Piezoelectric energy harvesting and applications

Presented by:

Nathan Jackson Ph.D

Outline

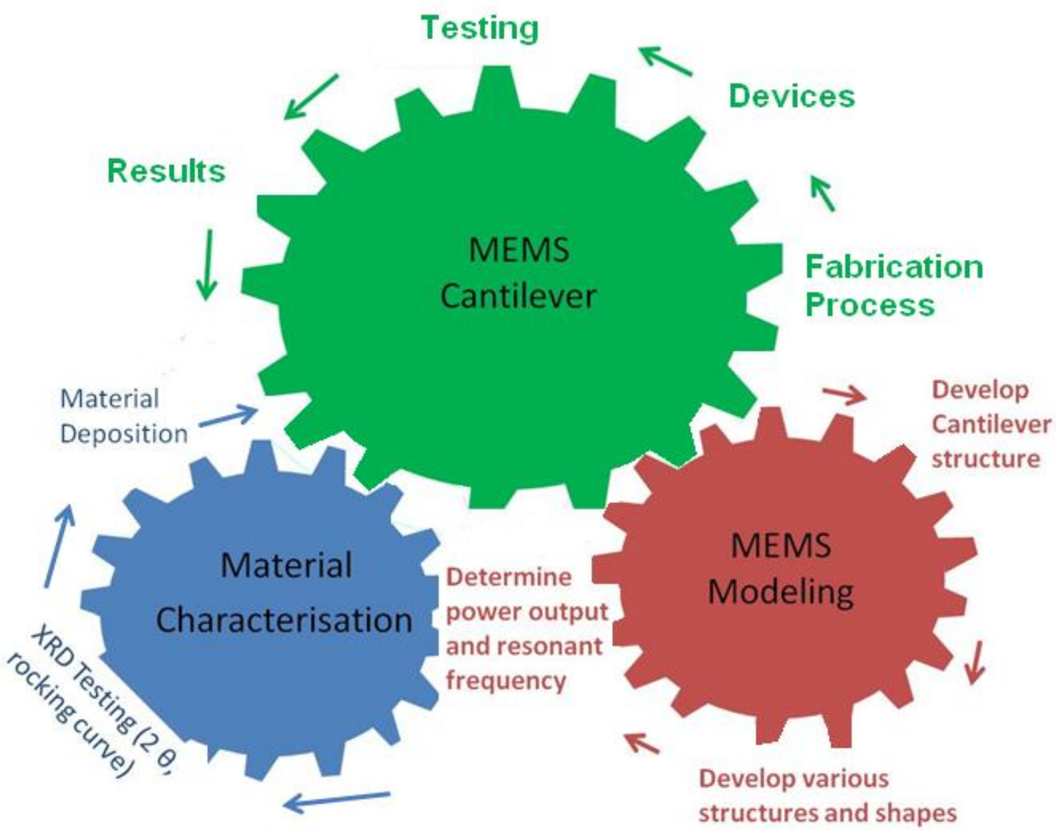
- Biography
- Background on Piezoelectric Energy Harvesting
- Piezoelectric Materials
- Latest Research on Piezoelectric Energy Harvesting
  - Tyndall National Institute
  - Other SOA Research
- Future of Piezoelectric Energy Harvesting using 1D Piezomaterials
- Other applications (Tyndall Research)

Biography

- Staff Research Scientist at Tyndall National Institute/University College Cork
- Team Leader of Piezo-MEMS team and Biomedical Microsystems Lab Manager in the Micro Nano Systems Centre
- Senior IEEE Member
- Background
  - PhD in Biomedical Engineering
  - Masters in Biomedical Engineering
  - Masters in Microelectronics Packaging
- Research Interests: Smart Materials, Bio-MEMS, Flexible/stretchable circuits.
- > 60 papers published & holds 5 patents or license technologies

Tyndall's Piezo-MEMS Team Philosophy

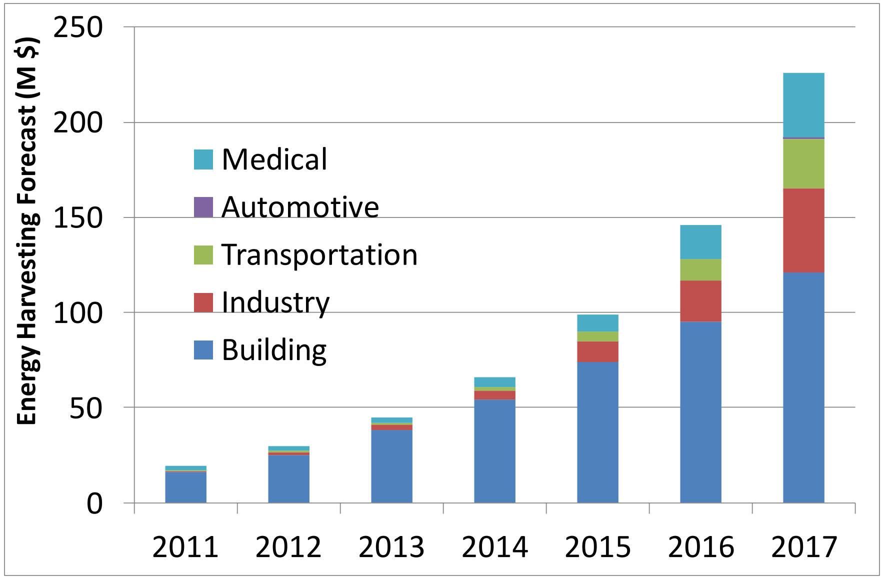
Atoms to Systems



BACKGROUND on PIEZOELECTRIC ENERGY HARVESTING

Motivation

Energy Harvesting Market from Yole 2012



Power source	Power (μW)/cm³	Energy (Joules)/cm³	Power (μW)/cm³/yr
Primary battery	N/A	2,880	90
Secondary battery	N/A	1,080	34
Micro fuel cell	N/A	3,500	110
Ultracapacitor	N/A	50–100	1.6–3.2
Heat engine	1×10^6	3,346	106
Radioactive (^{63}Ni)	0.52	1,640	0.52
Solar (outside)	15,000*	N/A	N/A
Solar (inside)	10*	N/A	N/A
Temperature	40*†	N/A	N/A
Human power	330	N/A	N/A
Air flow	380‡	N/A	N/A
Pressure variation	17§	N/A	N/A
Vibrations	375	N/A	N/A

–Power available from Ambient conditions

–Roundy et al. 2005

Energy Harvesting demand will continue to increase due to high demand for IoT

Energy Harvesting Scaling Down

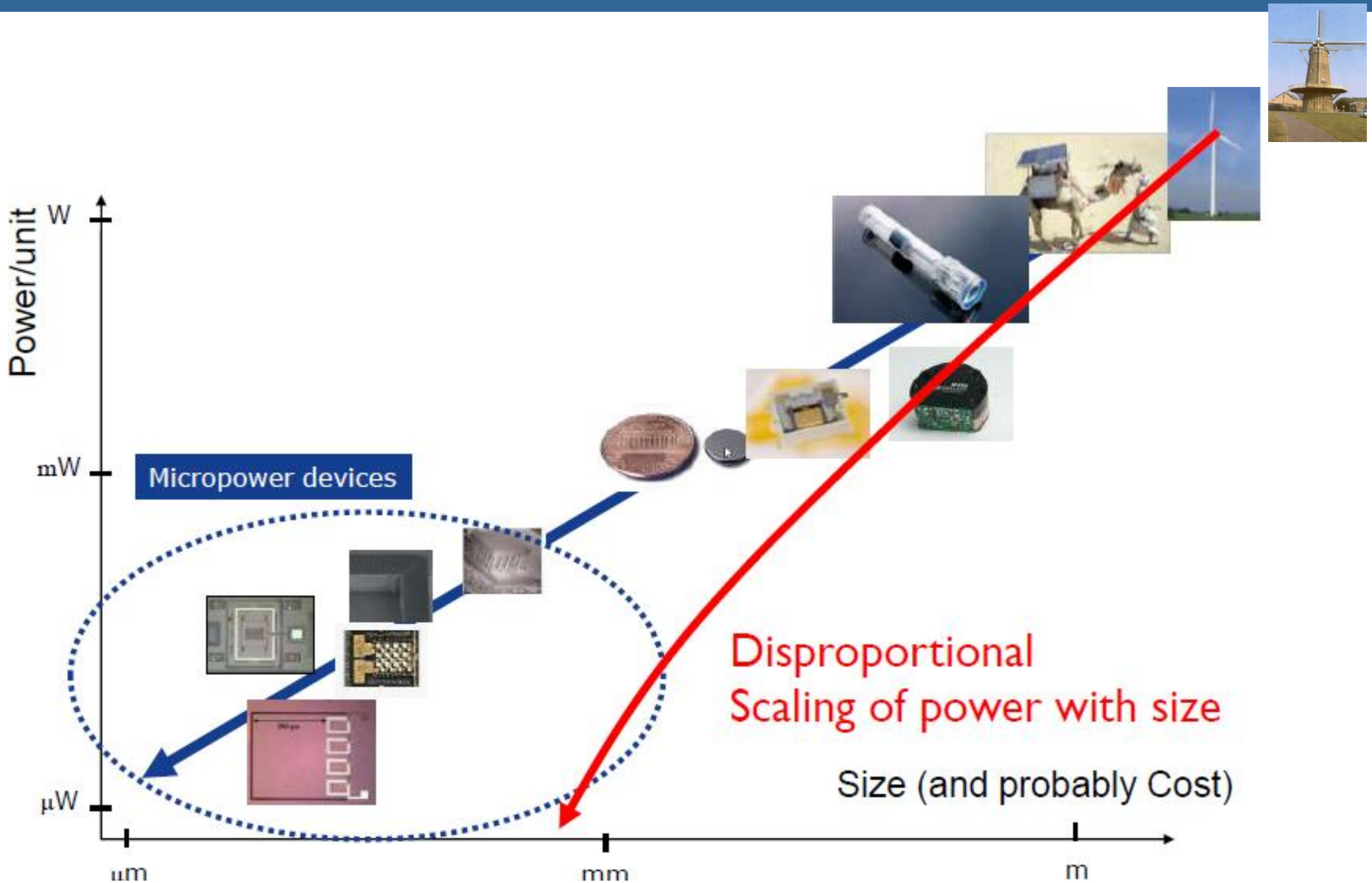
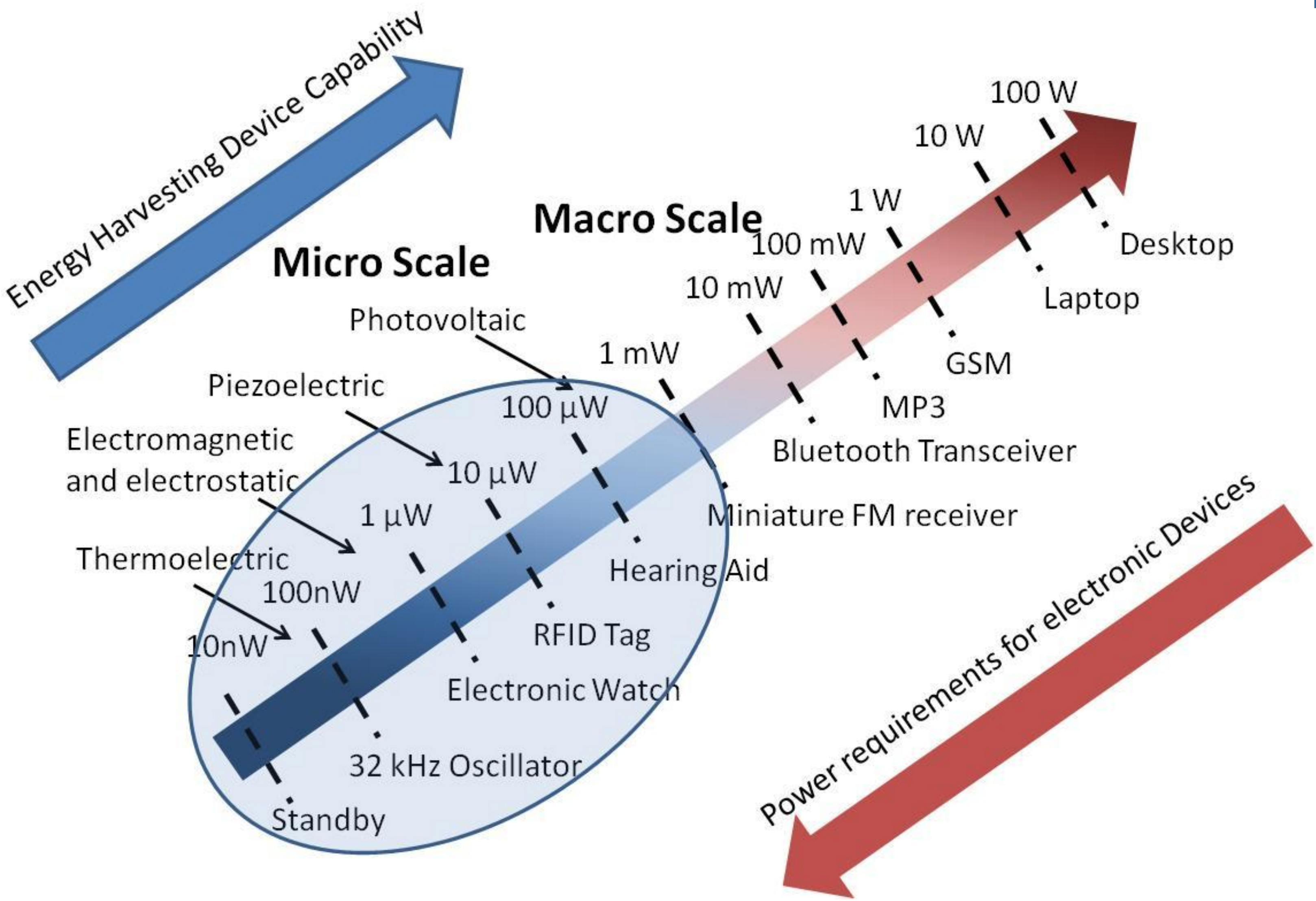


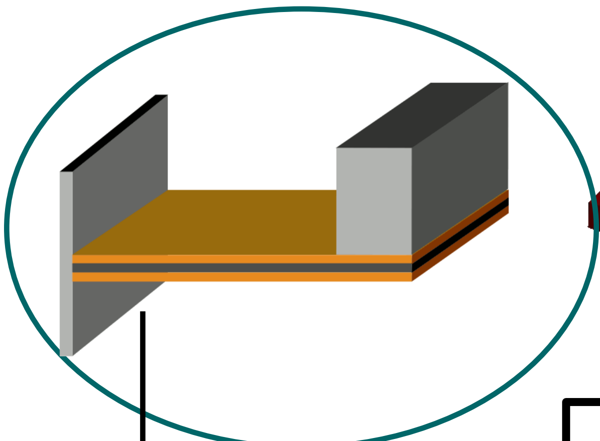
Image taken from IMEC


Energy Harvesting Device Capability
Micro Scale
Macro Scale
Photovoltaic
Piezoelectric
Electromagnetic
and electrostatic
Thermoelectric
10nW
100nW
1 µW
10 µW
100 µW
1 mW
10 mW
100 mW
1 W
10 W
100 W
Standby
32 kHz Oscillator
Electronic Watch
RFID Tag
Hearing Aid
Miniature FM receiver
Bluetooth Transceiver
MP3
GSM
Laptop
Desktop
Power requirements for electronic Devices

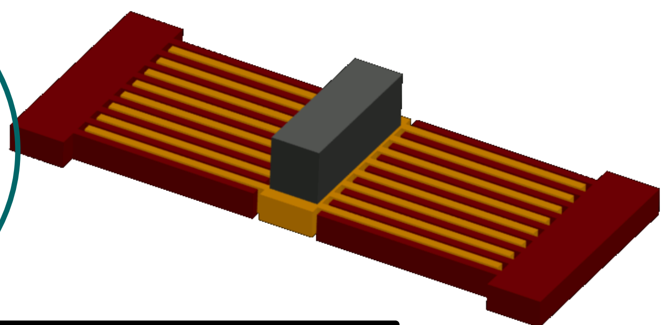
Different types of Vibrational Energy Harvesting

Mechanical

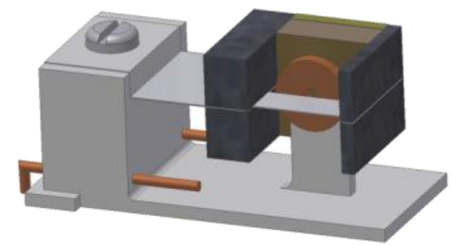
Piezoelectric



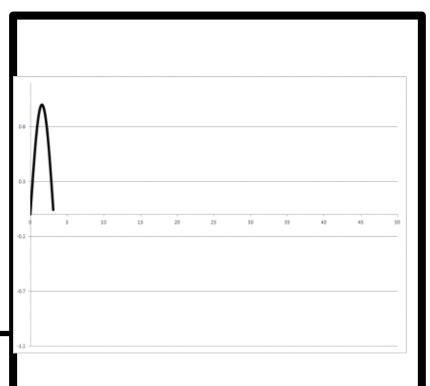
Electrostatic



Electromagnetic



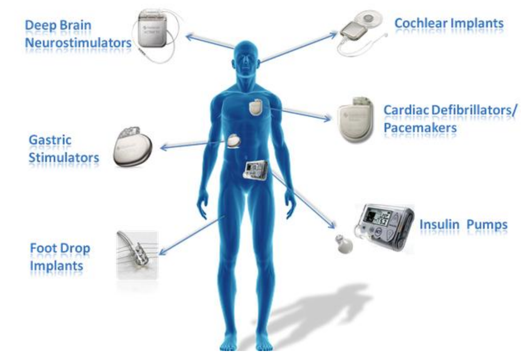
-Beeby *et al*. 2008



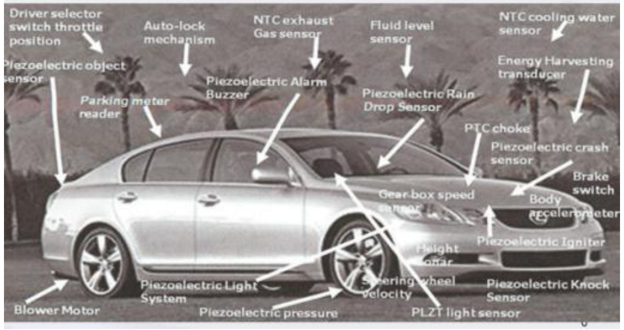
Applications

Structural Health Monitoring

Industrial



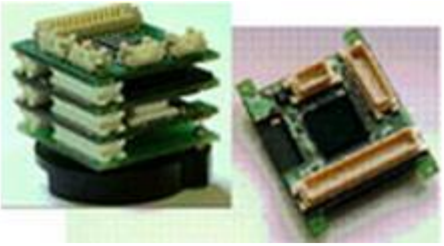
Health



Automotive

Military

Vibration Source	Acceleration (g)	Frequency (Hz)
Car Engine	1.22	200
3-axis machine	1.01	70
Clothes Dryer	0.7	121
Microwave Oven	0.23	118
HVAC vents	0.15	60
Building Windows	0.1	~100
Fridge	0.02	240
Heart	0.25	1-3
Vacuum pump (sputter)	1.8	70
Vacuum pump (parylene)	0.9	60



WSN

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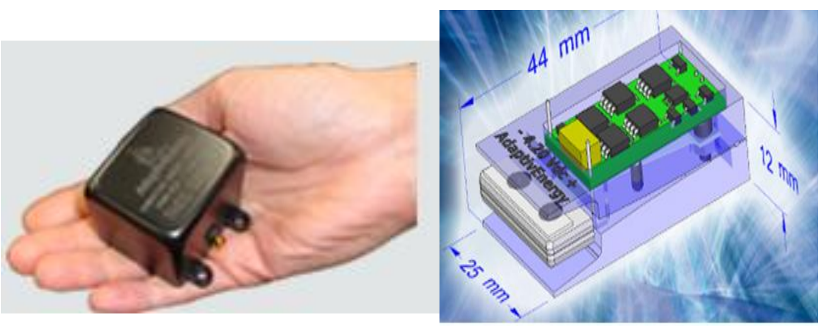
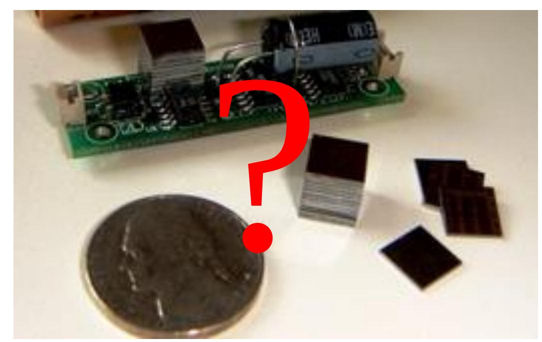
Commerical Systems

- AdaptivEnergy “Joule Thief”-piezoelectric
- Perpetuum- Electromagnetic Vibration
- Microgen- MEMS piezoelectric



AdaptivEnergy

Perpetuum
0.1 mW/cm^3



Microgen

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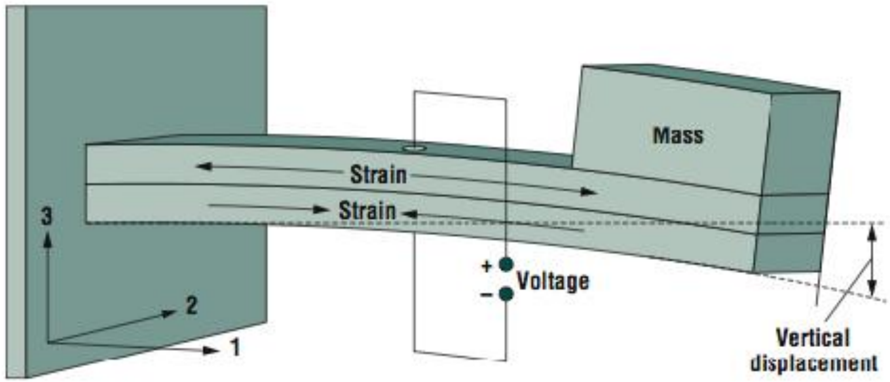
University College Cork, Ireland

AdaptivEnergy power comparison

MANUFACTURER	EH TYPE	POWER (mW@1.0 g_{rms})	Frequency (Hz)	Weight (g)	Volume (cm^3)	Power density (mW/cm^3)
Competitor #1	Piezoelectric	2.3	50	56.7	40.0	0.057
Competitor #2	Piezo Fiber Composite	2.8	18	281.5	834.2	0.003
Competitor #3	Electromagnetic	10.8 (@0.1 g_{rms} Input Limit)	60	289	133.4	0.08
Competitor #4	Electromagnetic	39.0	119	700	130.7	0.3
(1.8", 37 Hz)	Piezoelectric	**7.0**	**37**	**33**	**46.6**	0.15
(3.5", 15 Hz)	Piezoelectric	**44.3**	**15**	**25**	**90.7**	0.49

Theory and Systems



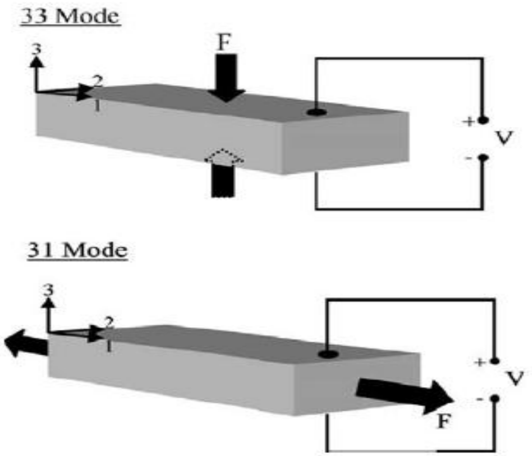
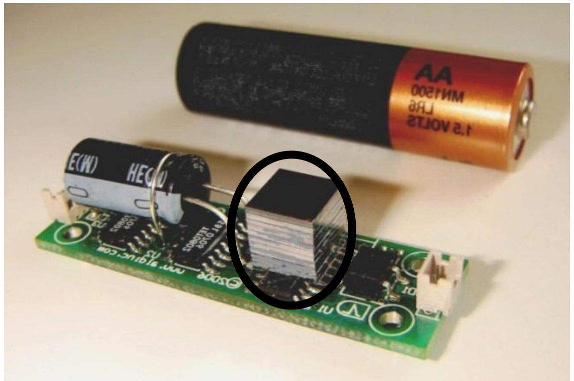


Image taken from Roundy et al. 2005



Microgen

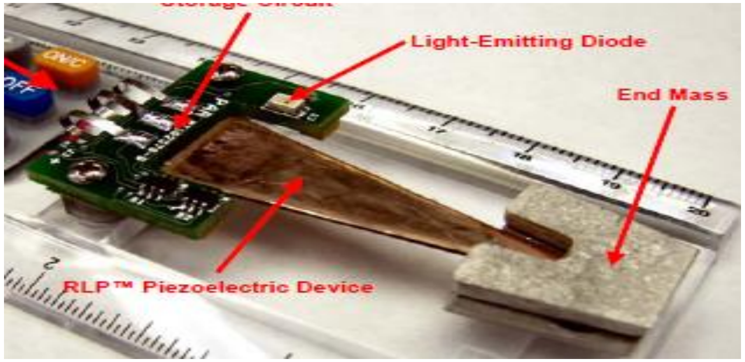
Energy Harvesting is just one component

Other components include

- Rectifying circuit
- Low power Microcontroller
- Storage

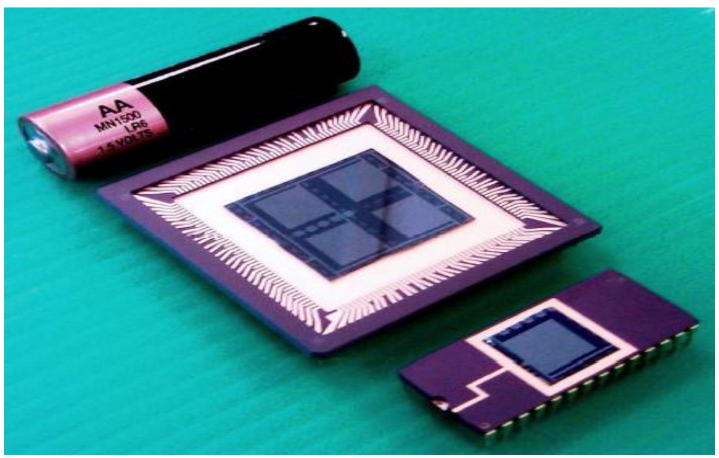
SOA Industry and Research

Commercial



Adaptivenergy-

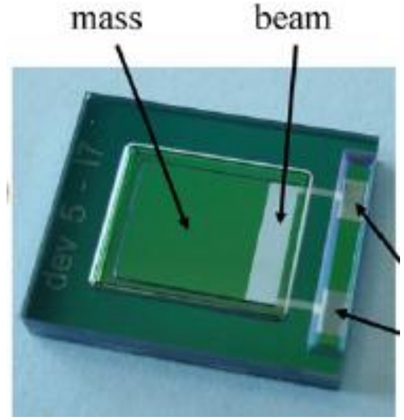
Power density= 0.48 mW/cm^3/g^2



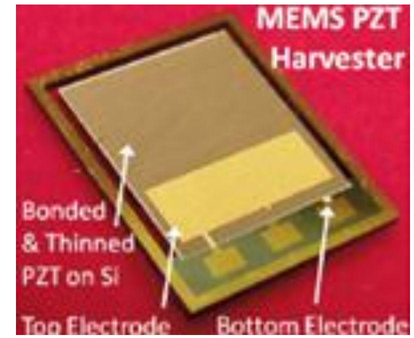
Microgen-

Power density= 1.3 mW/cm^3/g^2

Research Products



IMEC 2010



Michigan 2011

MIT 2012

Numerous Universities or Institutes are doing research in this area, but most of them have low power (nW) and high frequency.

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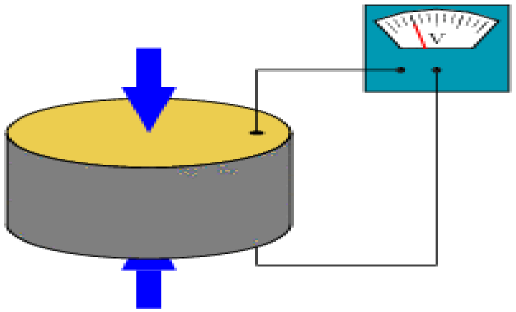
Piezoelectric Materials

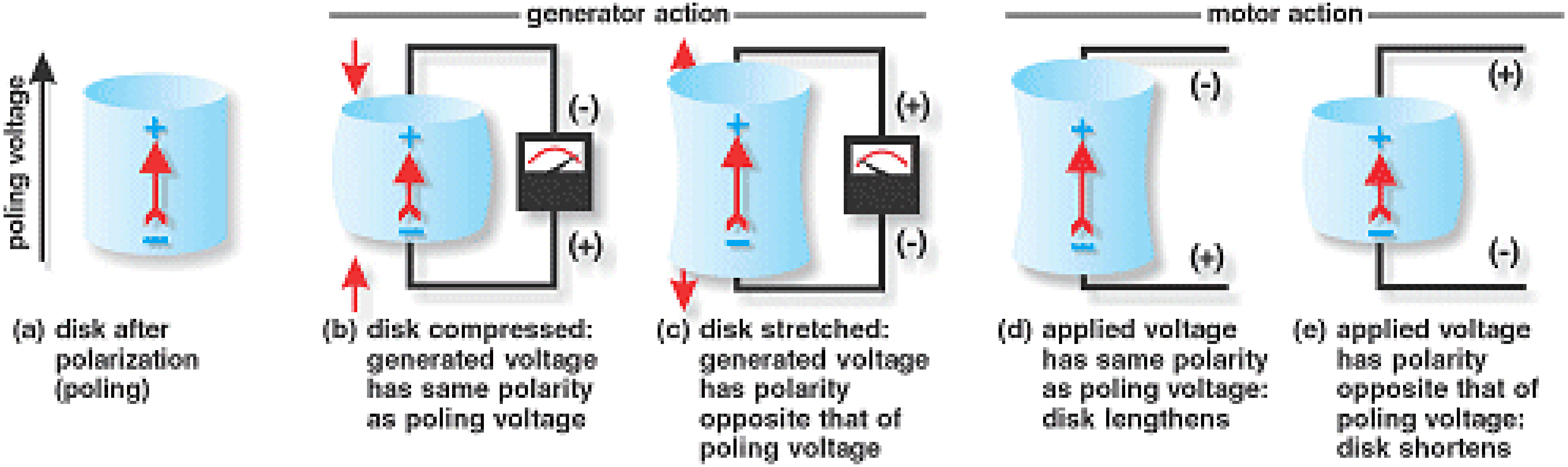
Piezoelectric Material Background

1) Piezoelectric (greek word meaning "to press")- dielectric material that displaces anions and cations when an external electric field is applied



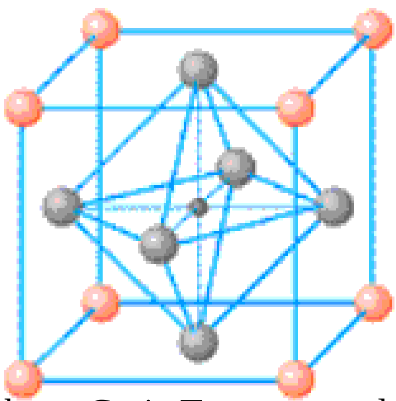
Direct effect

Converse Effect



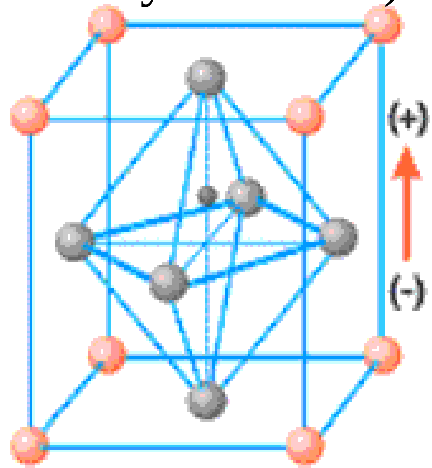
Piezoelectrics Crystal Lattice

Lead Zirconate Titanate (PZT crystal lattice)



Above Curie Temperature lattice is centro-symmetric thus no dipole moment formed during compression, as the dipoles cancel each other for a net of 0.

Ions move symmetrically so NO net polarisation is formed.



Below the Curie temperature the crystal structure is non-centrosymmetric. So under mechanical stress the ion structures separate creating a dipole moment

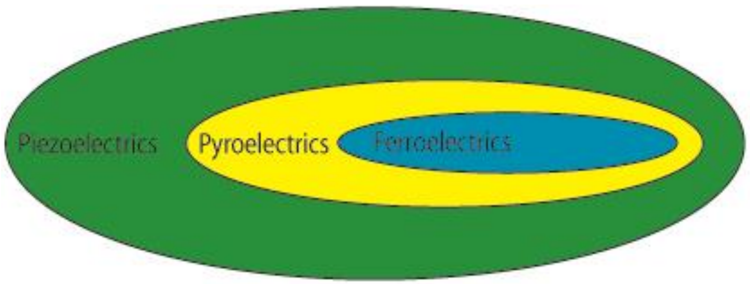
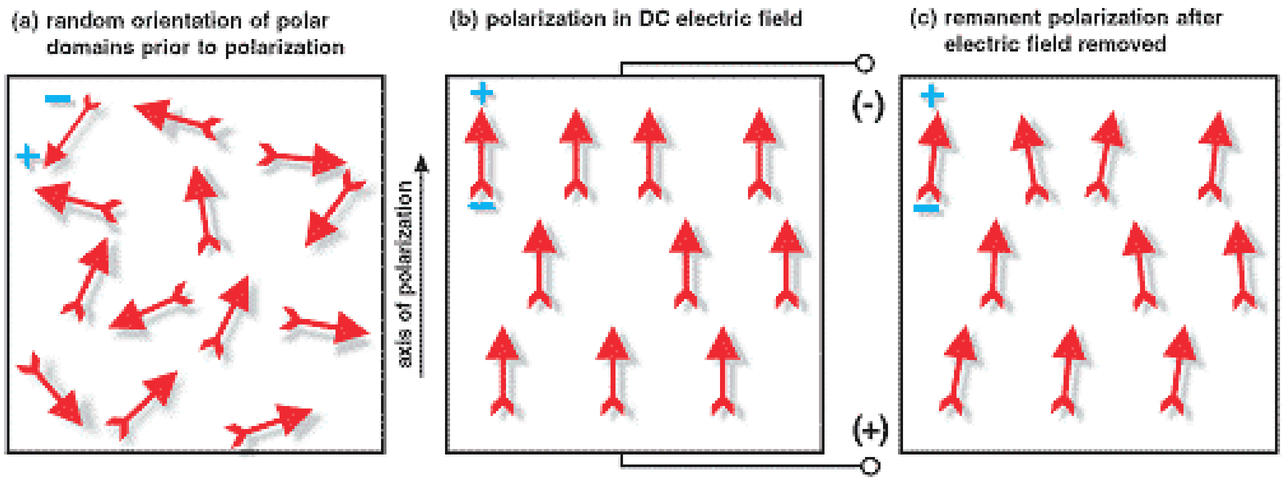


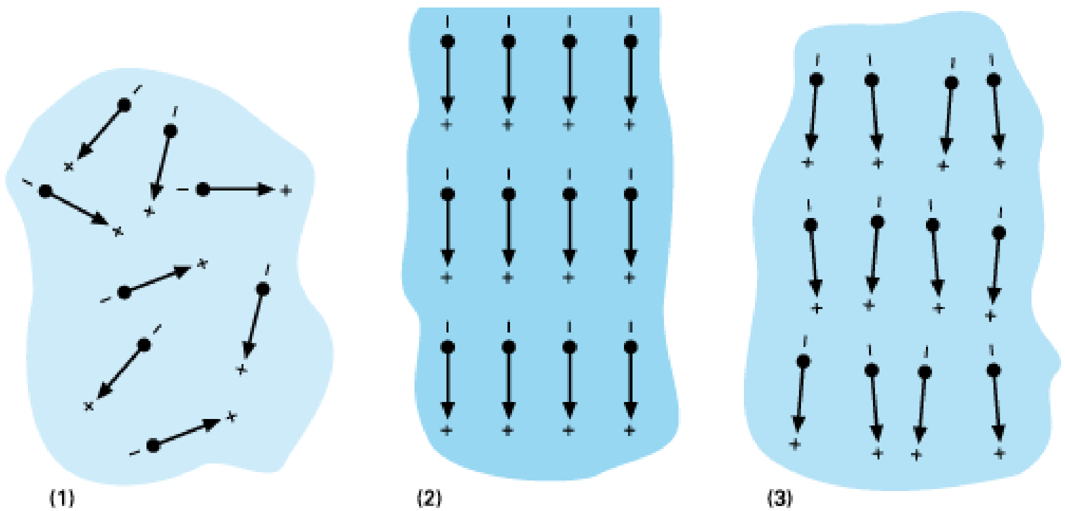
Image taken from University of Cambridge

<table>
<tr><th colspan="4">32 Crystalline classes</th></tr>
<tr><th colspan="3">20 classes piezoelectric</th><td rowspan="3">non piezoelectric</td></tr>
<tr><th colspan="2">10 classes pyroelectric</th><td rowspan="2">non pyroelectric</td></tr>
<tr><th>ferroelectric</th><td>non ferroelectric</td></tr>
</table>

PZT, PVDF, BaTiO3, Lithium Niobate | AlN, ZnO | Quartz,

Ferroelectrics and Poling





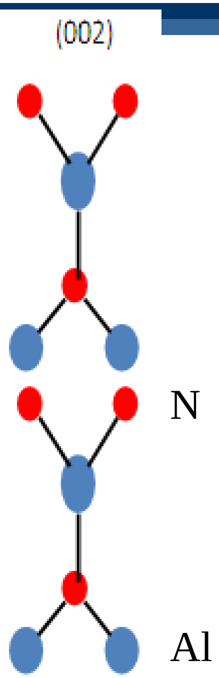
–Electric dipoles in Weiss domains;

(1) Un-poled ferroelectric ceramic

(2) during and

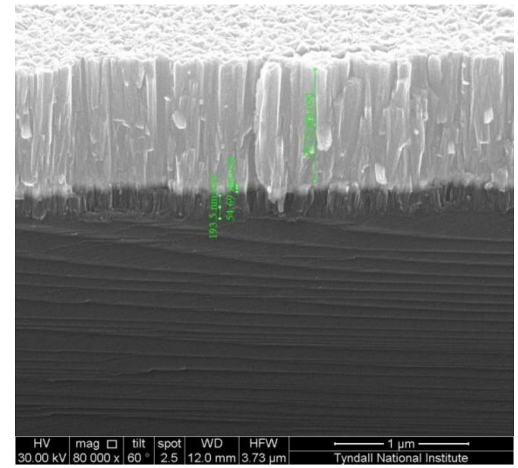
(3) after poling (piezoelectric ceramic)

Non-Ferroelectrics (AlN and ZnO)



Mother Nature

AlN (Tyndall)



DO Not need Poling- polarisation created during deposition or growth.

Deposition or growth parameters critical for high quality film, as opposite polarisation results in net effect of 0

Piezoelectric Material

	PZT	PVDF	ZnO	AlN
Require Poling (MV/m)	100	50-80	No	No
Sol-Gel	Yes	Yes	No	No
Sputter/ALD	No	No	Yes	Yes
Thin films	Yes	No	Yes	Yes
Nanowire capability	No	No	Yes	Yes
Deposition Temperature (C)	>600	<100	<100	250-400
Piezoelectric constant (d33 (pC/N))	100-300	-33	6	5
Piezoelectric constant (d31 (pC/N))	-170	22	3	-2
Piezoelectric voltage constant (g33 (10^-3 Vm/N))	25	-300	60	50
Dielectric constant (e33)	300-1300	13	11	10.5
Curie Temperature (PZT, PVDF) Melting temp(ZnO, AlN)	360	150	1900	2200
Biocompatible	No	Yes	No	Yes
CTE (10–6/C°)	2	50-100	~10	4.5
Bandgap (eV)	-	-	3.3	6
Youngs Modulus (GPa)	63	6	58	350
enviromental friendly	No	Yes	Yes	Yes
Power Density (mW/cm^3)	0.3-7	0.6-3	1-3 or 10-20 pW/um^2	0.6-2 or 8-15 pW/um^2
Power Generation figure of merit (e31^2/ε)	0.08	0.04	0.09	0.12

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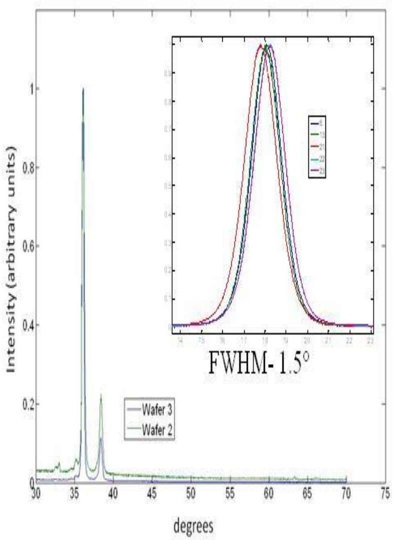
AlN Material Development

On Silicon



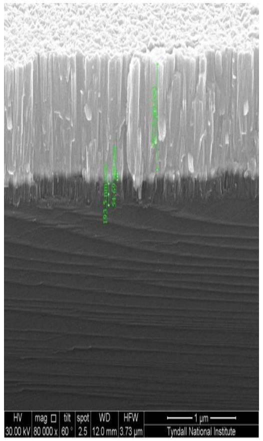


Figure- (left) XRD results showing the high crystalinity of the AlN with a FWHM of 1.5^{0}. (right)- SEM image showing the columnar (002) AlN orientation

	PZT	Tyndall AlN	Typical values for AlN
Piezoelectric Constant d31 (pm/V)	100-300	2.97± 0.75	~2
K^2 % (electromechanical coupling)	18-25	15± 2.8	~10

On Flexible Substrate

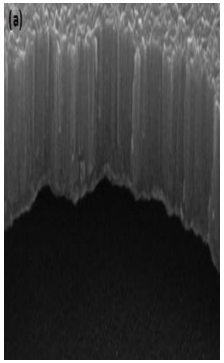


Figure- above picture showing flexible material and SEM image showing columnar AlN material

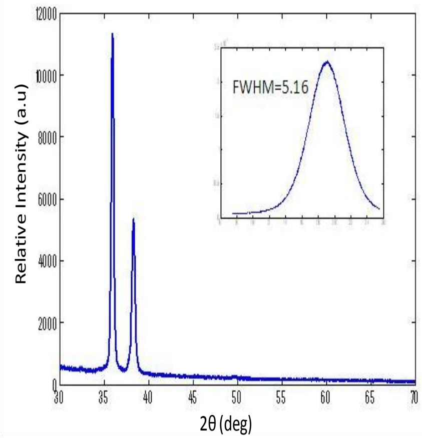


Figure left- XRD results showing the crystallinity of the AlN material (insert shows the rocking curve omega scan)

	Other Researchers AlN/Polyimide	Tyndall (AlN/polyimide)	Tyndall (AlN/Si)
FWHM (AlN)	8.16	5.16	1.7
Multiple peaks	Yes	No	No
$D_{33,f}$ (pm/V)	0.56	1.12	4.87
$D_{15,f}$ (pm/V)	NA	0.784	0.35

Jackson et al. 2013

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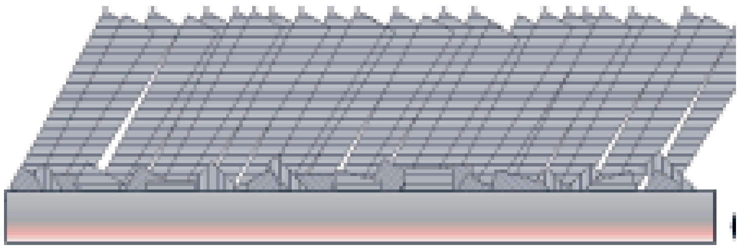
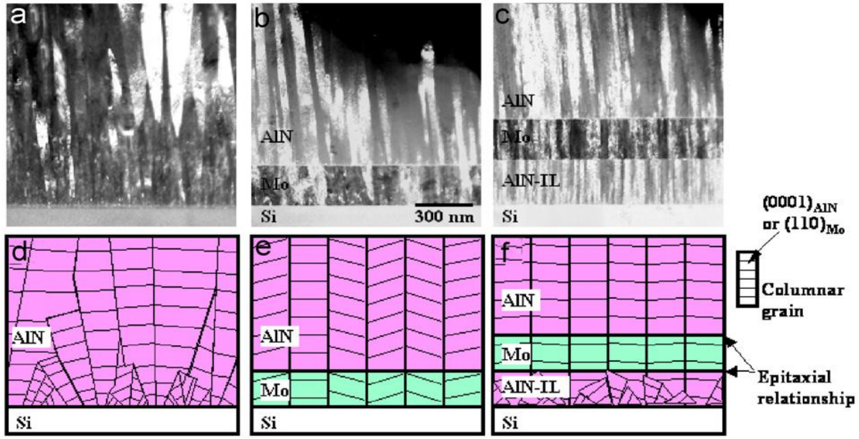
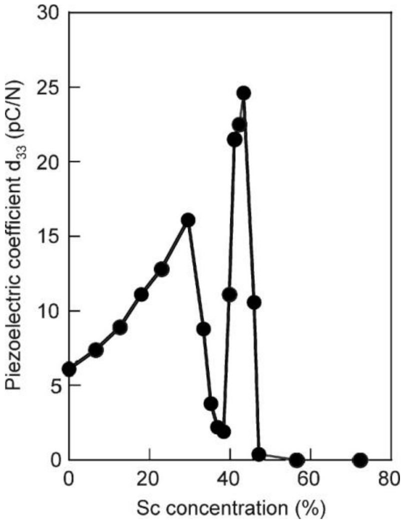
Enhancing AlN Materials

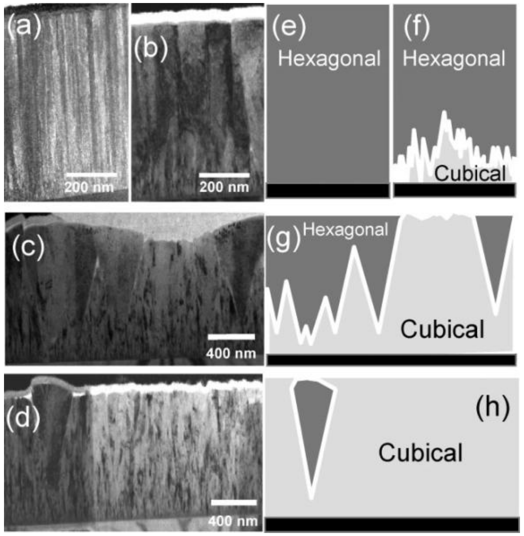


Tilting c-axis AlN for use in SH-SAW or FBAR for sensors in liquid enviroments



Dual Sputtering





Enhanced piezo-response

Kamohara 2009

Piezoelectric Energy Harvesting Devices and Research

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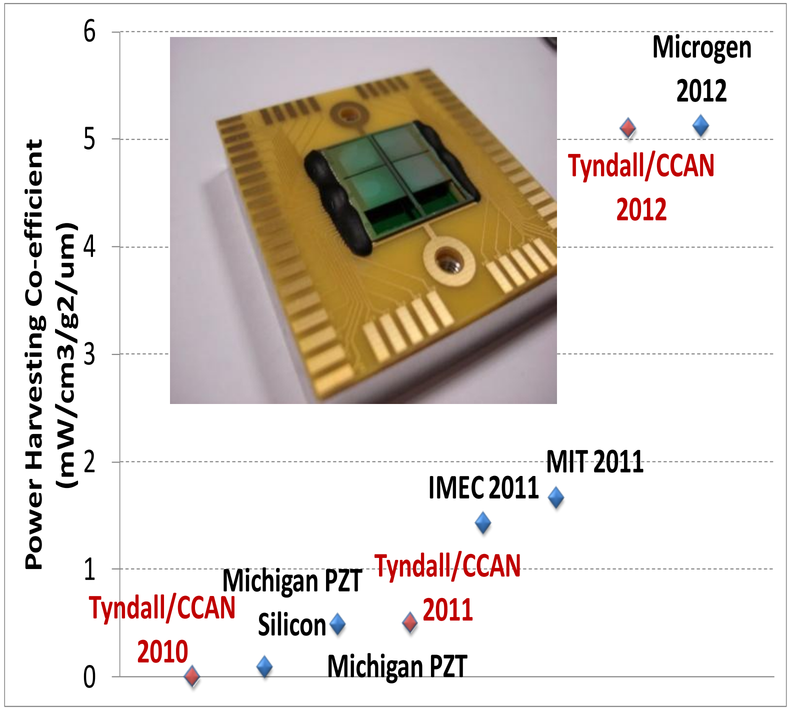


Ongoing Research

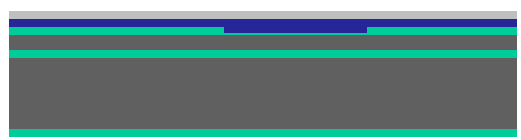
- Developing Novel Methods for Increasing Bandwidth
- Optimisation of AlN film to increase power density
- Improved Reliability
- Flexible Piezoelectrics
- Application Specific Energy Harvesters

Device	Centre Frequency (Hz)	Bandwidth per Cantilever (Hz)	Bandwidth of a 4 cm^2 area (Hz)	Power Density low BW ($mW/cm^3/g^2$)	Power Density high BW ($mw/cm^3/g^2$)
Wide	149	1.2	4.8	2.5	0.63
Trapezoid	118	0.9	9	0.78	0.08
Narrow	97	0.82	26.4	0.65	0.025

Fabrication Process

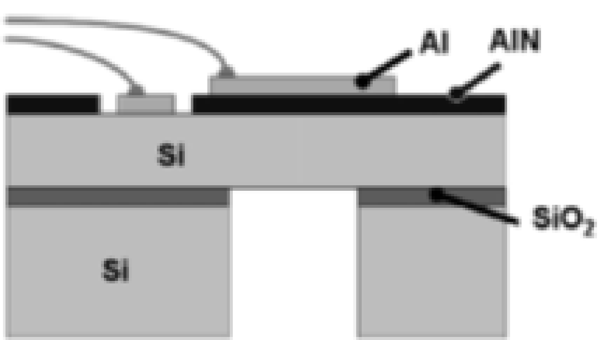
Deposit Oxide on SOI

Etch oxide on Cantilever beam

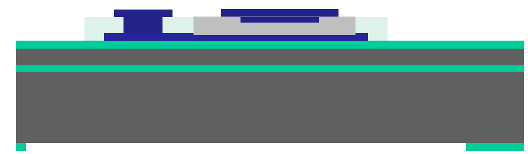


Deposit Ti and AlN

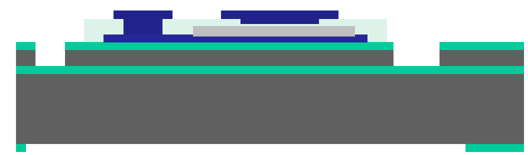
Pattern Ti and AlN layers

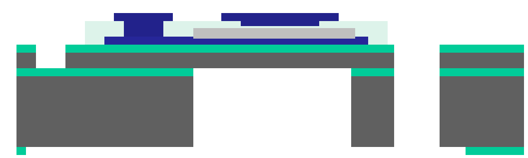


Deposit oxide barrier layer



Deposit and pattern Al layer for electrode



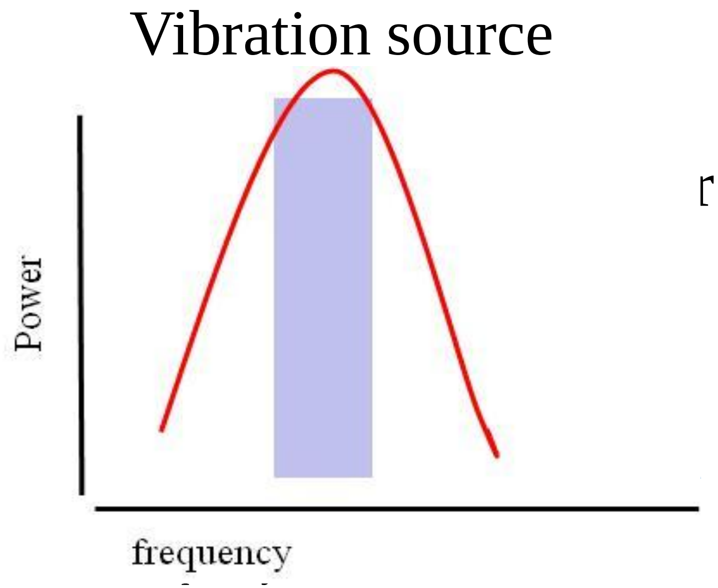


Backside DRIE to define cavity and mass

Challenges Associated with Vibrational Energy Harvesters

1. Low Frequency applications (< 250 Hz)
2. High Power density (> 2 $mW/cm^3/g^2$)
3. Wide Bandwidth (typical devices have large Q factor)

- **Si-based cantilevers have HIGH Q-Factor, which makes them operate a specific frequency (good for sensor, challenging for energy harvester)**



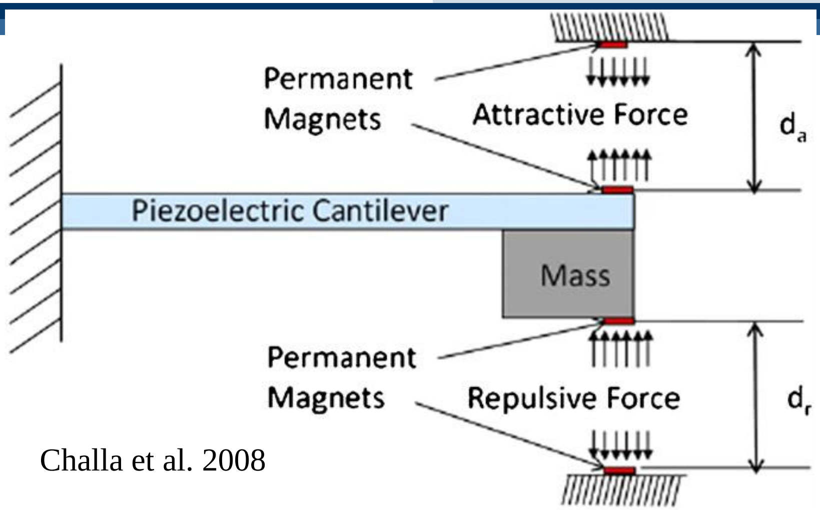
Solutions:

1) Increase Bandwidth (most common approach): Disadvantage (reduced power)
2) Tuneable Frequency: Difficult to implement
3) Ideal case broaden bandwidth without decreasing power
4) Pick an application where the frequency is known and does NOT deviate

Research being conducted at Tyndall

- Widening the Bandwidth
- Developing novel methods to prevent deviation in resonant frequency
- Energy harvesting for IoT
- Biomedical Engineering Harvesting

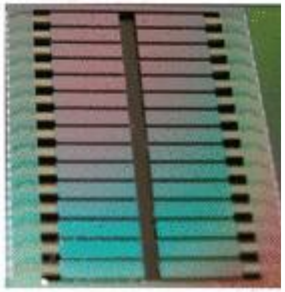
Background and SOA Wide Bandwidth

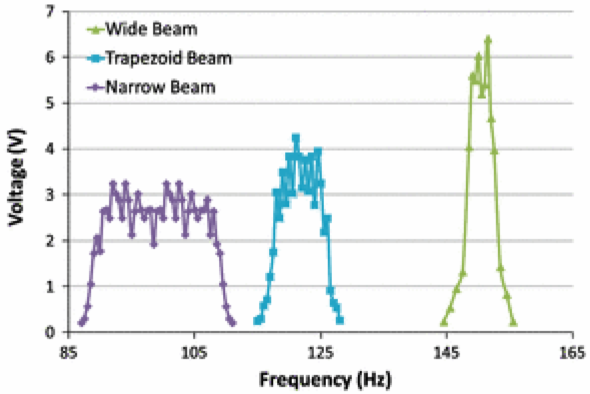


Challa et al. 2008

–Use magnets as an attractive or repulsive force to dampen

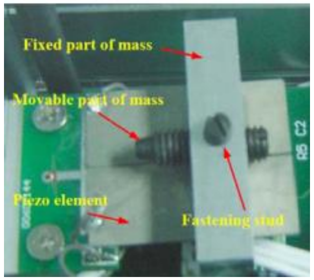
Array of cantilevers with varying mass

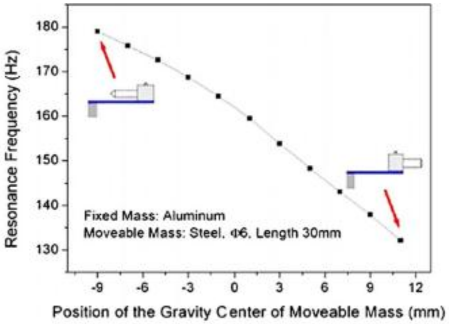




Jackson et al. 2014 Microsystem Technologies

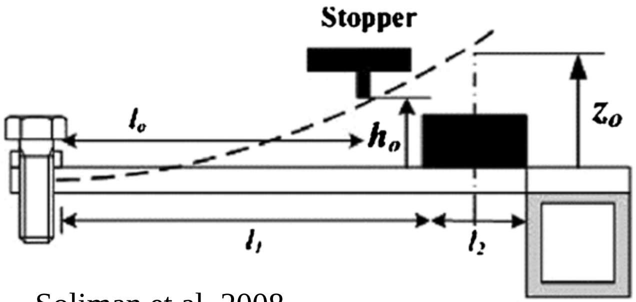
Movable mass





Wu et al. 2008.

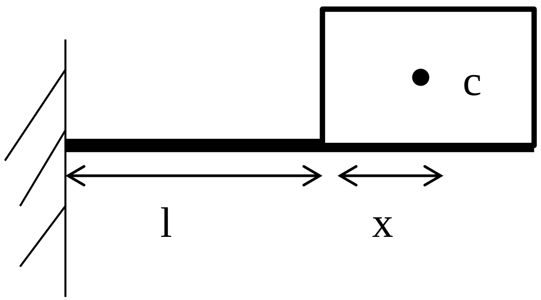
Varying Masses



–Beam bangs into top causing it to dampen

Soliman et al. 2008

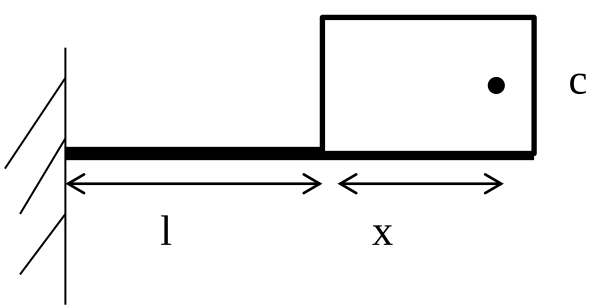
Changing the centre of Mass

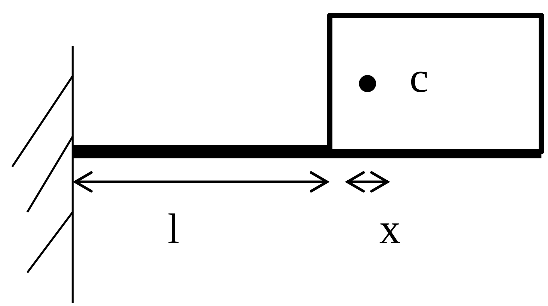


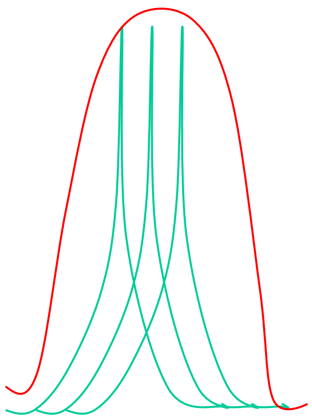
$$f = \left(\frac{1}{2\pi} \sqrt{\frac{3E}{m_{eff}}} \right) \sqrt{\frac{wt^3}{L^3}}$$

$$f = \frac{1}{2\pi} \sqrt{ \frac{Ewt^3}{12ml^3} * \frac{\left(\frac{x}{l}\right)^2 + \frac{6x}{l} + 2}{8\left(\frac{x}{l}\right)^4 + 14\left(\frac{x}{l}\right)^3 + 10.5\left(\frac{x}{l}\right)^2 + \frac{4x}{l} + \frac{2}{3}} }$$

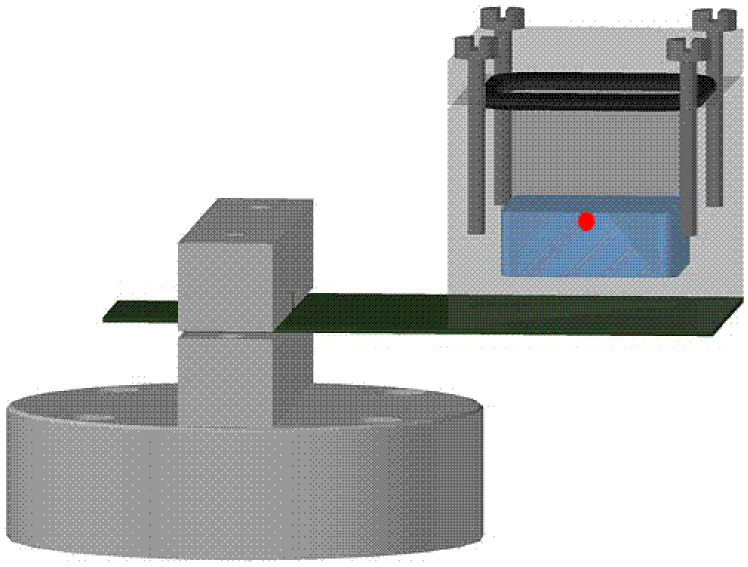
Our approach is widen the band width is to create a dynamic mass which changes its centre of gravity thus changing its resonant frequency as the cantilever oscillates







Liquid filled Mass



● Represents centre of gravity

Liquid filled mass creates a non-uniform mass load distribution

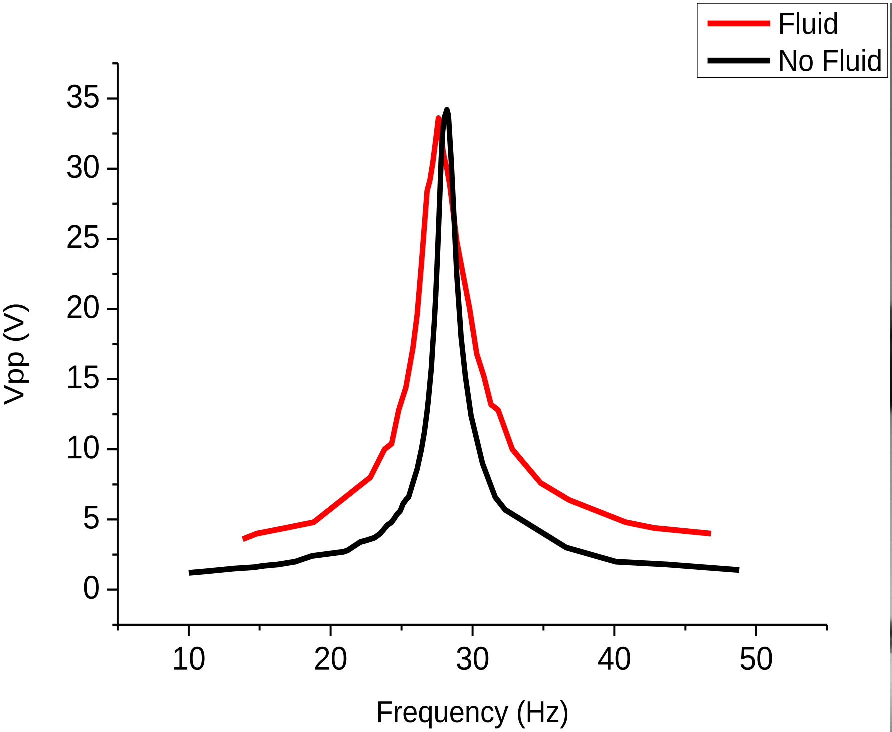
Operating Procedures required to create moving mass

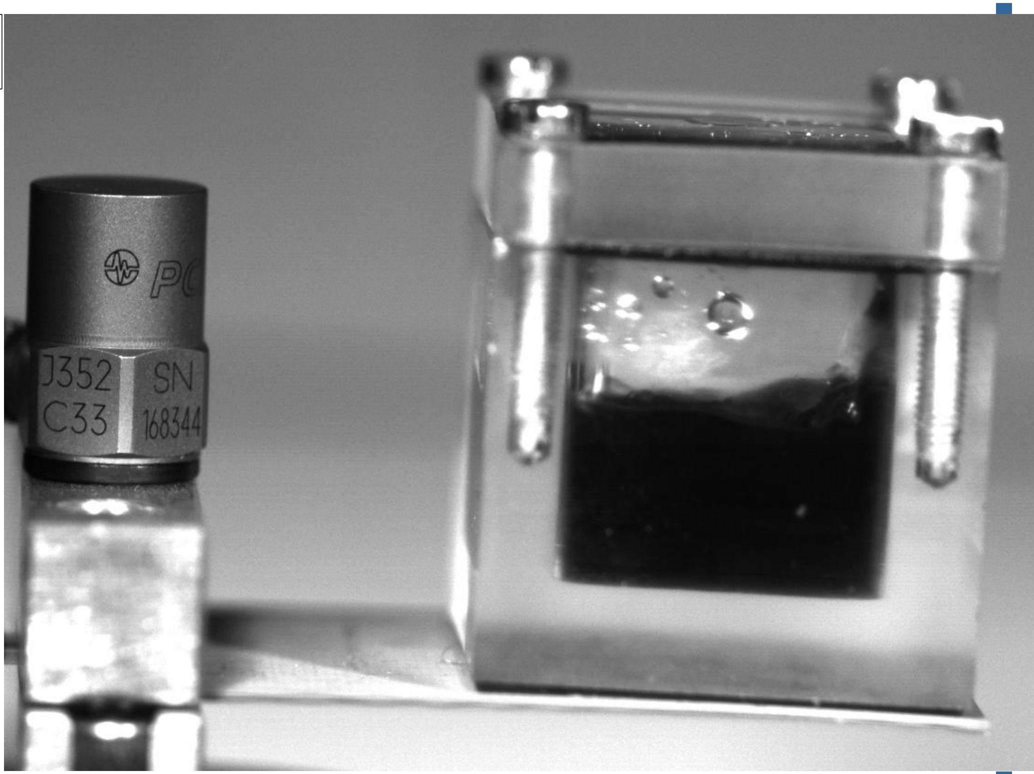
- Low Frequency
- High acceleration

Parameters that will affect bandwidth

- Density of Fluid
- Viscosity

4g Acceleration



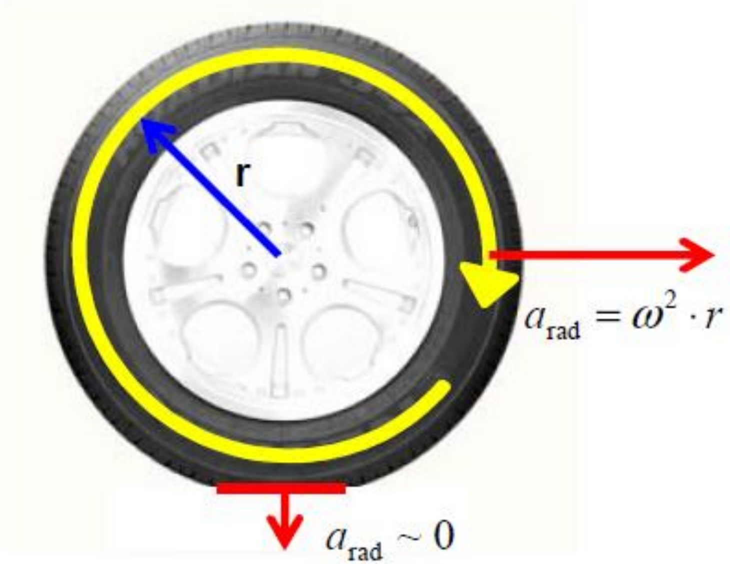


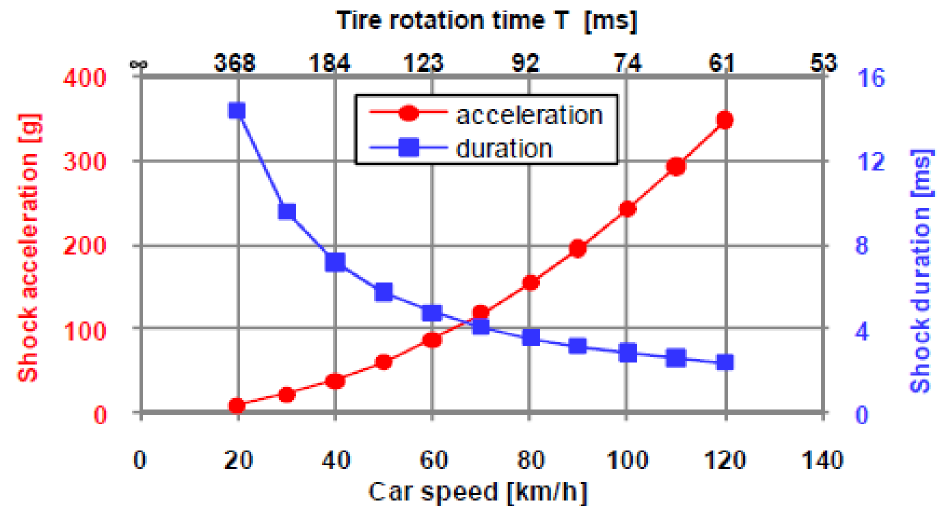
Cantilever	FWHM (Hz)	V_{pp} (V)
4 g Open	1.8	34.2
4 g Fluid	4.45	33.6

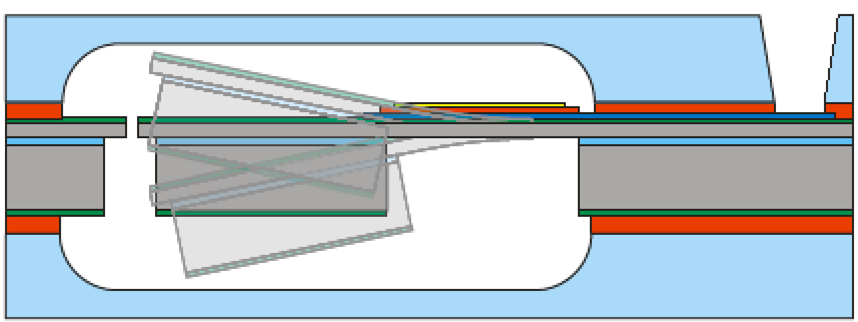
BW increase of ~2.5x

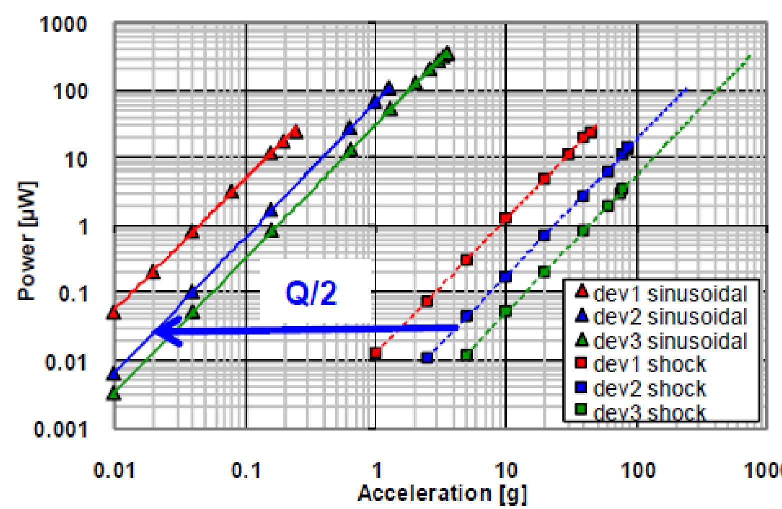
Application specific EH using vibration source that do not deviate

IMEC Tire Pressure EH





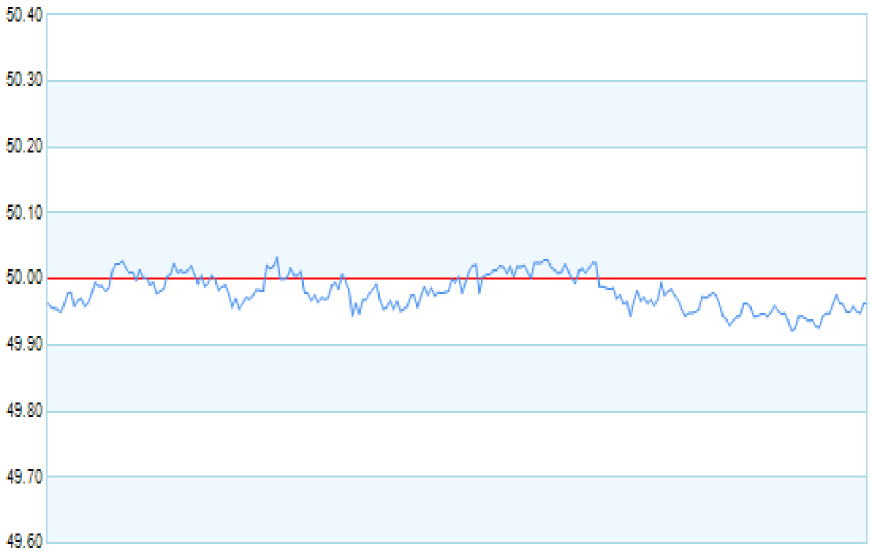




EH Application with Reliable Vibration Source

- **What application has a constant frequency?**

–Answer- Power Mains (current flowing through wires have a frequency of 50/60 Hz and only deviate by 0.2 Hz maximum



Frequency drift in UK over 1 day- average 49.96 taken on July 23rd 2014

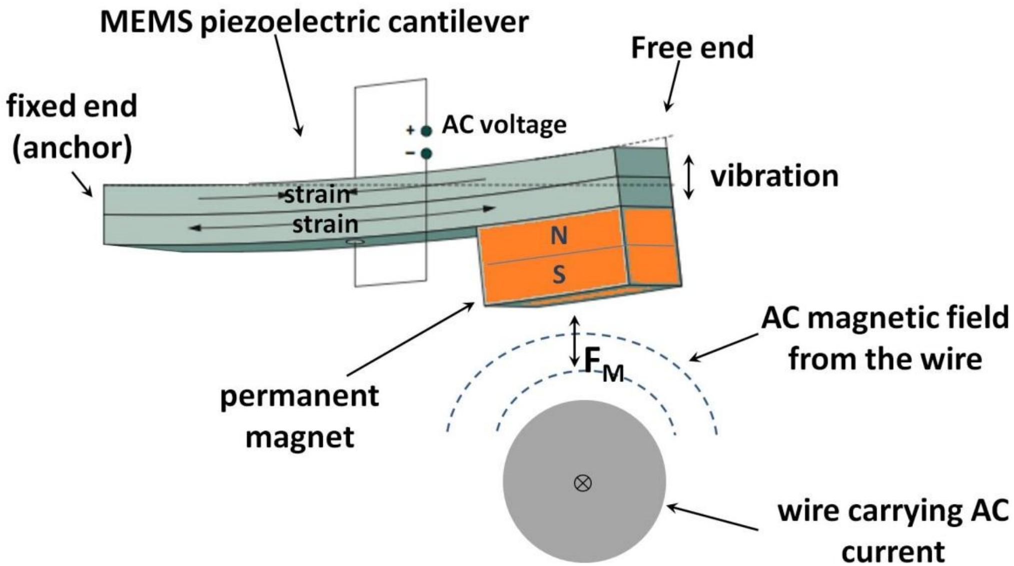
EU Regulations

•Deviation of <20 mHz is allowable

•Deviation of 20-200 mHz forces primary control to start and should be regulated back to <20 mHz of 50 Hz within 15 minutes

Harvesting energy using Power Main as Vibration

- **So how do we create a vibration source from current flowing through a wire?**



$$\vec{F}_M = B_r \int \frac{d(H_z)}{dz} dV$$

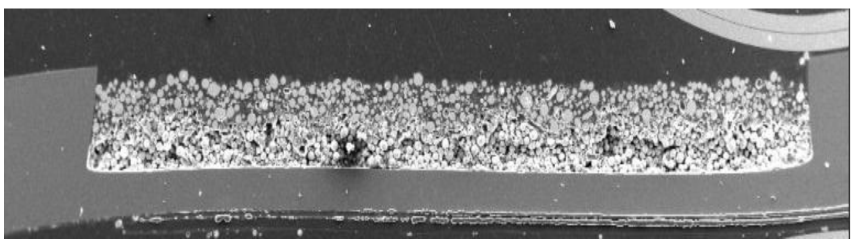
F_M – magnetic force
B_r – magnet remanence
V – magnet volume
H_z – vertical component of the magnetic field

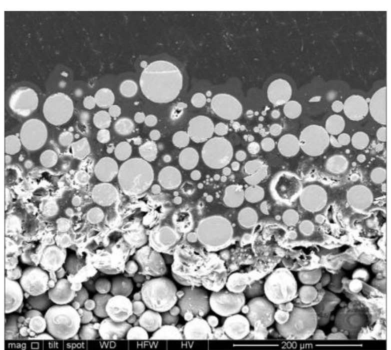
- Current flowing through a wire generates an AC magnetic field
- Adding a magnet to the end of a cantilever generates a force which forces the cantilever to resonant
- If the frequency of the current and the cantilever resonant frequency are equal large displacements should be attainable.

Hard Magnet Material Initial Results

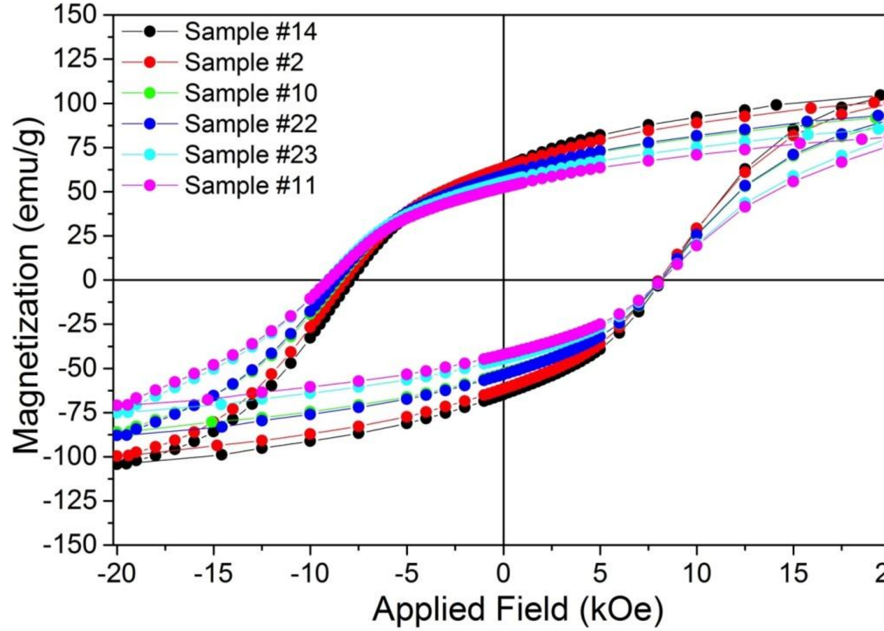
Impulse Magnetizer capable of supplying 5T Magnetic Field

SEM of magnetic material from Tyndall





Initial Results of Tyndall Hard Magnet



<u>Results</u>

- Br= 0.6 T (measured)
- H= 800 kA/m (measured)
- Theoretical maximum Br = 0.76T
- Optimization → ongoing test

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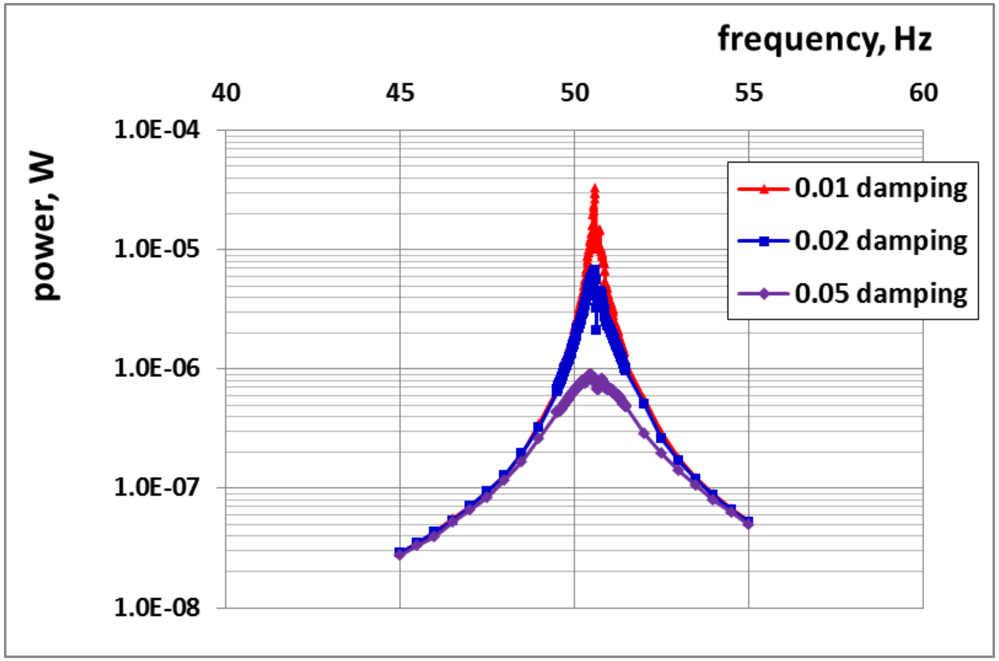
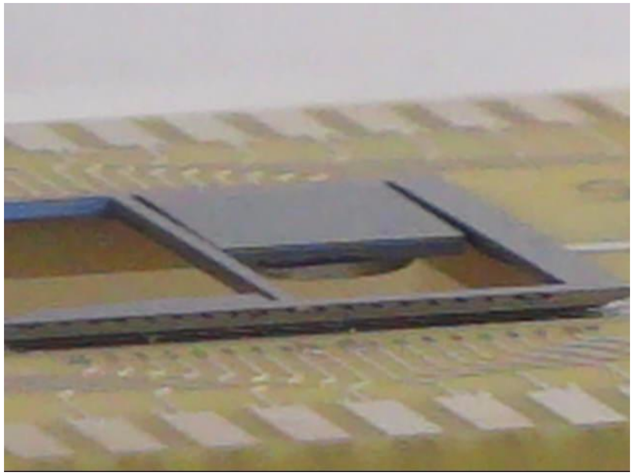
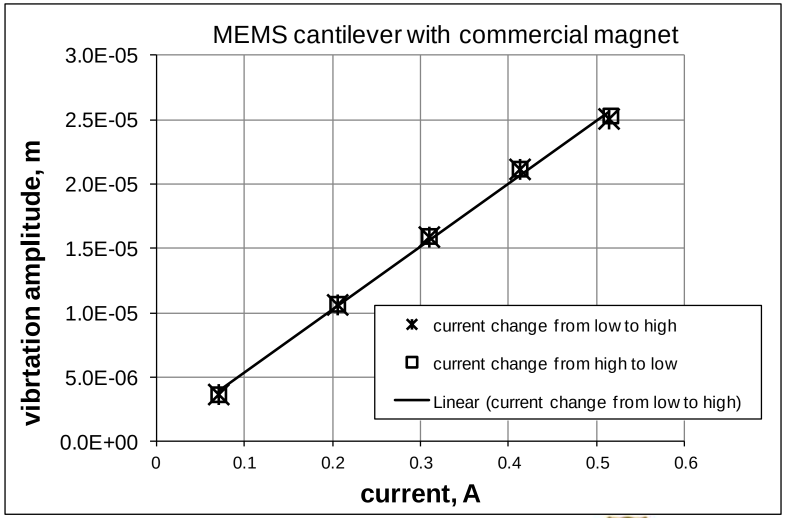
Results from EH from Power Main







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Medical Energy Harvesting

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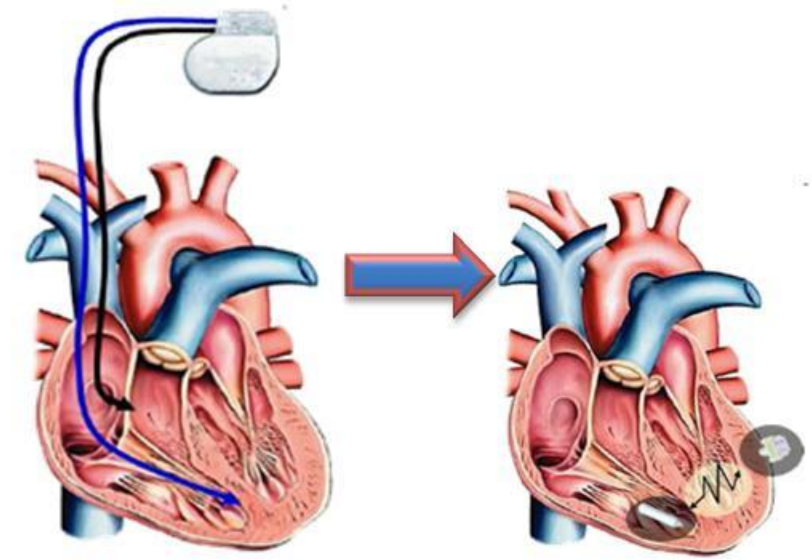
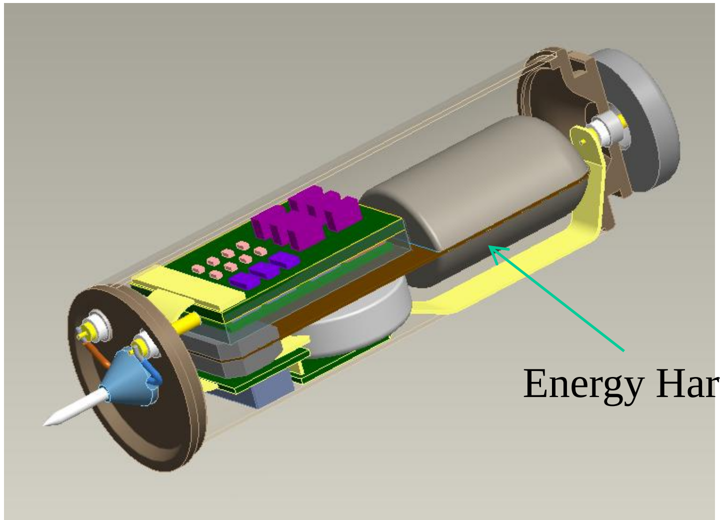
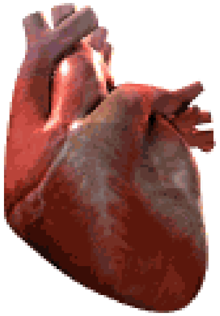
Energy Harvesting from the Heart (MANpower (FP7 NMP)



Current pacemaker

Future leadless pacemake





Jackson Smart Materials and Structures 2013)

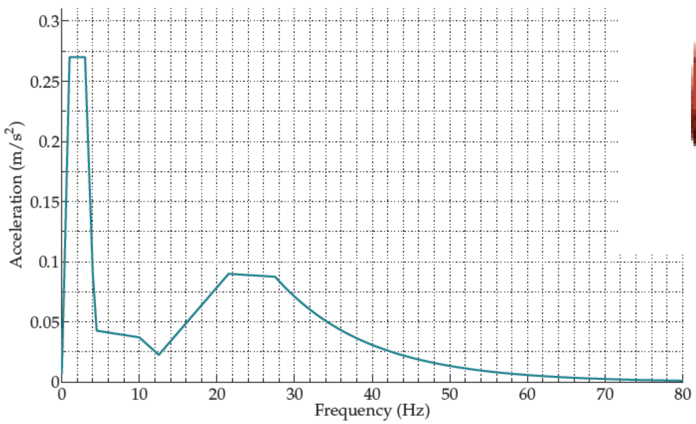
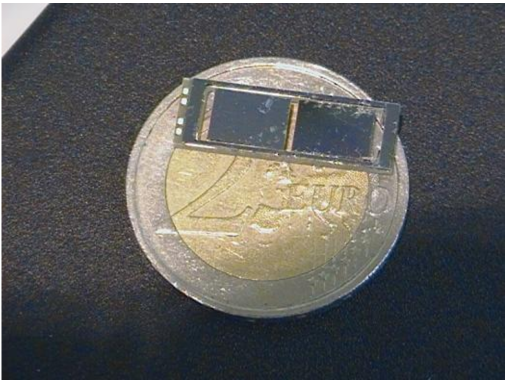
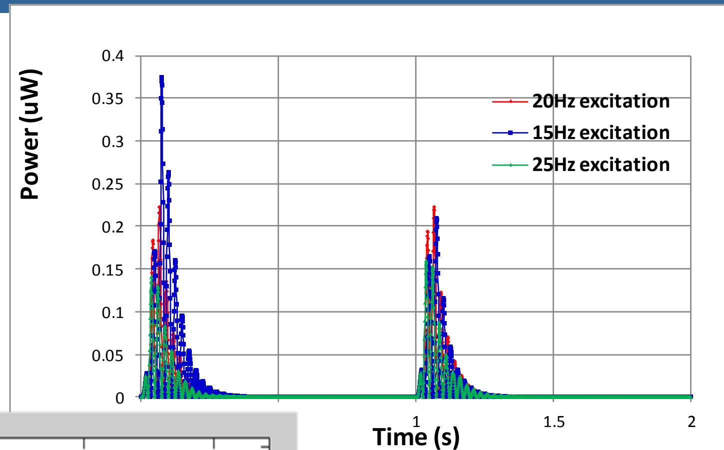
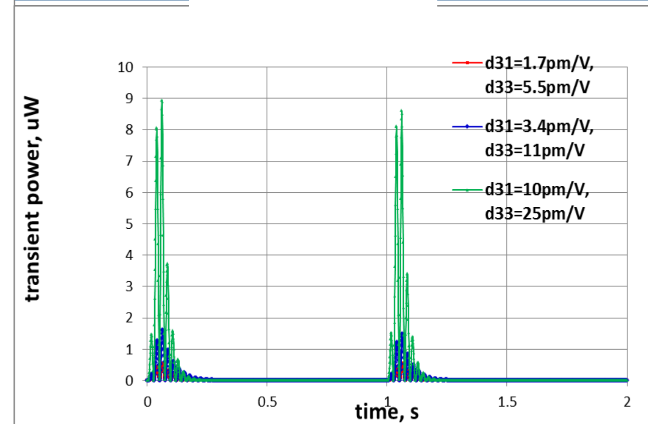


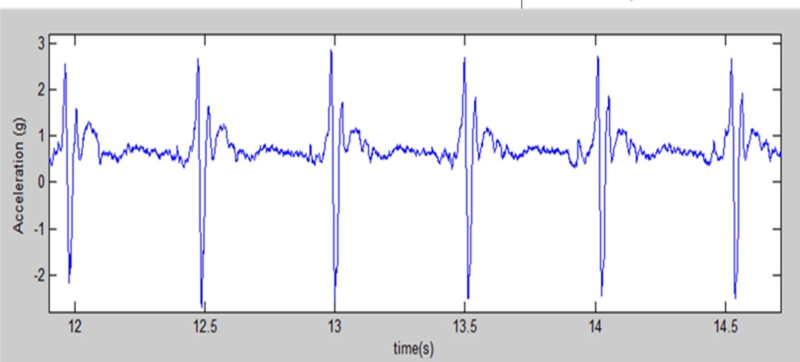
Figure 2.5: Typical shape of the acceleration spectrum measured in the right atrium.

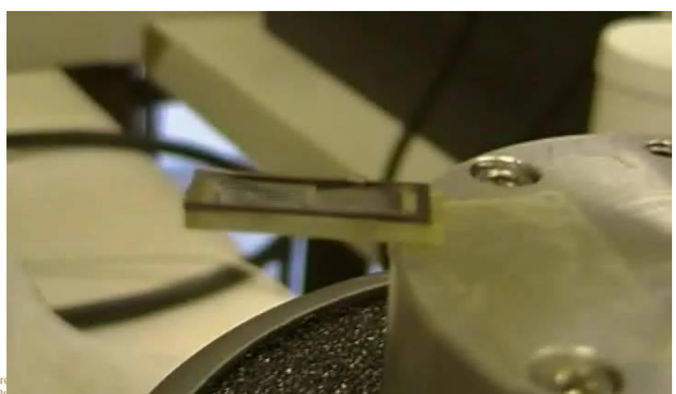
Results from Harvesting from the Heart

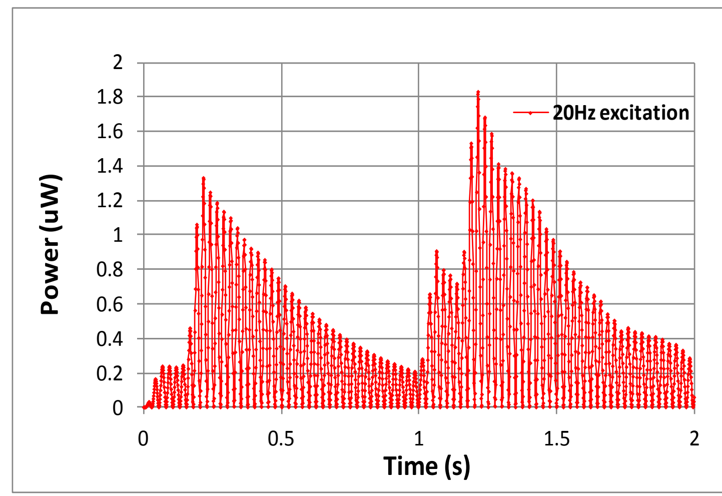












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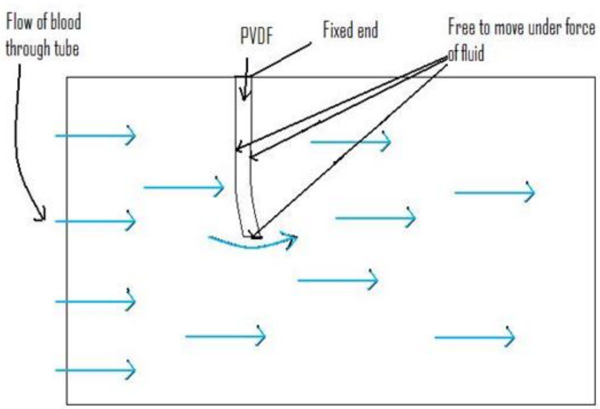
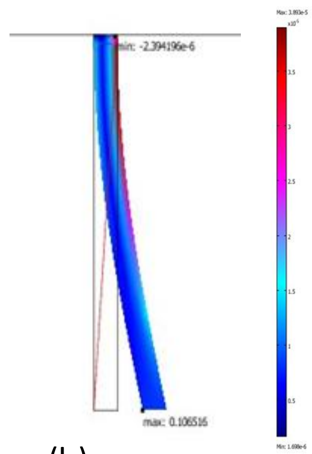
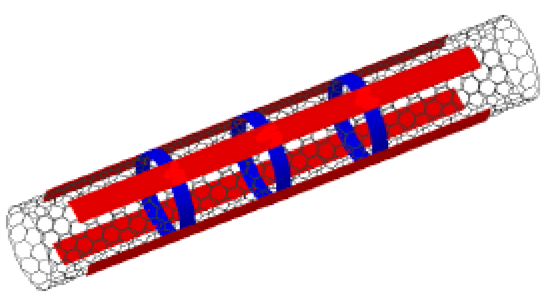
Implantable EH on Stent

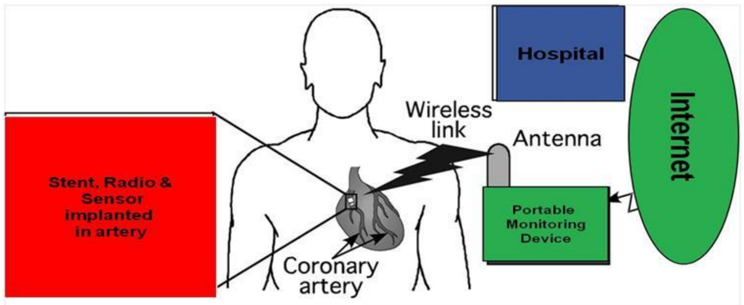


(a)

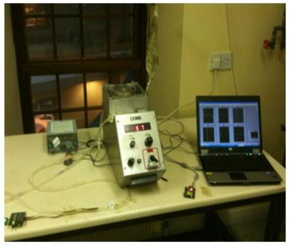


(b)

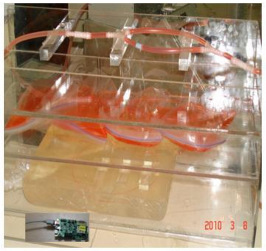




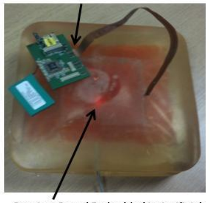
Perfusion System, Labview



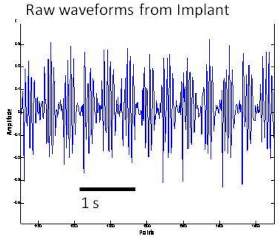
Blood Flow Simulation



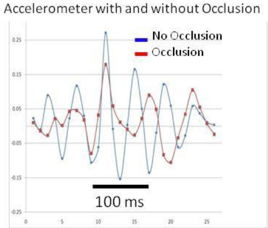
RF Testing in BioPhantoms



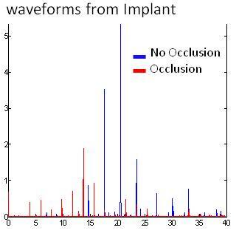
Raw waveforms from Implant



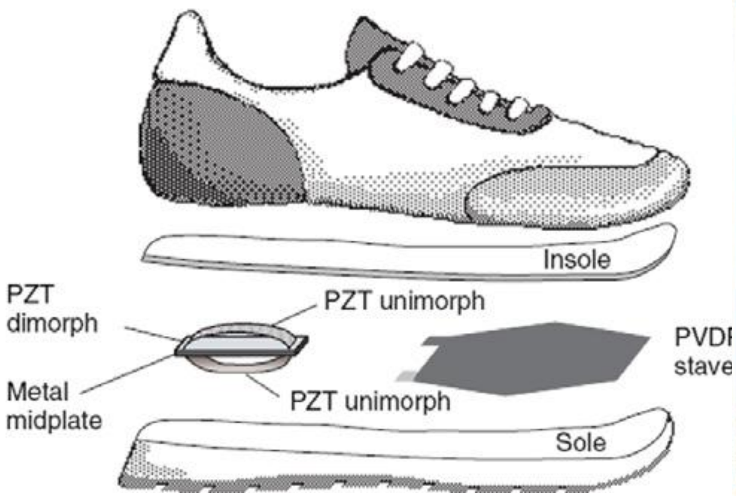
Average Waveform Detected by Accelerometer with and without Occlusion



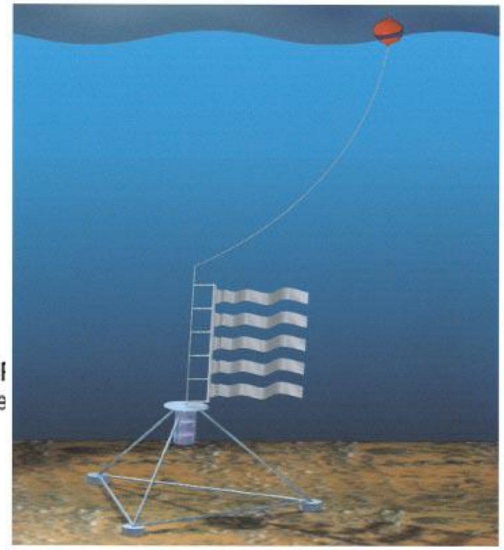
FFT (Fast Fourier Transform) of waveforms from Implant



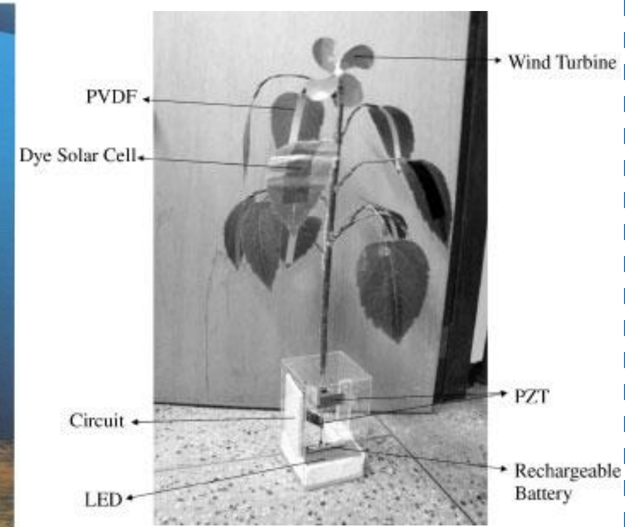
Other Applications for Energy Harvesting (less common)



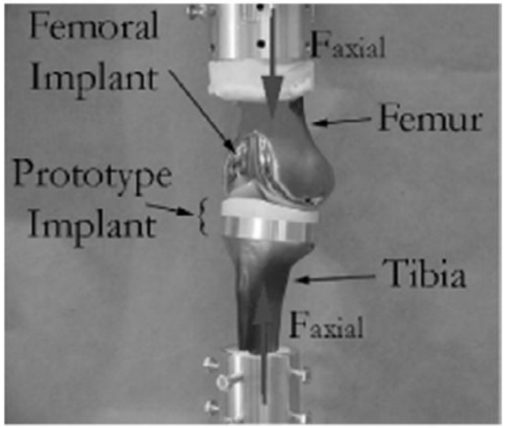
Schenck et al. 2001



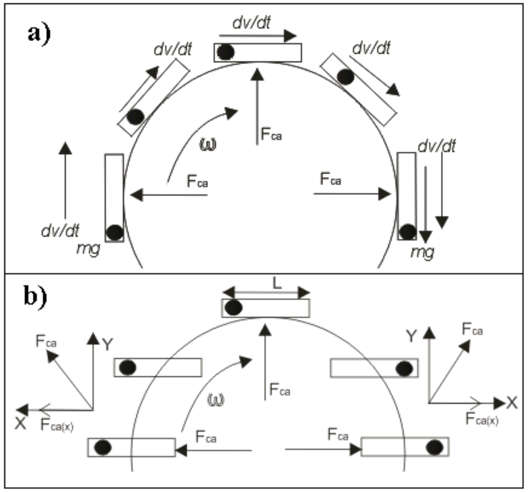
Taylor et al. 2001



Oh et al. 2010



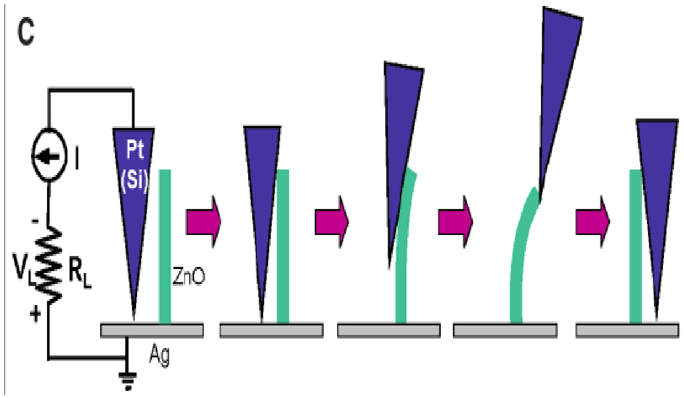
Platt et al. 2005

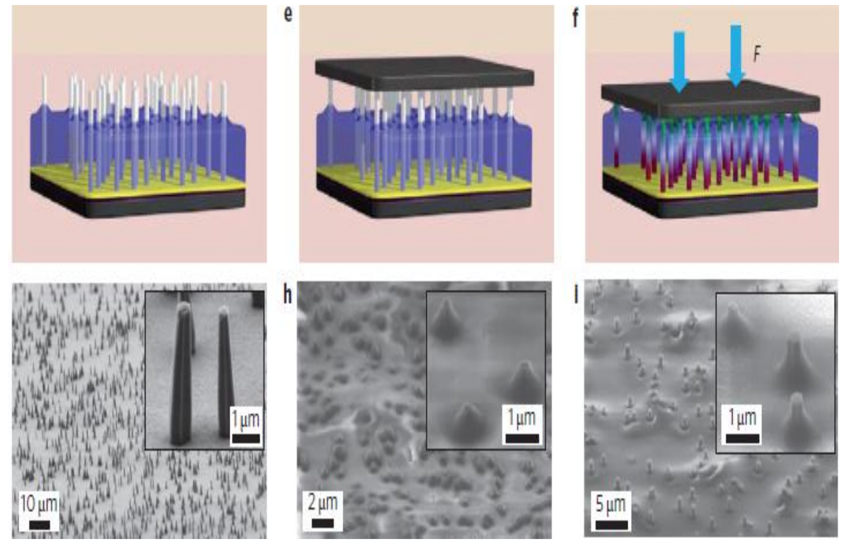


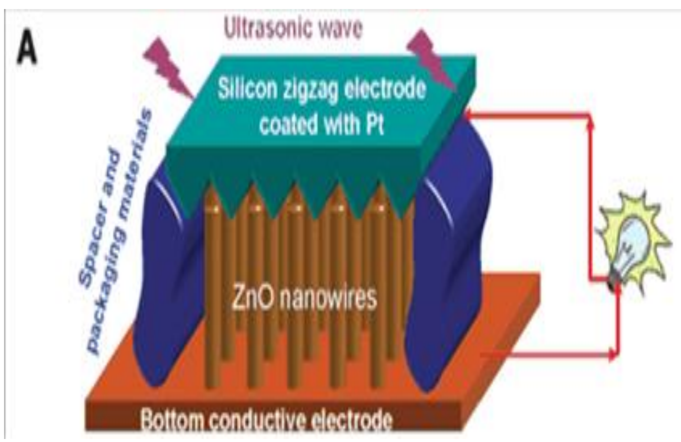
Manla et al 2009

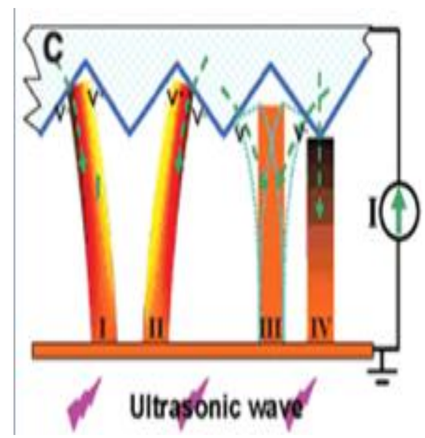
Future Piezoelectric Devices based on 1D Piezo-materials

ZnO Nanowire



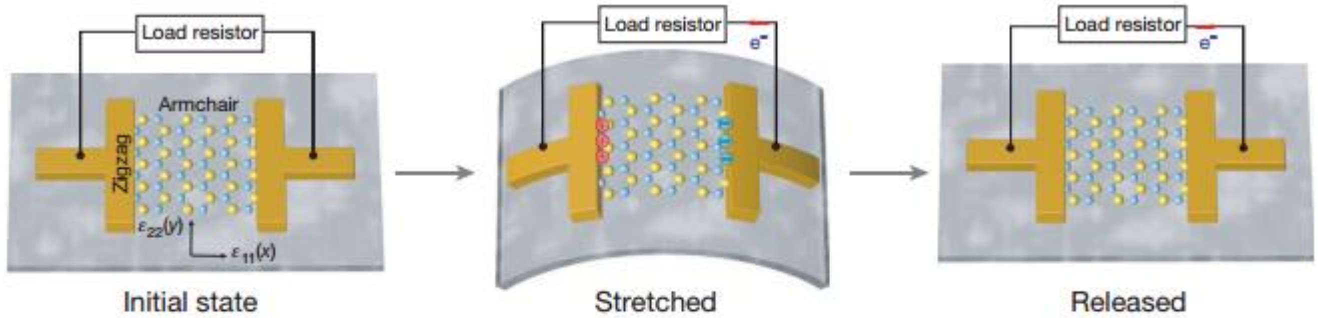


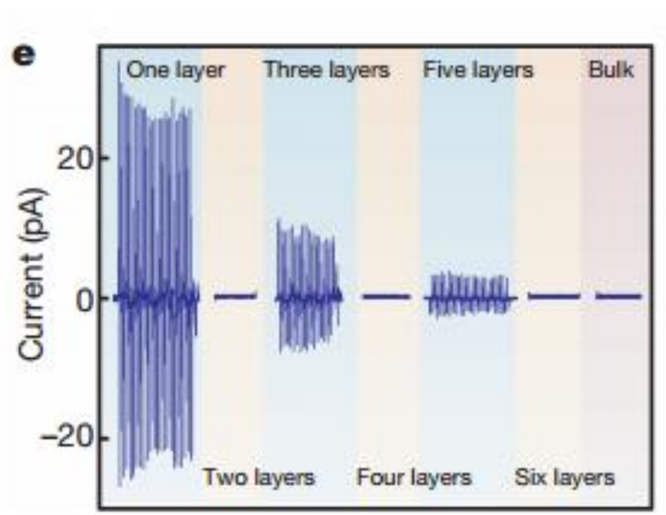


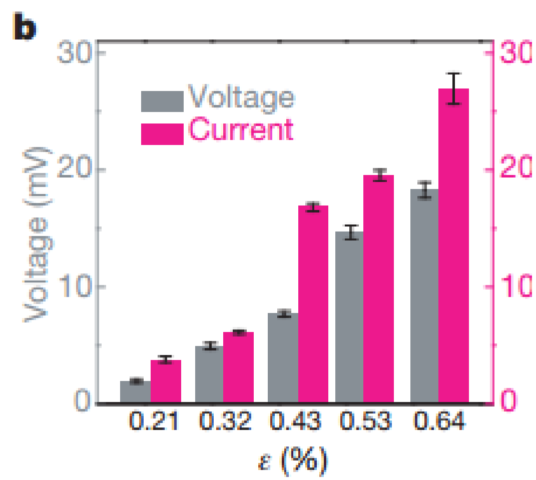


Images taken from Wang et al.

MoS2 Piezoelectrics







Images taken from Wu et al. Nature 2014

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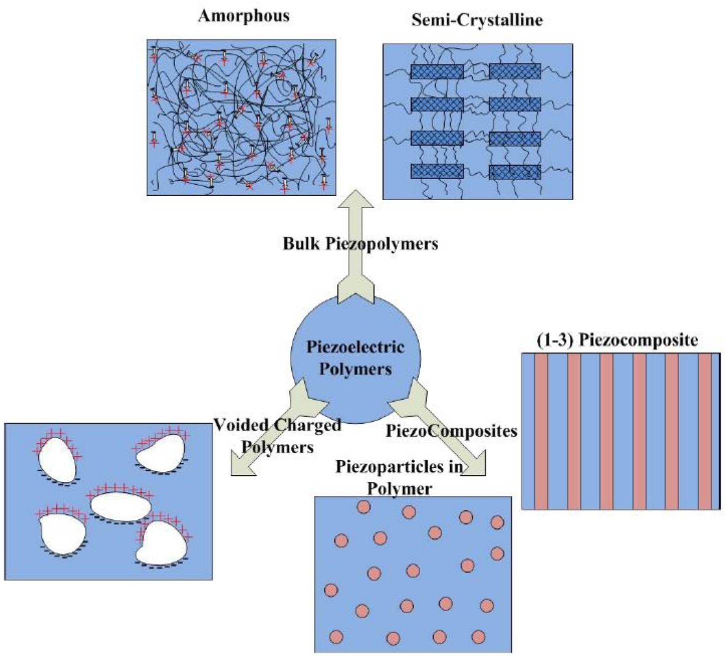
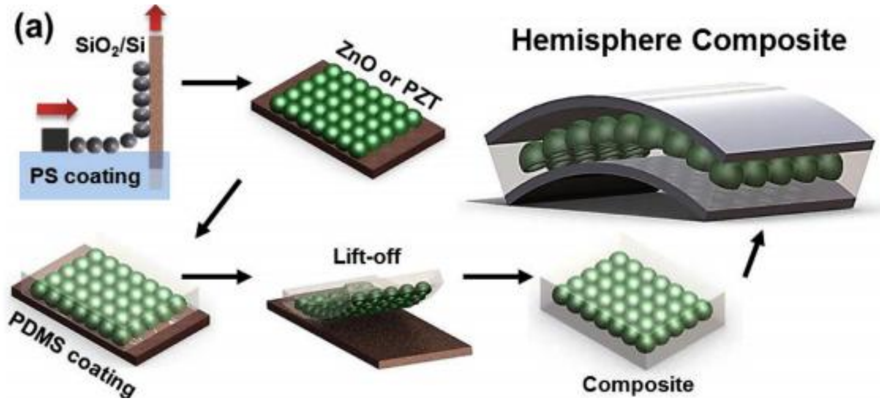
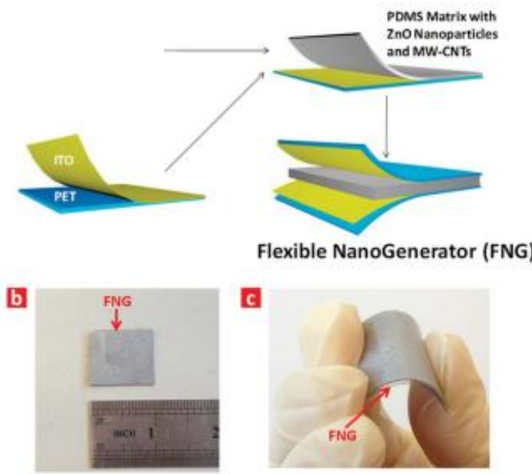
Flexible Nanocomposites

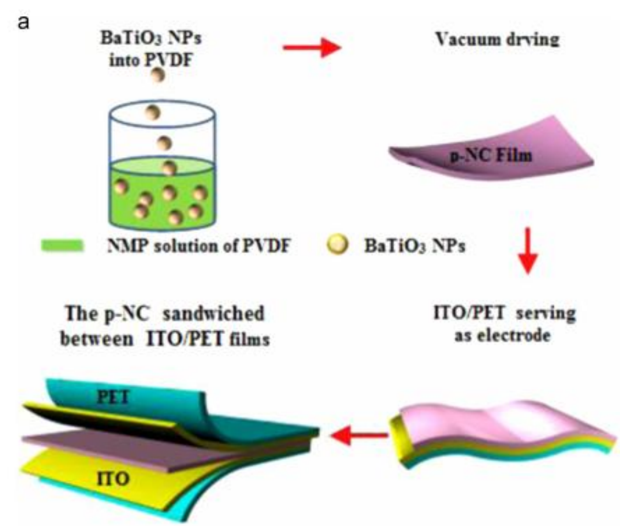


Ramadan et. al. 2014





Images taken from Sun et al. 2013



Zhao et al. 2014

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Other Applications for Piezoelectrics

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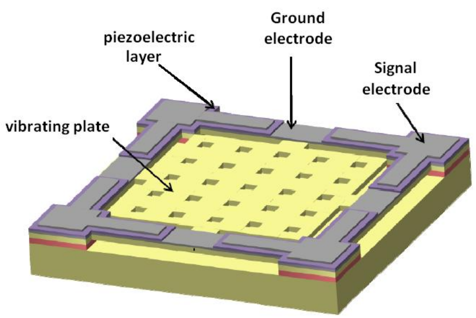
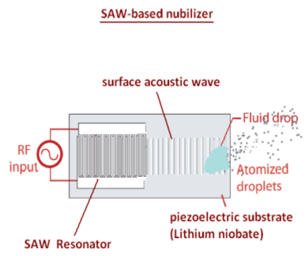
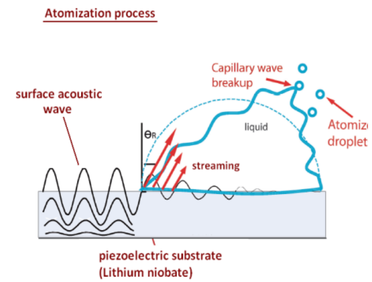
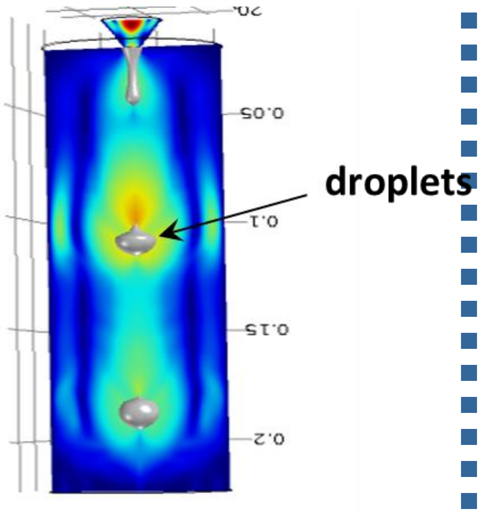
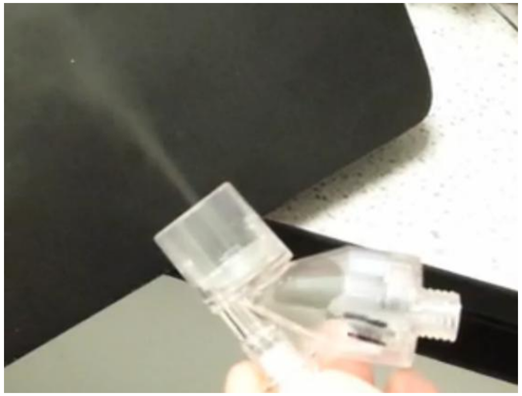
Drug Delivery based on MEMS Resonators (Nebulizer)





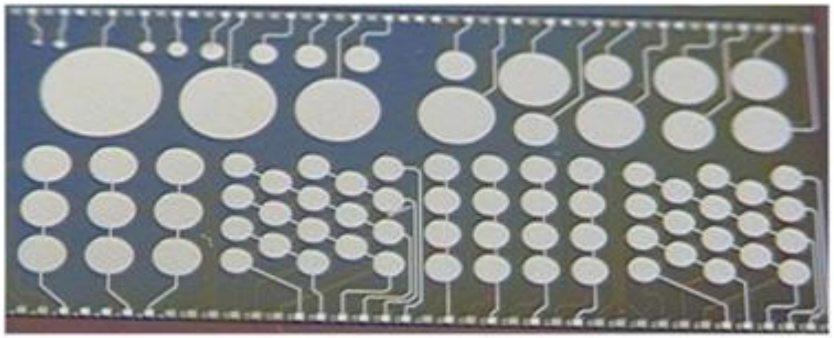


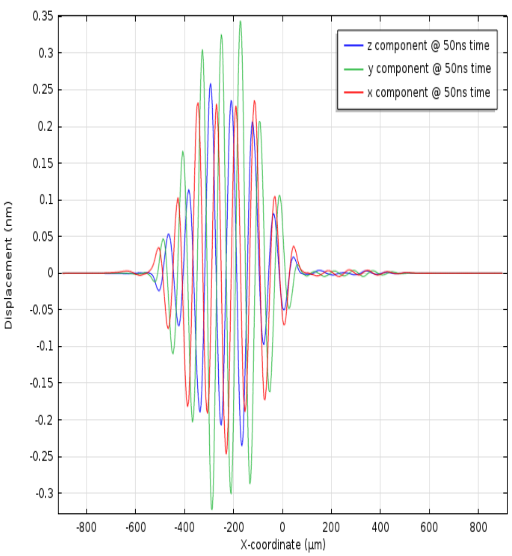


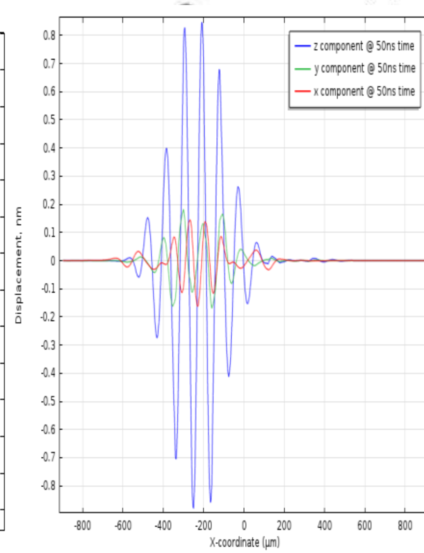


Initial Work

Ultrasound Resonators







BioSensor

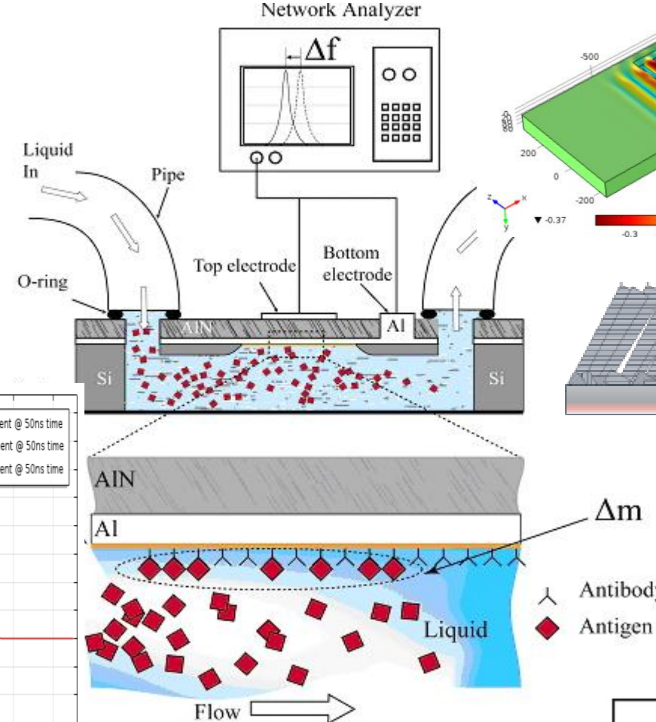
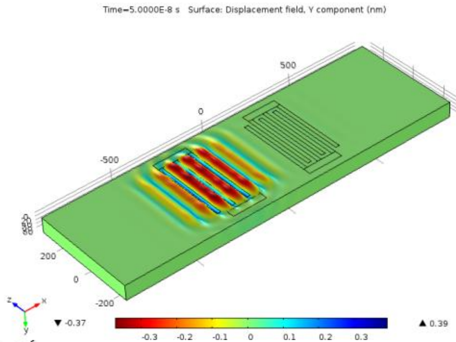
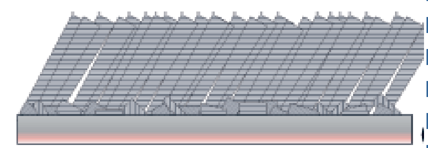
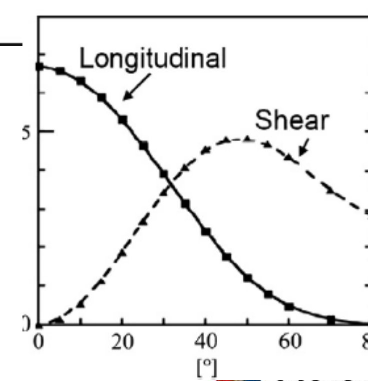


Image taken from Winquist et al.



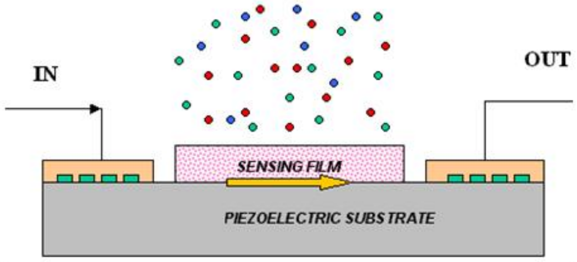




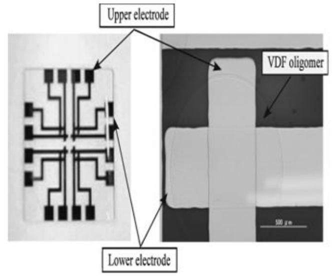
Future Applications in PiezoMEMS

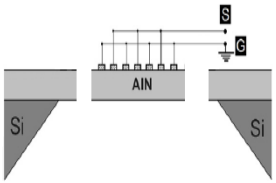
Sensors

- •Gas
- •Biosensor
- •Particle
- •Pressure
- •Tactile
- •Etc…
  - u-Pump

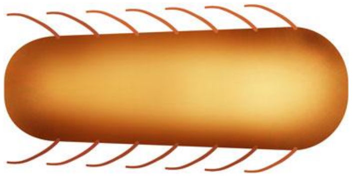


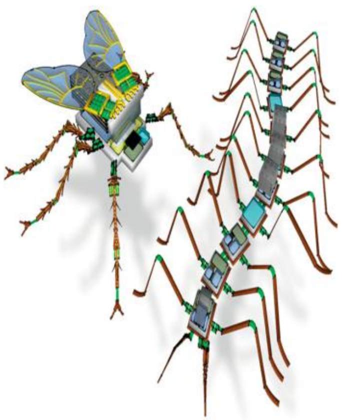
Tactile Sensor

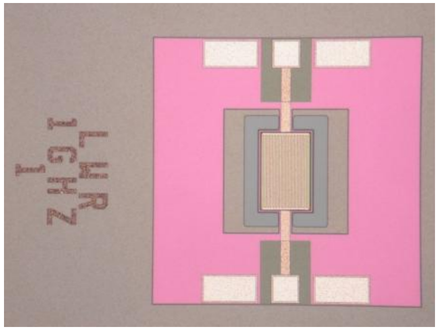


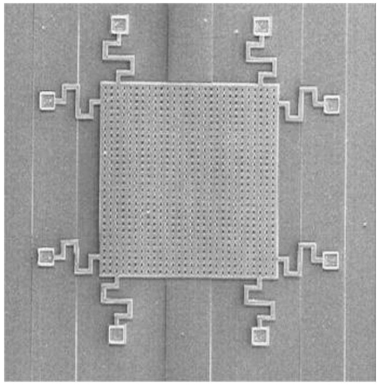


Nano-robots, cilia actuators for transportation

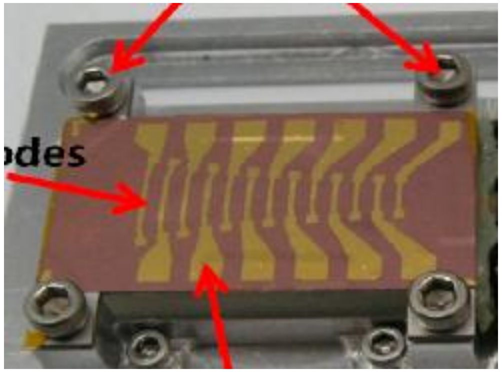




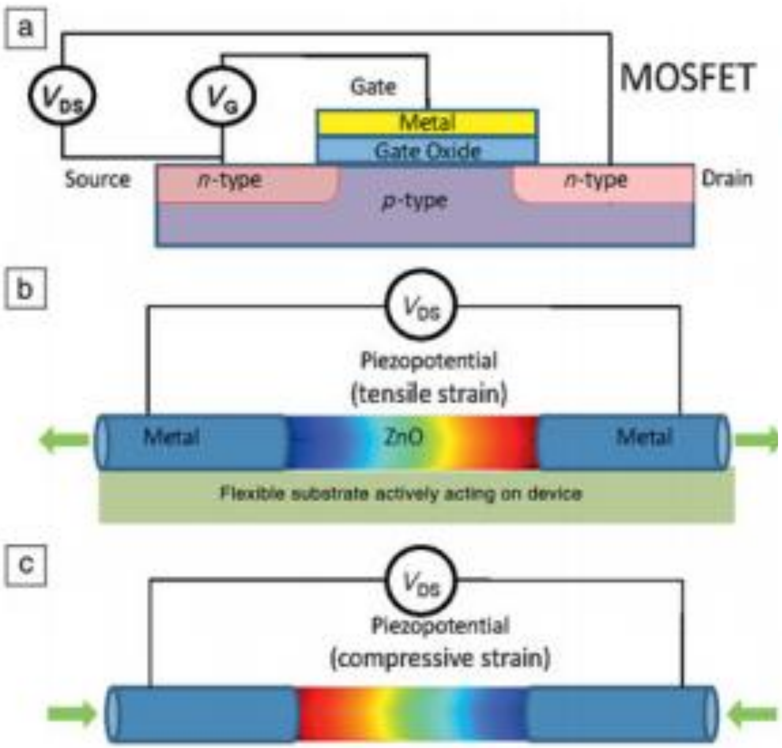




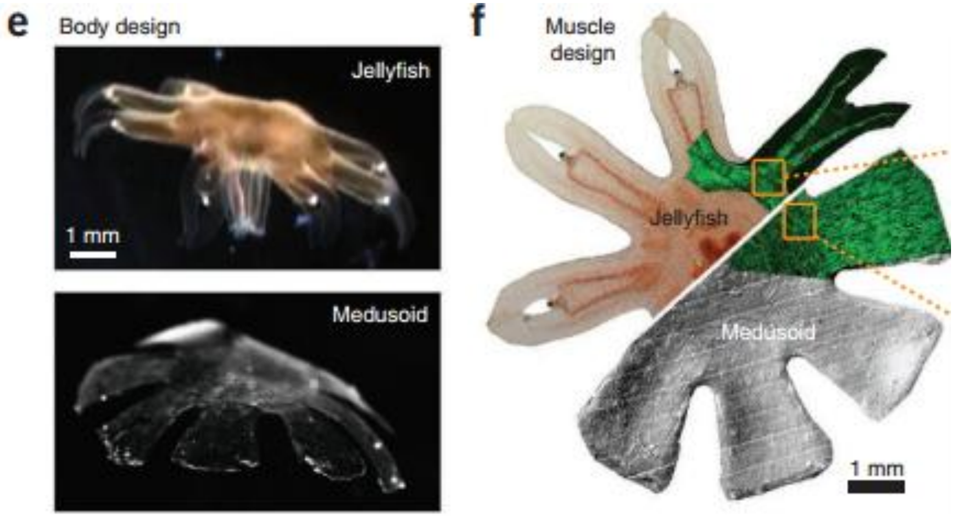
Cochlea Device



Future of Piezoelectrics



Wang et al. 2012



Feinberg et al. 2012 Science

Summary

- Piezoelectrics are smart materials that can be used to harvest energy from dynamic vibrational sources

- Research is being conducted to enhance current piezoelectric materials and to develop new materials

- To increase power harvesting
  - Optimise piezoelectric material
  - Optimise MEMS device

- Piezoelectrics can be used for numerous applications

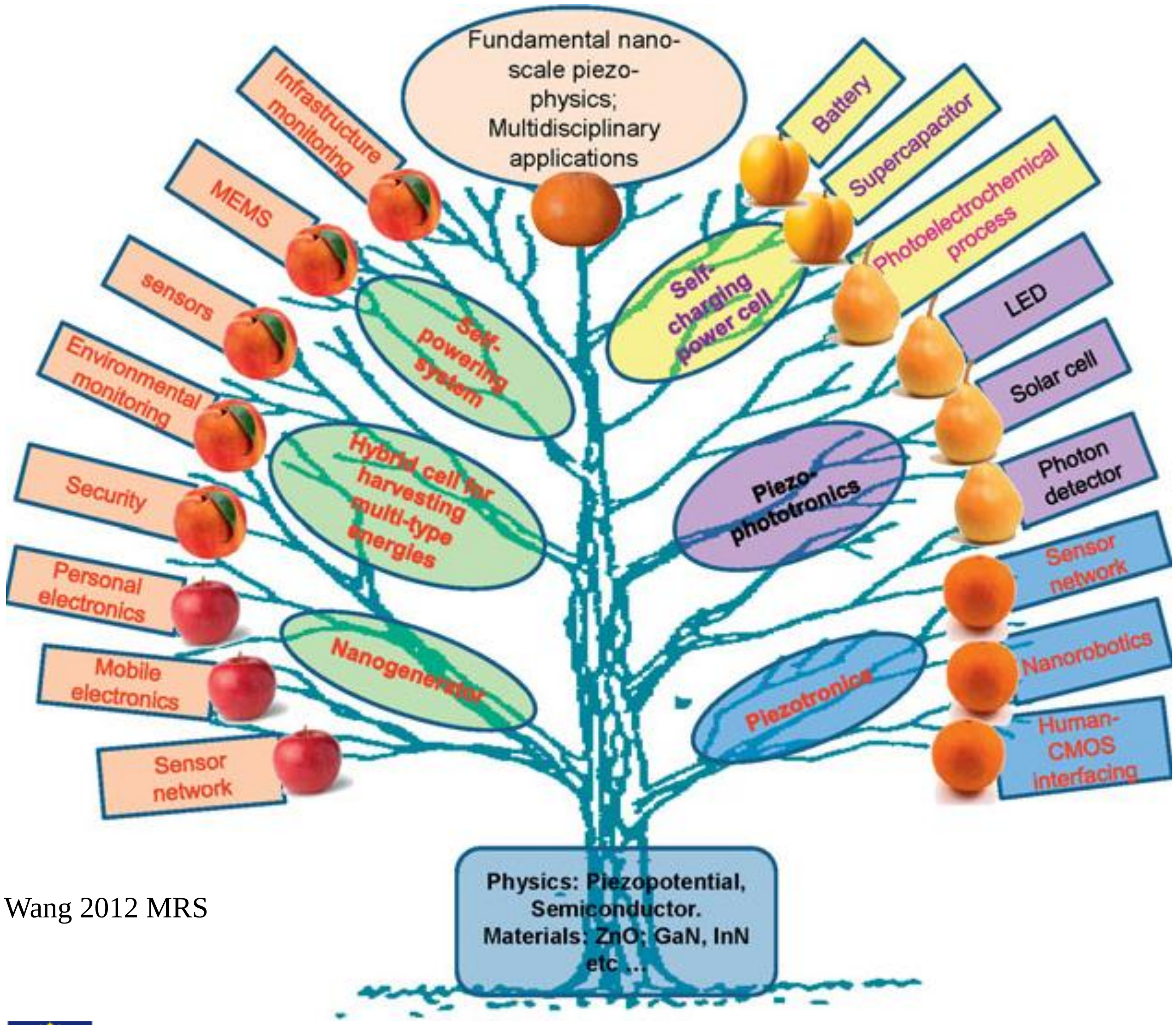


Image taken from Wang 2012 MRS

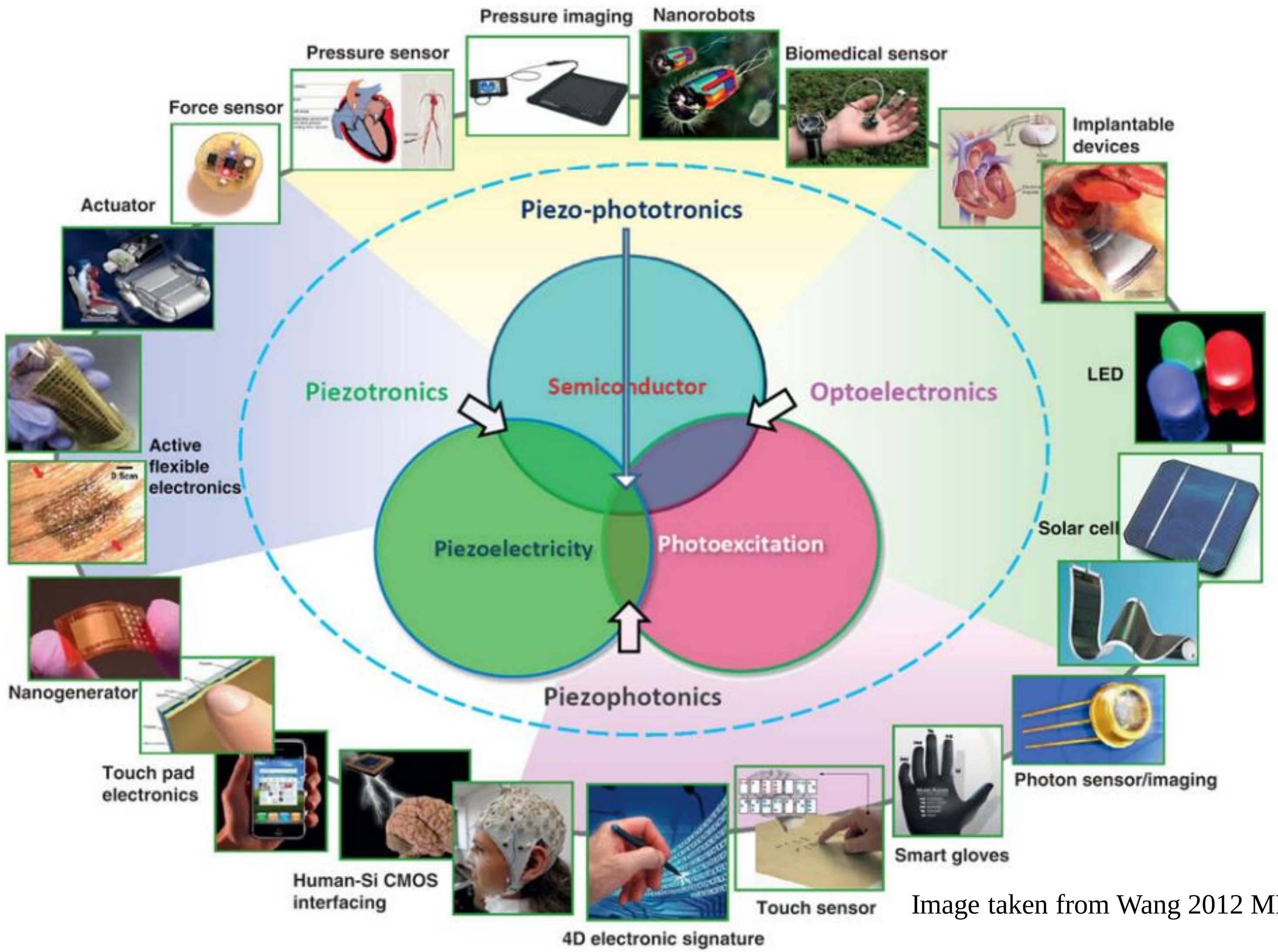


Image taken from Wang 2012 MRS

QUESTIONS???

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