# Energy harvesting & storage

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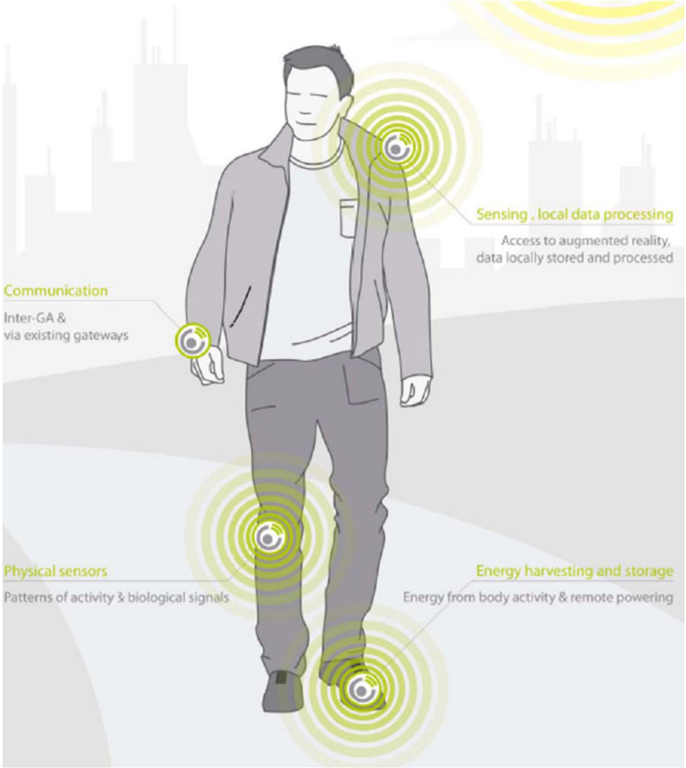
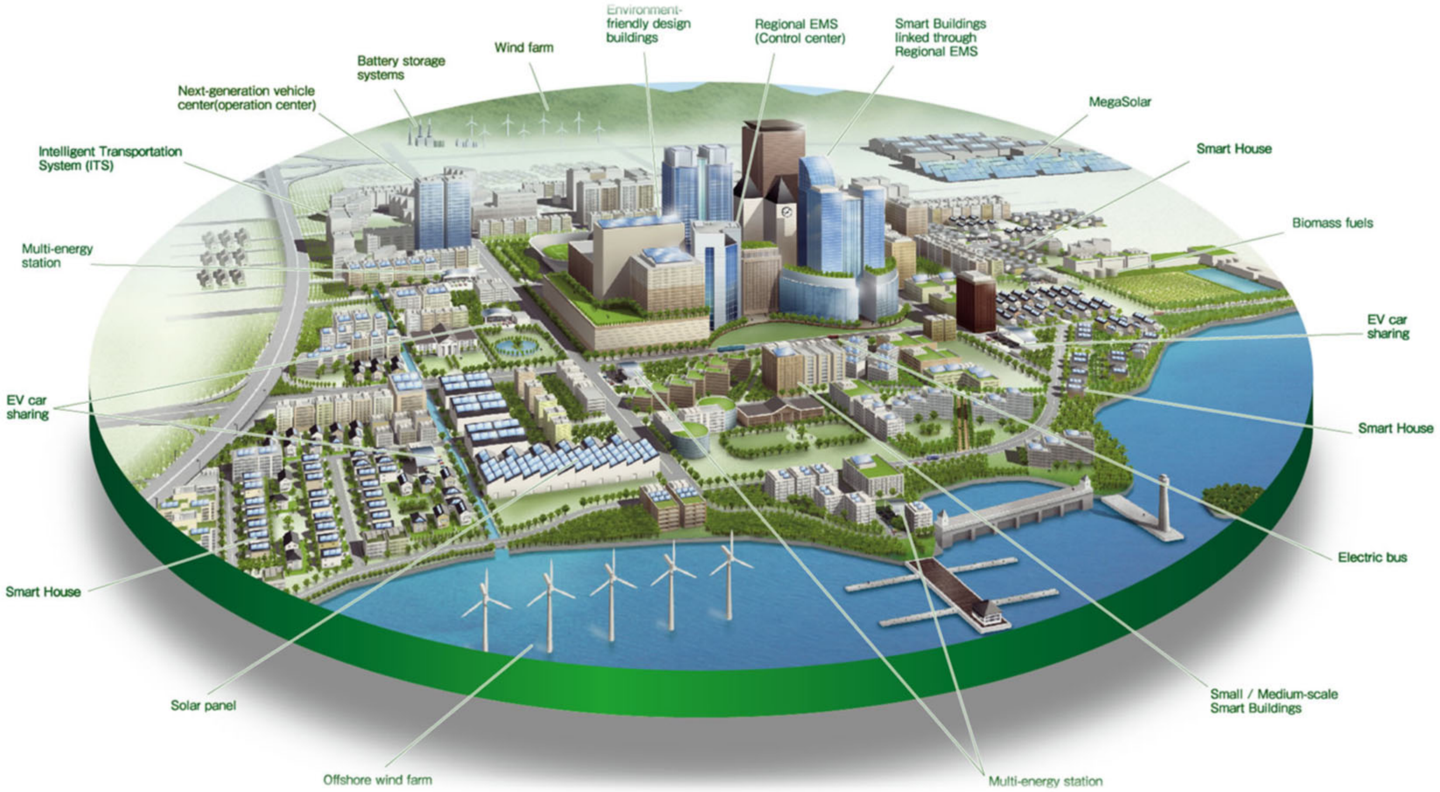
# Outline

- Energy efficient technologies for wearables and IoT
- Energy scavenging:
    - from light
    - from vibrations
    - thermoelectrical generators
- Energy storage: supercapacitors
- Roadmaps



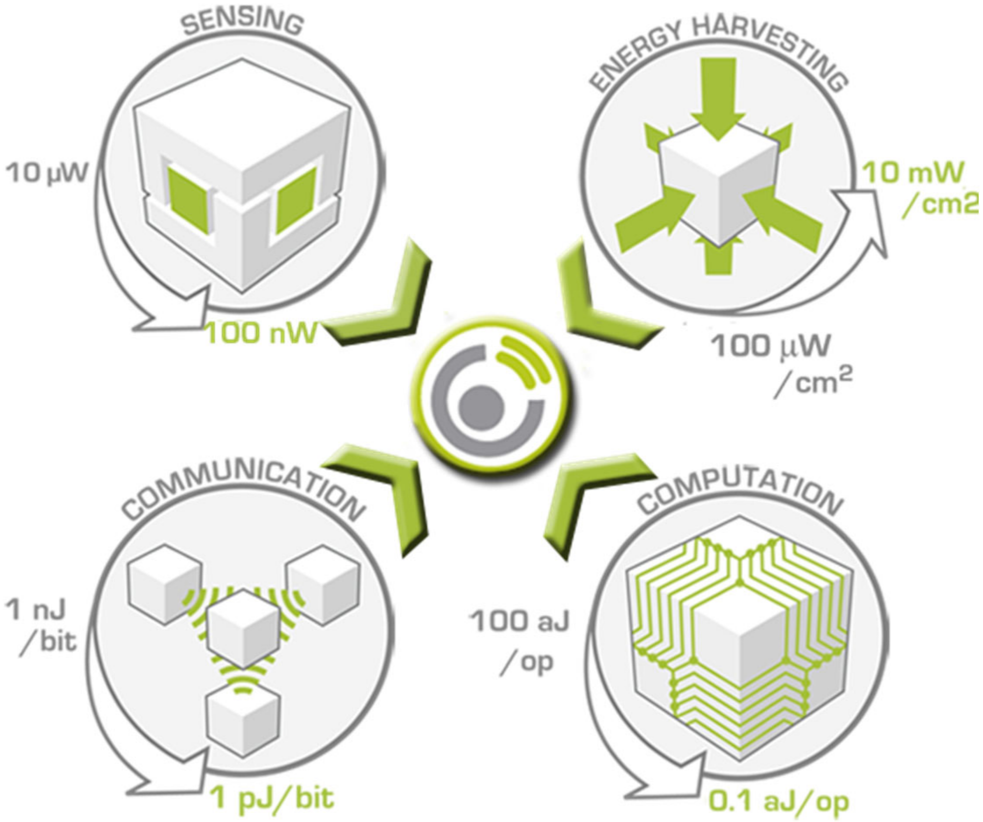
# Autonomous Smart Systems

Form the next Exponential Technology for Internet of  Things (IoT)and a Smarter Life!



# What is Zero-Power?

Zero-Power technology = Autonomous Smart Systems

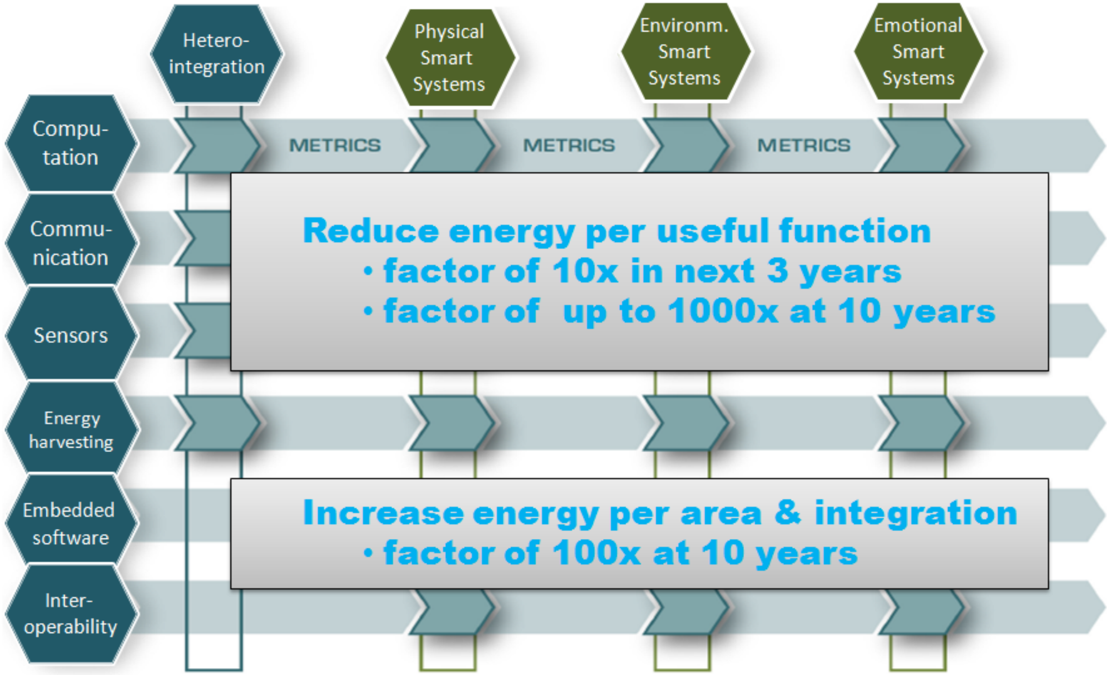


- x 1000 more energy efficient bit computation
- x 1000 more energy efficient bit transmission
- x 100 more efficient energy harvesting

# Key enabling technologies

- Low power sensors
- Low power wireless communications
- Low power computing
- Energy scavenging, storage, management
- Heterogeneous integration
- Interoperability

Multi-parametric sensing with adaptable form factor, weight, autonomy (energy)!



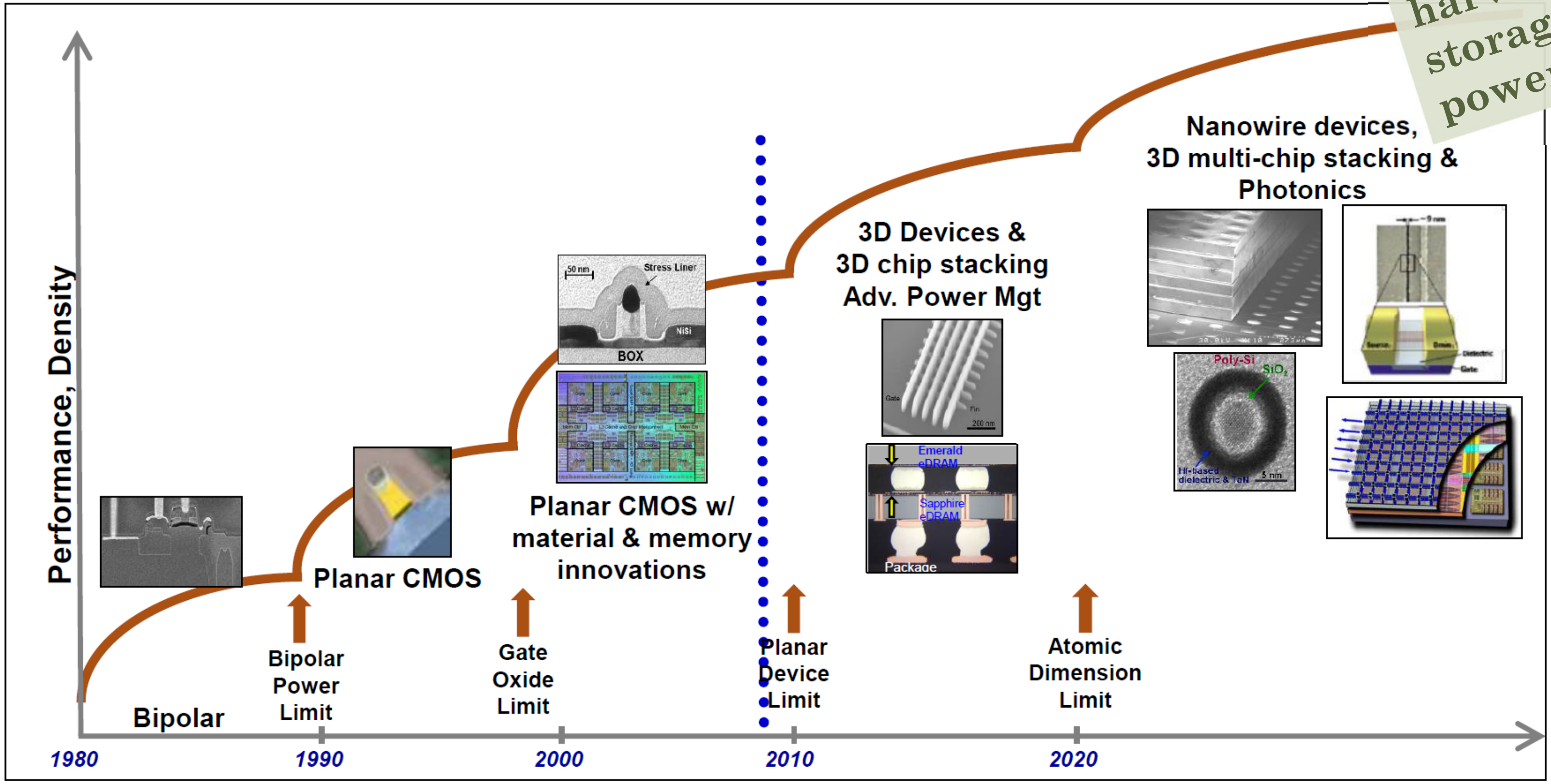
**Reduce energy per useful function**
- **factor of 10x in next 3 years**
- **factor of up to 1000x at 10 years**

**Increase energy per area & integration**
- **factor of 100x at 10 years**

# Si Technology goes 3D

- Major technology innovations “saturate” after about a decade
- “Disruptive” Innovations will enable the next decades of progress
- Design and Technology Co-Optimization key to coming Innovations

Integrated energy harvesting and storage: self-powered chips



Bipolar

Bipolar Power Limit

Planar CMOS

Gate Oxide Limit

Planar CMOS w/ material & memory innovations

Planar Device Limit

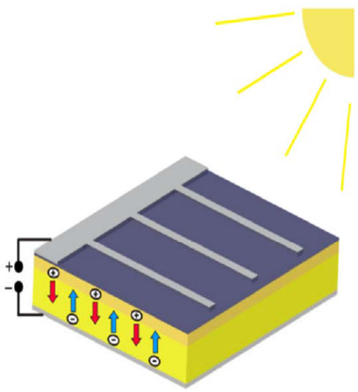
3D Devices & 3D chip stacking Adv. Power Mgt

Atomic Dimension Limit

Nanowire devices, 3D multi-chip stacking & Photonics

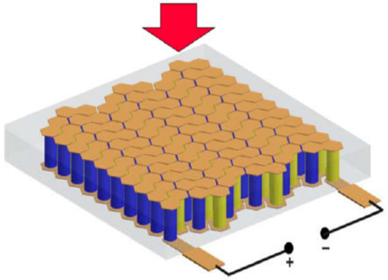
# Types of energy harvesting

**Solar Energy**



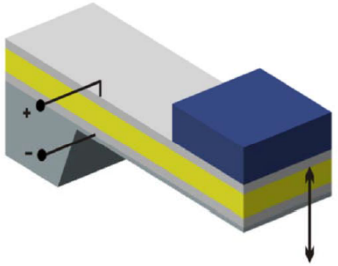
Photovoltaic Cells

**Thermal Energy**



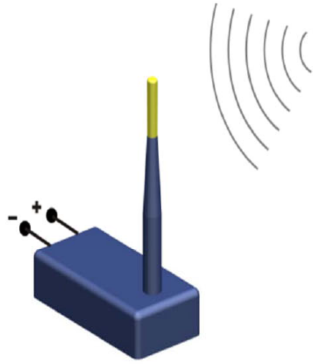
Thermoelectric Generators

**Vibration Energy**



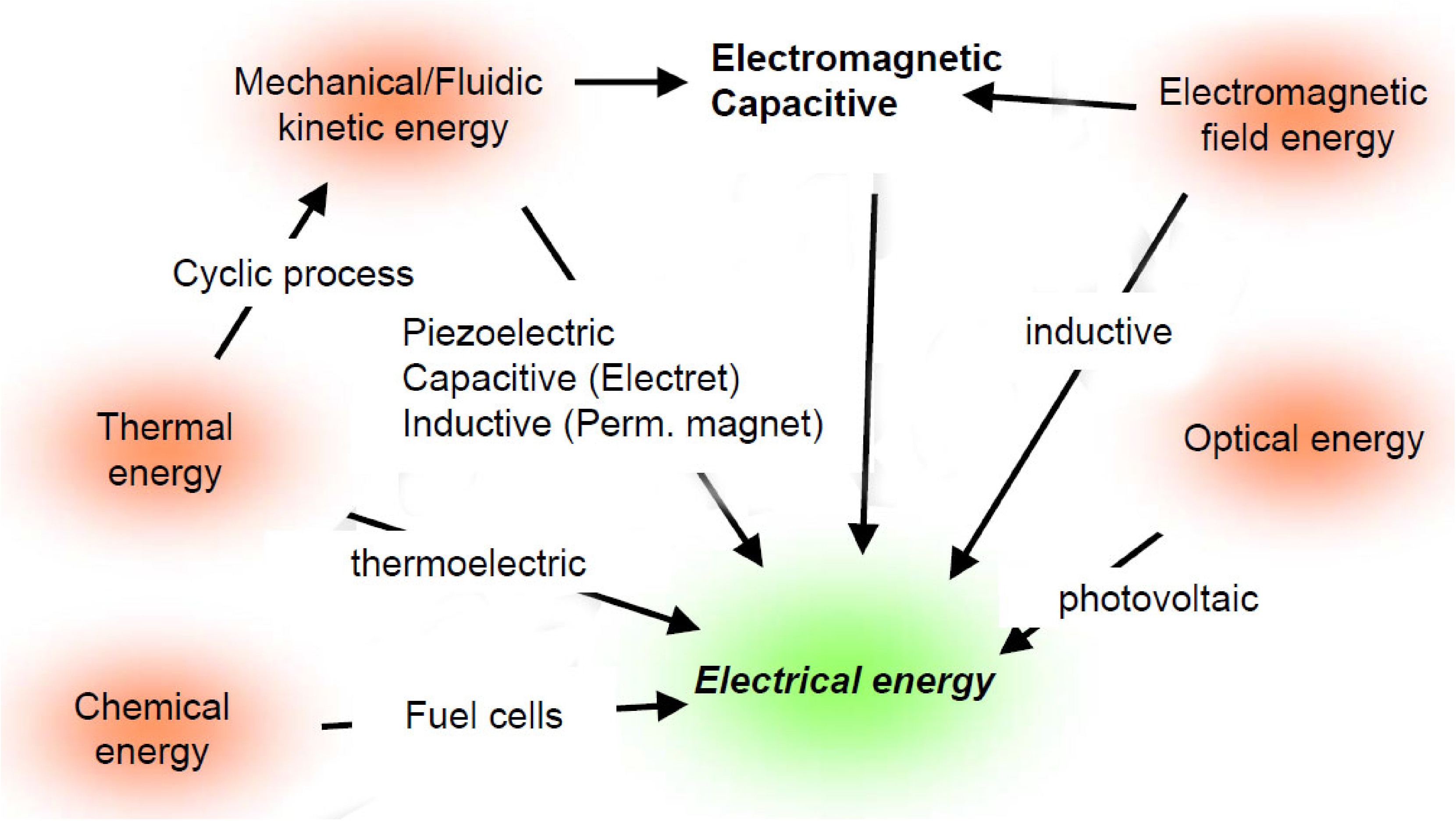
Piezoelectric
Electromagnetic
Electrostatic
Generators

**RF Energy**



Electromagnetic Generators

# Mechanisms of coversion to electrical energy



# Short Overview

## Micropower energy harvesting

R.J.M. Vullers [a,*], R. van Schaijk [a], I. Doms [b], C. Van Hoof [a,b], R. Mertens [b]

[a] IMEC/Holst Centre, High Tech Campus 31, 5656 AE Eindhoven, The Netherlands
[b] IMEC, Kapeldreef 75, 3001 Leuven, Belgium

Solid-State Electronics 53 (2009) 684–693

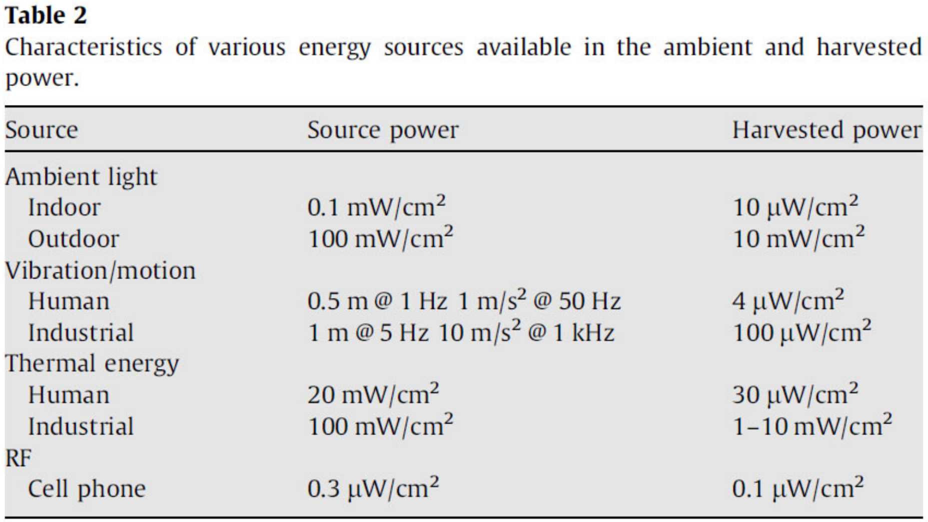


**Table 2**
Characteristics of various energy sources available in the ambient and harvested power.

| Source | Source power | Harvested power |
|---|---|---|
| Ambient light | | |
| Indoor | 0.1 mW/cm$^2$ | 10 µW/cm$^2$ |
| Outdoor | 100 mW/cm$^2$ | 10 mW/cm$^2$ |
| Vibration/motion | | |
| Human | 0.5 m @ 1 Hz 1 m/s$^2$ @ 50 Hz | 4 µW/cm$^2$ |
| Industrial | 1 m @ 5 Hz 10 m/s$^2$ @ 1 kHz | 100 µW/cm$^2$ |
| Thermal energy | | |
| Human | 20 mW/cm$^2$ | 30 µW/cm$^2$ |
| Industrial | 100 mW/cm$^2$ | 1–10 mW/cm$^2$ |
| RF | | |
| Cell phone | 0.3 µW/cm$^2$ | 0.1 µW/cm$^2$ |

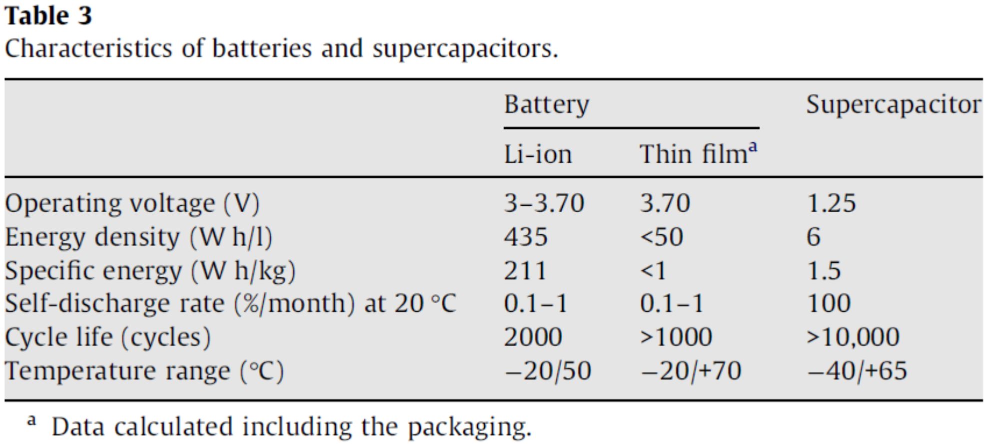


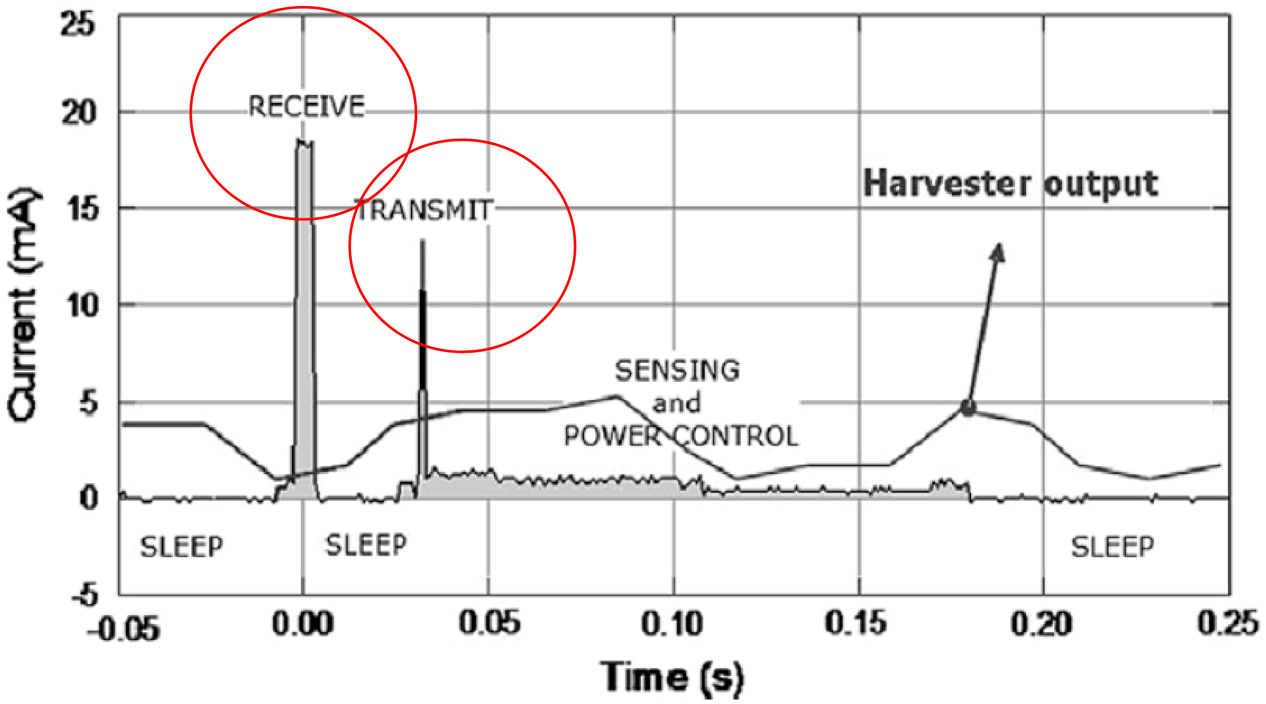
**Table 3**
Characteristics of batteries and supercapacitors.

| | Battery | | Supercapacitor |
|---|---|---|---|
| | Li-ion | Thin film[a] | |
| Operating voltage (V) | 3–3.70 | 3.70 | 1.25 |
| Energy density (W h/l) | 435 | <50 | 6 |
| Specific energy (W h/kg) | 211 | <1 | 1.5 |
| Self-discharge rate (%/month) at 20 °C | 0.1–1 | 0.1–1 | 100 |
| Cycle life (cycles) | 2000 | >1000 | >10,000 |
| Temperature range (°C) | −20/50 | −20/+70 | −40/+65 |

[a] Data calculated including the packaging.

# Scenario 1: energy harvesting by WSN

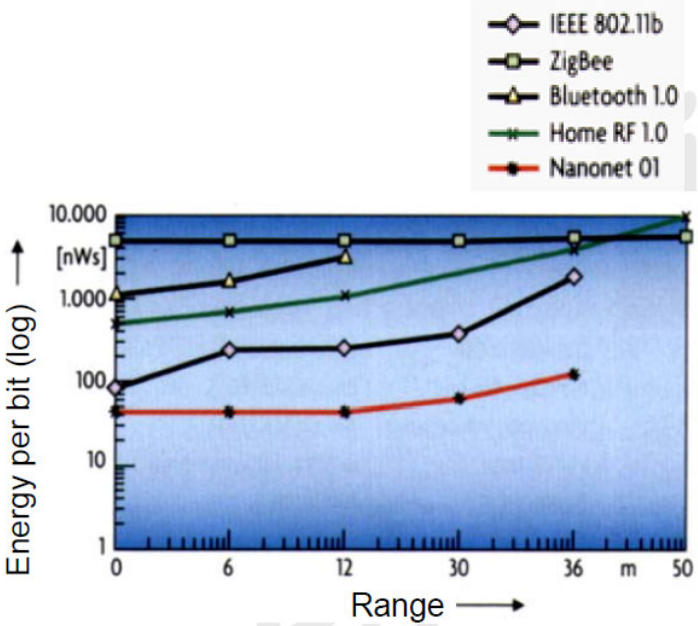
Peaks of ‘receive’ and ‘transmit’ cannot be supplied just by the harvester, even if the average energy consumption is very low. Need: **a hybrid energy management strategy**.

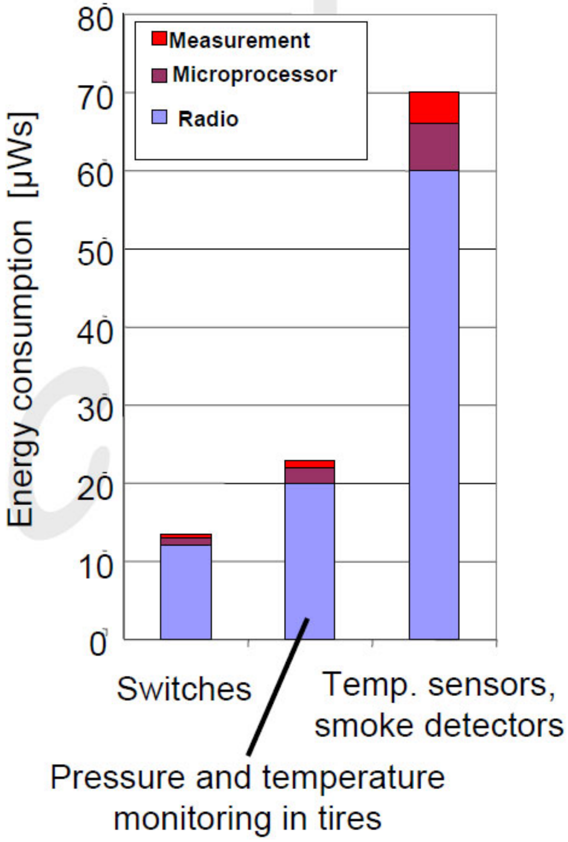


# Where the energy goes?

## Who is consumming so much? The communication links!

*Energy consumption per bit for various radio transmission standards (W. Haecker, Elektronik 22/2002, p. 48)*

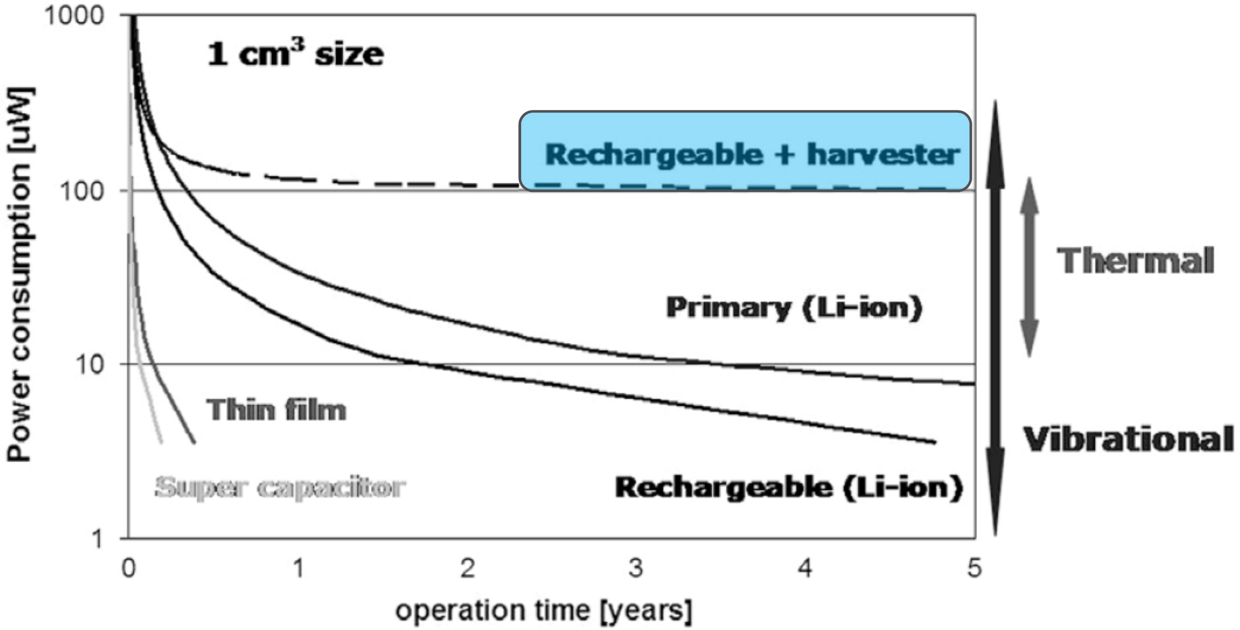




*Fraction of the various functionalities from the energy consumption of a microsystem (F. Schmid, EnOcean, 2003)*

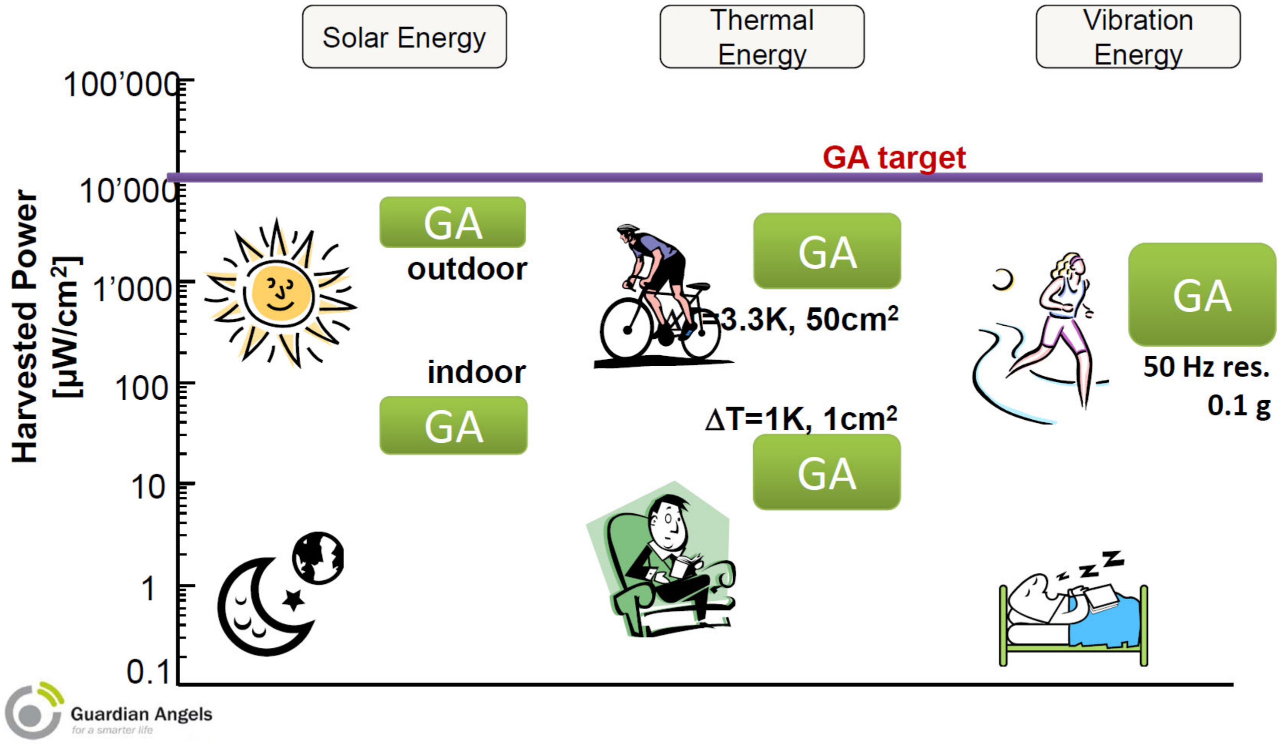
# Scenario 2: energy harvesting + rechargeable batteries

- A more reallistic solution: rechargeable battery + harvester.
- Battery lifetime and operation extended to months or years for 100microWatts sensor nodes.



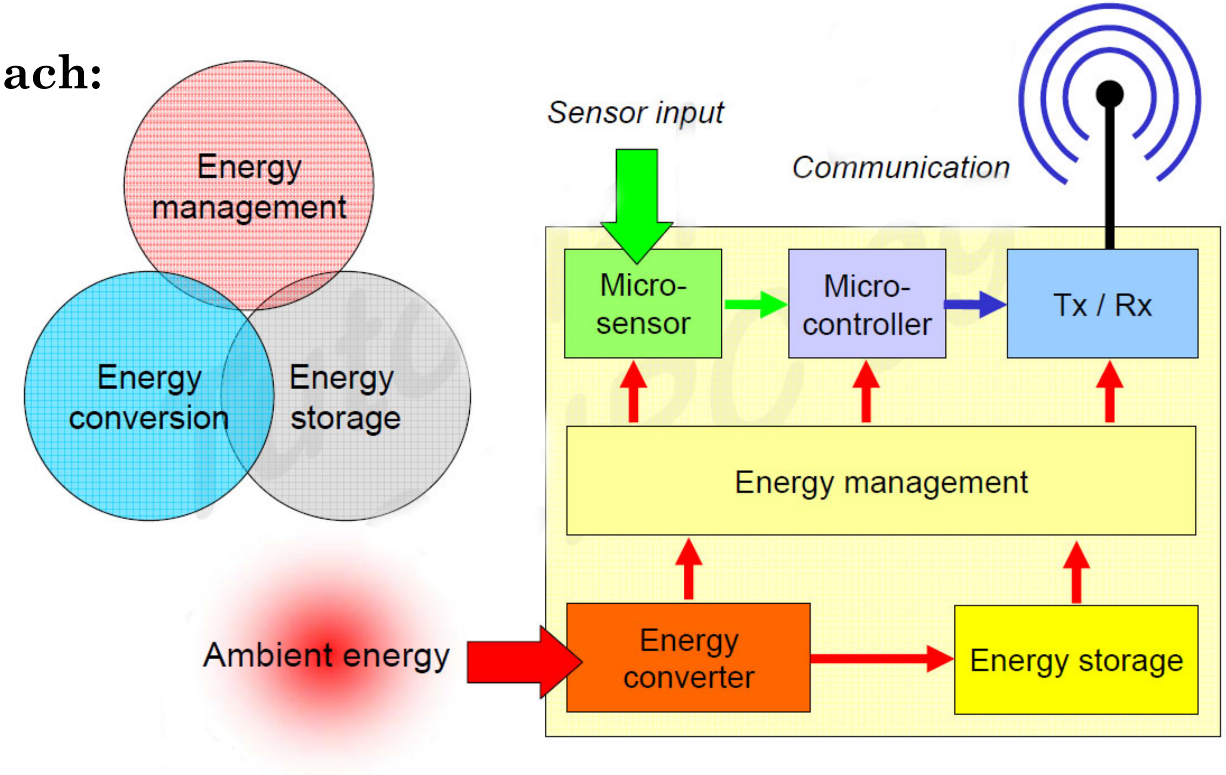
# Energy harvesting

- Challenge: continuous operation under dynamic conditions.
- Choose multi-harvesting interfaces, storage and form factors according to applications – **NO SINGLE UNIVERSAL SOLUTION AVAILABLE!**



# Energy scavenging is a system level problem!

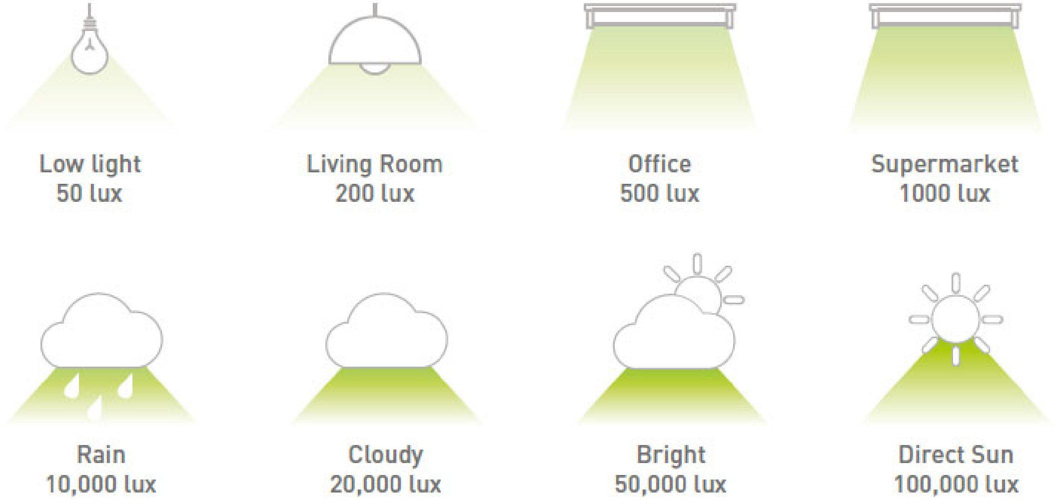
- **Complete and correct approach:**
  - **Energy conversion**
  - **Energy storage**
  - **Energy management**



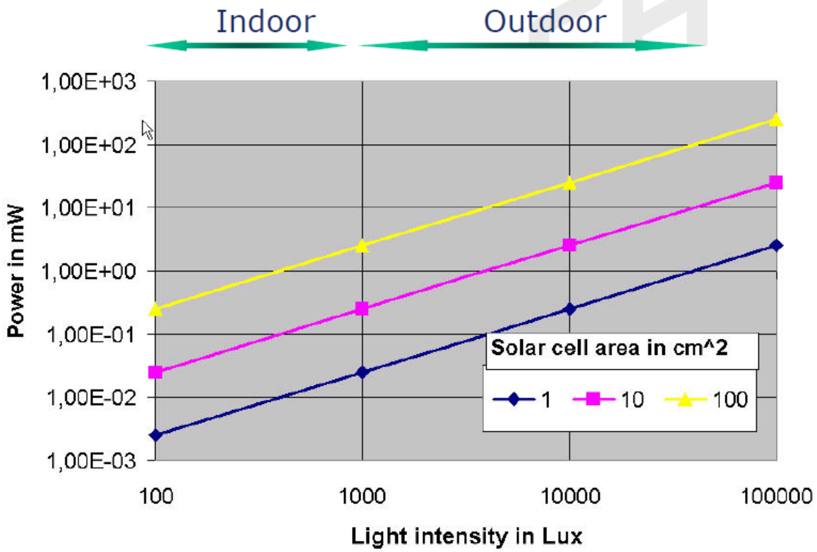
Source: prof. Manoli, IMTEK, Tutorial ESSCIRC 2009.

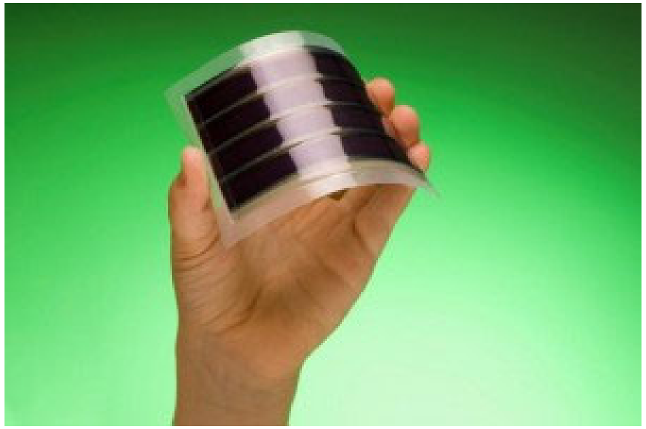
# Energy scavenging from light

**Challenge:**
**Indoor versus Outdoor!**
**Flexible solar cells:**
indoor Dye Sensitized Solar Cells (DSSC) that are flexible and boast superior low light performance (Gcell).

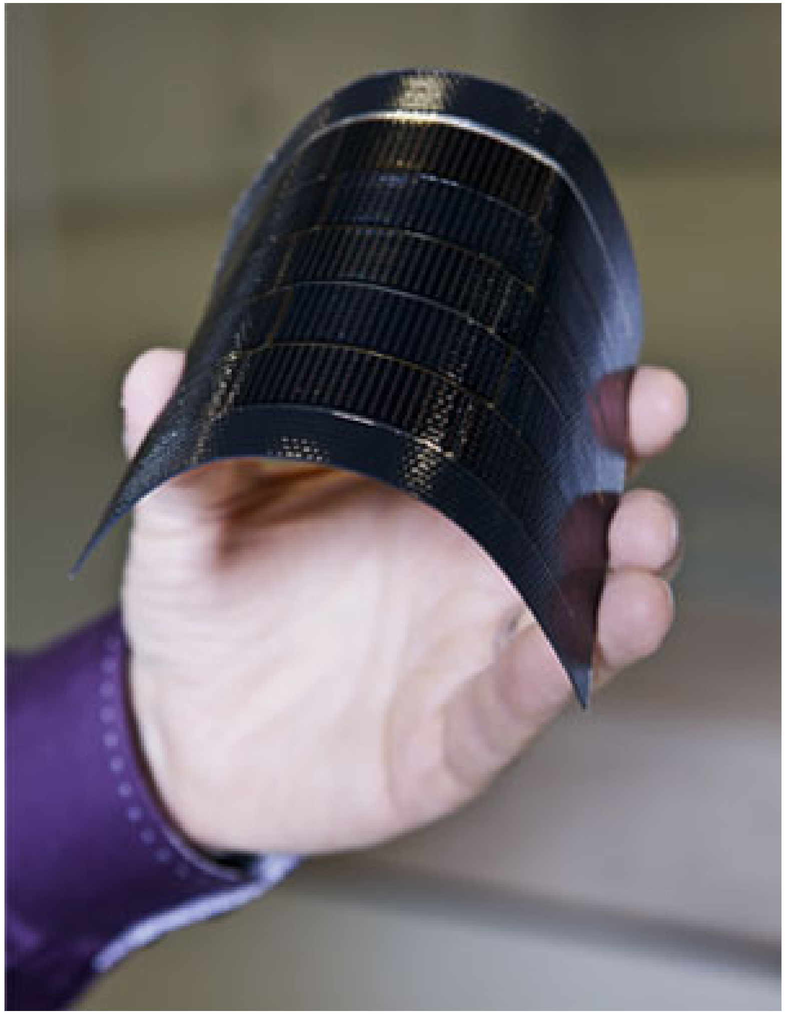


**Classical thin film cell**

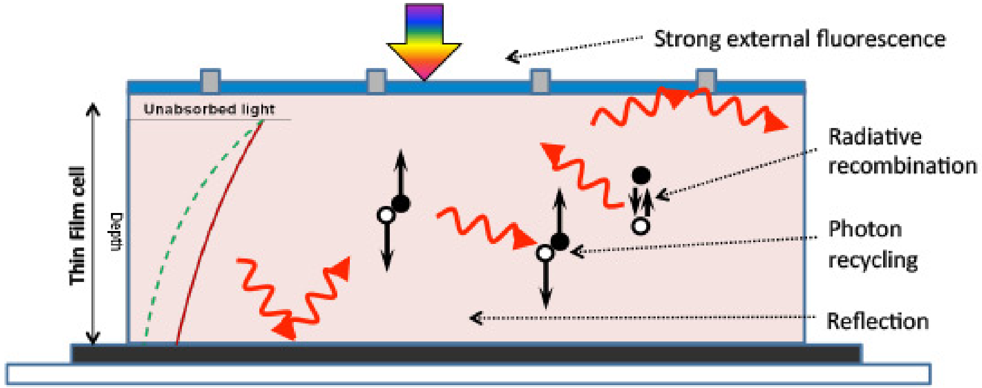




# Alta’s flexible solar cell

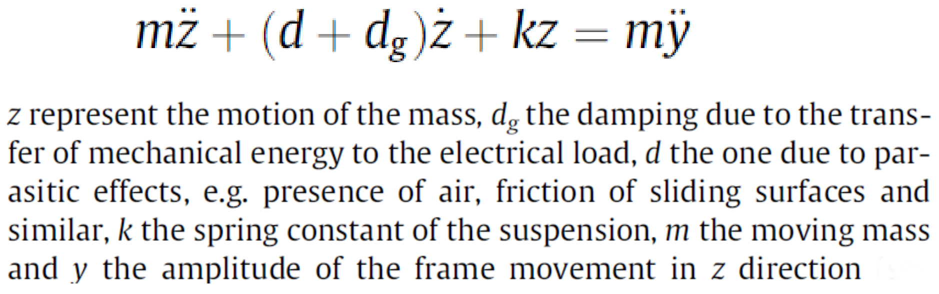


- Yablonovitch’s technique of “epitaxial liftoff,” which uses acids to precisely separate thin films of gallium arsenide (GaAS) from the wafers on which they are grown:
- Direct band gap material +observed phenomenon called “Photon Recycling”. Photons bounce off the back of the solar cell which allows them to be recaptured by the material and converted to electricity
- Alta Devices broke three world records: single junction cell performance at 28.8%, single junction module performance at 24.1%, and dual junction cell performance at 30.8%



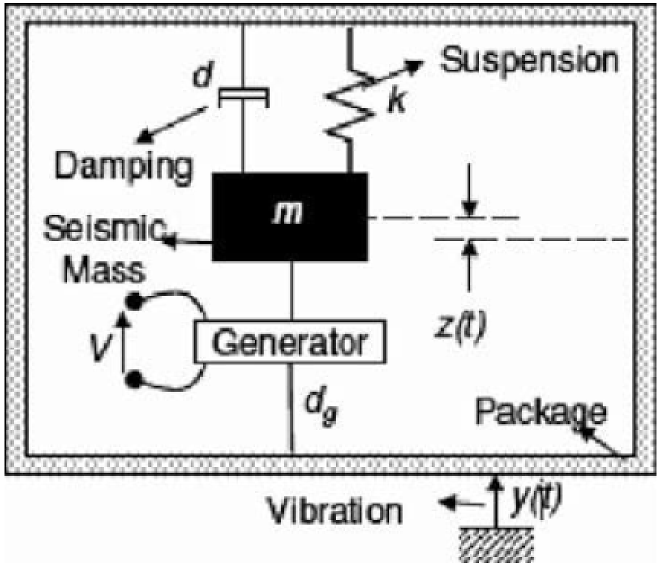
# Energy scavenging from vibrations

- Resonant vibration harvesters are by far the most widely investigated
- Resonant harvesters can be treated as a velocity damped mass spring system:



$$m\ddot{z} + (d + d_g)\dot{z} + kz = m\ddot{y}$$

$z$ represent the motion of the mass, $d_g$ the damping due to the transfer of mechanical energy to the electrical load, $d$ the one due to parasitic effects, e.g. presence of air, friction of sliding surfaces and similar, $k$ the spring constant of the suspension, $m$ the moving mass and $y$ the amplitude of the frame movement in $z$ direction

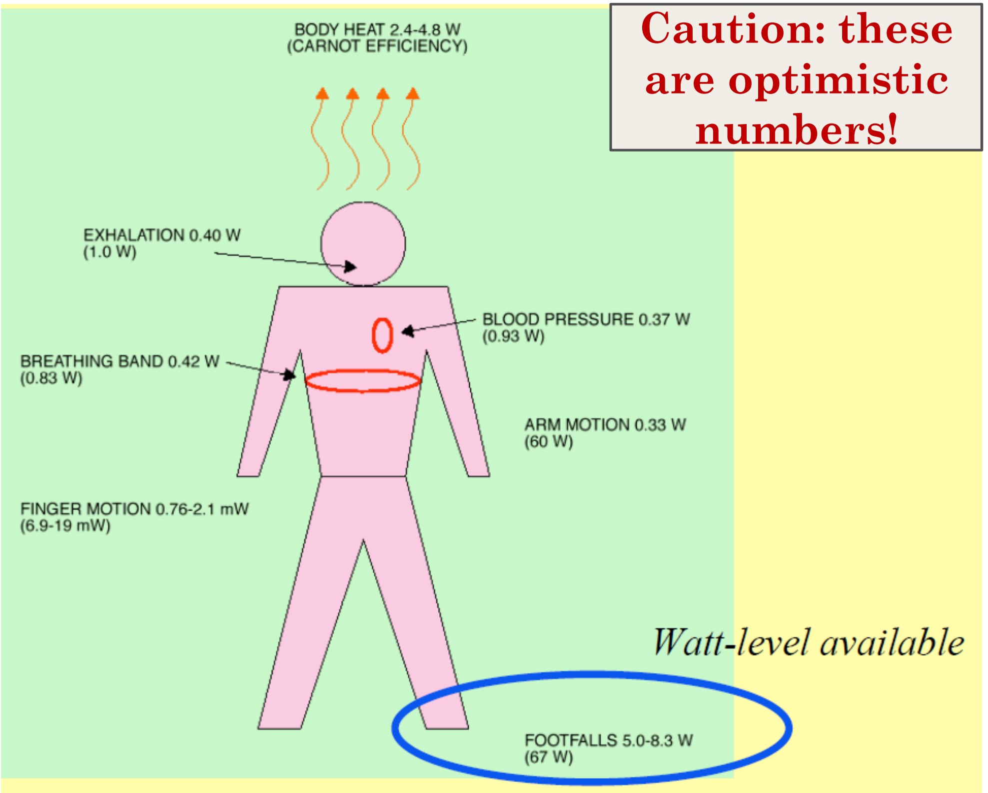


**Challenges:**
- **Frequencies not exactly known!**
- **Amplitudes?**
- **We need 100's of microWatts**
- **Efficient for large masses**
- **Good for automotive and for sport applications.**

# Motion harvesting: human energy >100’s W

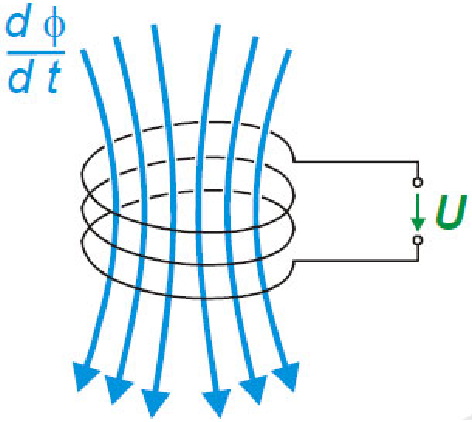
| *Activity* | *Kilocal/hr* | *Watts* |
|---|---|---|
| sleeping | 70 | 81 |
| lying quietly | 80 | 93 |
| sitting | 100 | 116 |
| standing at ease | 110 | 128 |
| conversation | 110 | 128 |
| eating meal | 110 | 128 |
| strolling | 140 | 163 |
| driving car | 140 | 163 |
| playing violin or piano | 140 | 163 |
| housekeeping | 150 | 175 |
| carpentry | 230 | 268 |
| hiking, 4 mph | 350 | 407 |
| swimming | 500 | 582 |
| mountain climbing | 600 | 698 |
| long distance run | 900 | 1,048 |
| sprinting | 1,400 | 1,630 |

**Where to tap the power?**



Caution: these are optimistic numbers!

# Electromagnetic harvesting (by movement)



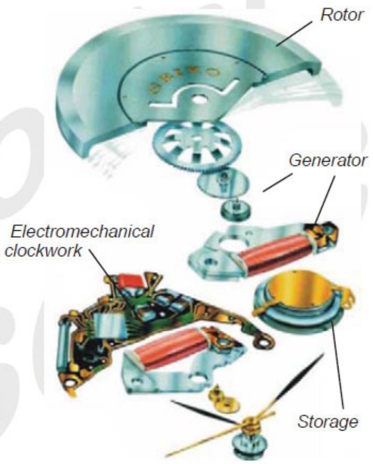
Generation of an AC current by an alternative field by movement: output power ~µWatt to mWatt

***P = 50 mW @ 1g acceleration***

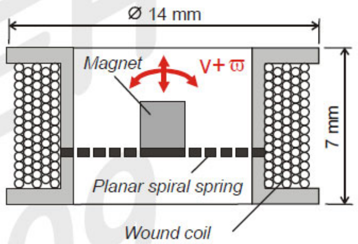
***The size of an apple!***

Perpetuum PMG17 ATEX/IECEx

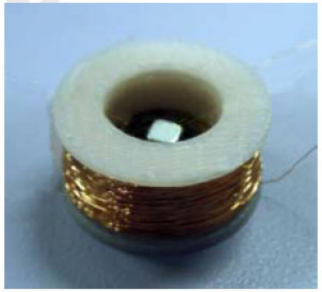
***P = 5 µW***



*Rotatory converter from Seiko Kinetic*

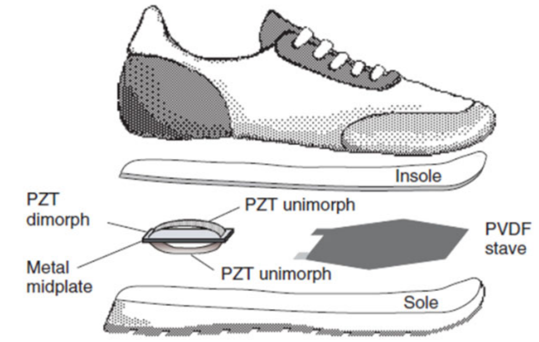


***P = 800 µW***



*Multimodal oscillating converter, University of Hongkong, 2002*

# MIT’s piezoelectric shoes (1998)



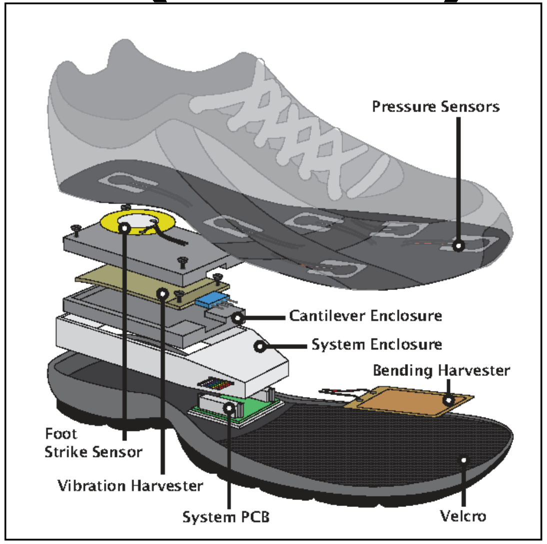
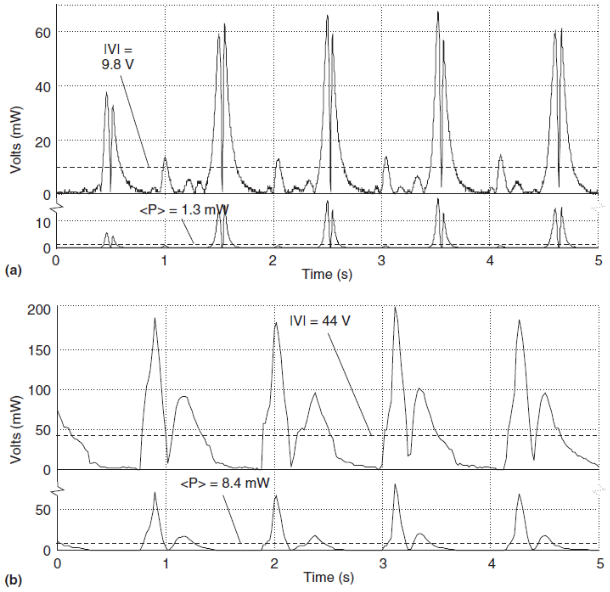


Fig. 1. Expanded view of the shoe system and all integrated components.



Rich Meier et al.,
A piezoelectric energy-harvesting shoe system for podiatric sensing, 2014 Conference of the IEEE Engineering in Medicine and Biology Society.

**10-20 µJ of energy per step**

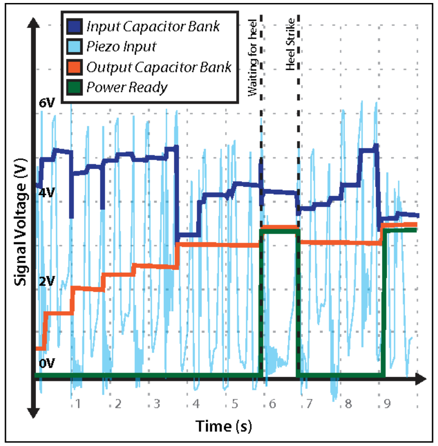
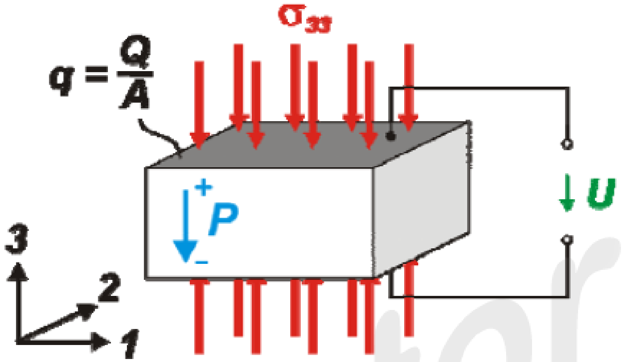
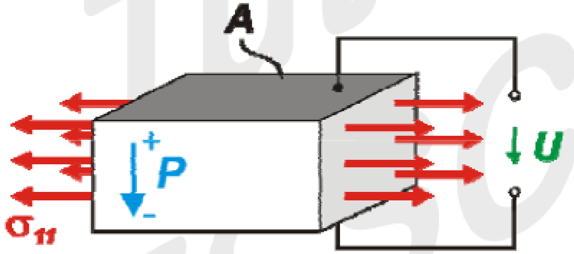


Fig. 3. A time-domain graph of energy capture in lab walking test. Note

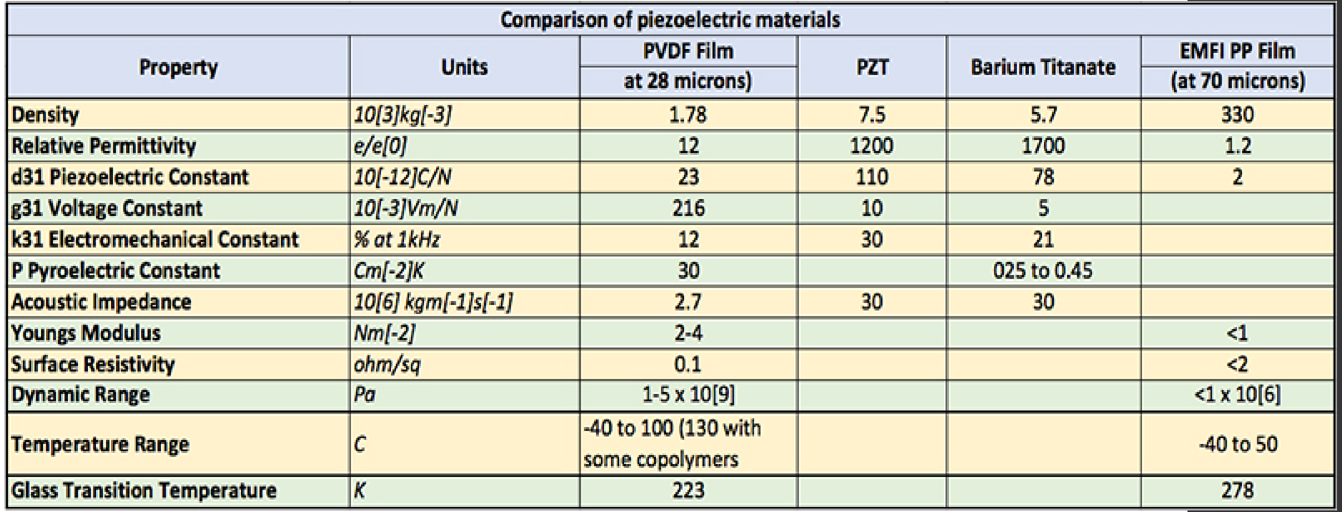
# Piezoelectric conversion/harvesting



Vertical mode: $q_3 = d_{33} \cdot \sigma_{33}$



Transversal mode: $q_3 = d_{31} \cdot \sigma_{11}$



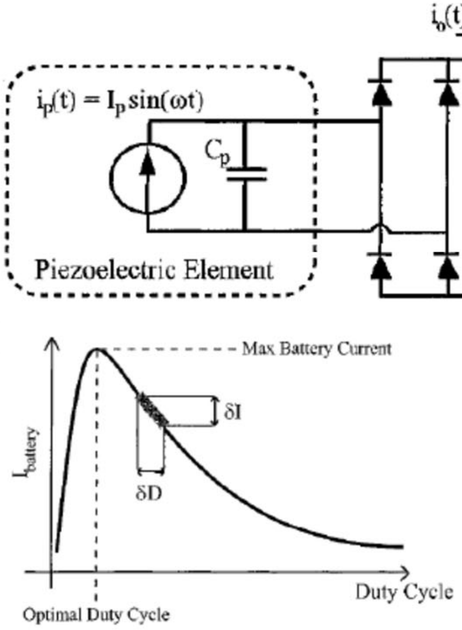
| Comparison of piezoelectric materials | | | | | |
|---|---|---|---|---|---|
| Property | Units | PVDF Film at 28 microns) | PZT | Barium Titanate | EMFI PP Film (at 70 microns) |
| Density | *10[3]kg[-3]* | 1.78 | 7.5 | 5.7 | 330 |
| Relative Permittivity | *e/e[0]* | 12 | 1200 | 1700 | 1.2 |
| d31 Piezoelectric Constant | *10[-12]C/N* | 23 | 110 | 78 | 2 |
| g31 Voltage Constant | *10[-3]Vm/N* | 216 | 10 | 5 | |
| k31 Electromechanical Constant | *% at 1kHz* | 12 | 30 | 21 | |
| P Pyroelectric Constant | *Cm[-2]K* | 30 | | 025 to 0.45 | |
| Acoustic Impedance | *10[6] kgm[-1]s[-1]* | 2.7 | 30 | 30 | |
| Youngs Modulus | *Nm[-2]* | 2-4 | | | <1 |
| Surface Resistivity | *ohm/sq* | 0.1 | | | <2 |
| Dynamic Range | *Pa* | 1-5 x 10[9] | | | <1 x 10[6] |
| Temperature Range | *C* | -40 to 100 (130 with some copolymers | | | -40 to 50 |
| Glass Transition Temperature | *K* | 223 | | | 278 |

- Charge based converter
- Generation of AC current by dynamic mechanical stress
- Output voltage: 1V…100 V
- Output power: µW…mW

# Circuit interfaces for piezoelectric harvesting (1)

## Iterative load matching

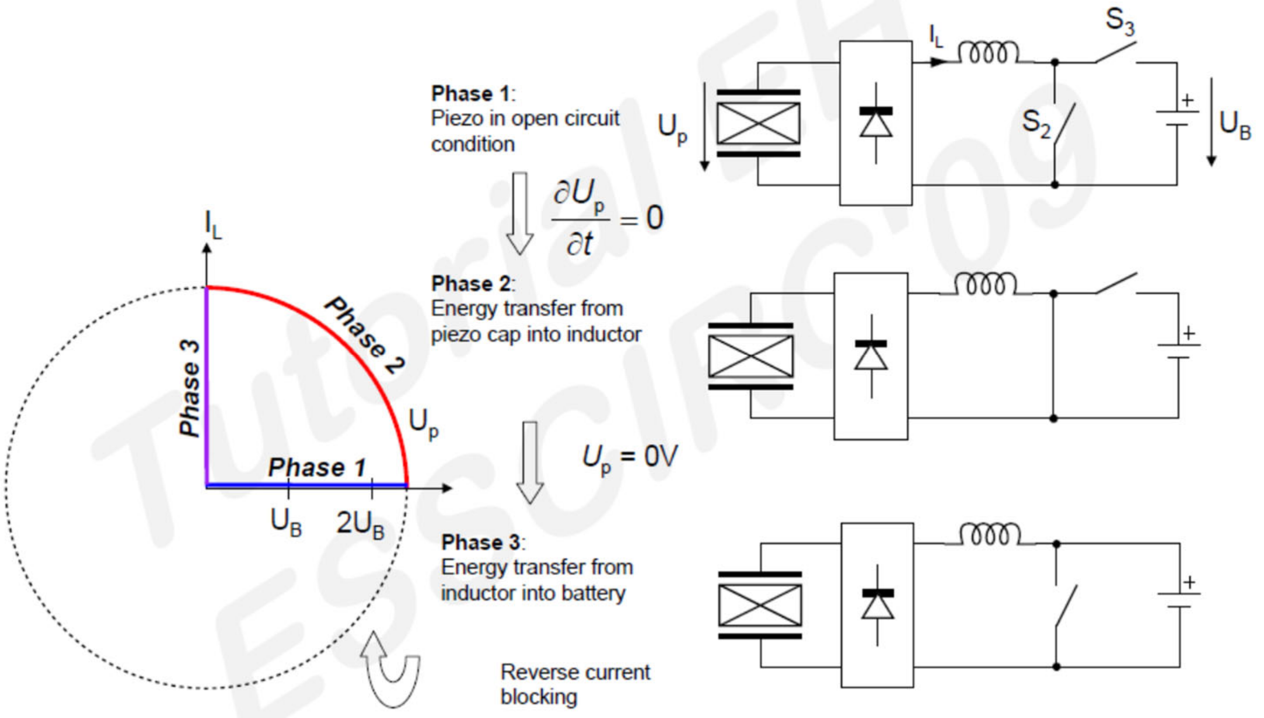
- Equivalent input resistance varies with duty cycle
- Iterative control is power extensive



[G. Ottman *et al.*, 2002]

# Interfaces for piezoelectric harvesting (2)

## Burst energy extraction



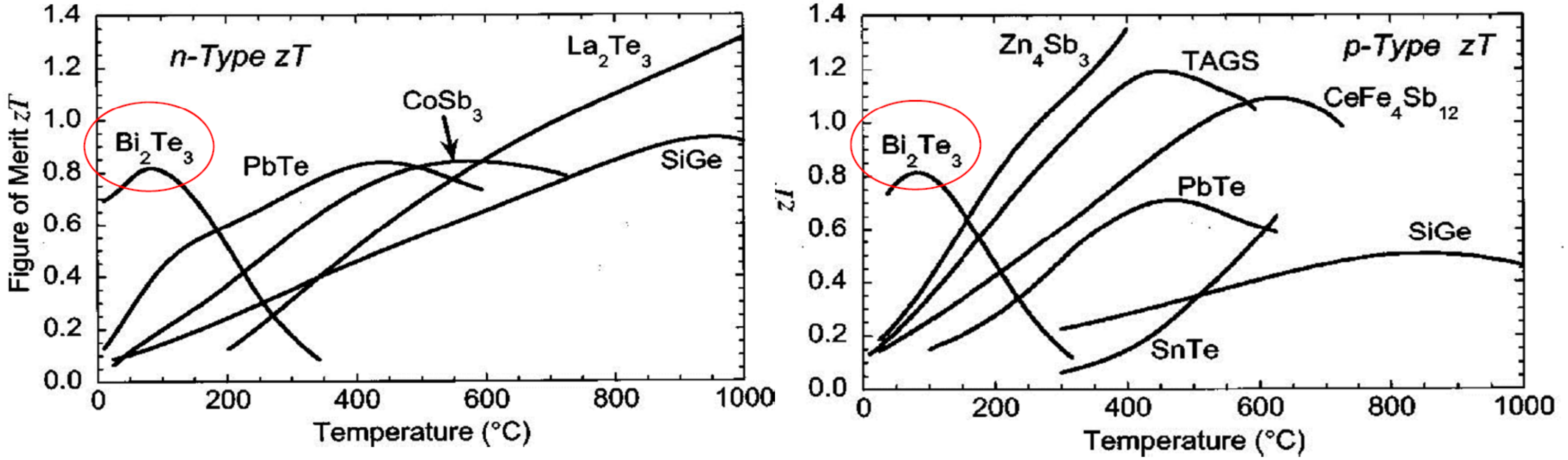
[T. Hehn *et al.*, 2008]

# Thermoelectrical (TEG) harvesting: materials

**The figure of merit *z* expresses a materials suitability for TE conversion:**

$$zT = \frac{\alpha^2 \sigma}{\lambda} T$$

$\alpha$ = Seebeck coefficient
$\lambda$ = thermal conductivity
$\sigma$ = electrical conductivity



Which material system? Bismut-Telluride (Bi2Te3) with best properties between 25°C and 150°C

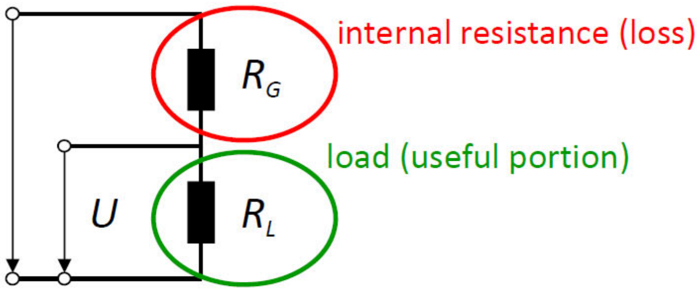
# TEG performance factors

Open Circuit voltage: $U_0 = m\alpha\Delta T_G$

$P_{max}$ (matched load $R_L=R_G$):

$$P_0 = UI = \frac{U_0^{\,2}}{4R_G} = \frac{m^2\alpha^2}{4R_G}\Delta T_G^{\,2}$$

$U_0$ = Seebeck voltage
$m$ = Number of thermocouples
$\alpha$ = Seebeck coefficient of thermocouple
$\Delta T_G$ = Temperature difference across generator

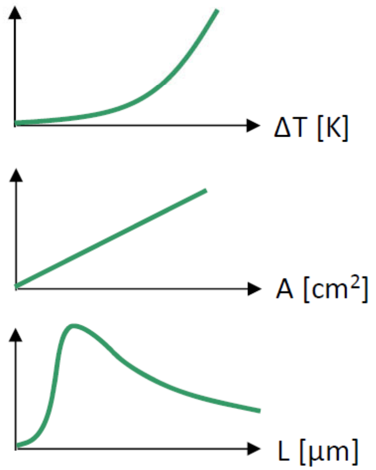


<u>Output power depends on:</u>

Temperature difference ⇒ **QUADRATIC**

TEG size ⇒ **LINEAR**

TEG thickness ⇒ **OPTIMIZED**



**Example:**

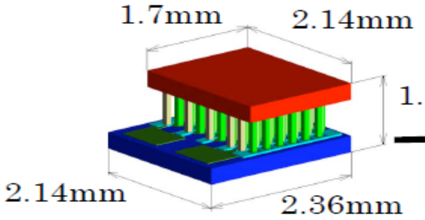
**Efficiency Factor: 10 µW/cm²/K², ΔT=10K, TEG size: 10x10cm²,**
**➔ 100mW output power**

Guardian Angels
for a smarter life

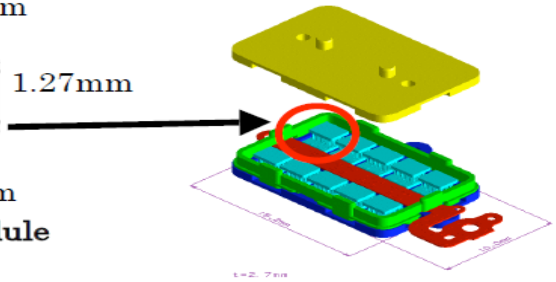
# Example

## Seiko SII Thermic® Heat-Powered Watch

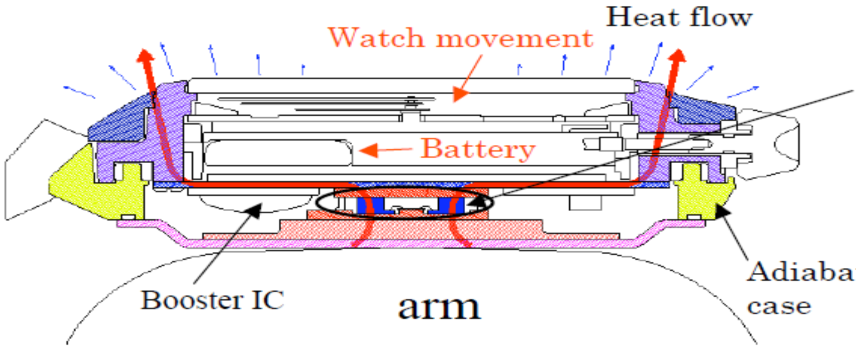
**Thermal energy watch**



**Thermoelectric module**



**Thermoelectric unit**



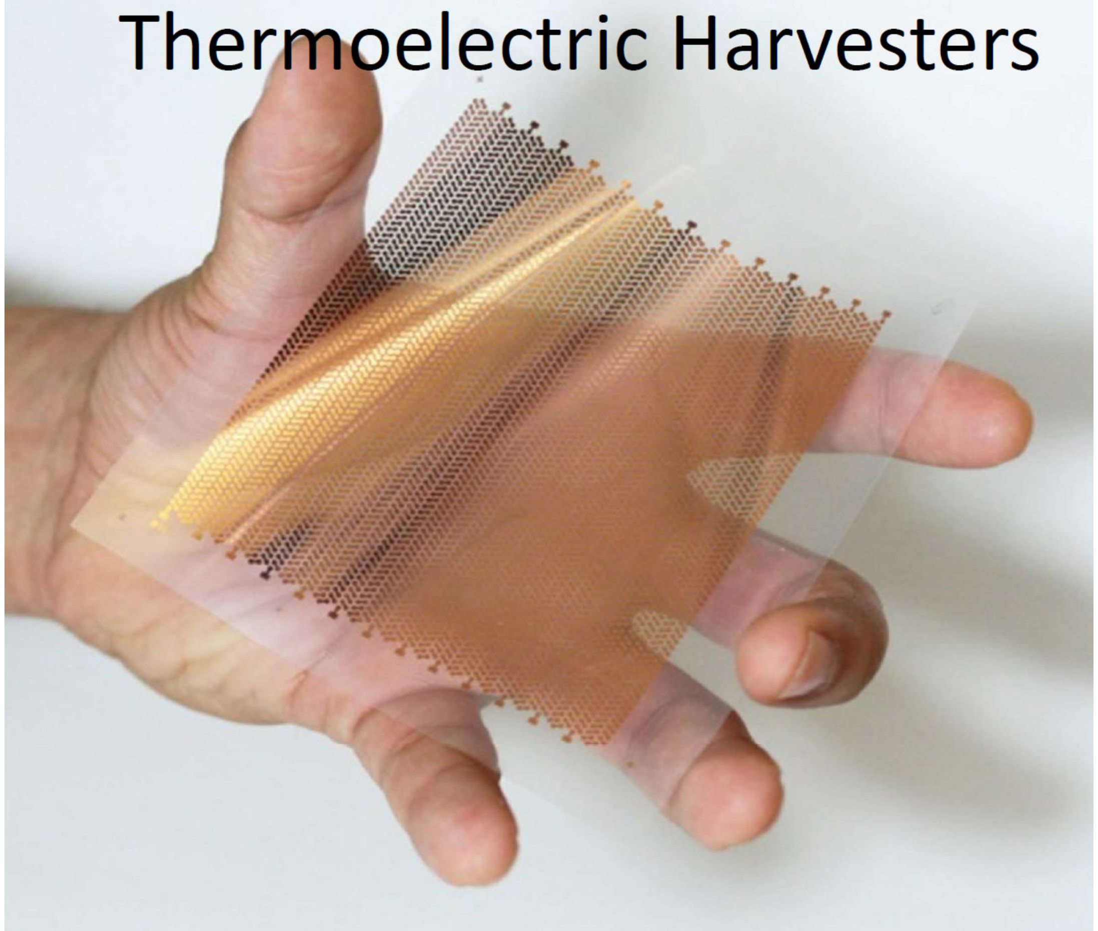
**Thermoelectric (Photo)**

- Uses 10 Thermoelectric modules and a booster IC
- Runs off body heat

  *Low ΔT, limited surface area, low efficiency -> Microwatts...*

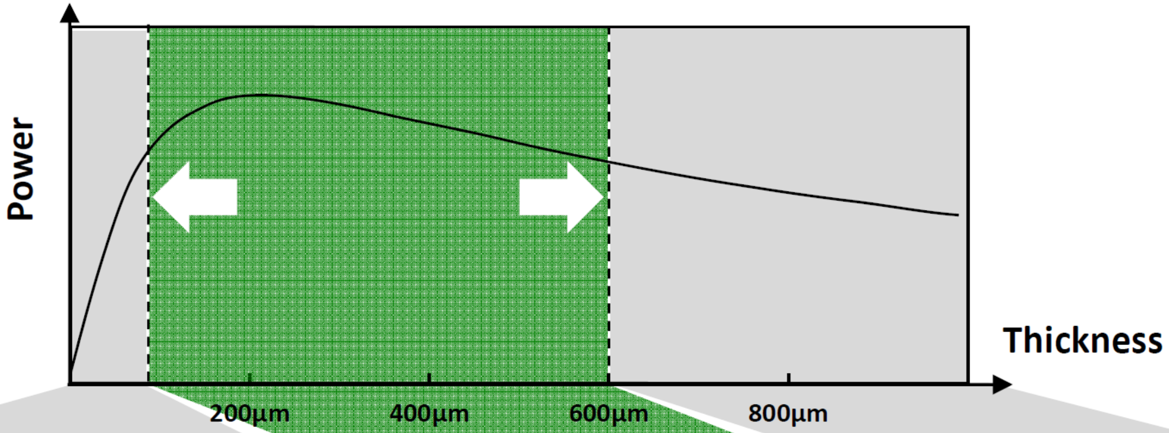
# Thermoelectrical harvesters

- On foil technology



greenTEG
efficiency enabled

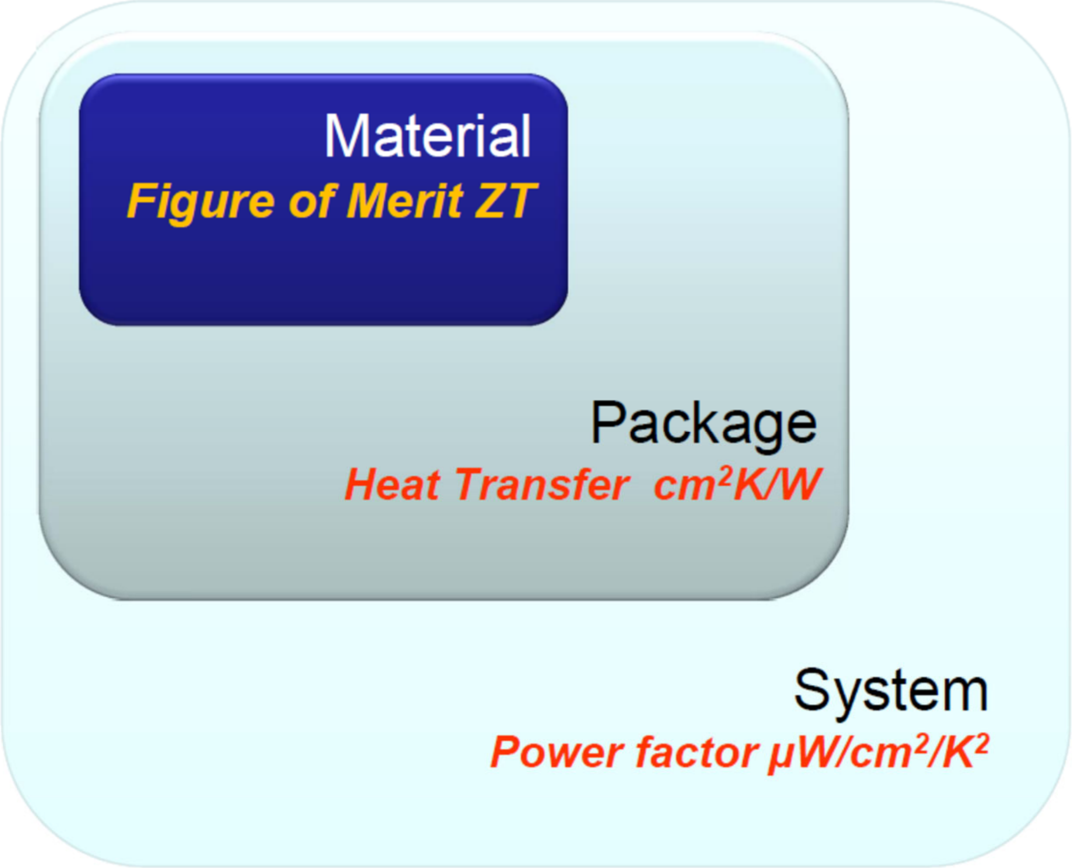
# TEG microsystem optimize power and cost



| | | |
|---|---|---|
| | greenTEG efficiency enabled  | |
| Thin film TEGs | Electro chemical deposition | Macroscopic assembly-based TEGs |
| mm$^2$ | m$^2$ | cm$^2$ |
| ~2.5kg/m$^2$ | ~1.4kg/m$^2$ | ~20kg/m$^2$ |
| $$$ | $ | $$ |

Source: Ch. Hierold, ETHZ.

# TEG efficiency: material to system



Material

*Figure of Merit ZT*

Package

*Heat Transfer cm$^2$K/W*

System

*Power factor µW/cm$^2$/K$^2$*

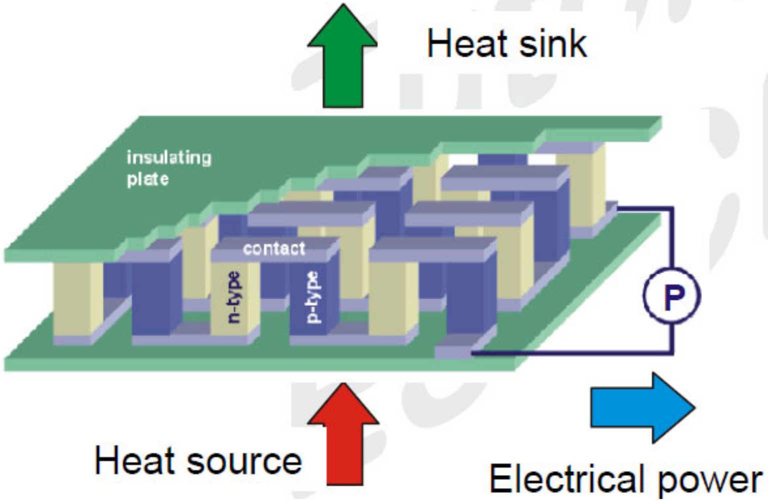
# Thermoelectric conversion from Hot ICs?

**Harvesting of dissipated thermal energy in hot electronic chips.**

$$\Delta U = \alpha \cdot \Delta T$$

Seebeck coefficients of relevant material couples:

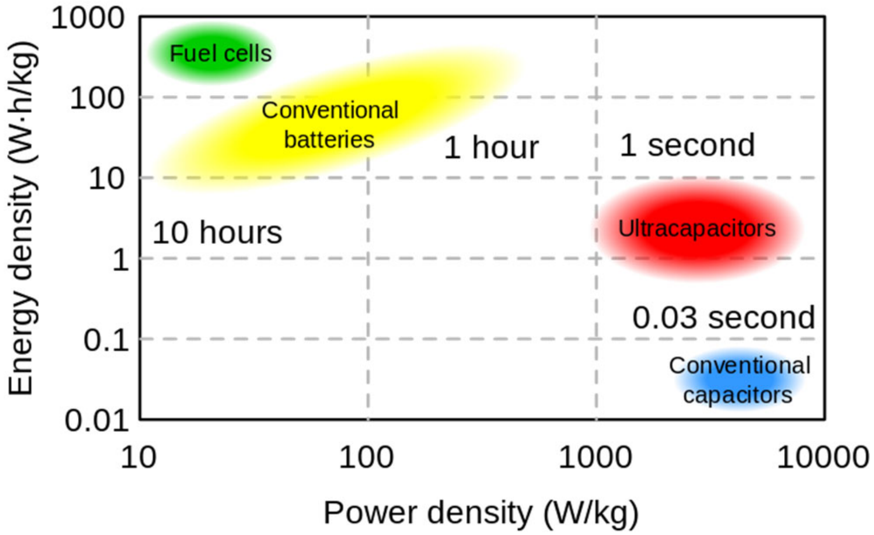
| | α [μV/K] |
|---|---|
| Al / p-Poly-Si | 195 |
| Al / n-Poly-Si | 110 |
| p-Poly-Si / n-Poly-Si | 190...320 |
| p-$Bi_{0,5}Sb_{1,5}Te_3$ / n-$Bi_{0,87}Sb_{0,13}$ | 200...420 |

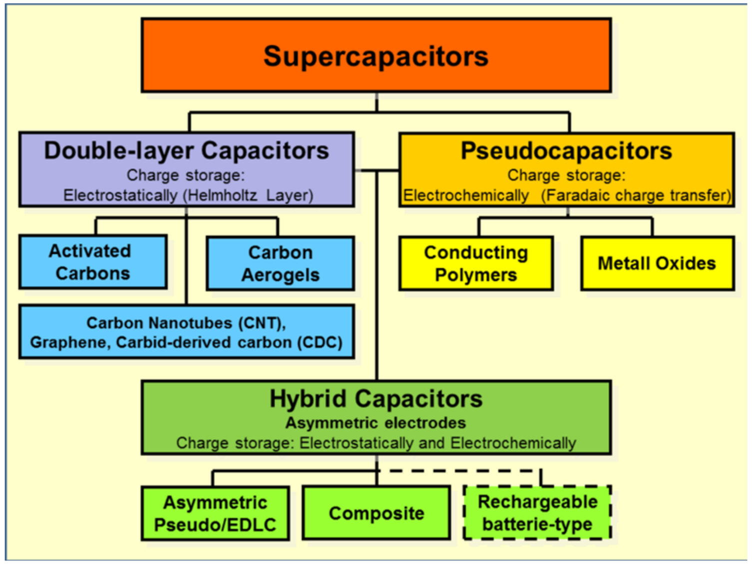


**Characteristics**

- Generation of DC current, but…
- … polarity changes with direction of temperature gradient!
- Output voltage: around 100 mV
- Output power: some μW

# Supercapacitors: rationale





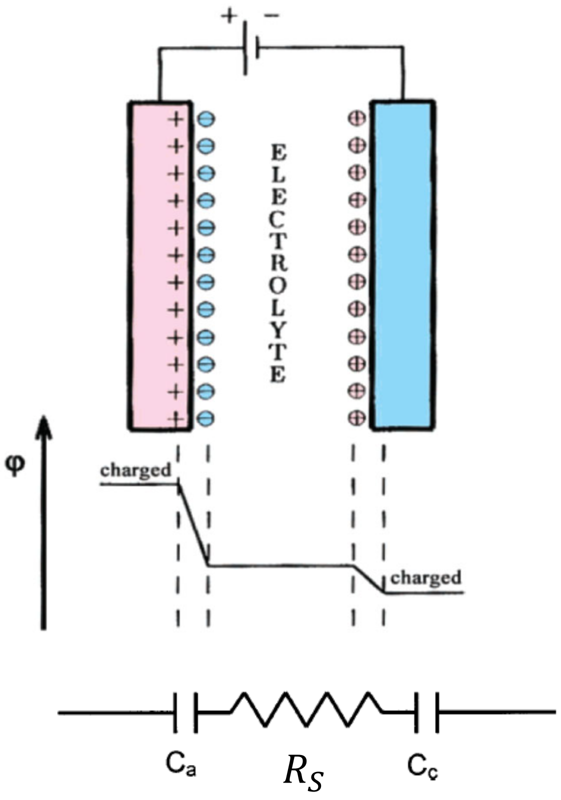
**Supercapacitors:**

- Higher power density
- Much faster charge and discharge rate
- Environmentally friendly
- Extremely low internal resistance High efficiency (97-98%)
- Over a million charge-discharge cycles

**Batteries:**

- Have higher energy density
- Typically 200–1000 charge-discharge cycles
- Contain highly reactive and hazardous chemicals
- Negatively effected by low temperatures

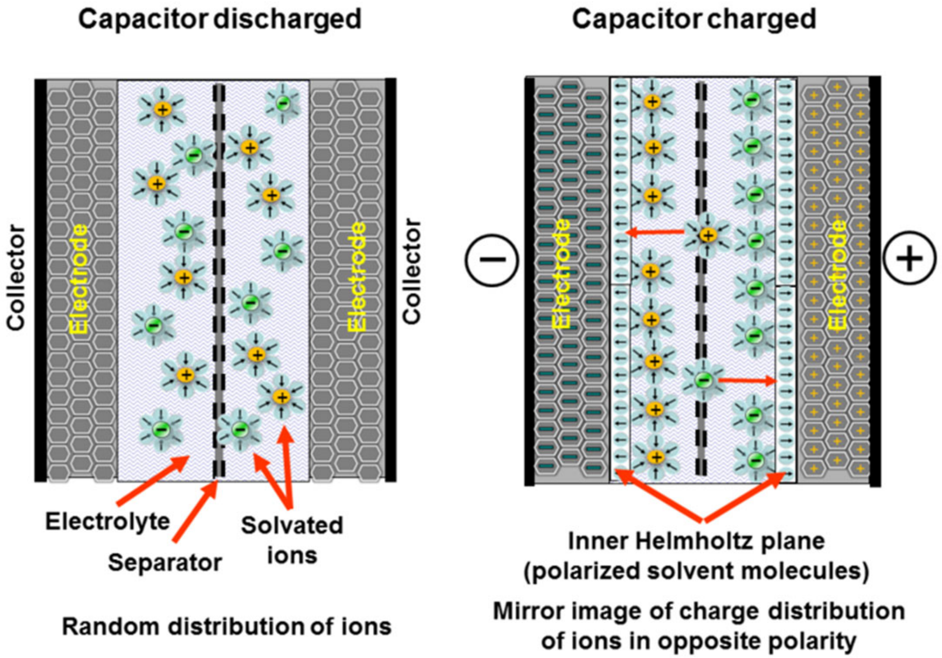
# Supercapacitors



$$1/C = 1/C_a + 1/C_c$$

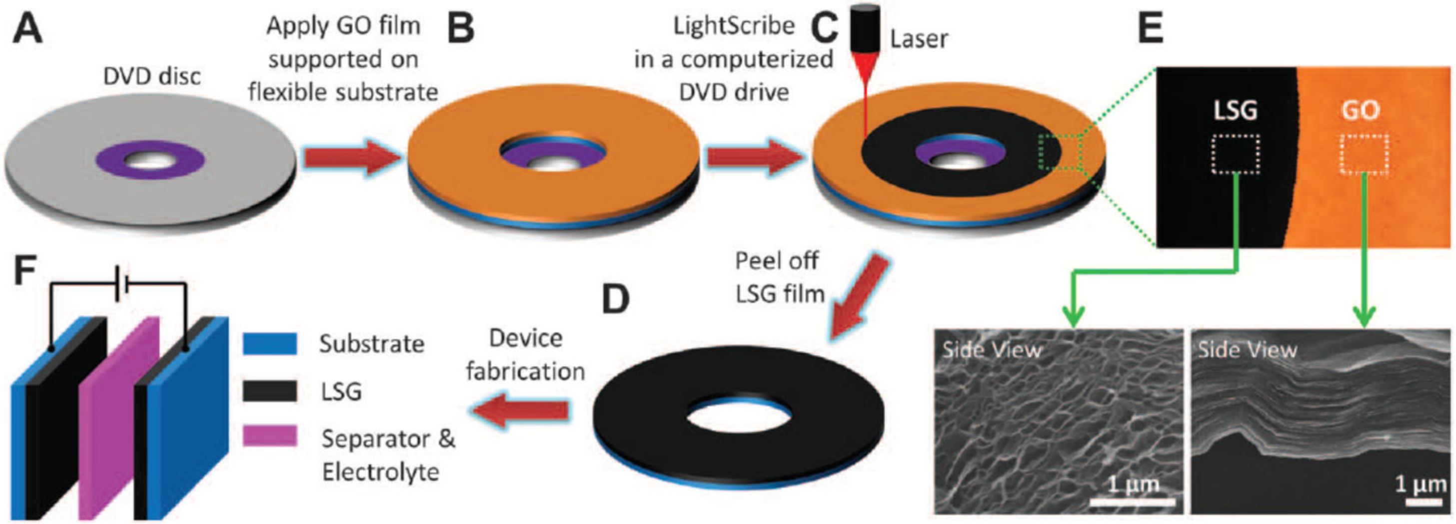
$$\boxed{Energy = \frac{1}{2} C\, V^2}$$

$$\boxed{Power = \frac{V^2}{4R_s}}$$



# Laser-scribed supercapacitor

| | |
|---|---|
| Electrical conductivity | 1738 S/m |
| Surface area | 1520 m2/g |
| Energy density | 1.36 mWh/cm$^3$ |
| Power density | 20 W/cm$^3$ |



El-Kady, Maher F., et al. *Science* 335.6074 (2012): 1326-1330.

# Hybrid supercapacitors

- **new designs for thin film energy storage devices with possible using graphene**

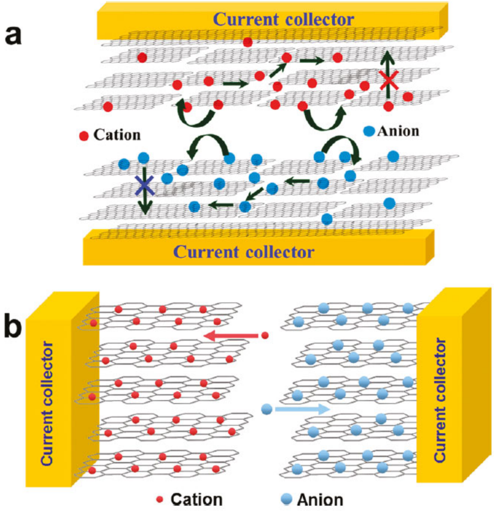


**Figure 1.** (a) Schematic depiction of the stacked geometry used for the

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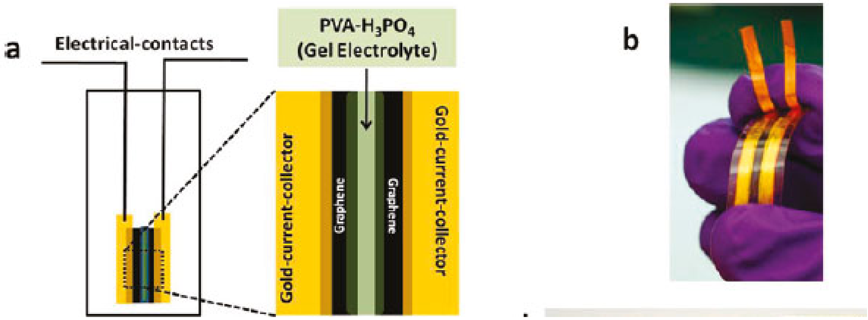
### Ultrathin Planar Graphene Supercapacitors

Jung Joon Yoo,[†,‡,⊥] Kaushik Balakrishnan,[†,⊥] Jingsong Huang,[§] Vincent Meunier,[*,§,¶] Bobby G. Sumpter,[§] Anchal Srivastava,[†,∥] Michelle Conway,[†] Arava Leela Mohana Reddy,[†] Jin Yu,[†] Robert Vajtai,[†] and Pulickel M. Ajayan[*,†]

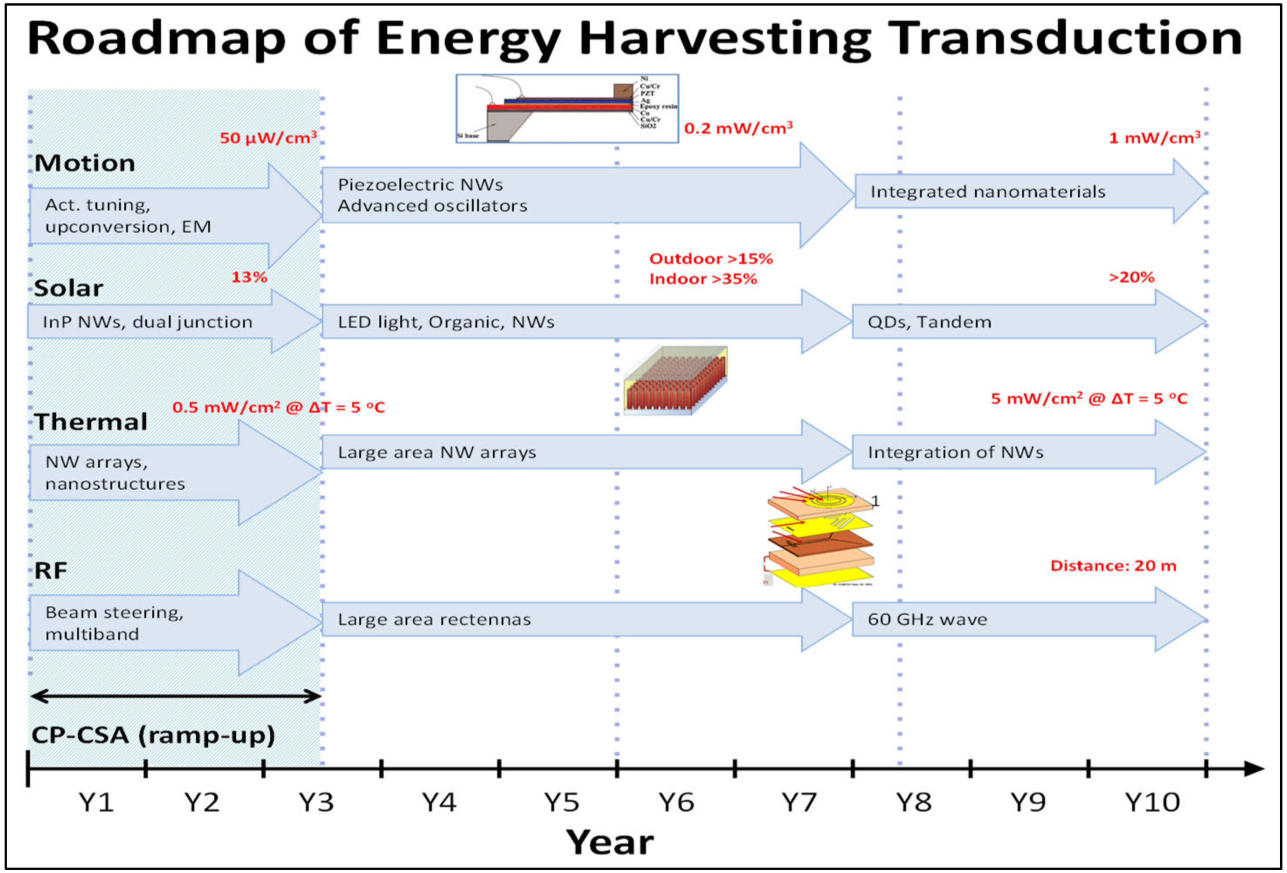
**Table 1. Performance Evaluation and Comparison of the G and RMGO 2D "In-Plane" Supercapacitors**

| | | device properties[a] | | | electrode properties[b] | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | specific capacity | | |
| mater | method | $N$ | $T$ (nm) | capacitance ($\mu$F) | mass ($\mu$g) | geometrical area (cm$^2$) | F g$^{-1}$[c] | $\mu$F cm$^{-2}$[d] | $\mu$F cm$^{-2}$[e] |
| G | CVD | 1 | | 3.333 | | 0.1 × 0.835 | | 80 | 80 |
| RMGO | LBL | 21[f] | 10 | 35 | 0.283 | 0.085 × 2.1 | 247 | 394 | 19 |

[a] $N$ = number of layers; $T$ = thickness of the electrode. The capacitance values are reported for the best performance obtained using the CD curves with current density of 281 nAcm$^{-2}$ for RMGO and 630 mAcm$^{-2}$ for G. [b] Electrode capacitance converted from the device capacitance assuming a symmetrical capacitor. [c] Normalized by the electrode mass. [d] Normalized by one electrode's geometrical area. [e] Normalized by one electrode's interface area. [f] Calculated using the mass, the geometrical area, and the specific area of one side of graphene (1310 m$^2$ g$^{-1}$).



# Roadmap



## Roadmap of Energy Harvesting Transduction

**Motion**
- 50 µW/cm³ — Act. tuning, upconversion, EM
- 0.2 mW/cm³ — Piezoelectric NWs, Advanced oscillators
- 1 mW/cm³ — Integrated nanomaterials

**Solar**
- 13% — InP NWs, dual junction
- Outdoor >15%, Indoor >35% — LED light, Organic, NWs
- >20% — QDs, Tandem

**Thermal**
- 0.5 mW/cm² @ ΔT = 5 °C — NW arrays, nanostructures
- Large area NW arrays
- 5 mW/cm² @ ΔT = 5 °C — Integration of NWs

**RF**
- Beam steering, multiband
- Large area rectennas
- Distance: 20 m — 60 GHz wave

CP-CSA (ramp-up)