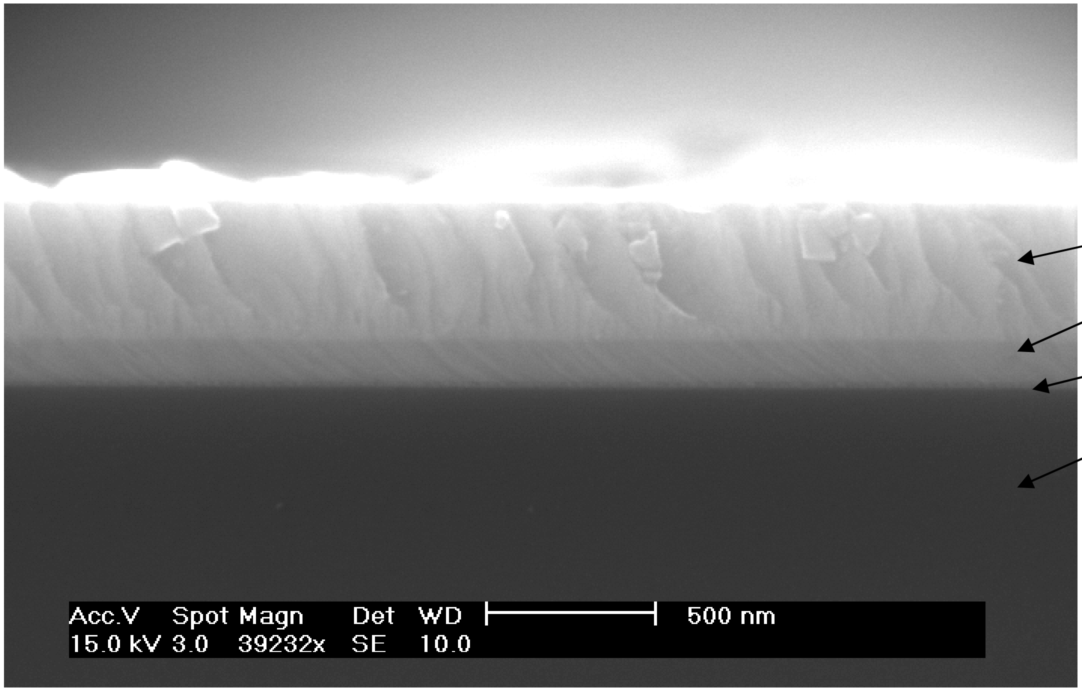
Electrical characteristic	Figure of merit
Power generation (P_F)	e_{31}^2/ε_r
Voltage generation (V_F)	e_{31}/ε_r
Current generation (I_F)	e_{31}

High piezoelectric coefficient
Low dielectric permittivity

Piezo material	$-e_{31}$ (Cm^{-2})	ε_r	P_F	V_F	I_F
AlN*	1.05	10.5	0.11	0.100	1.05
Poly-PZT (53/47)*	12	900	0.16	0.013	12
Epi-PZT (20/80)**	**18.2**	100	3.31	0.182	18.2

*S. Trolier-McKinstry and P. Muralt, J. Electroceram. **12**, 7 (2004)
**Measured data

Epi Piezo MEMS Harvester



Single crystalline piezoelectric film

SRO bottom electrode

STO

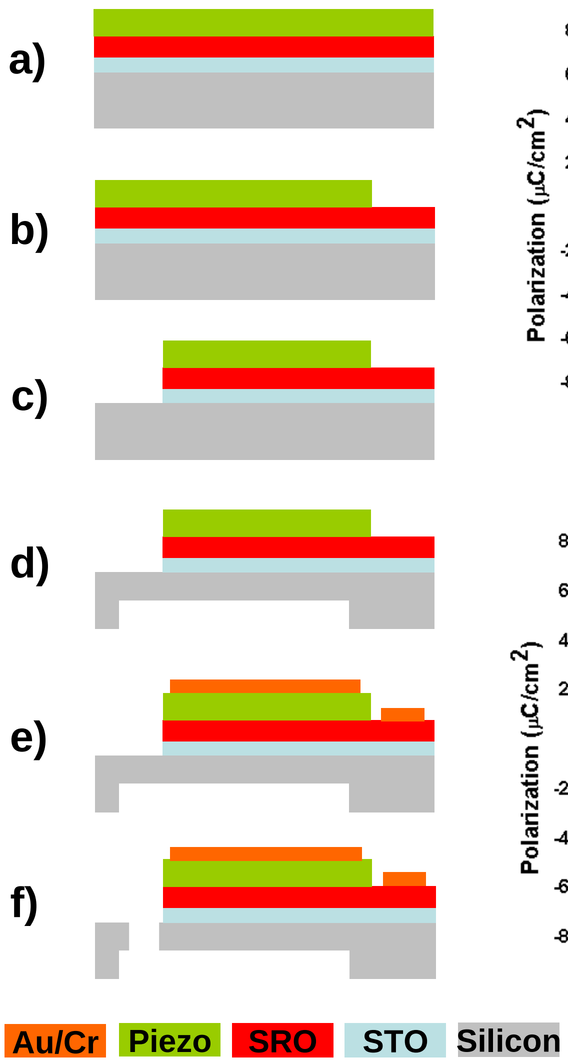
Si substrate

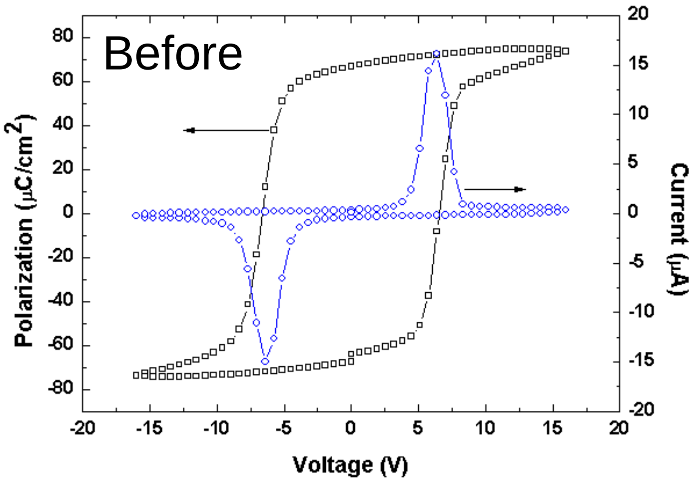
$SrTiO_3$: Strontium Titanate Oxide (STO)

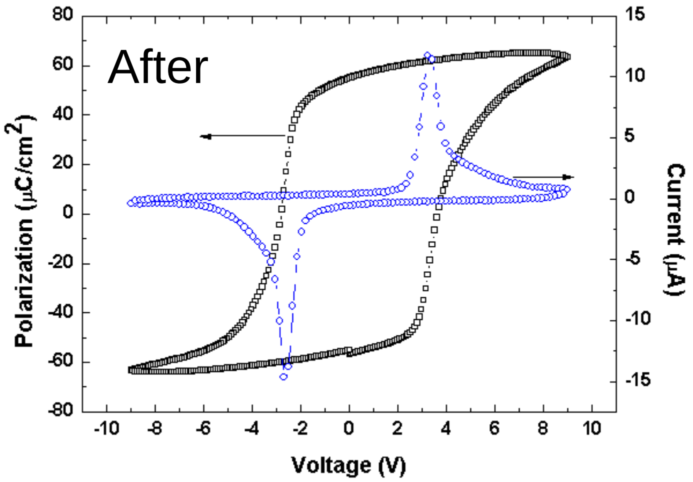
$SrRuO_3$: Strontium Ruthenate Oxide (SRO)

- Uniform control of the piezoelectric response over nanometer length scales
- Atomically smooth and exhibit microstructural homogeneities
- Very large piezoelectric coefficients
- Limited to maximum thickness of 0.5 µm

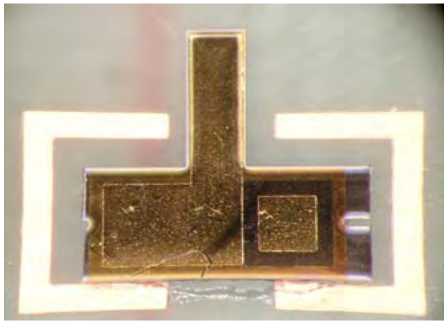
Technology platform

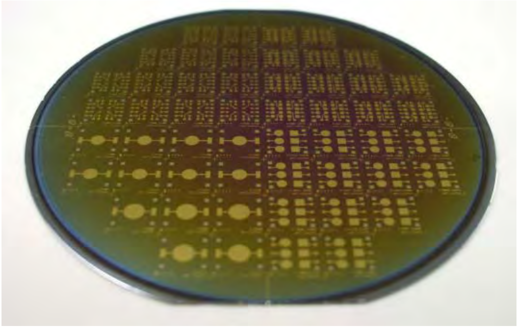


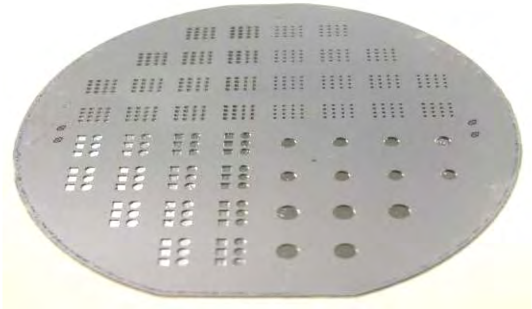




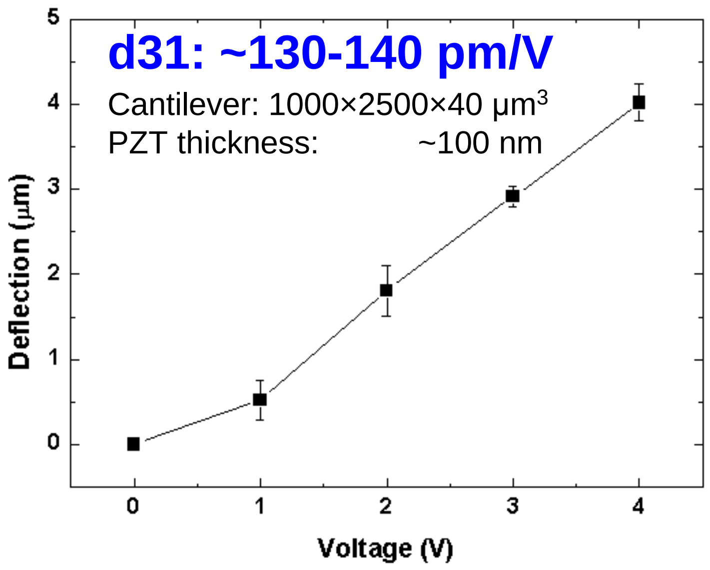
D. Isarakorn et al. JMM, 2010







Epitaxial PZT cantilevers

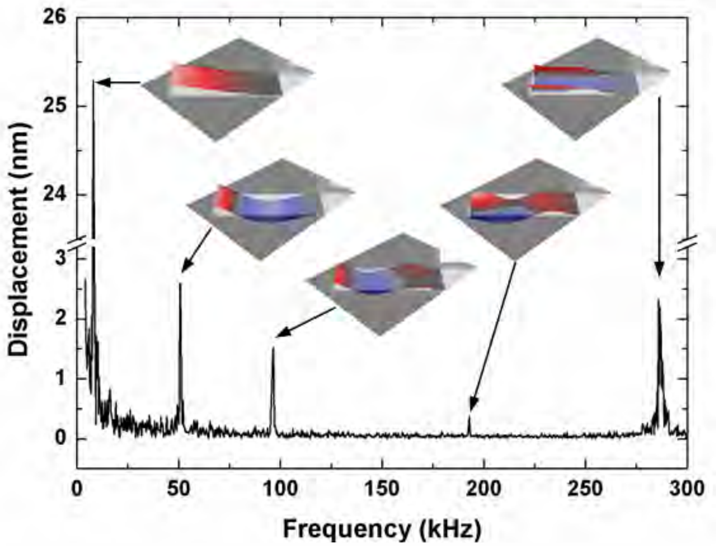

d31: ~130-140 pm/V

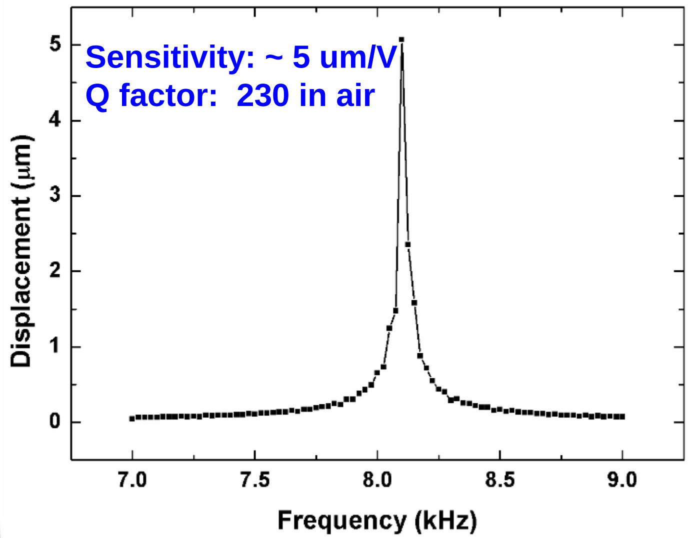
Cantilever: 1000×2500×40 µm^3
PZT thickness: ~100 nm

$$d_{31} = -\frac{1}{3}\frac{K}{s_s s_p h_s \left(h_s + h_p\right) L^2}\frac{\delta}{V}$$

$$K = 4 s_p s_s h_s h_p^3 + 4 s_p s_s h_s^3 h_p + s_p^2 h_s^4 + s_s^2 h_p^4 + 6 s_p s_s h_s^2 h_p^2$$

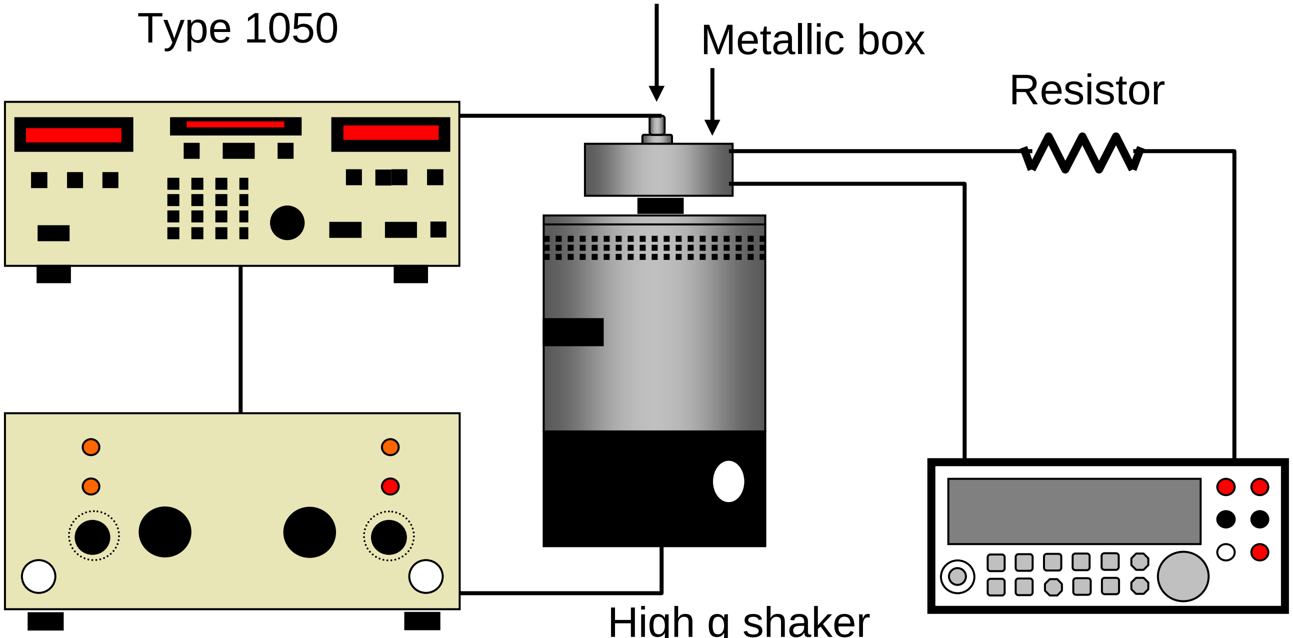
s_s : the compliance of the Si layer (7.7 × 10^{-12} m^2/N)
s_p : the compliance of the PZT film (12.4 × 10^{-12} m^2/N)
h_s : the thickness of Si layer
h_p : the thickness of the PZT film




Sensitivity: ~ 5 um/V
Q factor: 230 in air

D. Isarakorn et al. JMM, 2010

Experimental setup



Exciter Control
Type 1050

Accelerometer
Type 4374

Metallic box

Resistor

Power Amplifier
Type 2712

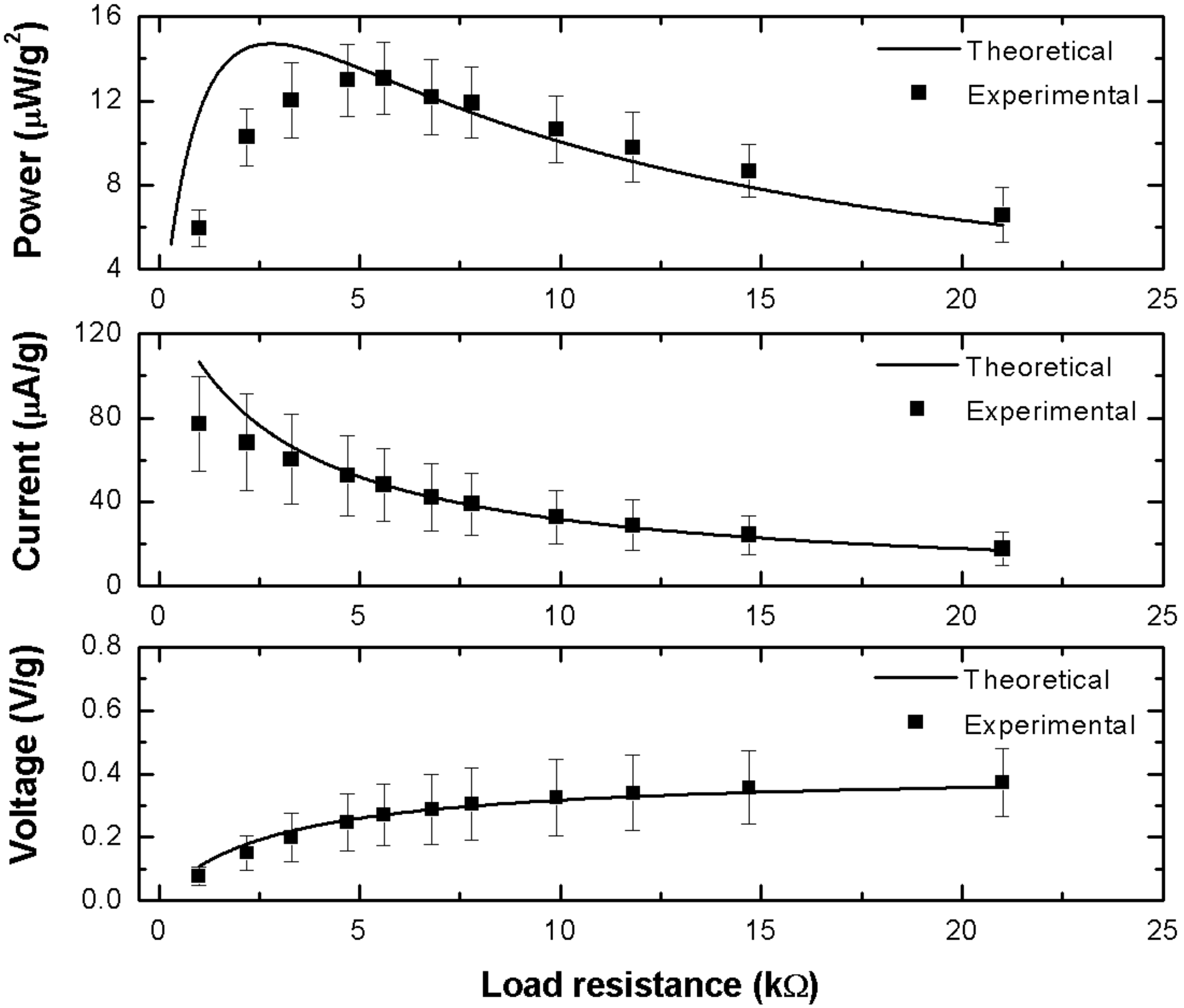
High g shaker
Type 4811

Multimeter
(Agilent 34411A)

Bruel & Kjaer vibration exciter system

- Max acceleration 210*g* - Maximum displacement 12.7 mm
- Frequency 1 Hz – 10kHz - Frequency resolution 1.19 mHz

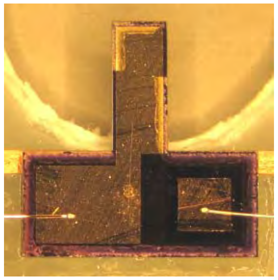
Experimental results

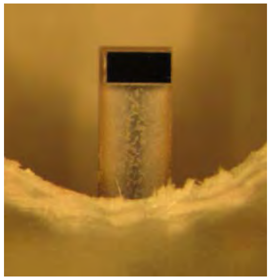


Epi PZT MEMS energy harvester

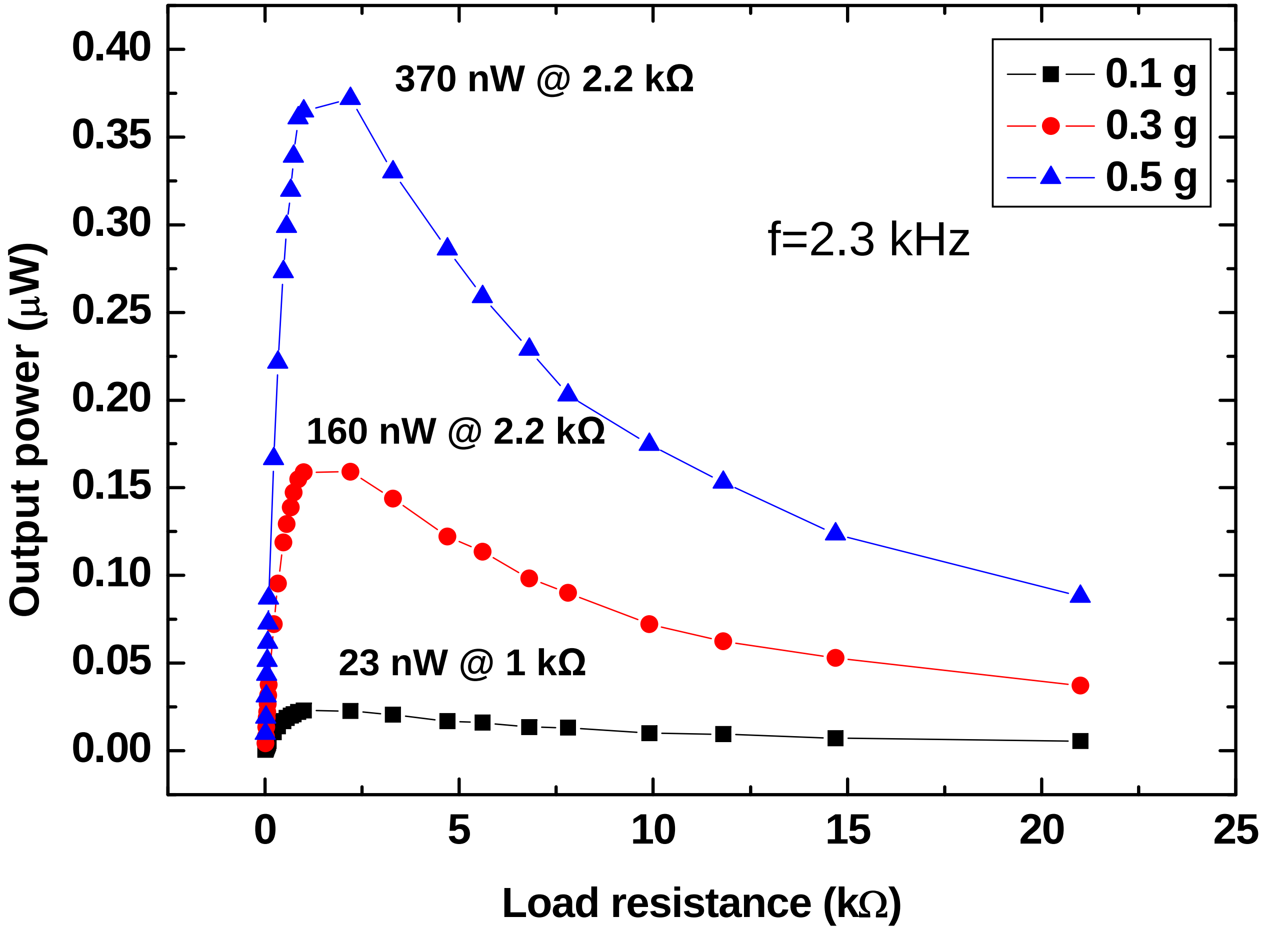
Epitaxial PZT cantilever with mass: ~500 nm PZT

Front





Back



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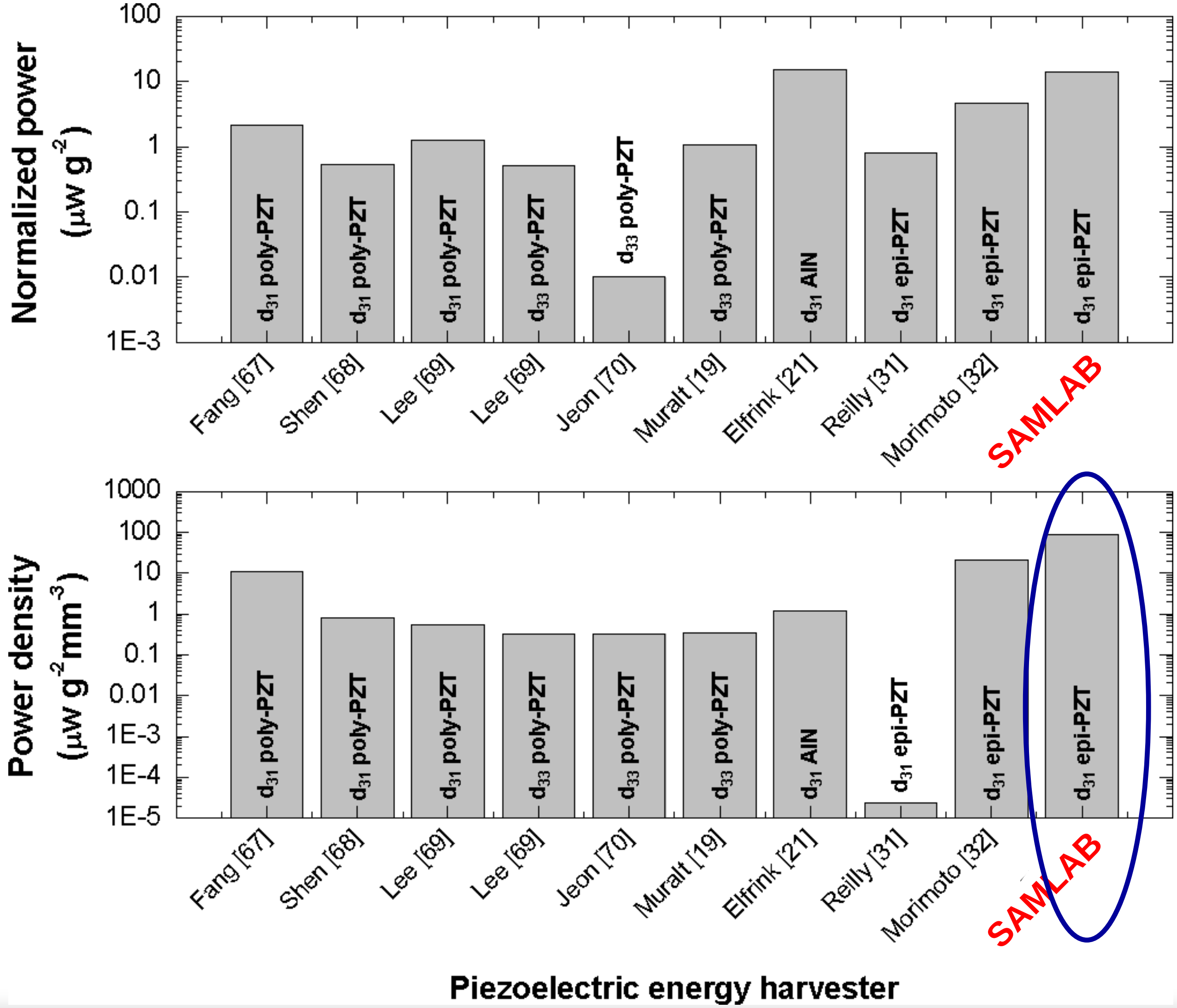
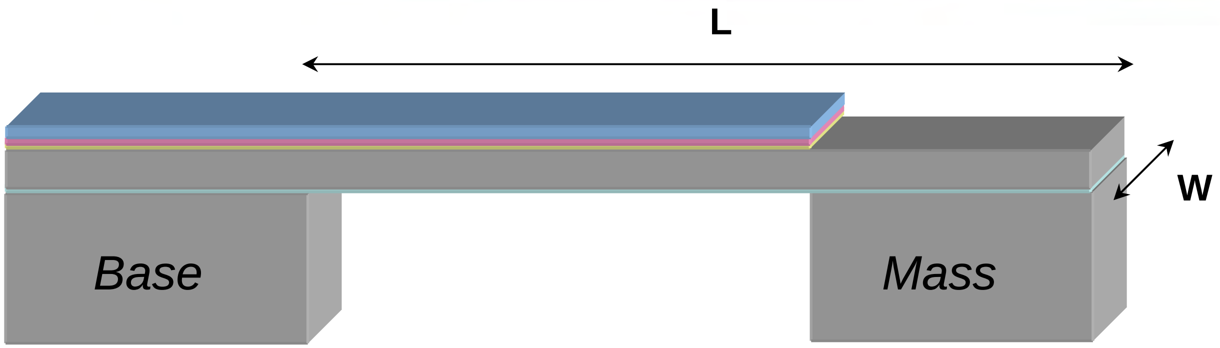
Epi Piezo MEMS Harvester - comparison



Epi Piezo MEMS Harvester - Optimisation



Simulation parameters

d31:	130 pC/N
Dielectric constant:	100
PZT thickness:	500 nm
k31:	0.23
Damping:	0.0004
Acceleration:	0.2 and 0.5g

Length of the beam: 1500 µm

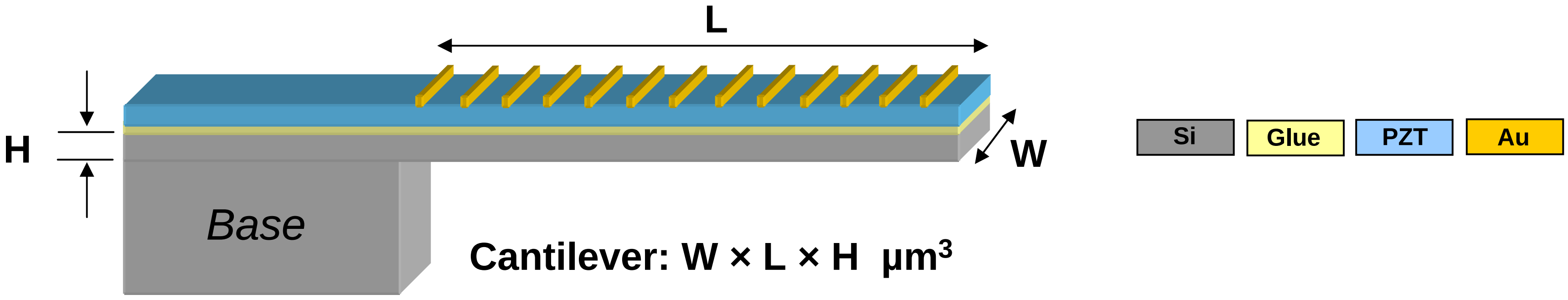
Width of the beam: 750 µm

Si **SiO2** **STO** **SRO** **PZT**

Simulation results @ 0.5g of acceleration

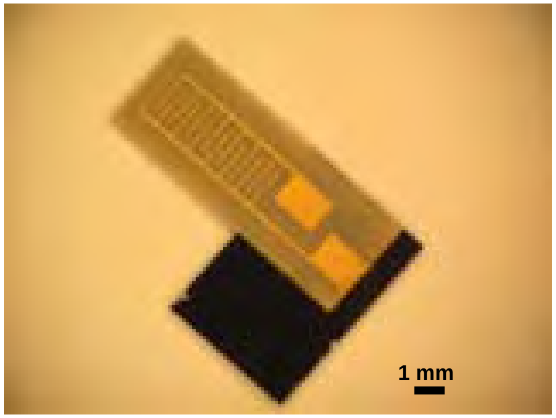
	P (µW)	I_{ac} (mA)	V_{ac} (mV)	f (Hz)	R_L (kΩ)	C (nF)
Typ	78	0.15	537	179	3.7	3.6

Thick PZT sheet harvesters



Cantilever: W × L × H µm³

- **Cantilever size: 3000 x 5000 x 50 (100 and 150) µm³**
- **Thickness of PZT sheet : 135 µm**
- **Adhesive bonding**
- **Gap of interdigitated electrodes : 150 - 200 µm**



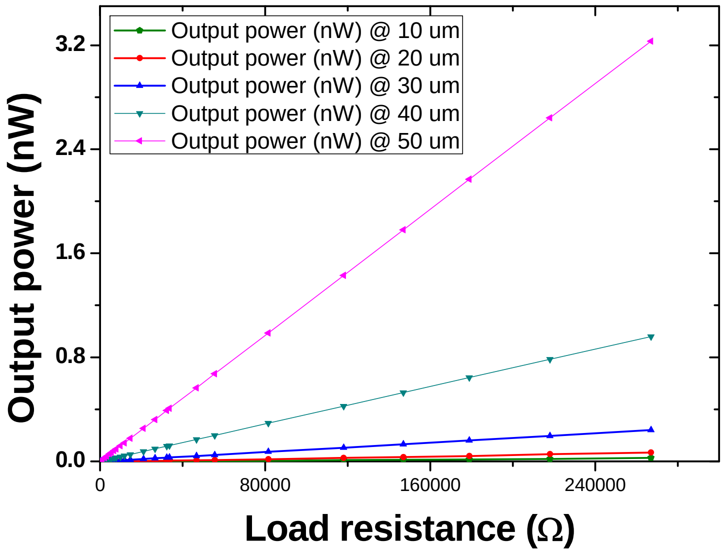
Thick PZT cantilever

Impact type harvester

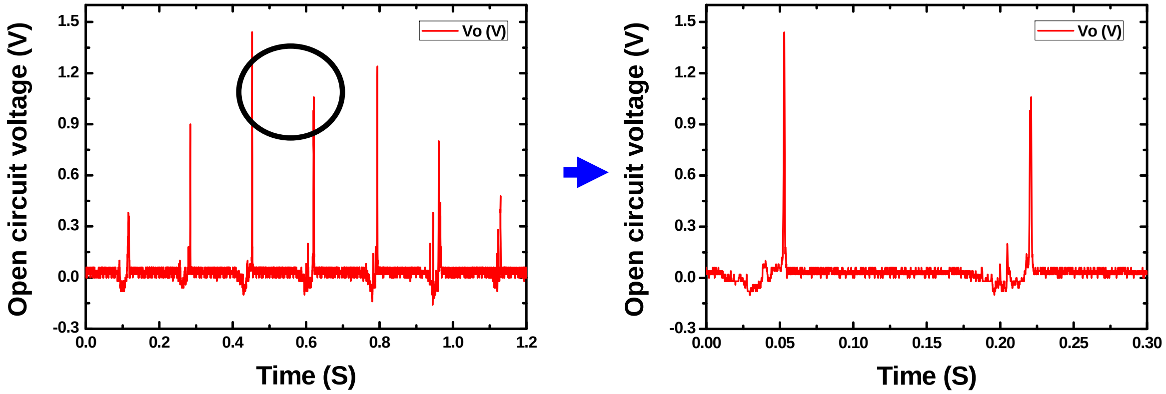
Ouput power measurement on impact mode

Open circuit voltage and current measurement

Amplitude (µm)	Max. Vo (Volts)	Max. I @ 10Ω (µA)
10	0.4	0.006
20	0.62	0.012
30	0.85	0.03
40	1.22	0.06
50	1.52	0.11



Open circuit voltage waveform



-Max. output power :

3.2 nW @ 267 kΩ

- Optimisation: cantilevers with different stiffness and different gaps of IDEs on piezo

Conclusions

- MEMS based energy scavengers
  - Resonant and impact types
  - Modelling, technology platforms, characterisation tools
  - Variety of materials and characteristics

- Potential for:
  - Compactness, multi-elements: Cost ???
  - CMOS integration on chip
  - Autonomous smart systems : no battery !

- Application first, solution second !!!

Acknowledgements

Research work

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