Future Trends in Zero-Power Systems

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2012 Summer School of Information Engineering - Bressanone

Focus on:

- General overview
- Zero power system: a standalone intelligent machine implementing micro- and nano-power harvesting techniques
- Integrated implementation

Overview of the talk

- Zero-power systems, when, where and why
- Definitions and challenges
- Energy consumption & storage
- Energy conversion & management
- Energy harvesting
  - Harvesting from vibrations
  - Harvesting from temperature
  - Harvesting from radio-frequency
- Summary & conclusions

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Environmental Energy as an Exploitable Source

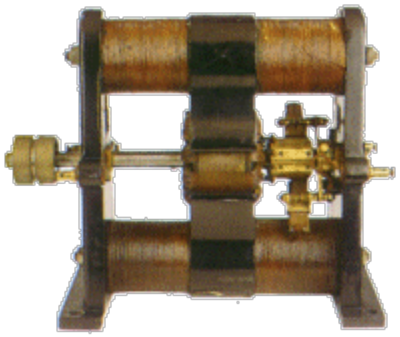
- The environment is a source of available energy in many different forms
- Man pursued its exploitation since centuries

windmills

water wheels

sails

- …then came electricity



electrochemical cells

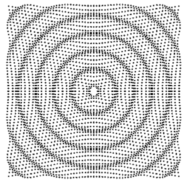
dinamo

wind turbines

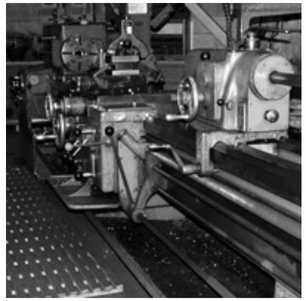
Where Energy?

- Environment as a source of highly-available low-density energy
  - Mechanical
  - Thermal
  - Electromagnetic
  - Solar
  - etc.

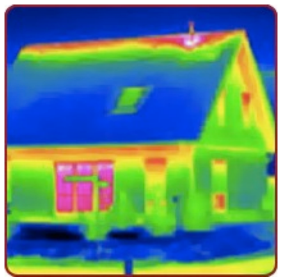
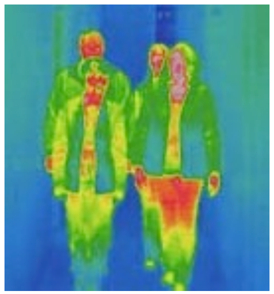
- Promising sources the research at Ing2 is focusing on
  - Vibrations
  - Electromagnetic radiation

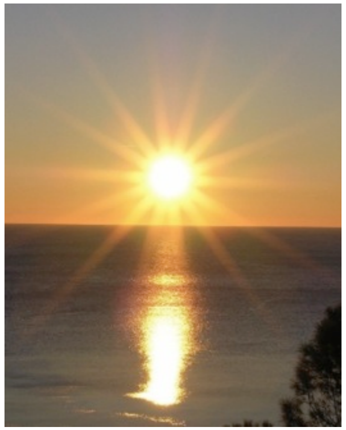
em radiation



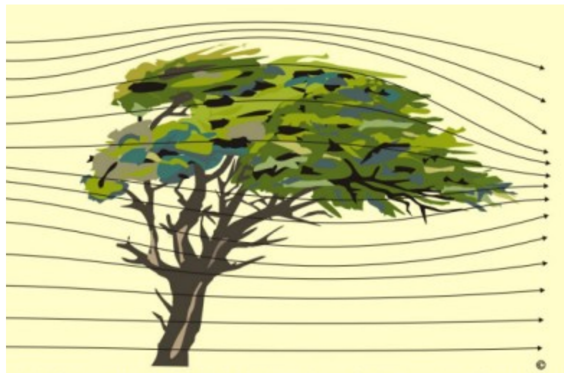

mechanical vibrations

thermal gradients

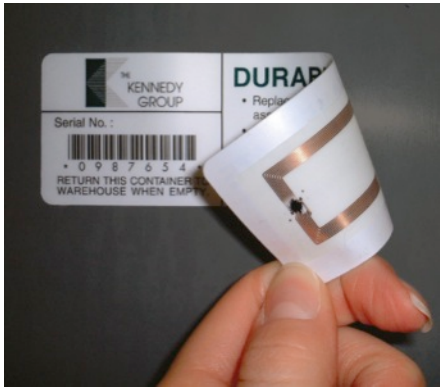


solar radiation

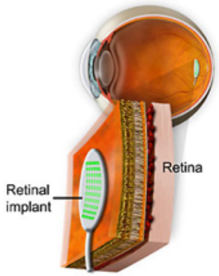


Why Energy?

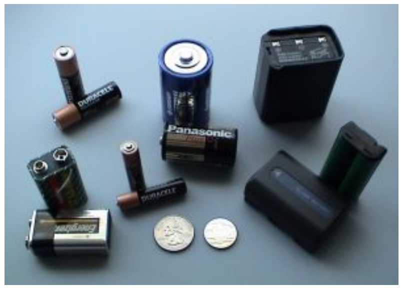
- Growing integration of electronics into human lives and environments
  - Paradigm of pervasivity



- Micro-/Nano-electronics allow for ultra-low power designs



- Sustainability and energy autonomy
  - Longer-lifes
  - Bulky batteries
  - Unprecedented applications



Why energy harvesting now?

From concepts

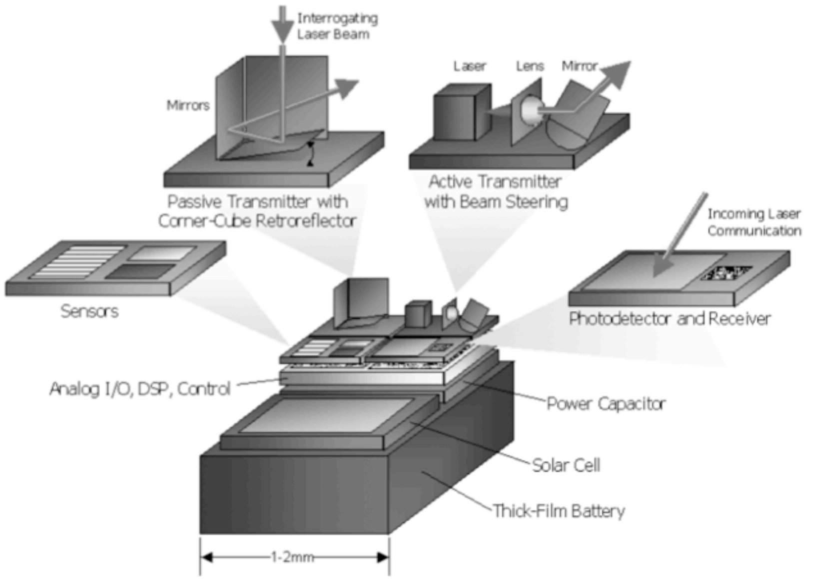
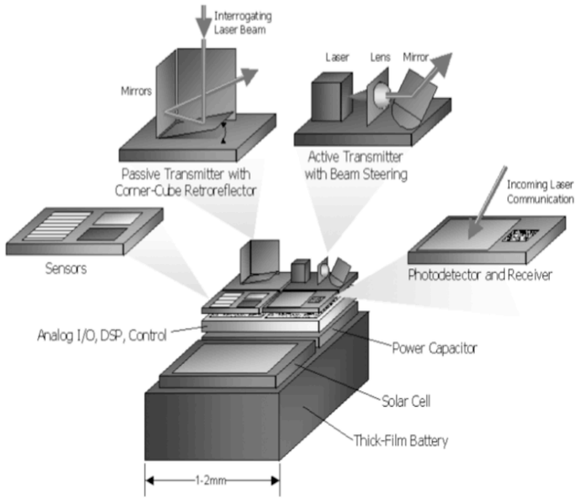


Fig. 1. Smart Dust concept. Tiny sensor nodes will combine sensing, computation, communications, and power.

K. Pister, B. Boser et al, University of California Berkeley, 1998

Why energy harvesting now?

To research…



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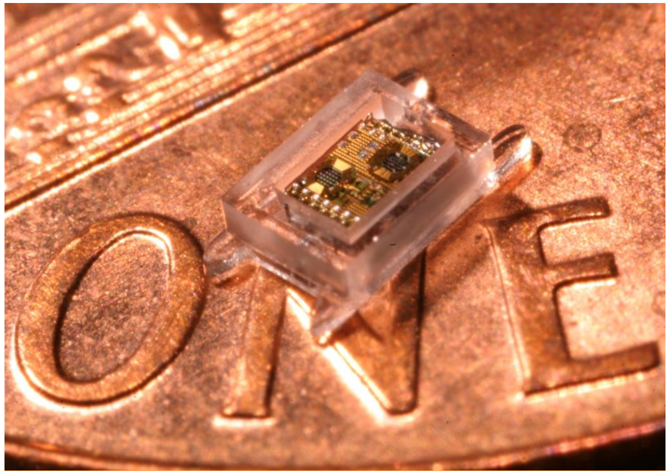


G Chen, et al, University of Michigan, 2012

Why energy harvesting now?

To products

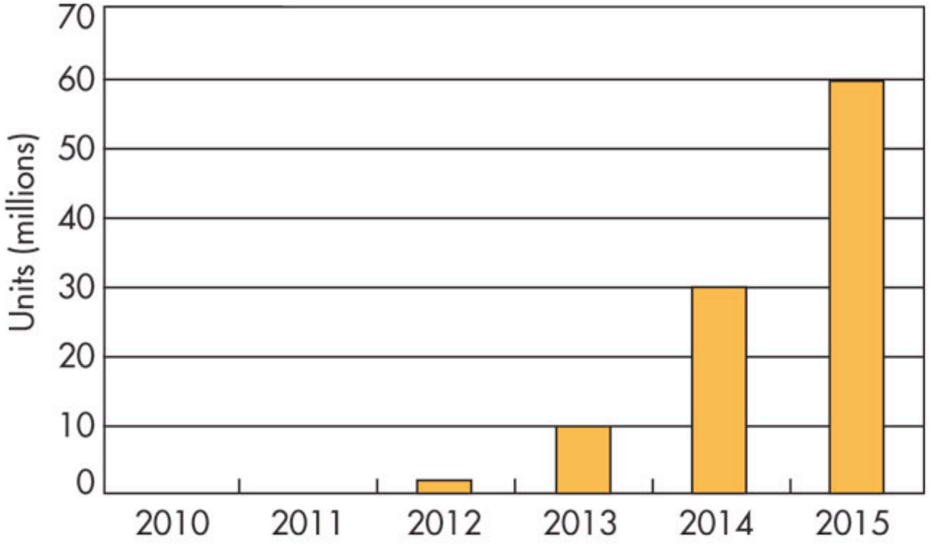
What About the Future Standards?

EnOcean Alliance with about 150 companies involved with interoperable devices, mainly for use in buildings, and well over 500,000 of them installed.

ZigBee is already the leading standard for parts of the smart grid and the in-building wireless network market, and it already has the International Electrotechnical Commission (IEC) seal of approval. Almost all ZigBee applications rely on batteries. This is why the ZigBee Alliance will amend its standard to work with more energy-harvesting devices, possibly battery free ones if they can crack the technical problems.

Ocean has one project with 10,000 wireless, battery-less sensors installed on a single building site. The MGM Center in Las Vegas has about 70,000 ZigBee radios installed but they are not solely reliant on energy harvesting.

Huge market applications…



1. The market for micro energy scavengers for use in tire-pressure monitoring systems (TPMSs) is slowly developing, with potential that should be realized by 2015. A lot of R&D is still necessary, though, before these devices can successfully come to the market. (courtesy of iSuppli Corp.)

2. Siemens VDO (now Continental) collaborated with Goodyear Tire and Rubber Co. to develop a TPMS device that can be mounted in the tire's rim. (courtesy of Goodyear Tire & Rubber Co.)

Everyday applications…

Interactive Telecommunications Program student Ohad Folman has created Pluggage as his final project - an item of carry-on luggage that harvests kinetic energy and solar power to charge small electrical devices.

The Pluggage has a built-in battery/inverter and a solar panel, enabling it to power up mobile devices each time the bag is rolled or exposed to direct sunlight. The kinetic energy from the rolling wheels at the base is converted via a generator/turbine into electrical energy.

Applications for sustainable development

GreenPix is a groundbreaking project where sustainable and digital media technology is applied to the curtain wall of Xicui entertainment complex in Beijing, near the site of the 2008 Olympic Games. Featuring one of the largest color LED displays worldwide and the first photovoltaic system integrated into a glass curtain wall in China, the building performs as a self-sufficient organic system, harvesting solar energy by day and using it to illuminate the screen after dark, mirroring a day's climatic cycle.

Weird applications…

To capture energy from the raindrops the scientists used a 25 micrometer thick PVDF (polyvinylidene fluoride) polymer, a piezoelectric material that converts mechanical energy into electrical energy.

Source: CEA/Leti

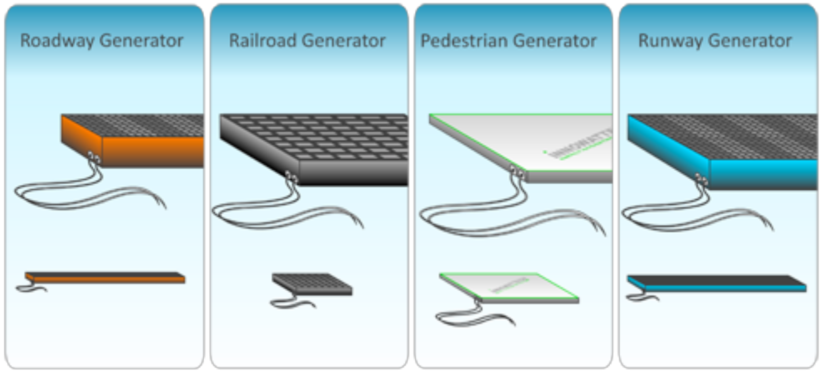
Fun applications…

Club Surya in London is one of a new generation of "eco-clubs" which encourages its patrons to work towards climate change. The club's main feature is the piezoelectric dance floor.

The dance floor uses piezoelectricity where crystal and ceramics create a charge to generate electricity. The nightclub has a "bouncing" floor made of springs and a series of power generating blocks which produce a small electrical current when squashed. As dancers move the floor up and down to squeeze the blocks, the current is fed into nearby batteries which are constantly recharged by the movement of the floor. The electricity created in this way is used to power parts of the nightclub such as the sound and lighting.

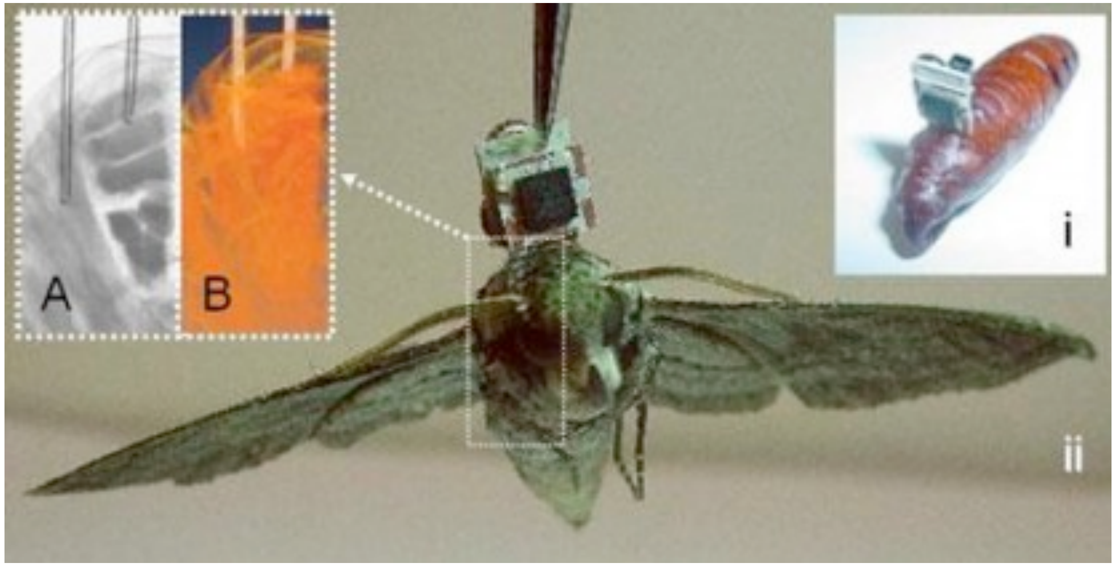
Transport applications…

	Wind	Solar	Geothermal	Hydro power	Coal	Oil & Gas	Energy harvesting from roads, railways & runways via IPEG™* INNOWATTECH
Cost, ¢ per kWh	3 – 10	10 – 20	2 – 10	2 – 10	8 – 10	8 – 16	3 – 10**
Payback, years***	12 – 30	20 – 30	10 – 20	12 – 15	15 – 20	10 – 13****	6 – 12**
Reliable	✗	✗	✓	✓	✓	✓	✓
Clean	✓	✓	✓	✓	✗	✗	✓
Mature Technology	✓	✓	✓	✓	✓	✓	✗
Deployment Availability	✗	✗	✗	✗	✓	✓	✓
Implementation in urban areas	✗	✓	✗	✗	✗	✗	✓
Low maintenance cost	✗	✗	✗	✗	✗	✗	✓
Successfully operates in Northern areas	✗	✗	✓	✓	✓	✓	✓
Preserves environment in original state	✗	✗	✗	✗	✗	✗	✓
Energy production cycle coincides with consumption peak cycle	✗	✗	✗	✗	✓	✓	✓



INNOWATTECH
ENERGY HARVESTING SYSTEMS

Very odd applications…



Insect Cyborgs

Defence Advanced Research Projects Agency (DARPA) is conducting a Hybrid Insect MEMS (HI-MEMS) program which is aimed at developing technology that provides more control over insect locomotion. This is done by developing tightly coupled machine-insect interfaces by placing micro-mechanical systems inside the insects during the early stages of metamorphosis.

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Zero-Power Systems: Definition

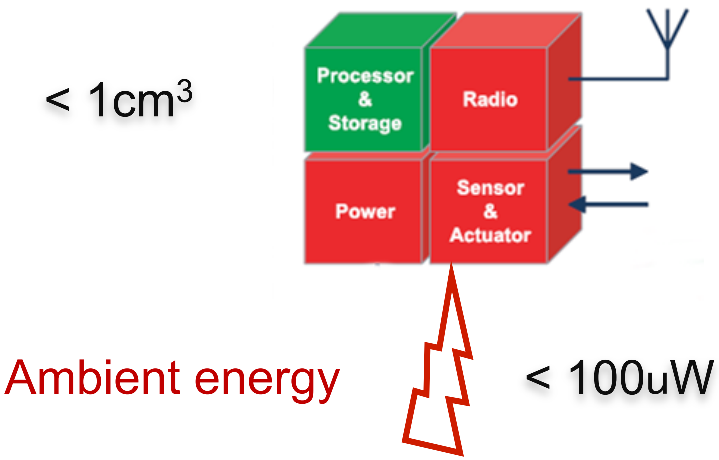
From Roundy (2003):

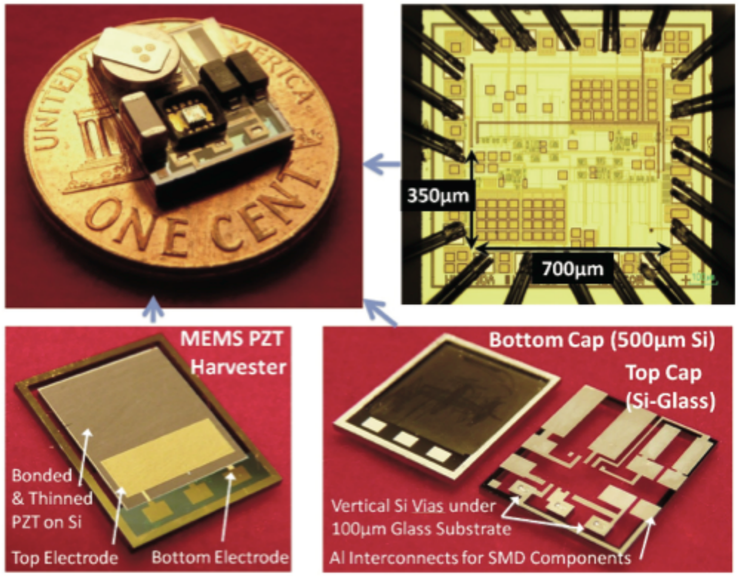
- Systems designed to operate and/or communicate in known/unknown environments over their all lifetime

- Target for harvesters: < 100uW/cm^3 on average, indefinitely

Nowadays target could be lowered to:

- ~1uW/mm^3





Right: piezo-harvester 70uW@1g, 26Hz in 0.3cm^3 (U.Mich)

Aktakka, … Najafi et al. *A Self-Supplied Inertial Piezoelectric Energy Harvester with Power-Management IC,* ISSC, 2011

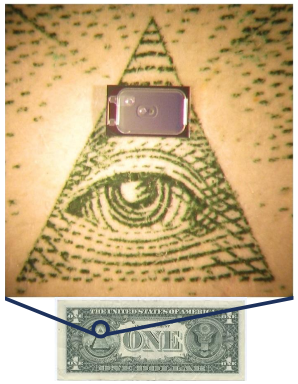
State-of-art zero-power systems (1)

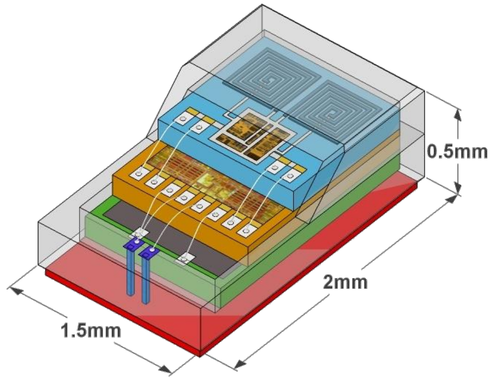
ISSCC 2011 / SESSION 17 / BIOMEDICAL & DISPLAYS

17.6 A Cubic-Millimeter Energy-Autonomous Wireless Intraocular Pressure Monitor

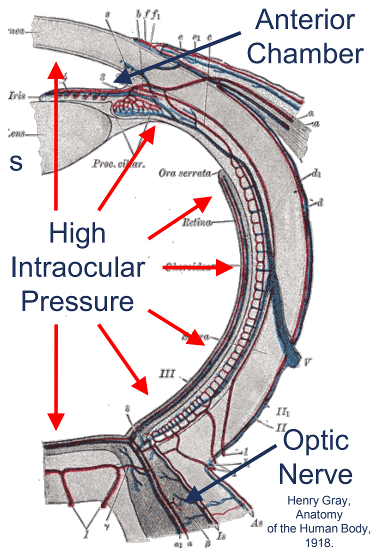
Gregory Chen, Hassan Ghaed, Razi-ul Haque, Michael Wieckowski, Yejoong Kim, Gyouho Kim, David Fick, Daeyeon Kim, Mingoo Seok, Kensall Wise, David Blaauw, Dennis Sylvester

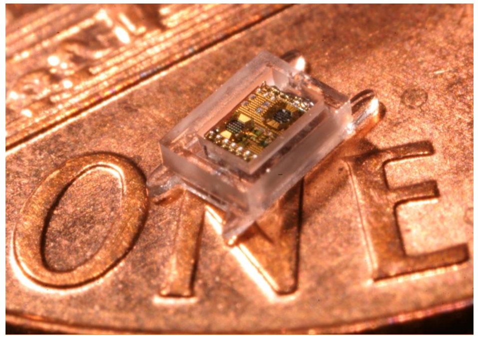
University of Michigan, Ann Arbor, MI





Dimensions	$1.5mm^3$
Average power consumption	10nW
Buffer battery	1uA/h by Cymbet®
Lifetime no harvesting	28 days
Power needed for 15 S/day and 1 transmission/day	5.3nW
Power supplied by embedded solar cell	80nW
Recharging time	10h/indoor 1.5h/sunlight





State-of-art zero-power systems (2)

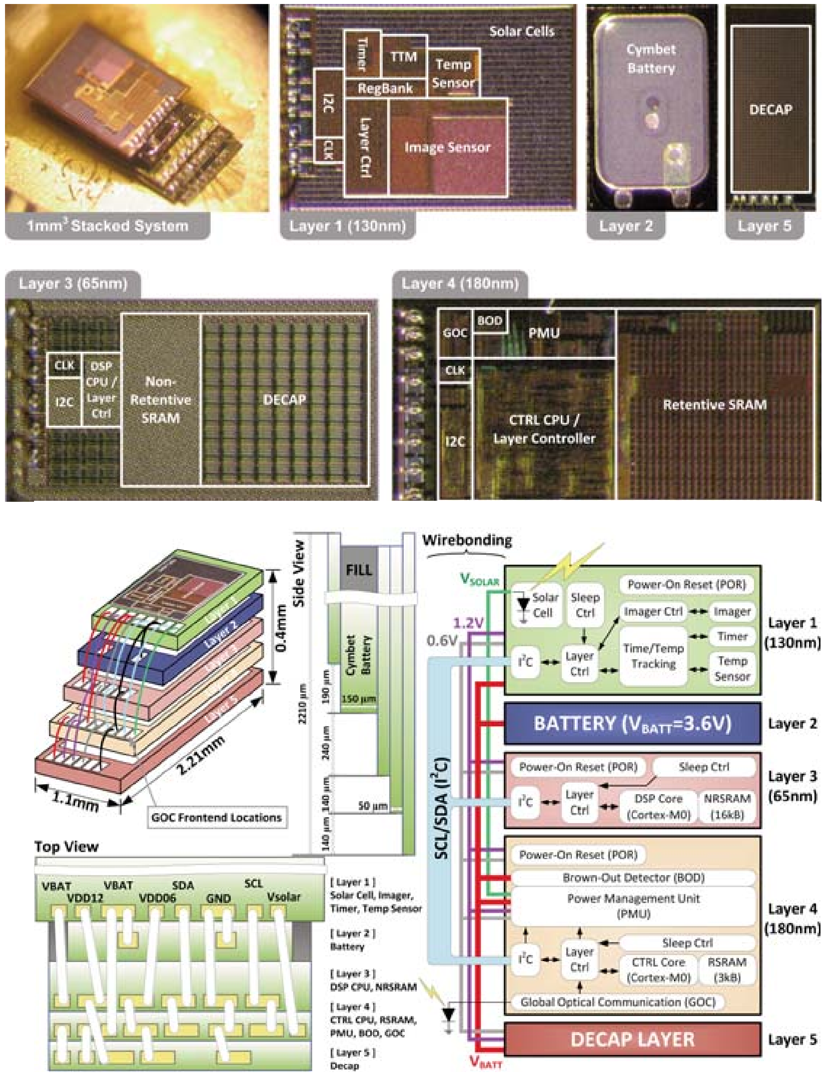
ISSCC 2012 / SESSION 23 / ADVANCES IN HETEROG

23.2 A Modular 1mm³ Die-Stacked Sensing Platform with Optical Communication and Multi-Modal Energy Harvesting

Yoonmyung Lee, Gyouho Kim, Suyoung Bang, Yejoong Kim, Inhee Lee, Prabal Dutta, Dennis Sylvester, David Blaauw

University of Michigan, Ann Arbor, MI

Dimensions	$1mm^3$
Average power consumption	185pW/40uW
Buffer battery	600nA/h by Cymbet®
Embedded sensors	temperature/ 96x96 imager
Energy per imager frame	680nJ/frame
Optical transmission consumption	x20,000 lower that RF state-art
Lifetime sleep mode	2.3 days



The Harvesting Issue

Problems

- Already proven:
  - Harvesters with $>> 100uW/cm^3$
  - Systems operating $<< 100uW/cm^3$

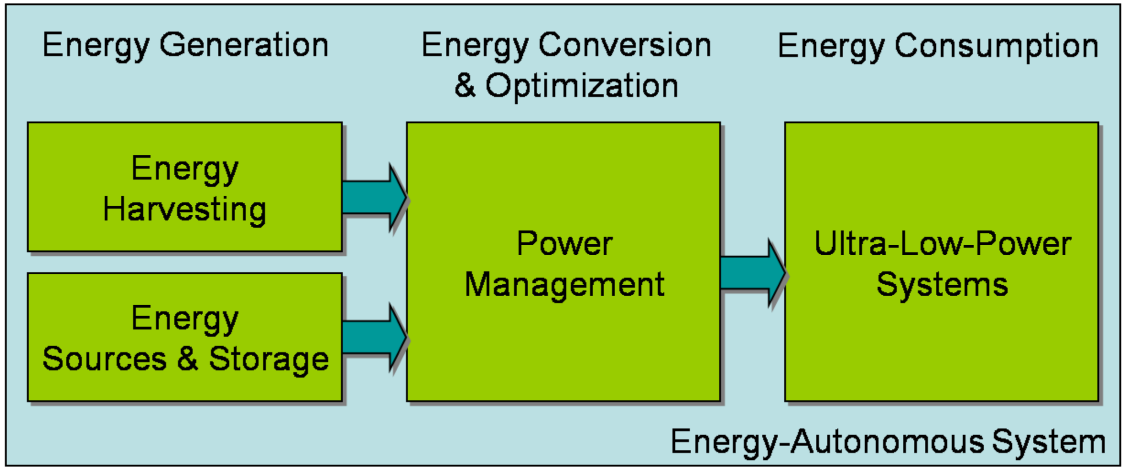
BUT

- The environment condition is critical. When? On which conditions?

Objectives & Challenges

- Focus on the energy instead of power domain
  - By increasing conversion efficiency
  - By using governance of resources
- Harvesting limited by two hard boundaries
  - Storage capabilities of temporary resources
  - Power requirements of the application

Energy Autonomous Systems: Functional Blocks



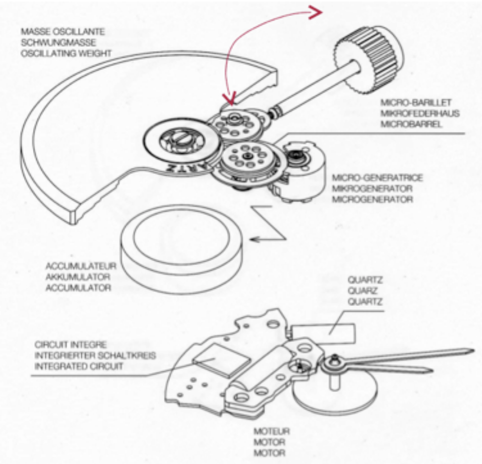
Energy Generation:

> **Energy Harvesting:** Devices or systems harvesting energy from correlated or uncorrelated sources of energy.
>
> **Energy Sources & Storage:** Any kind of energy storage element that could be used to accumulate energy in excess from the harvester and provide it to the system in its place whenever the energy is insufficient.

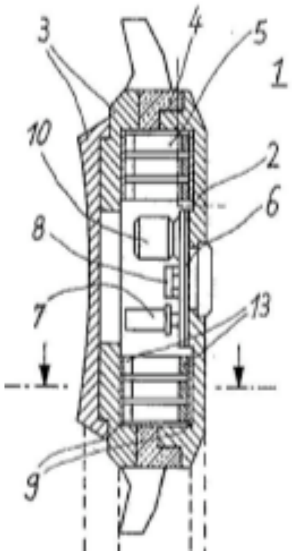
Energy Conversion and Optimization: Any energy conversion system that trades and optimizes the energy stored/harvested in the Energy Generation block to the Energy Consumption block.

Energy Consumption: Data acquisition, elaboration, storage and transmission.

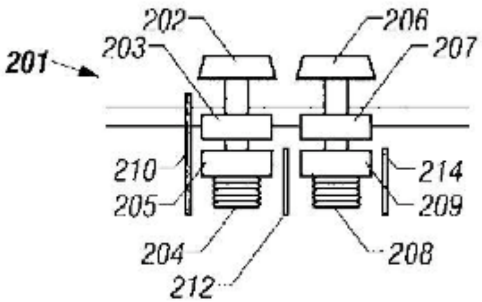
Not a Really New Concept…



ETA AutoQuartz mechanism, ‘90s



Thermoelectric generators for wristwatches, C. Piguet et al. US 4,106,279 1978



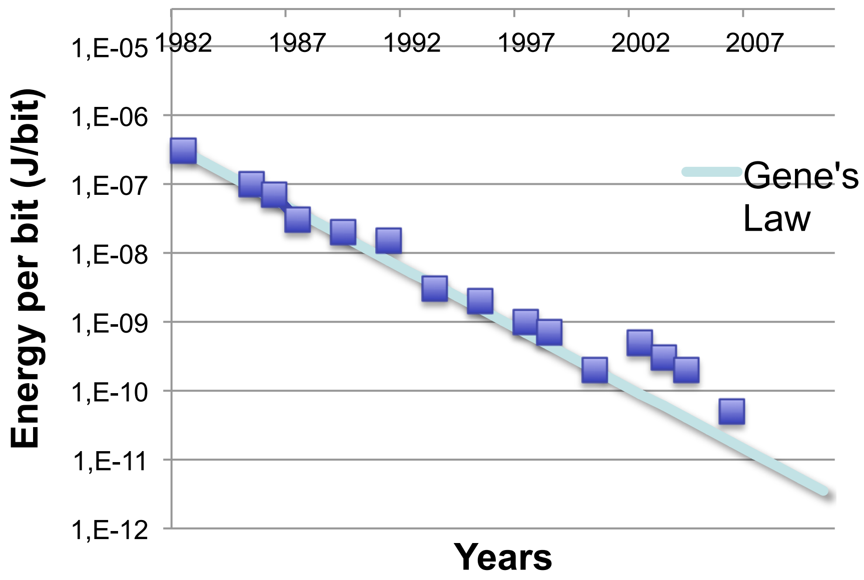
Power from typing
US 5,911,529 1999

Source: C. Piguet

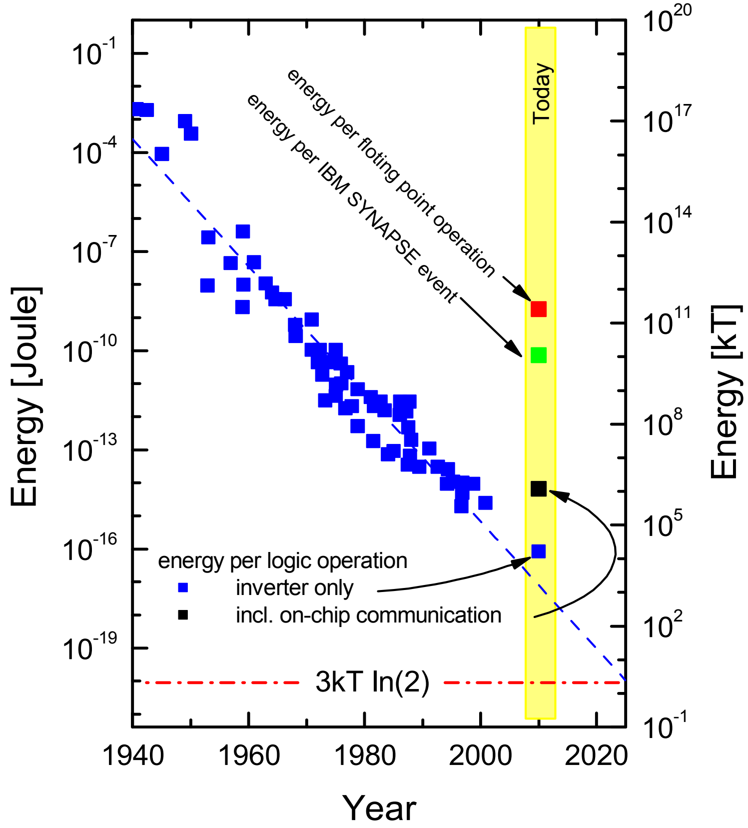
The ZENITH Space Commad, 1956

The Good

DSP Power Trend

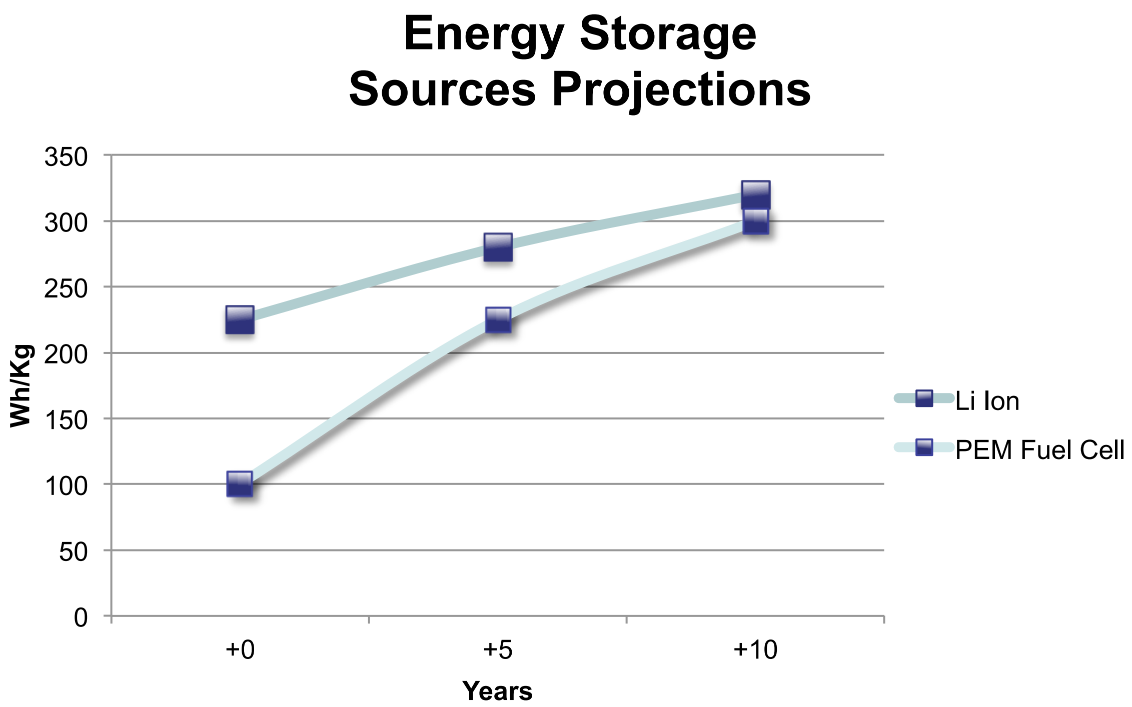


High Density Systems Trend



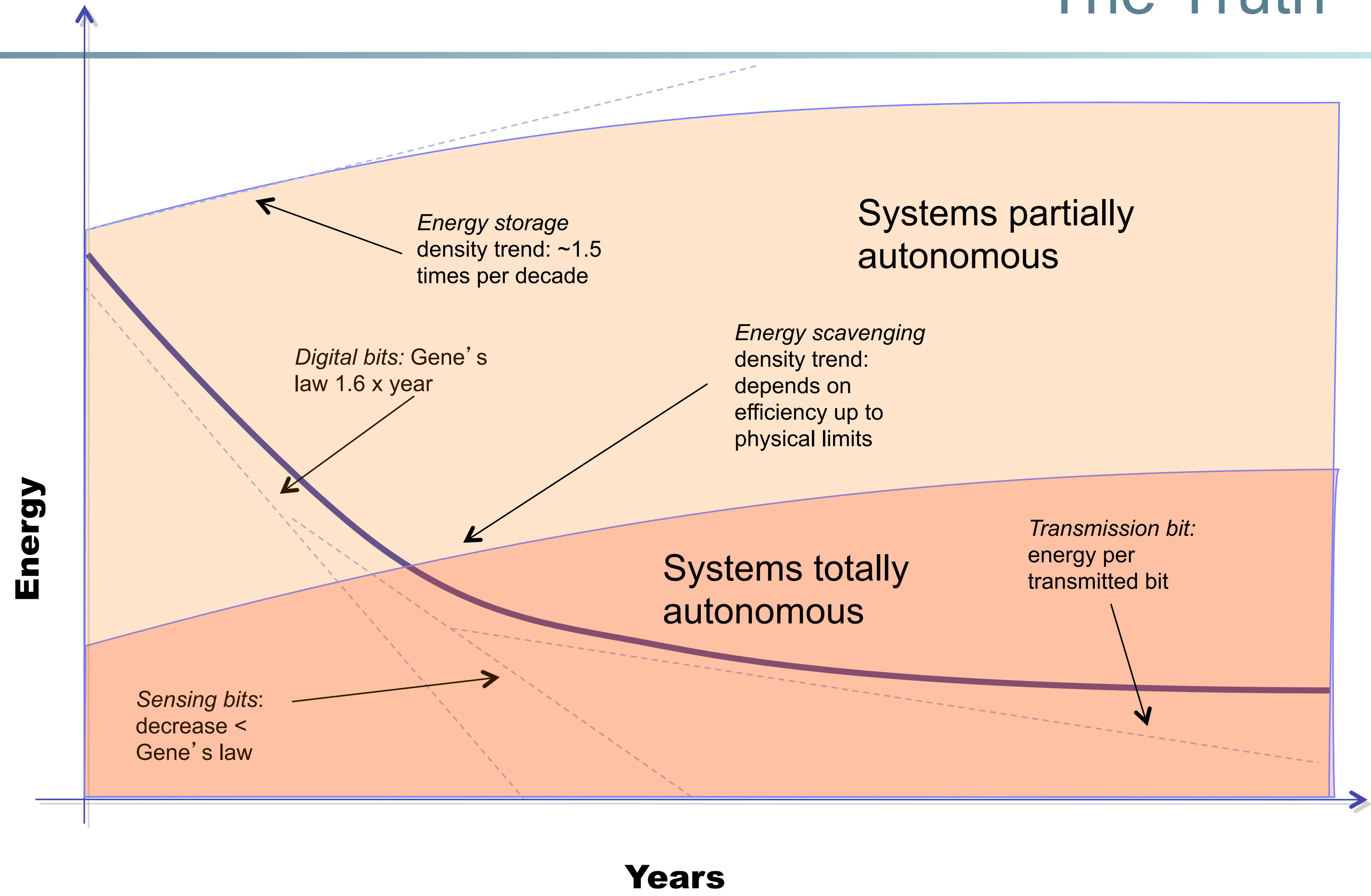
The energy per bit per computation decreases according to the technology trend (Gene's law: energy/bit ~1.6x/year)

The Bad



- Gene's law does not apply to analog sensing and transmission (slower decrease)
- Energy storage density increases only ~1.5x/decade (~1.04x/year)
- Energy conversion efficiency has physical limits

The Truth



Energy
Years
Energy storage
density trend: ~1.5
times per decade
Systems partially
autonomous
Digital bits: Gene's
law 1.6 x year
Energy scavenging
density trend:
depends on
efficiency up to
physical limits
Systems totally
autonomous
Transmission bit:
energy per
transmitted bit
Sensing bits:
decrease <
Gene's law

Zero-power Systems Scenarios

Scenarios		Characteristics	Examples
A	Sensing, elaboration and physical collection of data	Data is recovered by physical recollection	Smart-dust, some in-vivo diagnostics systems, …
B	Sensing, elaboration and collection of data by proximity energization	Data is recovered by providing external artificial burst energy	Passive/Semipassive RFID, some in-vivo diagnostic systems, …
C	Sensing, Elaboration and RF data transmission	Senses, elaborates and transmits data. The energy should be provided to the system lifelong	Truly autonomous wireless sensor networks

An Extreme Case: RF Harvesting

- The harvested energy is very low
- Example: very distant RF sources could provide available energy ~10nJ/h (~3pW)
- Assuming no conversion losses:

	State-art	Projection/Limit	State-art	Projection/Limit
Conversion	~10fJ/S	~1fJ/S	1M S/h	10M S/h
Elaboration	~1fJ/transition	~10zJ/transition	3k transitions/s	270M transitions/s
Transceiver (UWB, 2m)	~1nJ	~1pJ	10 transmissions/h	10k transmissions/h

The main hurdle lies in the limitations of power conversion techniques!!

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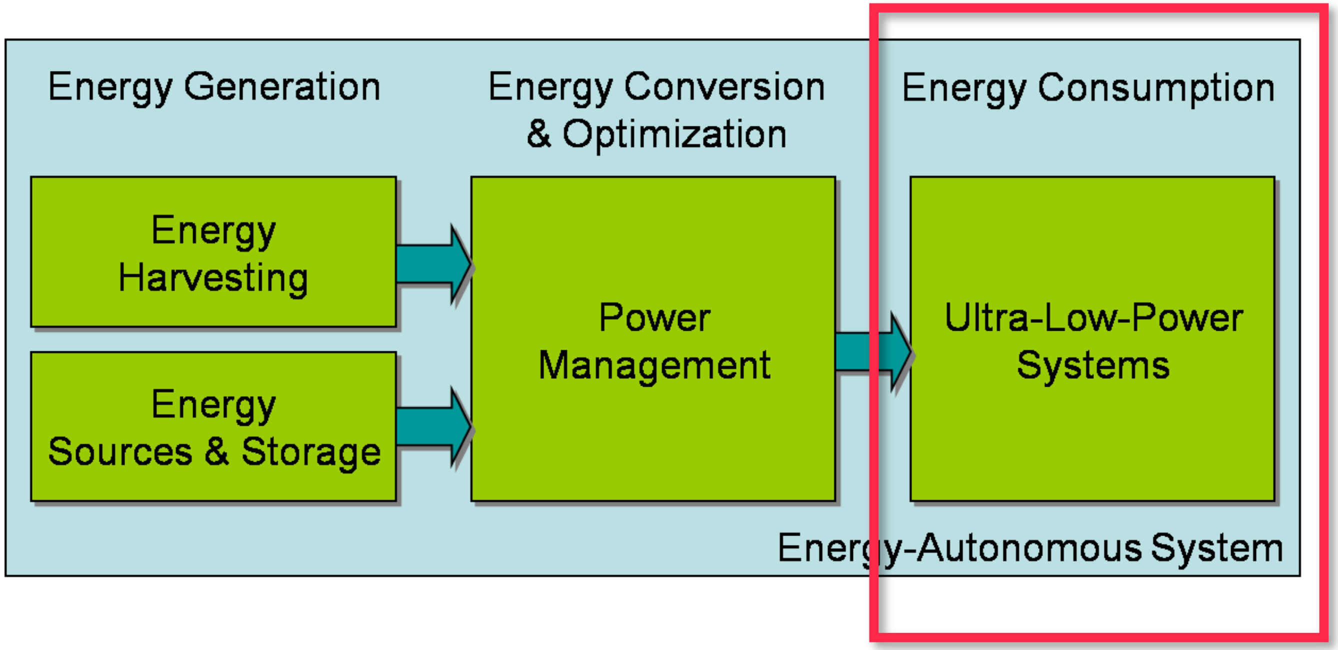
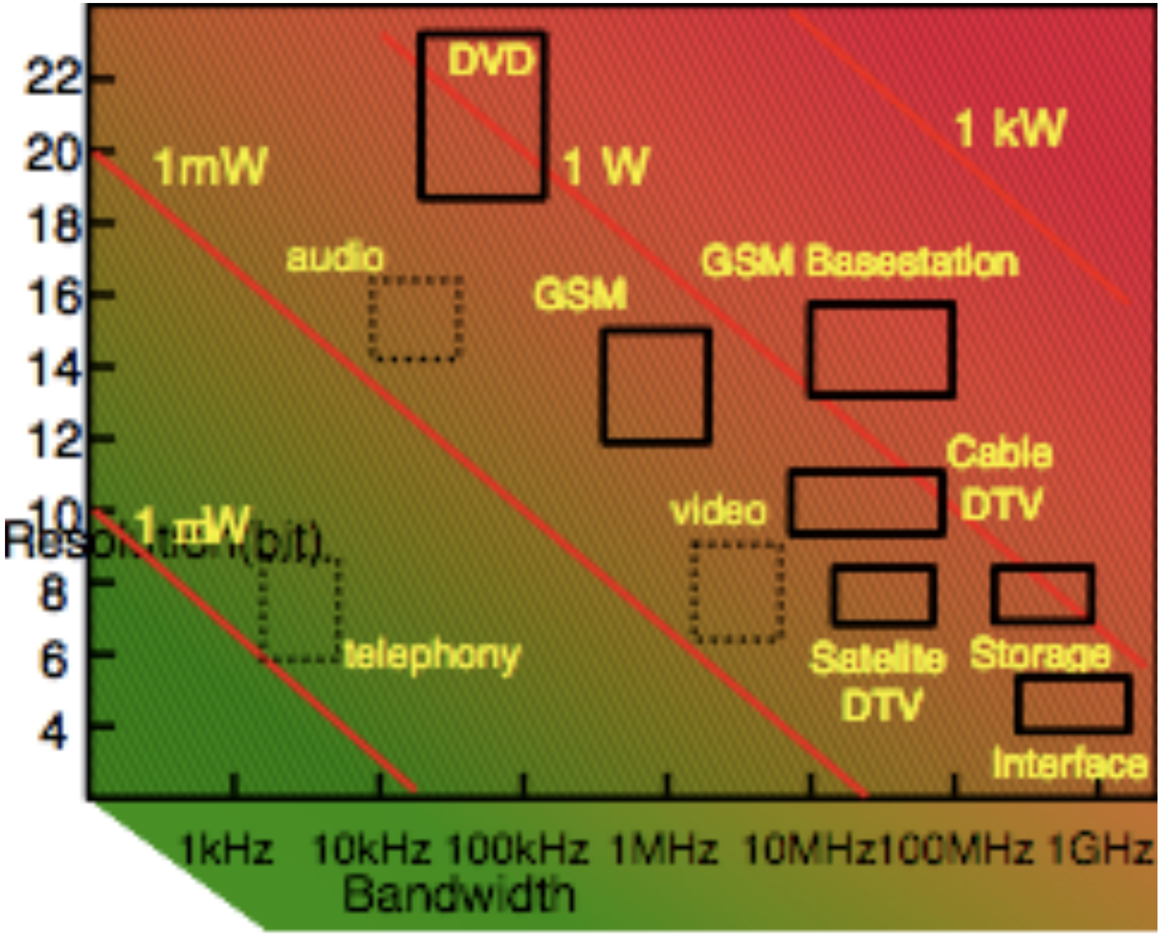
Energy Consumption



Bandwidth and Resolution



Energy demanded by various applications. The more precision and amount of data required, the more energy spent per time.
Data are based on 5pJ/ conversion.

Three directions for EAS:

- Interfaces
- Computing
- Wireless

(Source: M. Pelgrom)

Computing

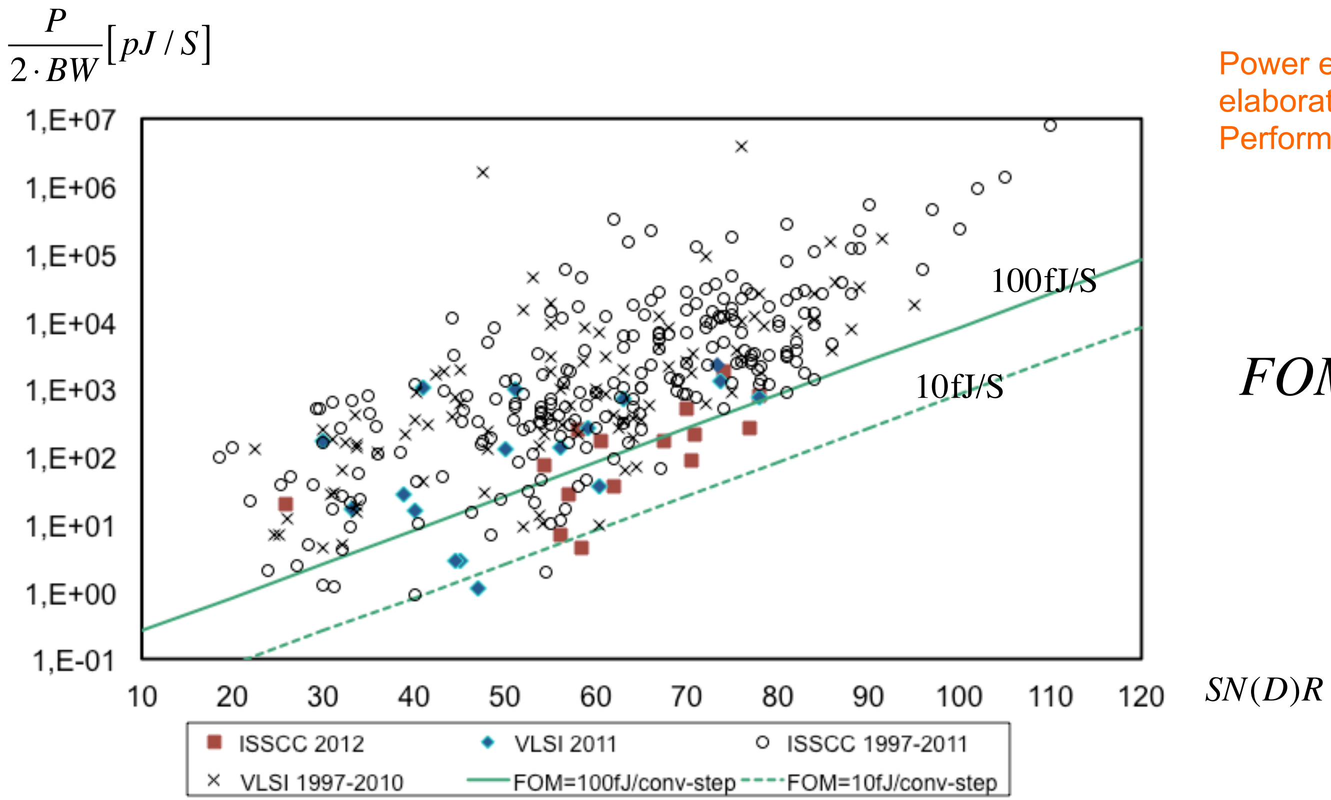
Chip	MOPS/mW
Conventional microprocessor	1
Conventional DSP core	45
Low-power DSP core	65
CSEM MACGIC core 180 nm	100
DSP + hardware accelerators	190
Dedicated hardware (no flexibility)	1900
Upper bond (not reachable)	2500

Specialization reduces power

Technologies
- Optimized memory access
- Multi-Vt
- Power gating

Architectures:
- Asyncronous logic
- Subthreshold logic
- Error tolerant logic
- Vdd tuning
- Probabilistic CMOS

A/D Interfaces



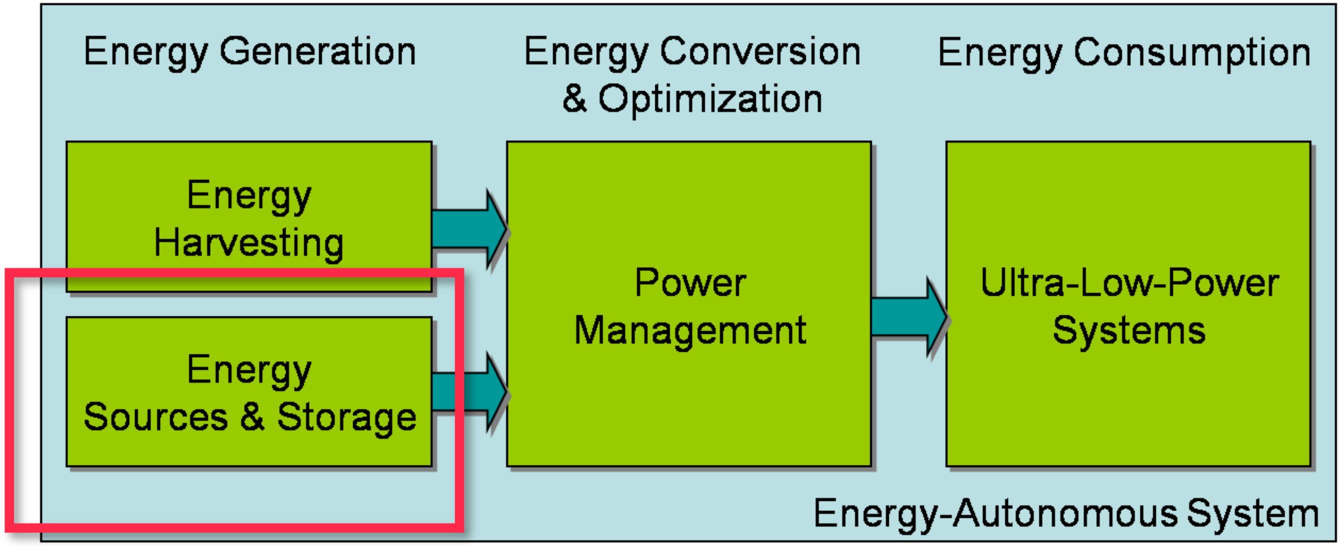
Power efficiency of ADCs evolution elaboration from: B. Murmann, "ADC Performance Survey 1997-2012," [Online]

$$FOM = \frac{P}{2^{ENOB} \cdot BW}$$

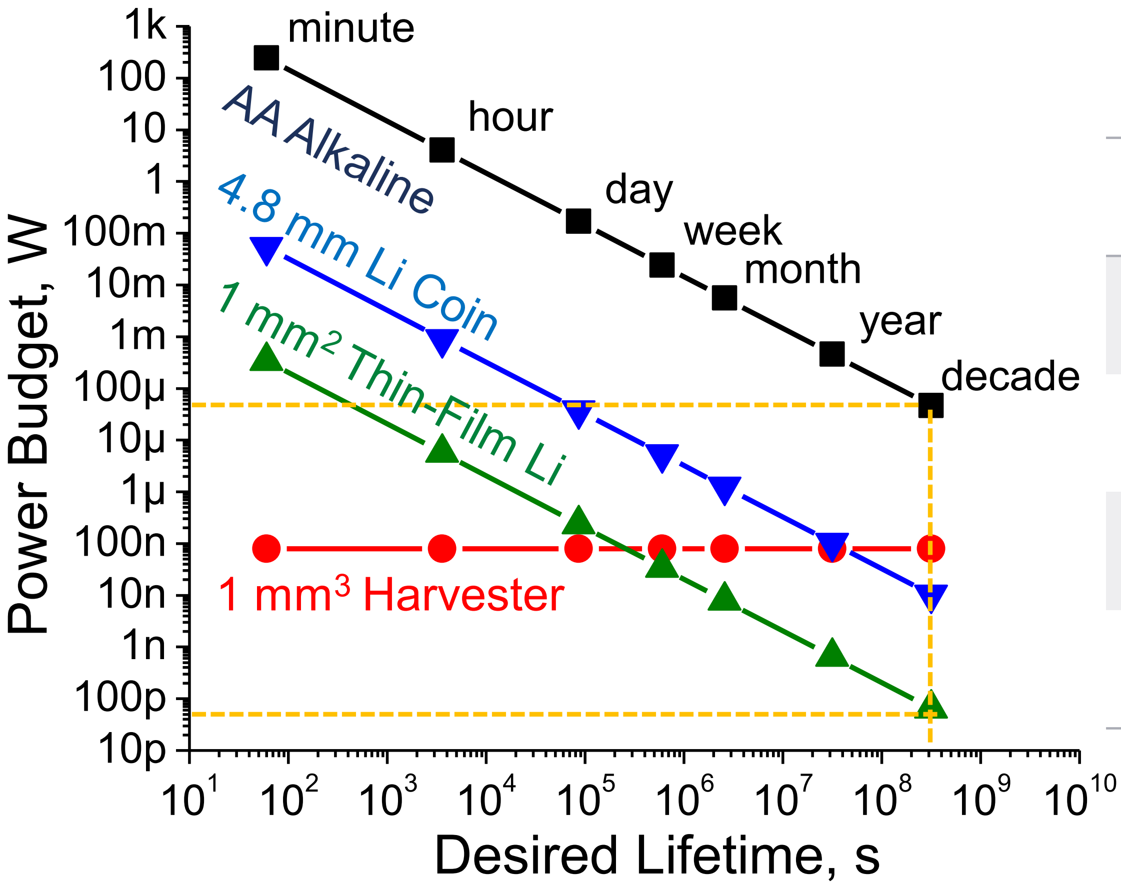
Year of production	2008	2009	2012	2015	2018
ADC power efficiency (pJ/S.)	2	0.7	0.2	0.07	0.03

Tentative Roadmap (2008) already surpassed!!

Energy Storage



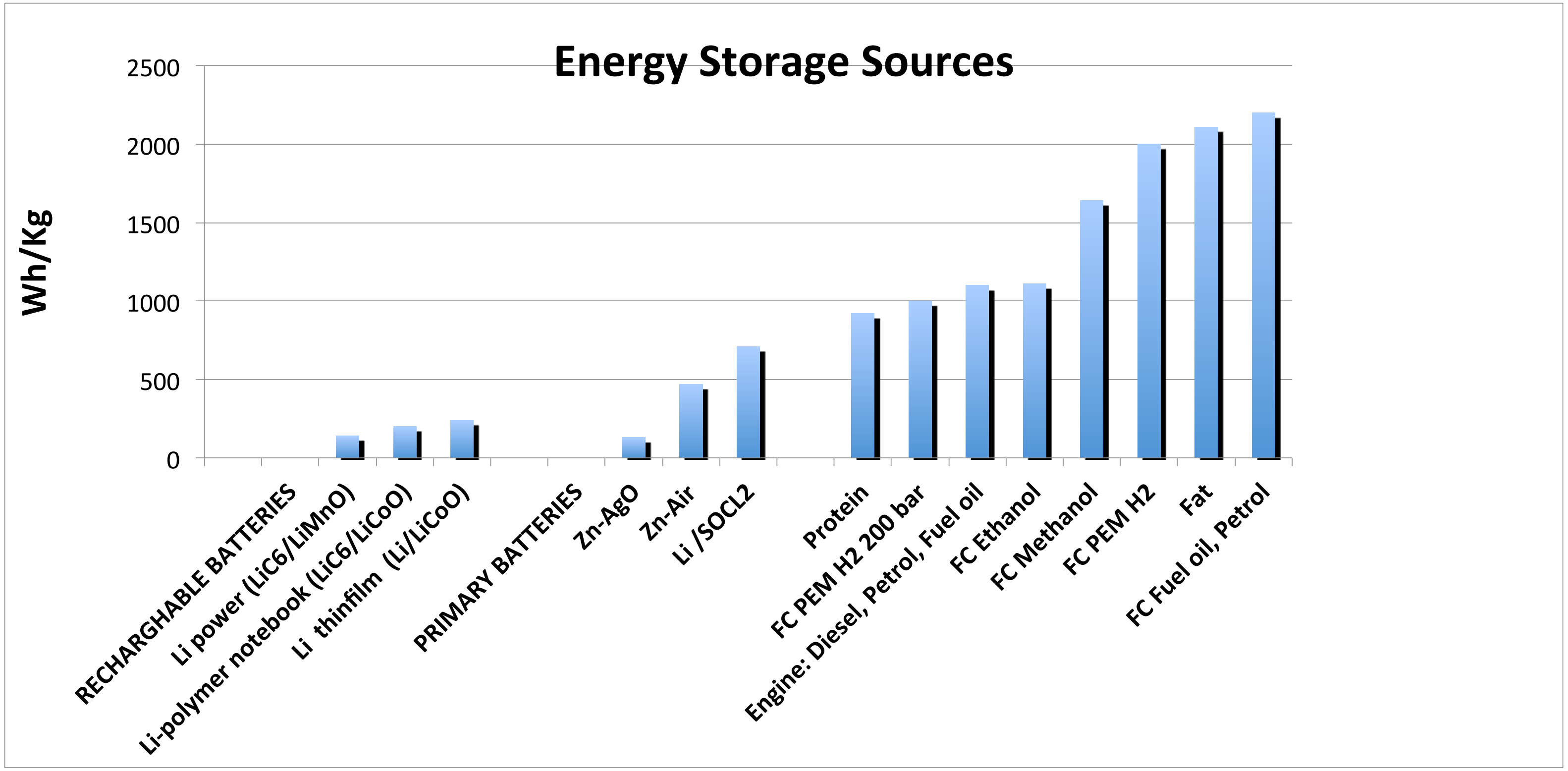
Power budget challenges



Battery	Peak Power
AA Alkaline	1.5 W
4.8 mm Li Coin	600 μW
1 mm^2 Thin-Film Li	40 μW
1 mm^3 Harvester	80 nW

From: G. Chen et al. ISSCC 2011

Energy Storage Sources & Capabilities

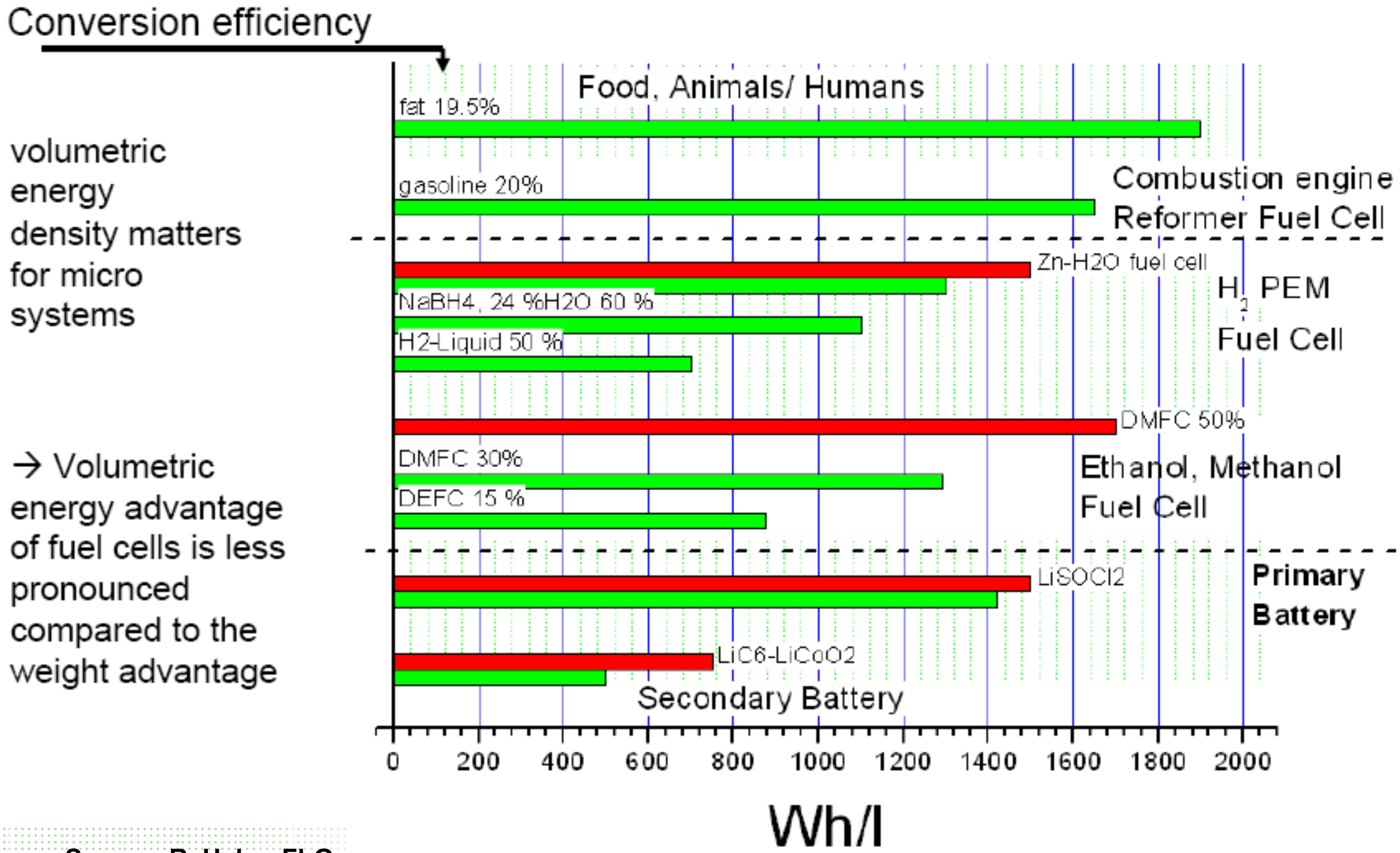


- The plot <u>does</u> consider the conversion efficiency
- The plot <u>does not</u> consider mass oxidizers

Fuel Cells vs Primary Batteries

volumetric energy density matters for micro systems

→ Volumetric energy advantage of fuel cells is less pronounced compared to the weight advantage



Source: R, Hahn, FhG

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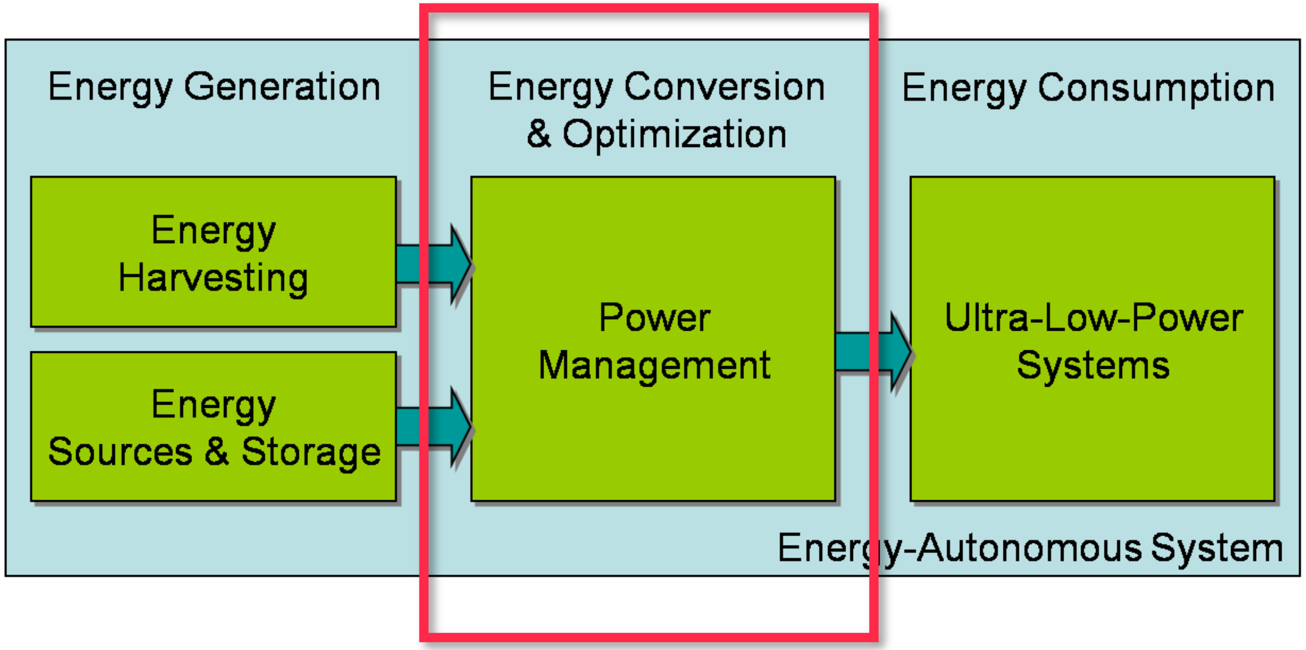
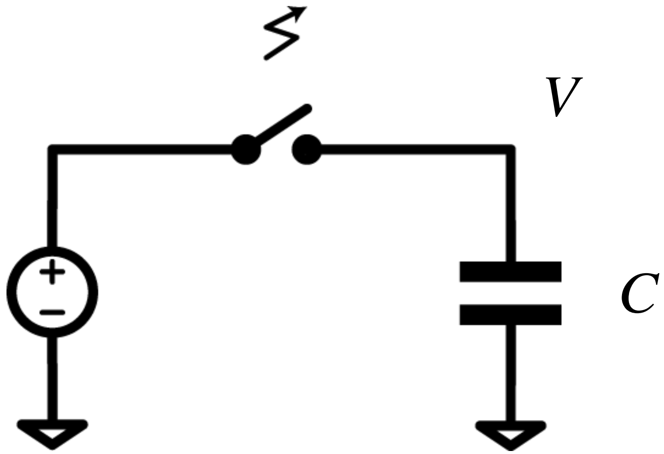
Energy Conversion & Optimization



Basic concepts of power management: transfer between capacitors



$$i(t) = C\frac{dV}{dt};\ \ i(t) = CV\delta(t)$$

energy drawn from reservoir =

$$= E_v = \int_0^\infty V \cdot i(t)\,dt = \int_0^\infty CV^2\delta(t)\,dt = CV^2$$

energy stored into C = $\frac{1}{2}CV^2$

missing = $\frac{1}{2}CV^2$

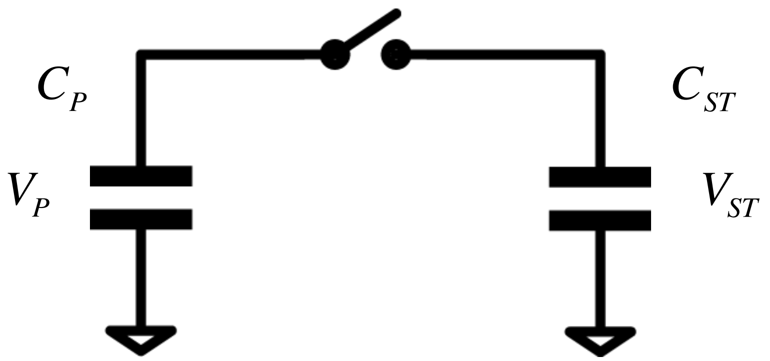
THUS any increase of stored energy:

$$\frac{1}{2}C(\Delta V)^2$$

implies an energy LOSS of:

$$\frac{1}{2}C(\Delta V)^2$$

Basic concepts of power management: transfer between capacitors



$$\Delta V_o = \frac{C_p}{C_p + C_{st}}\left(V_p - V_{st}\right) \quad V_{st} \rightarrow V_{st} + \frac{C_p V_p + C_{st} V_{st}}{C_p + C_{st}}$$

$$\varDelta E = \frac{1}{2}\frac{C_{st}}{C_p + C_{st}}\left[C_p^{\ 2} V_p^{\ 2} + 2C_p C_{st} V_p V_{st} - C_p V_{st}^{\ 2}\left(C_p + 2C_{st}\right)\right]$$

$$\Rightarrow$$

$$\varDelta E_{max} \Rightarrow \quad V_{st,max} = \frac{C_{st} V_p}{C_p + 2C_{st}} \approx \frac{V_p}{2} \quad \left(C_p \ll C_{st}\right)$$

CONCLUSION:

- the best energy transfer occurs when storage voltage is halfway of source potential

HOWEVER:

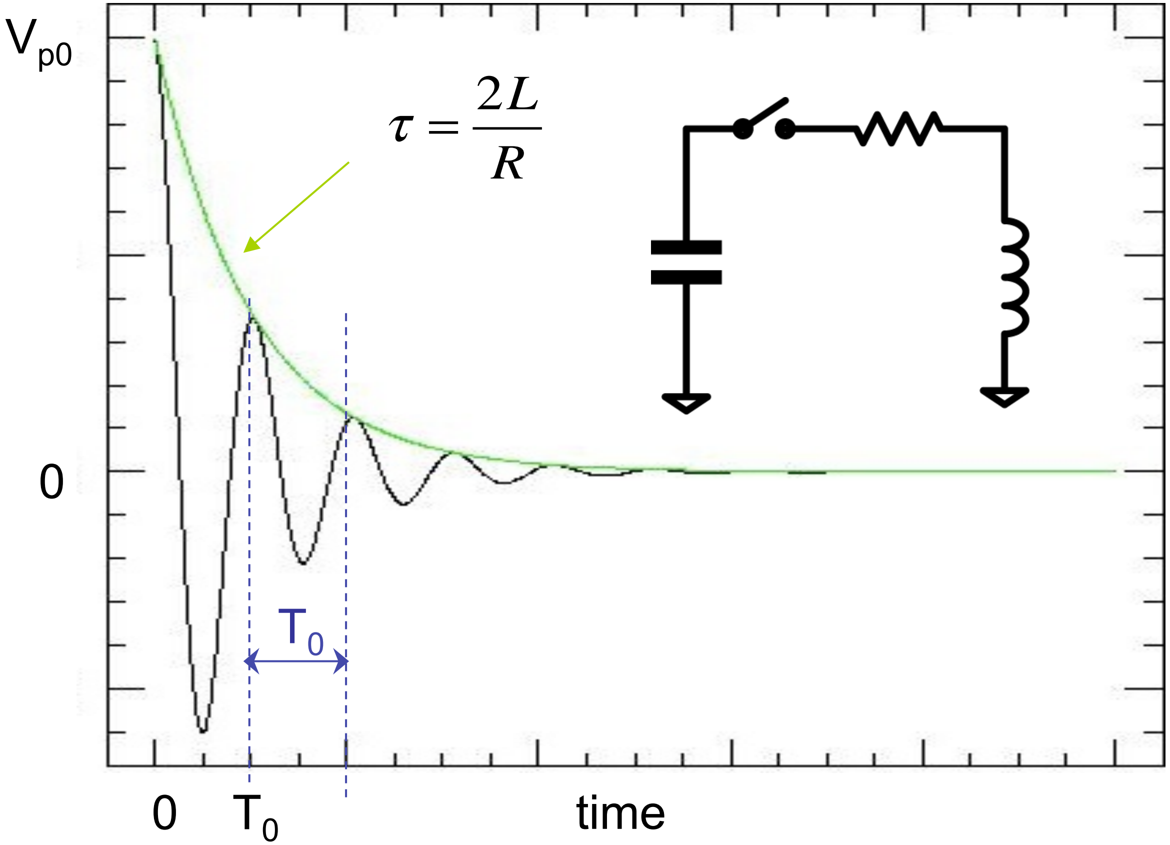
- An equal energy loss is always implied

$$\varDelta E = 0 \ if \ V_p = V_{st}$$

Basic concepts of power management: inductance usage

- Resonant RLC
- AfterT_0/4 energy transfered into L
- If R is negligible the energy transfer process is lossless

$$V_P(t) = V_{P0} \cdot e^{\frac{t}{\tau}} \cdot \cos(\omega_0^{'} t)$$



$$\omega_0^{'} = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

$$T_0 = \frac{2\pi}{\omega_0^{'}}$$

efficiency condition

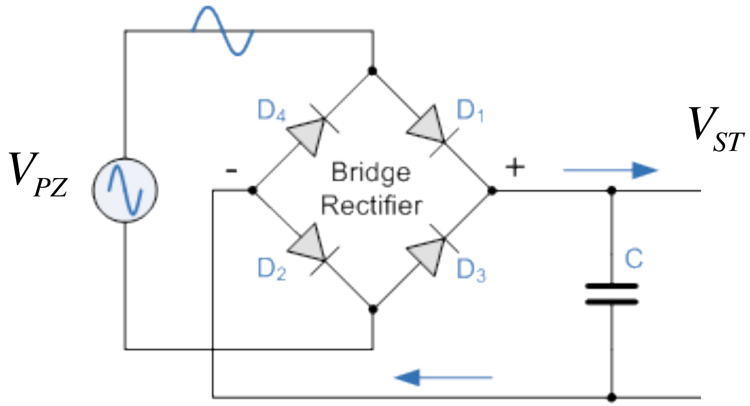
$$\tau >> T_0$$

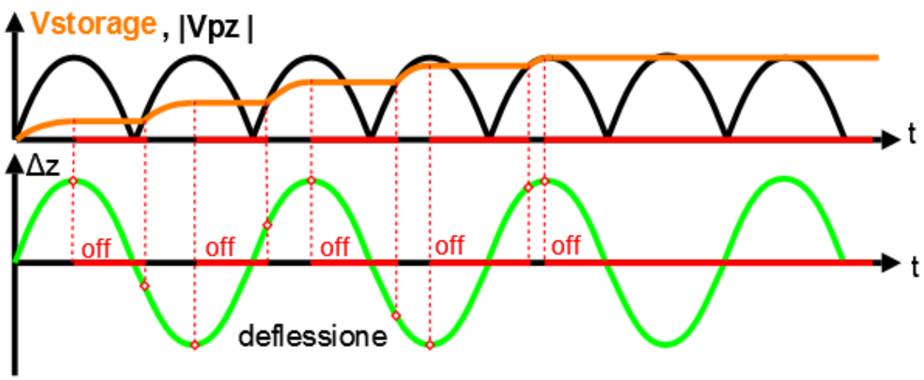
Conclusion on energy transfer techniques

- Power transfer techniques between capacitors is intrinsically lossy
  - The loss could be reduced by using “adiabatic” techniques:
    - constant current charge
    - multiple steps of small values
- Lossless power transfer is performed by using an inductor with negligible resistance

Common problems in micro-harvesting techniques

1. Device threshold voltages in charge transfer (i.e. rectifier: No energy harvested when $V_{ST}(t) < |V_{pz}(t)-2V_T|$)

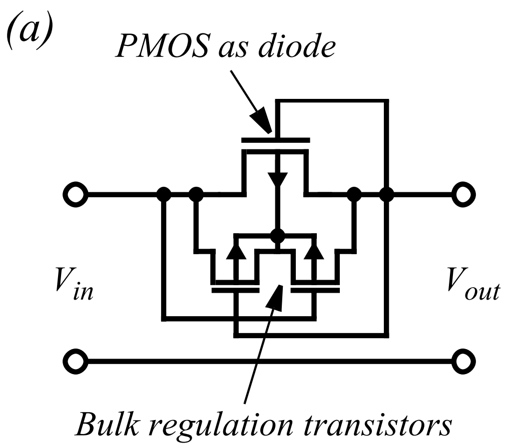




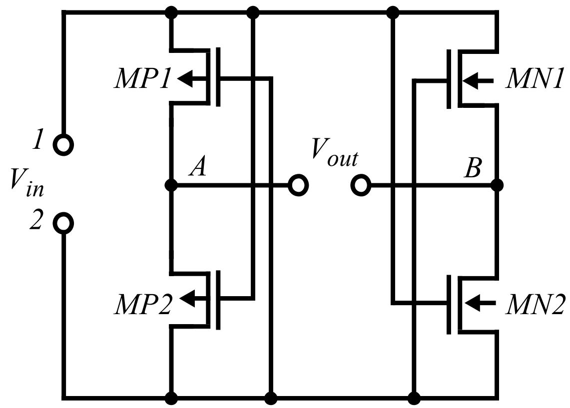
2. Power supply voltages (thus bulk) could be lower than input voltages

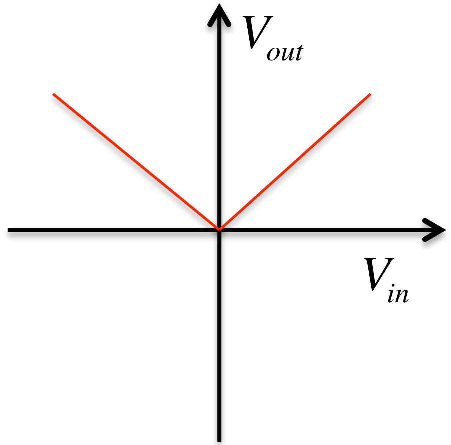
- Remedies:
  - zero-threshold devices (i.e. MOS depletion)
  - threshold adjustment by charge trapping (i.e. tunneling)
  - smart analog techniques

Dynamic bulk regulator

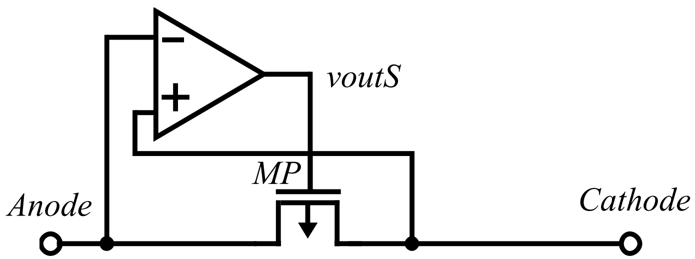


Negative voltage converter (NVC)





Problem2: input voltages could be higher than power supply one (especially during start-up phase)



Problem1: reduce threshold voltages as much as possible

From: C. Peters et al. *J. Micromech. Microeng., 2008*

Ideal diode

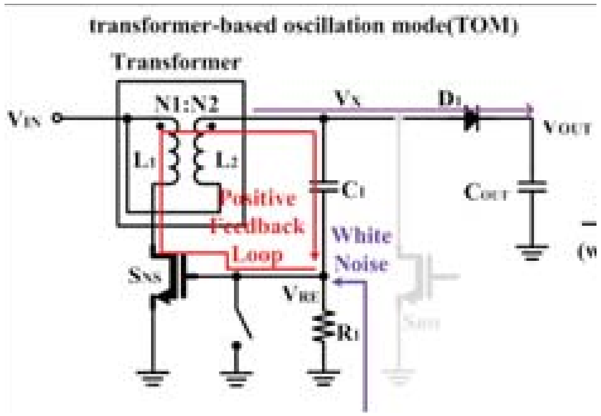
Common problems in micro-harvesting techniques

2. Low input voltages. This affects especially RF and thermal harvesters.

- Remedies:
  - zero-threshold devices (i.e. MOS depletion)
  - transformer based oscillators
  - smart analog techniques

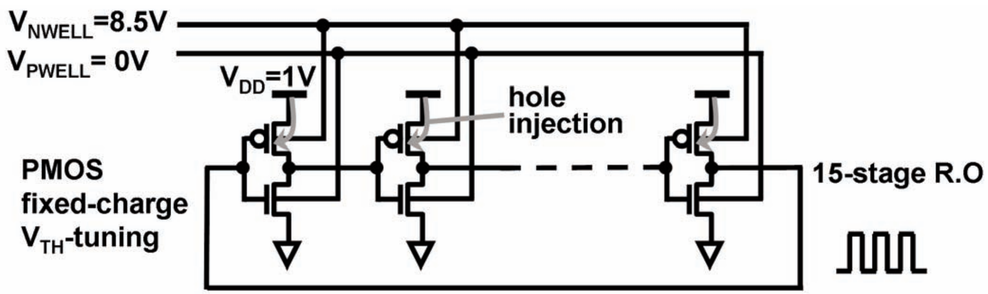
Analog techniques

Transformed-based oscillators

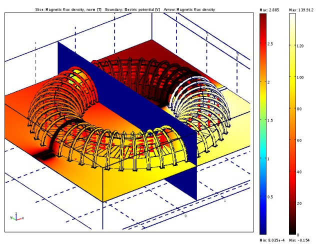


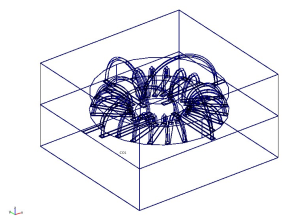
J.P. Im, et al. ISSCC 2012
40mV startup

VT tuned oscillators



P.H. Chen, et al. ISSCC 2011
95mV startup

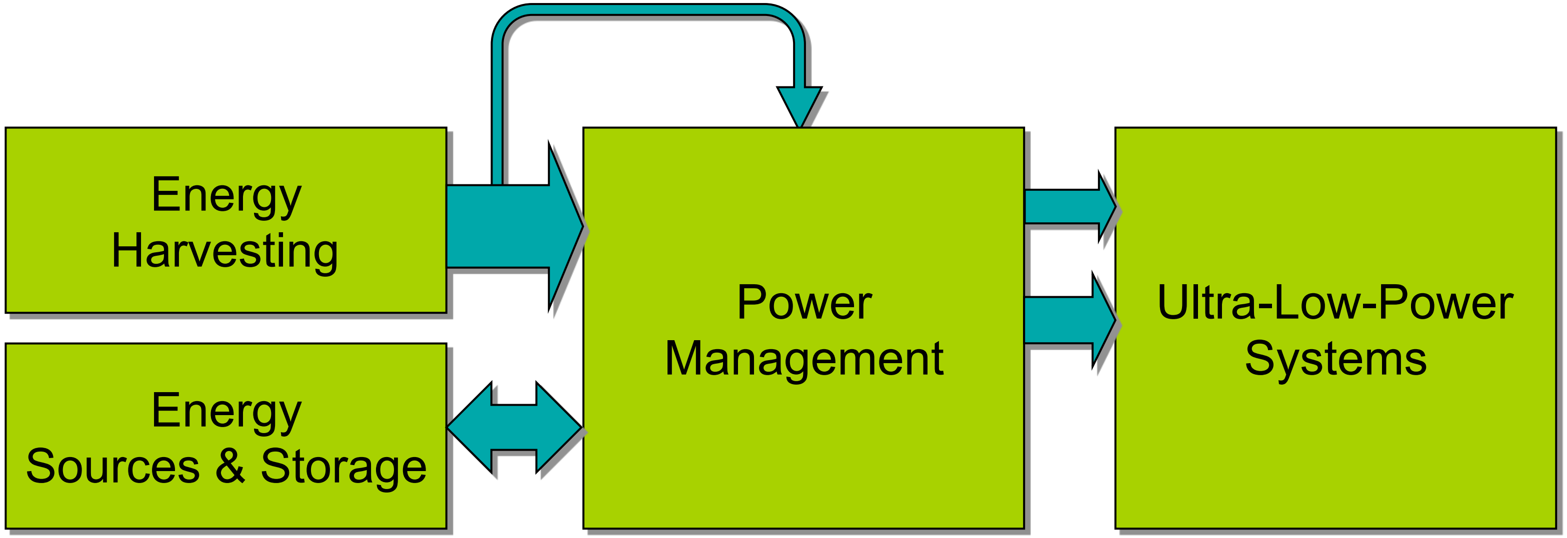




E. Macrelli, A Romani, M. Tartagni, to be submitted

Embedded magnetics

Active Power Management



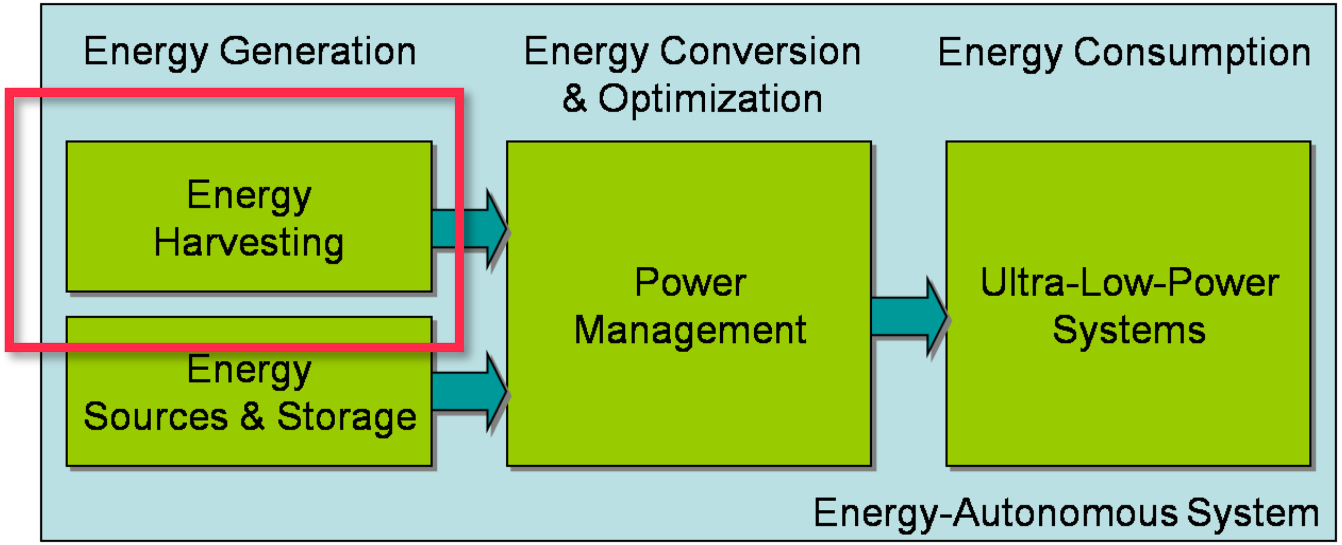
Two issues:

- intelligence should gain more energy from sources than what it consumes
- In zero-power systems two periods should be managed:
  - startup phase (Vdd problem, etc.)
  - operating phase

Overview of the talk

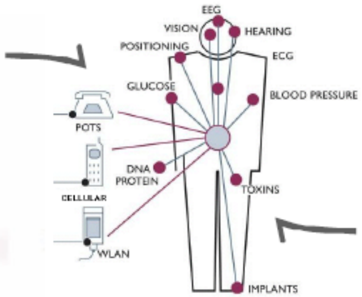
- Zero-power systems, when, where and why
- Definitions and challenges
- Energy consumption & storage
- Energy conversion & management
- Energy harvesting
  - Harvesting from vibrations
  - Harvesting from temperature
  - Harvesting from radio-frequency
- Summary & conclusions

Energy Harvesting



Power and Applications



1W	50mW	1mW	100uW	5uW	1uW
5 hours	24 hours	10 days		5 years	5 years

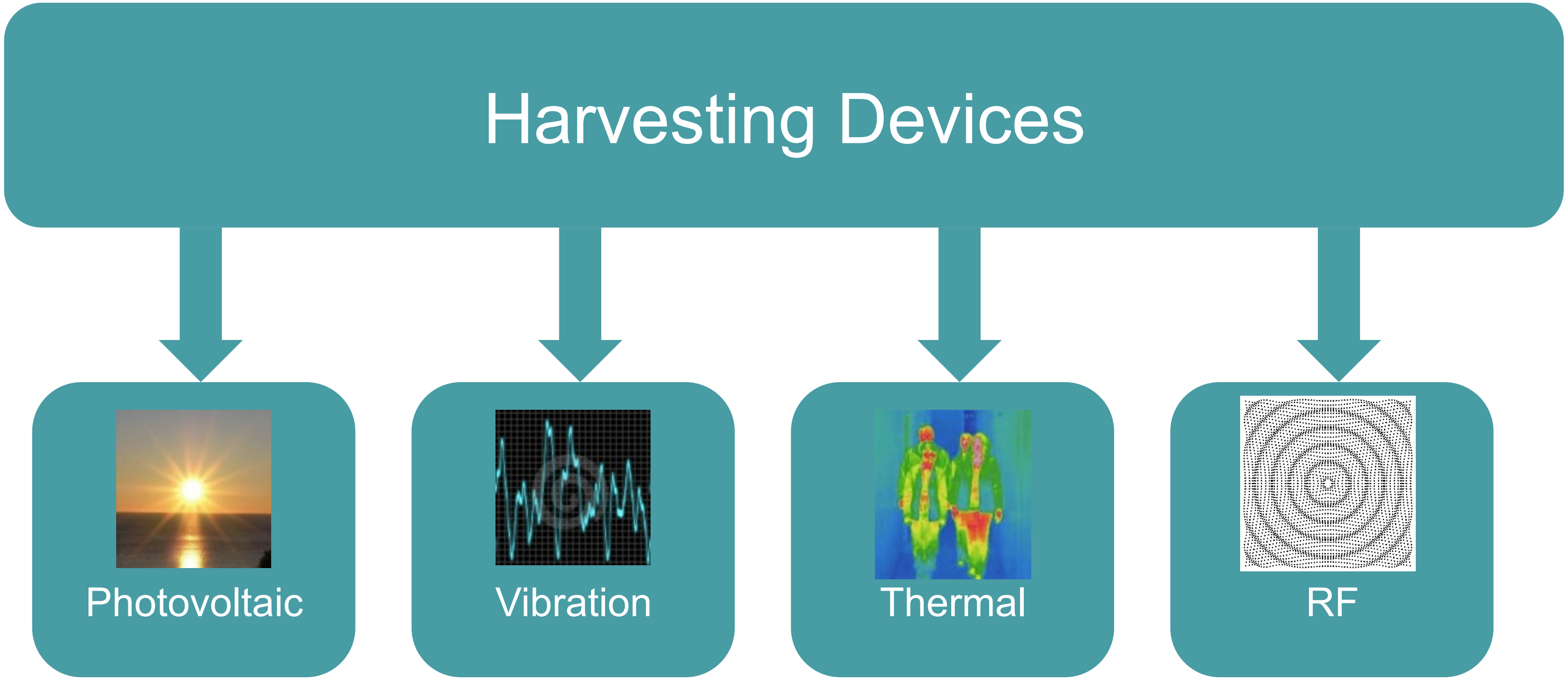
Requirements:

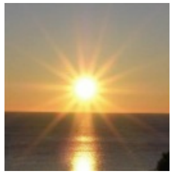
- Small, light energy sources for mobility
- Energy source exceed lifetime for autonomy
- Low cost

Primary batteries: ~1Wh/cm^3
Secondary batteries: ~0.3Wh/cm^3

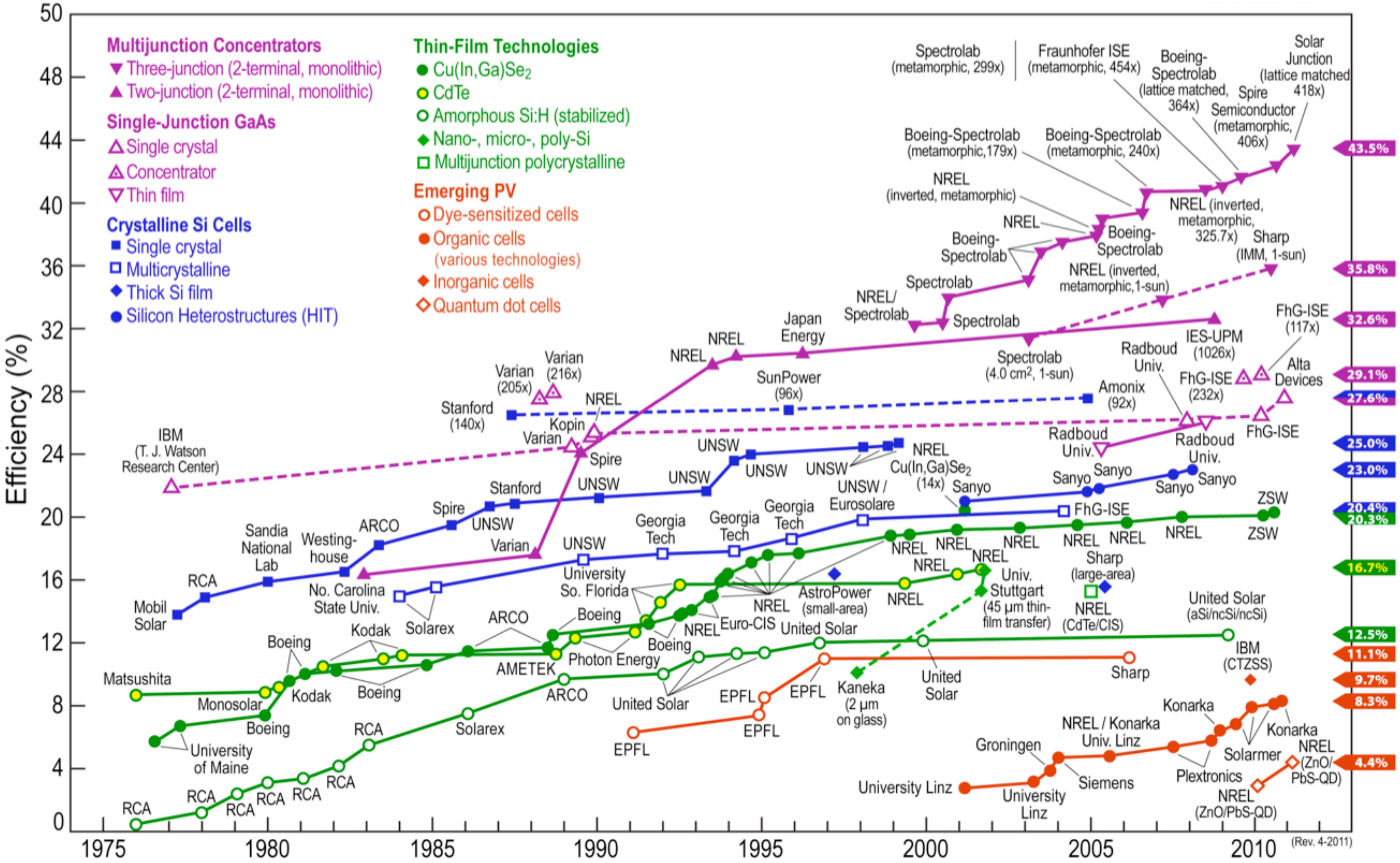
Example: At an average power consumption of 100 mW, you need more than 1 cm^3 of lithium battery volume for weeks of operation.

Source: C. van Hoof, IMEC


Harvesting Devices
Photovoltaic
Vibration
Thermal
RF



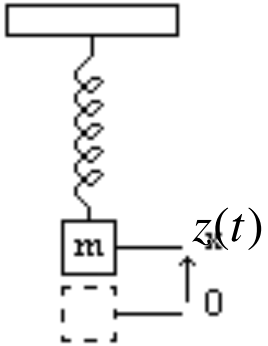
Light Harvesting



Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Vibrational mechanics recall



$$m\frac{d^2z}{dt^2} = -kz$$

m: mass

z = a cos(ω_0t+Δ) displacement

ω_0: natural frequency

k: spring constant

t: time

ω_0^2=k/m

… forced oscillator …

$$m\frac{d^2z}{dt^2} = -kz + F(t)$$

F(t)= F_0 cos(ωt) applied force

ω: resulting frequency (different from the natural one)

z = C cos(ωt)

C= F_0/m(ω_0^2-ω^2)

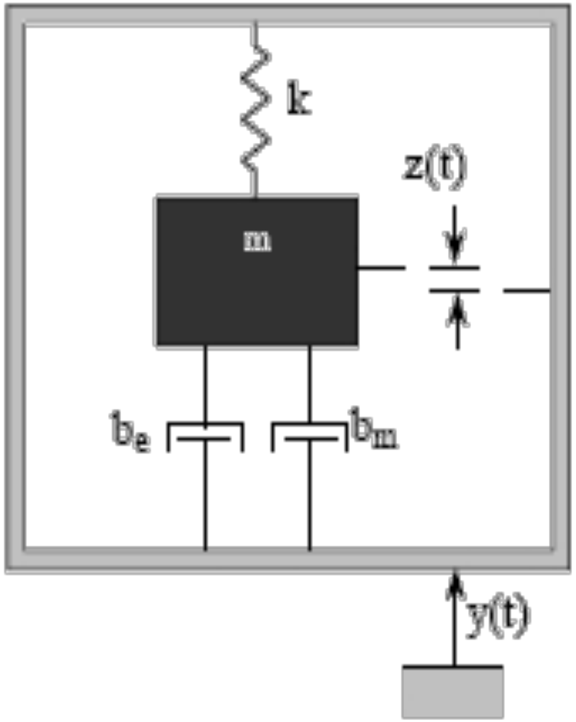
…adding damping force …

$$m\frac{d^2z}{dt^2} + c\frac{dz}{dt} + kz = F(t)$$

the damping force is proportional to the velocity

$$\ddot{z} + b\omega_0\dot{z} + \omega_0^2 z = \frac{1}{m}F(t)$$

General model of conversion for vibrational harvester



$$\ddot{z} + 2(\zeta_m + \zeta_e)\omega_0 \dot{z} + \omega_0{}^2 z = -\ddot{y}$$

z: mass internal displacement

y = Y_0 cos(ωt) shaking displacement

ζ_e: electrical damping ratio [.]

ζ_m: mechanical damping ratio [.]

$b_e = 2m\omega_0\zeta_e$: electrical damping ratio coefficient [Kg/s]

$b_m = 2m\omega_0\zeta_m$: mechanical damping ratio coefficient [Kg/s]

$$F_{e,m} = b_{e,m}\dot{z}(t)$$

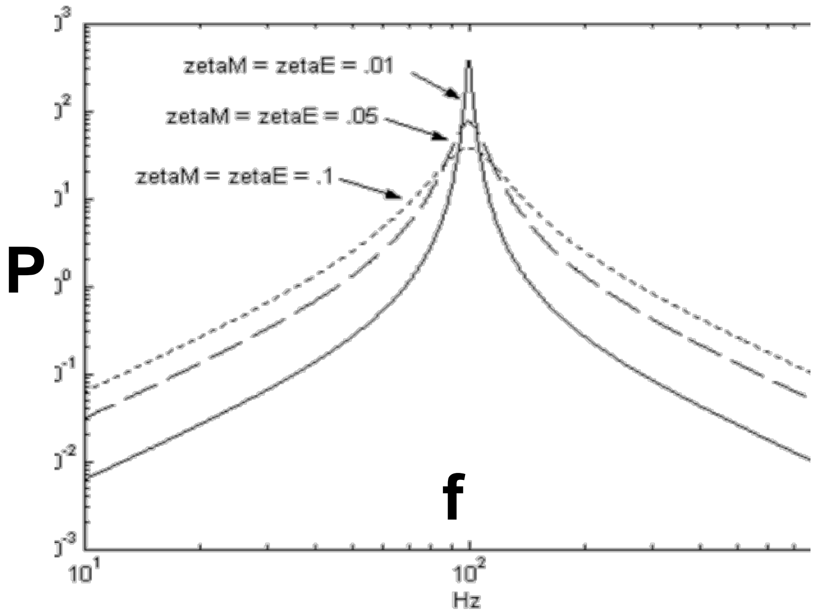
$$P_{e,m} = b_{e,m}\dot{z}(t)z(t)$$

Generated power

Harvested power

$$P = \frac{m\zeta_e \omega_0 \omega^2 \left(\frac{\omega}{\omega_0}\right)^4 Y_0^2}{\left(2\zeta_T \frac{\omega}{\omega_0}\right)^2 + \left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]^2} \xrightarrow[\text{at resonance}]{\text{per } \boldsymbol{\omega = \omega_0}} \boxed{P = \frac{m\zeta_e \omega_0^3 Y_0^2}{4\zeta_T^2} = \frac{m\zeta_e A^2}{4\omega_0 \zeta_T}}$$

$A = \omega^2 Y_0$ acceleration amplitude



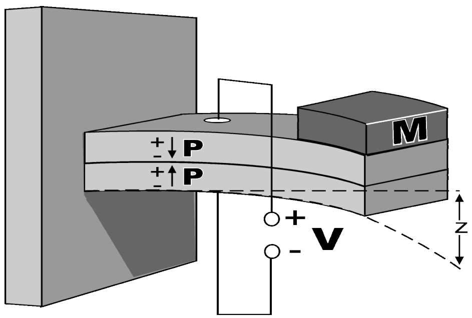
CONCLUSION:

- Maximum of power at resonance
- Power is proportional to the squared amplitude of acceleration and mass
- Power optimized when electrical damping (where energy is harvested) is equal to the mechanical one
- For a given acceleration power is inversely proportional to frequency

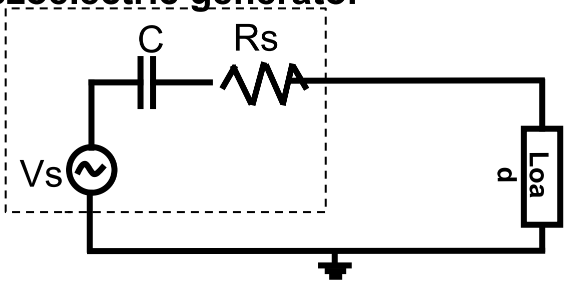
Vibrations Harvesting

Piezoelectric

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

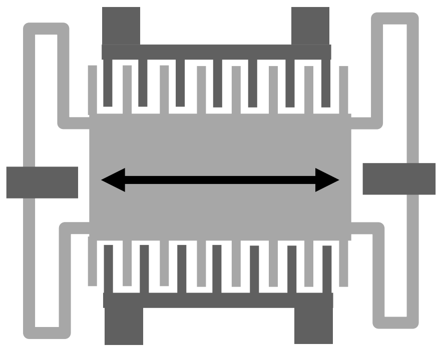


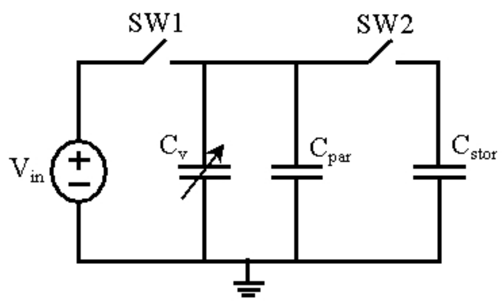
Piezoelectric generator



Capacitive

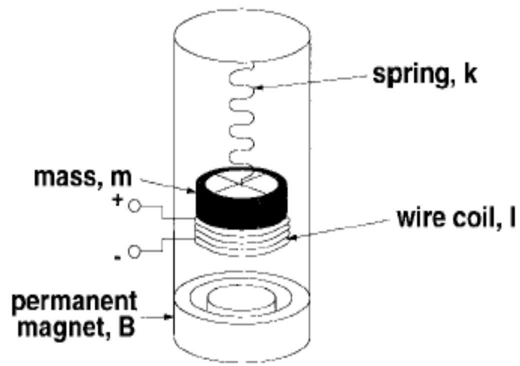
Change in capacitance causes either voltage or charge increase.





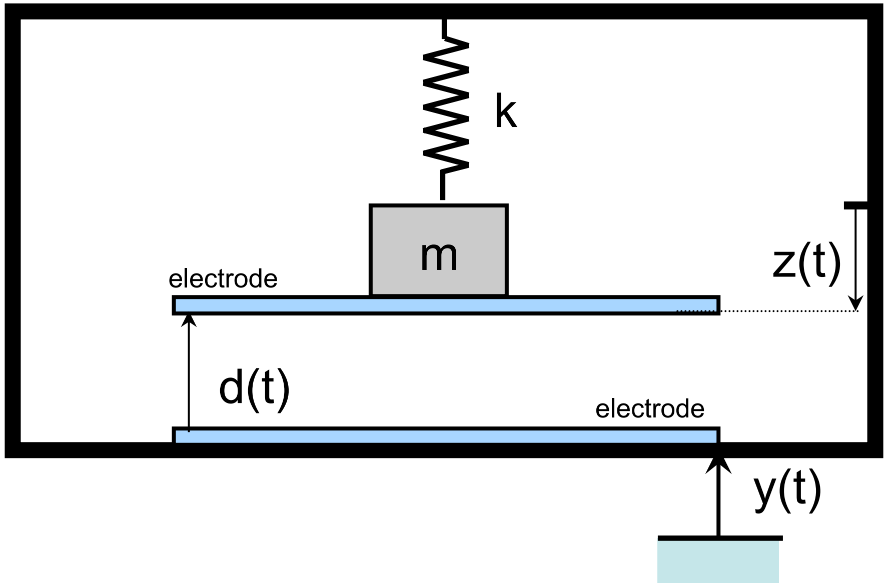
Electromagnetic

Coil moves through magnetic field causing current in wire.



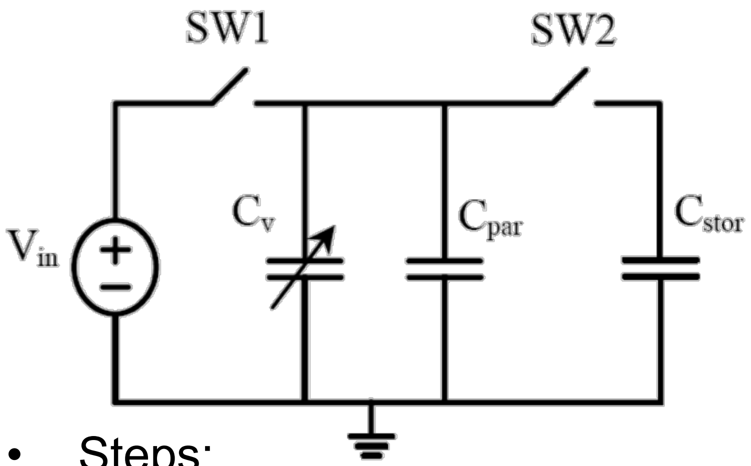
Source: S. Roundy

- Electrostatic generators
  - are basically composed of an oscillator with an attached variable capacitance
  - vibrations produce changes in electrical capacitance



Electrostatic Generators

- Basic Principle



C_v variable capacitor (vibrating structure)

C_{par} parasitic capacitance associated with the vibrating structure

C_{stor} storage capacitor

need for a switching controlling circuit

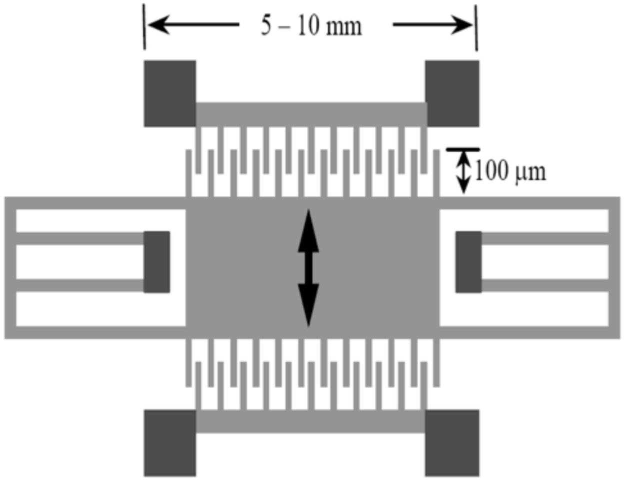
need for external V_{in}

- Steps:
  - when $C_v = C_{v,MAX}$ SW1 closes [C_v gets precharged] and then opens
  - vibrations induce change in C_v [$E = Q^2/2C_V$]
  - when $C_v = C_{v,MIN}$ energy is at the maximum level, SW2 closes, charge is tranferred to C_{stor}, then SW2 opens again

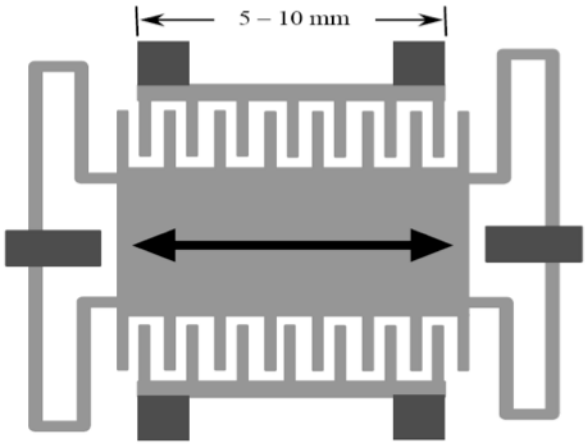
- Energy conversion

$$\Delta E = \frac{1}{2} V_{in}^2 \left(C_{\max} - C_{\min}\right)\left(\frac{C_{\max} + C_{par}}{C_{\min} + C_{par}}\right)$$

Electrostatic Converters - Topologies



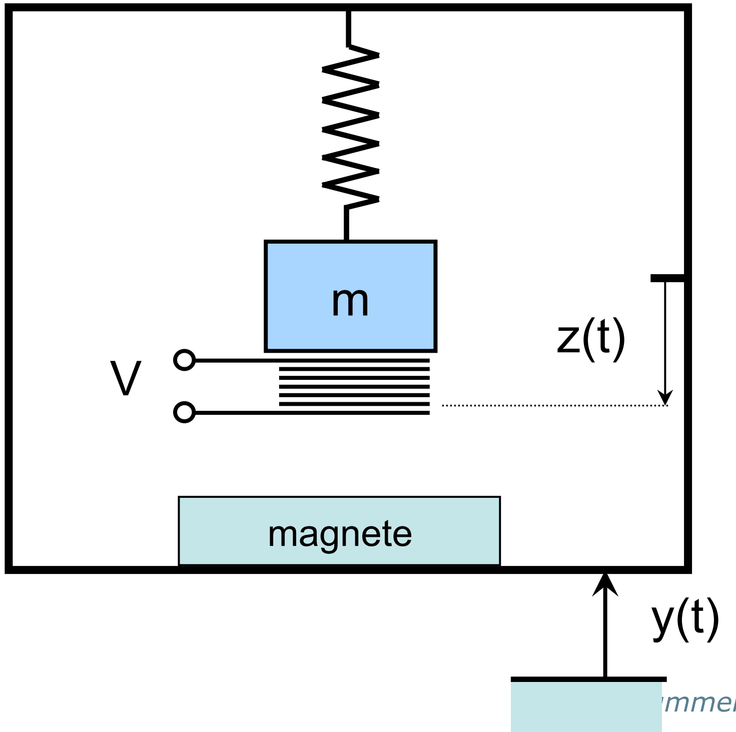
In-plane overlap type:
Capacitance changes by changing overlap area of fingers. (Not to scale)



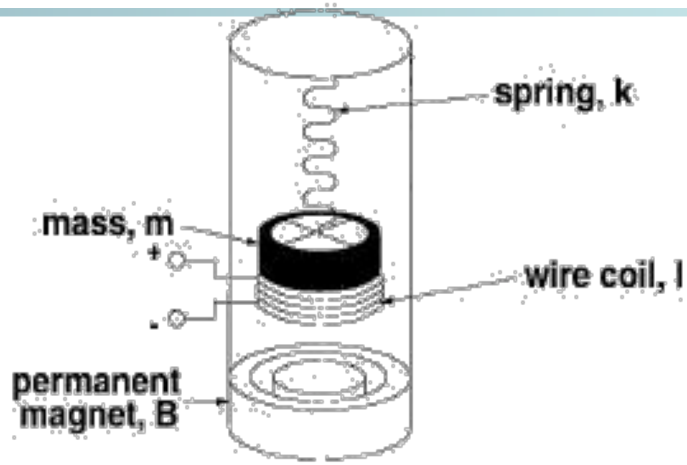
In-plane gap closing type:
Capacitance changes by changing gap between fingers. (Not to scale)

Out-of-plane gap closing type:
Capacitance changes by changing gap between two large plates. (Not to scale)

- An electromagnetic converter
  - is basically modelled as a mass/spring system, with a coil and a magnet
  - the housing is subject to vibrations
  - electromagnetic induction



Example of electromagnetic harvester



- Mass connected to a spring and attached to a rigid housing.
- As the housing vibrates, the mass moves relatively to the housing and energy is stored in the mass/spring system.
- A wire coil is attached to the mass and moves through the field of a permanent magnet as the mass vibrates. This induces a voltage on the coil.

- A prototype generator following this design was built using discrete components:
  - the generator was tested by giving the mass an initial displacement and then releasing it.
  - The device size is 4cm*4cm*10cm.

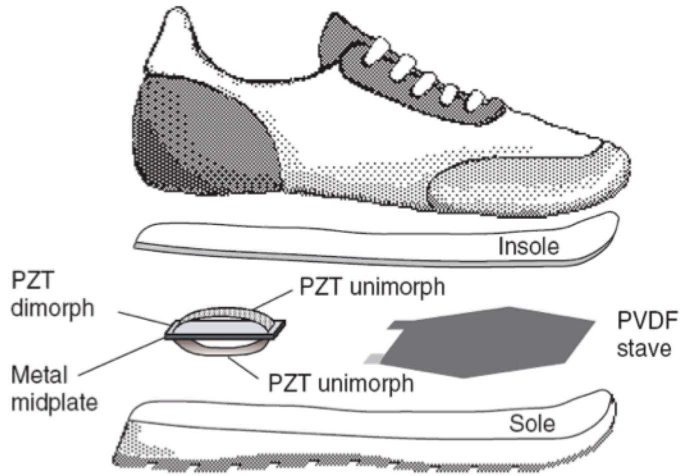
- With R_L = 10Ω, m = 0.5g, k = 174N/m
  - natural frequency of the generator of 94Hz and peak output voltage of 180mV.

- A transformer is necessary to create a large enough voltage from the generator output to be efficiently rectified by a diode

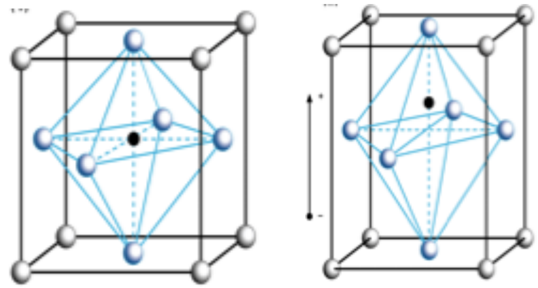
- This model was simulated to generate a stochastic output power:
  - the best-case estimate of the average output power is 400μW
  - but the source is under idealized circumstances (no mechanical damping or losses)
  - this is just an estimated value.
  - The vibration magnitude was of about 2cm at about 2Hz.

The Origin: Shoe Mounted PiezoElectrics, 2001

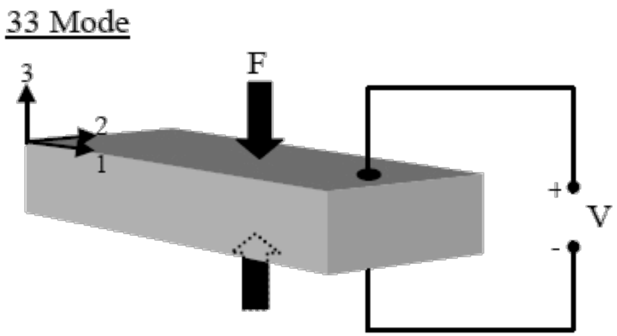
- Shenck, N., and Paradiso, J.A., *Energy Scavenging with Shoe-Mounted Piezoelectrics*
- Low-frequency piezo source
  - Mainly capacitive
  - High-voltage, low-energy, low-duty cycle current pulses
  - Linear regulator not very suitable ☹
  - Forward-switching converter ☺ (normal components)
- PZT dimorph: 8.4 mW w/500kW-load at walking pace (1Hz)
- $V_{pp} > 100V$, $V_{avg} = 40V$
- Powering RFID tag system

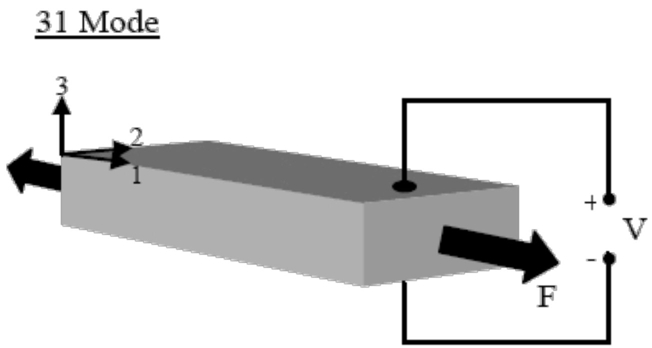


Piezoelectric Effect



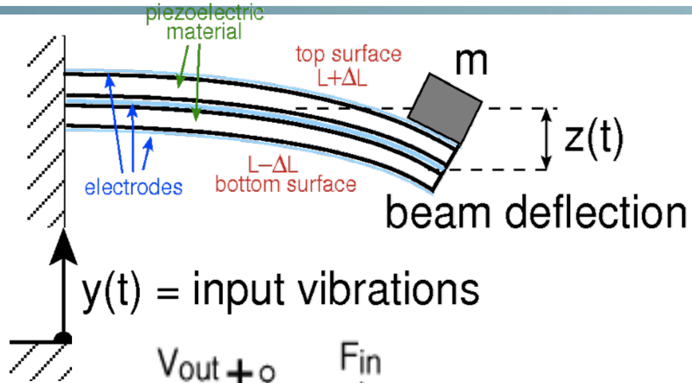
- Piezoelectric effect
  - coupling of mechanical stress and electric field
  - Initial polarization process (→ modes)
- Materials
  - PVDF (polyvinylidene), PZT (lead zirconate titanate)
  - Bimorphs, PZN-PT (lead zync niobate, lead titanate)
- Modes:

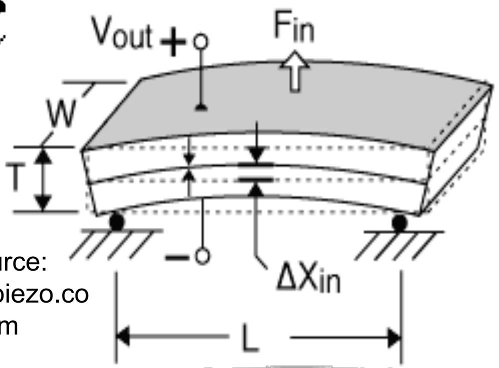




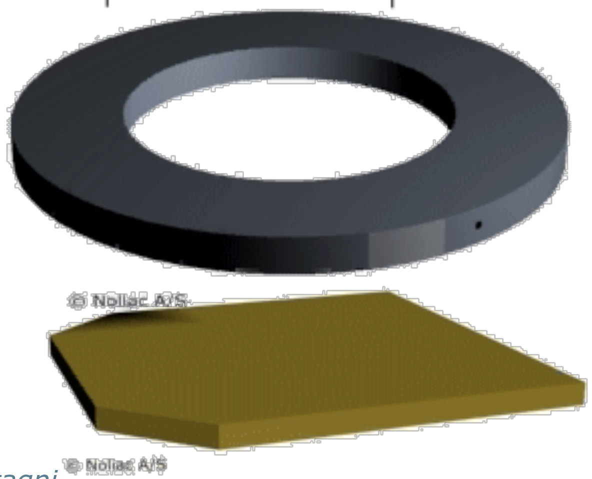
  - Directions of electric field and mechanical stress
  - Better results with cantilever and flexion (mode 31, less coupling, but more elastic!)

Piezoelectric energy harvesters





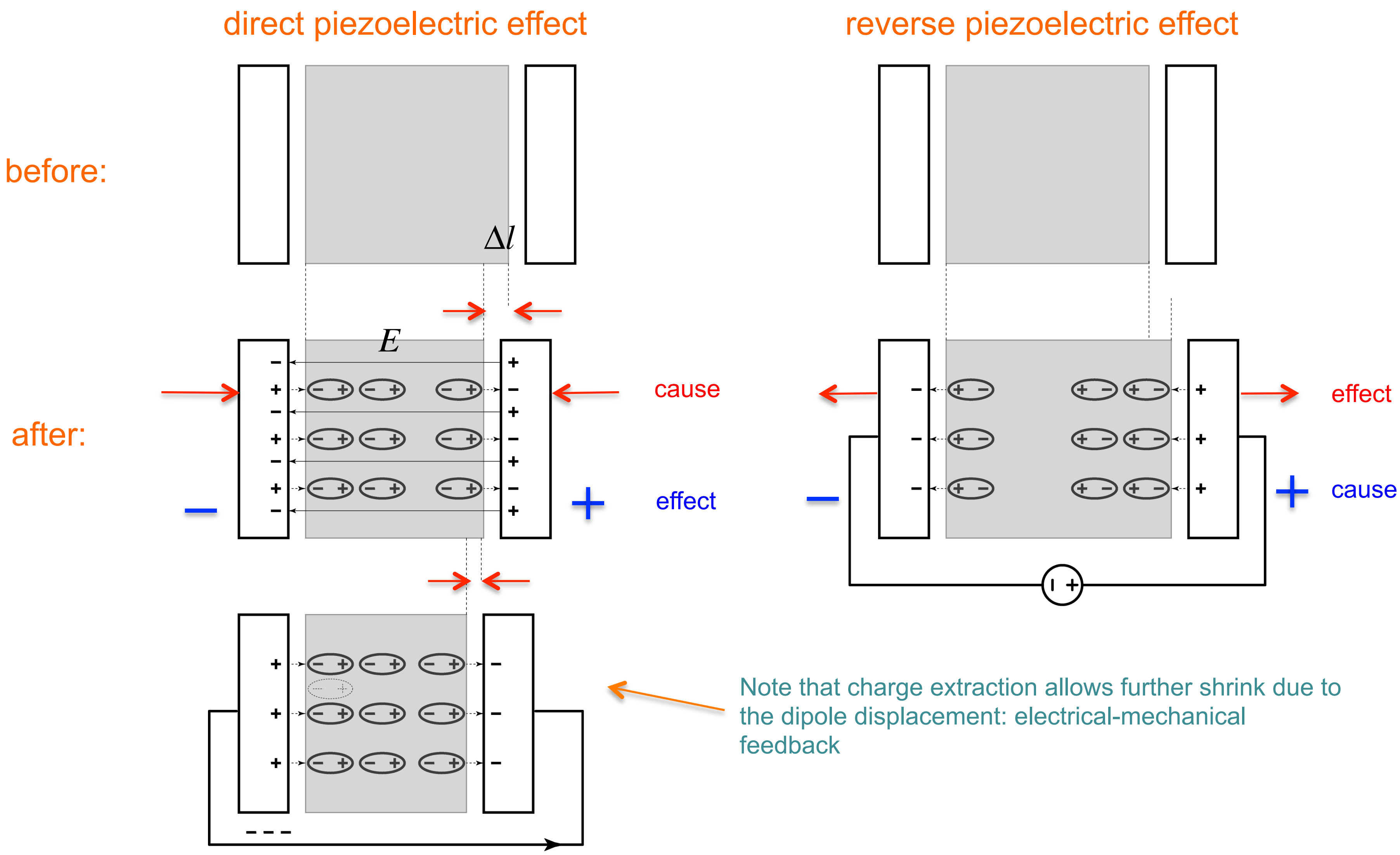
source: www.piezo.com



source: www.noliac.com

- Vibrations as an energy source
  - Widely diffused in many environments such as transportation systems, industrial machinery, human motion, etc.
- Piezoelectric energy harvesters are usually oscillating structures composed of:
  - a seismic mass
  - a piezoelectric transducer
- Common structures are: cantilevers, simple beams, rings, membranes, etc.

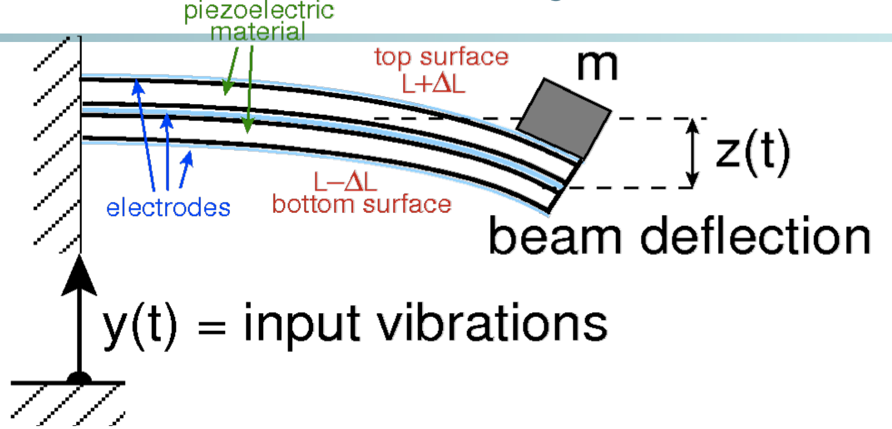
Piezoelectricity



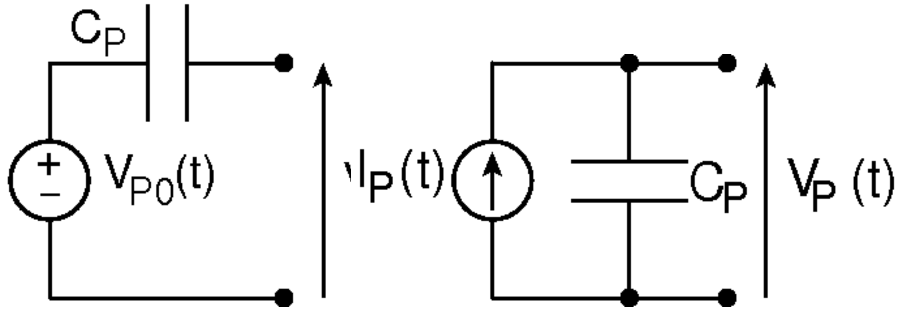
Note that charge extraction allows further shrink due to the dipole displacement: electrical-mechanical feedback

Piezoelectric Mass-Cantilever Systems

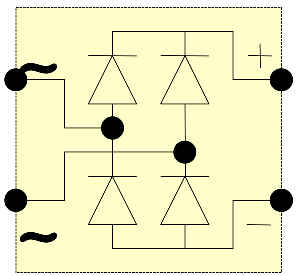
- Cantilevers are common structures for harvesting energy from vibrations
  - usually piezoelectric bimorphs
  - a mass cantilever system has a fundamental resonant frequency (single-degree-of-freedom models)



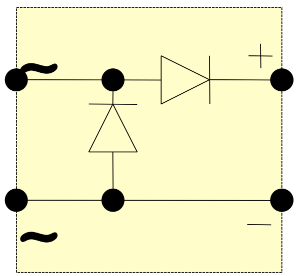
- A common representation is a generator with an output capacitance



- Rectifier circuits are the simplest solution for harvesting energy from vibrations
  - their efficiency can be improved with switching circuitry and smart control



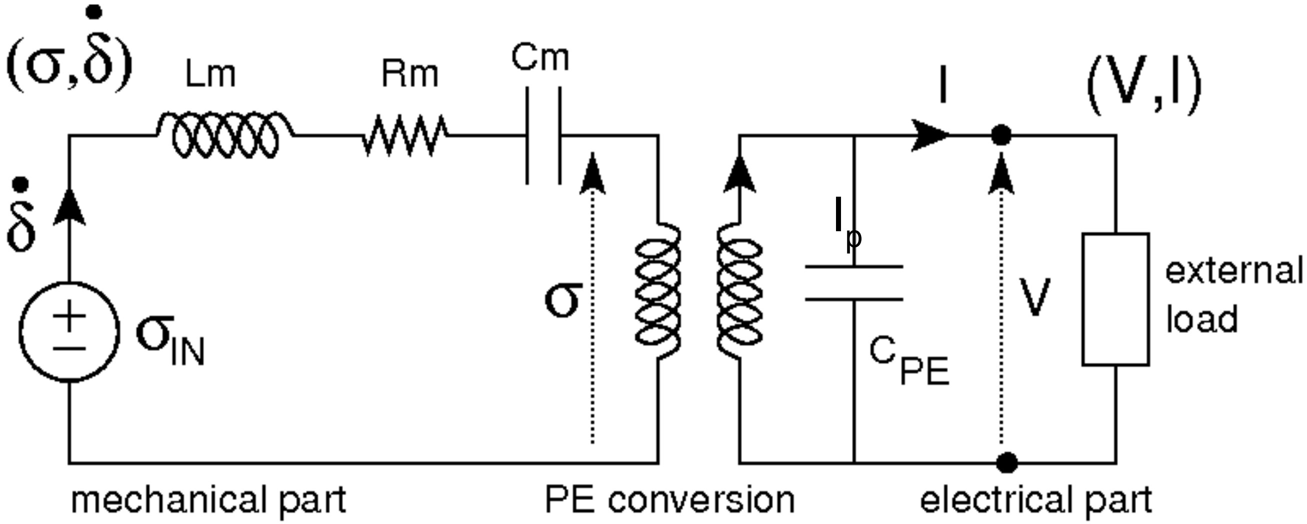
full-wave rectifier



voltage doubler rectifier

Equivalent electro-mechanical model

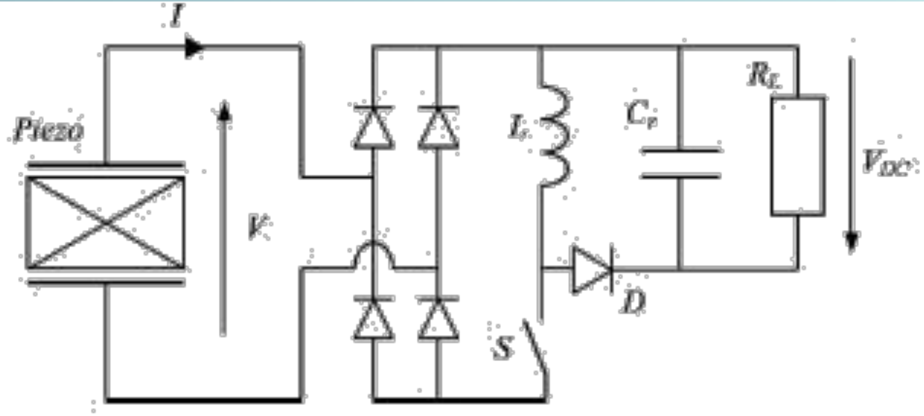
- Piezo equivalent electromechanical circuit model
- Left: P/V, Right: P

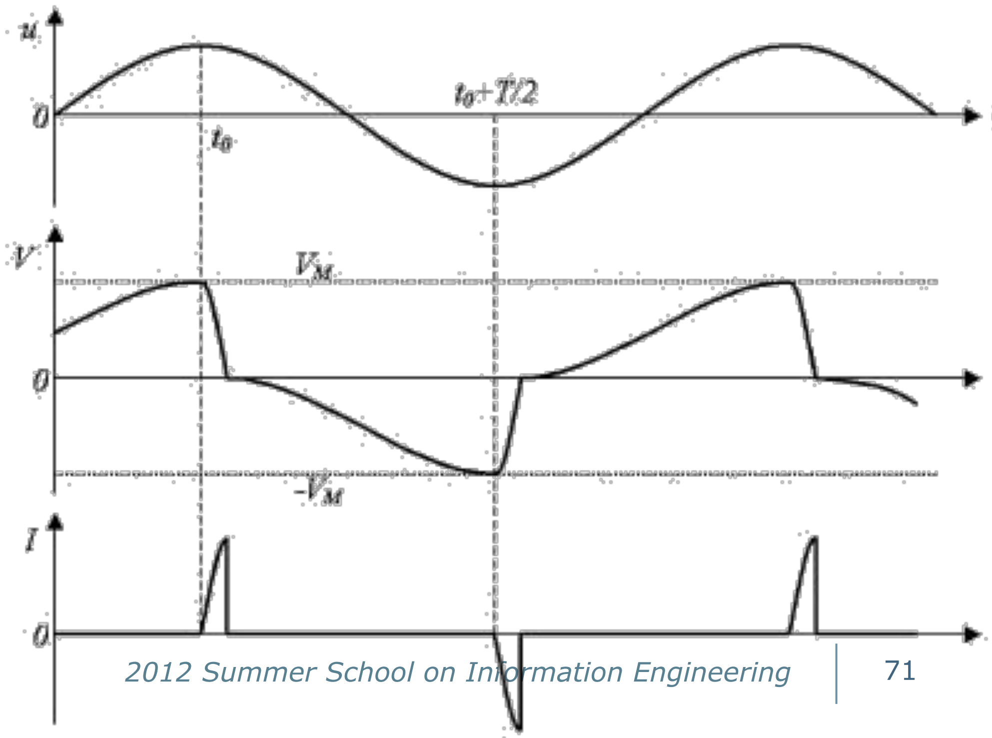


s mechanical stress, d strain, L_m inertial mass(&speed) effects, R_m mechanical losses, C_m elastic energy storage

Synchronous charge extraction (SCE)

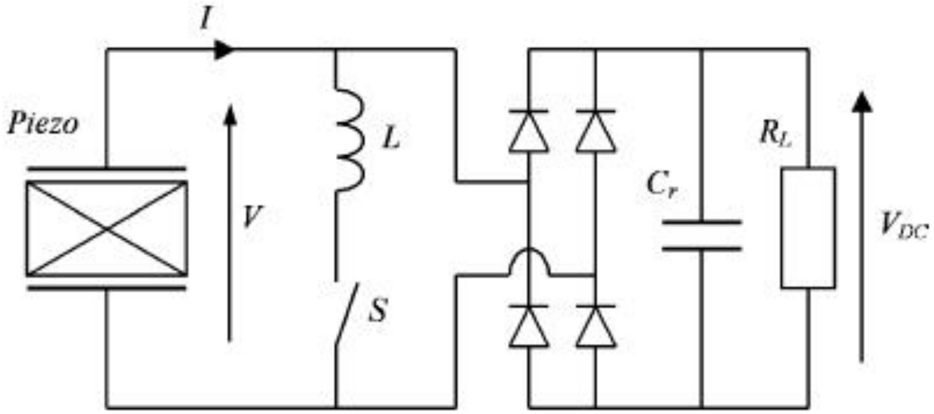
- The synchronous charge extraction principle consists
  - in periodically removing the electric charge accumulated on the blocking capacitor of the piezoelectric element
  - and then to transfer the corresponding amount of electrical energy to the load or to the energy storage element.
- The extraction instants are triggered on the minima and maxima of the voltage V(t) or displacement u(t)

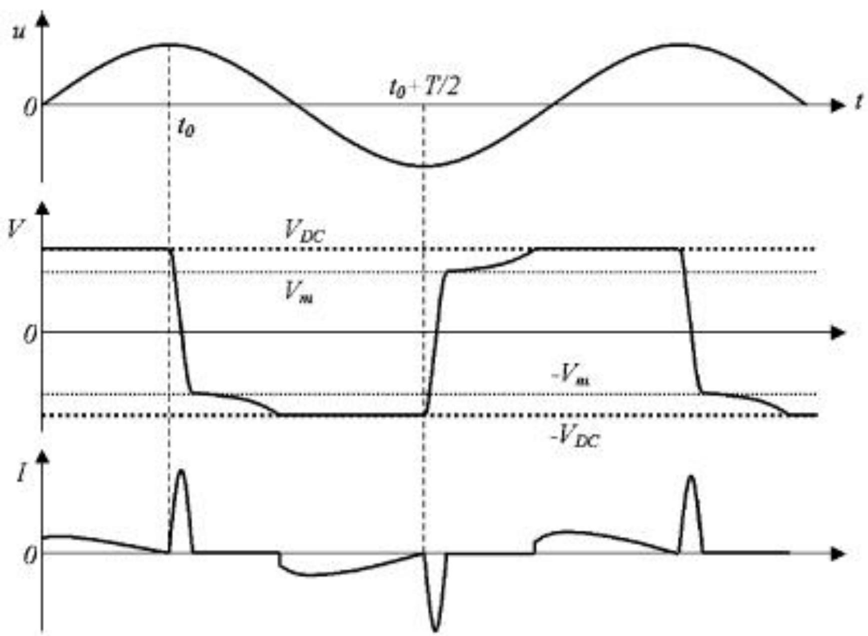




Parallel Synchronized Switch Interface (SSHI)

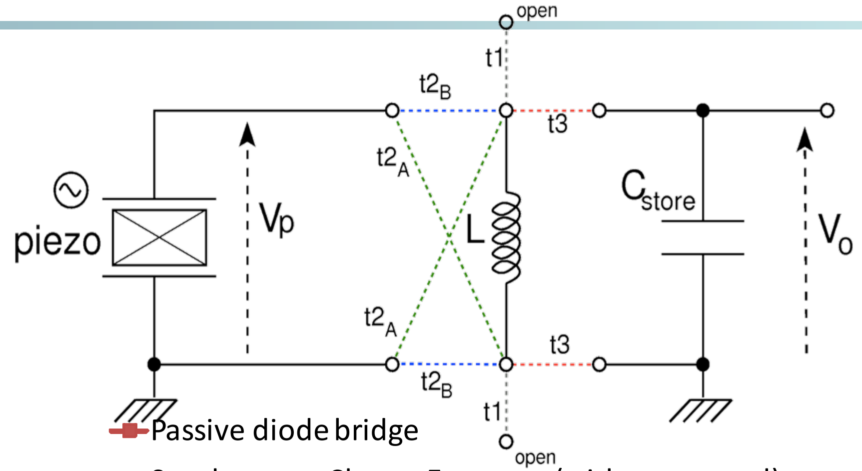
- SSHI is based on a non-linear processing circuit:
  - an inductor L in series with an electronic switch connected in parallel with the piezoelectric element
- The electronic switch is briefly turned on when the mechanical displacement reaches a maximum or a minimum.
  - The switch is turned off after a half electrical period, resulting in a quasi-instantaneous inversion of V.
- The non-linear process induces energy losses
  - Electrical losses in the resonant circuit
  - Mechanical damping

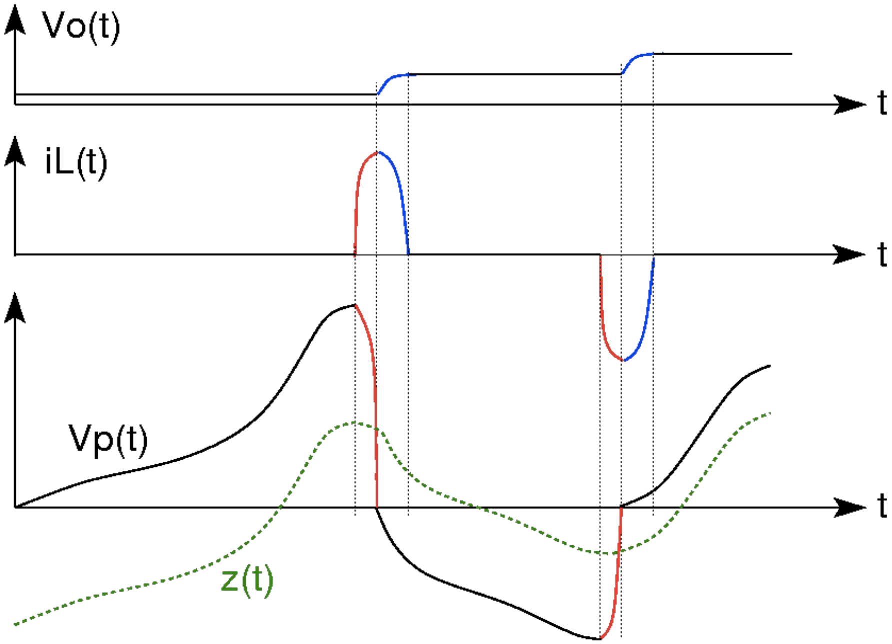


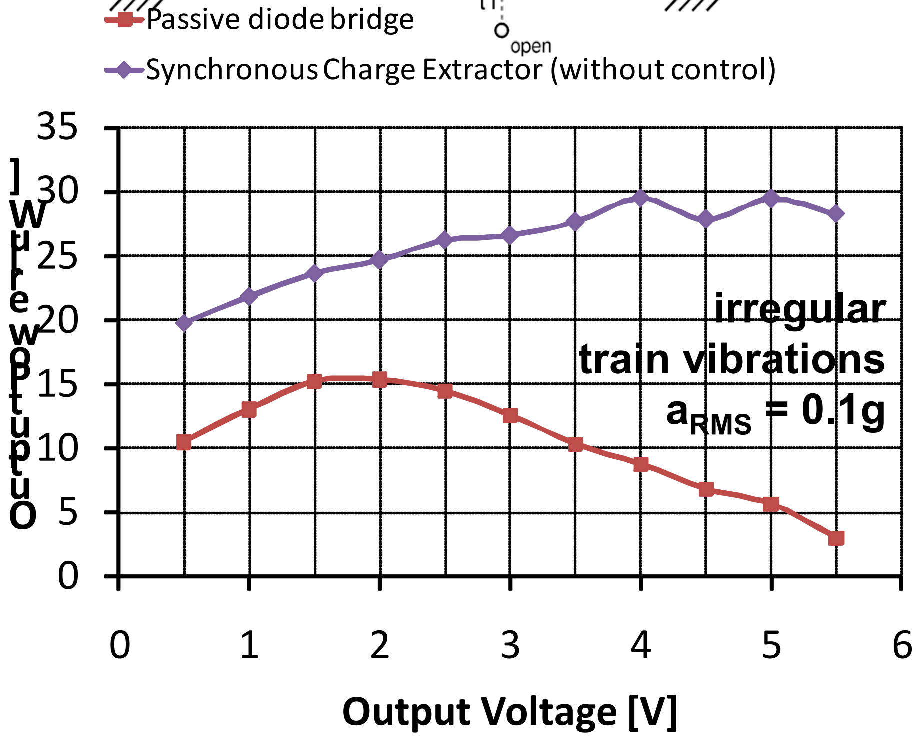


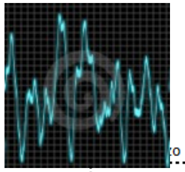
Synchronized Switch Converter (SSC)

- A solution based on SCE without diodes and rectifiers was developed at Unibo
  - A. Romani et al., "Dynamic switching conversion for piezoelectric energy harvesting applications", IEEE Sensors 2008



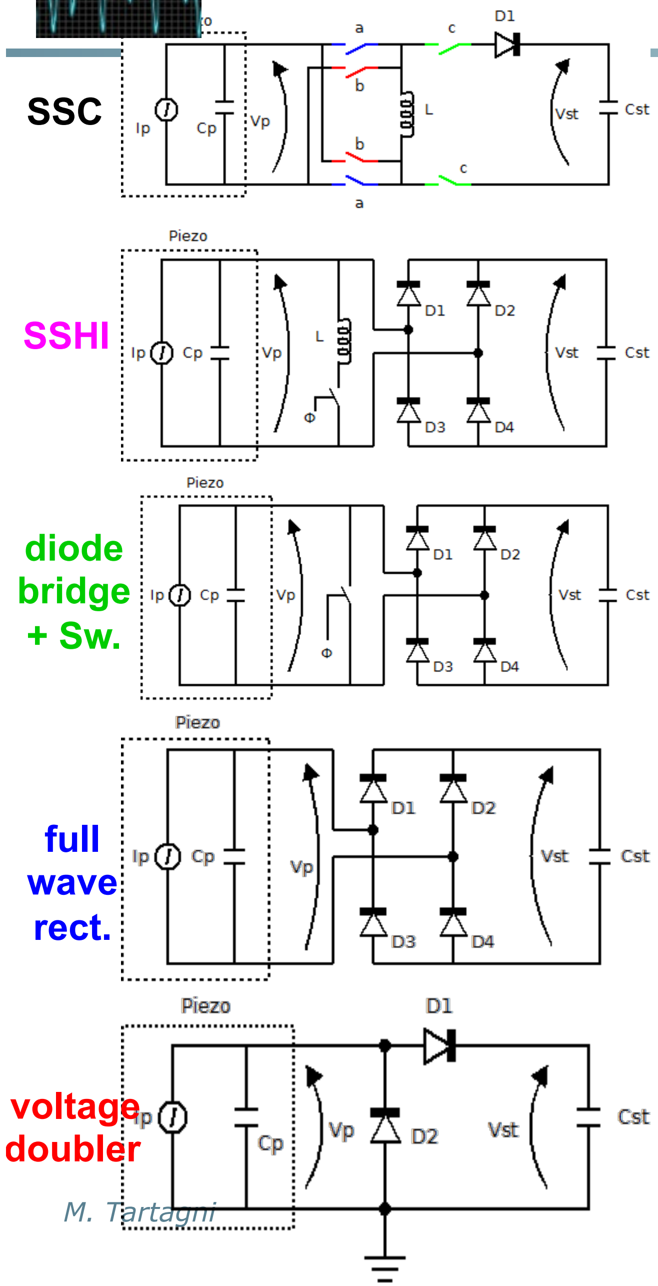


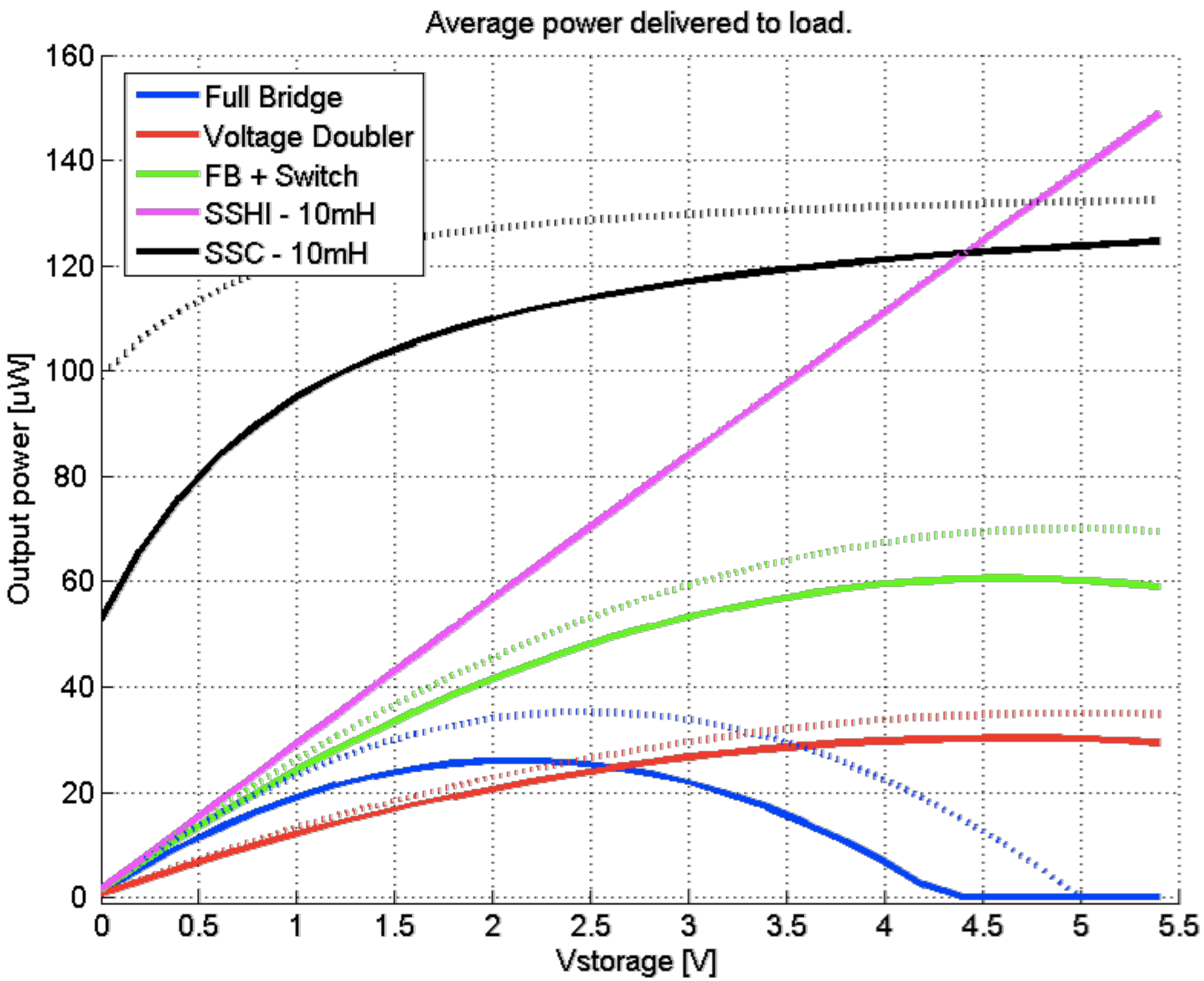




Predicted Performance

V_P = 5V, f = 27.1 Hz, L = 10mH,
C_{ST} = 4.7 uF, C_P = 52 nF, V_g = 0.35V

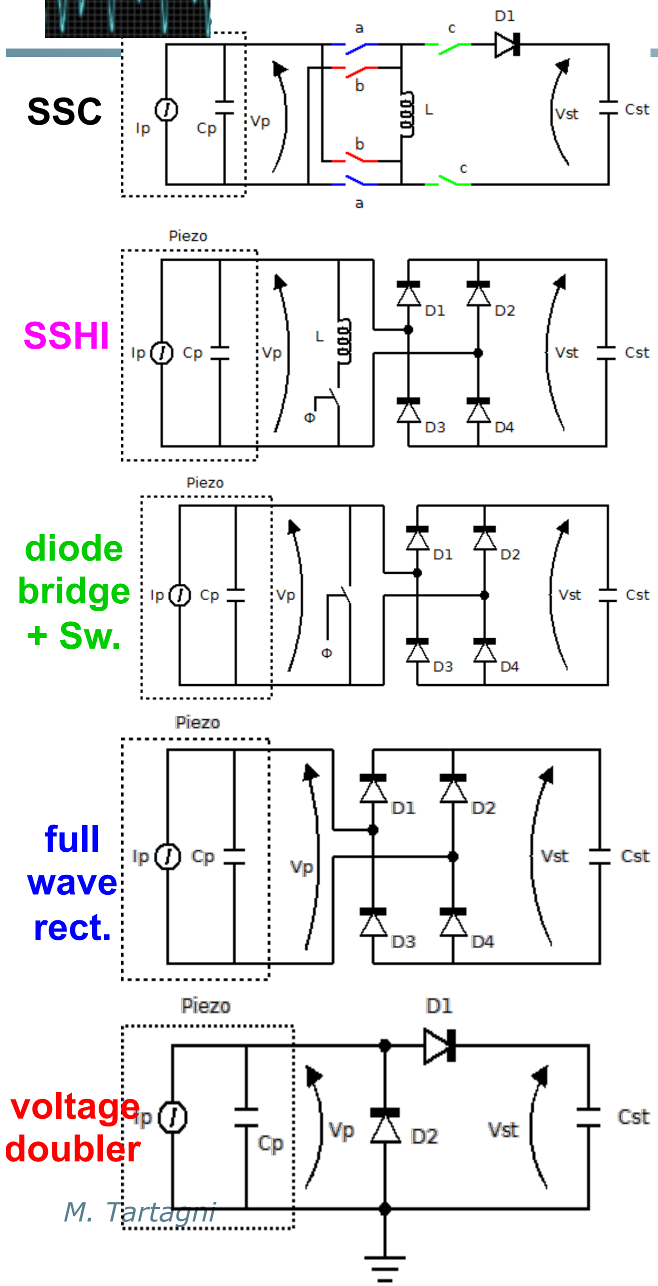


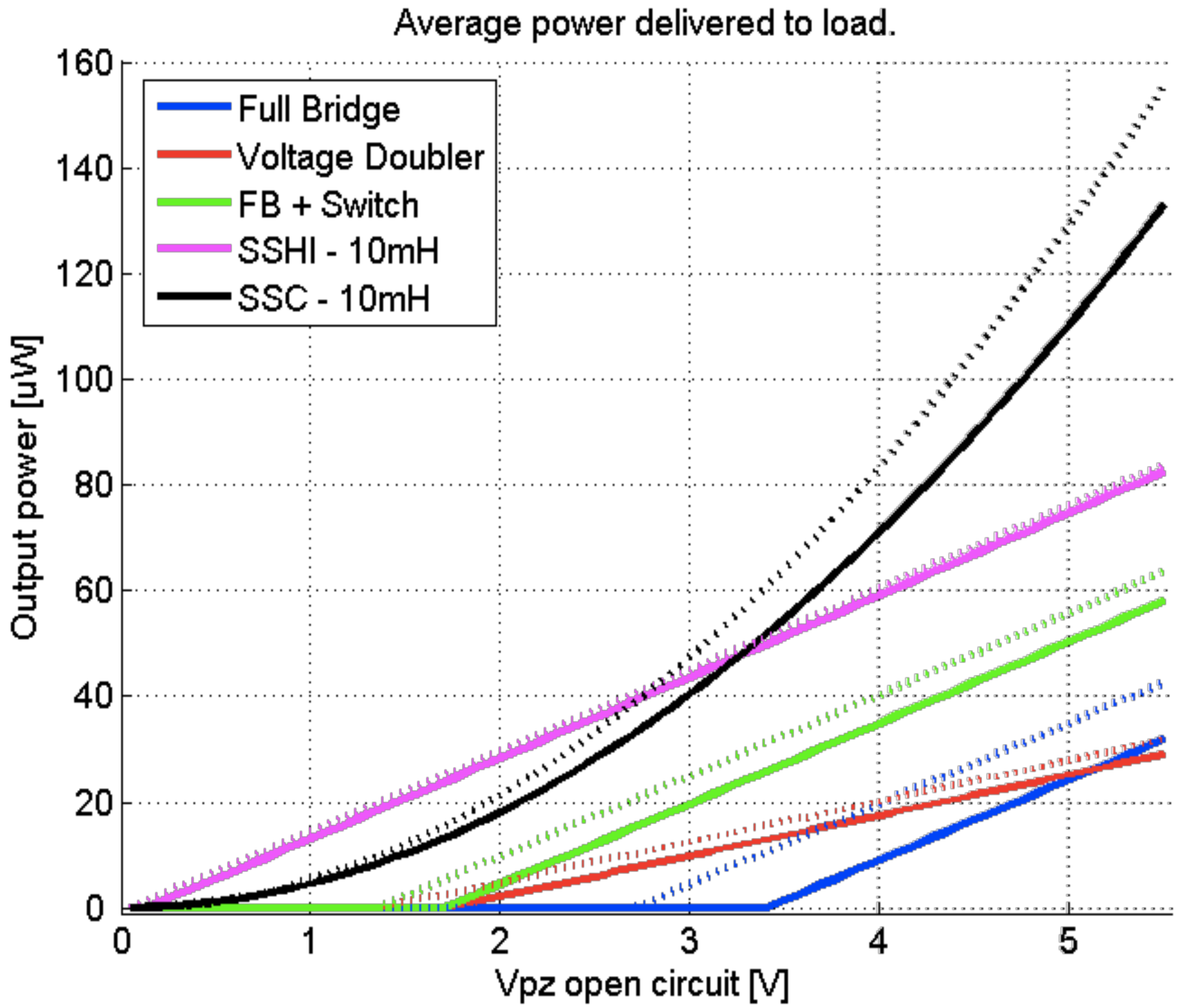


constant input amplitude

Predicted Performance

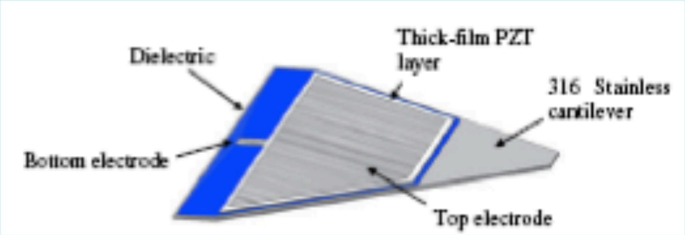
V_{ST} = 2.7V, f = 27.1 Hz, L = 10mH,
C_{ST} = 33 uF, C_P = 52 nF, V_g = 0.35V



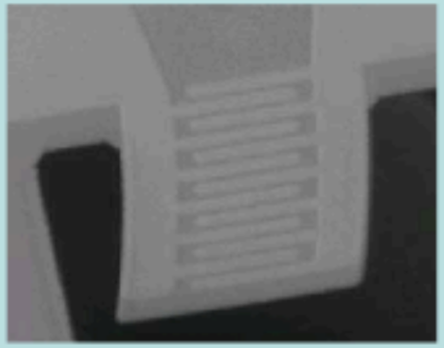


constant output bias

State-of-the-art Piezoelectric

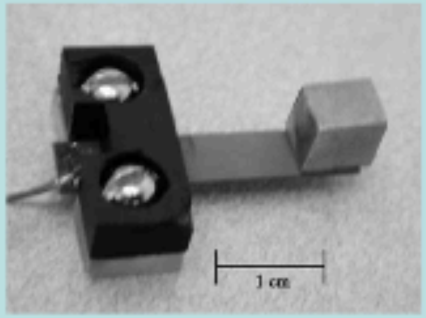


Glynne-Jones et al., 2001
University of Southampton
3 µW, 1 g @ 80Hz

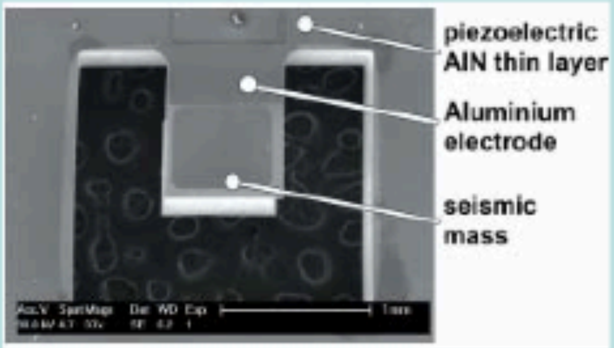


Sang-Gook Kim, Rajendra Sood, MIT, 2004
1 µW @ 2.36 V (0.74 mW-h/cm^2)

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

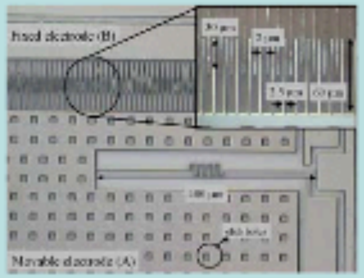


Shad Roundy et al, Berkeley, 2003
70 µW, 2.25 m/s^2 @ 100Hz, 1cm^3

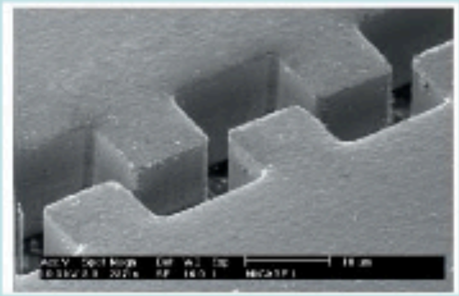


M. Marzencki et al, Tima Labs, 2007
2 µW, 2g @ 840 Hz, 25mm^3

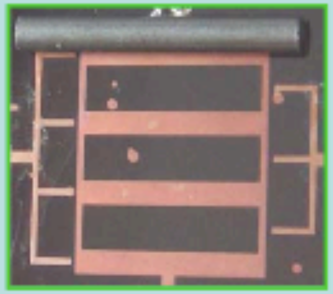
State-of-the-art Capacitive



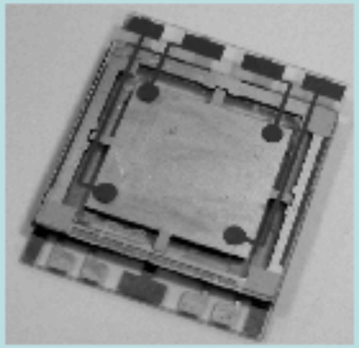
T. Sterken et al., 2003
IMEC, K.U. Leuven
12 nW, 1 g @ 1 kHz, 2 mm^3



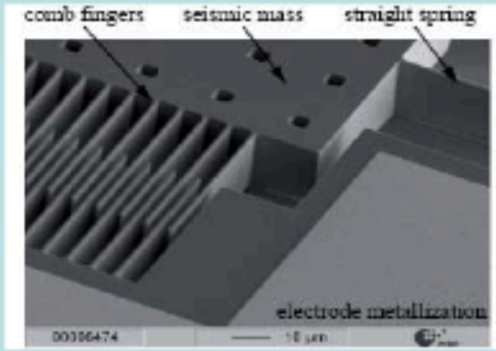
G. Despesse et al, 2007
LETI – MINATEC
12 μW, 0.3g @ 50 Hz, 1cm^2



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

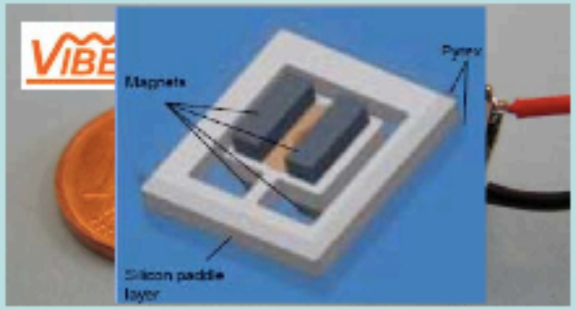


U. Bartsch et al., 2007
IMTEK

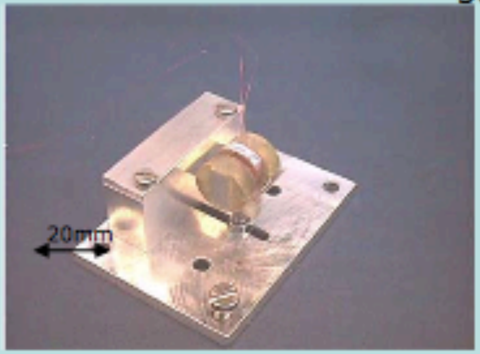
State-of-the-art Electromagnetic

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, 0.4 g @ 50 Hz, 0.1 cm^3

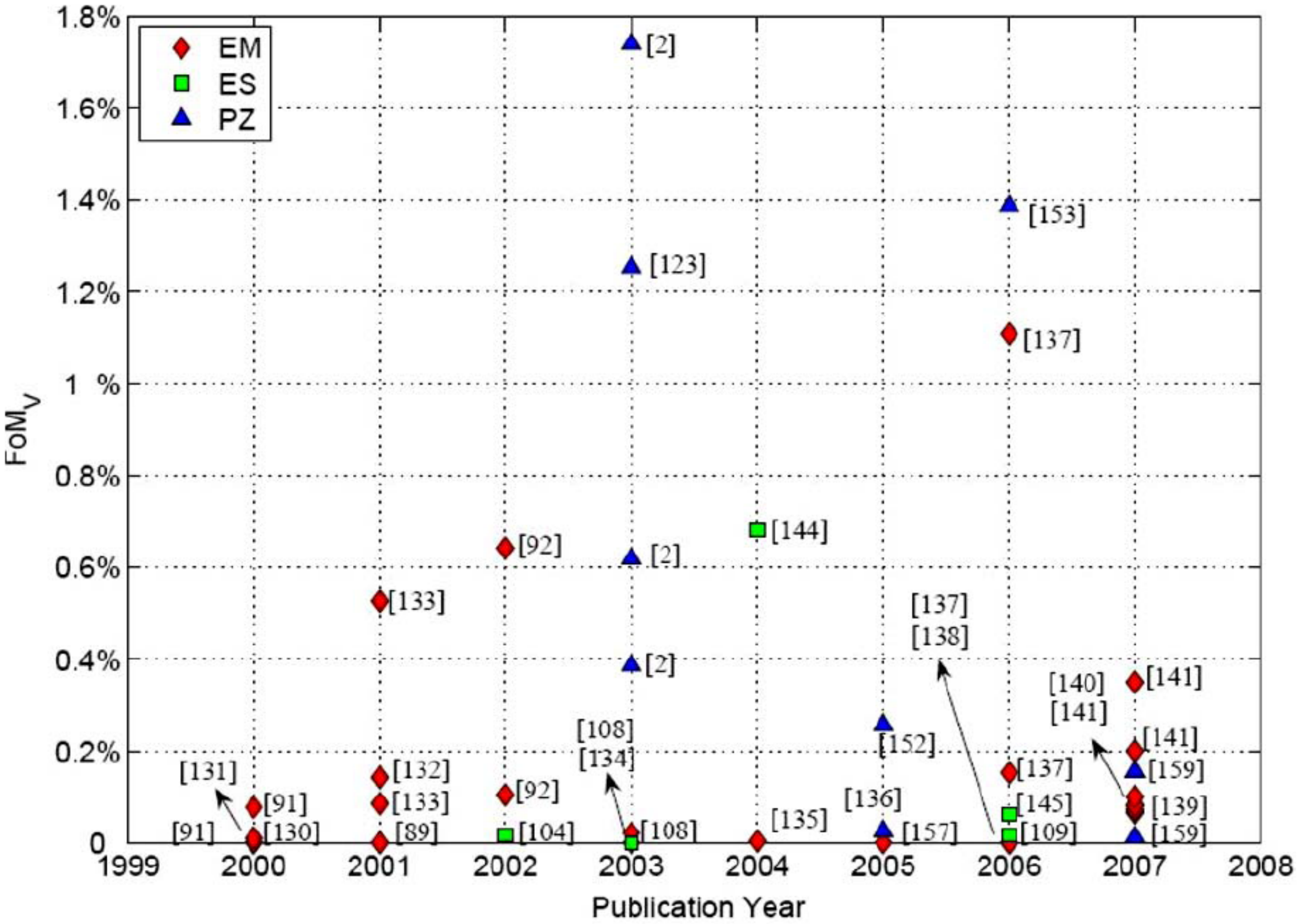


Glynne-Jones et al, 2004
University of Southampton
600 µW at 4.3m/s^2 @ 100 Hz

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

A Comparison Between three Methods



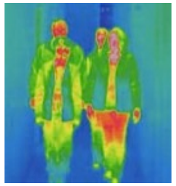
Piezoelectric devices give best performances over the time…

Source: P. D. Mitcheson, 2008 IEEE

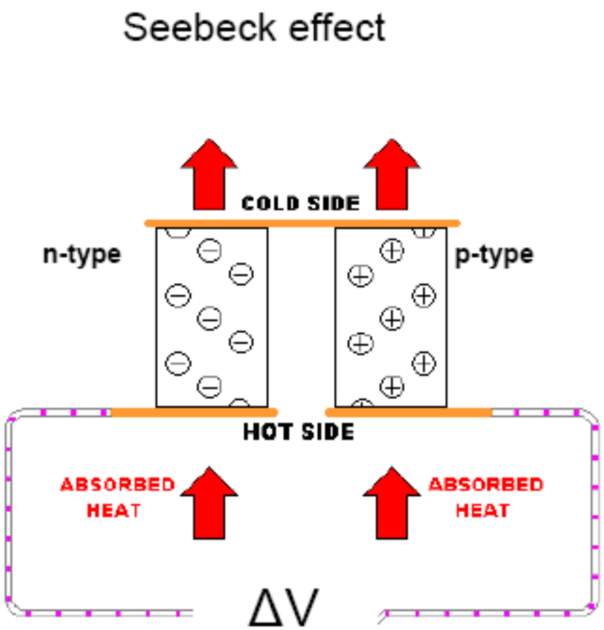
Integrated MEMs/CMOS Devices State-of-art

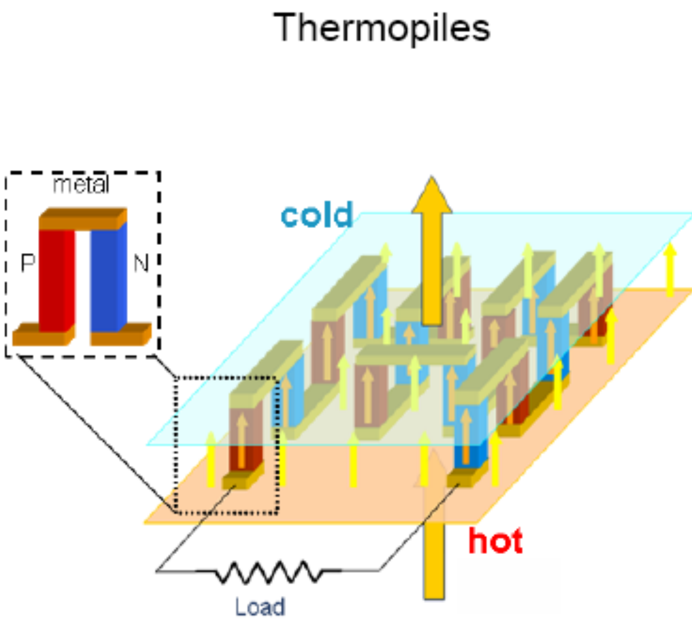
Ref.	Vibration Harvester	Harvester Size (mm^3)	Res. Freq.	$P_{IN-UNLOADED}$ (Output on R_{OPT})	N.P.D. ($\mu W/mm^3/g^2$)	Band-width	Sys. Volume (w/ Circuitry)
This Work	MEMS Harvester with thinned PZT unimorph	27.3	429 Hz	1.8μW at 0.1g	6.45	16.0 Hz	< 0.3 cm^3
			419 Hz	67.9μW at 1.0g	2.49	26.3 Hz	
[4]		12.1	80 Hz	3.75μW at 0.3g	3.44	2.5 Hz	N/A
[1] IMEC	MEMS Harvester with sputtered AlN unimorph	28.7	353 Hz	17μW at 0.64g	1.45	-	1 cm^3
			325 Hz	85μW at 1.75g	0.97	3 Hz	
[2] MIT	Meso-scale Commercial PZT bimorph	130.3	225 Hz	- at 3.35g	-	-	N/A
[3] Gatech	Meso-scale Commercial PZT bimorph	228.8	100 Hz	40 μW -	-	-	N/A

Aktakka, … Najafi et al. *A Self-Supplied Inertial Piezoelectric Energy Harvester with Power-Management IC,* ISSC, 2011

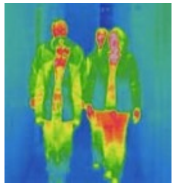


Thermal Harvesting

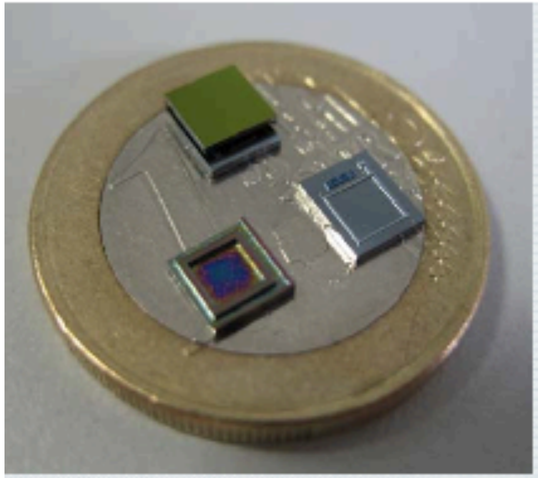




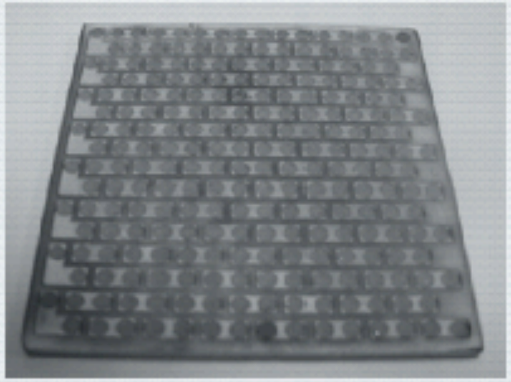
Differently doped semiconductors are joined by metal contacts and placed in a temperature gradient making a “thermopile”

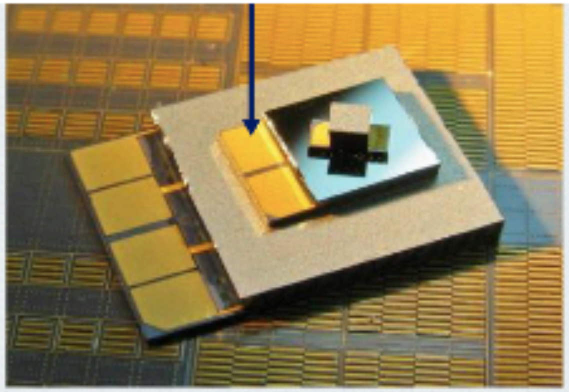


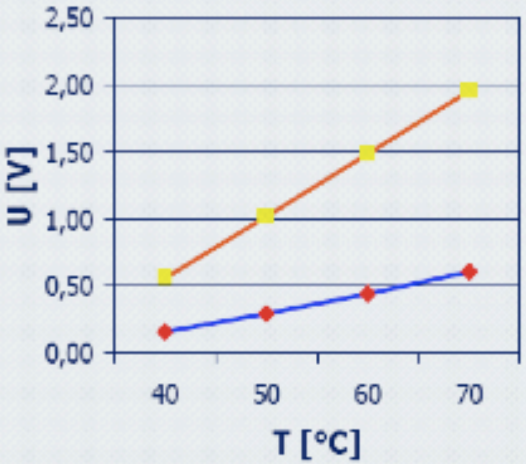
Thermal Energy Harvester State-of-the-art



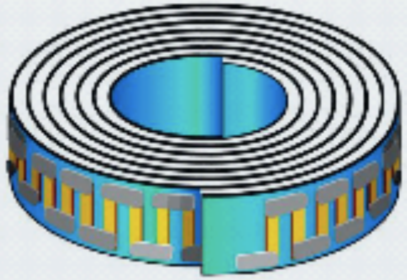
polySiGe thermopiles
Source: Leonov & Wang, IMEC







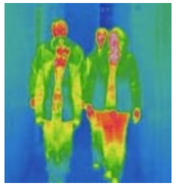
Source: Micropelt TEG (shown without cooler)



5200 BiTe thermocouples on kapton tape

$123\mu W$ at $\Delta T = 5K$
(42.5uA at 2.9V)

Source: ThermoLife



Main Issue: Very Low Input Voltages

	Startup mechanism	Min. Startup Voltage	Typical Input Voltage (V_{IN})	Output Voltage @V_{IN}	Peak Efficiency @V_{IN}	Process
[1]	Mechanical switch	35mV	50mV	1.8V	58%	350-nm CMOS
[2]	External Voltage	650mV	100mV	1V	75%	130-nm CMOS
[3]	Charge pump	180mV	180mV	0.74V	N/A	65-nm CMOS
[4]	Charge pump	360mV	500mV	7V	82%	350-nm SOI-BCD
This Work	Charge pump with V_{TH}–tuned oscillator	95mV	100mV	0.9V	72%	65-nm CMOS

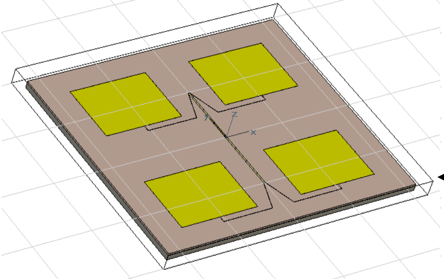
P. Chen et al. *A 95mV-Startup Step-Up Converter with VTH-Tuned Oscillator by Fixed-Charge Programming and Capacitor Pass-On Scheme,* ISSC, 2011

RF Scavenging

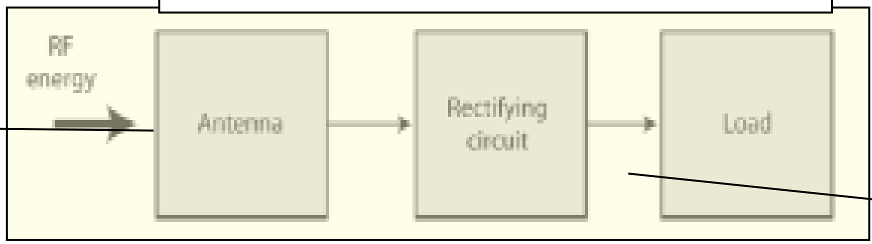
- Wide diffusion of RF communications devices (cell phones, wi-fi hot-spots, etc.) in humanized environments
  - Electromagnetic waves transfer information <u>and energy</u> at dinstance

- The idea: to collect energy rather than information
- How: the RECTENNA concept
  - Antenna + rectifying circuit
  - Appliable to many common wireless standards(GSM-900, UMTS, IEEE802.11, …), easy to realize and integrate

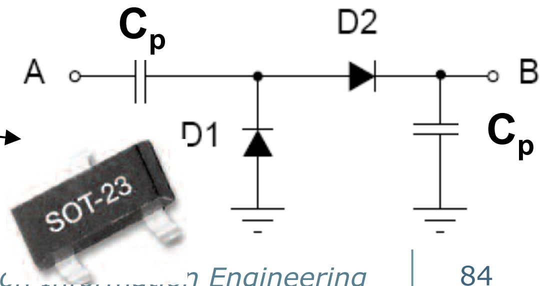
1. Patch antenna



Rectenna conceptual scheme



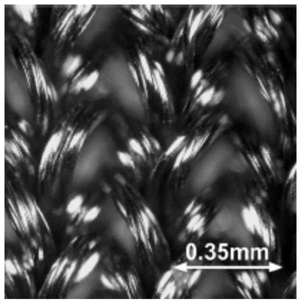
2. Charge pump circuit

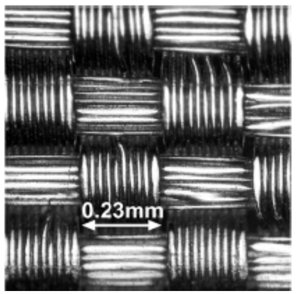


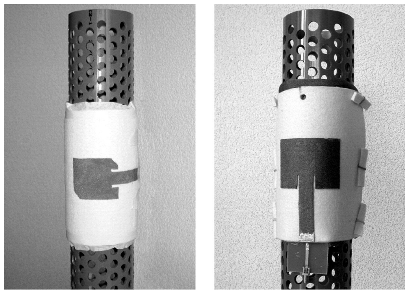
Towards Wearable Implementations

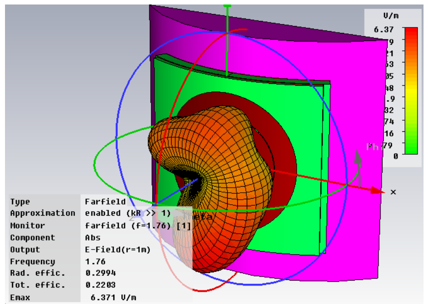
- **A challenging technology conversion, which implies:**
  - An overview of suitable electrotextile materials
  - A detailed investigation about antenna performances when bent on curved surfaces

- **Electro-textiles:** generally created by incorporating conductive threads into fabrics by means of weaving and knitting









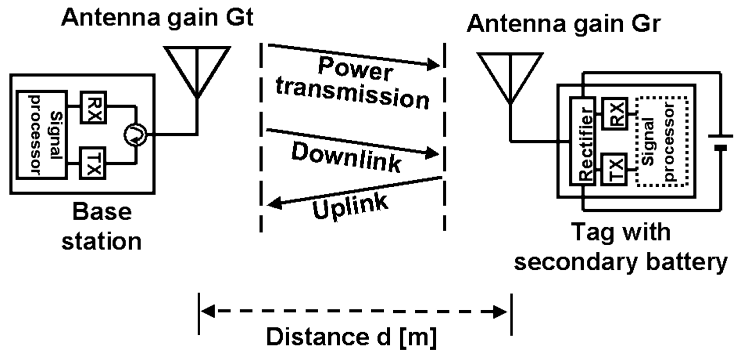
- **Performance during bending must be preserved.** In our design at 0.9 and 2.45 Ghz it remains unchanged

Source: A. Costanzo, UniBO

RF Harvesting as a support to the RFID concept?

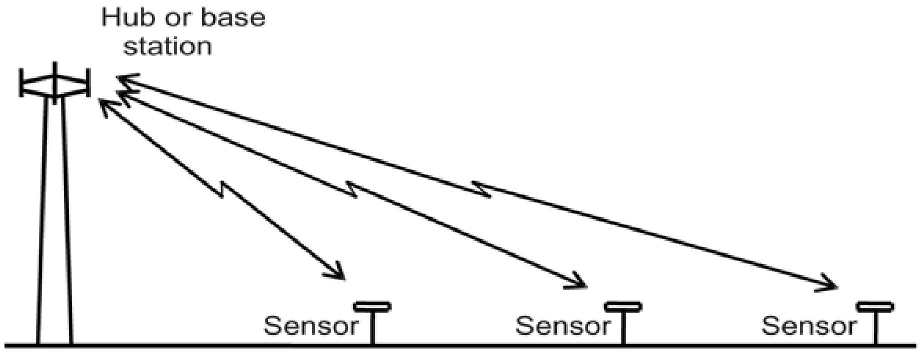
	Active TAG	Semi-Passive TAG	Passive TAG
Communication distance	Long	Moderate	Short
Incorporation of sensors	Easy	Possible	Difficult
Necessity of battery	Need	Need	No need
Cost	High	Moderate	Low

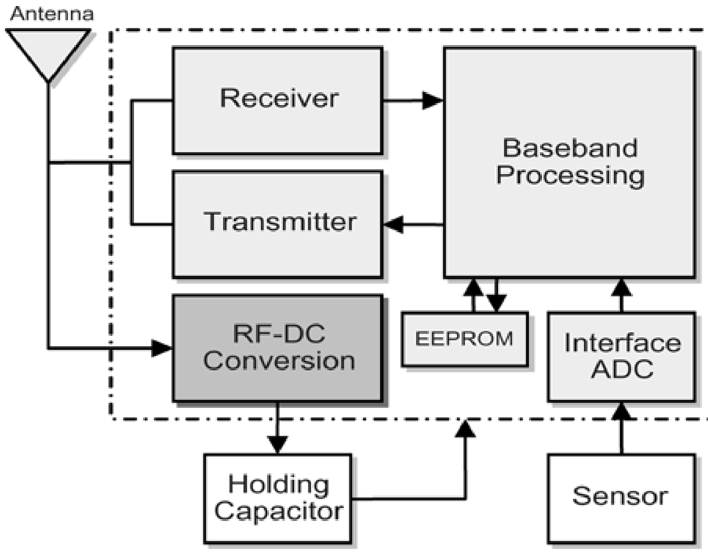
- **Active TAG:** has some external components such as a battery and a crystal, and transmits ID data of the tag using the battery
- **Passive TAG:** the passive tag can communicate using backscatter to the base station without a battery by using transmitted power from a base station
- **Semi-Passive TAG:** has a data storage and could communicates to the base station using a backscatter method



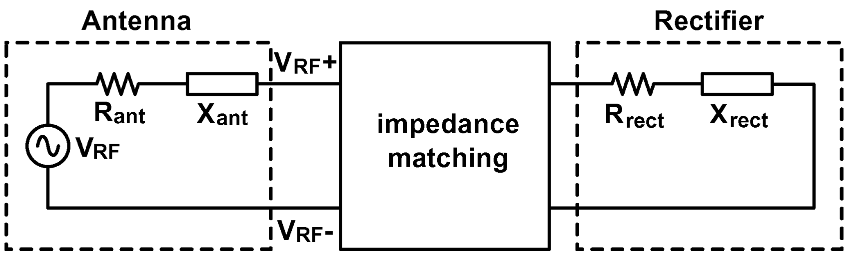
Umeda et al. *A 950-MHz Rectifier Circuit for Sensor Network Tags With 10-m Distance*, JSSC, 2006

The concept and the system structure



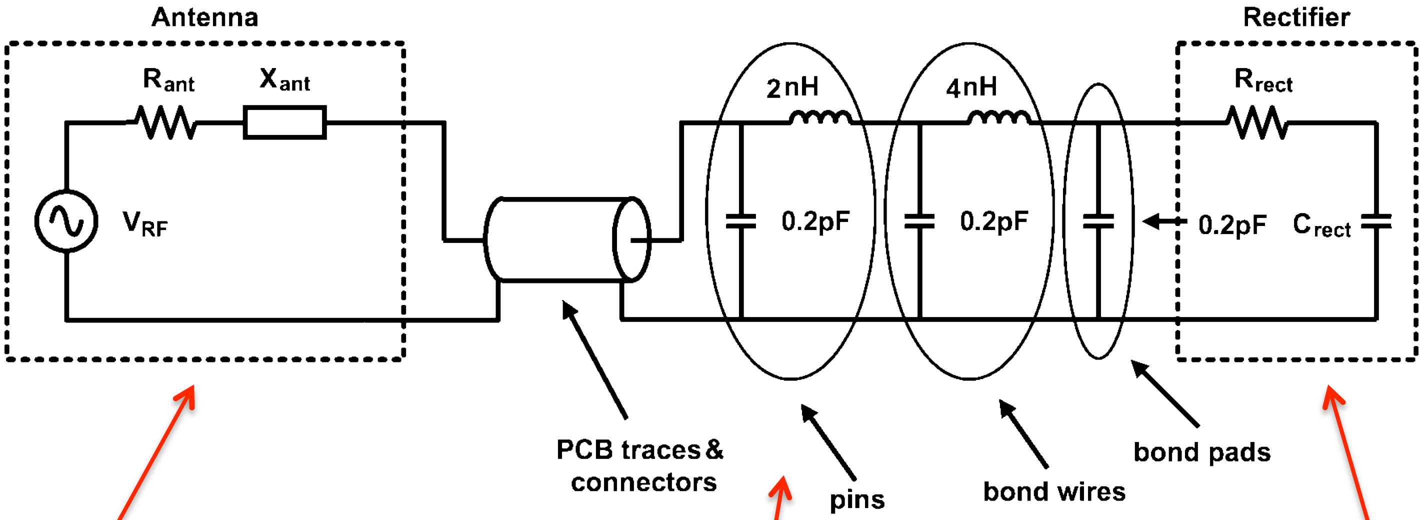


The "rectenna" concept



Le, … Fiez et al. *Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks,* JSSC, 2008

Main issues



Optimize antenna gain and bandwidth

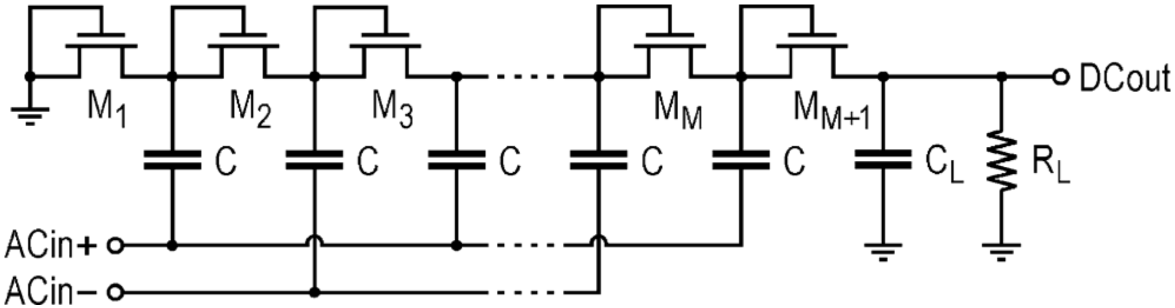
Optimize impedance match

Amplify low voltage signals

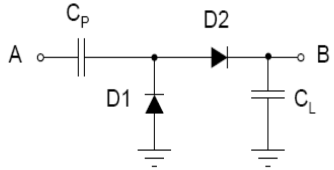
For -20/-30dBm signal could be as low as in the mV range!

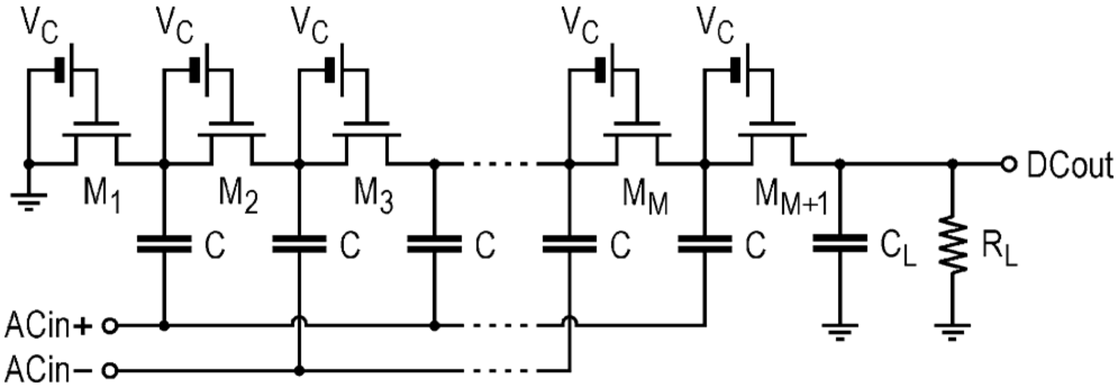
Le, … Fiez et al. *Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks,* JSSC, 2008

First: amplifying the signal



Conventional Dickson multi-stage rectifier





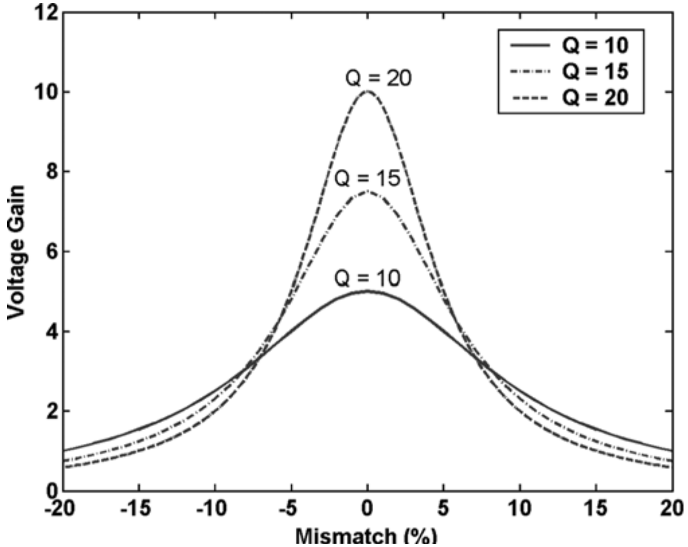
Dickson rectifier with compensation of the threshold

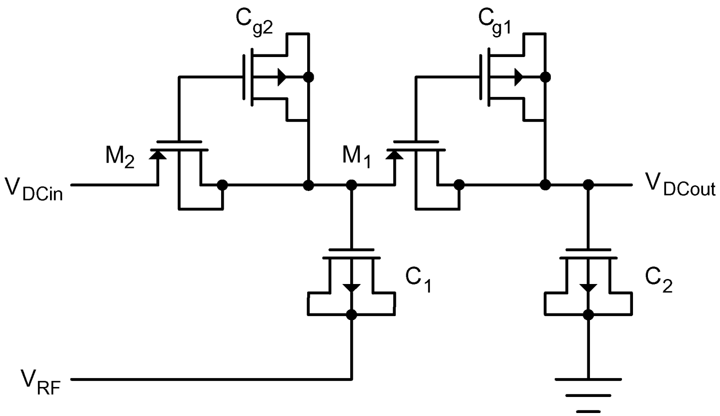
$$V_{\mathrm{O}} = M\left(\frac{C}{C + C_{\mathrm{P}}}V_{\mathrm{AC}} - \frac{I_{\mathrm{O}}}{f(C + C_{\mathrm{P}})} - V_{\mathrm{TH}}\right) - V_{\mathrm{TH}}$$

$$V_{\mathrm{AC}} > \frac{C + C_{\mathrm{P}}}{C}\frac{M+1}{M}V_{\mathrm{TH}} + \frac{I_{\mathrm{O}}}{f\,C}$$

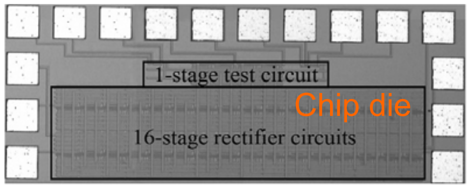
Papotto, … Palmisano et al. *A 90-nm CMOS Threshold-Compensated RF Energy Harvester,* JSSC, 2011

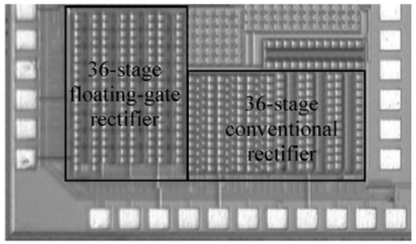
Le et al. JSSC 2009





- Use of resonator for amplifying voltage signal
- Problem: works fine for narrow bandwidths

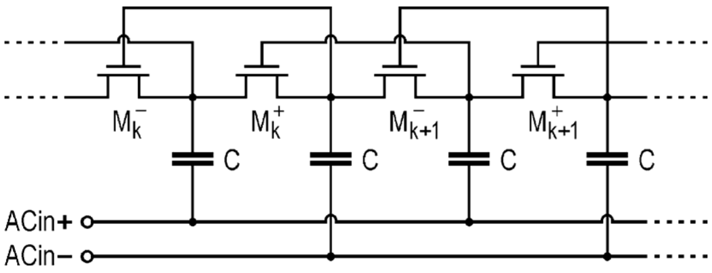




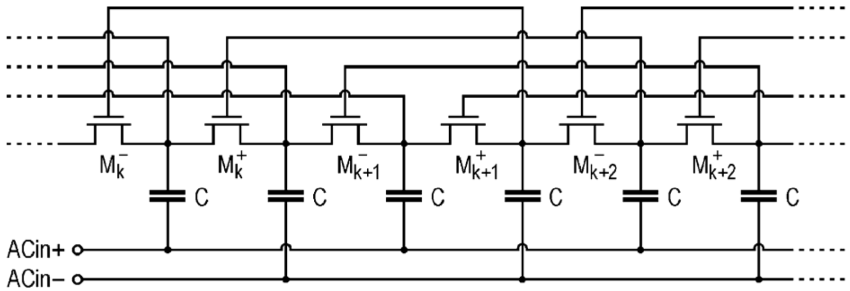
- Use of floating gate MOS with charge trapped by FN tunneling
- Problem: should be performed by post-processing

Le, … Fiez et al. *Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks,* JSSC, 2008

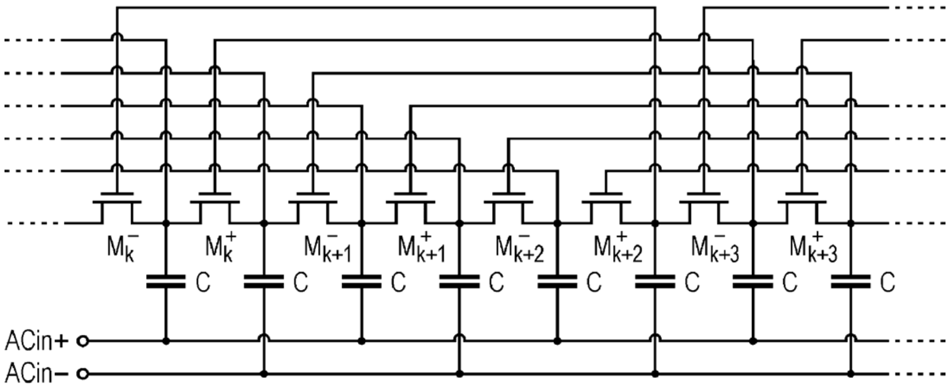
Papotto et al. JSSC 2011 (1)



Dickson rectifier with threshold self-compensation



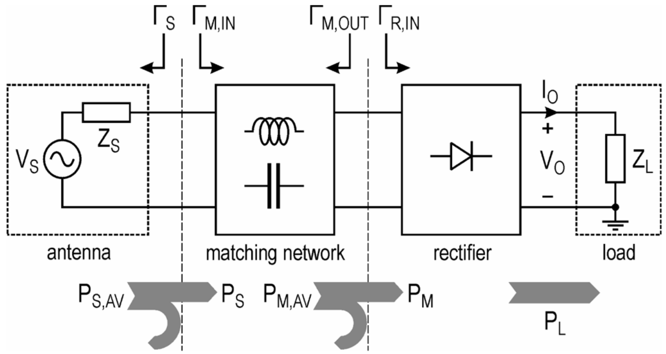
Order-4 compensation



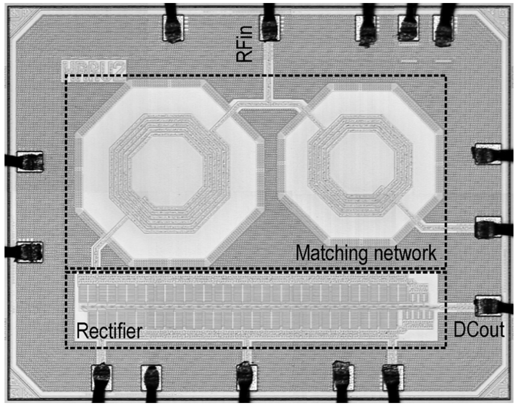
Order-6 compensation

Papotto, … Palmisano et al. *A 90-nm CMOS Threshold-Compensated RF Energy Harvester,* JSSC, 2011

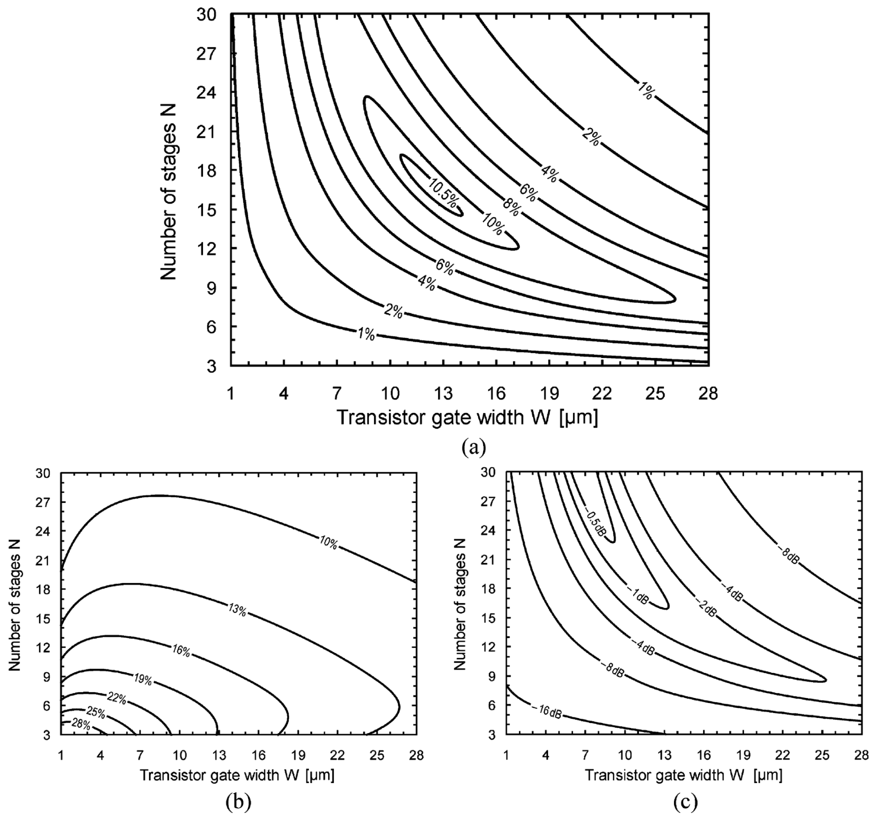
Papotto et al. JSSC 2011 (2)



Block diagram of the rectenna



Chip die



Problem: complex design issues for perfect optimization

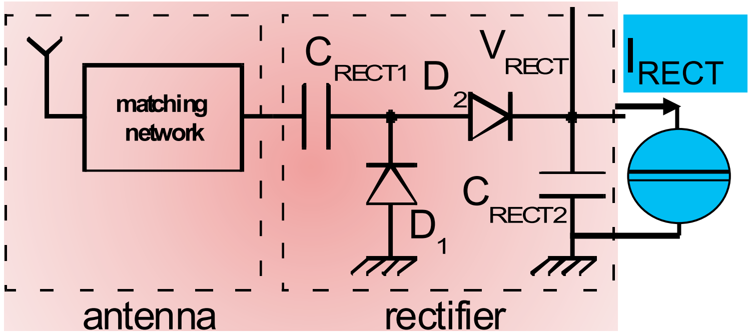
Papotto, … Palmisano et al. *A 90-nm CMOS Threshold-Compensated RF Energy Harvester,* JSSC, 2011

CMOS Integration Comparison

Reference	This work	T. Le *et al.* 2008 [7]	H. Nakamoto *et al.* 2007 [5]	F. Kocer *et al.* 2006 [4]	T. Umeda *et al.* 2006 [3]	U. Karthaus *et al.* 2003 [2]
CMOS technology node	90 nm	0.25 μm	0.35 μm	0.25 μm	0.3 μm	0.5 μm
Typical threshold voltage	0.45 V	0.55 V		0.15 V	0.53 V	0.2 V
Operating frequency	915 MHz	906 MHz	953 MHz	450 MHz	950 MHz	869 MHz
Additional requirements	Deep *n*-well	Pre-charge phase is needed	//	Low-V_{TH} transistors are exploited	Auxiliary battery is needed	Schottky diodes are exploited
Minimum RF input power	–24 dBm $V_O = 1$ V $R_L = \infty$	–22 dBm $V_O = 2$ V $R_L = \infty$	–9 dBm $V_O = 2.4$ V	–18.6 dBm $V_O = 1.2$ V $R_L = 1$ MΩ	–14 dBm $V_O = 1.5$ V $I_O = 400$ nA	–20.1 dBm $V_O = 1.5$ V $I_O = 950$ nA
	–18.83 dBm $V_O = 1.2$ V $R_L = 1$ MΩ	–17.9 dBm $V_O = 1.4$ V $R_L = 1.32$ MΩ				
Rectifier's efficiency at minimum RF input power	11% (a)	9.2% (a)	15.4% (a)	10.4% (a)	1.5% (b)	14.5% (b)

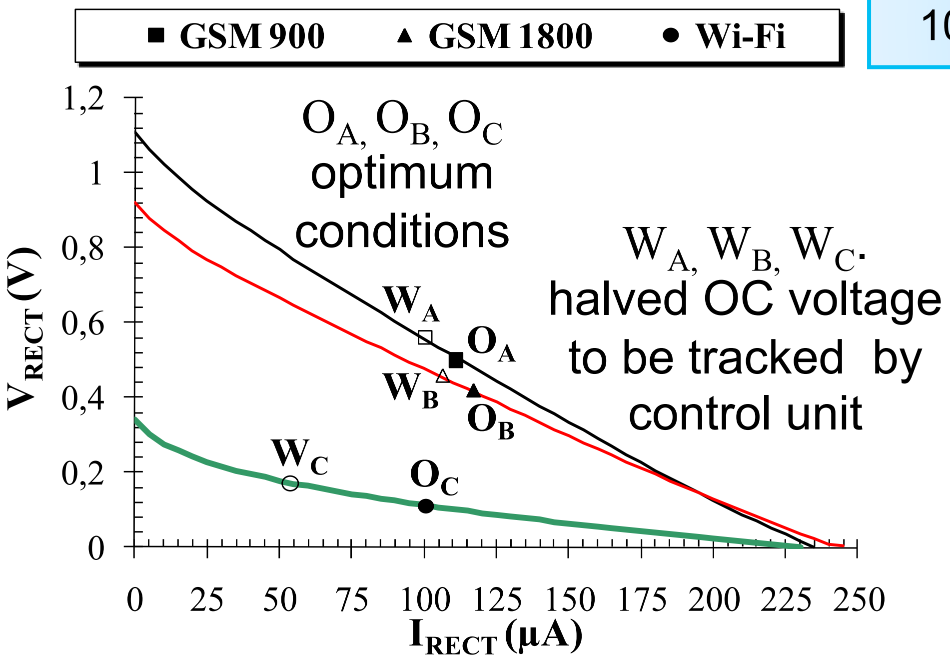
Papotto, … Palmisano et al. *A 90-nm CMOS Threshold-Compensated RF Energy Harvester,* JSSC, 2011

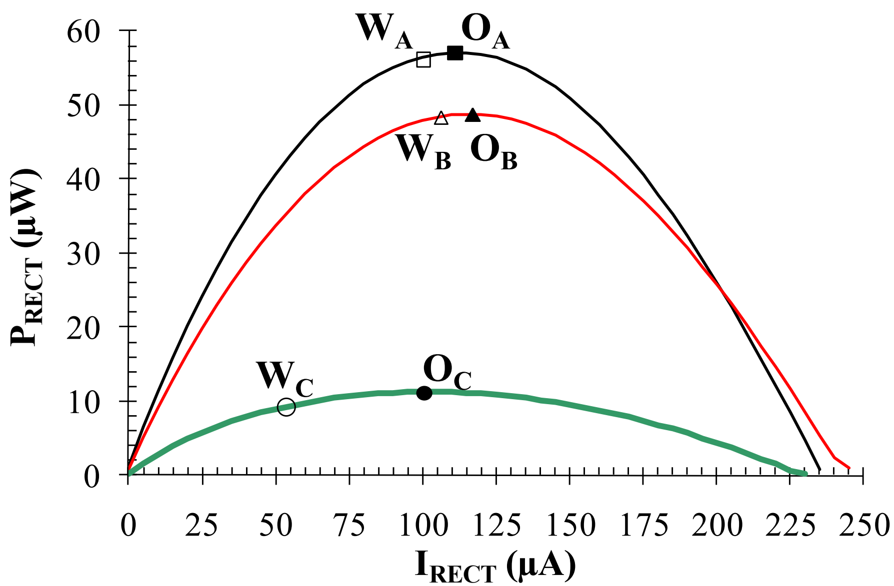
Costanzo, Romani et al. (MTT2010)



- DC current source I_{RECT} replaces the converter
- Optimize the average DC voltage V_{RECT} and the matching network to maximize the rectified power: $P_{RECT} = V_{RECT}\, I_{RECT}$

100-uW RF available power at center frequency

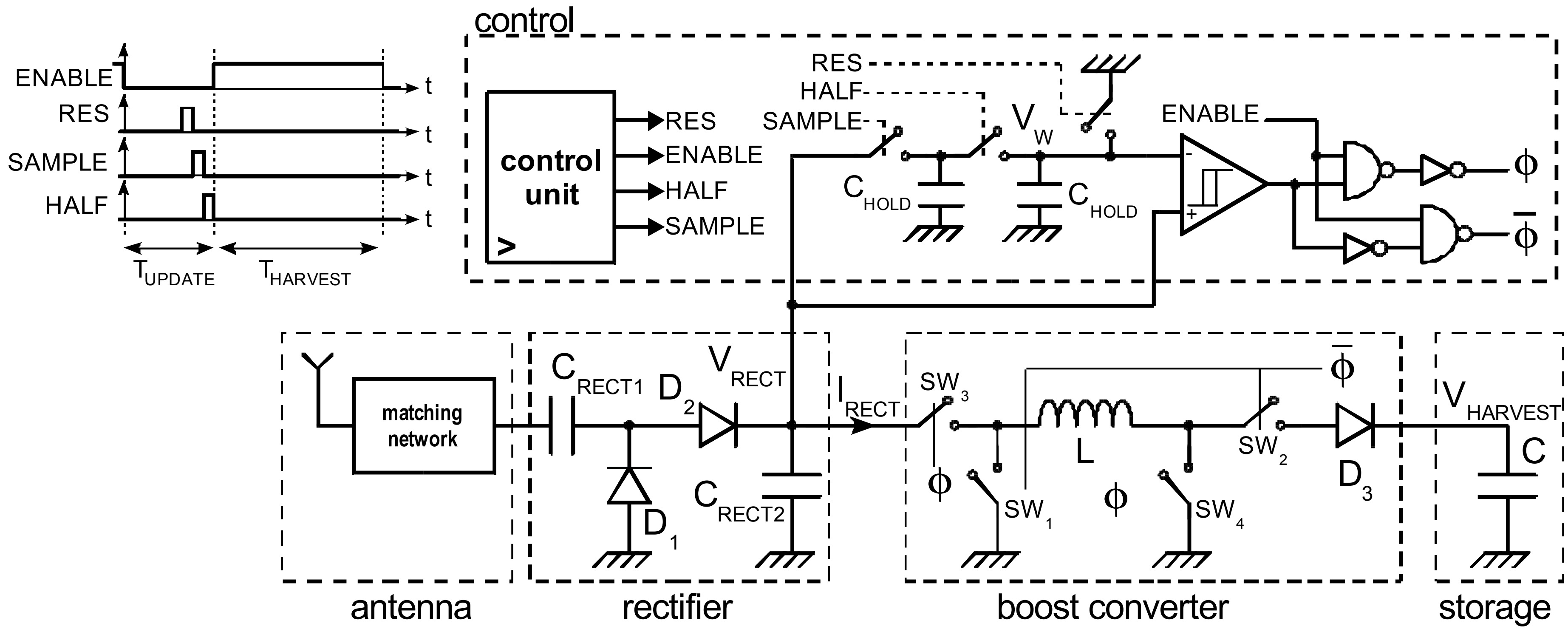




4 to 5 dB constant antenna directivity in each band

P_{RECT} decreasing function of the RF frequency (effective area proportional to f^{-2})

Micro-Power Converter for RF with MPPT

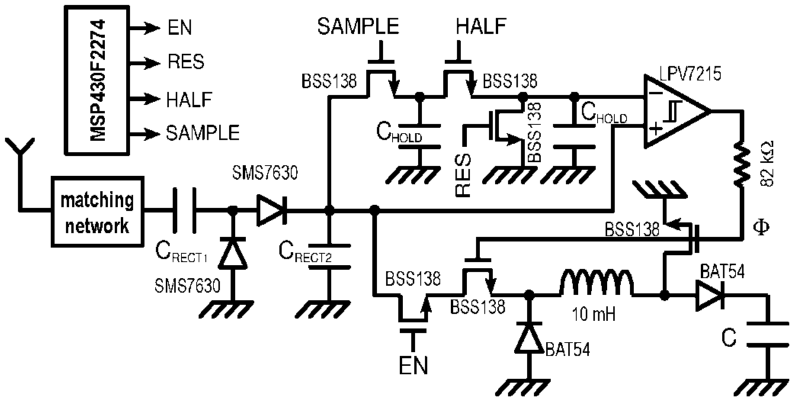


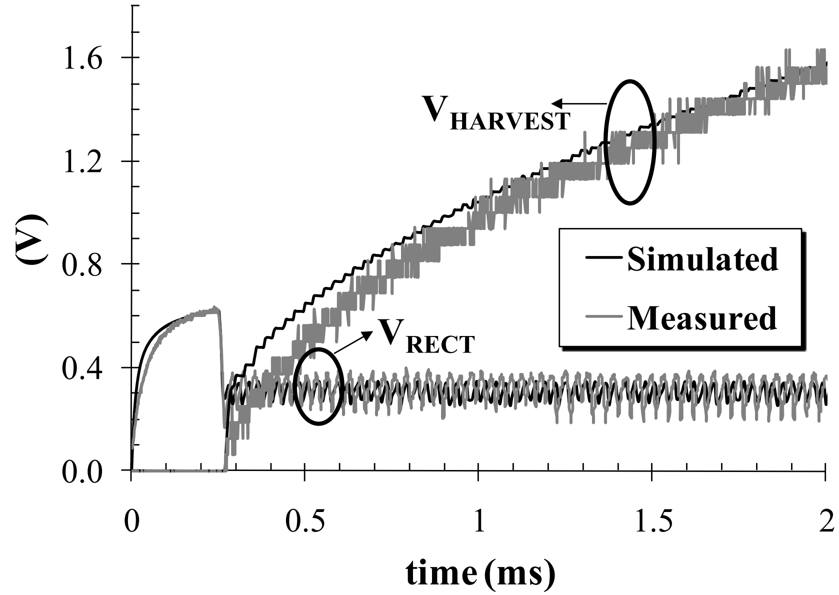
Converter to dynamically keep the rectified voltage at one half of its open-circuit value

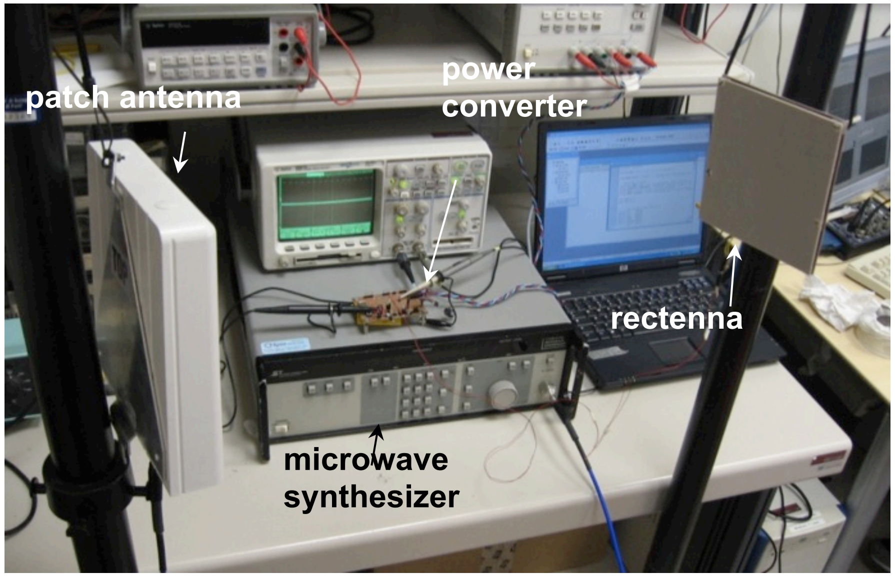
A. Costanzo, et al., 2010 IEEE MTT-S Int. Microw. Symp. Digest, May 2010, pp. 856-859
A. Costanzo, A. Romani, et al., RF/Baseband Co-design of Switching Receivers for Multiband Microwave Energy Harvesting, Sensors and Actuators A: Physical

Micro-Power Converter for RF with MPPT

- An ultra-low power PCB implementation was designed with discrete components
  - P_{CONV} = 9uW
- Experiments were performed considering typical values of radiated power in the 900MHz and 1800 MHz frequency band





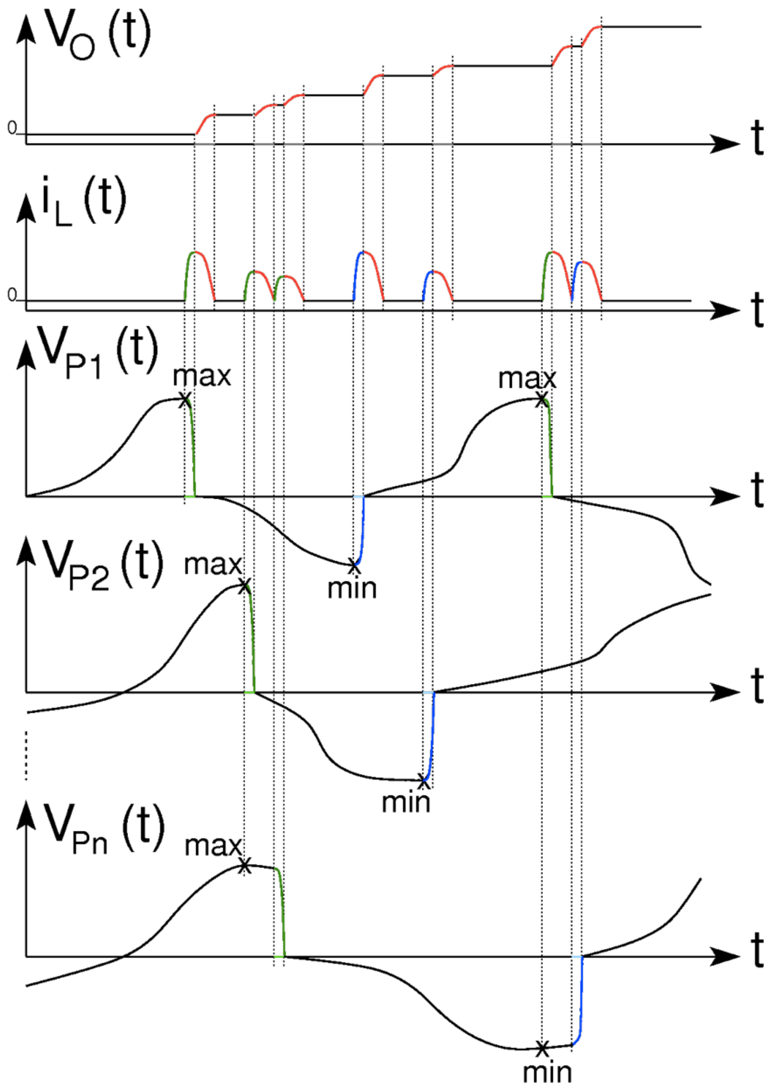


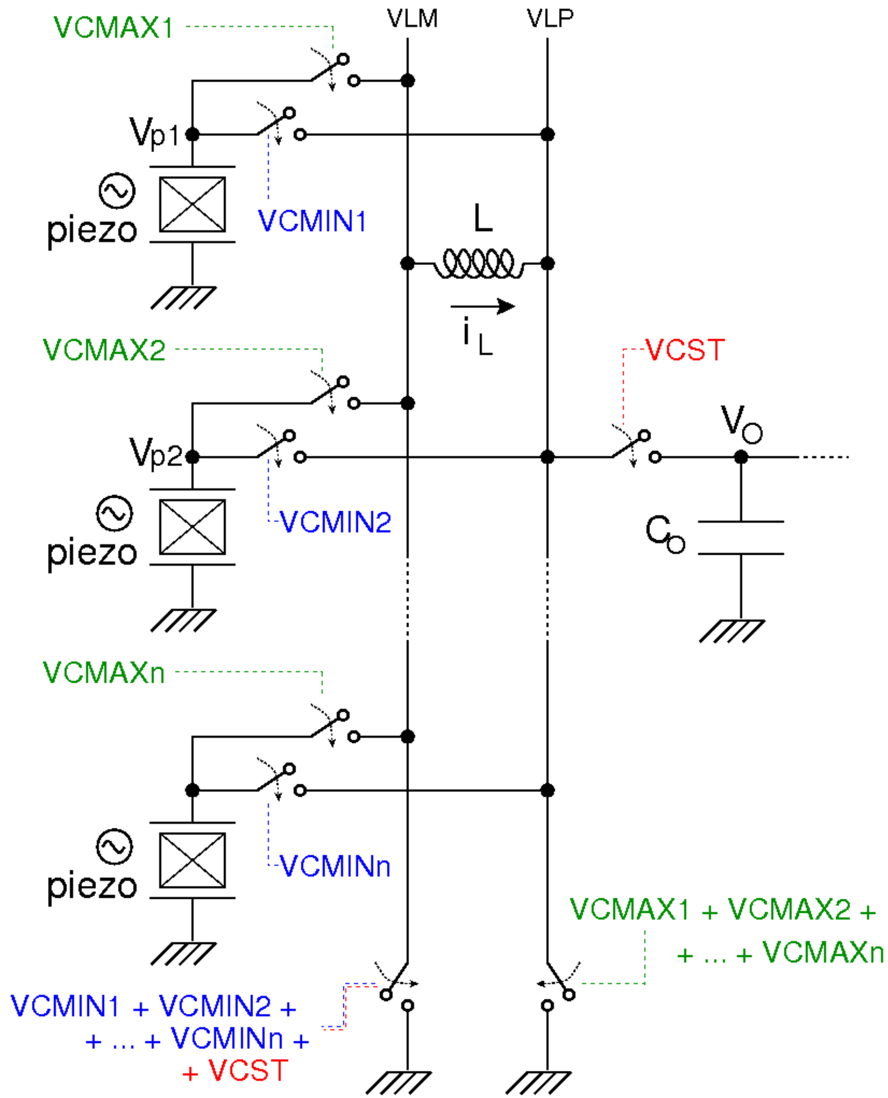
Harvesting Technologies Summary

SOURCE			SOURCE CHARACTERISTICS	PHYSICAL EFFICIENCY	HARVESTED POWER
PHOTOVOLTAIC					
	Office		0.1mW/ cm²	10-24%	10 μW/cm²
	Outdoor		100mW/ cm²		10mW/ cm²
VIBRATION/ MOTION					
	Human		0.5÷1m/s²@1÷50Hz	1-30%	4 μW/ cm²
	Industry		1÷10m/s²@5÷1kHz		100 μW/ cm²
THERMAL ENERGY					
	Human		20mW/ cm²	0.10%	25 μW/ cm²
	Industry		100 mW/ cm²	3%	1-10mW/ cm²
RF					
	GSM	900MHz	0.3-0.03 μW/ cm²	50%	0.1 μW/ cm²
		1800MHz	0.1-0.01 μW/ cm²		

Source: C. van Hoof, IMEC

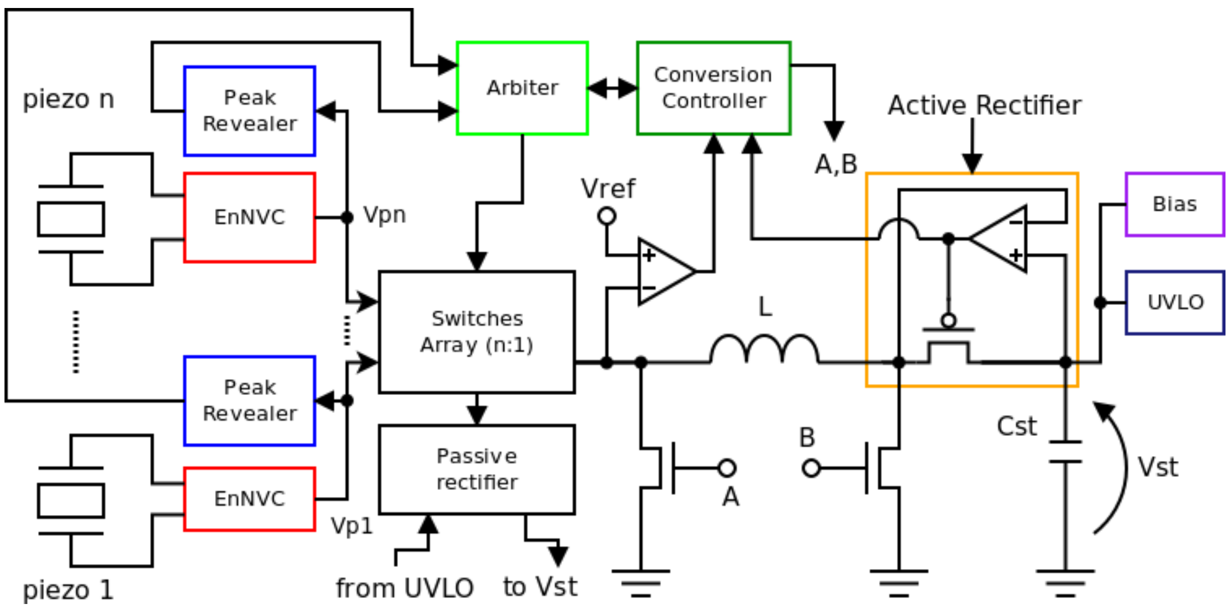
From our Research: PZT Multi-source Architecture





CMOS Generic Multi-source Architecture

- CMOS energy harvesting IC for operation with multiple piezoelectric and DC sources
- STMicroelectronics BCD6 technology with 0.35um resolution (only CMOS-compatible devices used)



- The IC is able to harvest power from:
- Intrinsic power consumption is 1.2 uW when operating with all 6 sources
- Consumed energy per cycle: 226 pJ. Typical available energy per commutation: 0.65 uJ Electrical efficiency: 80%

Overview of the talk

- Zero-power systems, when, where and why
- Definitions and challenges
- Energy consumption & storage
- Energy conversion & management
- Energy harvesting
  - Harvesting from vibrations
  - Harvesting from temperature
  - Harvesting from radio-frequency
- Summary & conclusions

Conclusions

- Energy efficiency of Energy Autonomous Systems requires system level design
- Power optimization can be maximized by exploiting application specific attributes
- Energy harvesting for industrial application is a new concept just started few years ago
- The energy harvesting paradigm fits perfectly in the energy sustainability today's vision
- The number of applications is increasing exponentially