HSG-IMIT
Institut für Mikro- und Informationstechnologie

IMTEK
Department of Microsystems Engineering

Energy Harvesting – from Devices to Systems

Prof. Dr.-Ing. Yiannos Manoli
IEEE Distinguished Lecturer Program
Austin, May 10, 2011

University of Freiburg
Faculty of Engineering

Outline

- Motivation & Application Areas
- Energy Conversion
  - Solar
  - Thermoelectric
  - Motion, Vibration (Piezoelectric, Electromagnetic, Capacitive)
  - Application Specific Design
  - (Bio) Fuel Cells
- Energy Storage
- Energy Management
  - Energy Allocation
  - Conversion Efficiency
  - Adaptive Interface for Generators

Application areas of distributed embedded microsystems

- Automotive
  - ➢ Tire pressure monitoring system
- Industrial
  - ➢ Machine monitoring & control
- Building & home automation
  - ➢ Wireless switches & sensors
- Environmental monitoring
  - ➢ Agriculture monitoring
- Medical
  - ➢ Pacemaker, implants
- Consumer
  - ➢ Battery chargers

© Guidant


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© Solar Style, Inc.

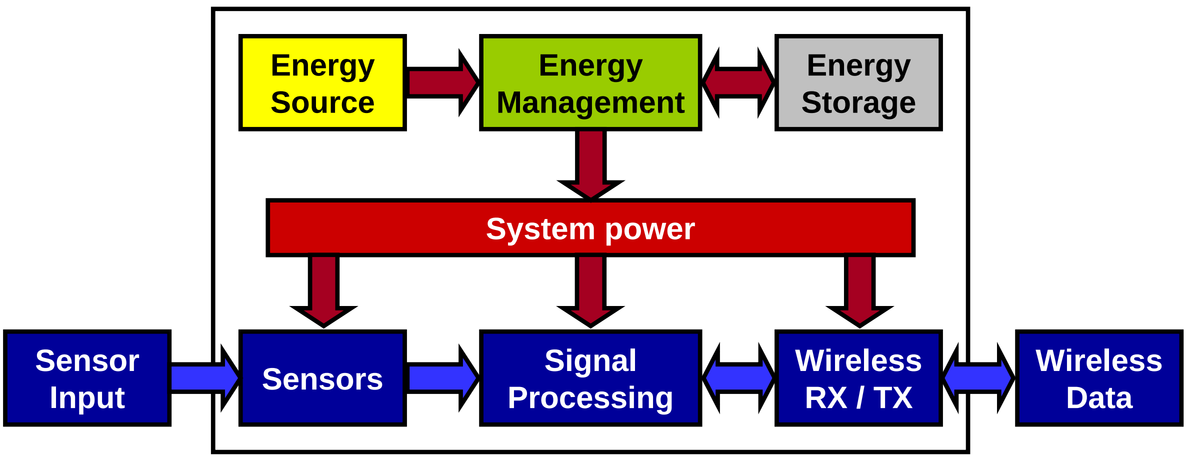

© EnOcean


© Crossbow Technology

Embedded Microsystems

What do such systems look like?

But where does the energy come from?



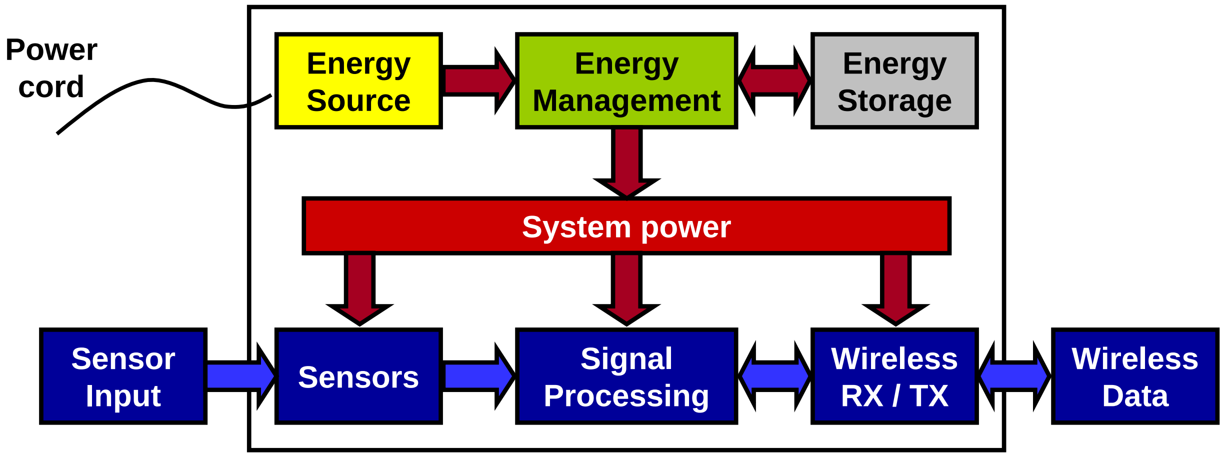
Line powered systems

Problems

- Infrastructure (Jacks, Cables)
- Installation costs
- Extension costs
- Maintenance costs

3 km of cables !

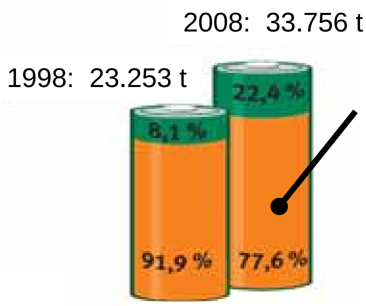
Porsche 911



Battery powered autonomous systems

Problems

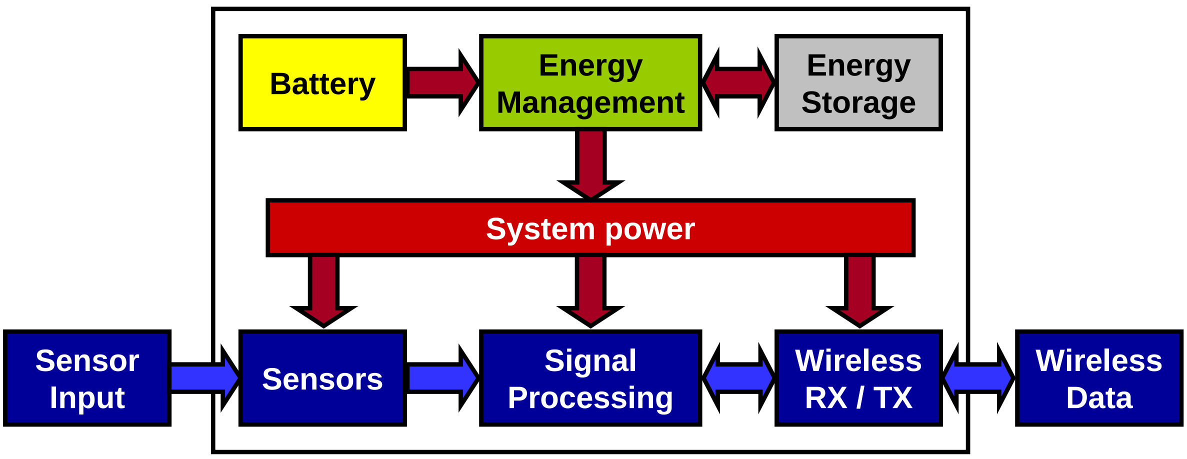
- Limited lifetime
- Limited application (Temperature, …)
- Replacement costs
- Environmental problems



2008: > 33.000 tons of batteries sold in Germany!

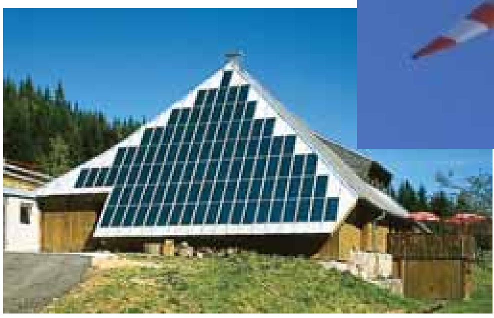
© GRS Batteries

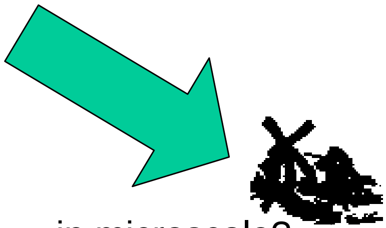
Sales quantity in metric tons.
Secondary cells
Primary cells



Energy autonomy …

Are batteries and cables the only options?

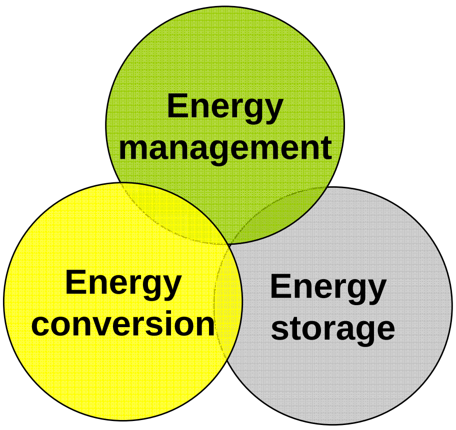


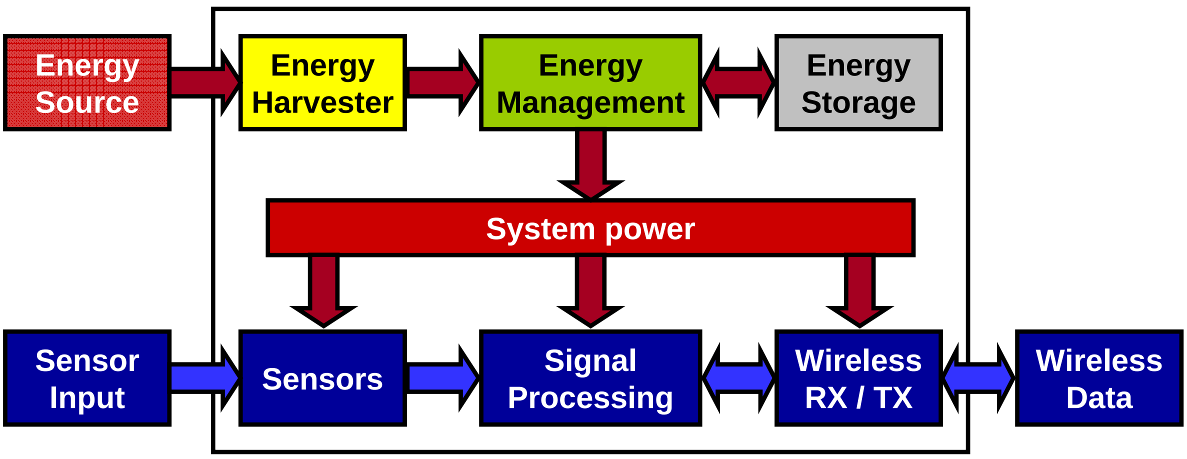


… in microscale?

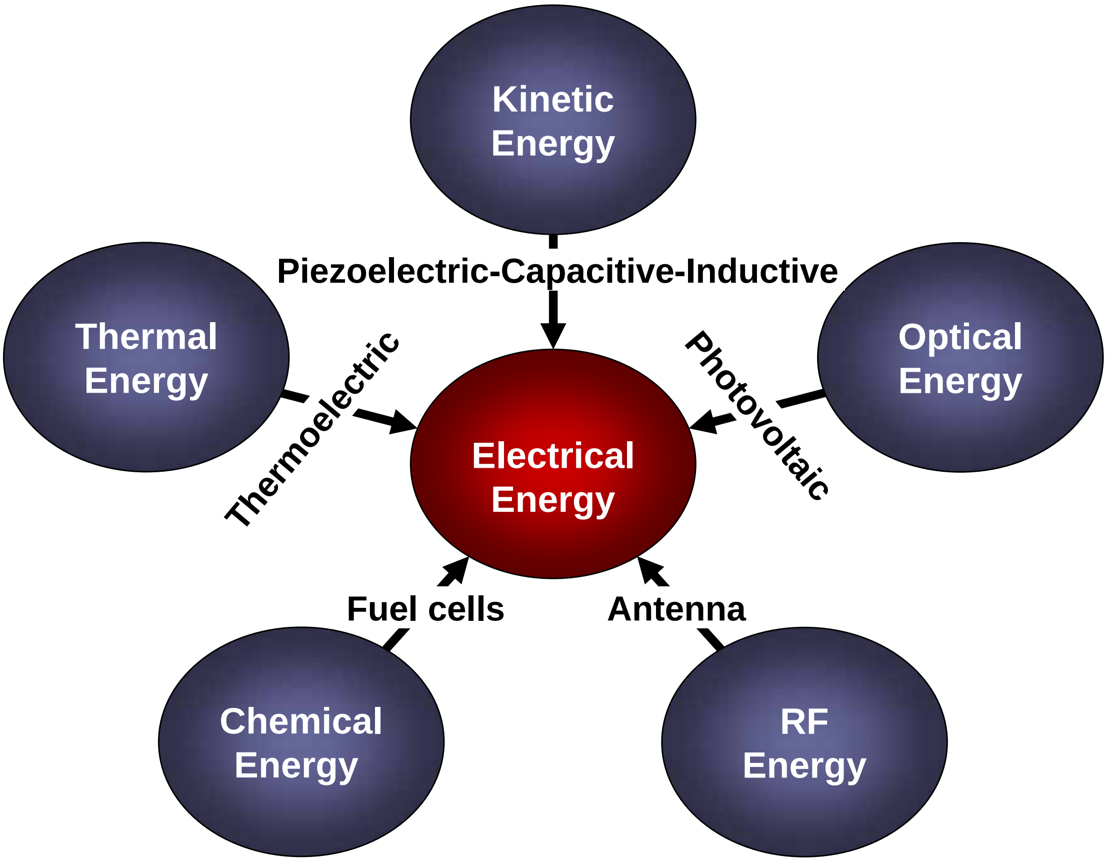
Energy supply by Energy Harvesting

- Total autonomy
- “Unlimited” lifetime
- Less maintenance
- Easy installation
- Operation at not easily accessible places

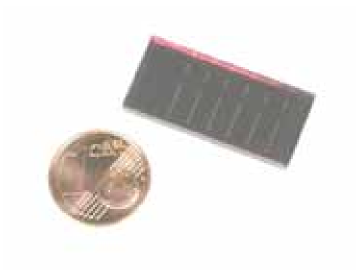




Ambient forms of energy and conversion mechanisms



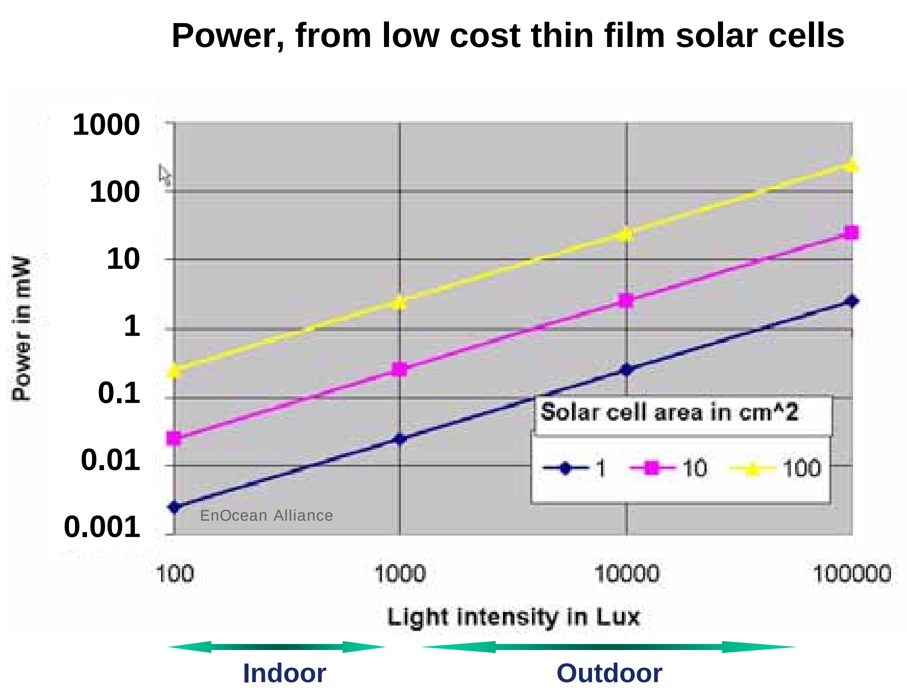
Light energy



Thin Film Solar Cell:

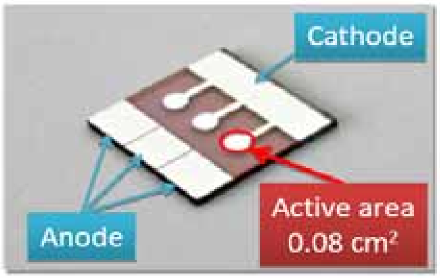
1cm² active Area

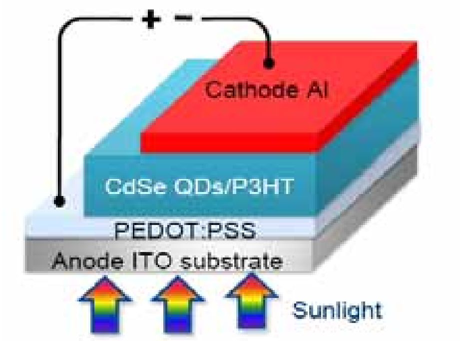
"Quick Start"



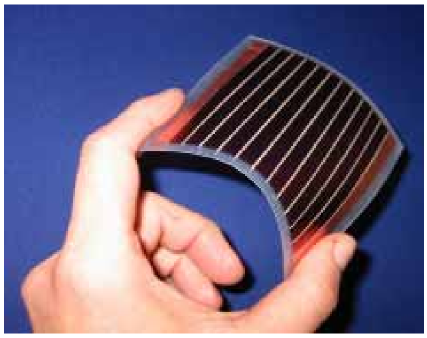
Solar cells

Hybrid solar cell based on CdSe nanocrystals and conjugated polymers





Yunfei Zhou, IMTEK

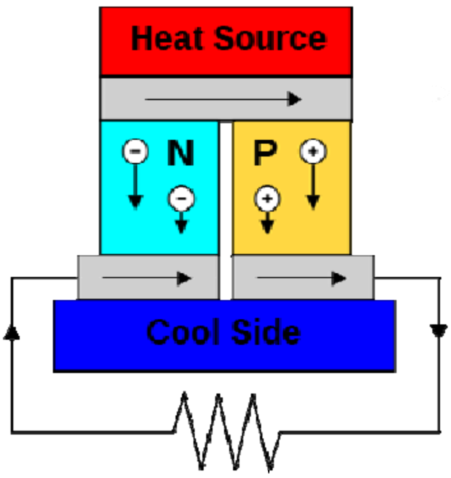


Si thin film cell on polymer carrier
© Flexcell

Characteristics

- DC voltage source
- Open circuit voltage: ~0.6 V
- Efficiency: ~2-3%
- Sunlight: ~3 mW/cm²
- Condition: Illumination intensity of 100 mW/cm²

Thermoelectric converters



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

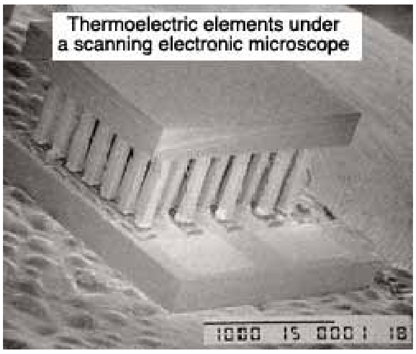
Seebeck coefficients of relevant material couples:

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

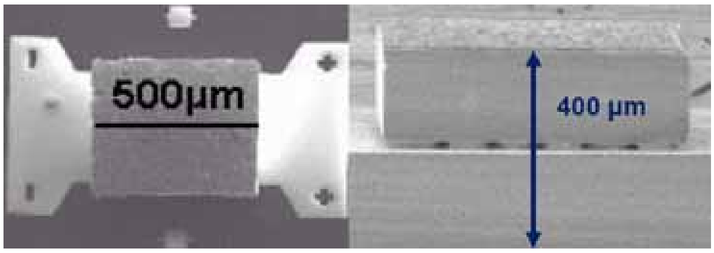
Characteristics

- Generation of DC current
- Polarity changes with direction of temperature gradient!
- Output voltage: around 100 mV
- Output power: some µW - mW

Examples of thermoelectric converters

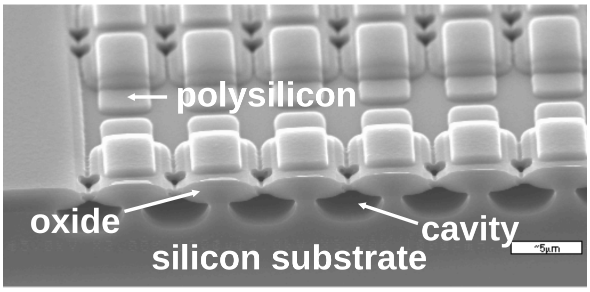


Micro-TEG of Seiko (1994)



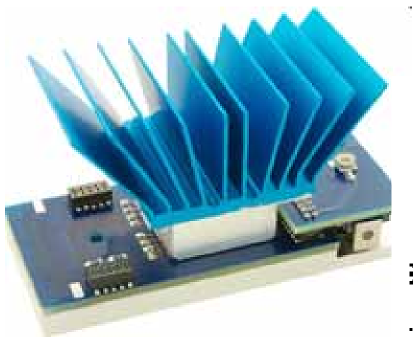
Micro Peltier cooler in 3D silicon technology
© MicroPelt

P = 3 µW/cm²
ΔT = 1..3 K
„Seiko Thermic" (limited production in 1998)

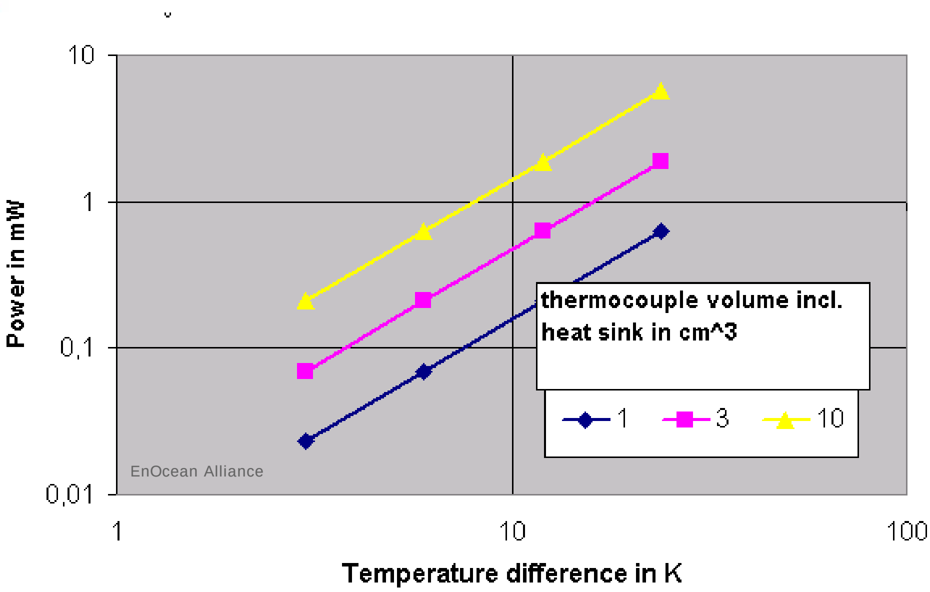


P = 1 µW/cm² @ ΔT = 5 K
Micro-TEG in CMOS technology
© Infineon, 2003

Thermal energy

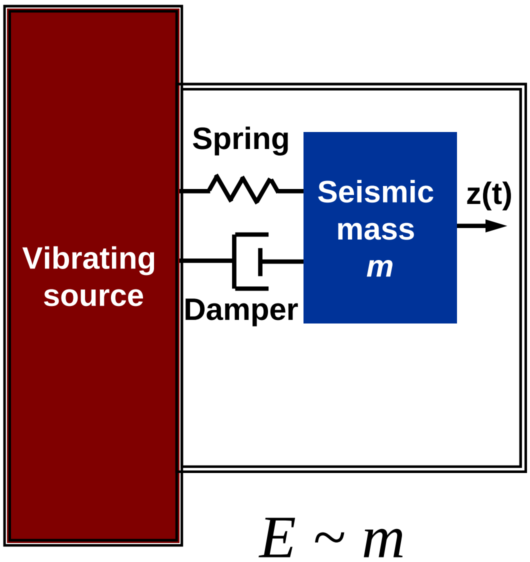


www.micropelt.com



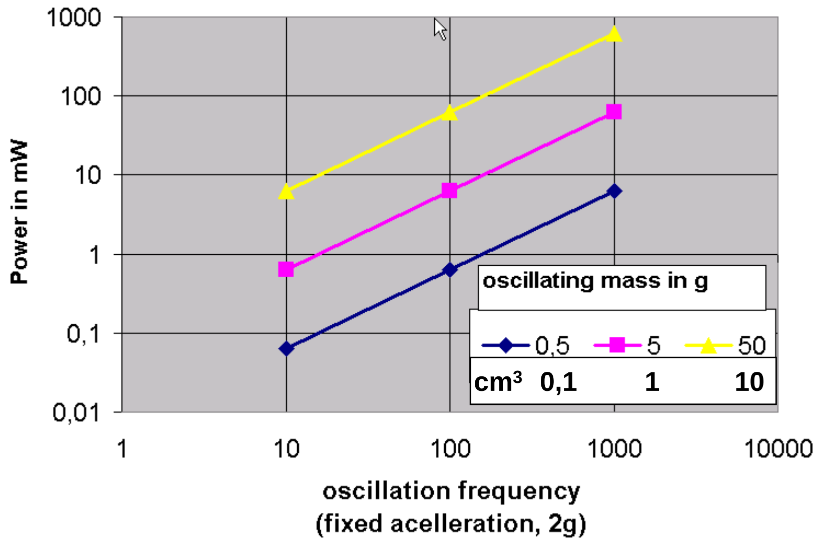
Power from thermoelectric converters depending on size and temperature difference

Kinetic / Vibration energy



$$E \sim m$$

Power from vibrations depending on mass and frequency



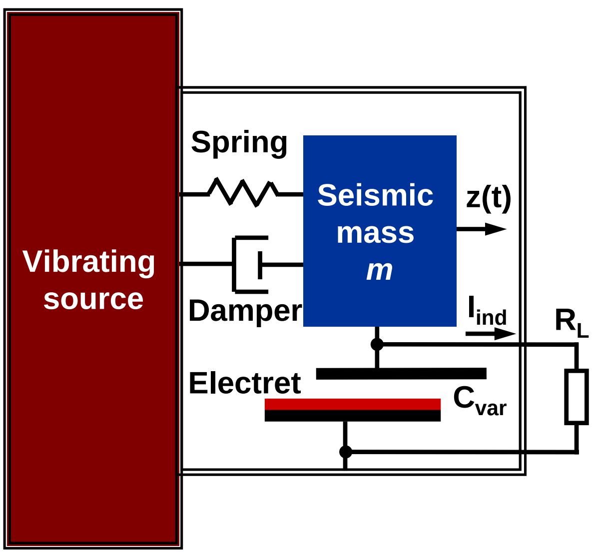
Problems:

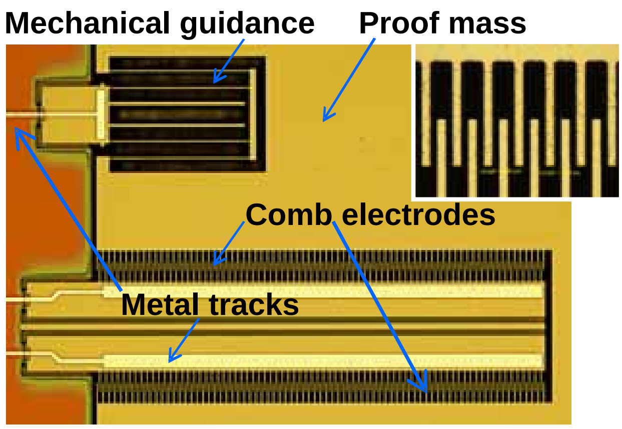
- Small amplitudes (10 µm)
- Unknown frequency (10…1000 Hz)
- Unknown direction of vibration

Conversion:

- Capacitive (Electret)
- Piezoelectric
- Inductive (Coil & Perm. magnet)

Capacitive converters





Variable overlapping area

⇒Variable capacitor between C_{min} and C_{max}

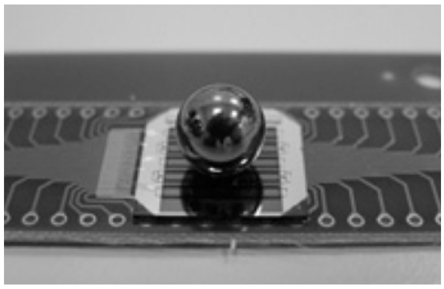
$$i(t) = \frac{dC(t)}{dt} \cdot V_{bias}$$

Characteristics

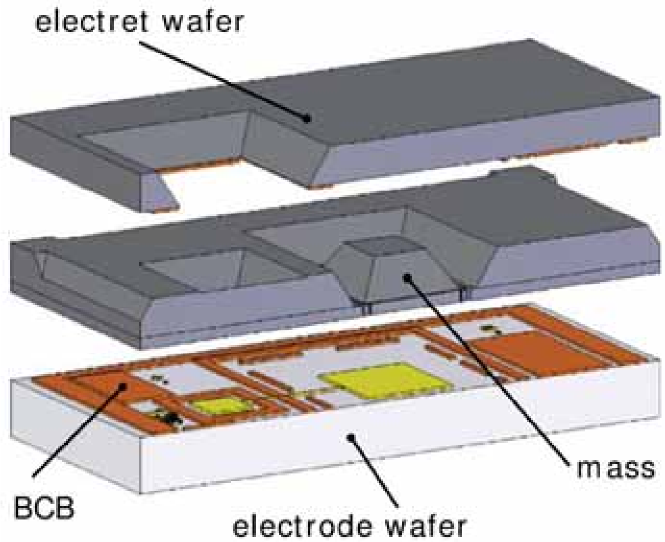
- Generation of AC current by dynamic capacitance variation
- Miniaturized (accelerometers)
- Bias voltage necessary
- Active control necessary
- Output voltage: some V
- Output power: some µW

Examples for capacitive converters

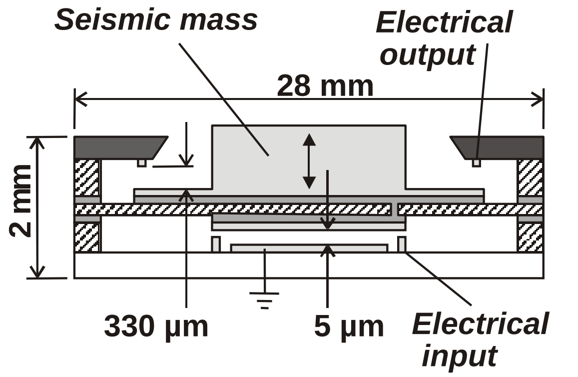
- Power: 0.8 to 10 µW/cm^2
- Frequency: 50 to 1.9 kHz
- Size: from 18x16 mm^2 to 6x5 mm^2



National Chiao Tung University, Taiwan, 2008

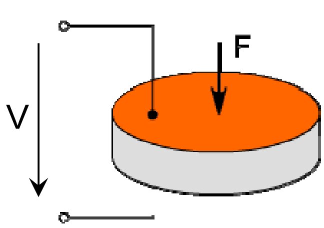


IMEC-NL, Netherlands, 2009

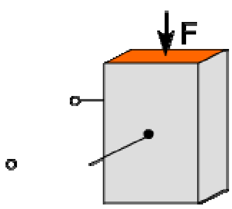


Vertical capacitor design, Imperial College, London, UK, 2003

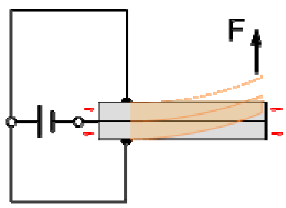
Piezoelectric converters



Vertical mode



Transversal mode



Bimorph

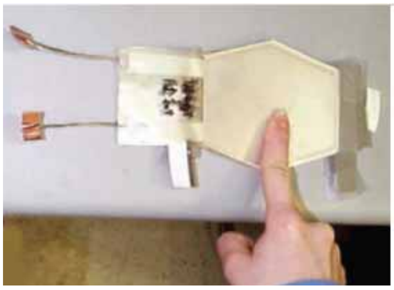
An external force F produces a voltage V due to charge separation

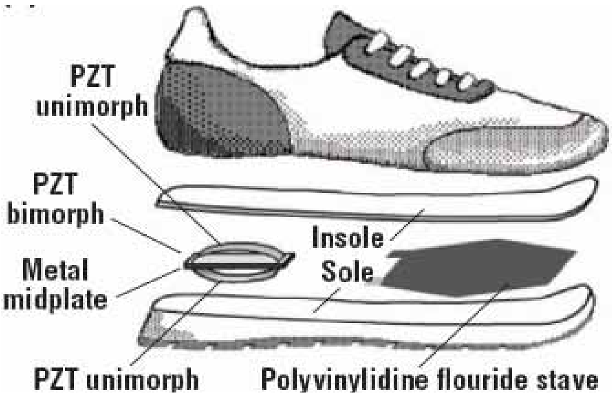
Q220-A4-103YB
© Piezo Systems, Inc.

Characteristics

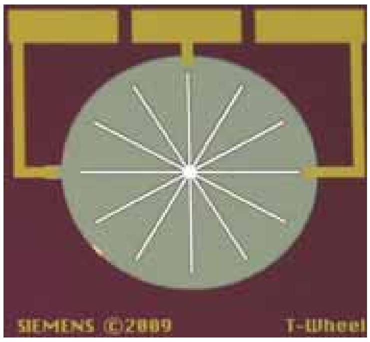
- Materials: PZT, $LiNbO_3$, PVDF
- Charge based converter
- Generation of AC current by dynamic mechanical stress
- Output voltage: 1V…100 V
- Output power: µW…mW

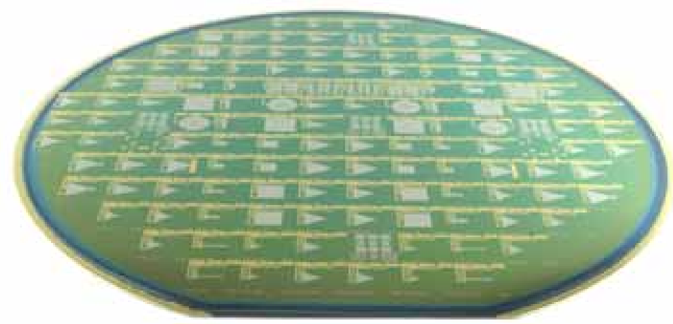
Examples of piezoelectric converters





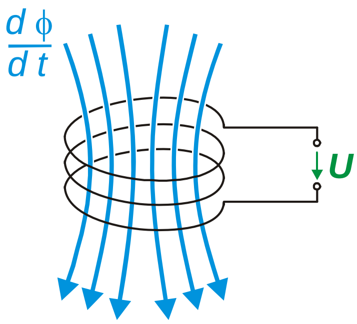
In-shoe piezoelectric generator,
Pmax = 8 mW, N. Schenck, MIT, 1999



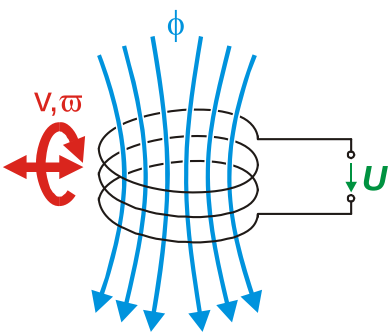


Wafer with MEMS Piezo generators,
Siemens, 2009

Electromagnetic (inductive) converters



Induction by alternating field



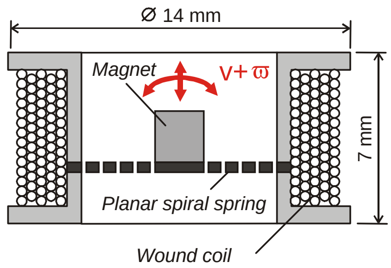
$$\text{Electromechanical generator}: \frac{d\Phi}{dt} = f(v, \varpi)$$

$$U = -N \cdot \frac{d\Phi}{dt}$$

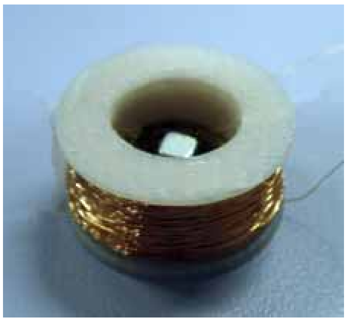
Characteristics

- Generation of AC current by alternating field or relative motion
- Output voltage: mV…V
- Output power: µW…mW

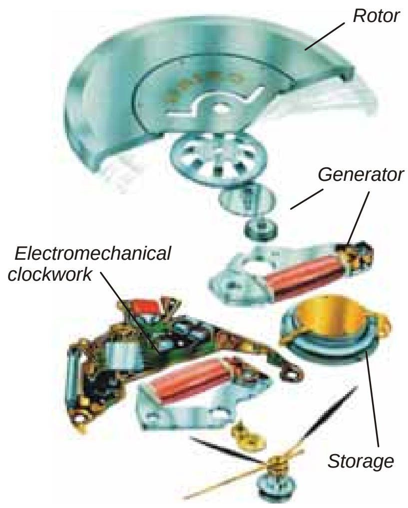
Examples of electromagnetic converters



P = 800 µW



P = 5 µW



P = 50 mW @ 1g acceleration
The size of an apple!

Multimodal oscillating converter
University of Hongkong, 2002

Rotatory converter
from Seiko Kinetic

Perpetuum
PMG17 ATEX/IECEx

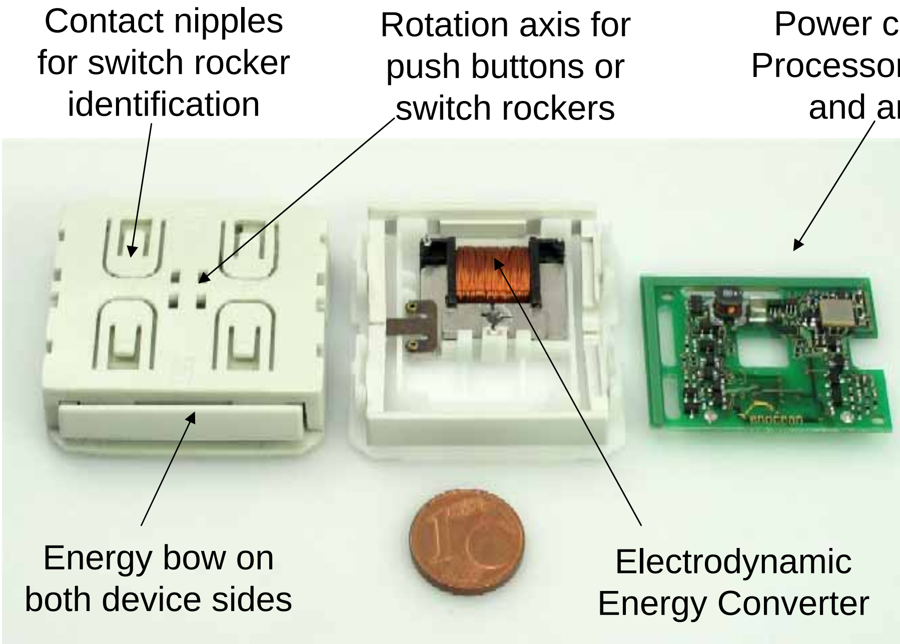
Wireless – Cost effective solution for Asset Management

- Annual maintenance spend 5-7% of Replacement Asset Value - Best in Class: 2-3% ($5 trillion in US)
- High expense & production loss
- Avoid “run to failure” to reduce cost - more data from sensors
- Very expensive to add sensors by conventional wiring
- Energy harvesting and wireless is great opportunity for easily installing sensors at low cost

Ormen Lange Gas Field (Shell)

perpetuum

Wireless Light Switch



© EnOcean

Wiring: Expensive & Invasive

Conventional Wired Solutions:

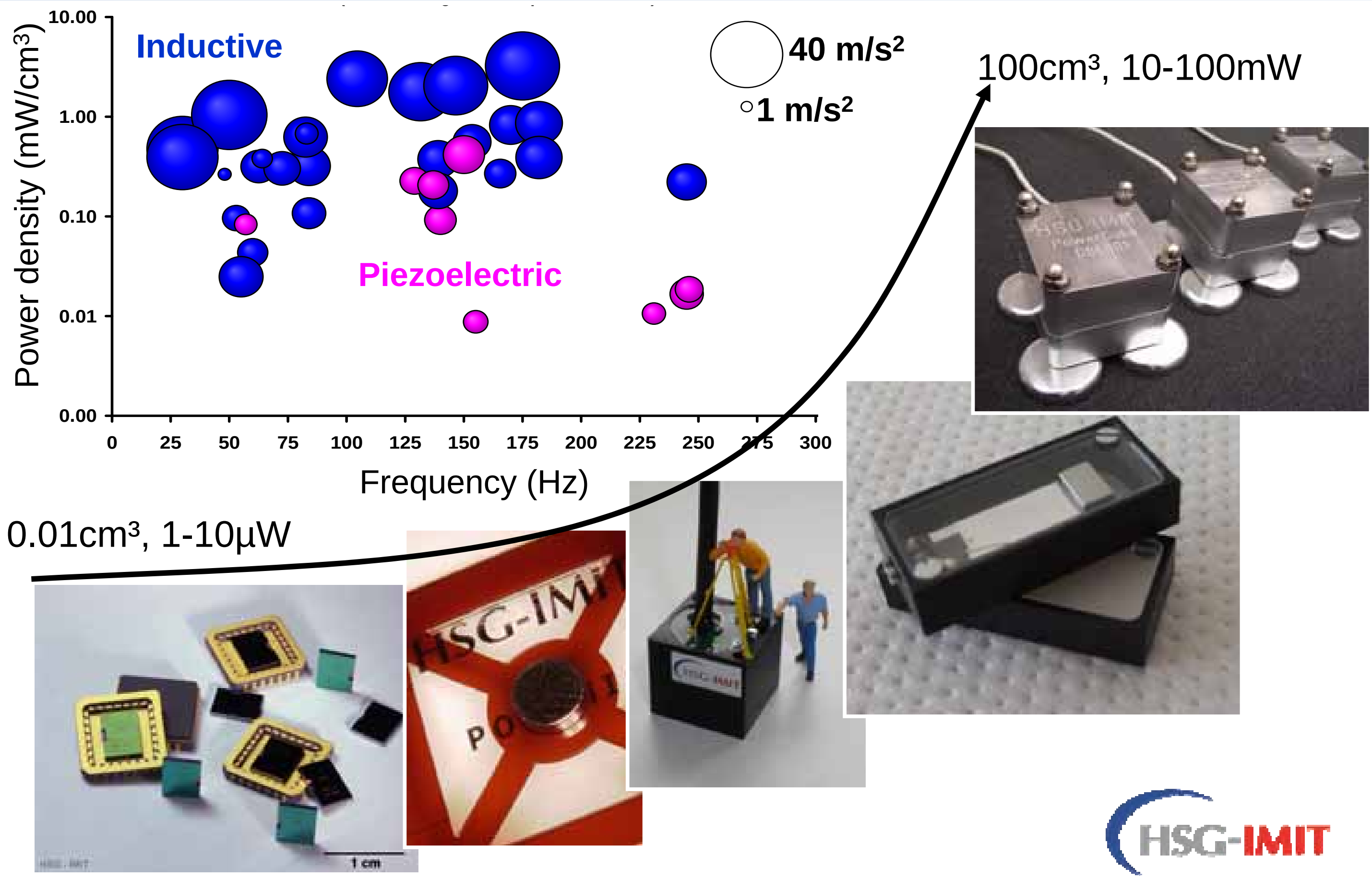
- Time consuming
- Building chaos
- Environmentally unfriendly
- Inflexible & expensive over lifespan

Solution:

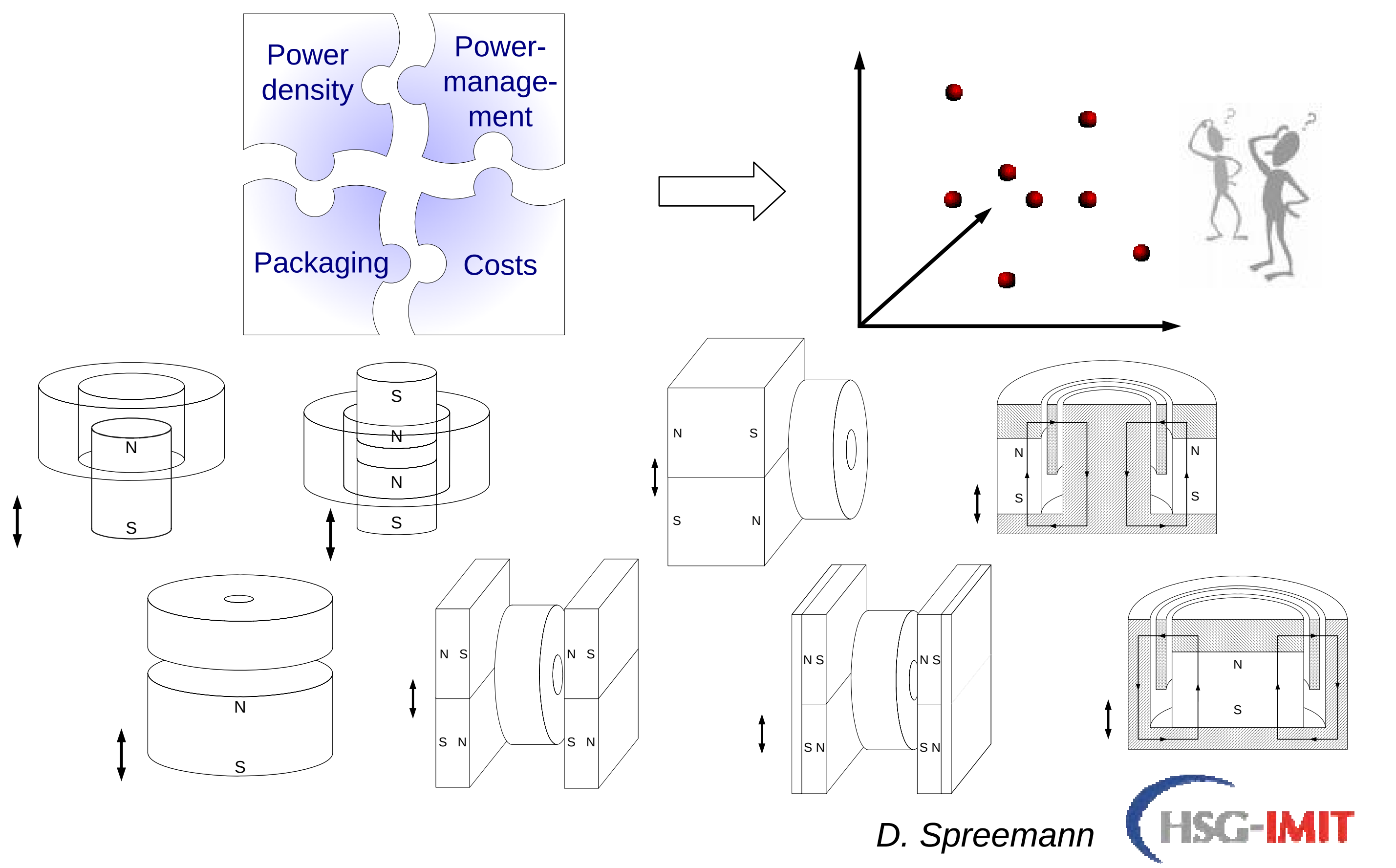
- Wireless & battery-less light switches
- Occupancy & daylight sensors
- Savings:
  - Kilometers of cable
  - Lighting energy costs
  - Cost of retrofitting

© EnOcean

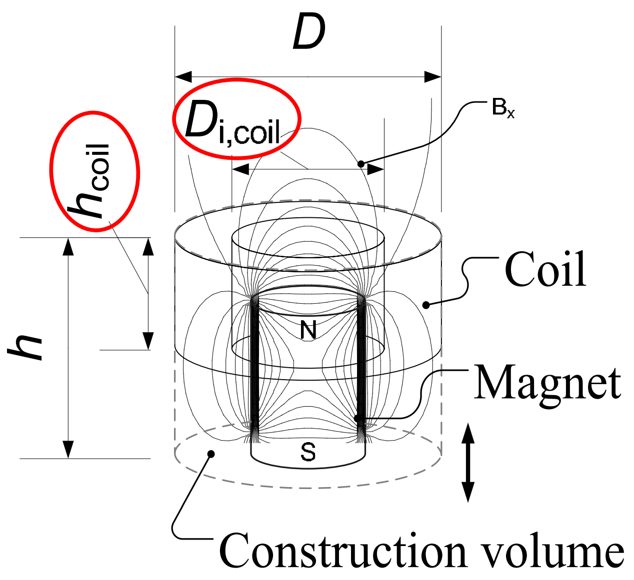
Application Specific Vibration Converters



Types of electromechanical coupling



Power and voltage optimization approach



Parameters	Unit
Geometry	
Volume (coil/magnet)	cm³
Gap	mm
Maximum displacement	mm
Magnet	
Remanence	T
Density of magnet	g/cm³
Coil	
Copper filling factor	1
Wire diameter	µm
Resistance per length	Ω/m
Other	
Excitation amplitude	m/s²
Vibration frequency	Hz
Mechanical damping	N/m/s

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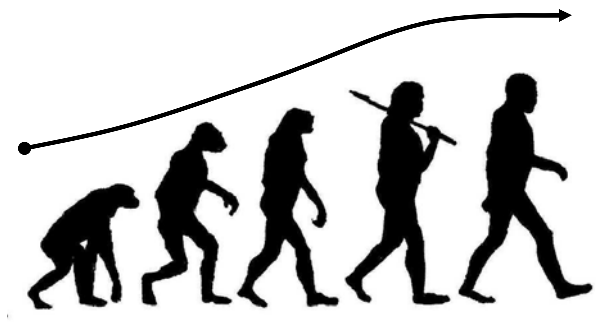
Evolution optimization strategy

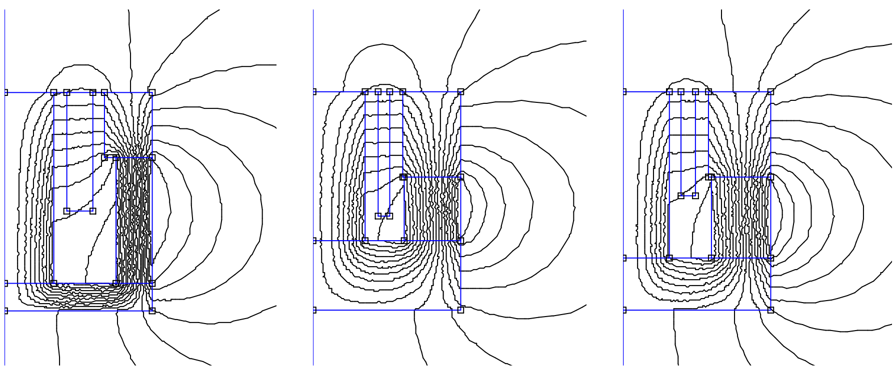
Initialization

- Random distribution of individuals (geometry and fitness) in the search space
- Low fitness
- Best individuals are selected for reproduction

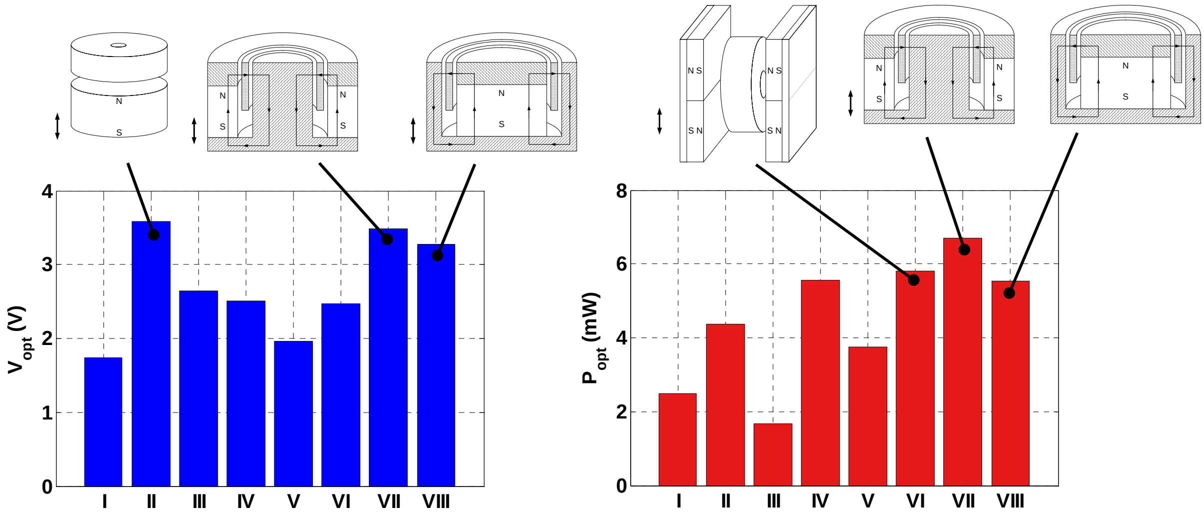


Stop criterion fulfilled

- Individuals are very similar
- Only negligible increase of fitness for further generations



Maximum performance for architectures with and without back iron



Voltage Output **Power Output**

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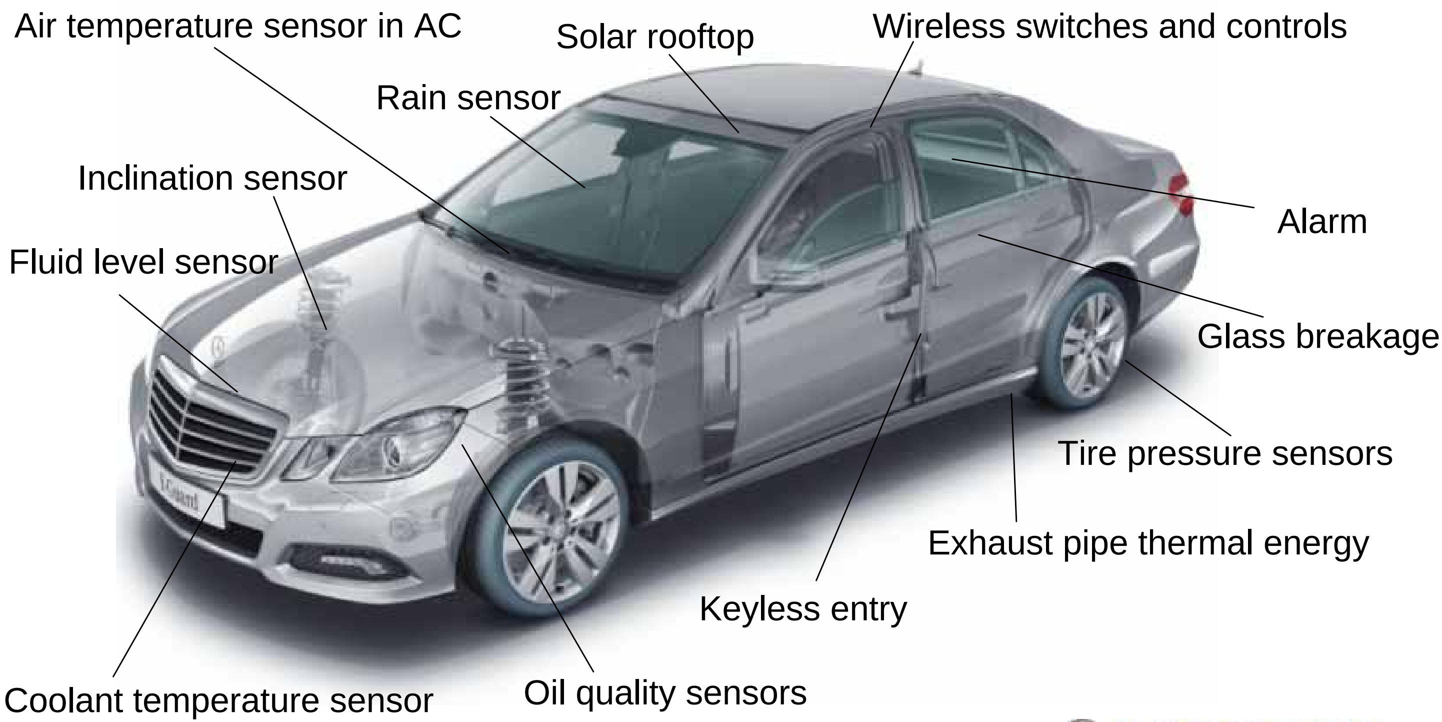
Energy Autonomous Systems in Cars



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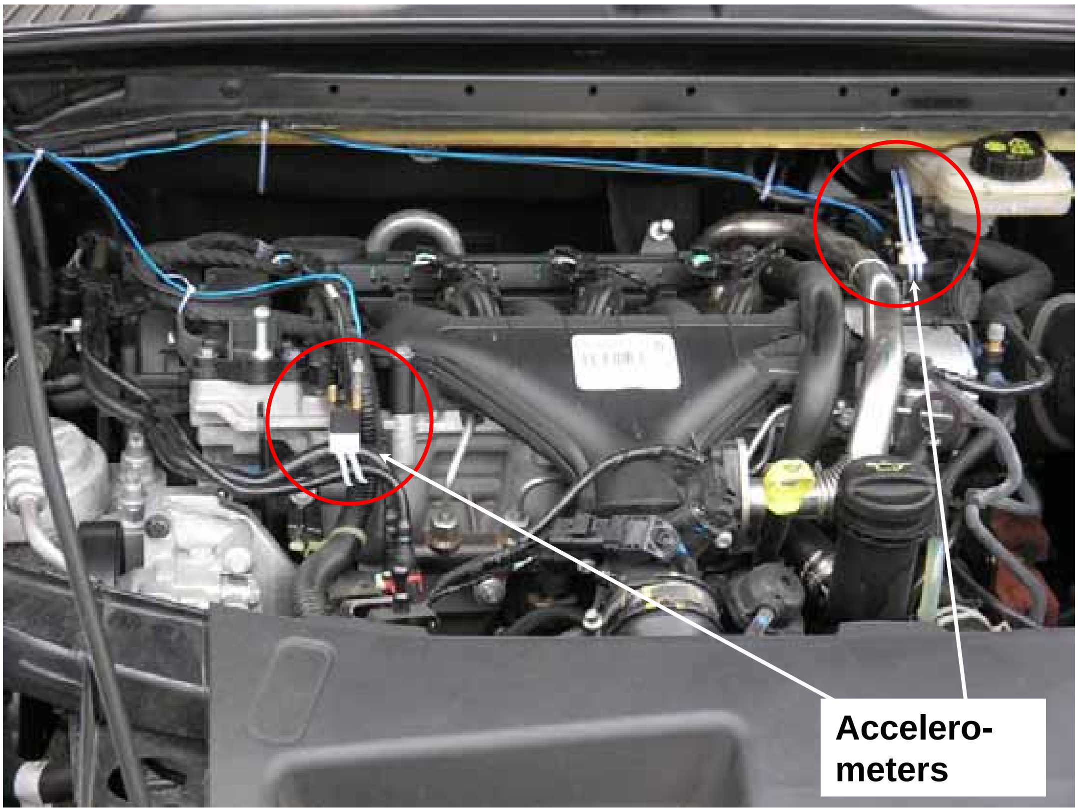
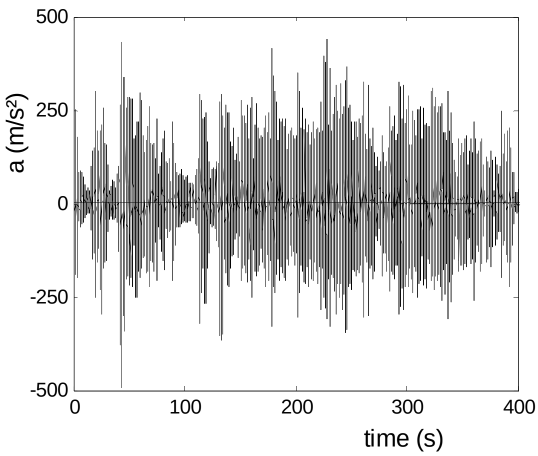
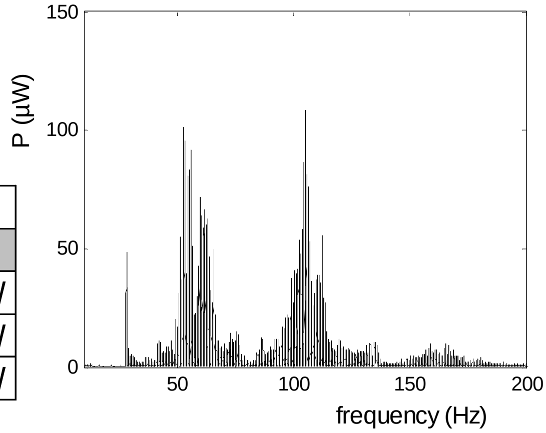
Transducers on Motor Block



Transducer for intelligent fluid quick connector

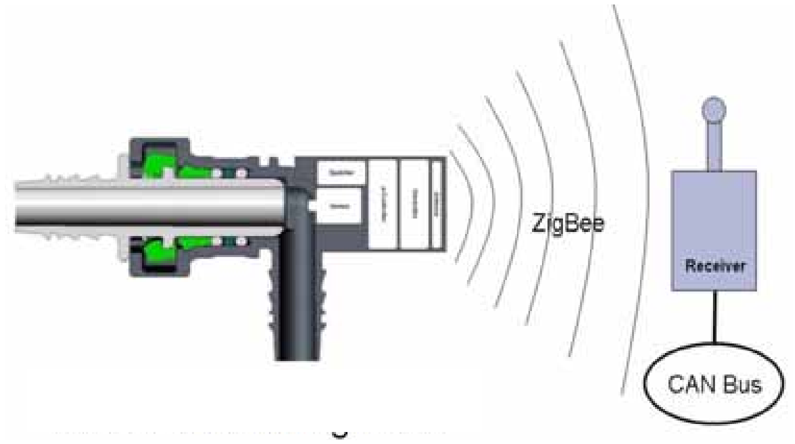
Transient simulation with measured acceleration as excitation (virtual operation of vibration transducer)

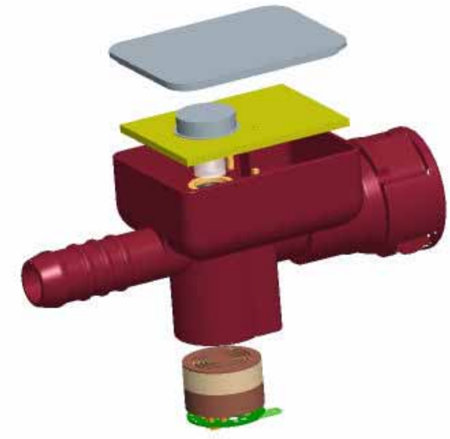




	City	Country	Highway
Threshold (V)	Mean Power	Mean Power	Mean Power
300mV	290µW	473µW	275µW
700mV	270µW	464µW	264µW
1000mV	266µW	451µW	248µW

Transducer for intelligent fluid quick connector





ARaymond GmbH & Co. KG

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Ongoing Research: Anti-Theft Sensor

Questions:

Does the vibration have enough energy to:

- Sense the signal
- Process the data
- Transmit info

What is the conversion efficiency?

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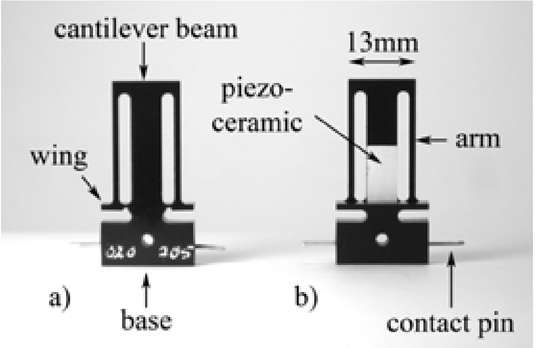
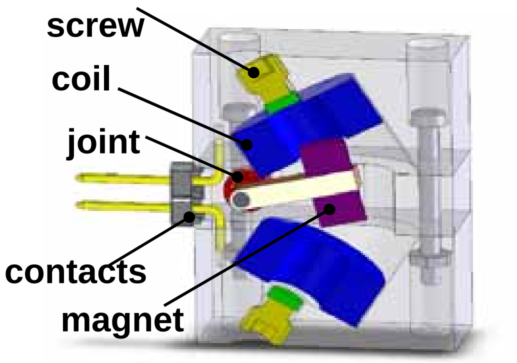
Frequency tunable converters





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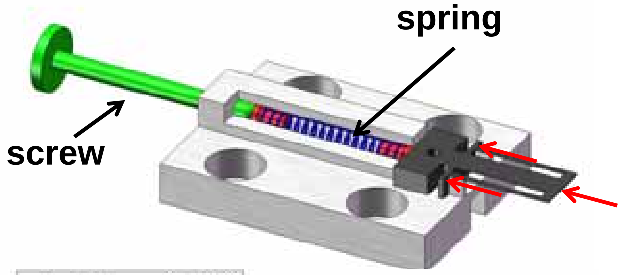
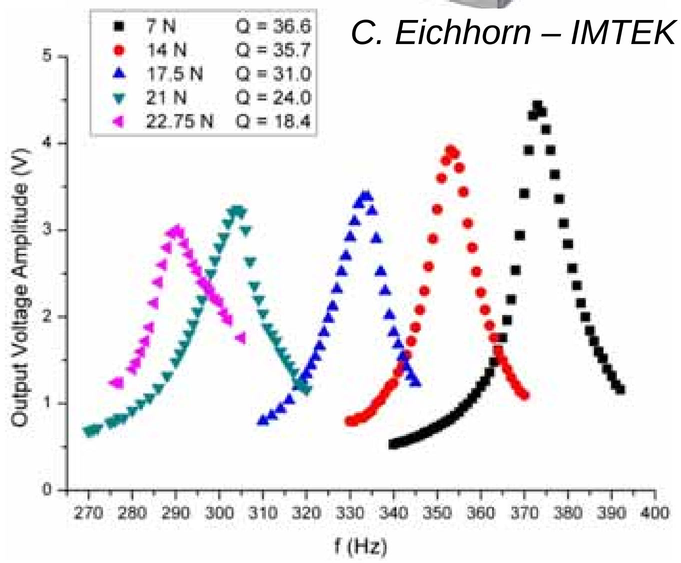
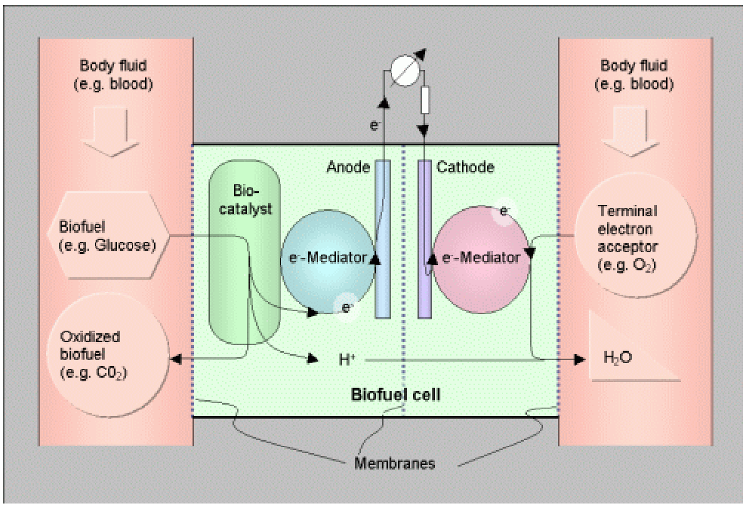
Frequency shift by axial preload



C. Eichhorn – IMTEK



Bio fuel cells

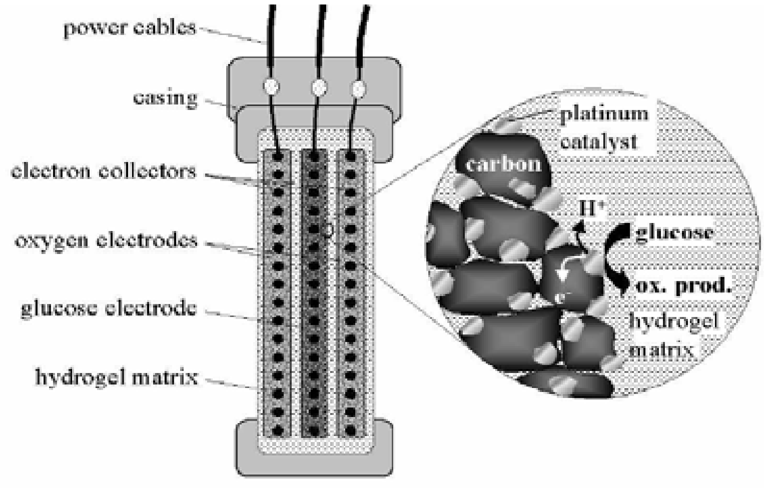


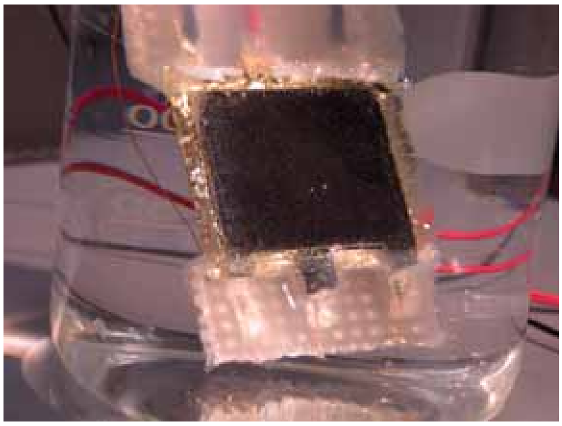
IMTEK, Laboratory for MEMS applications

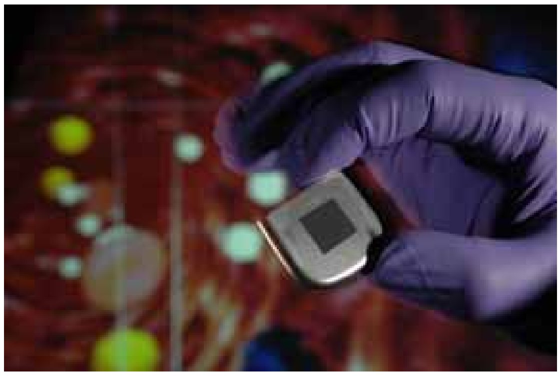
Characteristics

- Generation of DC current by catalytic oxidation of biofuel (e.g. glucose)
- Use of different (bio)catalyzers (enzymes, microbes, metals)
- Output voltage: 0.1…0.5 V
- Output power: µW…mW

Direct glucose fuel cell





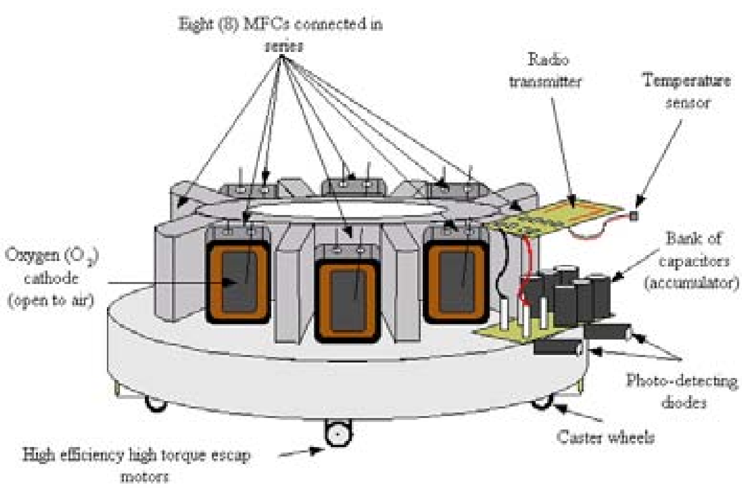


S. Kerzenmacher, R. Zengerle, IMTEK

The „self-feeding“ Robot!

„Autonomous“ robot „EcoBot II“ with 8 microbial fuel cells

- Max. speed: 10…30 cm/h
- Typical “consumption”: 8 flies within 5 days



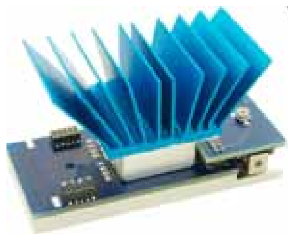
University of Bristol
http://www.ias.uwe.ac.uk/Energy-Autonomy-New/ecobot_download_page.htm

Hybrid Harvesting System

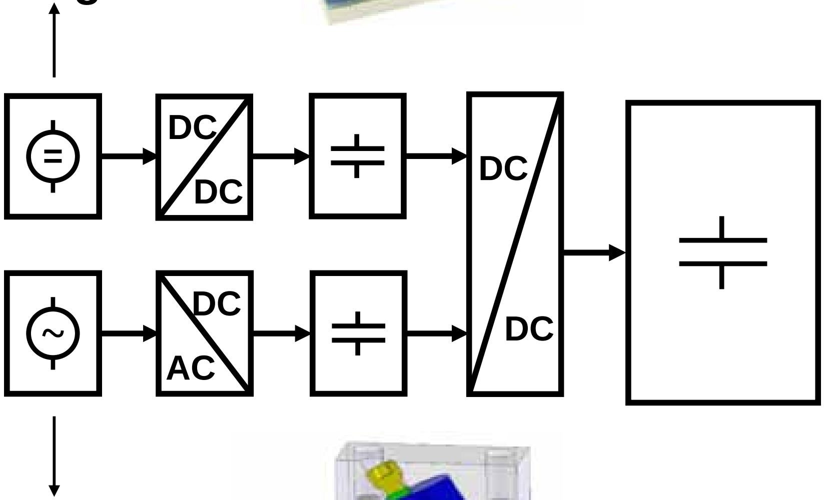
Use different harvesters to complement energy supply

e.g. vibration and heat in a motor

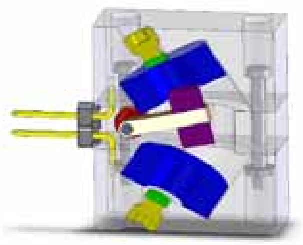
e.g. vibration and light in an industrial application



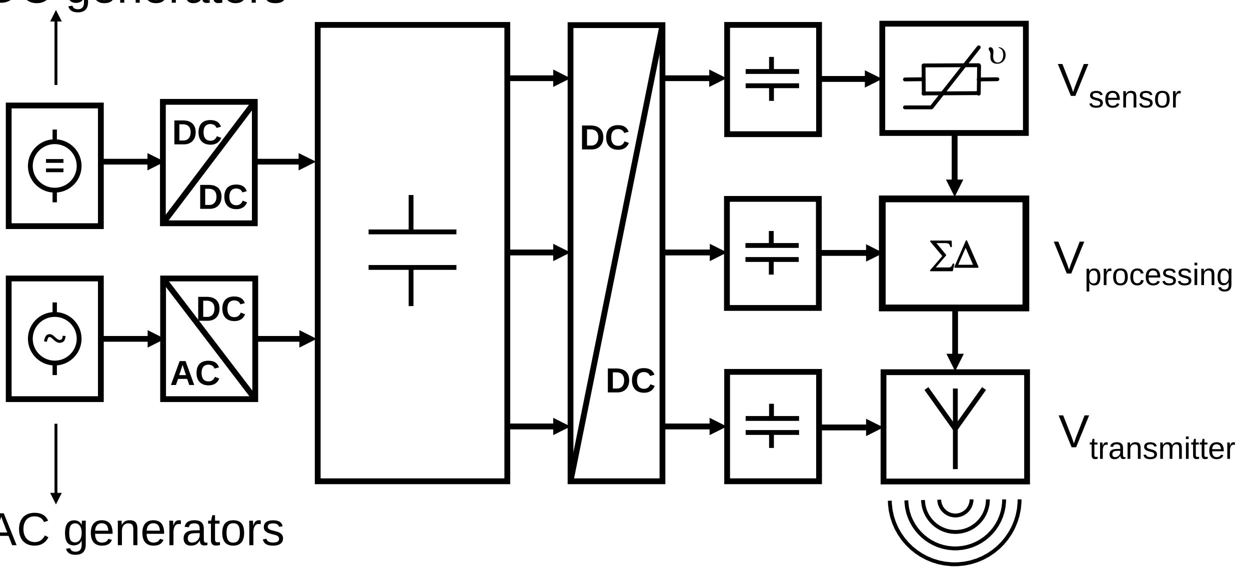
Light / Heat



Vibration



Energy aware power management unit



Energy Aware Hierarchy of Functions

IMTEK

Analog

A/D - Conversion

Energy Conversion
Power Management
Band Limiting
Amplification
Compensation
Linearization
Filtering
Calibration
Compression
Storage
Analysis

Transmission

Digital

Power Requirements

IMTEK

Sensor → Low Power Interface → ADC → Digital Sig. Proc. & Control → Data Transmit & Protocol

Power Needed:

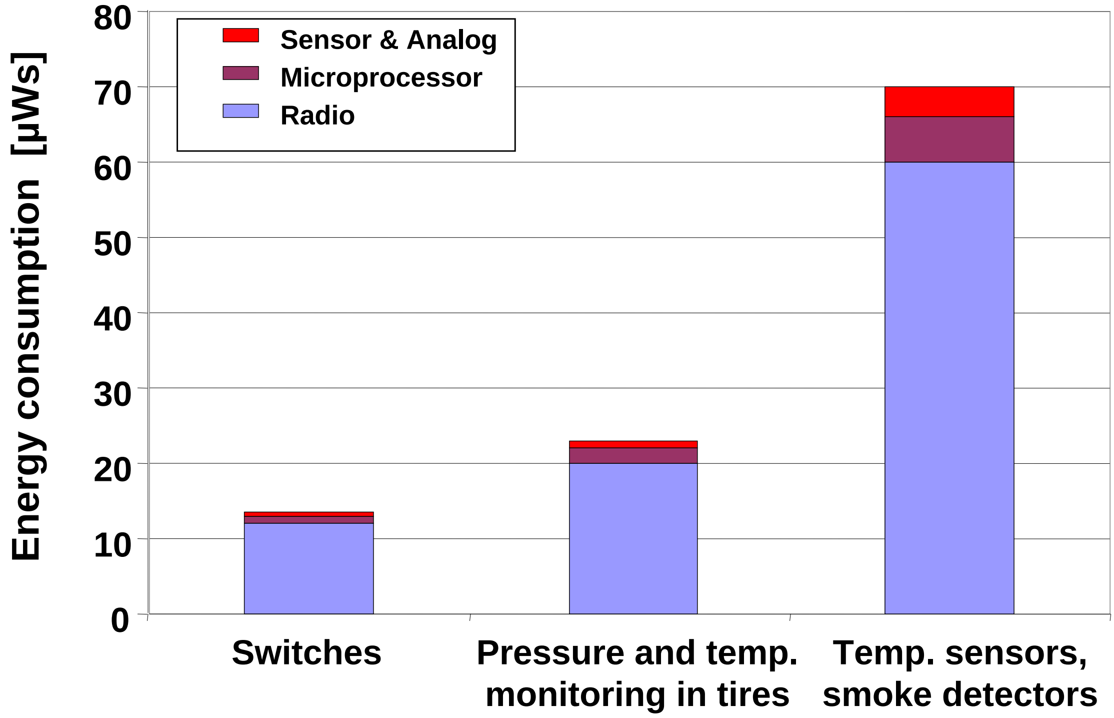
Data Acquisition and A/D Conversion: 1nJ / sample

Computation: (32bit Instructions) 1nJ / Instruction

RF-Link (10-100m) 100nJ / bit

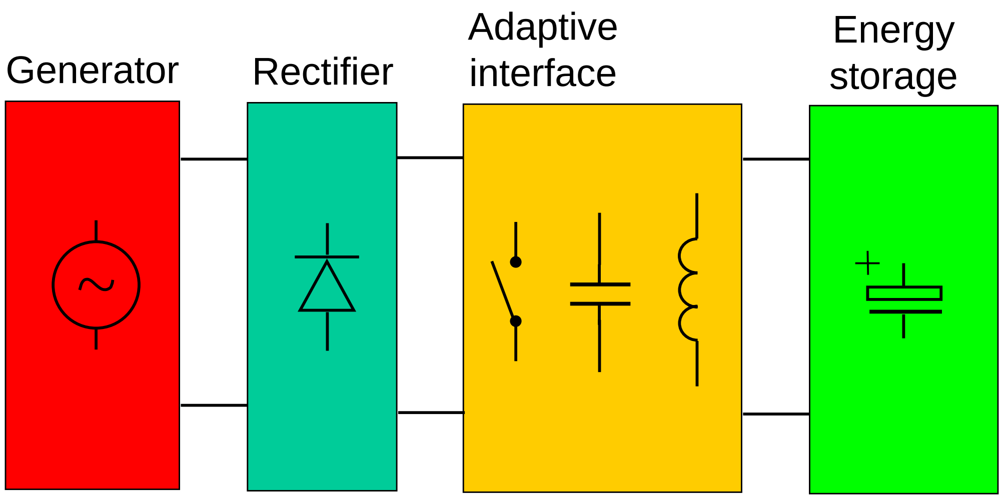
Compute before transmitting!
For every transmitted bit we can afford 100 computations

Who is consuming how much current?

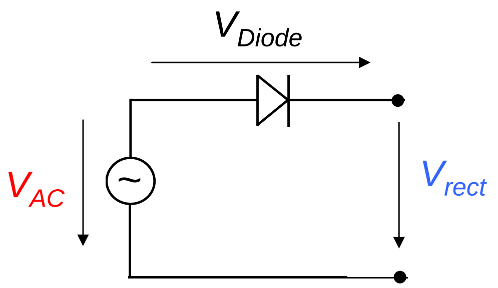


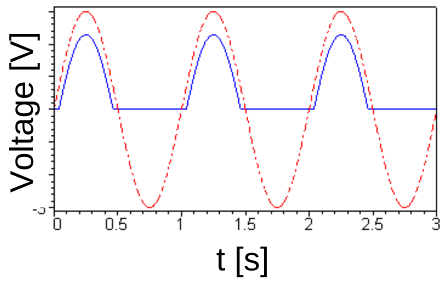
80%-90% of energy goes to transmission (EnOcean, 2003)

Interfaces for AC generators

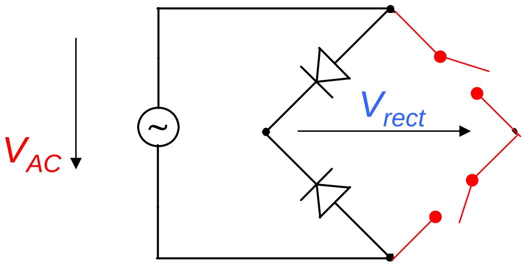


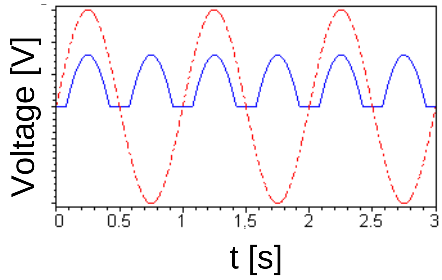
One-Way and Full-Wave Bridge Rectifier





Only every second half-wave is rectified → large energy loss





Both half-waves are rectified → smaller energy loss, but double voltage drop

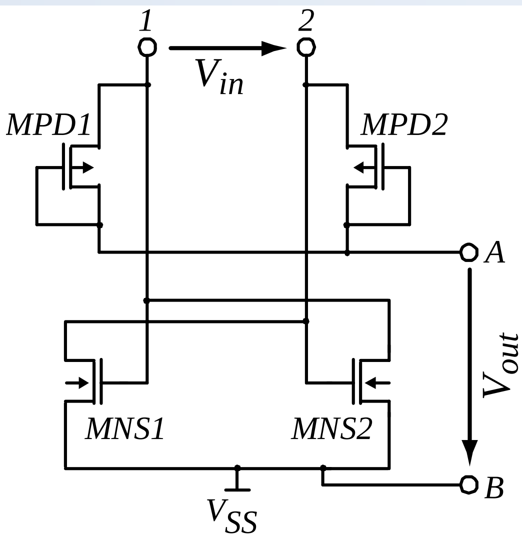
Low-Voltage Rectification

MOSFETs as switches

- Full-Bridge with only 1 “diode” voltage loss
- Integration in standard CMOS is easy
- Diodes prevent excessive reverse leakage

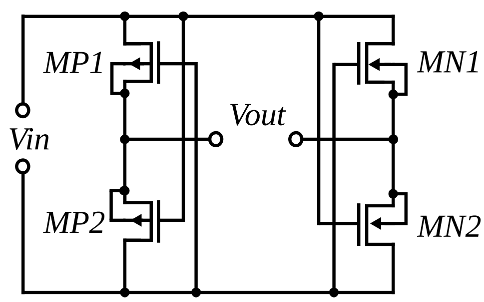
$$V_{loss} \approx V_{th} + \cancel{IR_{DS,on}}$$

small



Cross-coupled Inverters

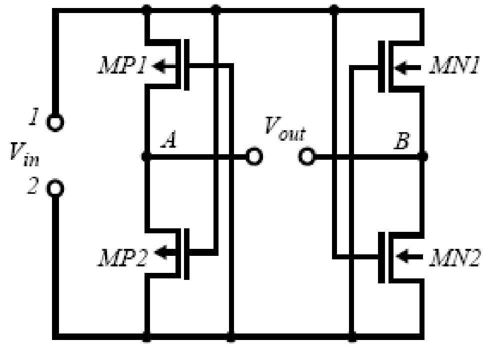
- No significant voltage drop
- Integration in standard CMOS is easy
- But bidirectional functionality

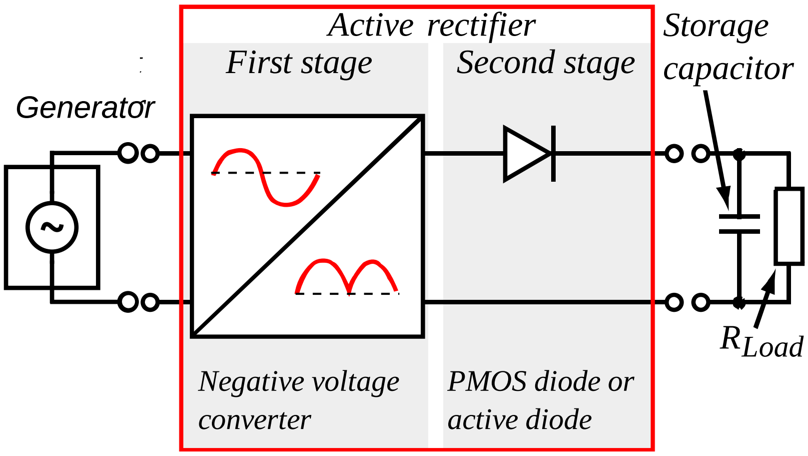


Active Rectifier

Two stage approach:

- First stage:
  - ➢ Negative voltage converter →
- Second stage:
  - ➢ Diode part



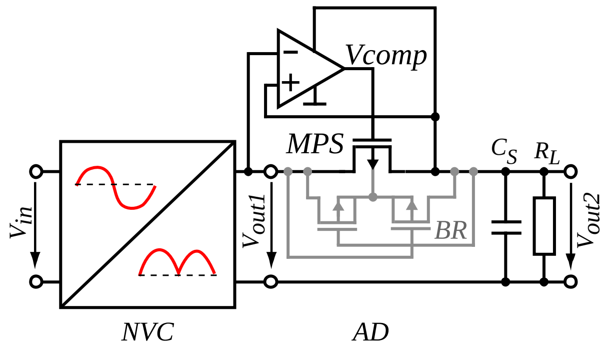


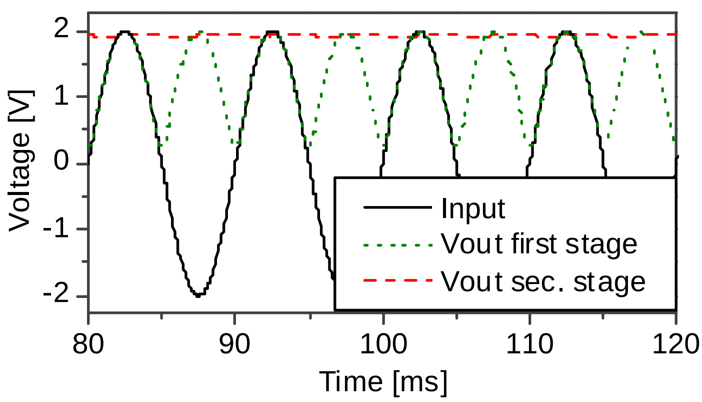
C. Peters, IMTEK

Active Rectifier – Active Diode

Second Stage – Active Diode

- Concept:
  - ➢ pMOS switch driven by a comparator
- Very small voltage drop
  - ➢ $V_{drop}=R_{DS}*I$
- But: Active elements
  - ➢ Permanent current consumption
  - ➢ Reduced bandwidth

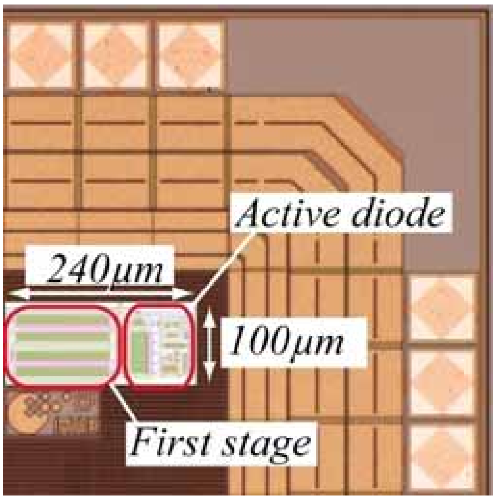


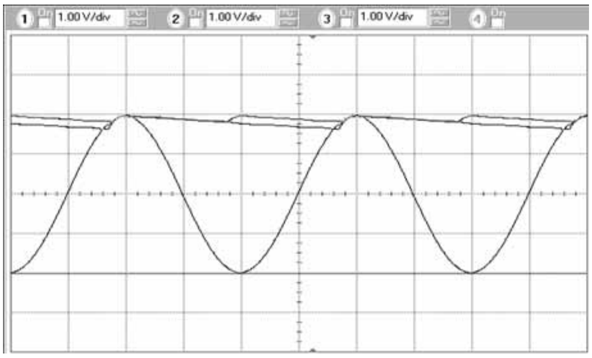


Active Rectifier – Results

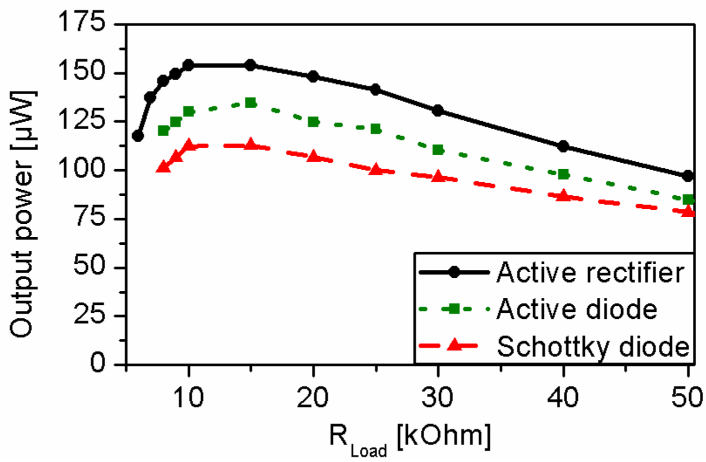
Implementation:

- CMOS 0.35µm process
- No special process options needed
- ~30% more output power!

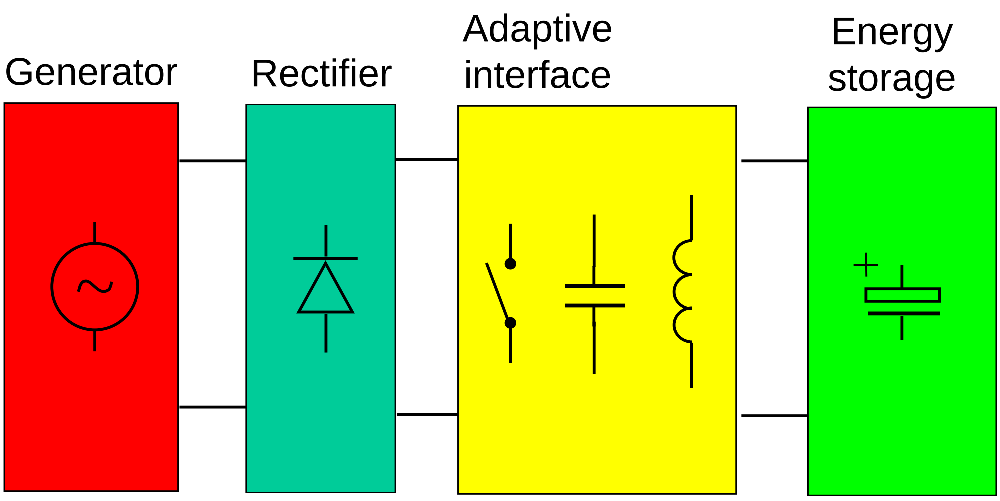




125kHz, 680pF, 50kΩ

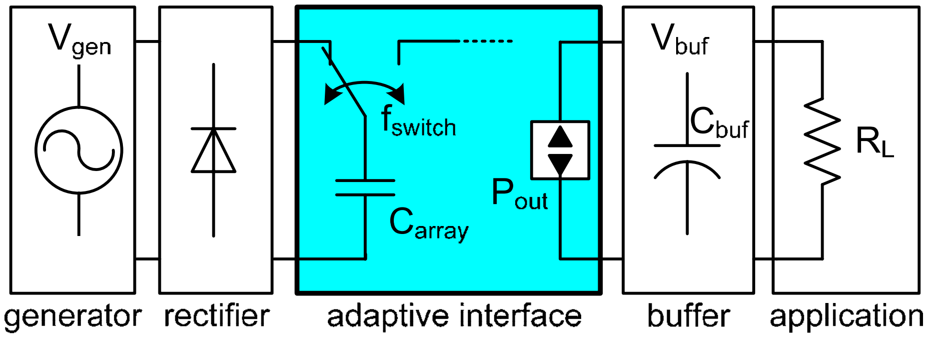


Interfaces for AC generators

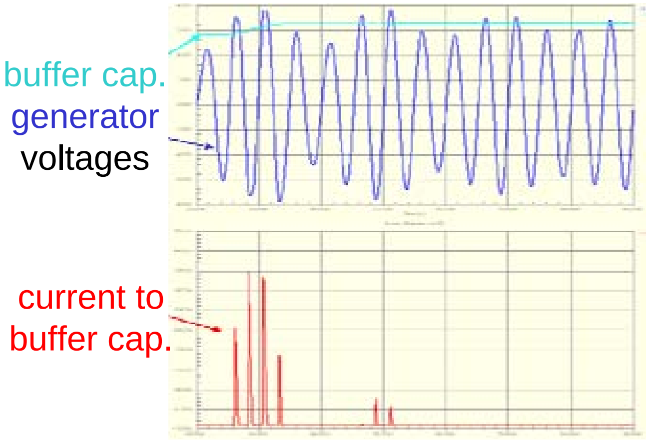


Interface for inductive generators

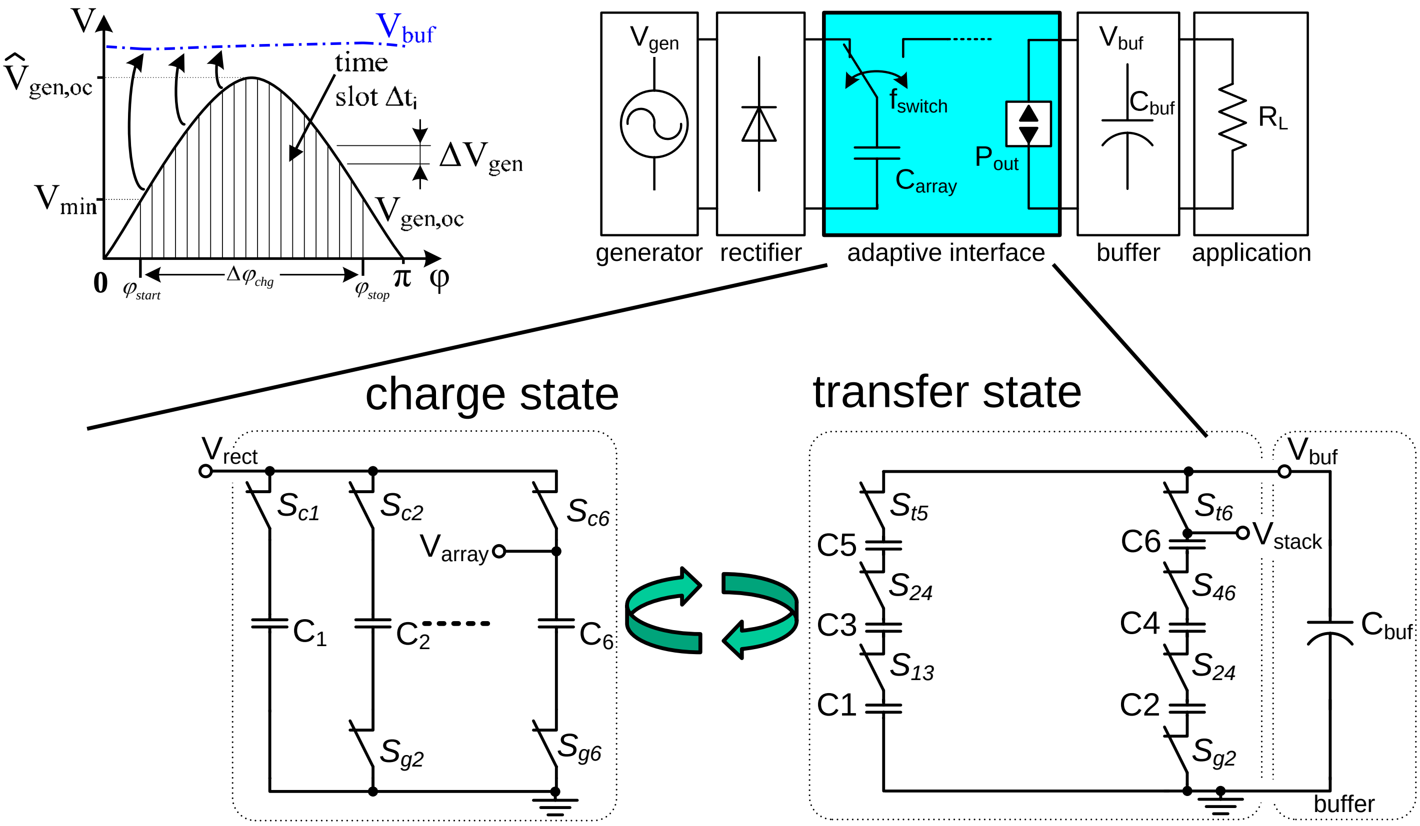
Switch Capacitor Array between Rectifier and Buffer



- Provides the opportunity of
  - Decoupling of generator and buffer cap.
  - Matching the impedance of the generator
  - Immediate voltage conversion

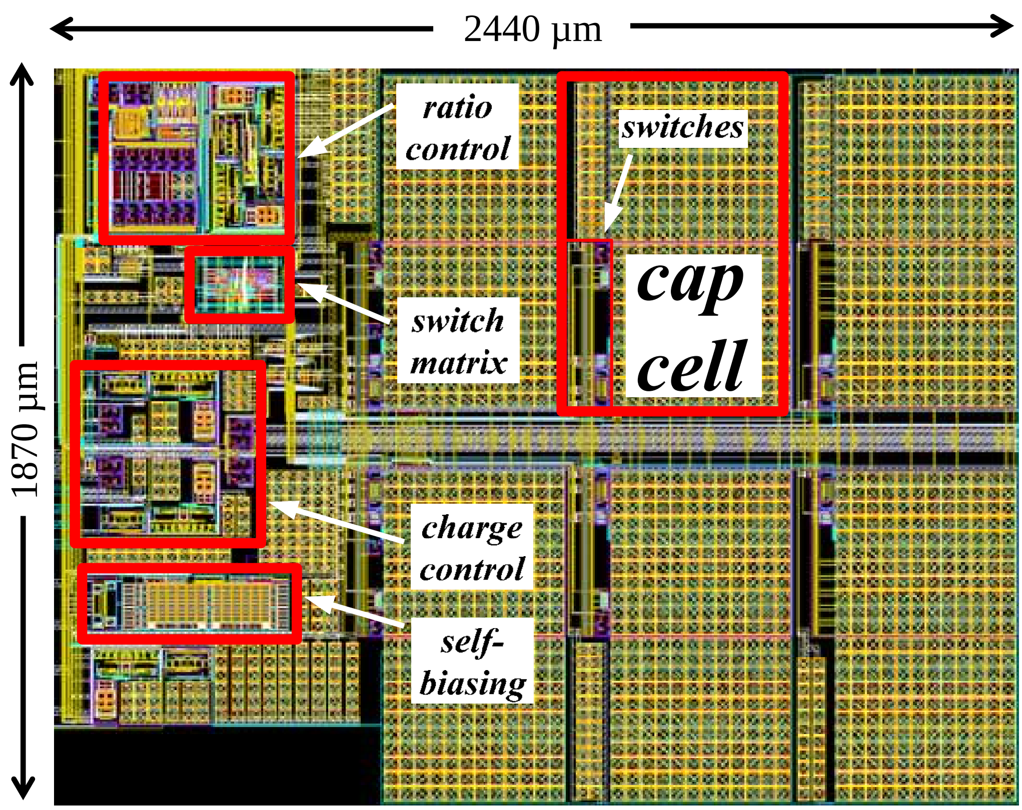


Parallel - Stack Operation



D. Maurath, ESSCIRC 2009

Implementation – 0.35 µm CMOS



CMOS	*0.35µm*
Area	*4.56 mm²*
$V_{pp,min}$	*> 1.1V*
$V_{pp,max}$	*7.2 V*
$P_{out,typ}$	*300-700 µW*
$P_{control}$	27µW
f_{gen}	*< 500 Hz*
R_i	*1-10 kΩ*

D. Maurath, ESSCIRC 2009

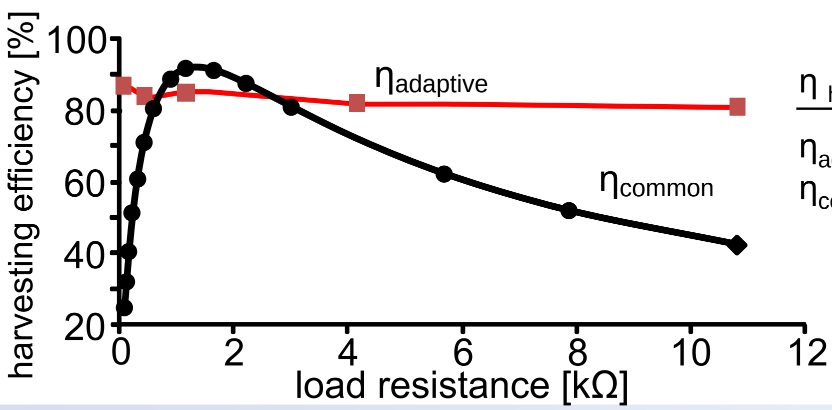
Comparison of Harvesting Efficiencies η_{hvst}

Less peak efficiency

- but ideal load condition rarely occurs (e.g. in a sensor network node)
- Medium load (e.g. active - measure state of a sensor node)

High harvesting efficiency for

- Low load (e.g. sleep state of a sensor node)
- High load (e.g. transmit state of a sensor node)

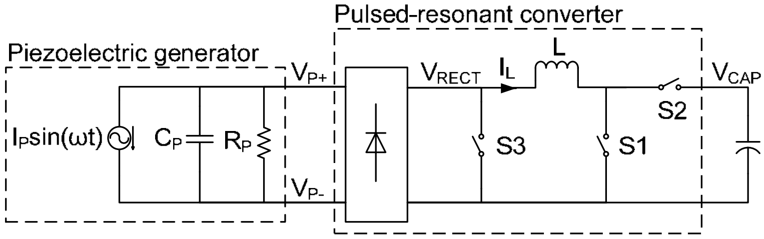


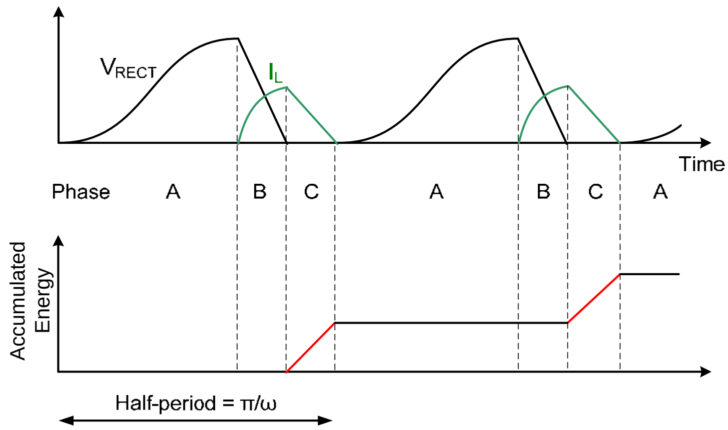
η_{hvst} – Efficiency

$\eta_{adaptive}$: with interface
η_{common}: without interface

Principle of operation - SECE

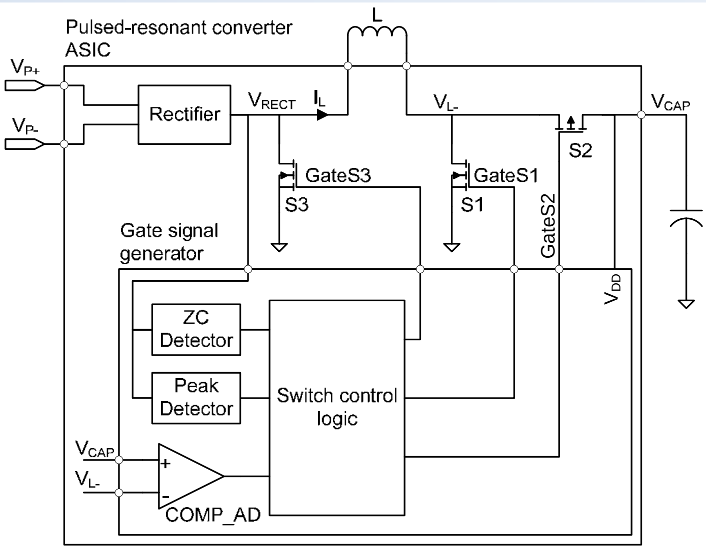
- Synchronous electric charge extraction (SECE)
- Pulsed operation, triggered by peak of V_{RECT}
- Temporary energy storage in coil
- Energy accumulated in large storage capacitor, unregulated output voltage V_{CAP}
- Duration of transfer process (phases B+C) much shorter than half-period of excitation
- Challenge: Generation of control signals for S1, S2, S3

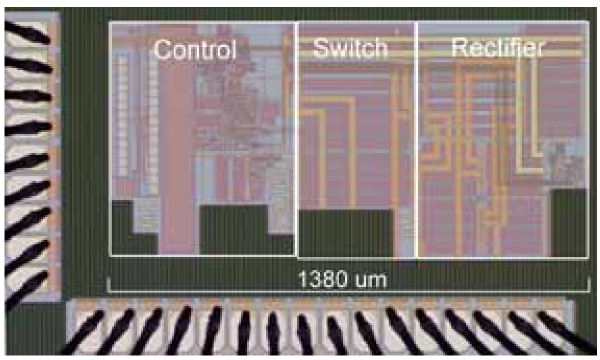




SECE CMOS implementation

- 0.35 µm CMOS process with high voltage option
- 5 V input transistors
- Bidirectional “rectifier”: Reverse current blocked by S2
- Autonomous operation:
  - ➢ Gate signal generator powered by storage capacitor
  - ➢ Low average power (µW range) consumption due to dynamic enable/disable
- Timing independent from V_{CAP}

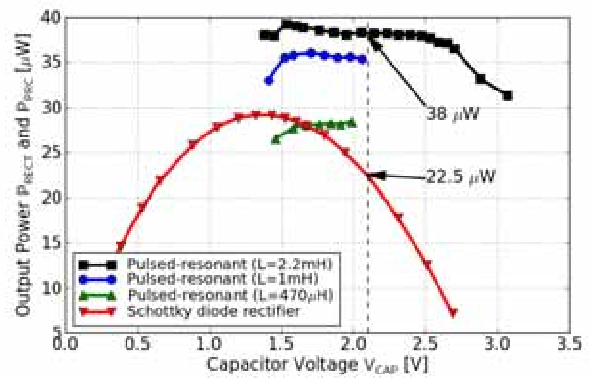




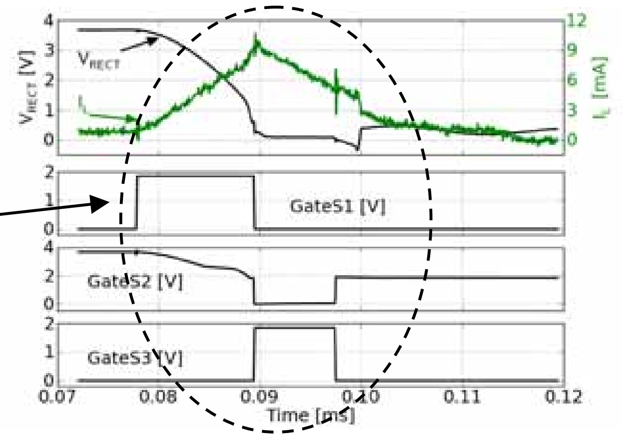
T. Hehn, PowerMEMS 2010

SECE measurement results

- Best performance using the 2.2 mH coil (R_{DC} = 5.4 Ohm)
- Output power quite constant for V_{CAP} = 1.5 V … 2.5 V, higher power consumption and higher dynamic losses with higher V_{CAP}
- Power gain compared to Schottky diode rectifier (V_D = 0.2 V):
  - 1.3x @ V_{CAP} = 1.4 V
  - 1.7x @ V_{CAP} = 2.1V
  - 5x @ V_{CAP} = 2.7 V



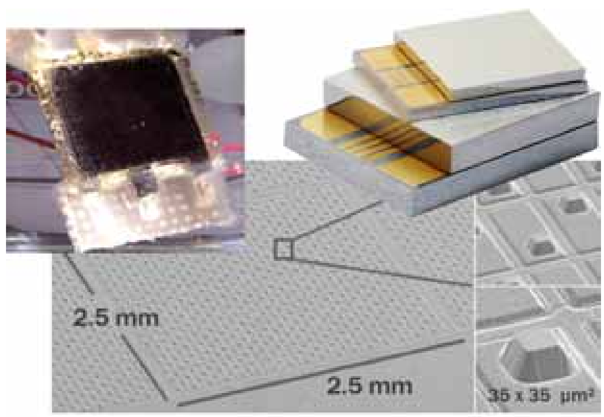
One transfer process



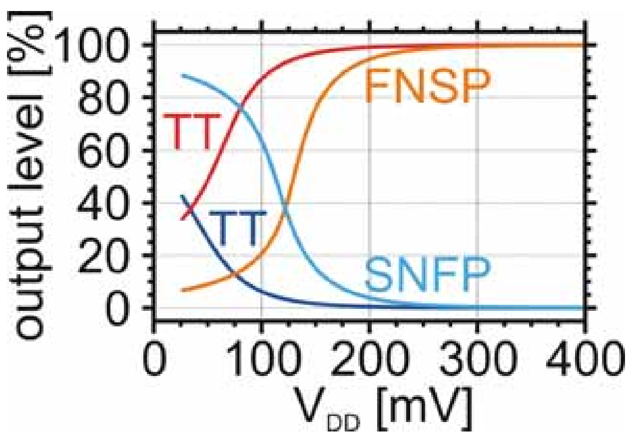
Minimum Supply Voltage of Digital Blocks

Supply voltage reduction beyond minimum energy per operation point for…

- Energy harvesting devices delivering low VDD
- Always-on circuits with low speed requirements
  - Standby power reduction
- BUT: On- to off-current ratio degrades with decreasing VDD



Source: Micropelt GmbH / University of Freiburg



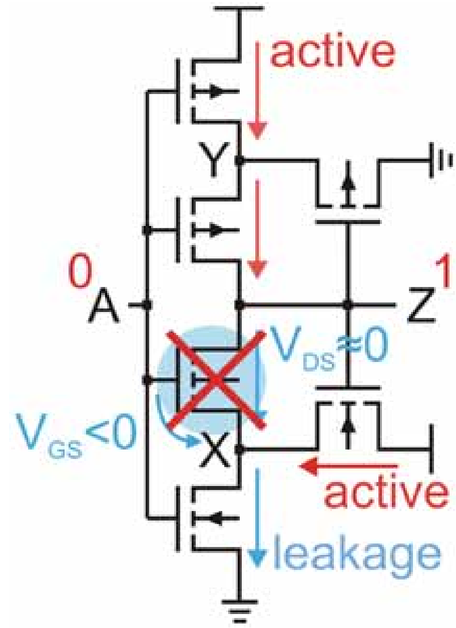
Leakage Quenching in Schmitt Trigger

Feedback: Node X close to V_{DD}

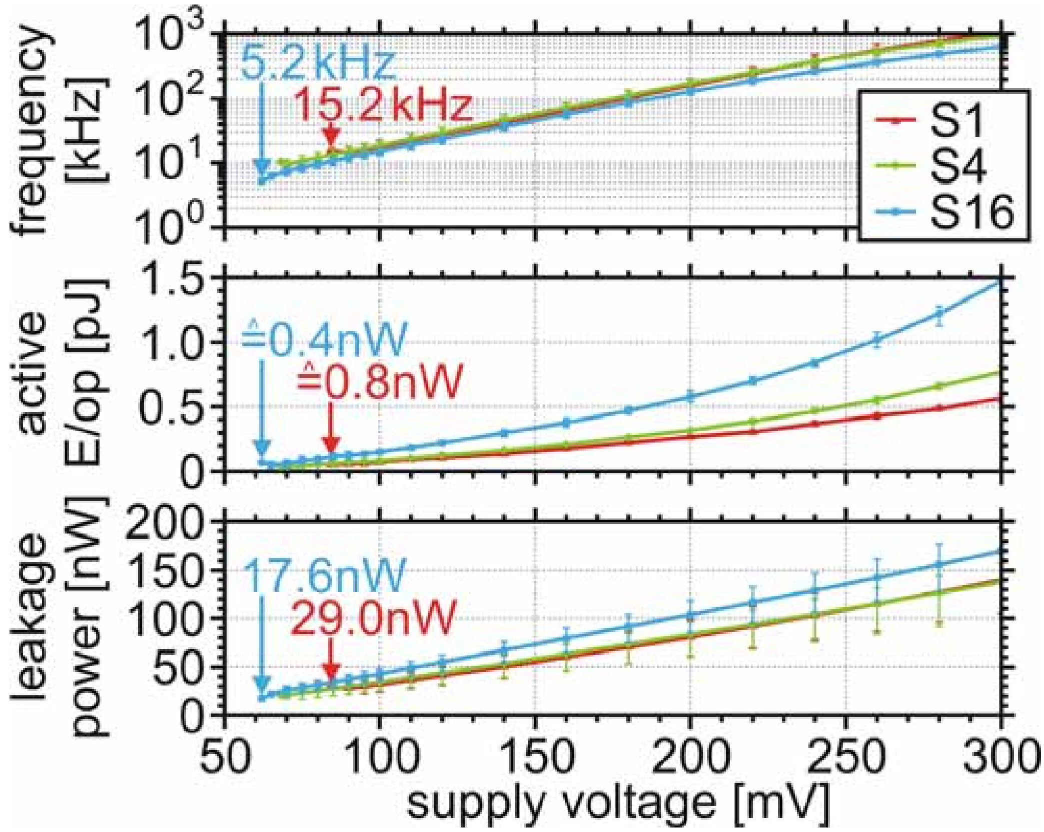
V_{DS} of middle transistor close to zero

V_{GS} of middle transistor below zero

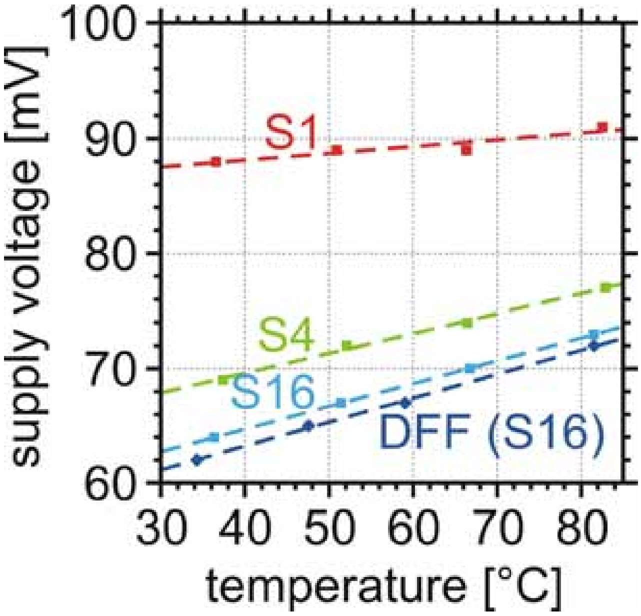
=> Leakage Quenching

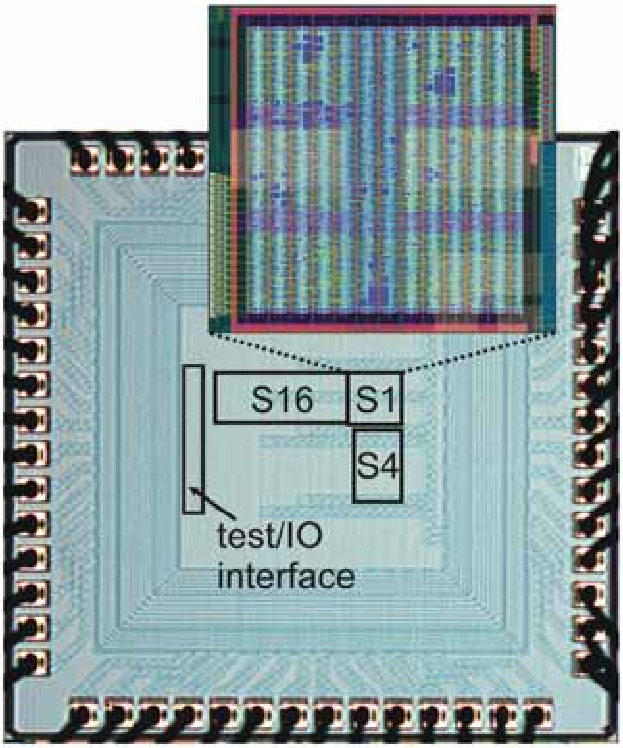


Speed / Energy / Power



Minimum Supply Voltage – Temperature Dependence





Conclusions

- Energy Harvesting provides new opportunities
  - Sensor applications
  - Condition monitoring
  - Remote areas
- Codesign of generator and interface electronics
  - More than More than Moore
- Power efficient adaptive interfaces
  - Impedance matching
  - Frequency matching
- Ultra low-power sensor electronics
  - Digital and analog subthreshold design
- Hybrid Systems
  - More than one generator type for reliable supply