# ENERGY HARVESTING FOR WIRELESS AUTONOMOUS SENSOR SYSTEMS

Rob van Schaijk

Holst Centre
Open Innovation by IMEC-NL and TNO

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# SMART SYSTEMS EVERYWHERE

"Blood pressure too high"

"Traffic jam ahead"

"I'm sensing corrosion"

"We're ripe"

"I'm here Mummy"

"I'm all out of milk"

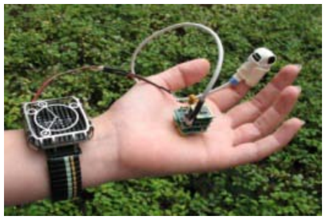
"Time for walkies"

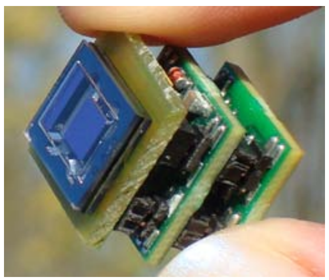
"We're 98% full"

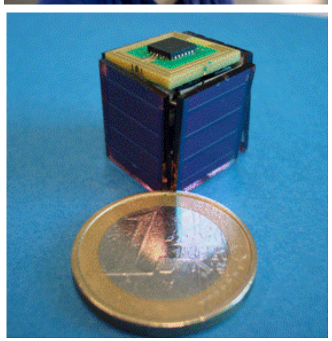
"You left me here"

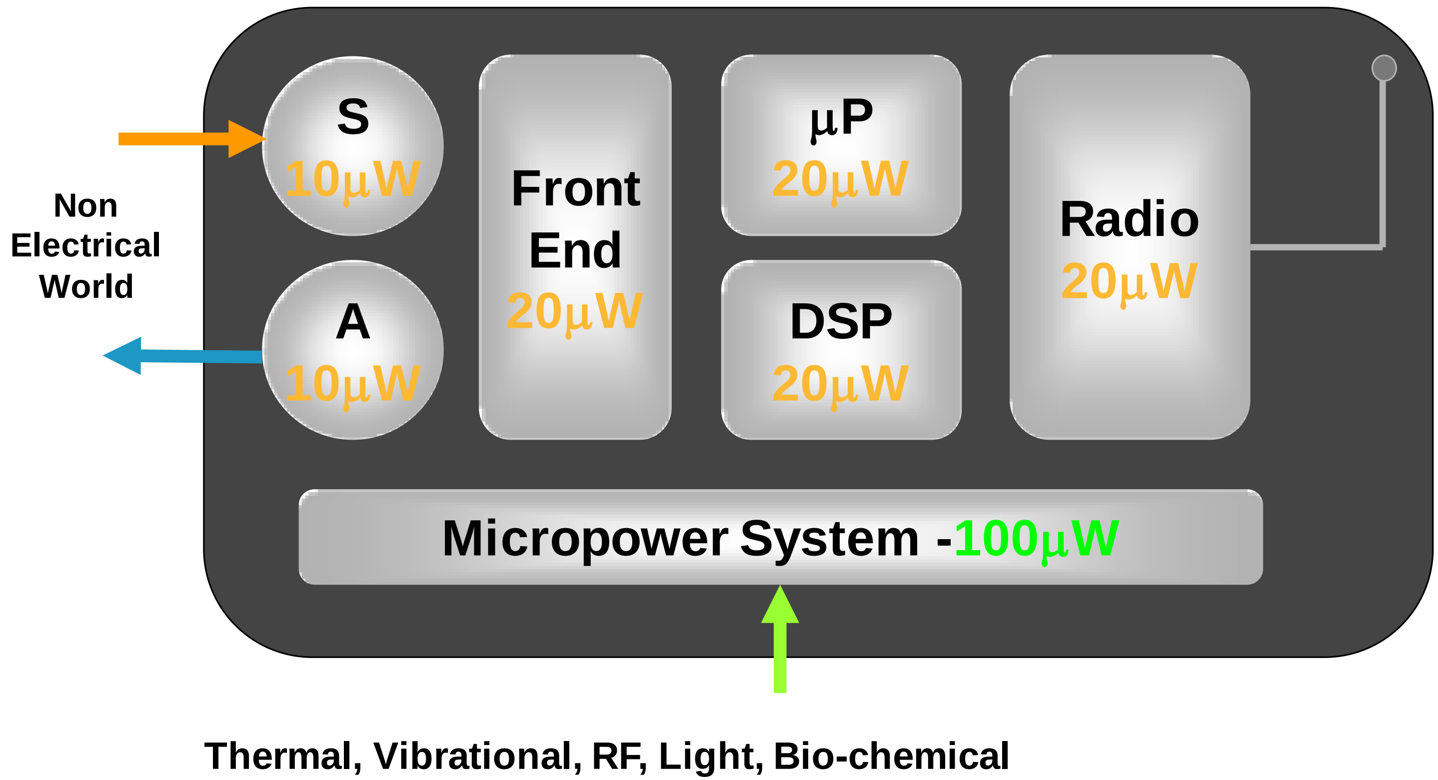
"Send me energy"

# THE WIRELESS AUTONOMOUS SENSOR NODE





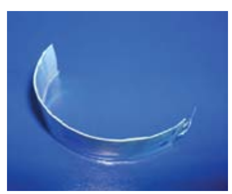




# CAN WE STICK WITH BATTERIES?

- Few specifications:
  - Smart systems everywhere
    - Large numbers
    - Accessibility to devices
    - Battery replacement is not always an option
    - Device autonomy exceeds lifetime
    - **Size and Weight important factor**

*Thin-film-flexible*



*Lithium-flexible*

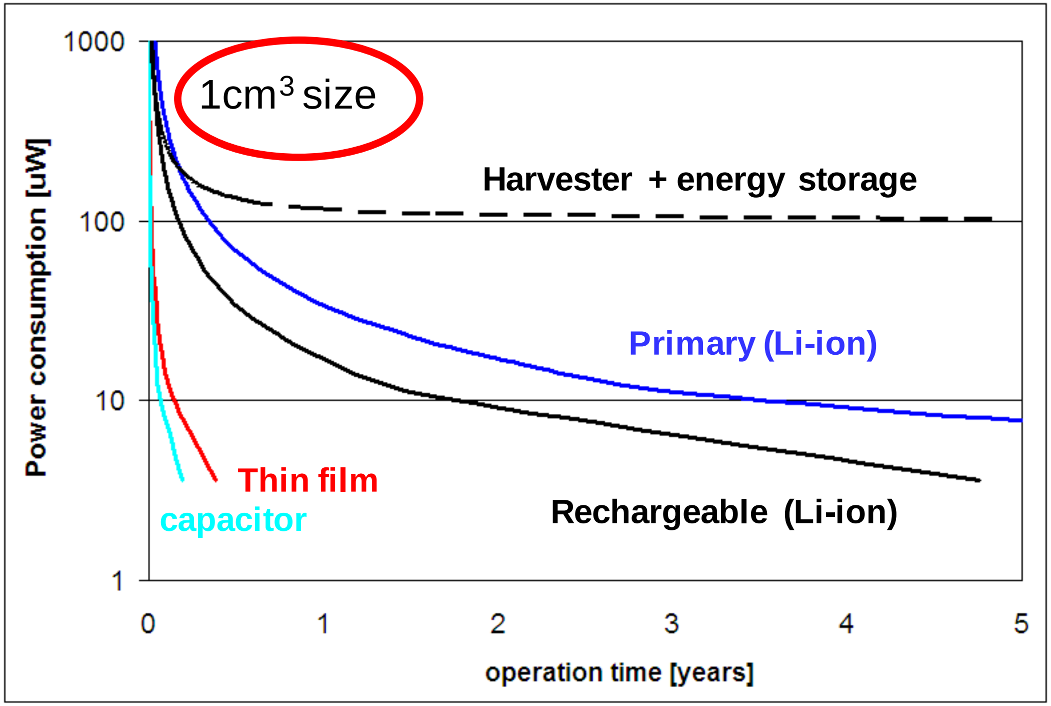
*Lithium-coin*

*Printable*


*Supercapacitor*

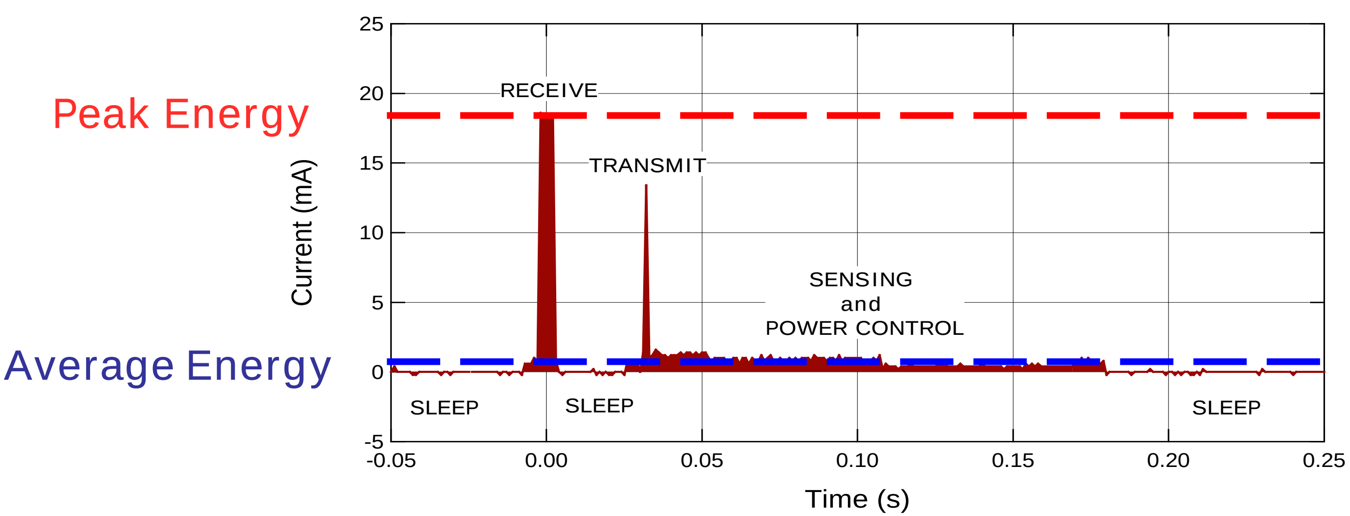
# ONLY BATTERY

- Small battery alone do not offer autonomy



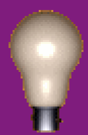
# ONLY HARVESTER

- Energy buffer in sensor system is essential.
  - NO buffer: harvested energy = Peak energy
  - With buffer: harvested energy = Average Energy
- A small battery or Super Capacitor is therefore needed




*A typical energy consumption scenario*

# Power levels “MEMS” based harvesters*

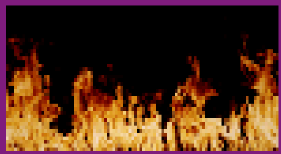


## Photovoltaic

Outdoor
10 mW/cm$^2$
Indoor
10 μW/cm$^2$

## Vibration

Man
4 uW/cm$^2$
Machine
100 μW/cm$^2$



## Thermal

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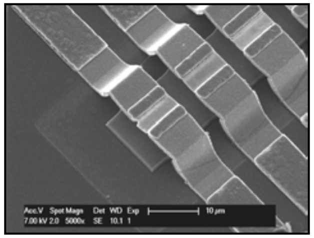
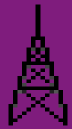
1-10 mW/cm$^2$



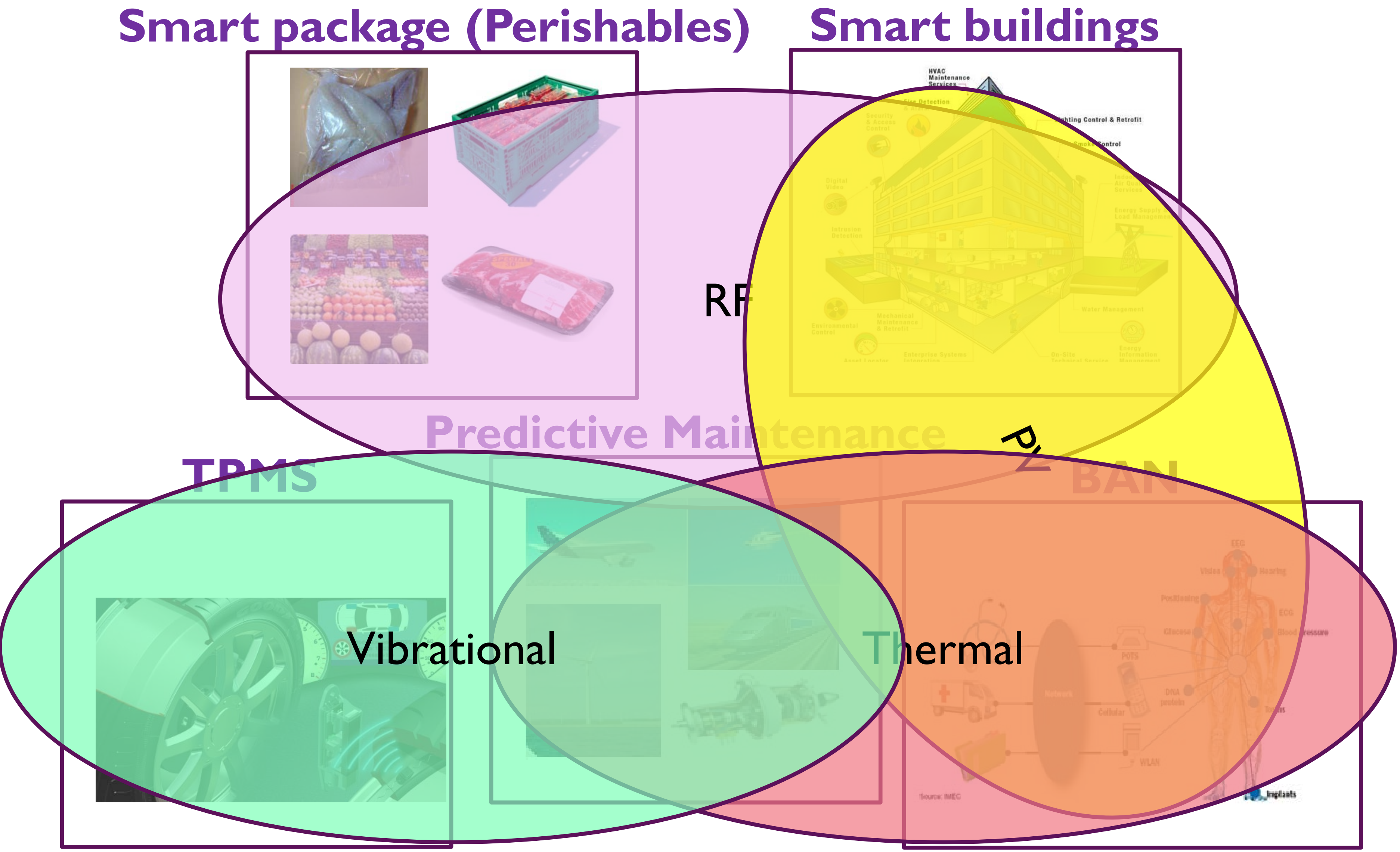


## RF

GSM
0.1 μW/cm$^2$
WiFi
0.01 μW/cm$^2$

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

# APPLICATION FIELDS ENERGY HARVESTING



# “NOT ENOUGH POWER IS GENERATED”

you don’t generate enough !

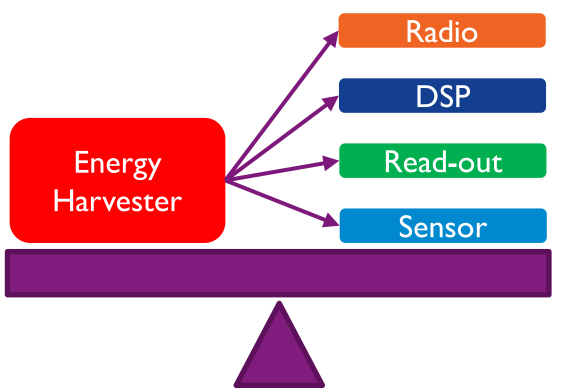
you consume too much !

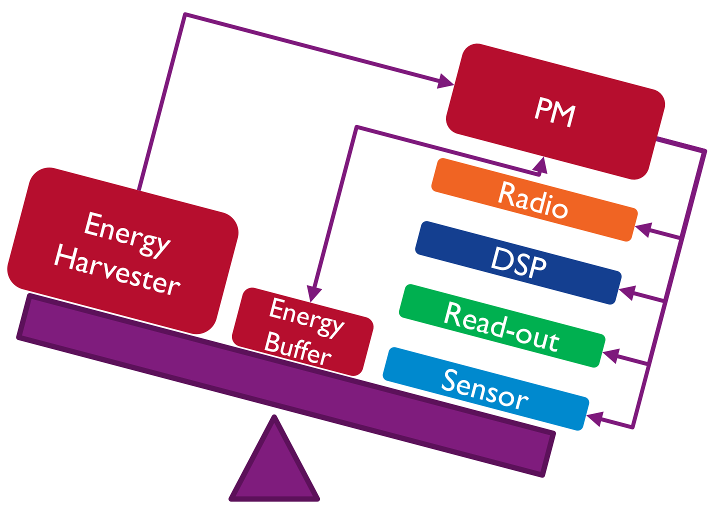
And this largely explains the absence of killer applications using energy harvesting

# THE ENERGY BALANCE

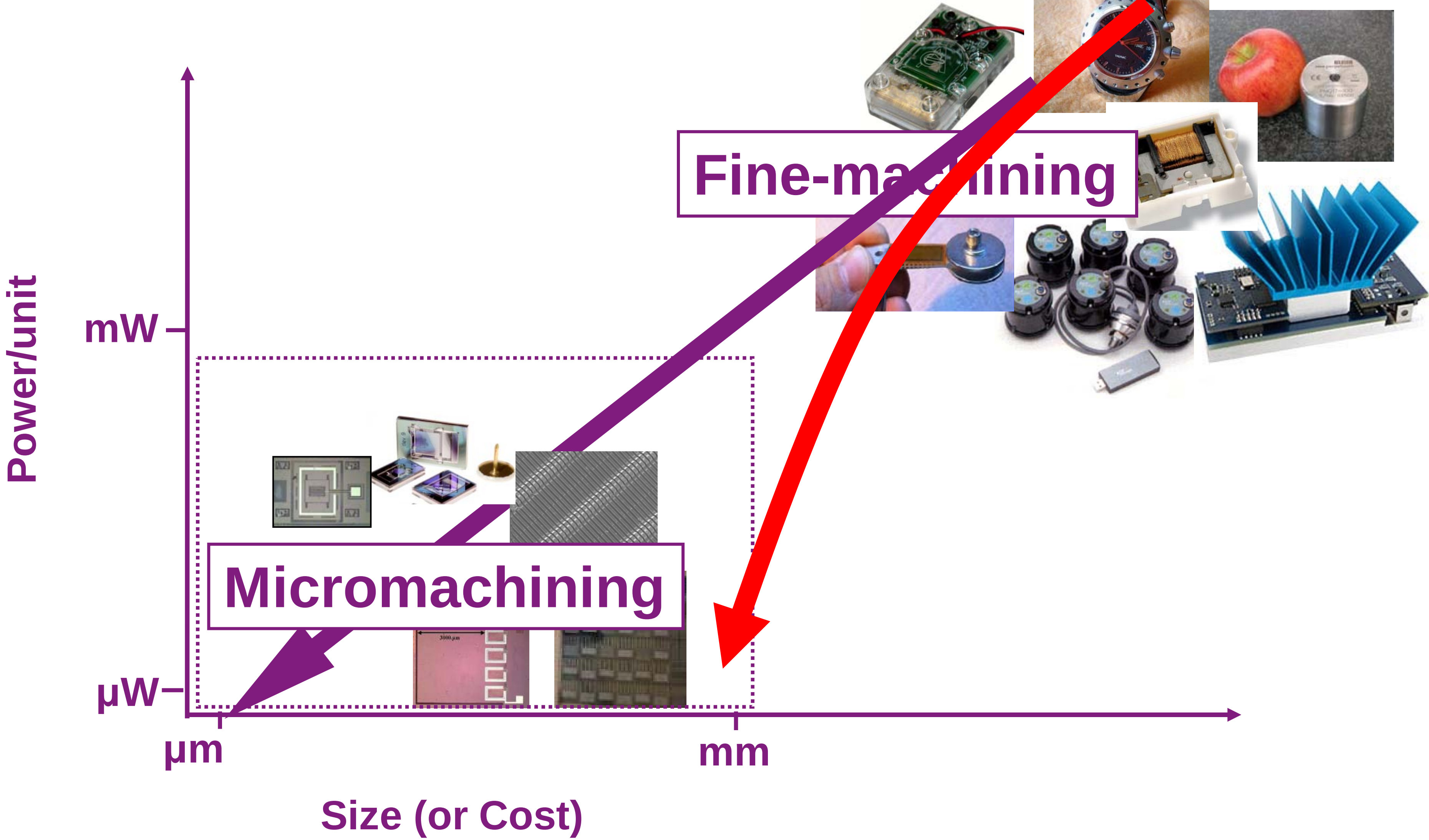
For a successful introduction of MEMS based Energy Harvester:

- The Power usage needs to be reduced
  - Of the shelf components use ‘too’ much power
  - Power optimization needed towards ultra low power
- Energy harvesters have to increase power output
  - Increase of harvesting efficiency
  - Increase of conversion efficiency -> Power Management is key!



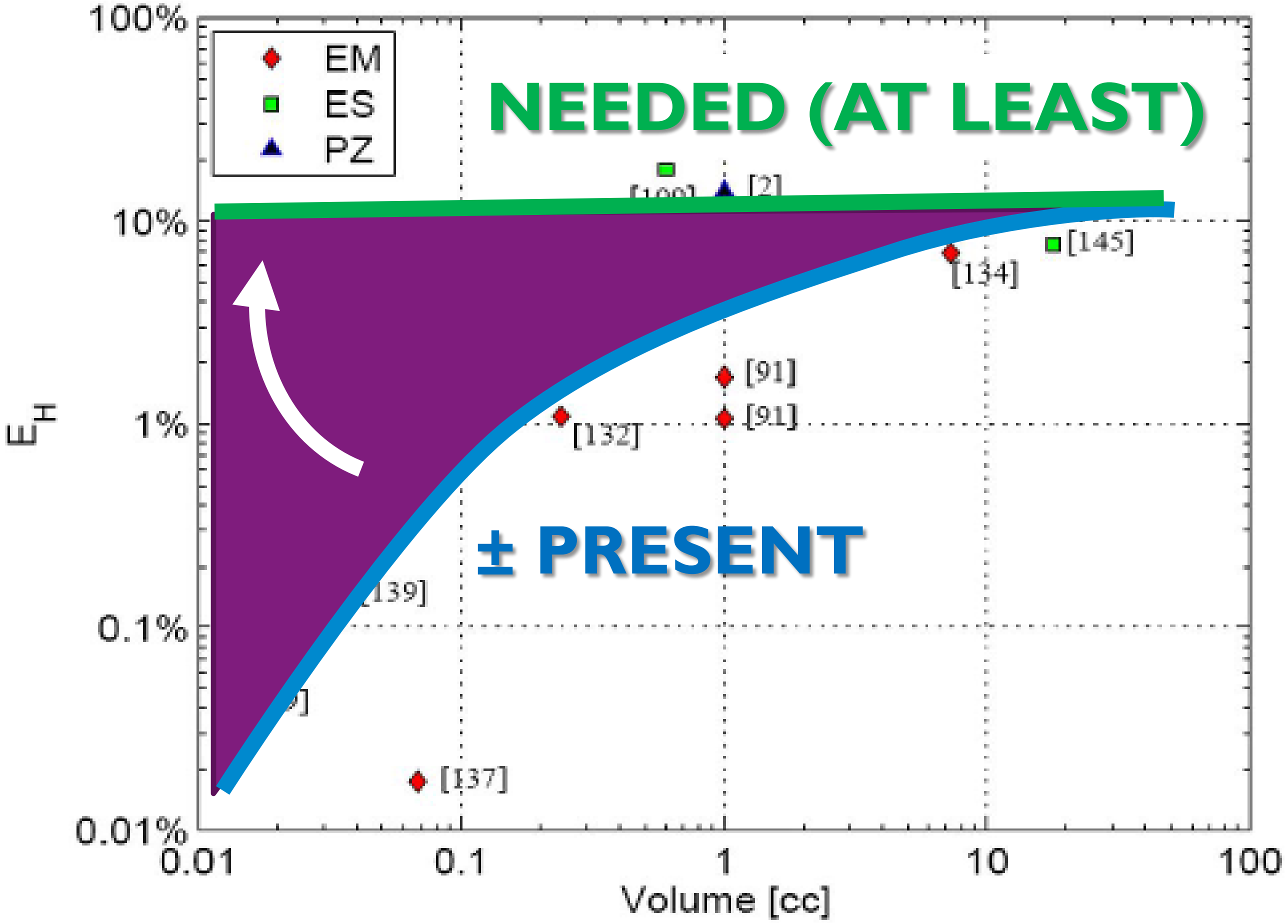



# COST REDUCTION THROUGH MICRO-SYSTEM APPROACH



# SOMETHING ELSE IS (REALLY) WRONG WITH ENERGY HARVESTING TODAY: *SCALING !*

## DISPROPORTIONAL SCALING WITH MINIATURIZATION (CASE OF VIBRATIONAL ENERGY HARVESTING)

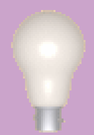



$$FOM_V = \frac{P_{meas}}{\frac{1}{16} Y_o \rho_{Au} Vol^{\frac{4}{3}} \omega^3}$$

$$P_{norm} = \frac{P_{meas}}{P_{max}} = E_H$$

P.D. Mitcheson et al.; Proceedings of the IEEE, 96, No. 9, pp. 1 (2008)

# Power levels “MEMS” based harvesters



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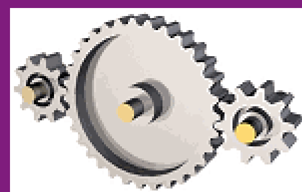

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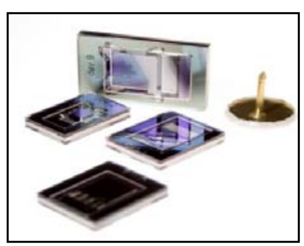
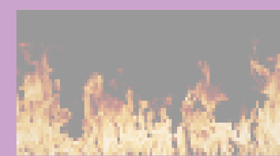
100 $\mu W/cm^2$





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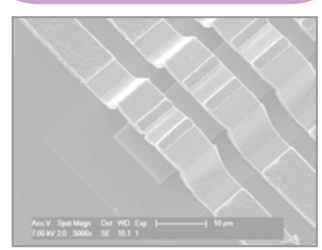

## RF

GSM
0.1 $\mu W/cm^2$
WiFi
0.01 $\mu W/cm^2$

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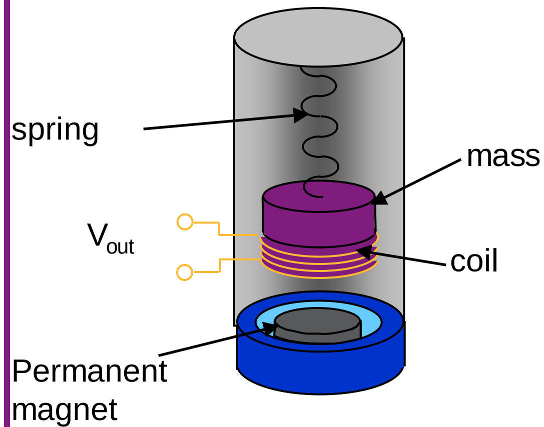
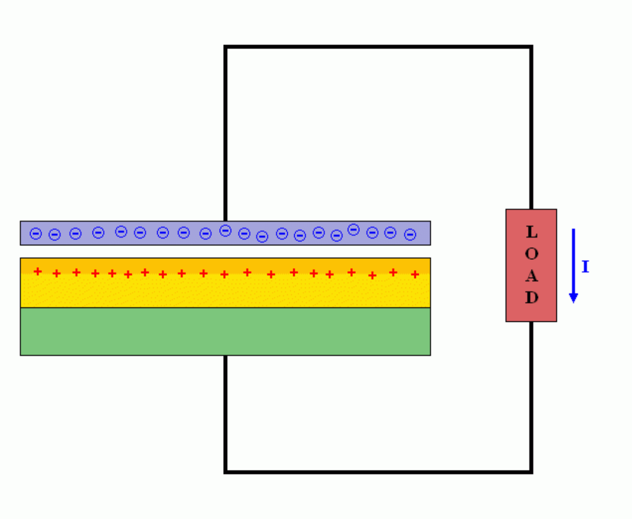
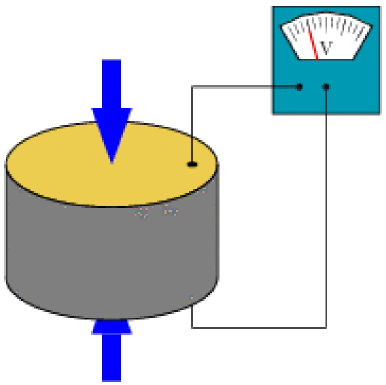
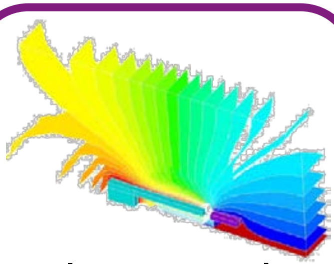
# VIBRATION HARVESTING: THREE MECHANISMS



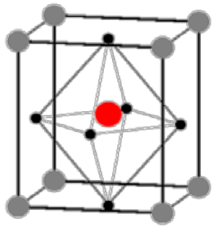



Electro-magnetic



Electrostatic



Piezoelectric

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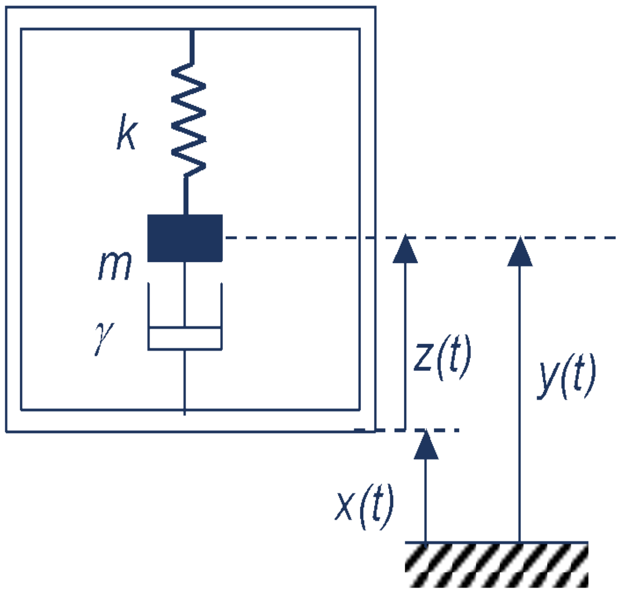
# Mechanical power generation: General principle

## Velocity damped resonator



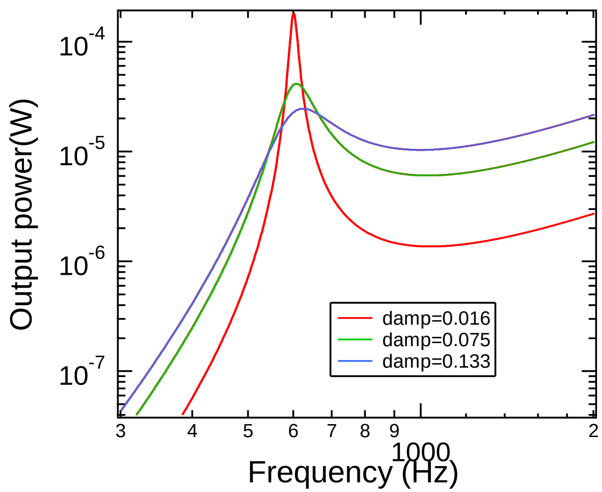

Power

$$P(\omega_0) = \frac{m\omega_0^3 X_0 L}{4}$$

$$\varsigma = \frac{\gamma}{2m\omega_0} = \frac{X_0}{L}$$

$X_0$: vibration amplitude
L: system dimension
m: system mass
$w_0$: resonance frequency

## Maximum power conditions




Possible range:
10 -100 μW/cm$^2$

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Optimal transformation of mechanical energy into electricity occurs at the resonance frequency of the harvester!

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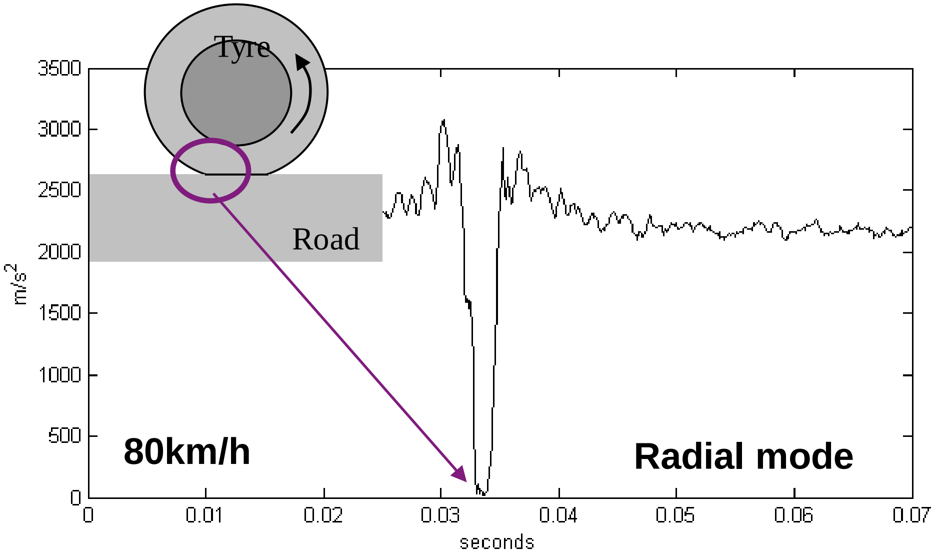
# INTELLIGENT TIRE

- Intelligent tire: measurement of forces for improvement of active safety systems
- Resonant excitation ↔ high acceleration shock
- Shock → Self resonance → ring down mode

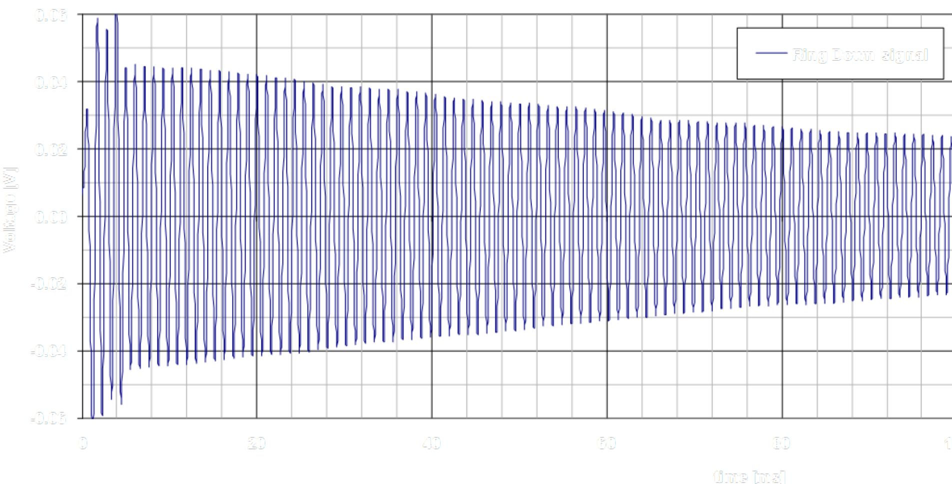
80km/h → ~20 shocks/sec

300G shock → comparable to resonance at 1G for Q=300

Friction coefficient between tire and road → improvement of active safety systems

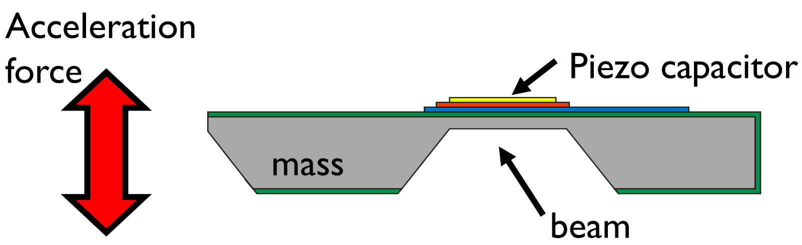



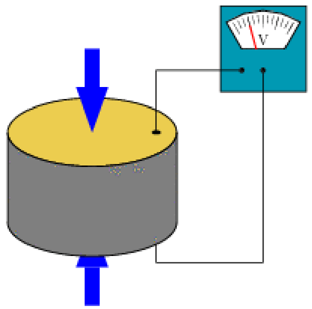

*Source: Pirelli tire company*

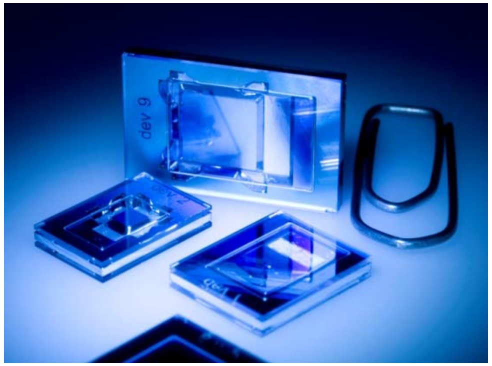


*Ring down signal after shock (16G for 0.5ms) in matched load resistor*

# MEMS BASED PIEZOELECTRIC ENERGY HARVESTERS



Motion changes polarization

**World Record output power**

**Aiming for 500µW**

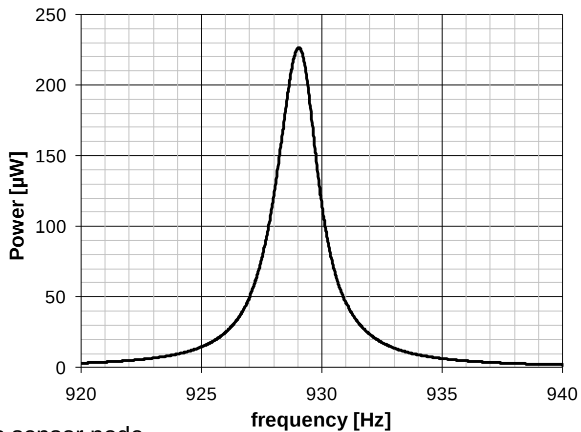
**2010** **AlN: 225µW@929Hz (2.5g)**

**2009** **AlN: 100µW@572Hz (1.0g)**

**2008** **AlN: 60µW@572Hz (2.0g)**

**2007** **PZT: 40µW@1.8kHz (2.5g)**

**AlN power vs frequency**

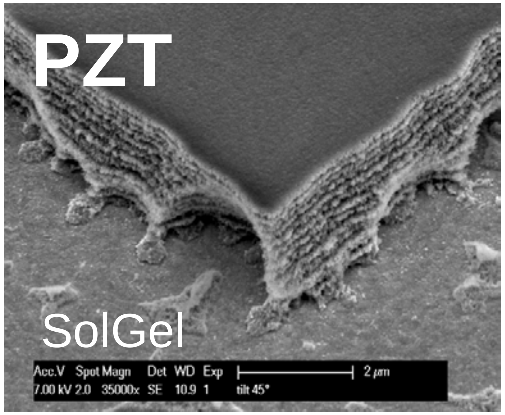



**IEDM 2009**: R. Elfrink et al., "First autonomous wireless sensor node powered by a vacuum-packaged piezoelectric MEMS energy harvester"

# PIEZOELECTRIC MATERIALS

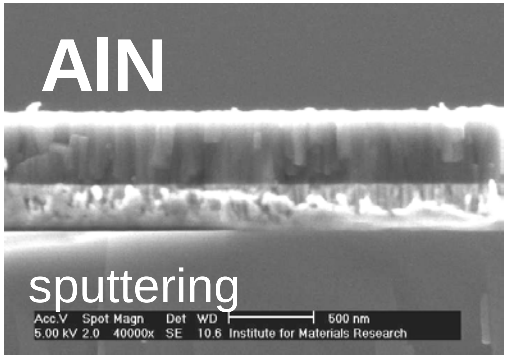
$$FOM = \frac{e_{31}^{2}}{\varepsilon_r}$$

$e_{31}$ ~ -8 -12 C/m$^2$
$e_r$ ~ 1000
tan d ~ 0.03 → high loss
Z ~ few kΩ → < 0.1 Volt




- not IC fab compatible
- SolGel
  - limited thickness
  - low reproducibility
  - no topography allowed
- Sputtering
  - low deposition rate
  - composition control

$e_{31}$ ~ -1.1 C/m$^2$
$e_r$ ~ 10
tan d ~ 0.003 → low loss
Z ~ few MΩ → few Volt

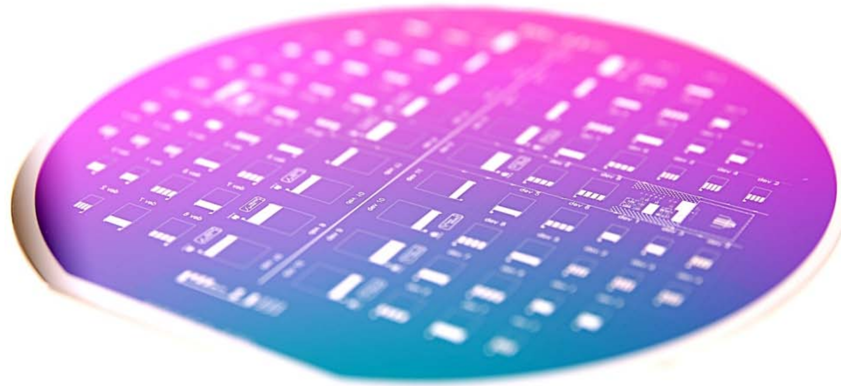


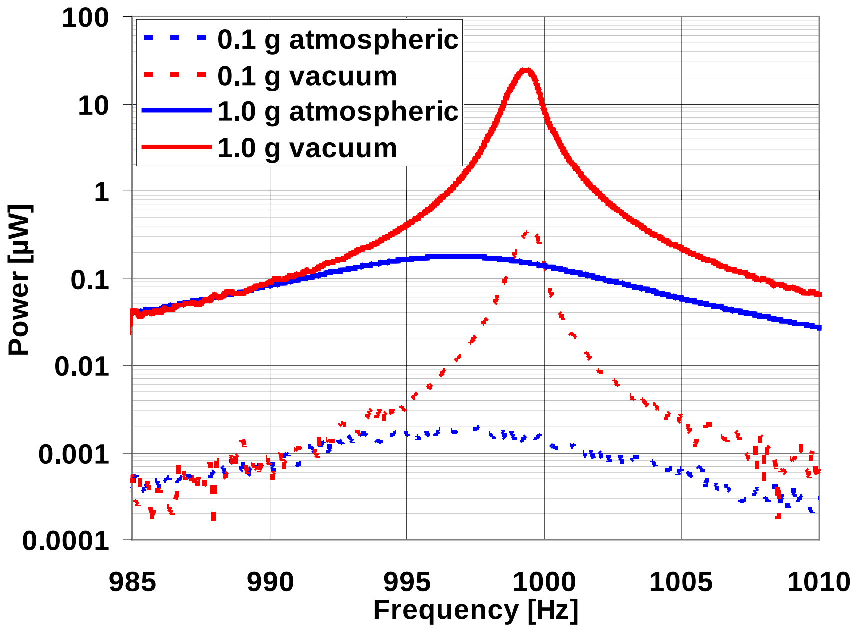

- IC fab compatible
- Sputtering
  - high deposition rate
  - stoichiometric

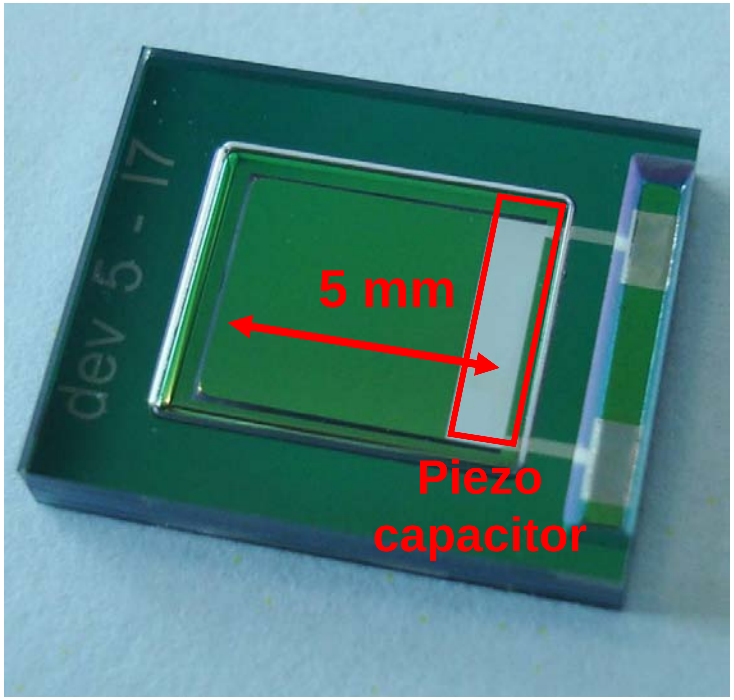
**Aluminum Nitride is good candidate for energy harvester**

# WAFER LEVEL PACKAGE

- SU-8 on rolling wheel
- wafer at elevated temperature (~80C)
- topography is no issue
- vacuum inside package



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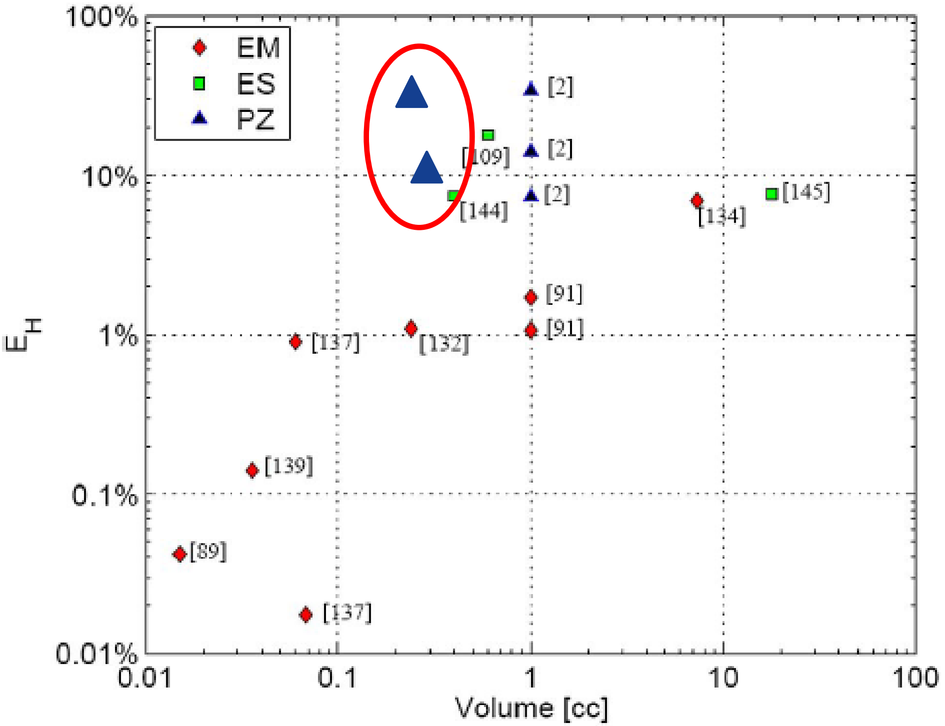
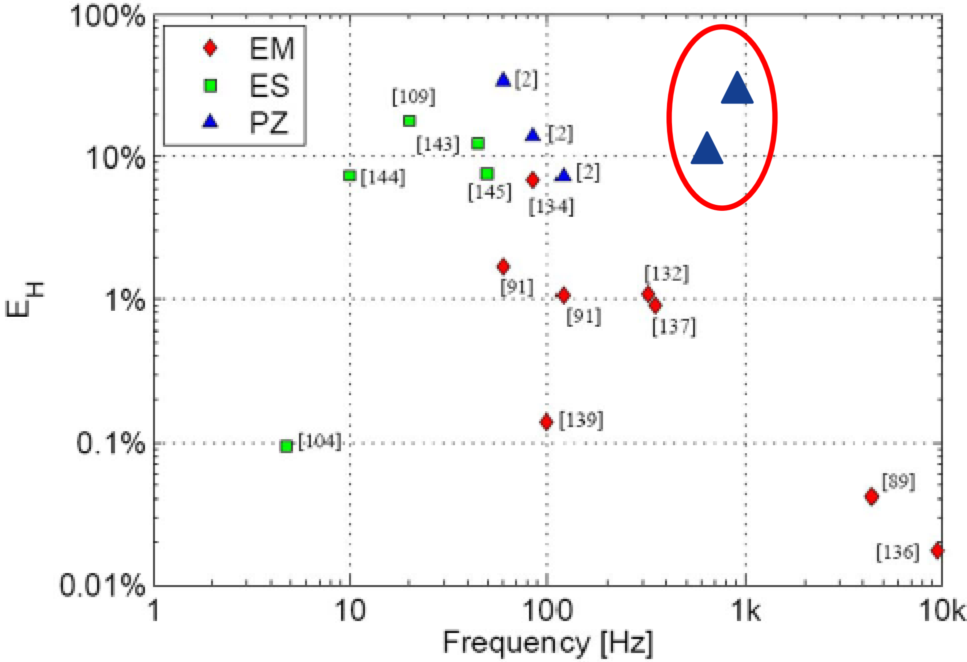
# HARVESTER EFFECTIVENESS OF REPORTED DEVICES

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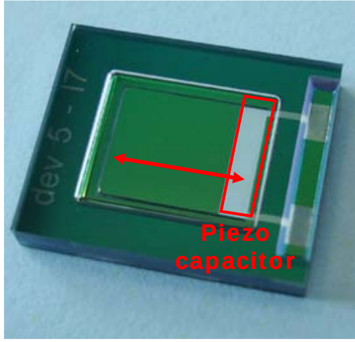
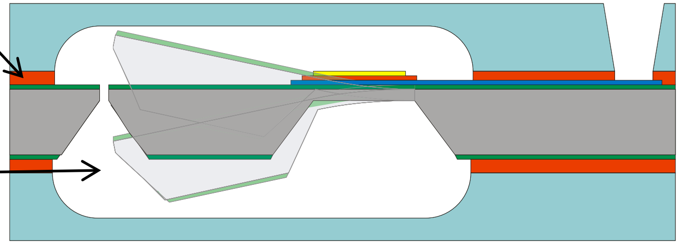
$$P_{norm} = \frac{P_{meas}}{P_{\max}} = E_H$$

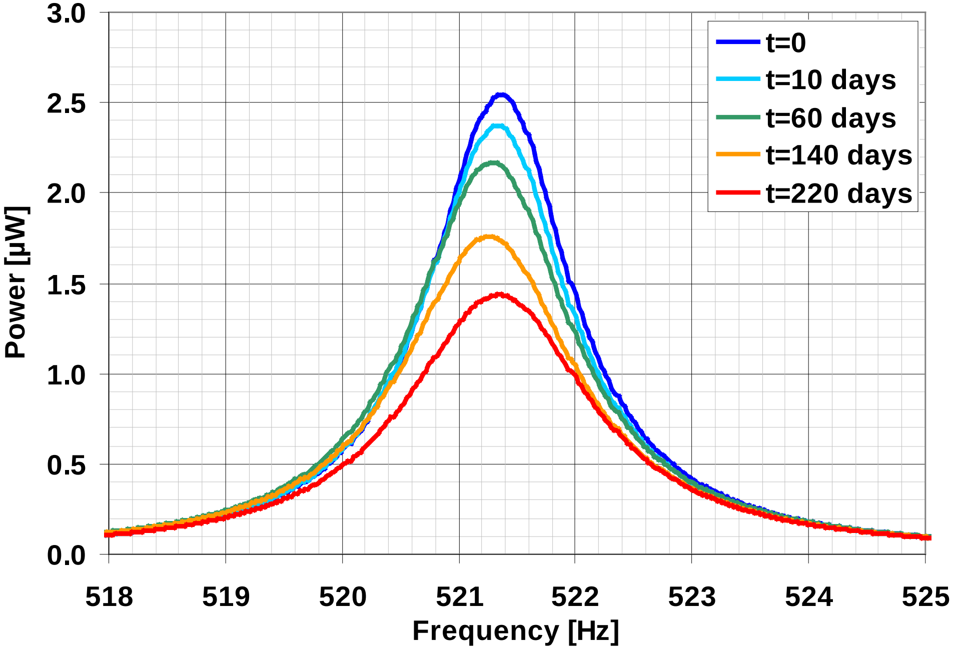
P.D. Mitcheson et al.; Proceedings of the IEEE, 96, No. 9, pp. 1 (2008)

# LEAKAGE OF WAFER LEVEL PACKAGE




- Reduction of power due to air leak into package
- ~50% power loss in half year time
- Hermetic wafer level package (long term vacuum to minimize air damping)
  - Improvements of polymer based bonding
  - extra (metal) barriers
  - extra cavity
  - molding layer
  - Eutectic bonding



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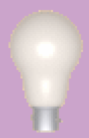

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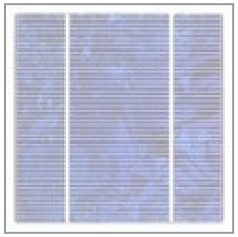

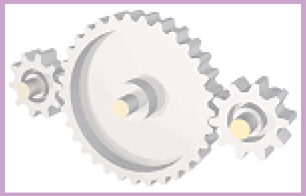

Vibration

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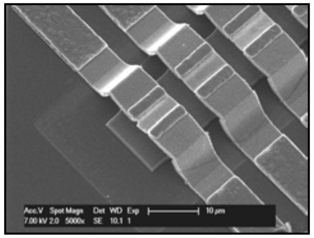

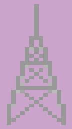

RF

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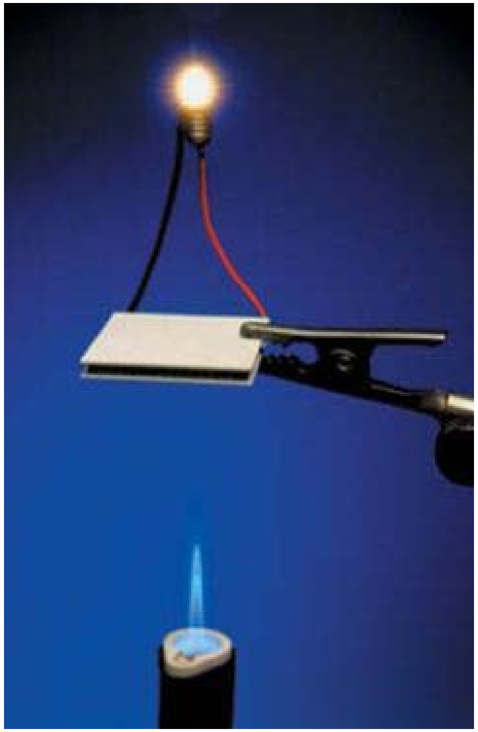
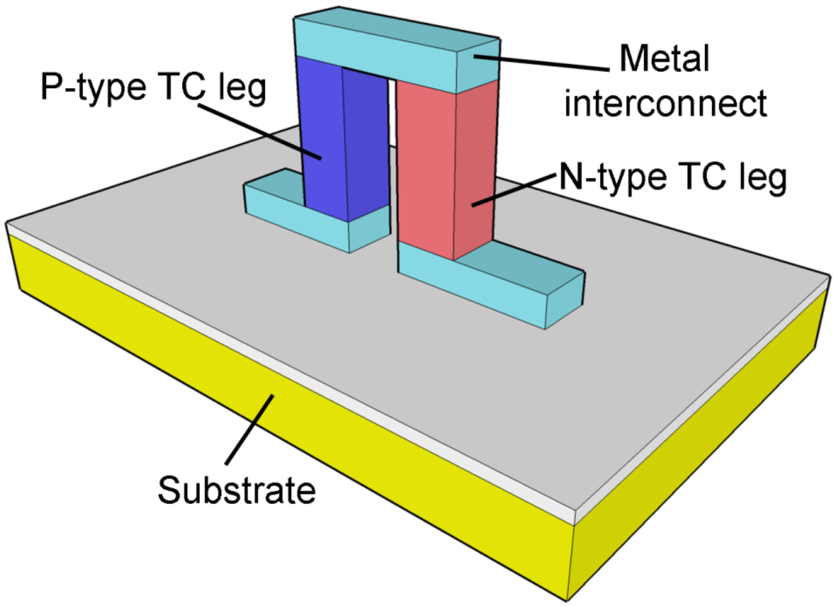
0.1 µW/cm$^2$
WiFi
0.01 µW/cm$^2$

# THERMO ELECTRIC ENERGY HARVESTING

## Seebeck effect (mechanism)



## Thermocouple structure

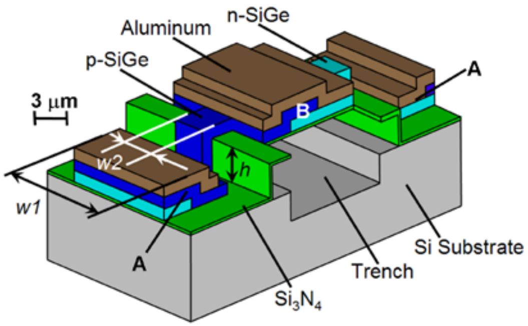



Seebeck effect: Voc = Seebeck * Δ T
Human body ΔT ~ 1-3 K

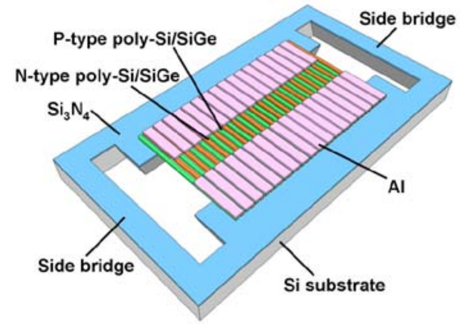
→ Voltage output typically few mV

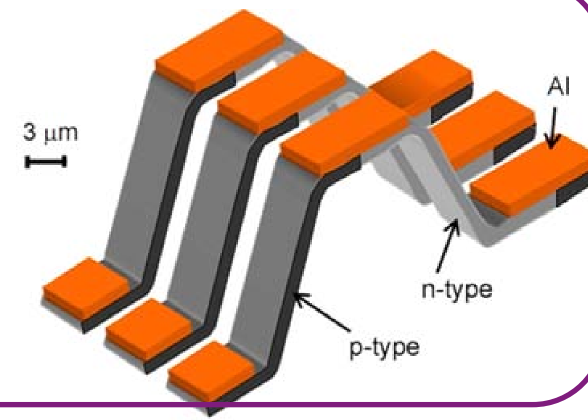
# MEMS BASED TEG ENERGY HARVESTERS; RESULTS

**Planar** | **In-plane** | **High-topography**




High-topography thermocouple



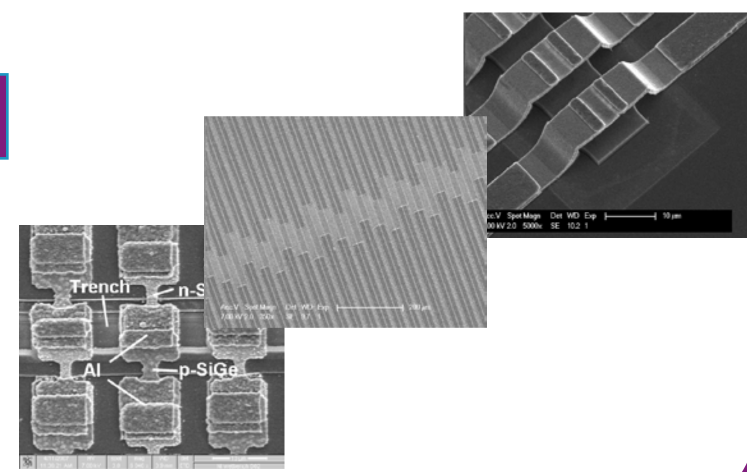




**World Record output voltage**

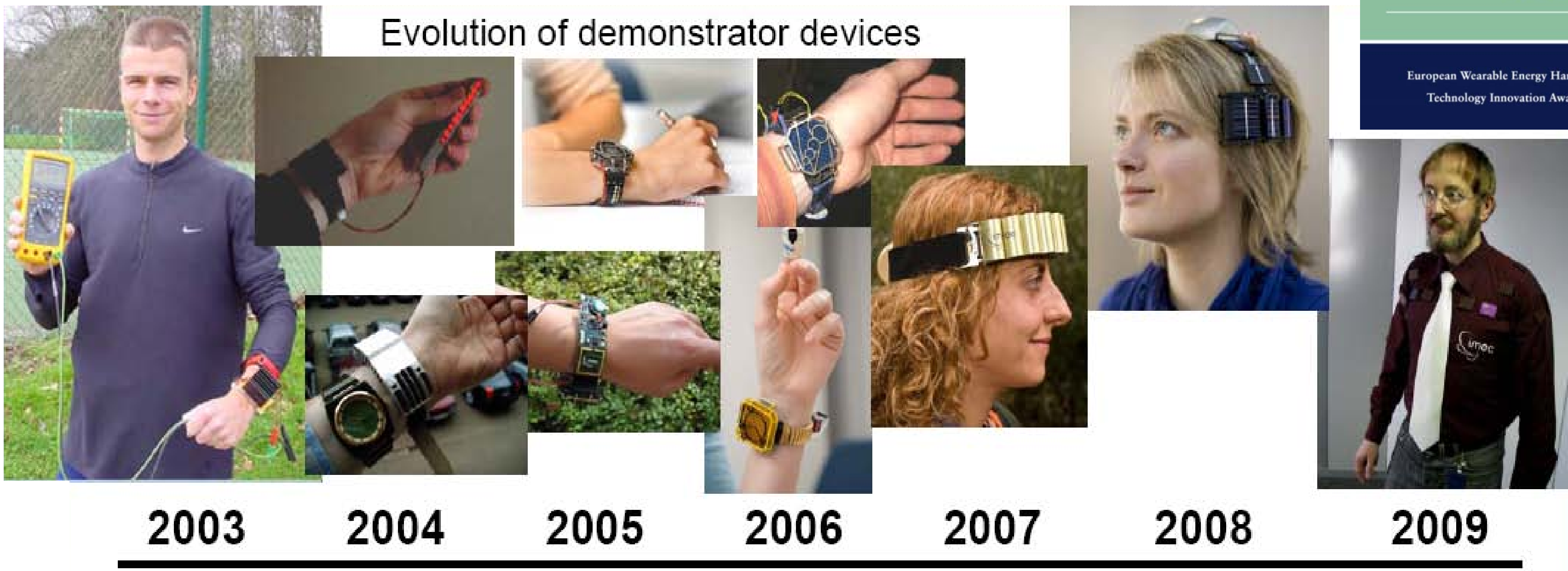
**Aiming for 1V/K**

**Experimental result**

- **2009** — High-topography 258 mV/K
- **2008** — In-plane 92 mV/K
- **2007** — Planar 250 mV/K

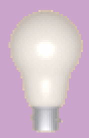


# HISTORY OF MICROPOWER DEMONSTRATORS

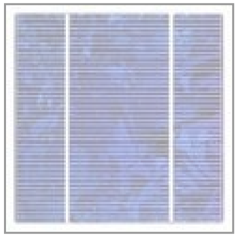

- show feasibility of WATS systems for body area networks
- use of off-the-shelf components
- supporting research by investigate limits
- Includes new technology and circuit designs developed by IMEC
- **Has resulted in Frost & Sullivan Award for ECG shirt**

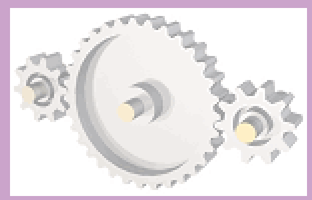
# Power levels “MEMS” based harvesters



Photovoltaic

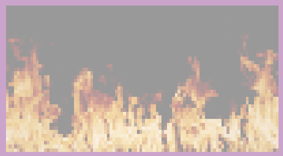
Outdoor
10 mW/cm$^2$
Indoor
10 μW/cm$^2$





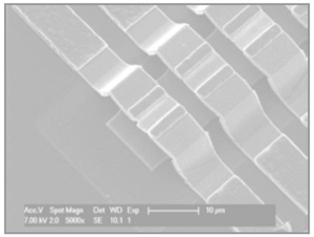
Vibration

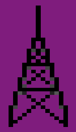
Man
4 uW/cm$^2$
Machine
100 μW/cm$^2$



Thermal

Man
20 μW/cm$^2$
Machine
1-10 mW/cm$^2$





RF

GSM
0.1 μW/cm$^2$
WiFi
0.01 μW/cm$^2$

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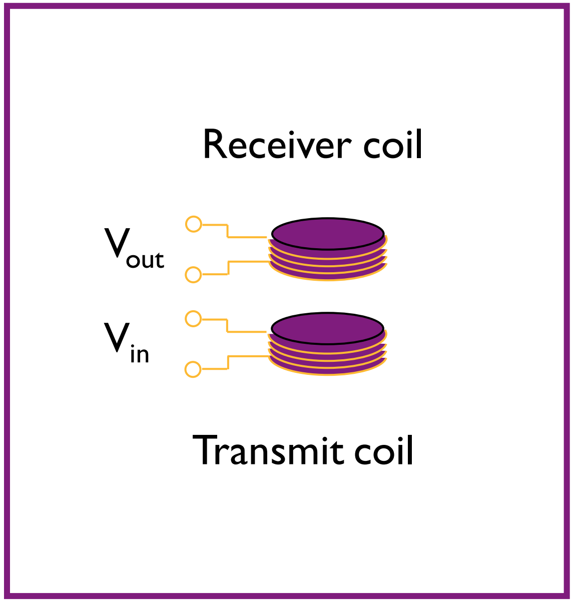
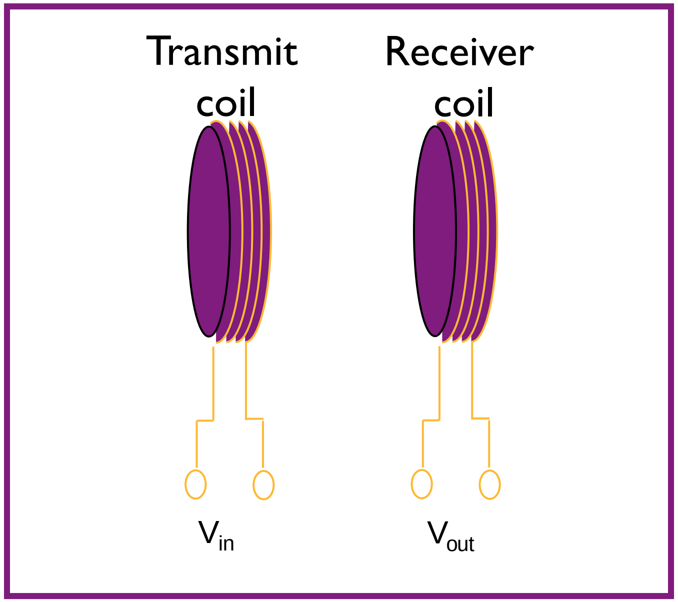
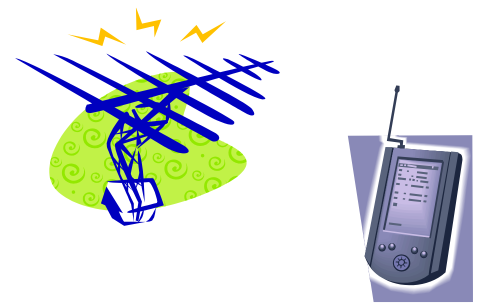
# RF ENERGY TRANSFER INSTEAD : THREE MECHANISMS



•Inductive coupling
•Close contact

•Non-radiative coupling
•Intermediate distances

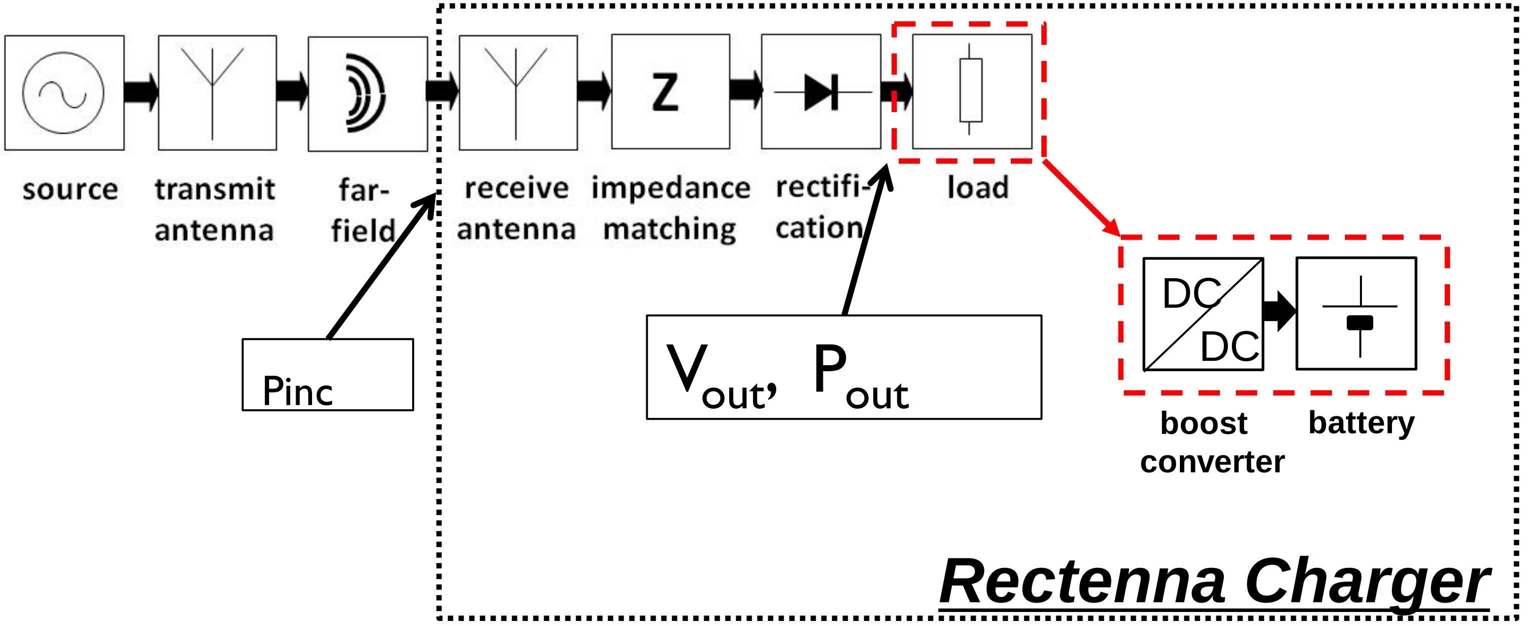
•Radiative Coupling
•Large distances

*Power transfer: Friis equation*
*$\lambda$: Wavelength used*
*$G_r$, $G_T$: Antenna Gain*
*$P_T P_R$; Power transmitted, received*

$$P_{inc} = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 r^2}$$

imec

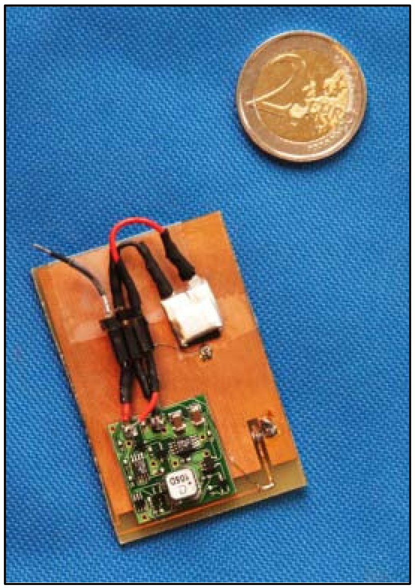
# RF BATTERY CHARGING

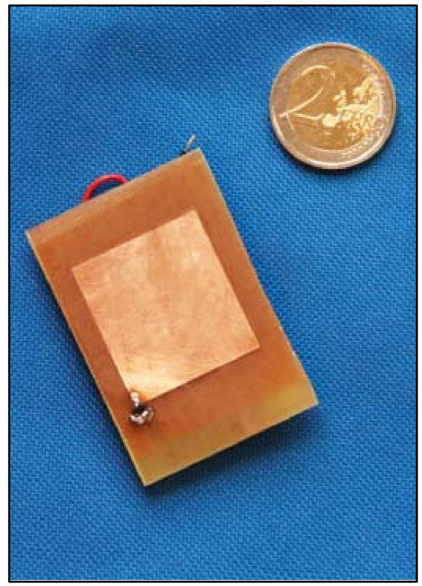


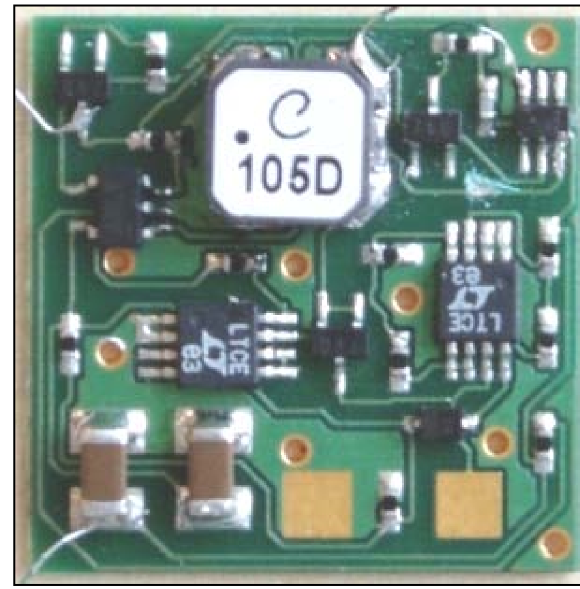

For use in WSN, battery needs to be recharged:
Minumum voltage is needed for IC = 0.2V
→ Vout determines distance
→ Pinc determines charging time

# SMALL-SIZE RECTENNA APPLICATIONS

## RF Battery charging





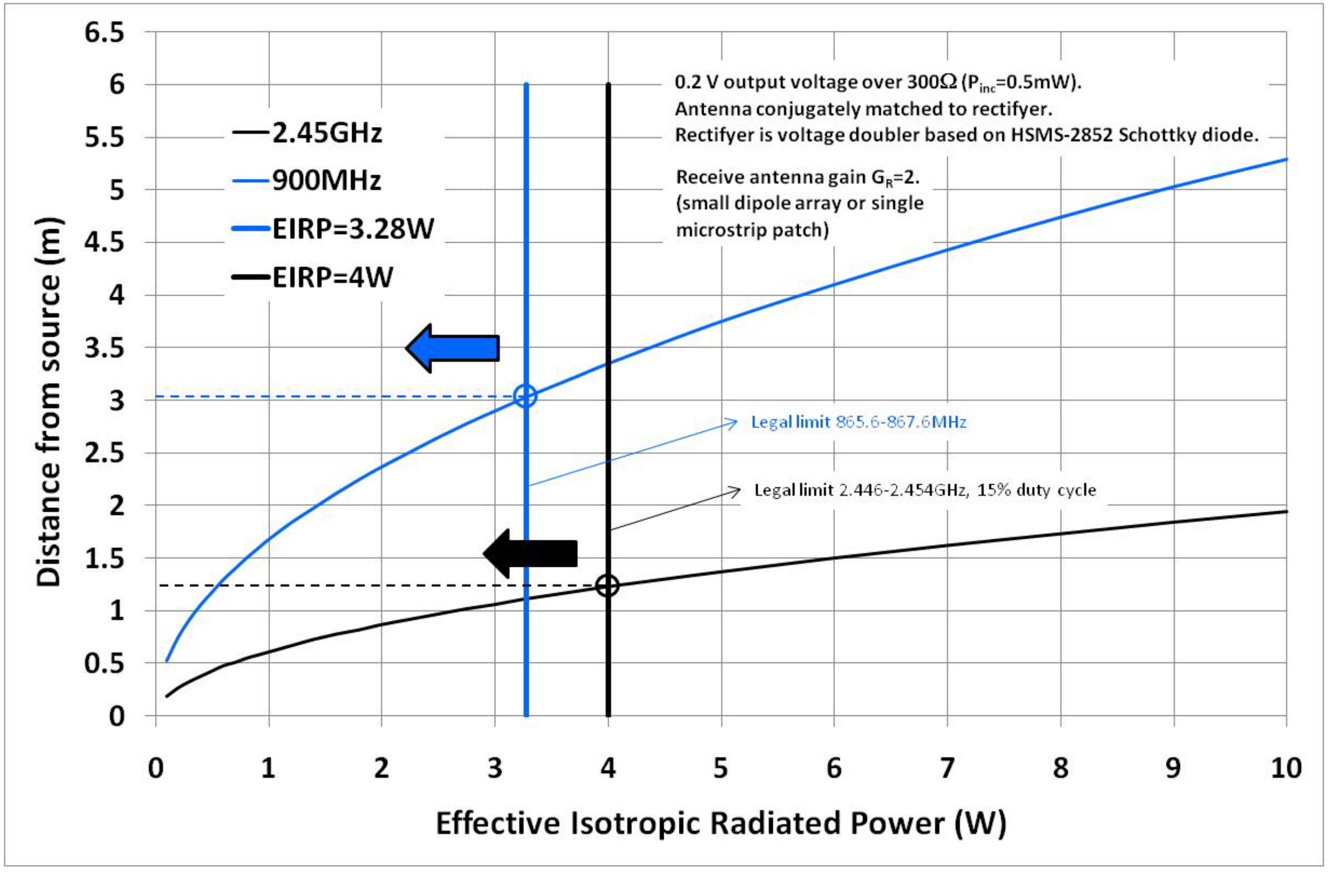



Charging 4.2V Li-Ion battery at 60 cm with EIRP=1.2W at 2.45GHz

Charging 2.9V Li-Ion battery at 166 cm with EIRP=1.2W at 2.45GHz

# Buck-boost converter
# $V_{in\text{-}min}$=0.21V, $V_{out}$=3.0-4.2V

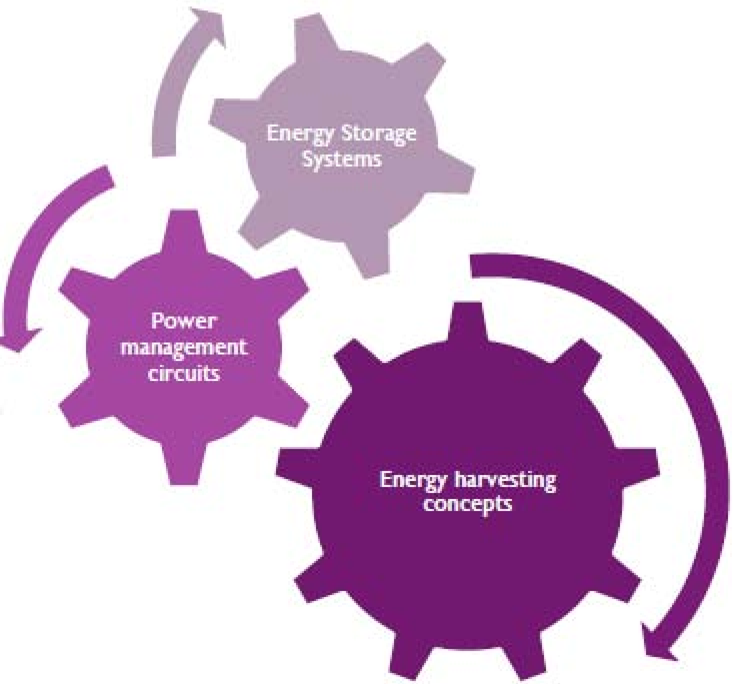
## Theoretical distances for single-cell rectennas




**More cells is larger distance**

# SUMMARY

- For autonomous wireless sensor system one needs:
  - Small low cost energy harvester
  - Power optimization of complete sensor system
  - Harvester + power management + energy storage




- MEMS technology
  - Capable of $100\mu W/cm^2$
  - Key for mass application
- Still in research phase
  - Higher power output needed
  - Reliability and robustness

**IMEC SMART SYSTEMS**
Building a flexible interactive world

# THANK YOU FOR YOUR ATTENTION.