Green engineering WORKSHOP

Thursday 28th January 2010, Neuchâtel

imec aspire invent achieve

Holst Centre

Open Innovation by IMEC-NL and TNO

Energy harvesting: microwatt generation enabling megawatt savings

Chris Van Hoof

chris.vanhoof@imec.be

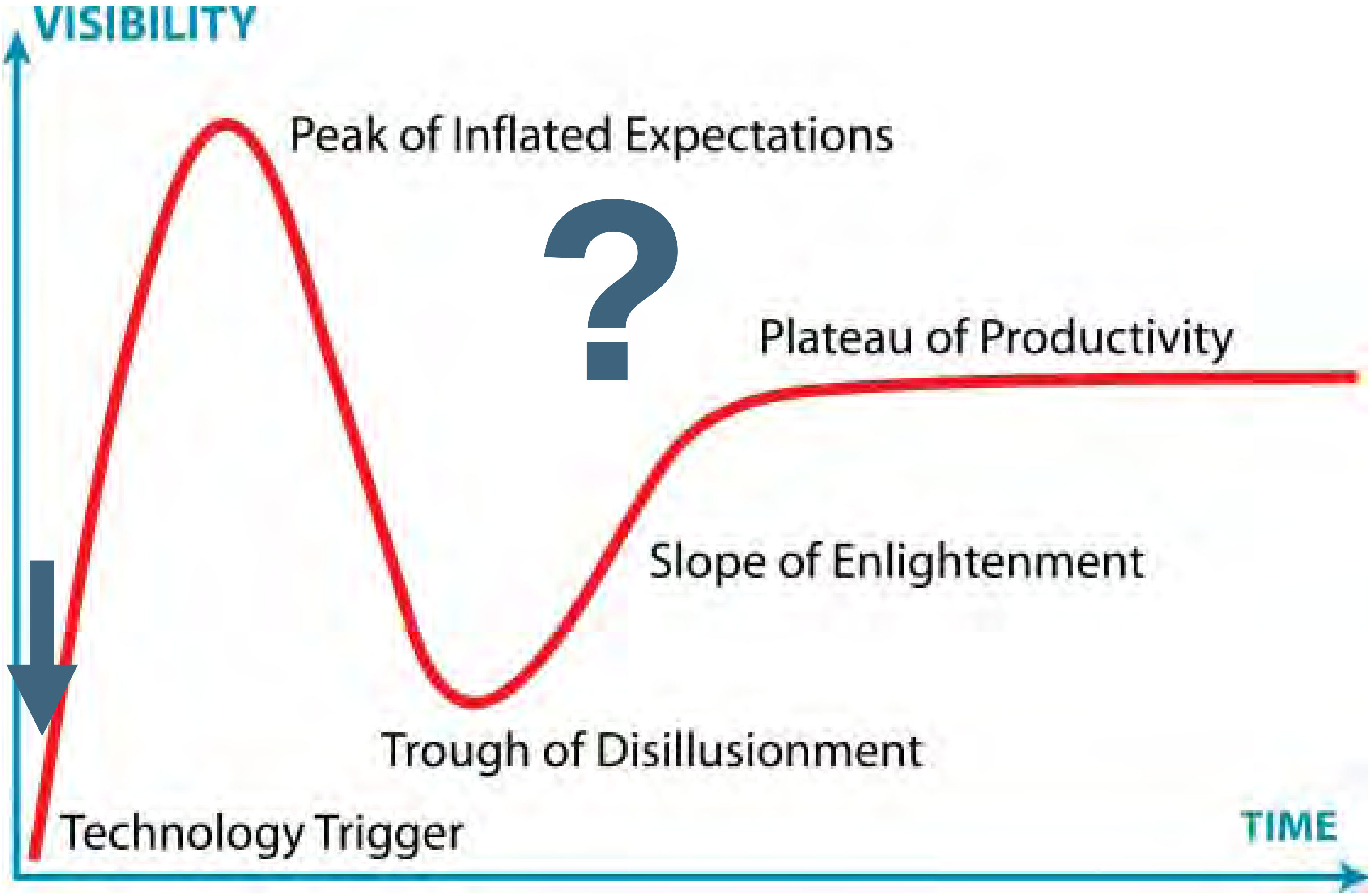
IMEC – HOLST Centre

Leuven, Belgium and Eindhoven, the Netherlands

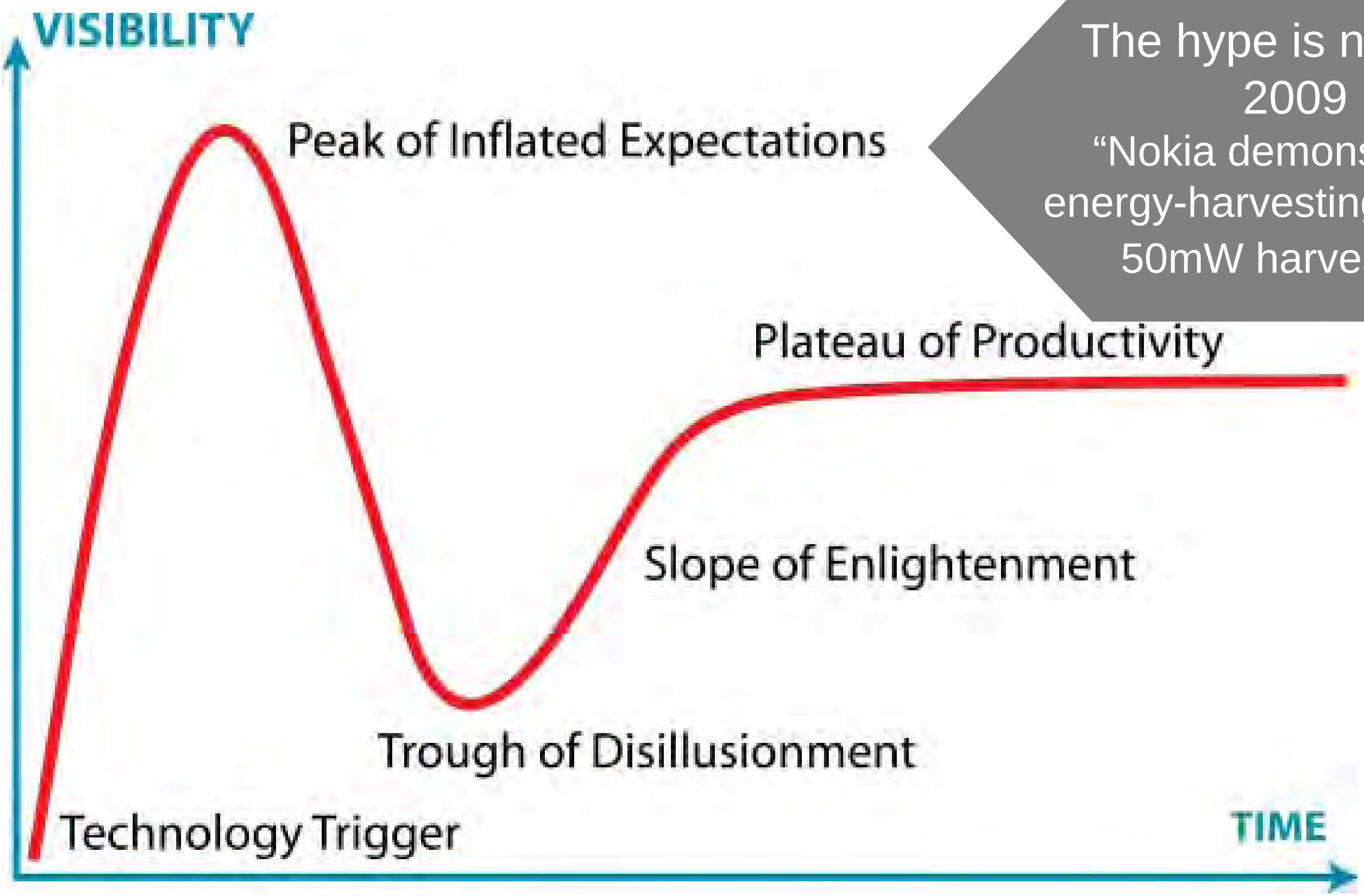
Overview

- The hype: “free energy to power wireless sensors will enable the revolution of the smart connected world”
- Why not stick to batteries ?
- The road towards energy autonomy: Solar, Vibration, Thermal, RF energy harvesting
- Energy harvesting applications → ***microwatt generation enabling megawatt savings ?***
- Cost - this minor detail
- A (bright green) future ?

Energy harvesting: microwatt generation enabling megawatt savings ? The hype cycle

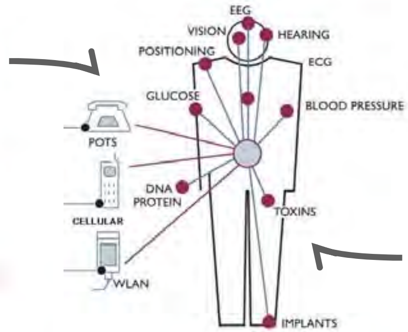


Energy harvesting: microwatt generation enabling megawatt savings ? The hype cycle



The hype is not over
2009
“Nokia demonstrates energy-harvesting handset 50mW harvested”

Why not stick to batteries ?



1W	50mW	1mW	100µW	10µW	1µW
5 hours	24 hours	10 days	**Autonomous**	5 years	5 years

NEEDED:

A small (<<1cm³) and low-cost energy source that lasts the lifetime of the system

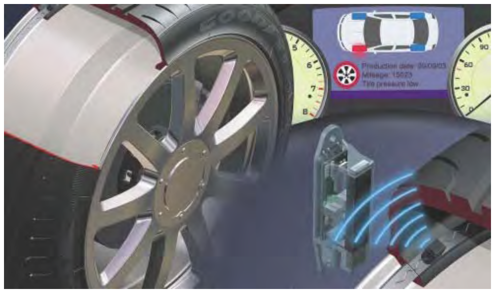
AVAILABLE:
Batteries

Primary	1.0 Wh/cm3
Rechargeable	0.3 Wh/cm3

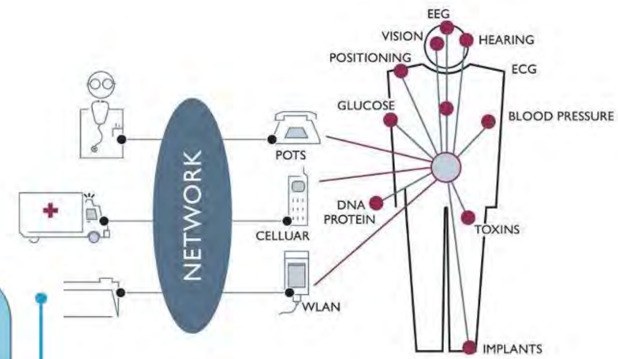
Energy Autonomy needs are not fulfilled by today's batteries alone

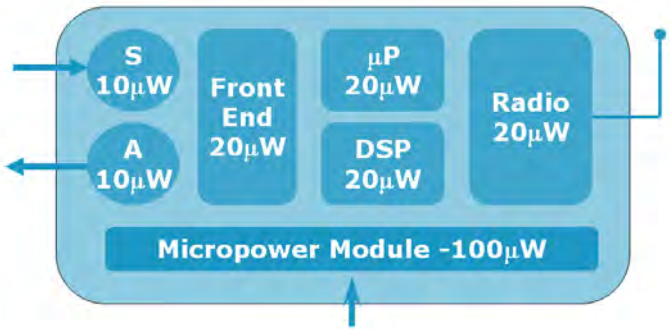
Why Not Stick To Batteries ? Autonomous "Health" Monitoring Needs Long-term "Chronic" Solutions

TPMS: Tire Pressure Monitoring System



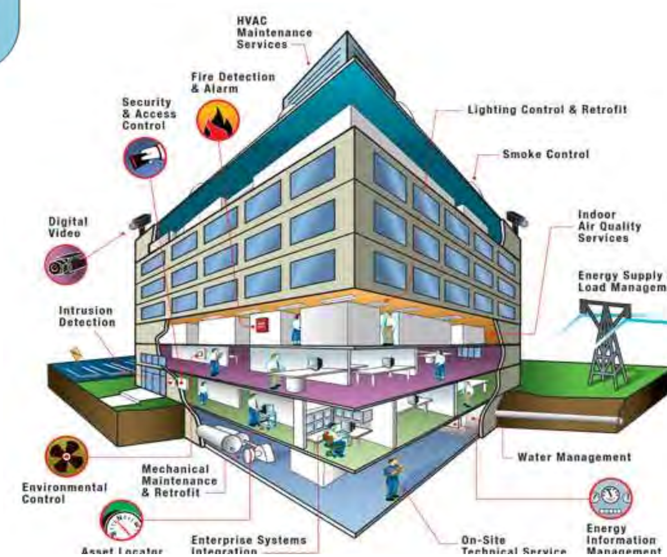
BAN: Body Area Network



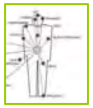


Predictive Maintenance

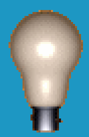
Smart Buildings



Why Not Stick To Batteries ? Autonomous "Health" Monitoring Needs Long-term "Chronic" Solutions

	On The Body 	Tire Pressure Monitoring 	Machine Health 
Source	**Thermal / PV**	**Vibration**	**Thermal / Vibration / PV**
Autonomy	**0.5-5 years**	**10-20 yrs**	**10-50 yrs**
Environment	**Human Body** • **Moderate T** • **Moderate to low light level**	**"Harsh" environment** • **High Temperature** • **High pressure** • **High accelerations** • **Large shocks**	**"Harsh" environment** • **High Temperature** • **Very low to very high light level** • **Very large vibrations**
Cost	**Low**	**Lower than battery replacement cost**	**Lower than replacement or engine repair cost**
Form Factor	**Unobtrusive** **Thin, flex, ...** **$<<1\ cm^3$**	**Small / Light** **$<1cm^3$**	**Variable** **application-dependent**

How much power is available ?

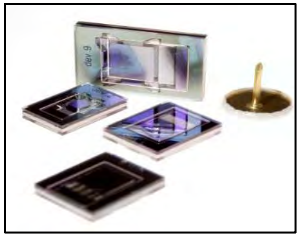


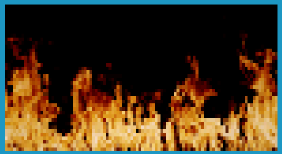
Photovoltaic

Outdoor
10 mW/cm²
Indoor
10 μW/cm²

Vibration

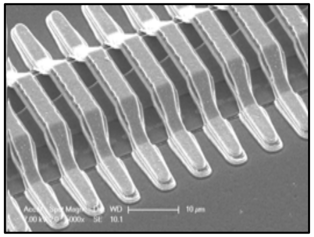
Man
4 μW/cm²
Machine
100 μW/cm²

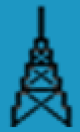




Thermal

Man
20 μW/cm²
Machine
1-10 mW/cm²





RF

GSM
0.1 μW/cm²
WiFi
0.01 μW/cm²

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

Energy harvesting is not at all new …

...but it is getting smaller

Vibration

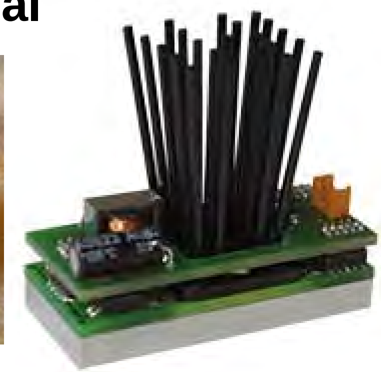
KCF Technology

Perpetuum

Microstrain

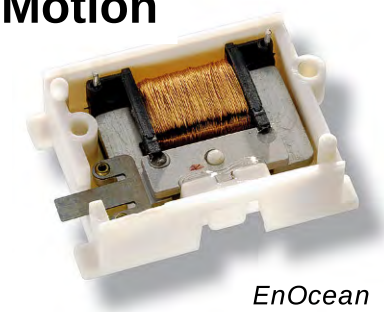
Thermal

Seiko



Micropelt

Motion



EnOcean

HOWEVER … today's systems are only addressing niche applications:

- too little power generated
- or too big/heavy
- too expensive

Even Energy harvesting for on-the-body devices is not new…

ABRAHAM-LOUIS PERRELET
(1729 - 1826)
Swiss watchmaker, inventor of a self-winding watch.

The other related inventions:

1799 – battery re-invented (Alessandro Volta)

1831 – dynamo (Michael Faraday)

Mechanical Energy

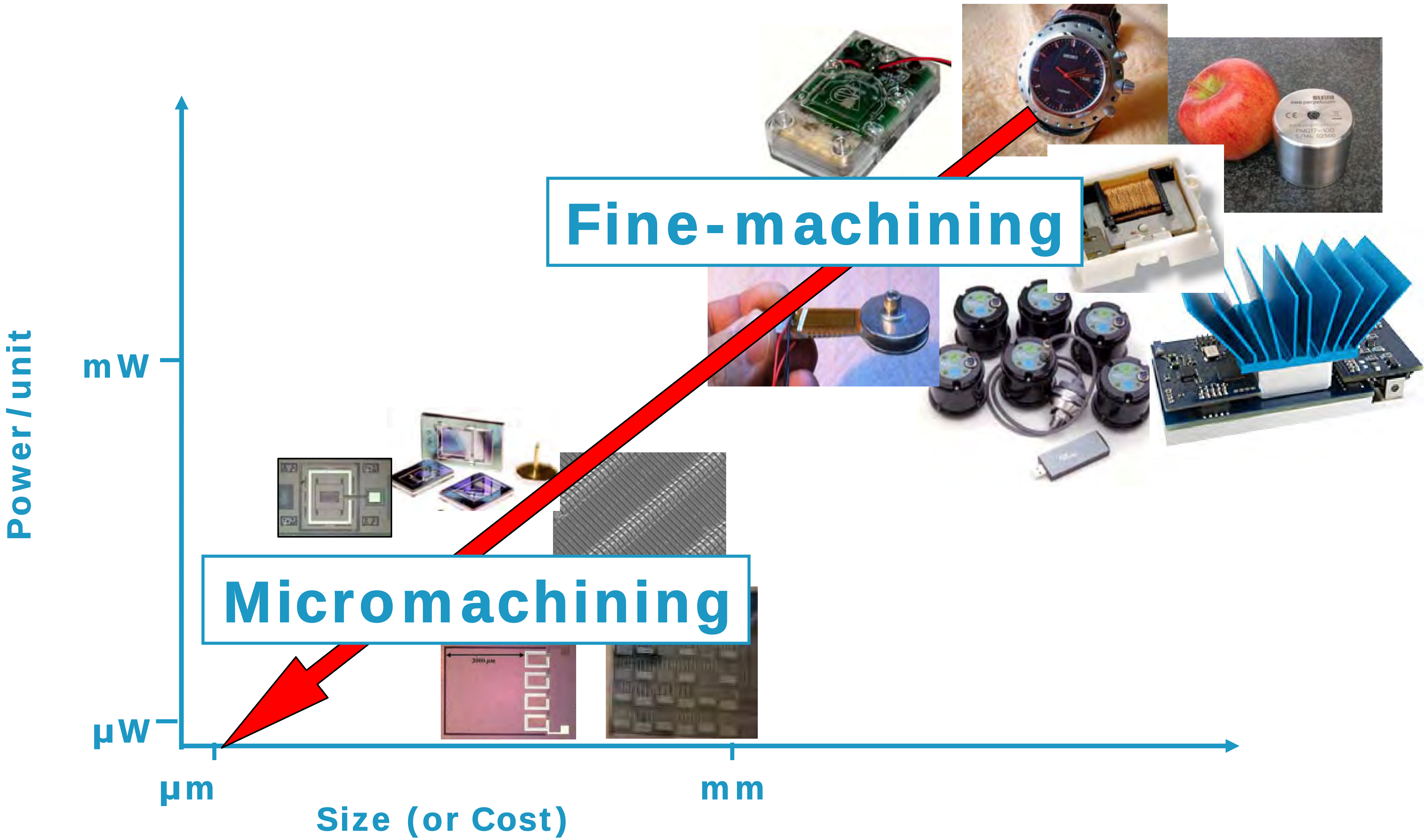
Synchronar 1972

Energy of light

Thermal energy

Bulova Thermatron 1980

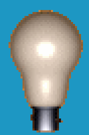
Cost reduction through Miniaturization



The road towards energy autonomy

the good
the bad
the ugly

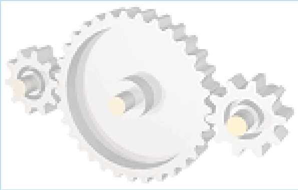
Micropower: Harvesting Sources



Photovoltaic

Outdoor
10 mW/cm^2

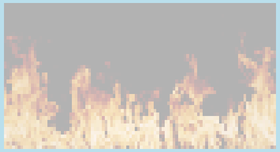
Indoor
10 μW/cm^2



Vibration

Man
4 μW/cm^2

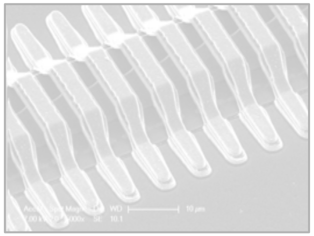
Machine
100 μW/cm^2



Thermal

Man
20 μW/cm^2

Machine
1-10 mW/cm^2



RF

GSM
0.1 μW/cm^2

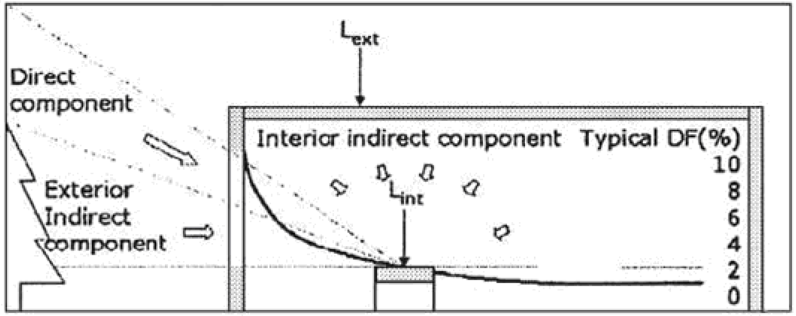
WiFi
0.01 μW/cm^2

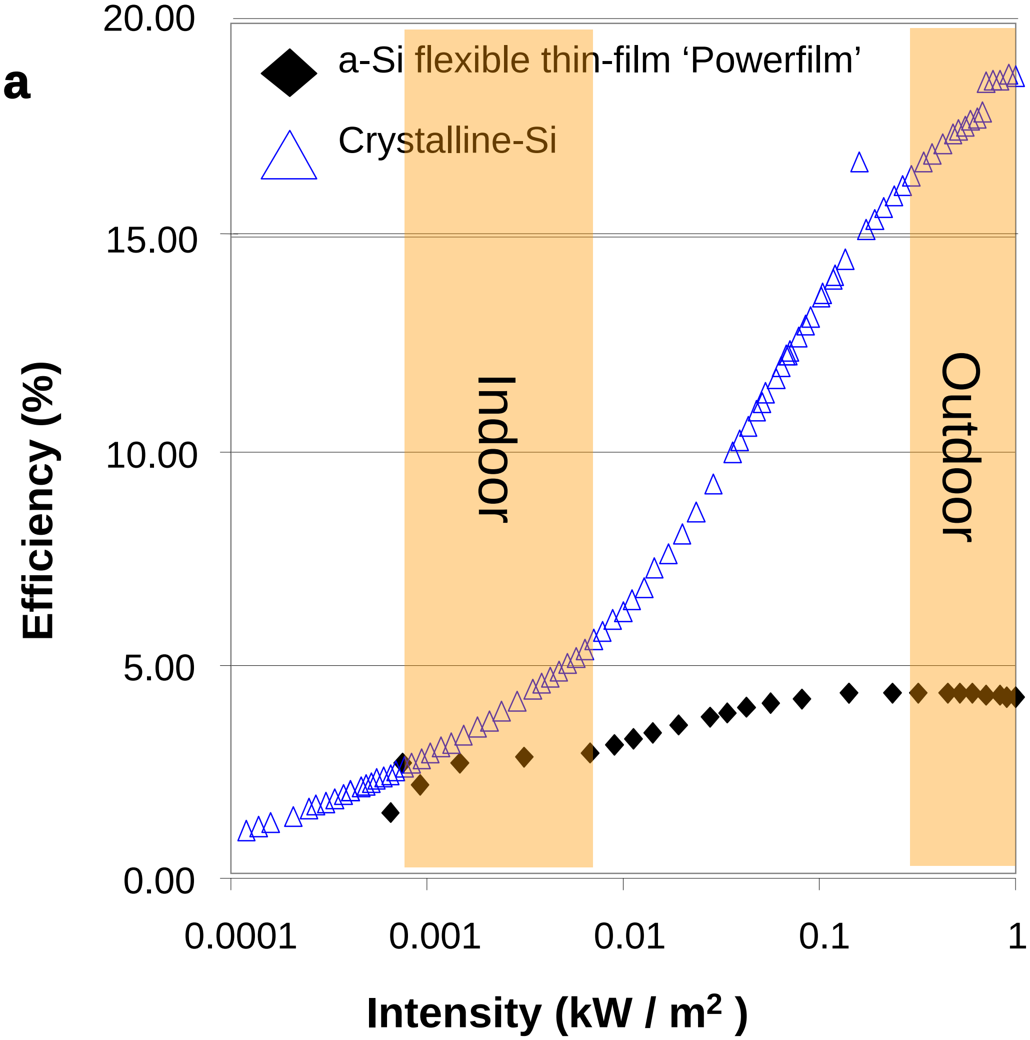
Indoor photo micropower generation

Compared to outdoor, indoor PV is much more of a challenge

- Much lower light intensity
- Cell efficiency decreases
- Spectrum is different
- Area is smaller

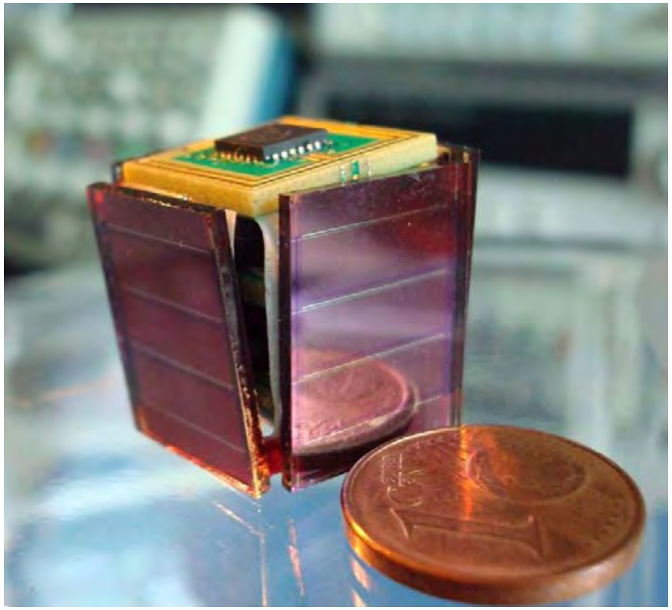
→ Total power is much lower





Indoor Photovoltaic module example

- **Applications for Indoor Use:**
  - Office light (~400 lux)
  - On average 12hrs of light/day



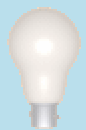
Goal: Real Time data

Application: EMG

Goal: Small size

Application: T Sensor

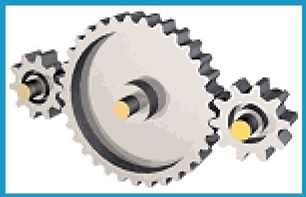
Micropower: Harvesting Sources



Photovoltaic

Outdoor
10 mW/cm^2

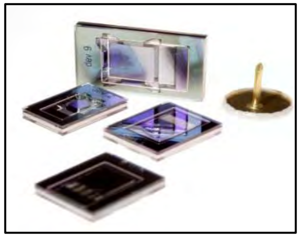
Indoor
10 μW/cm^2

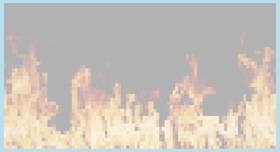


Vibration

Man
4 μW/cm^2

Machine
100 μW/cm^2

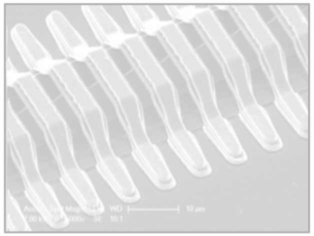




Thermal

Man
20 μW/cm^2

Machine
1-10 mW/cm^2



RF

GSM
0.1 μW/cm^2

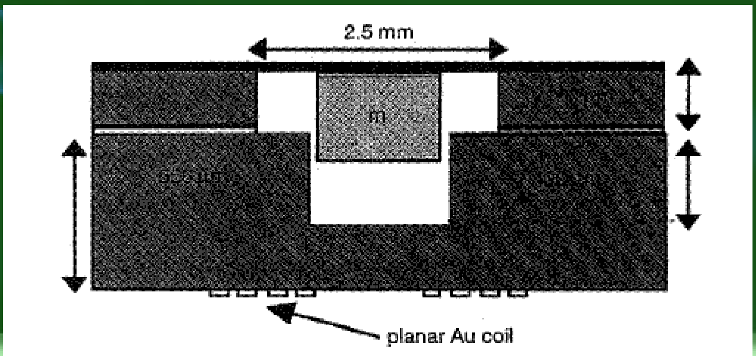
WiFi
0.01 μW/cm^2

Vibration Harvester State-of-the-art
Electromagnetic **transducers**

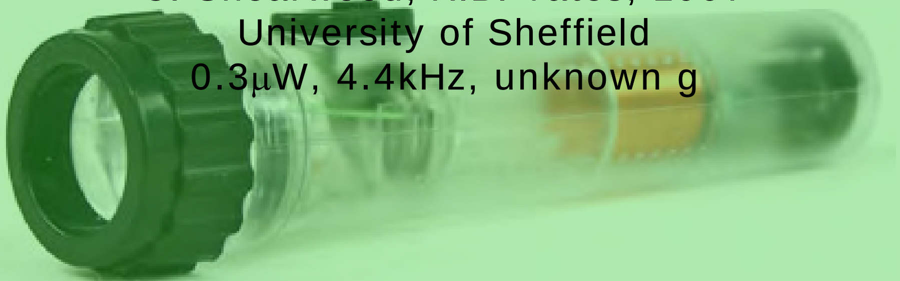
- **Basic principle: Faraday's law of induction**
- **Many macroscopic embodiments**
- **First miniature embodiment in 1997**

Forever Flashlight

MACRO



C. Shearwood, R.B. Yates, 1997
University of Sheffield
0.3μW, 4.4kHz, unknown g

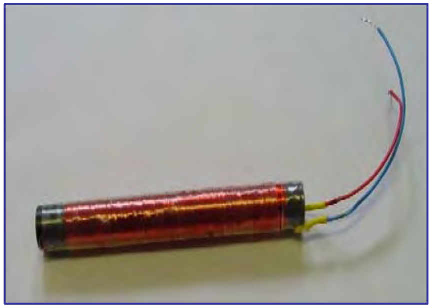


MINI

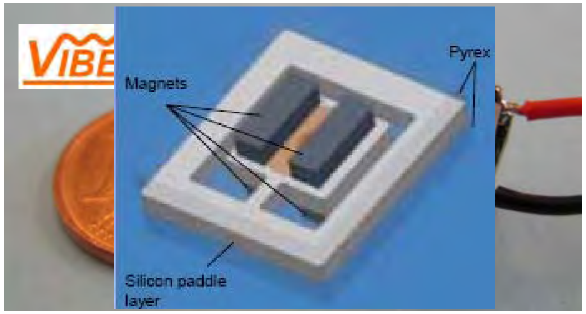
Vibration Harvester State-of-the-art
Electromagnetic **transducers**

- **Several embodiments, same principle**
- **Typically for industrial applications: high g, high f**

Wen J. Li et al., 2000
Chinese univ. of Hong Kong
680 μW, 9.5g @ 110 Hz, 1 cm^3

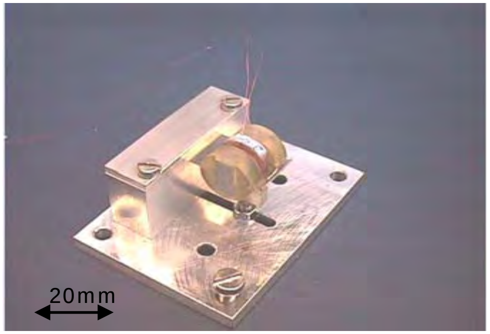


T. Sterken et al., 2005
IMEC, K.U. Leuven
300 μW, 50 g @ 5 Hz, 5 cm^3



S. Beeby et al., 2007
University of Southampton
58 μW, 0.6 m/s^2 @ 60 Hz, 0.1 cm^3

S. Beeby et al., 2007
University of Southampton
150 mW, 4.4 g @ 8 Hz, 0.8 cm^3

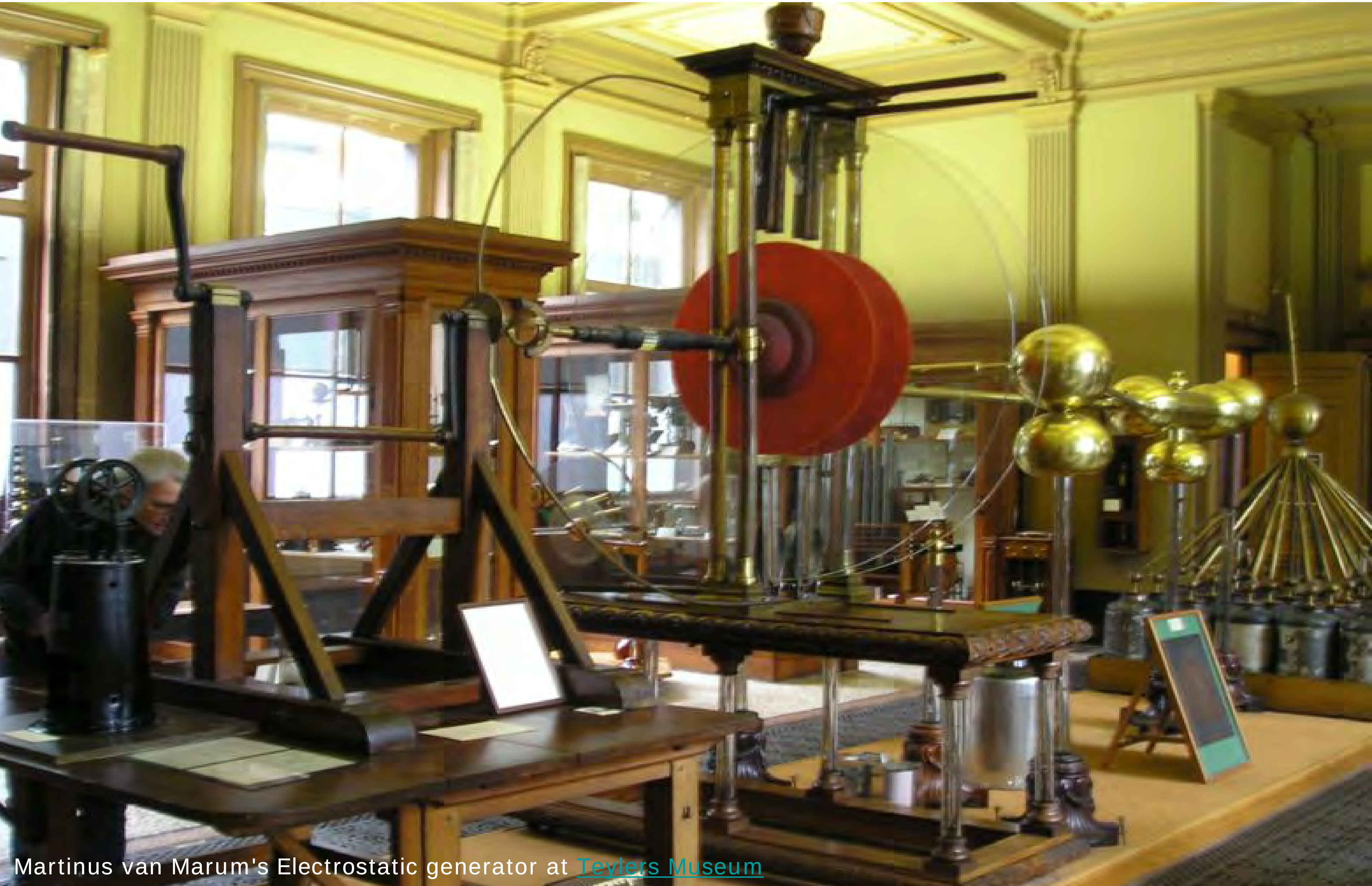


Glynne-Jones et al, 2004
University of Southampton
600 μW at 4.3m/s^2 @ 100 Hz

D. Spreemann et al., 2006
HSG-IMIT
260 μW, 4 m/s^2 @ 25 Hz, 1.5cm^3

PMG Perpetuum
40 mW, 1 g @ 100 Hz,
110 cm^3

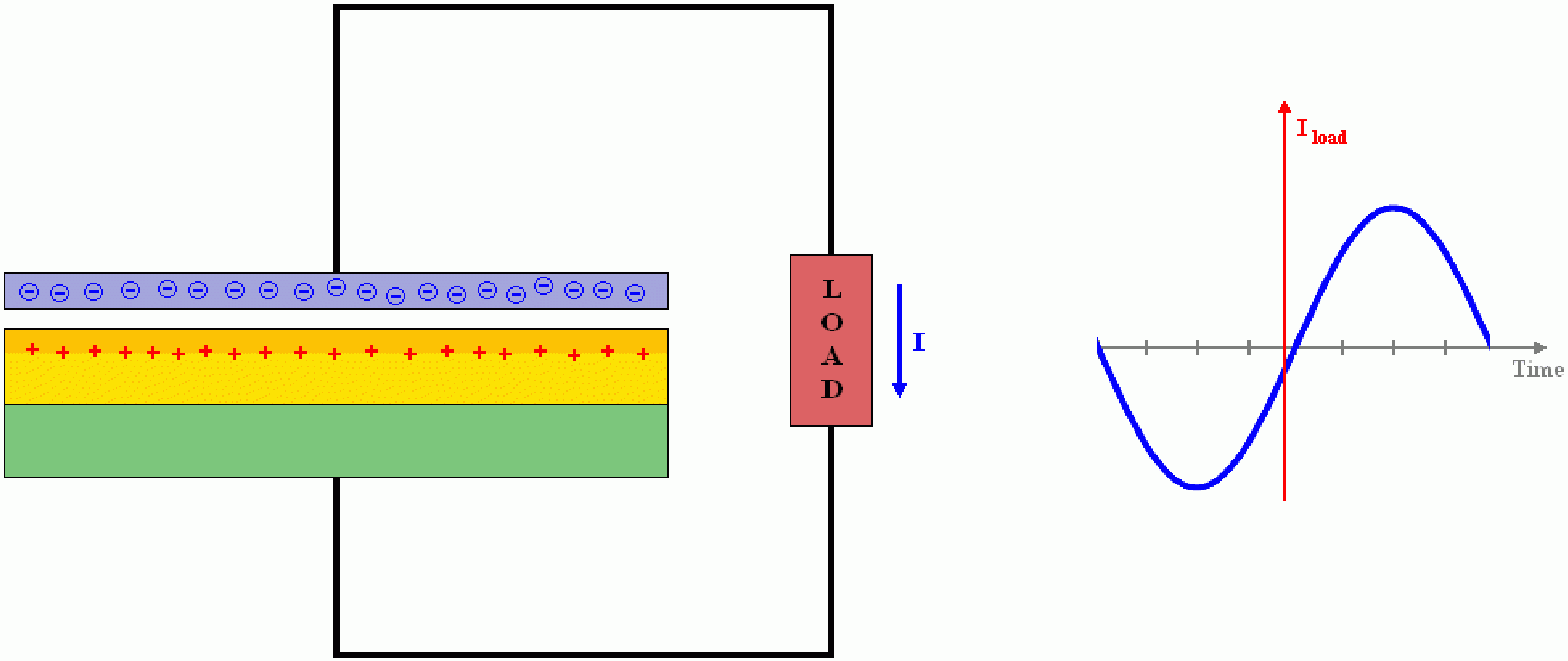
Vibration Harvester State-of-the-art
Electrostatic **transducers**



Martinus van Marum's Electrostatic generator at [Teylers Museum]

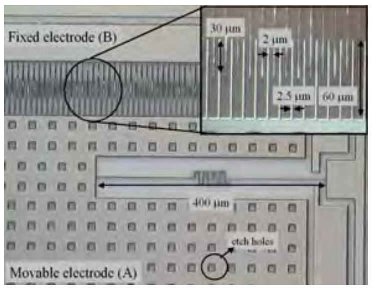
Vibration Harvester State-of-the-art
Electrostatic **transducers**

- **Basic principle: charge and discharge of capacitor**
- **Charge or voltage constrained**
- **Miniaturization helps: larger capacitance variation**
- **First micromachined embodiment in 2003**

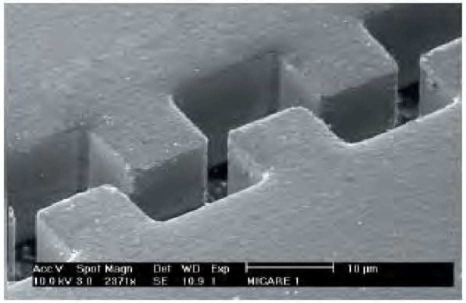


Vibration Harvester State-of-the-art
Electrostatic **transducers**

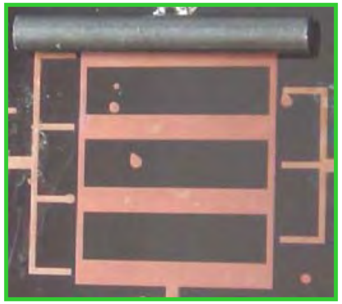
- **Two kinds: resonant (most) and non-resonant**
- **Mostly a 2D embodiment**



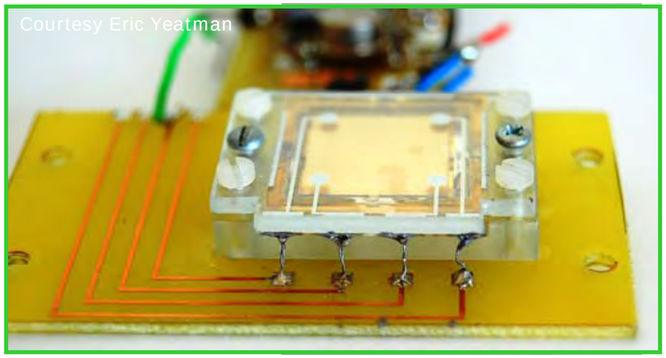
T. Sterken et al., 2003
IMEC, K.U. Leuven
12 nW, 1 g @ 1 kHz, 2 mm^3



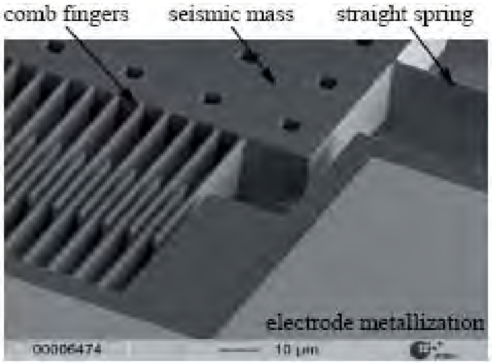
G. Despesse et al, 2007
LETI – MINATEC
12 µW, 0.3g @ 50 Hz, 1cm^2



M. Kiziroglou et al, 2008
Imperial College London



E. Yeatman et al., 2006
Imperial College London
2.4 mW, 40g @ 20 Hz, 2 cm^3



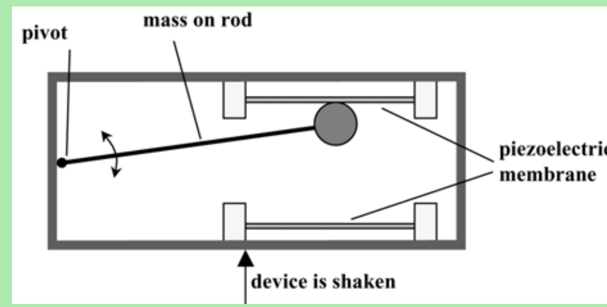
U. Bartsch et al., 2007
IMTEK

Vibration Harvester State-of-the-art
Piezoelectric **transducers**

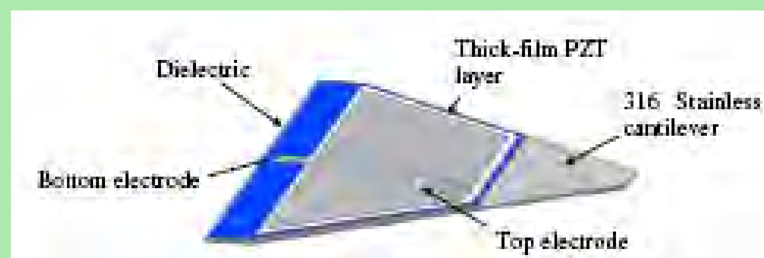
- **Basic principle: mechanical stress generates charges**
- **Relative vs absolute motion**
- **First miniature embodiment in 2001**

Joseph Paradiso, MIT
1-2mW average, 20-80mW peak
1998

MACRO



Umeda et al., 1996
Niigata Polytechnic College

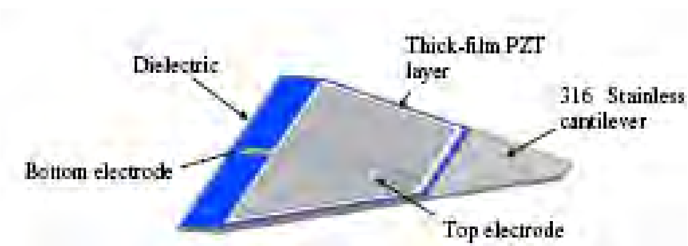


Glynne-Jones et al., 2001
University of Southampton
3 μW, 1 g @ 80Hz

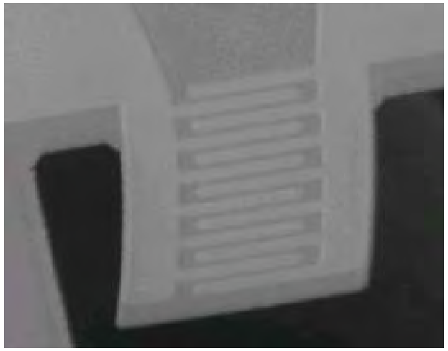
MINI / MICRO

Vibration Harvester State-of-the-art
Piezoelectric **transducers**

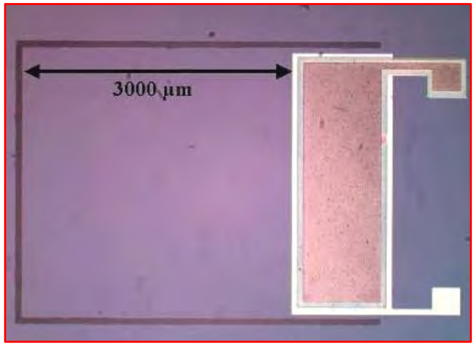
- **Micromachined devices are resonant transducers**
- **PZT or AlN used (high d_{31} or low ε)**



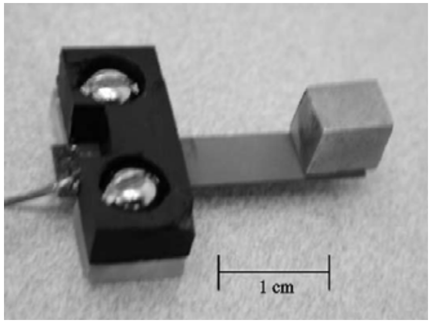
Glynne-Jones et al., 2001
University of Southampton
3 μW, 1 g @ 80Hz



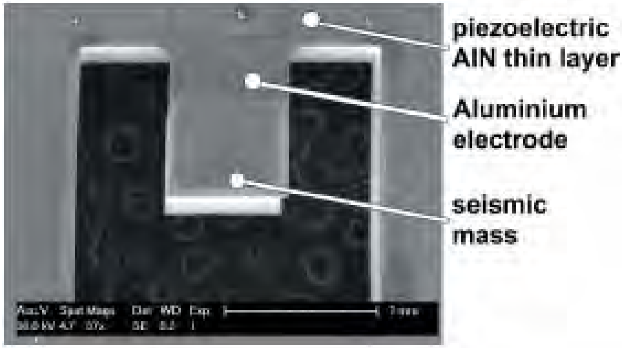
Sang-Gook Kim, Rajendra Sood, MIT, 2004
1 μW @ 2.36 V (0.74 mW-h/cm^2)



M. Renaud et al., 2007
IMEC, K.U. Leuven
40 μW, 20g @ 1.8 kHz, 25 mm^3



Shad Roundy et al, Berkeley, 2003
70 μW, 2.25 m/s^2 @ 100Hz, 1cm^3

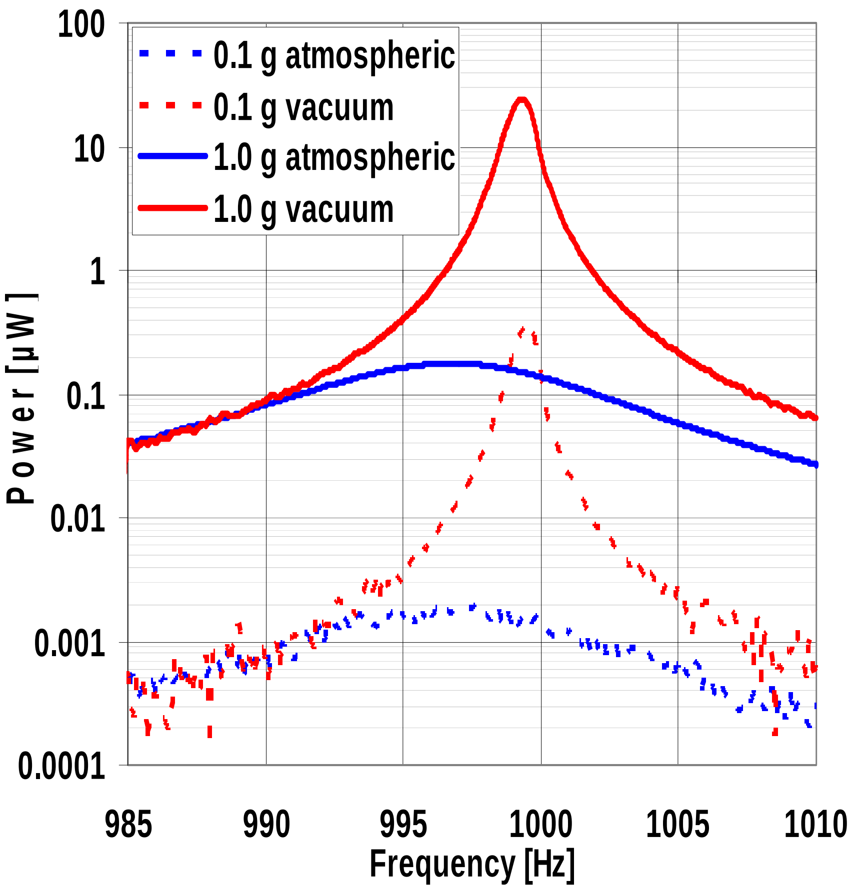


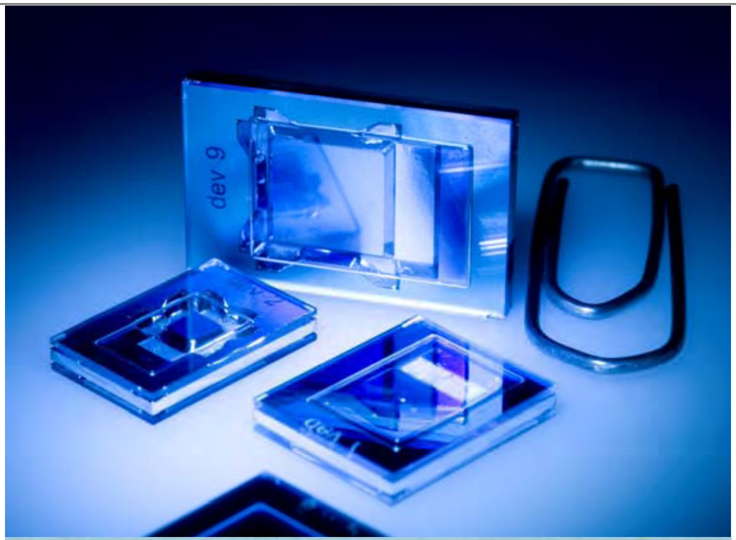
M. Marzencki et al, Tima Labs, 2007
2 μW, 2g @ 840 Hz, 25mm^3

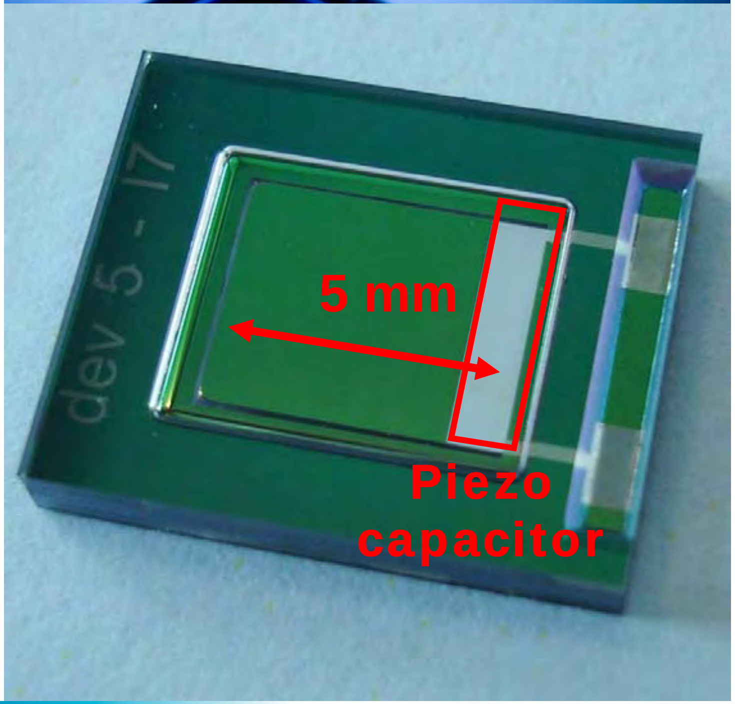
Elfrink et al., 2008, IMEC
60 μW, 2g @ 572Hz, 0.2 cm^2

MEMS based piezoelectric energy harvesters

R. Elfrink @ HOLST/IMEC, IEDM2009

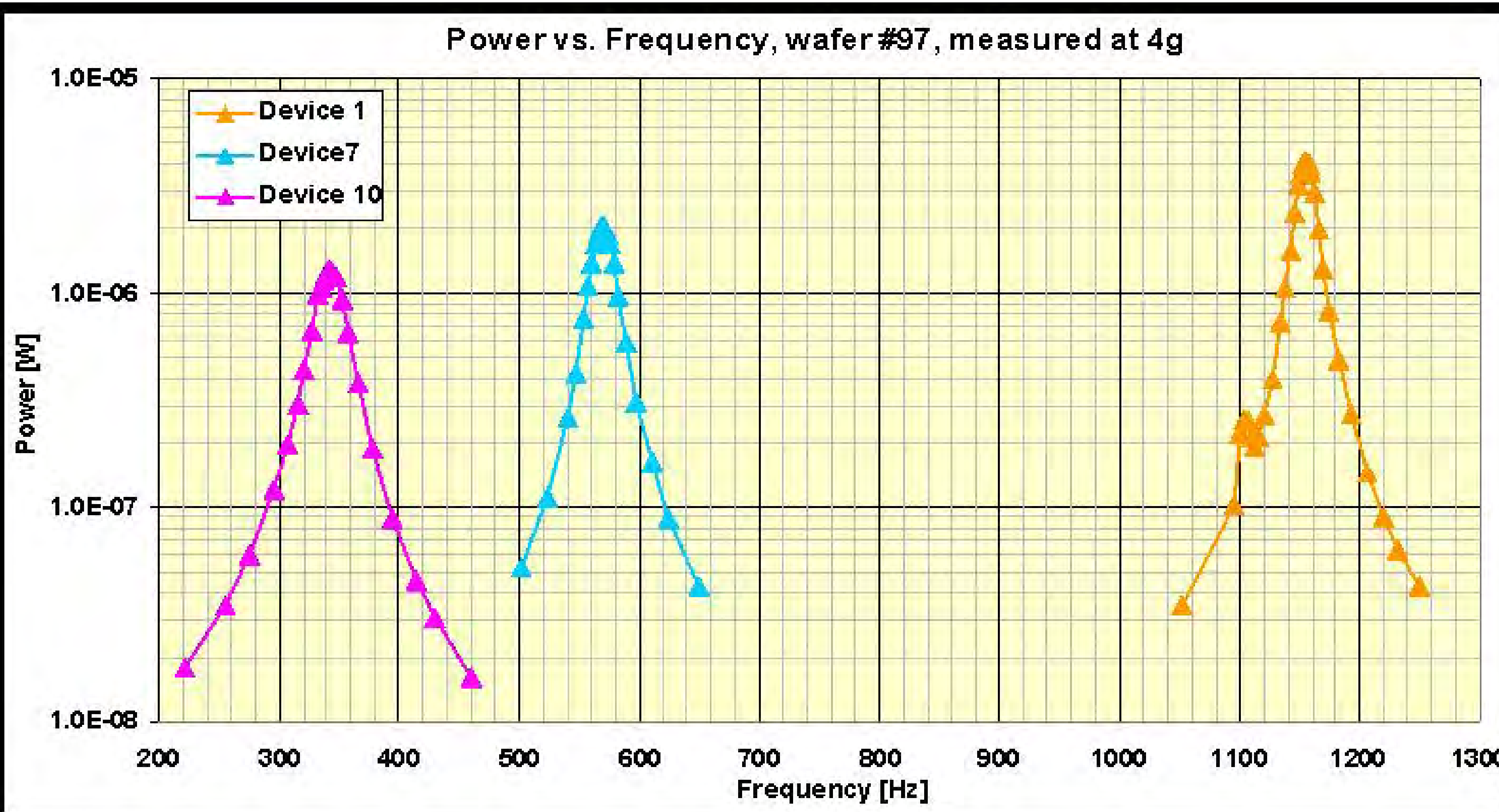






After the good … now the bad and the ugly …

RESONANCE



After the good … now the bad and the ugly …

GENERATED VOLTAGES !!

- Voltage output can be in the millivolts
- Voltage output can be in the 100’s of volts

RELIABILITY !!

- Large deformation at resonance
- Friction and stiction

Need for Co-DESIGN !!

- Multiphysics problem

After the good … now the bad and the ugly …

MECHANICS

- Increase **mass**
- Increase (maximum) **travel**
- Reduce **air damping**
- Reduce **size**

resonance

match power transfer

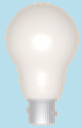
TRANSDUCER

- Increase **transformation ratio**
- Minimize **parasitics**
- Minimize **capacitance** (LPF)

ELECTRONICS

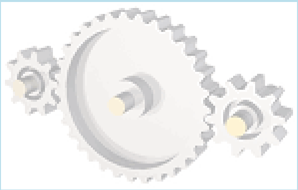
- Minimize **power consumption**
- Minimize **power losses**
- Increase **voltage range**

Micropower: Harvesting Sources



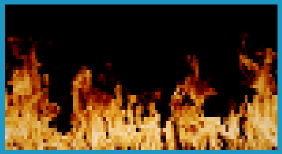
Photovoltaic

Outdoor
10 mW/cm^2
Indoor
10 μW/cm^2



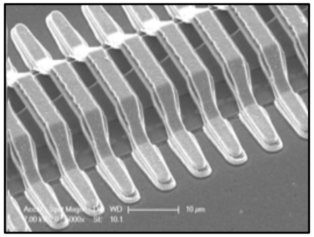
Vibration

Man
4 μW/cm^2
Machine
100 μW/cm^2



Thermal

Man
20 μW/cm^2
Machine
1-10 mW/cm^2



RF

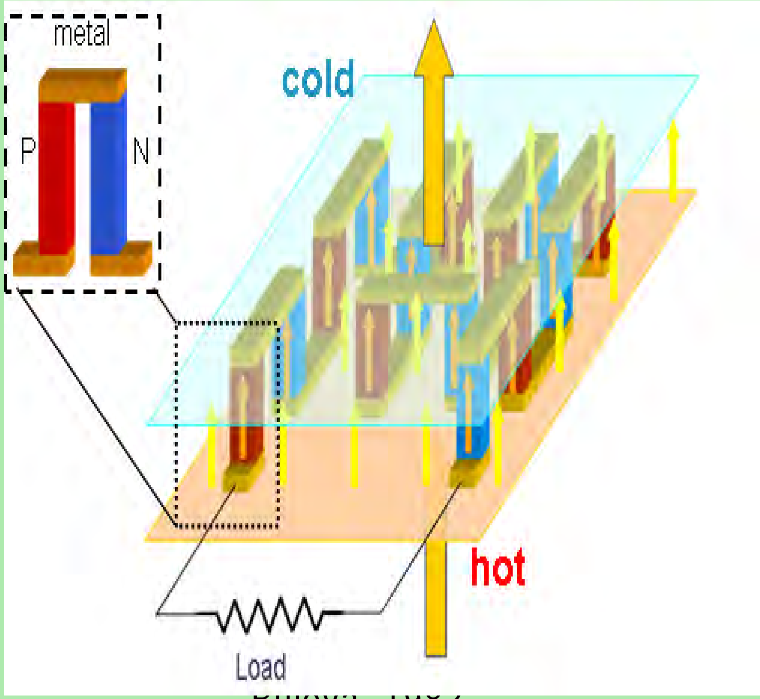
GSM
0.1 μW/cm^2
WiFi
0.01 μW/cm^2

Thermal Energy Harvester State-of-the-art
Thermoelectric **generators**

- **Basic principle: Seebeck effect**
- **Many macroscopic embodiments**
- **First miniature embodiments in watch industry**

Voyager RTG
^{238}Pu
87.7 years half-life
390 Watt generated
(7200 Watt thermal)

(not a ‘true’ scavenger)



Bulova, 1982

MACRO

MINI

Thermal Energy Harvester State-of-the-art
Body-temperature harvesters date back 30 years !

- **Bulova Thermatron**
  - Reported and introduced 1980
  - 2000 $ (1982)
  - 700 thermocouples, 0.25mV/thermocouple, 175mV open circuit voltage, 10µWatt generated power

" Los Angeles Times Special in Chicago Sun-Times, August 17, 1980, p. 37.

Bulova Watch Co. researchers in Switzerland have scored a technological breakthrough that may have a permanent impact on not only the watch industry, but also on other small battery-powered appliances, such as hearing aids .

Describing an electric quartz watch that needs no battery, the article explains:
It operates off a sophisticated new solid state device called a Thermatron, which uses body heat to generate electricity to power the watch. Unlike batteries, which last about a year, the Thermatron lasts almost indefinitely, Bulova says.
The Thermatron is a tiny thermo-electric generator that produces energy when it detects even a 1 degree difference-between body heat and an insulated portion of the quartz mechanism.

Thermal Energy Harvester State-of-the-art
Body-temperature harvesters date back 30 years !

- **Bulova Thermatron**
  - Reported and introduced 1980
  - 2000 $ (1982)
  - 700 thermocouples, 0.25mV/thermocouple, 175mV open circuit voltage, 10μWatt generated power

proved with the purchase of modern equipment and technology.

In the marketing area a new merchandising team redesigned and upgraded the entire Accutron, Bulova and Caravelle watch lines in order to give each a distinct look in its price range. Introductions will take place throughout 1981. A marketing program has been developed to emphasize the prestige and beauty of the Bulova Swiss Watch collection.

Substantial sales progress was achieved by the Bulova Clock Division, which now has a line of boutique, alarm, mantel and wall clocks comprising almost 200 models.

Confidence in the steps taken to improve quality has led to the introduction of a two-year warranty for watches instead of the one-year term customary in the watch industry.

Development of a patented new watch called Thermatron®, which incorporates a unique system using body heat to power the watch, was announced during the year.

While the jewelers' 1980 Christmas season, traditionally the most important in the watch business, was generally soft, the programs planned to mature in 1981 should result in solid progress for Bulova.

period, 2,421,521 shares of common stock were issued on exercise of outstanding warrants to purchase shares of the Company's common stock, which expired on November 29, 1980. At February 27, 1981, 12,822,000 shares of common stock were outstanding.

Loews management continues to be sensitive to the uncertain economic conditions impacting our businesses. Continued devotion to building those businesses, with careful allocation of capital where we believe it will result in the greatest returns for our shareholders, will enable us to continue to grow and prosper.

In this annual report, on pages 40 through 42, shareholders will find balance sheets, statements of income and statements of changes in financial position, accounting for CNA as an investment under the equity method of accounting, as compared to its consolidation in our financial statements in accordance with generally accepted accounting principles. We think these statements will aid you in assessing our inherent strengths.

On behalf of the Board of Directors, we thank our employees and shareholders for their commitment and support.

Confidence in the steps taken to improve quality has led to the introduction of a two-year warranty for watches instead of the one-year term customary in the watch industry.

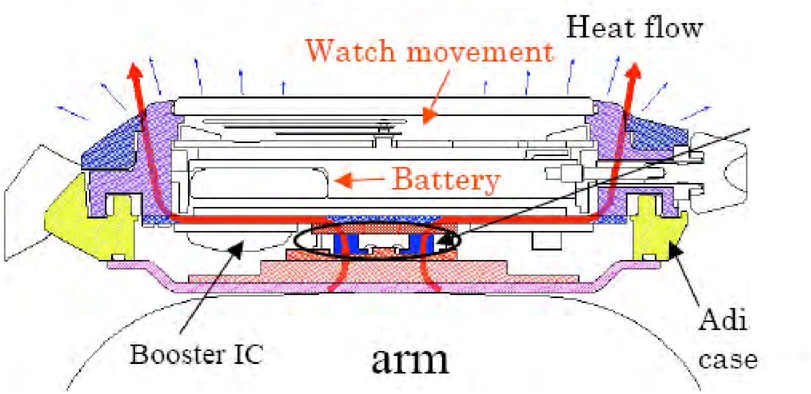
Development of a patented new watch called Thermatron®, which incorporates a unique system using body heat to power the watch, was announced during the year.

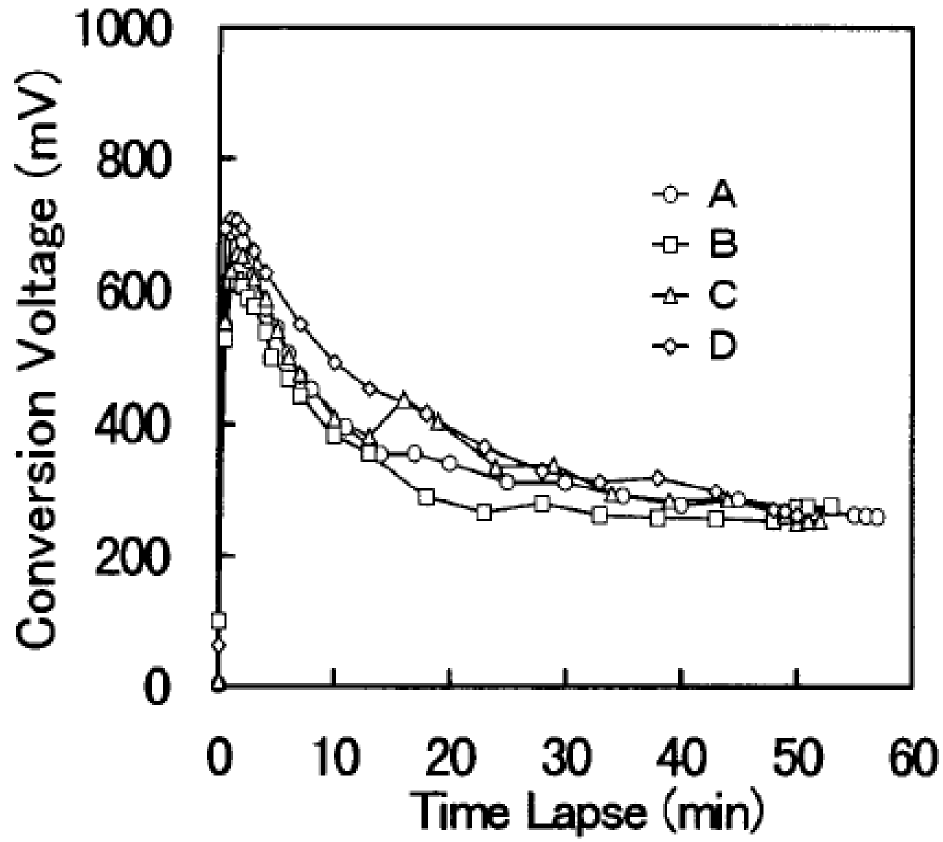
While the jewelers' 1980 Christmas season, traditionally the most important in the watch business, was generally soft, the programs planned to mature in 1981 should result in solid progress for Bulova.

Thermal Energy Harvester State-of-the-art
Body-temperature harvesters date back 30 years !

- **TEG watches revisited: Seiko SII Thermic® from 1998**
  - Uses 10 thermoelectric generator modules and a DC/DC convertor IC
  - 300,000 yen

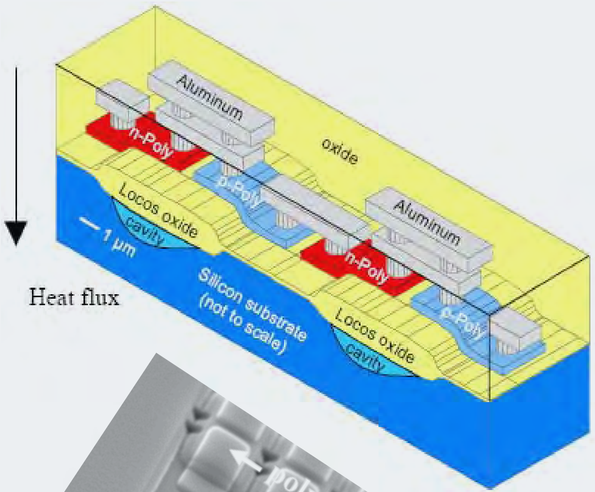
Thermal energy watch

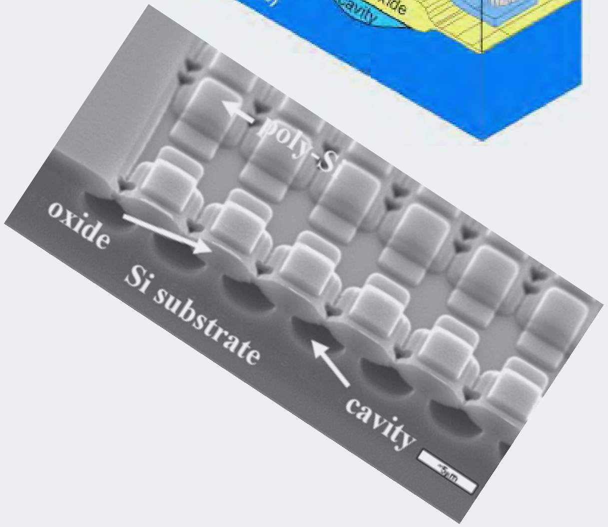




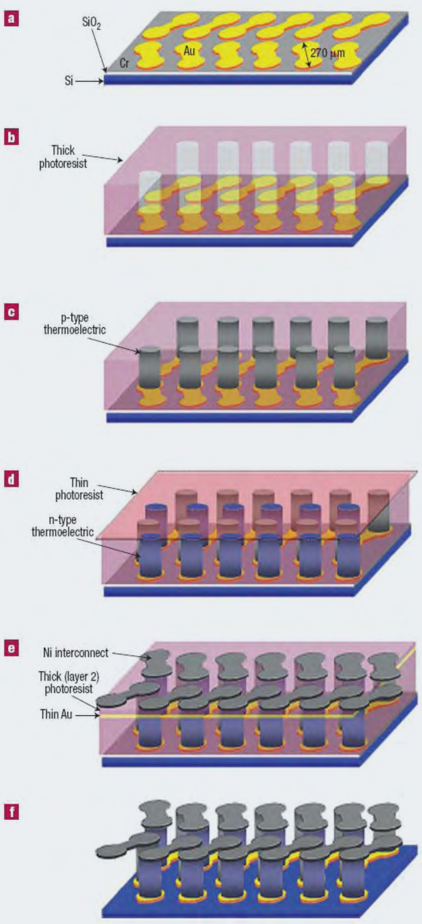
source : SEIKO

Thermal Energy Harvester State-of-the-art
Miniature or Micromachined Thermal Generators

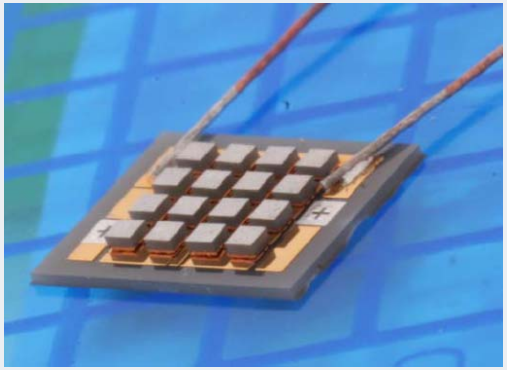




Strasser, Infineon,
Sensors & Actuators 2002
(0.1) 1uW/cm2 for (4) 14 °C
forced temperature difference



G. J. Snyder, J.R. Lim, C-K Huang, J-P. Fleurial, JPL
Nature Materials 2003
1µW at 2mV under external flux



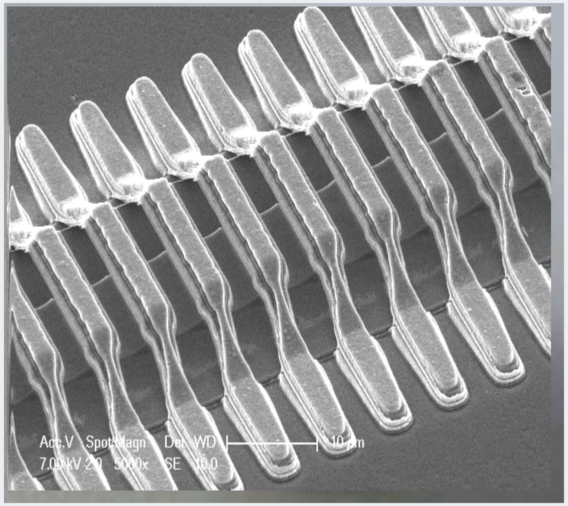
Nextreme Thermal Solutions BiTe/SbTe SL

140µW at ΔT = 0.8K, 5mV open circuit voltage

Source: Fraunhofer 2007

200mV open circuit voltage

Thermal Energy Harvester State-of-the-art
Miniature or Micromachined Thermal Generators

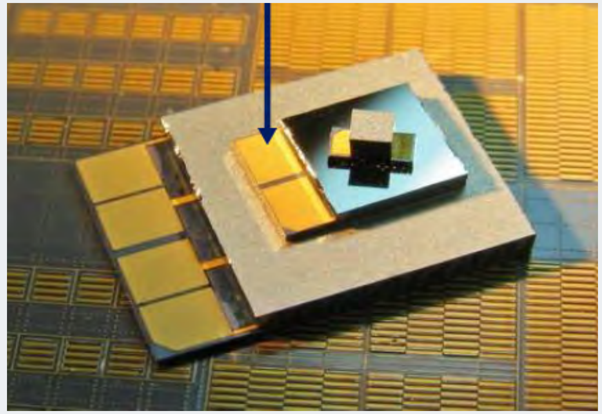


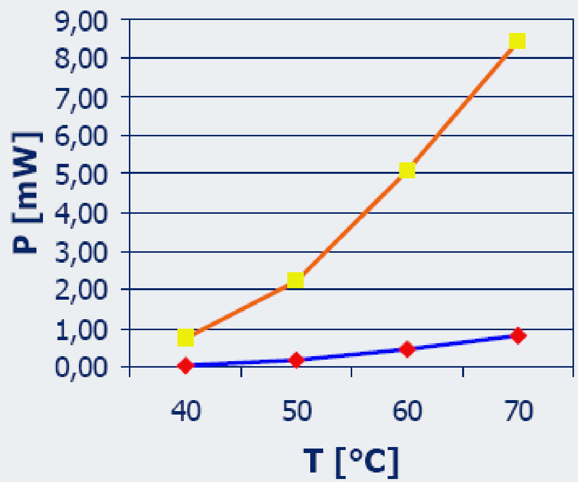
polySiGe thermopiles
Source: Leonov & Wang, **IMEC**

Source: LETI

4 $\mu W/cm^2$ at $\Delta T = 1^oC$

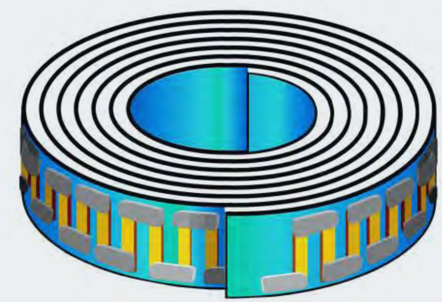
1 V at $\Delta T = 60^oC$





Source: Micropelt TEG (shown without cooler)

Courtesy Harald Böttner, FhG IPM



5200 BiTe thermocouples on kapton tape

123μW at ΔT = 5K
(42.5uA at 2.9V)

Source: **ThermoLife**

After the good … now the bad and the ugly …

GENERATED VOLTAGES !!

- Voltage output can be in the millivolts

RELIABILITY !!

- MEMS production YIELD challenge: Many elements in series

COST !!

- Traditional TEG manufacturing is too expensive
- Exotic new materials are promising but cost TBD

After the good … now the bad and the ugly …

- **Further improved PERFORMANCE could be achieved using new materials**
- **Provided the COST and RELIABILITY are manageable**

Typ	Material	Price in $/kg (metals)
V-VI	Bi_2Te_3	140
IV-VI	PbTe	99
Zn_4Sb_3	Zn_4Sb_3	4
Silicides	p-MnSi1.73	24
	n-$Mg_2Si_{0.4}Sn_{0.6}$	18
	$Si_{0.80}Ge_{0.20}$	660
	$Si_{0.94}Ge_{0.06}$	270
Skutterutides	$CoSb_3$	11
Half-Heusler	TiNiSn	55
n/p-Clathrate	$Ba_8Ga_{16}Ge_{30}$	1000 without Ba
Oxides	p-$NaCo_2O_4$,	17 without Na, O
Zintl Phasen	p-$Yb_{14}MnSb_{11}$	92
Th_3P_4	$La_{3-X}Te_4$	160

Courtesy: Harald Böttner

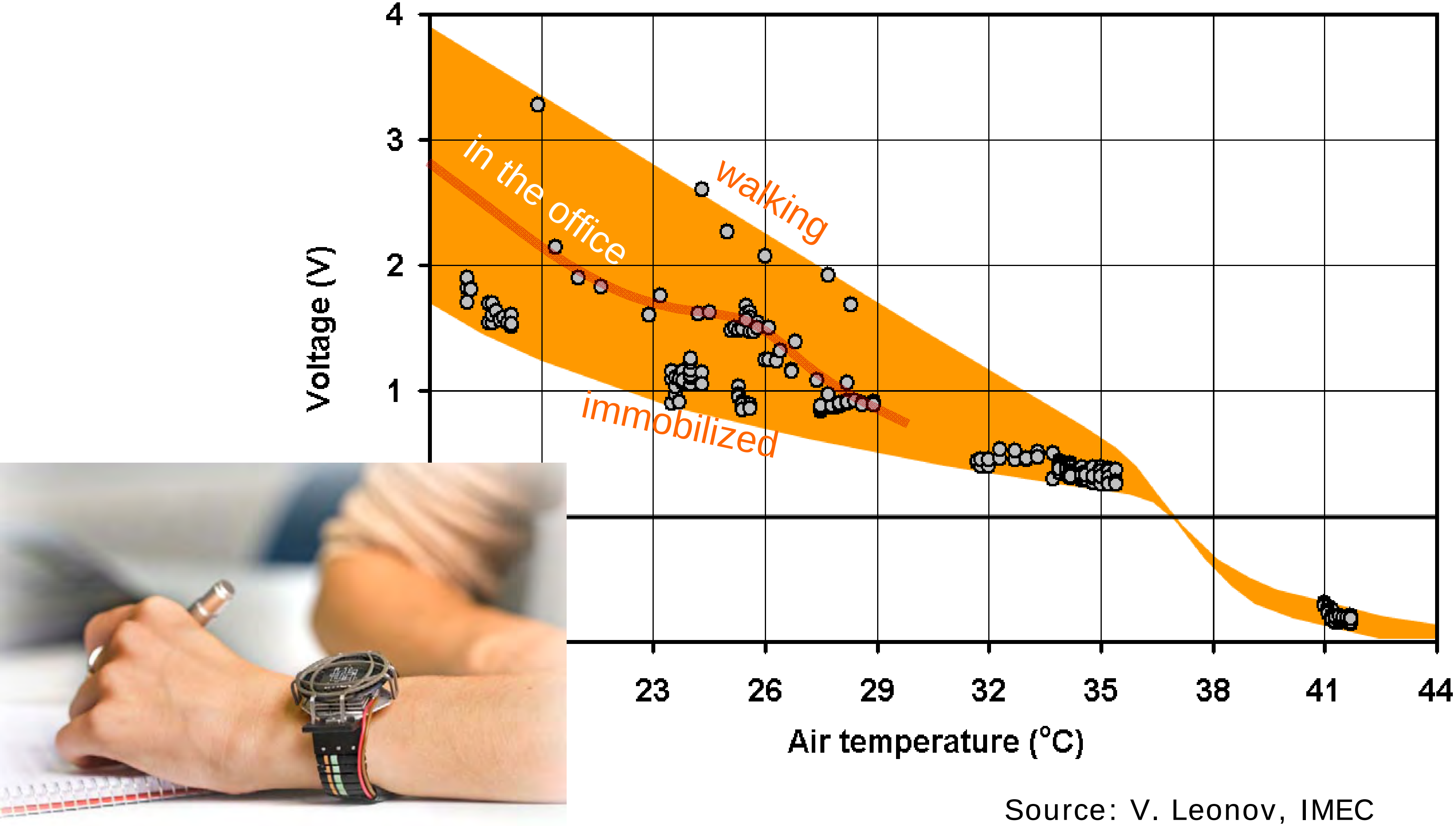
Fraunhofer IPM

IPM

Fraunhofer Institut Physikalische Messtechnik

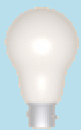
After the good … now the bad and the ugly …

- CAUTION: **thermal generation from humans in a real-life environment depends on many factors: metabolism, heat balance, activity, ambient temperature, humidity, …**



Source: V. Leonov, IMEC

Micropower: Harvesting Sources

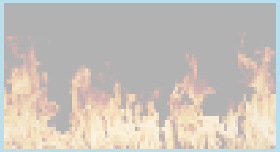


Photovoltaic

Outdoor
10 mW/cm^2
Indoor
10 µW/cm^2

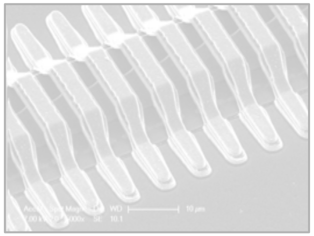
Vibration

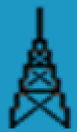
Man
4 µW/cm^2
Machine
100 µW/cm^2



Thermal

Man
20 µW/cm^2
Machine
1-10 mW/cm^2

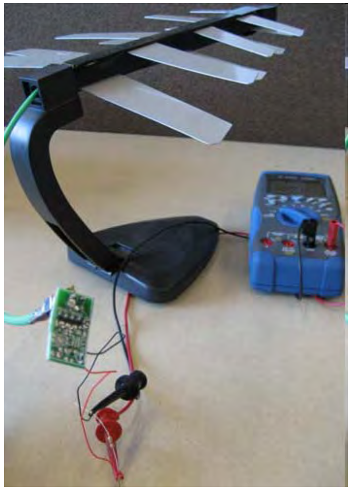




RF

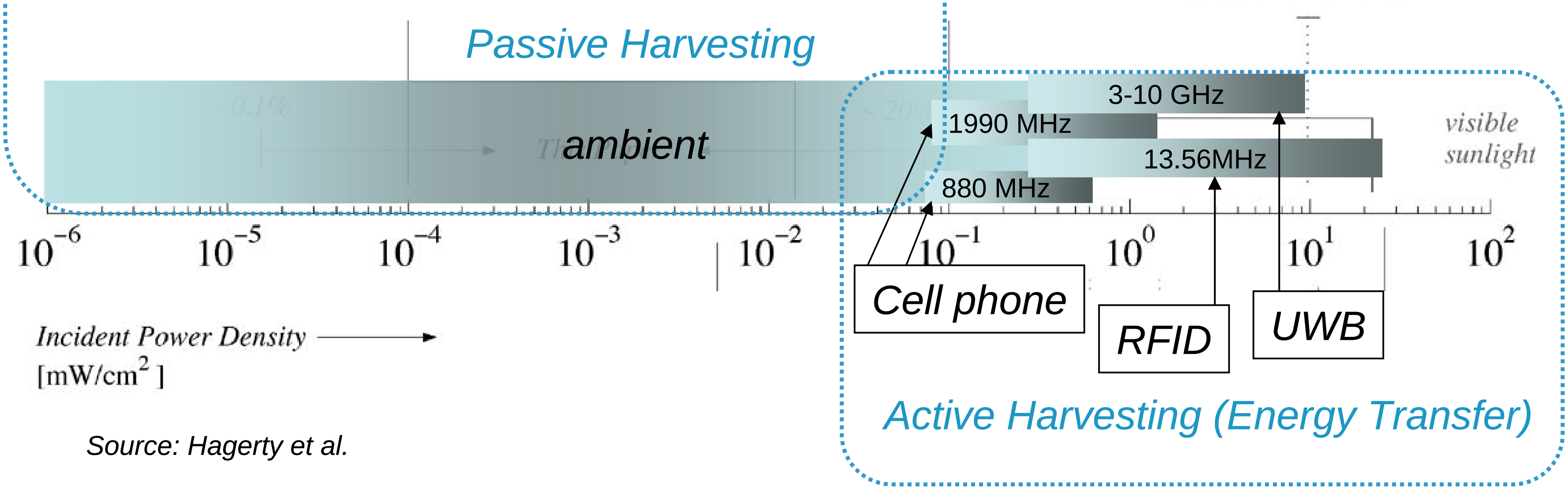
GSM
0.1 µW/cm^2
WiFi
0.01 µW/cm^2

Passive vs. Active RF Harvesting



Intel demo:
Area ~ 30x20 cm^2
Power ~ 60 µW -> 0.1µW/cm^2
At 4 km of source

The US E-M spectrum



Source: Hagerty et al.

RF Energy Transfer

First systems on the market
Room for improvement

Power transfer: Friis Eq:

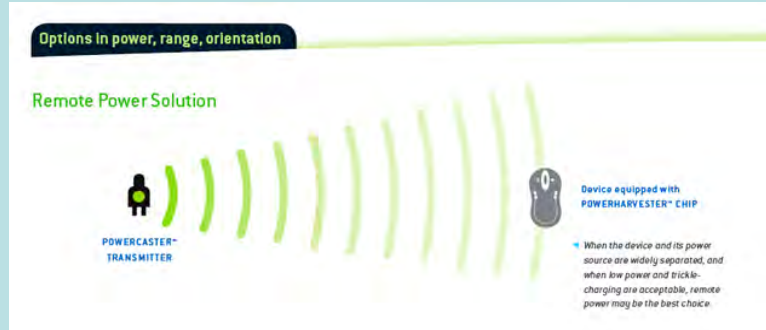
$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2}$$

λ: *Wavelength used*
- **Standardization**

G_r, G_T: *Antenna Gain*
- **Optimize Design**

$P_T P_R$: *Power transmitted, received*
- **AC-DC converter gain**
- **Integration**
- **Legal/Health Regulations**

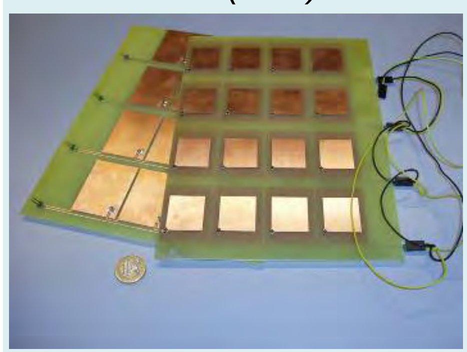
POWERCAST simply wire free

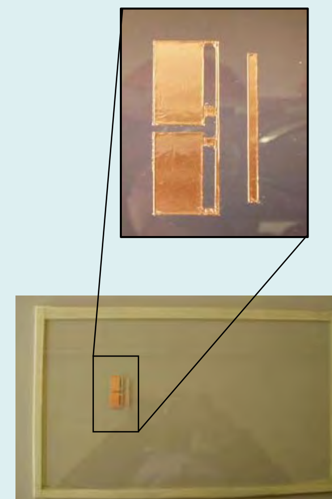


15mW@30cm
P_T ~ 3W

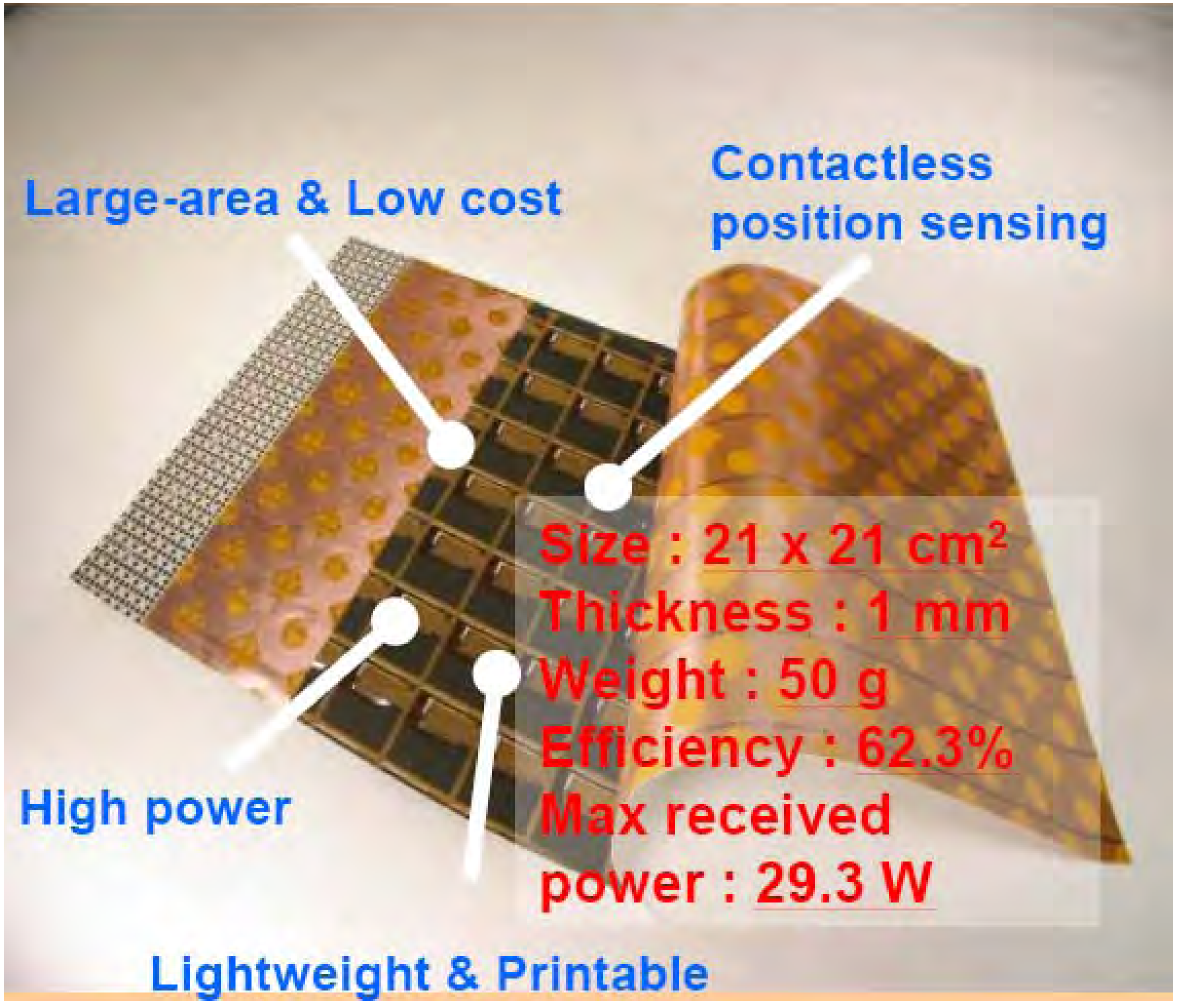
www.powercast.com

P_T = 100mW
P_R=1.5mW@20cm
Visser et al. (Imec)



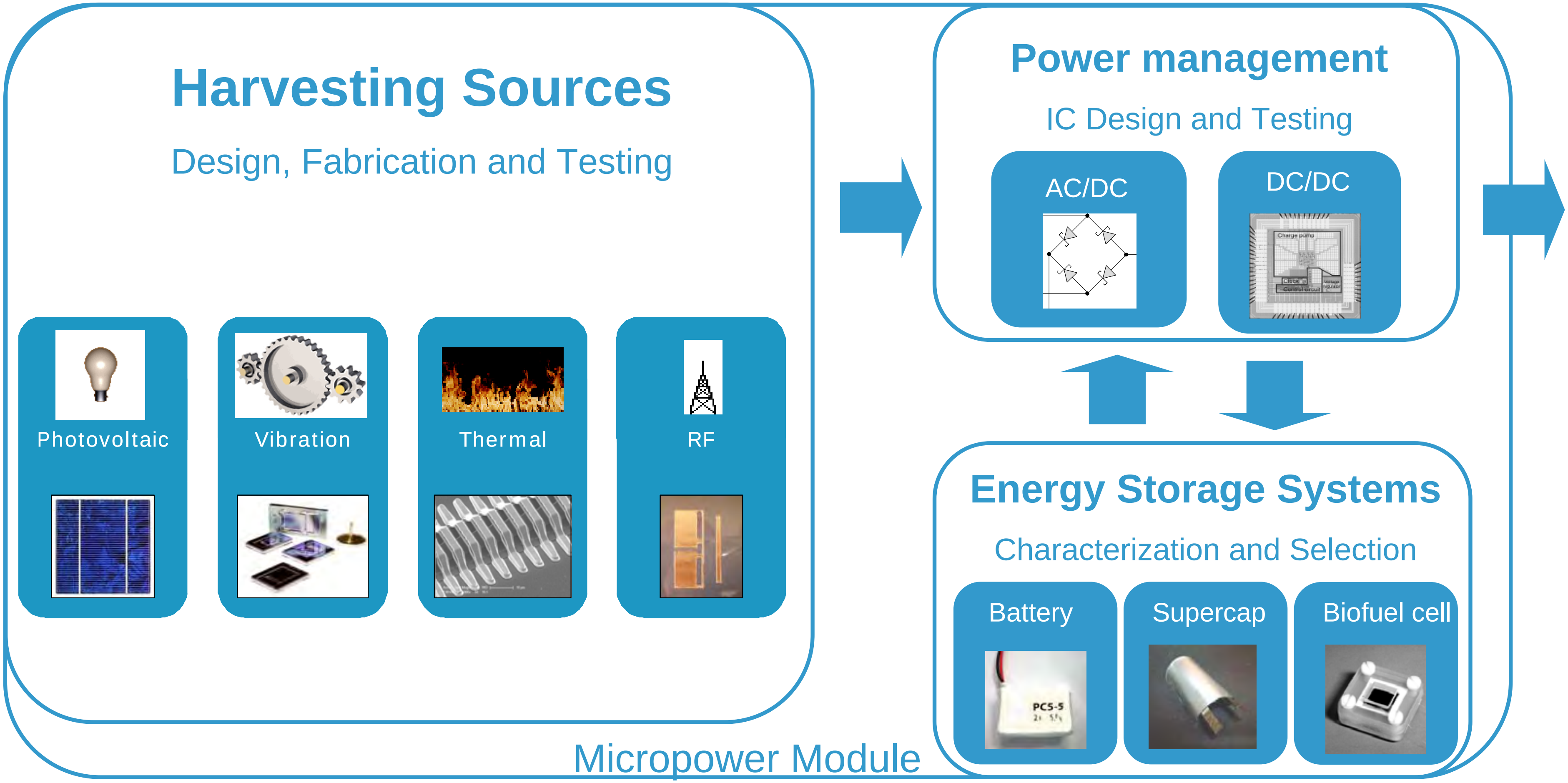


RF Energy Transfer
RF powering for ambient intelligence applications



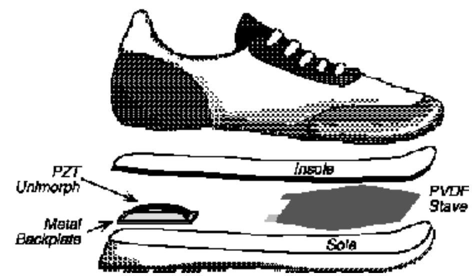
Takayasu Sakurai, University of Tokyo
IEDM2006, ISSCC2007, ISSCC2008

No practical power without power *management*

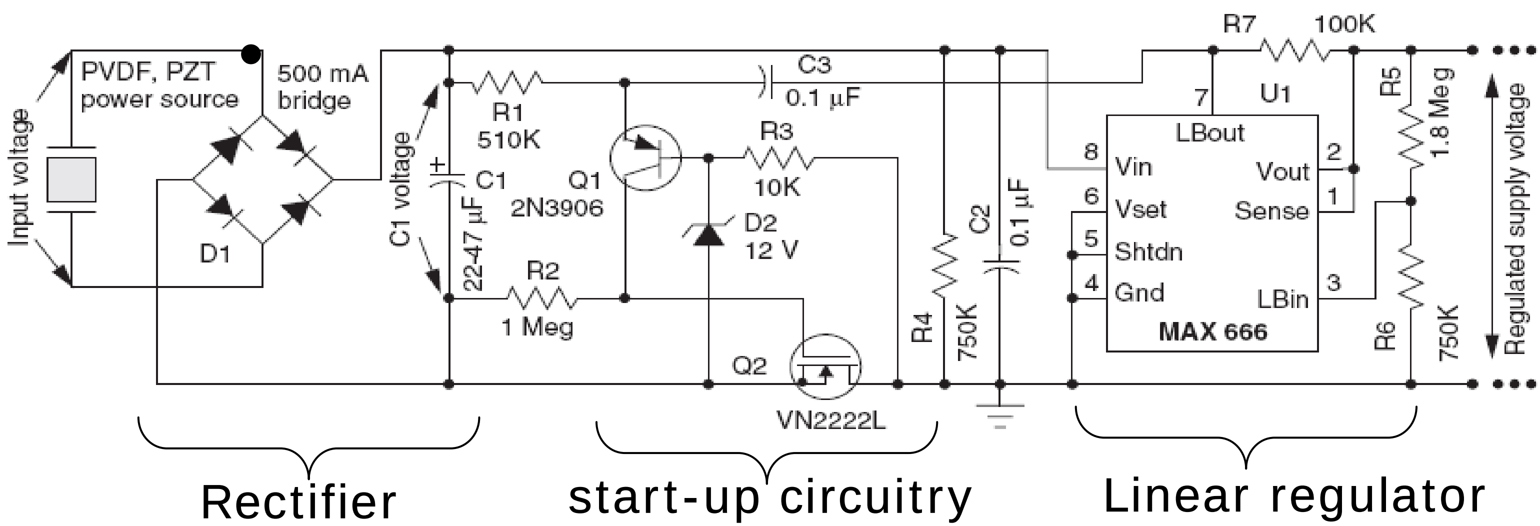


Power Management Circuits for Vibration / Motion Energy Harvesters

- **The earliest (basic but complete) system**
  - + Low power consumption, simple control: 15 µA
  - + Input power: ~1.3 mW
  - + Self-starting
  - - Voltage drop across diodes
  - - Losses in linear regulator



source : J.A. Paradiso, 2001



Integration of micropower storage (mW-μW range) is a challenge

Thin-film-flexible

Lithium-flexible

Lithium-coin

Printable

Supercapacitor

Emerging (thin film) storage systems are being introduced

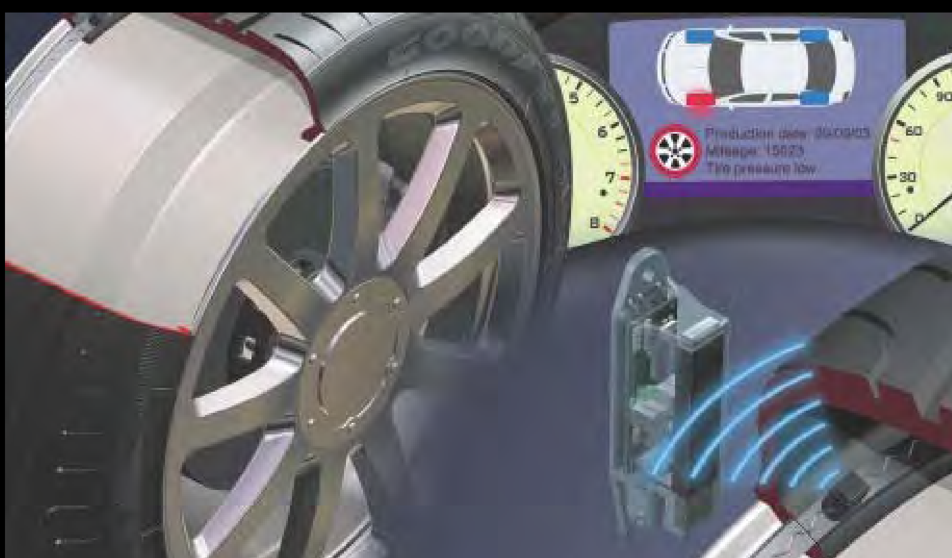
The road towards Energy Autonomy

Towards Practical Use Cases

Anticipated killer applications of Vibrational Energy Harvesting

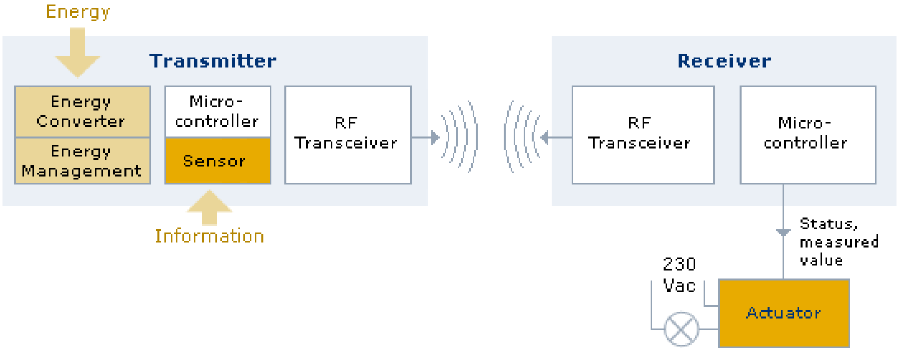
Predictive Maintenance

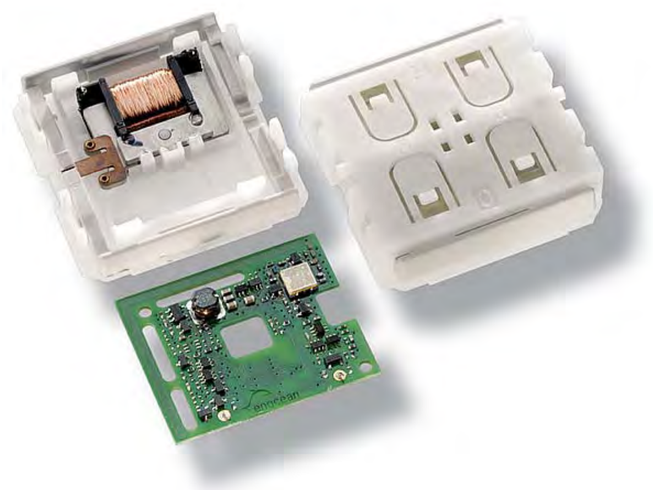
TPMS
Tire Pressure Monitoring System



Selected Current Use Cases (not MEMS enabled)
Electromagnetic transducers

- ENOCEAN, **targeting light switching**





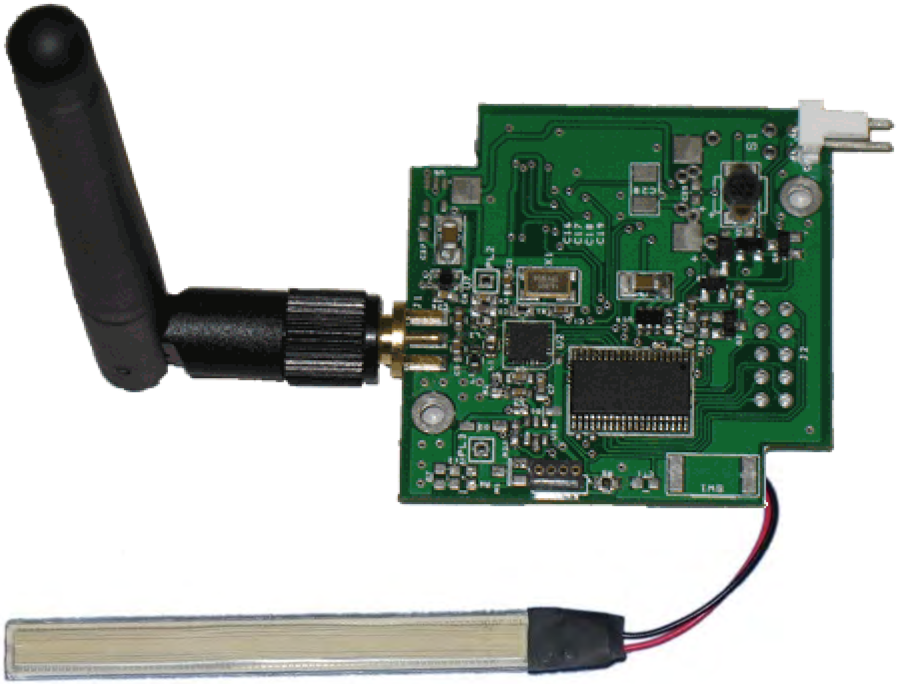
Source: Enocean
http://www.enocean.com/en/

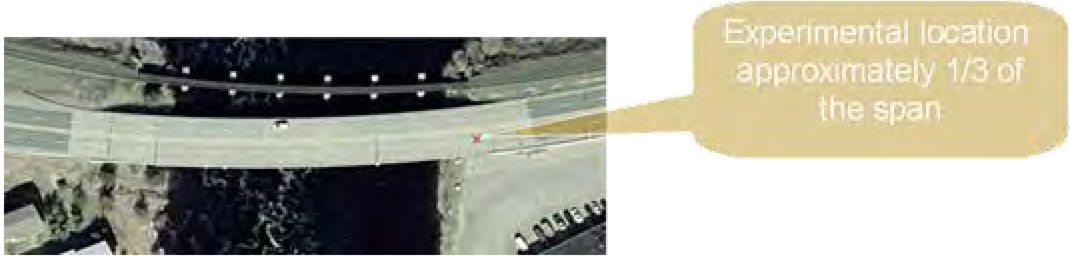
- PERPETUUM, **targeting oilfield applications (intrinsically-Safe)**
  - Operates from the prevalent 100Hz and 120Hz vibration bands on electrical machines
  - Typically >0.3mW power output on 95% of machines
  - Sealed stainless steel, 10 year operational lifetime

Source: perpetuum, http://www.perpetuum.co.uk/
Courtesy Steve Beeby, Uni. Southampton

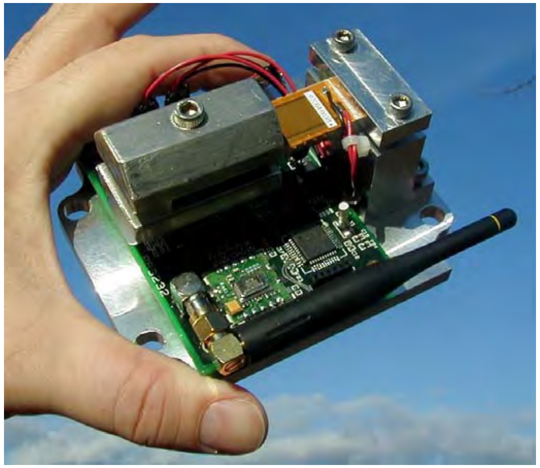
Selected Current Use Cases (not MEMS enabled)
Piezoelectric Transducers

- Ambiosystems **Wireless Mote**



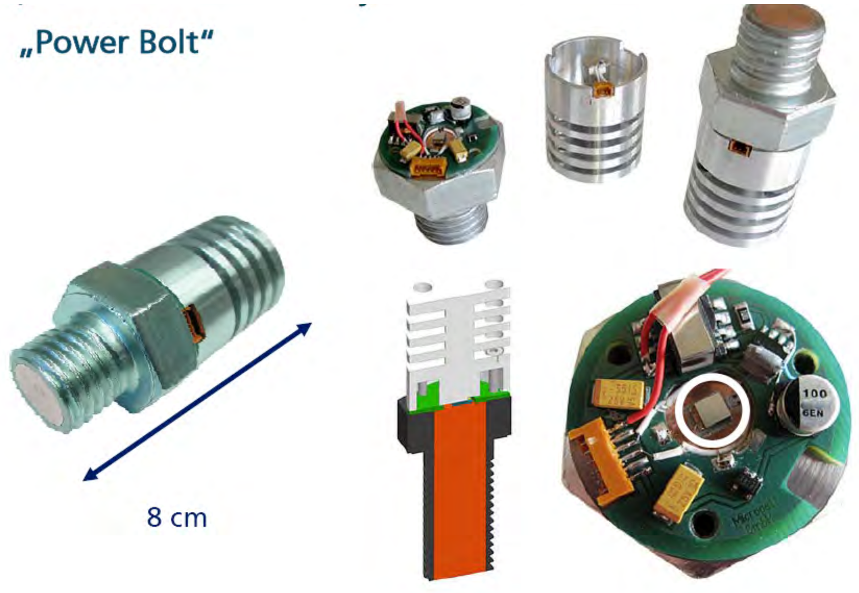


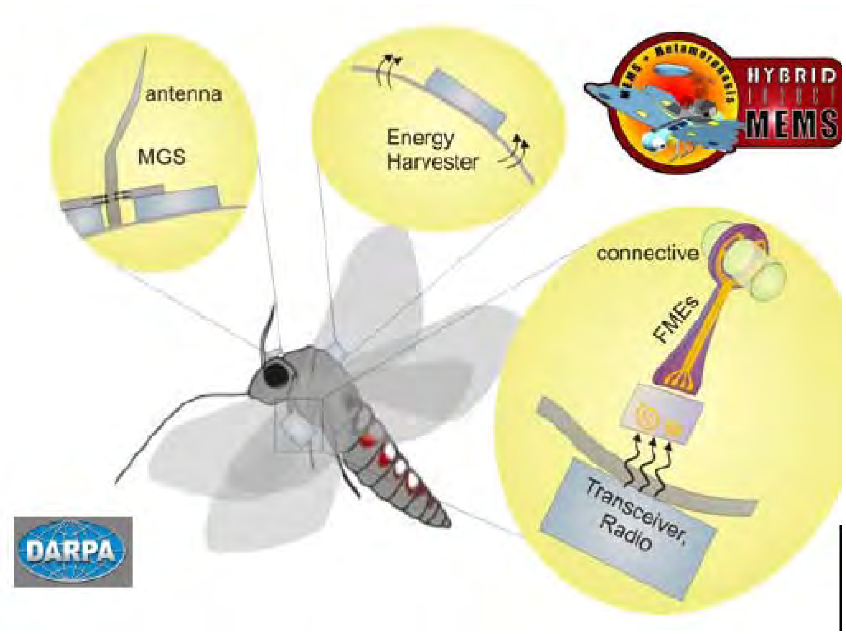
- Microstrain **Wireless Sensor Nodes**



Towards Practical Use Cases
Ongoing research examples

- **Powerbolt - Self-powered Status Monitoring (FhG & Micropelt)**
- **Self-powered flight control of flying insects (MIT)**

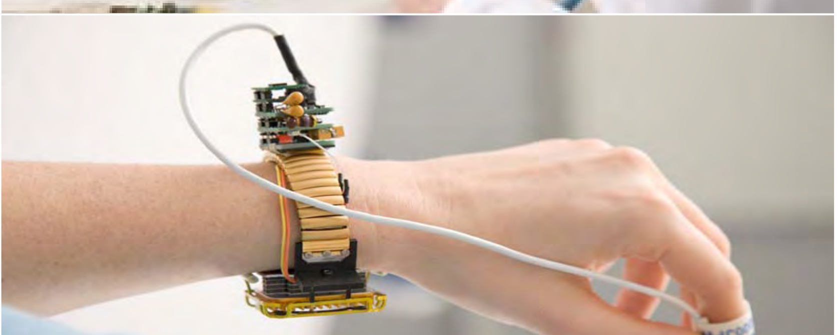




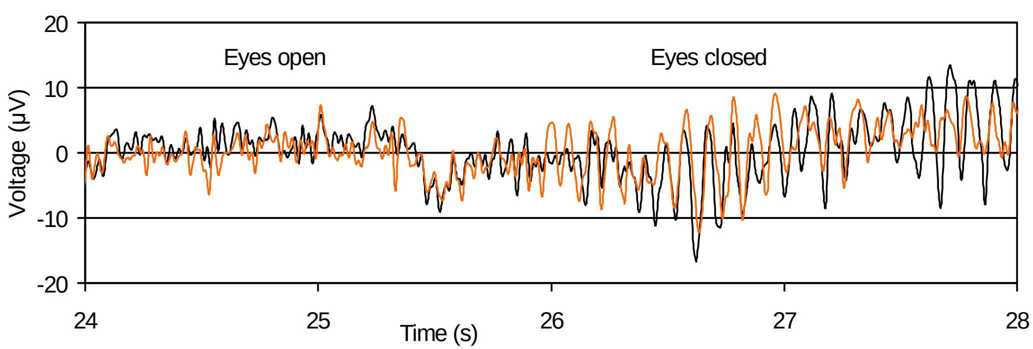
Courtesy: Harald Böttner
Fraunhofer IPM

Courtesy: Anantha Chandrakasan, MIT
Program PI: Joel Voldman, MIT

Towards Practical Use Cases - Ongoing research examples: Body-heat Self-powered Devices



wireless autonomous pulse oximeter



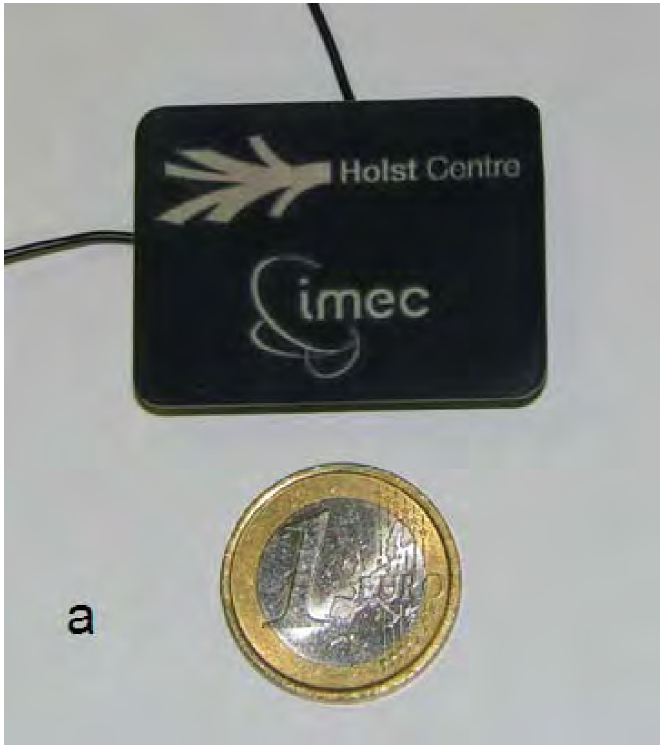
wireless autonomous EEG monitoring

Towards Practical Use:
Thermal generator in-a-shirt

2 PV devices and 14 TEG

1-2mW indoor (when walking)

3mW outdoor (when walking)



Wireless

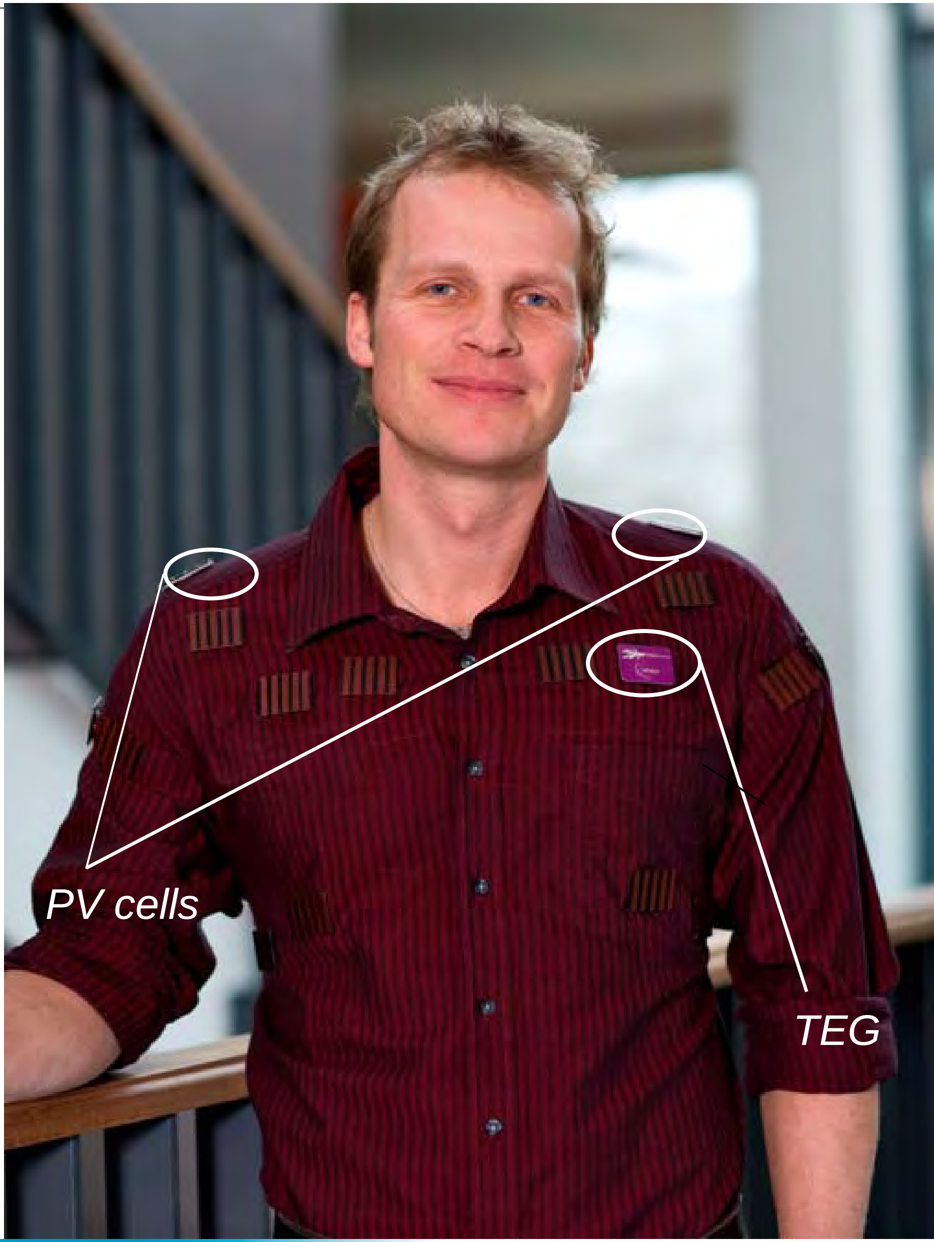
ECG

System

Efficient power management

+

ULP biopotential readout ASIC



Cost – this minor detail

- Remember: COST nearly bankrupted early adopters of thermal energy harvesting in the watch industry …
- Micromachined energy harvesters are mainly benchmarked with respect to their power output, not their cost / Wh
- A correct cost comparison should not compare the cost of a harvester to that of a battery but to the total number of batteries or the total recharge cost

How Green is Energy harvesting (really) ?

- Whether this is "GREEN" energy depends on energy payback time (what is the energy used in the production of the harvesters)
- Whether this is "GREEN" energy depends on the bill of materials used in the production and a comparison of 1 harvester replacing many batteries

Conclusions and Outlook

- **Gradual evolution from HYPE to REALITY**
- **Green Engineering using energy harvesting is however visibly emerging: real-life industrial (inc. automotive) and health applications are appearing on the market**
- **Methods to generate energy are diverse – no standard product yet**
- **From REALITY to MAINSTREAM/KILLER APPLICATION will depend on achievable *total cost* compared to competing (battery, fuel cell) technologies**

Acknowledgments

- **Steve Beeby, University of Southampton**
- **Harald Böttner, FhG IPM**
- **Anantha Chandrakasan, MIT MTL**
- MEDEA+ **Working Group on Energy Autonomous Systems** **(Marco Tartagni, Marc Belleville, Eugenio Cantatore, Hervet Fanet, Paolo Fiorini, Robert Hahn, Markus Kreitmair, Pierre Nicole, Marcel Pelgrom, Christian Piguet, Aldo Romani, Chris Van Hoof, Ruud Vullers)**
- **Eric Yeatman, Imperial College London**
- **Energy Scavenging Group, Imec - Holst centre**

Feel secure

Save energy

Lower cost

Save time

Keep track

Stay tuned

Anticipate

Improve performance

Green engineering WORKSHOP

Thursday 28th January 2010, Neuchâtel

Holst Centre

Open Innovation by IMEC-NL and TNO