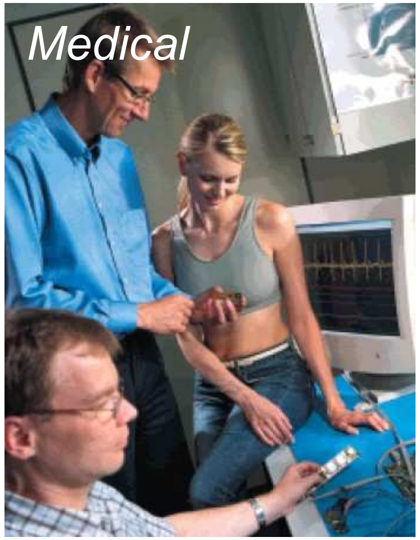
Micro Energy Harvesting
Power Supply for Distributed and Embedded Systems

Peter Woias

Albert-Ludwig-University of Freiburg
Department of Microsystems Engineering (IMTEK)
Laboratory for Design of Microsystems
Freiburg, Germany

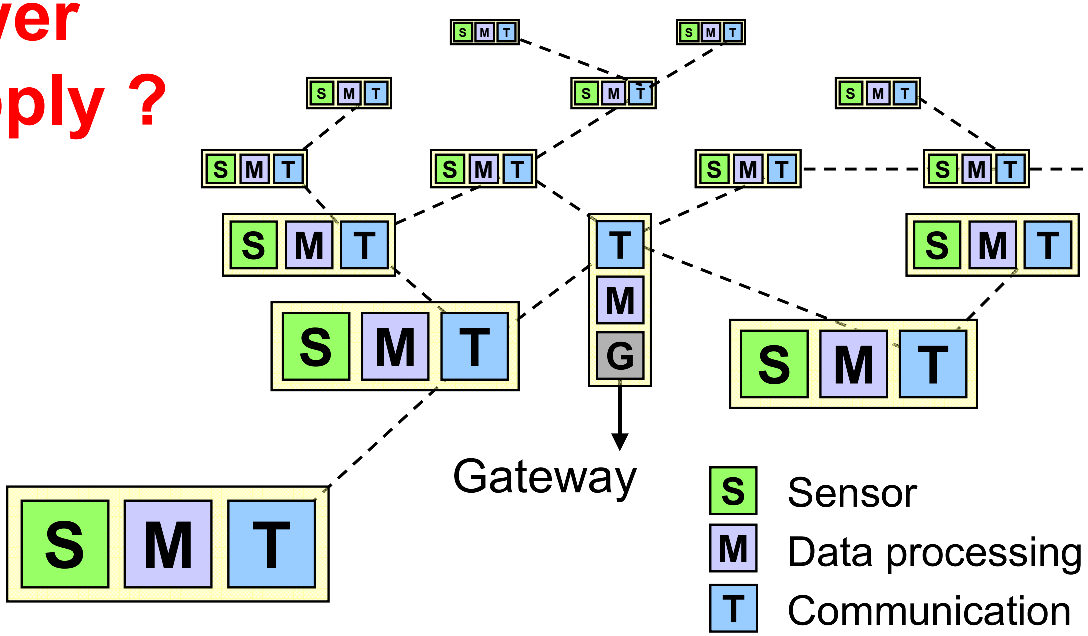
Distributed Micro-Embedded Systems (MES)



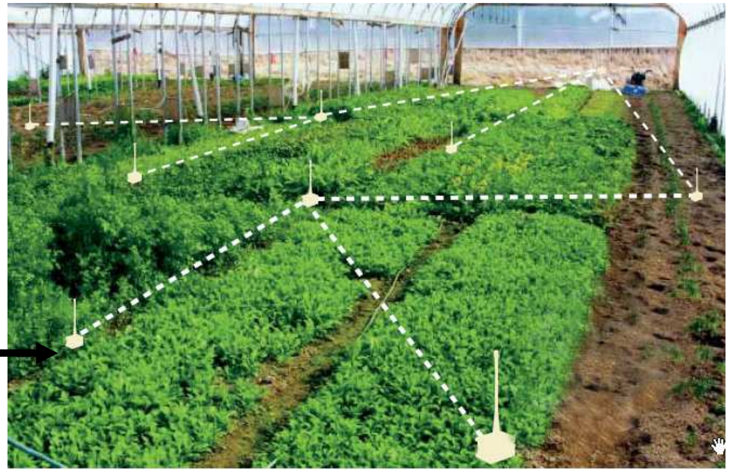
Space, ….

Fabrication and Transport

… power supply ?



Wire or battery … or what ?



*distributed and **„embedded“** sensor systems in greenhouses © Crossbow*

Sensors in redwood trees © University of California

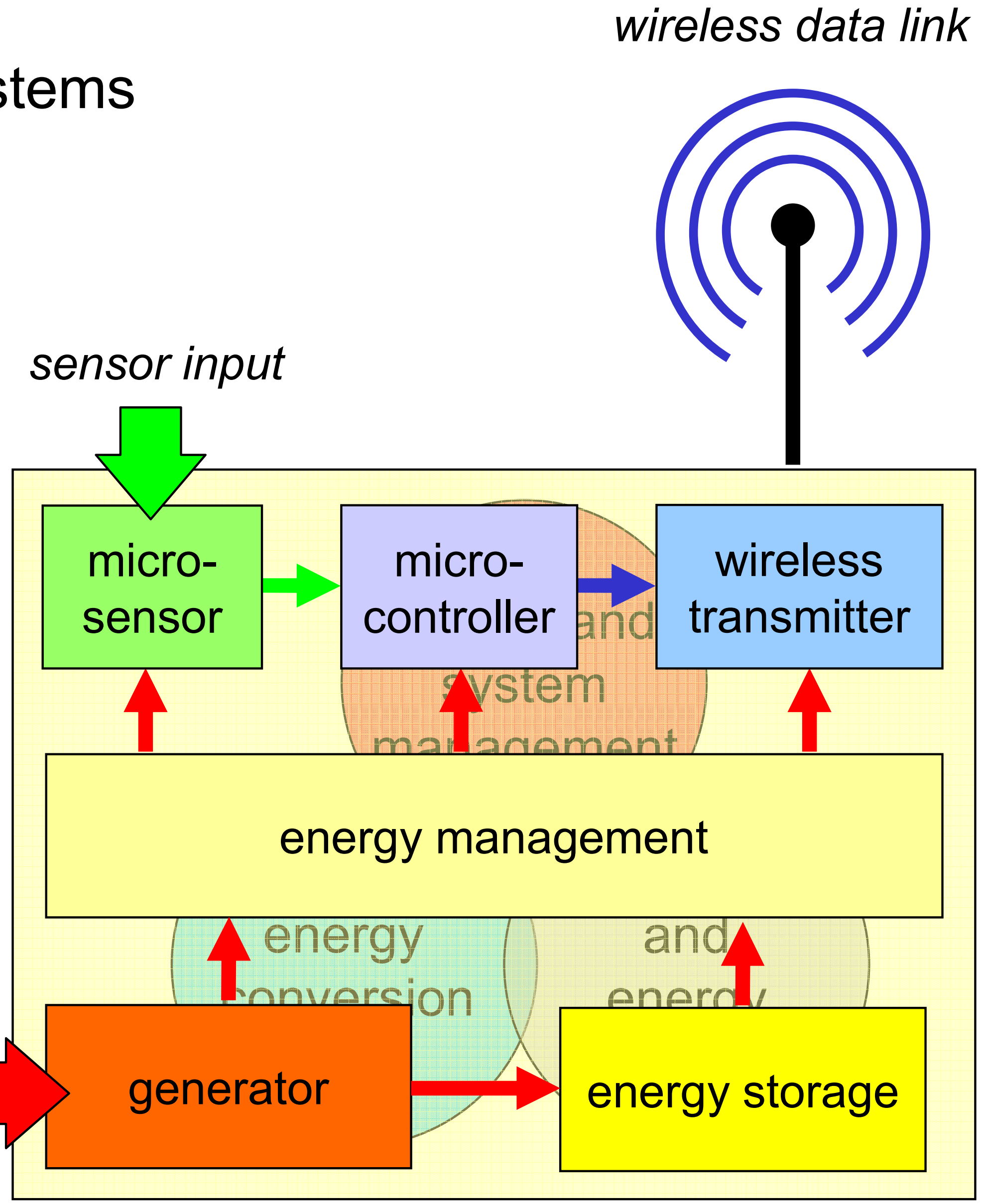
medical implants © Vitatron

tire pressure sensors

Micro Energy Harvesting: The Vision

Energy-Autonomous Embedded Systems

- „always on“
- no battery recharging or exchange
- no power cords
- easy to install …
- … at numerous application sites



IMTEK

Fact sheet

- financed by DFG and industry
- 3 associated members
- 22+1 PhD scholarhips
- start: October 2006
- run-time: 4.5 years (1st phase)

Research topics

- energy conversion
- materials for energy harvesting
- energy storage and management
- system considerations

Associated Members

ISE
Fraunhofer Institut Solare Energiesysteme

HSG-IMIT

IPM
Fraunhofer Institut Physikalische Meßtechnik

Members

IMTEK

FMF

Sponsors

SICK

E+H

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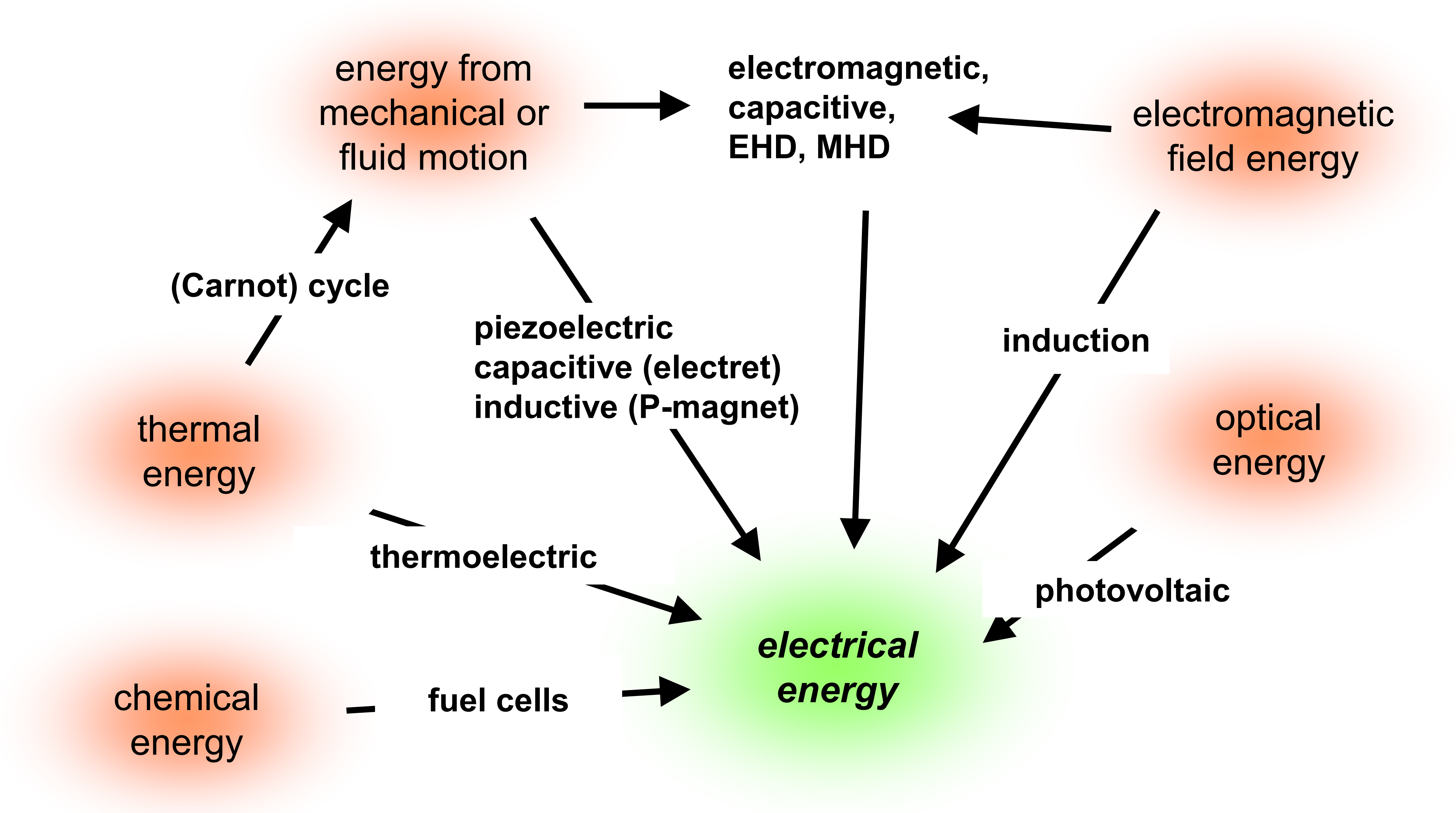
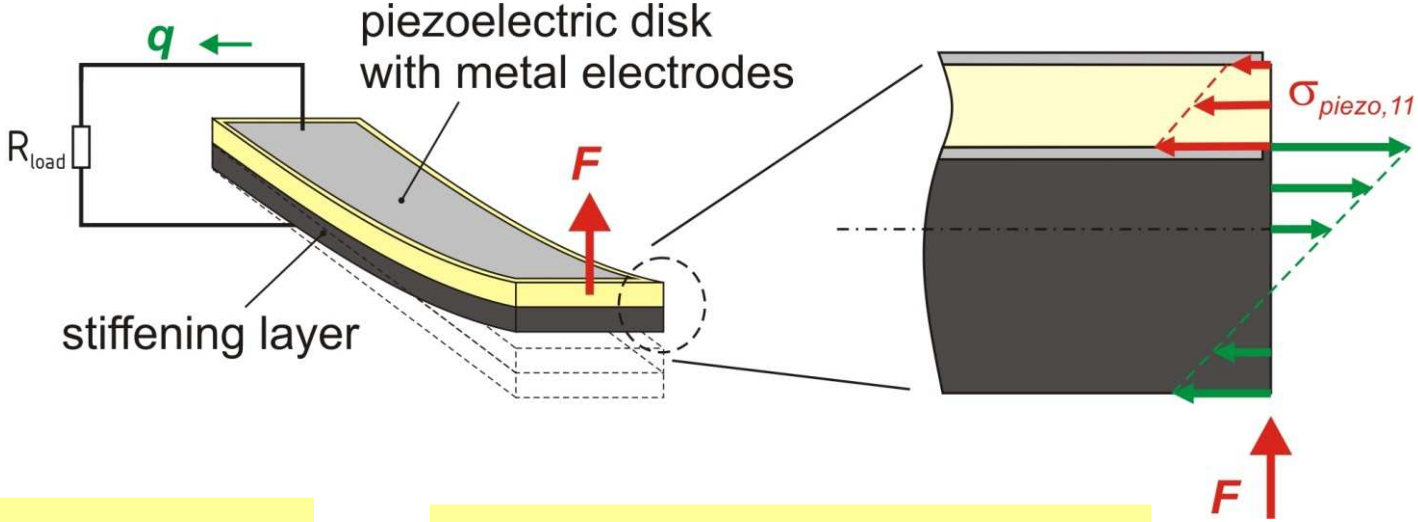
Ambient energy and related conversion mechanism



Piezoelectric bending generators: Principle



$$q = d_{31} \cdot \sigma_{piezo,11}$$

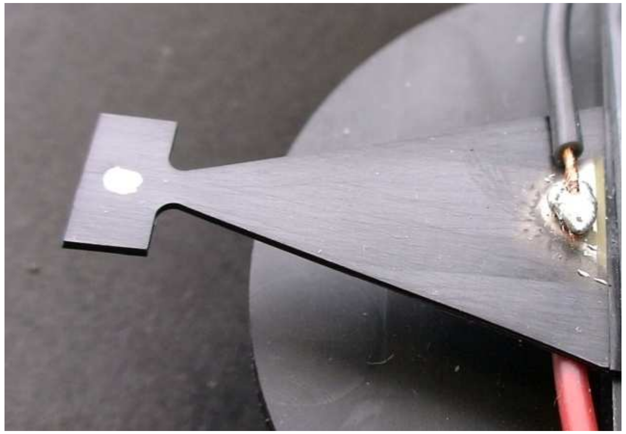
$$I = \frac{dq}{dt} = \frac{d}{dt}\left(d_{31} \cdot \sigma_{11}\right)$$

Design challenges

- homogeneous mechanical stress ➡ higher output power
- tunable resonance frequency ➡ broader application range, more power
- smart system integration ➡ cheaper, easier fabrication

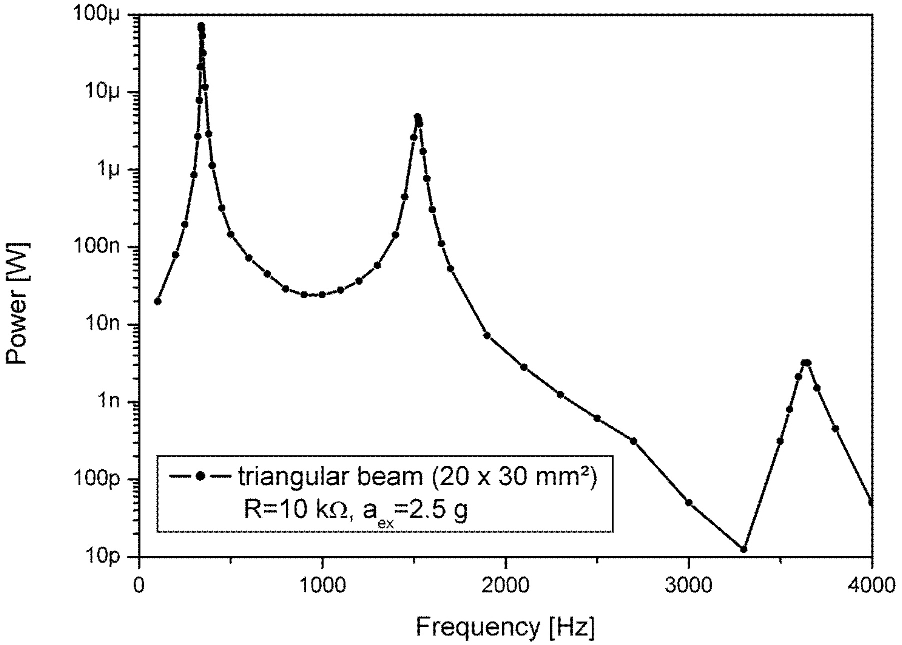
Optimized vibrational piezo generator (2007)

E. Just *et al.*, *Proc. GMM-Workshop “Energieautarke Mikrosysteme”*, 2006

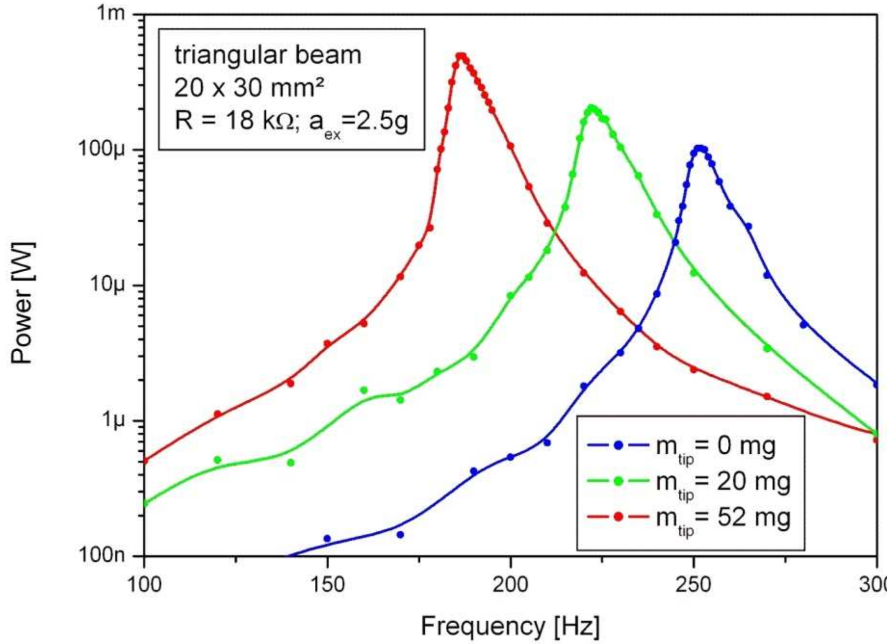


F. Goldschmidtböing, P. Woias,
Journ. Micromech. Microeng. 18, 2008, 104013

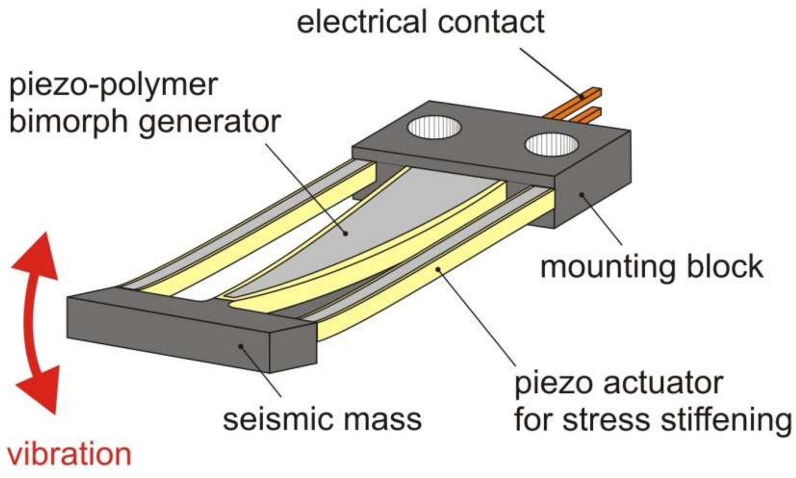
spectral output power (no seismic mass)

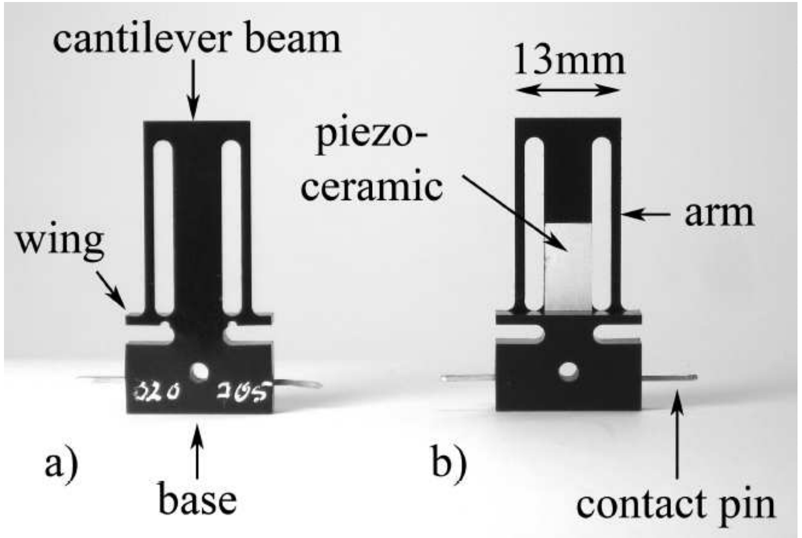


influence of a seismic mass



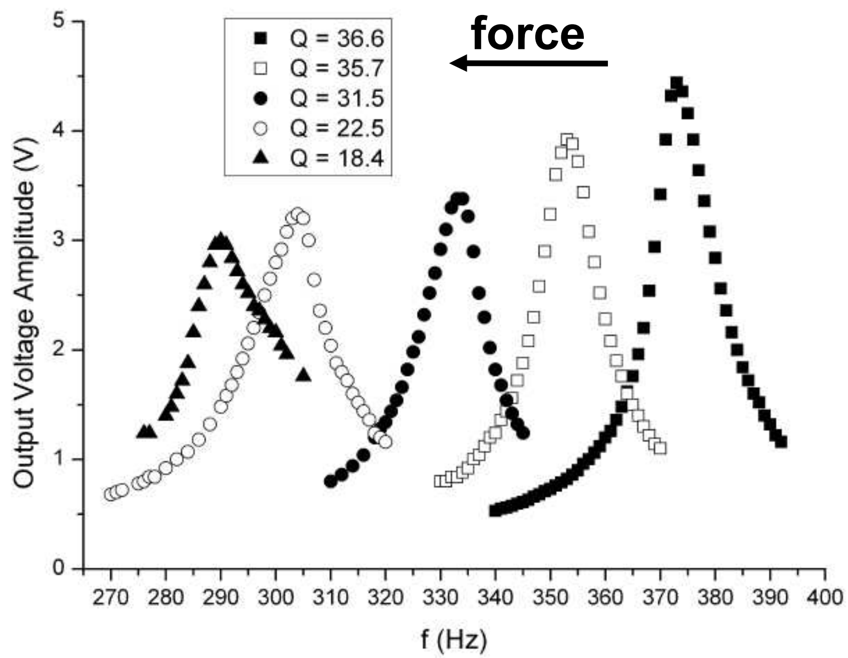
Frequency-tunable piezo generator (2008)





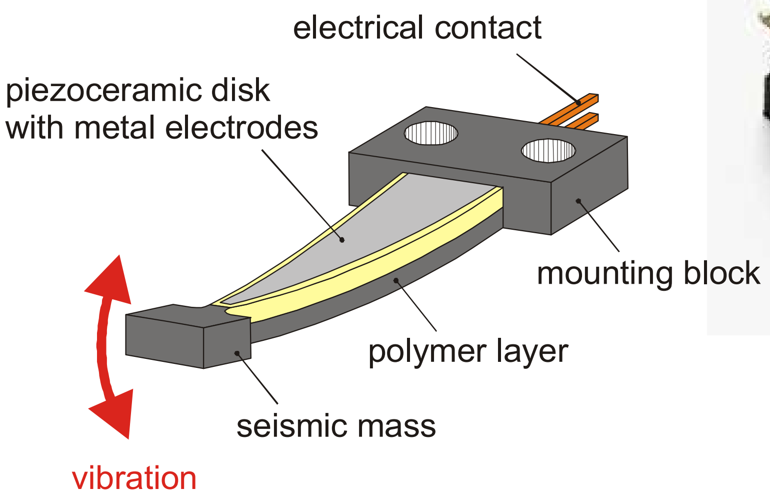
Principle

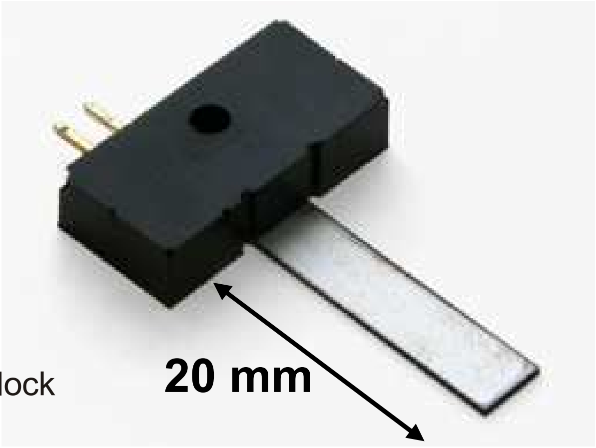
- Actuation force in the „arms“ will stiffen the resonating beam and thus change its resonance frequency
  - ➡ ***high tuning range (22%)***
  - ➡ ***loss of Q factor with increasing force***

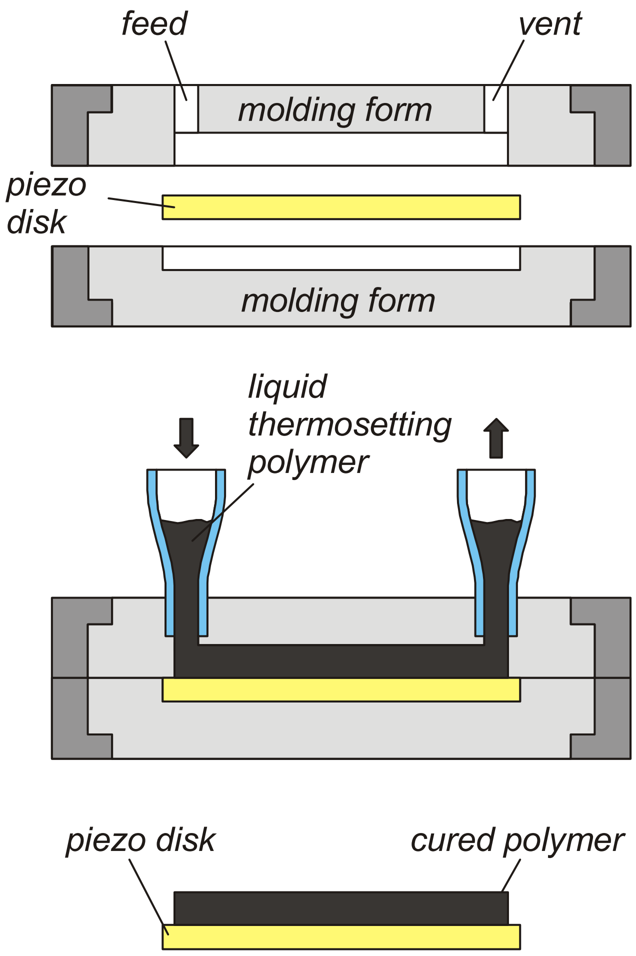


C. Eichhorn *et al.*, *Proc. PowerMEMS 2008*, Sendai, Japan, 309-312.

Fabrication: Piezo-Polymer-Composites (2003)



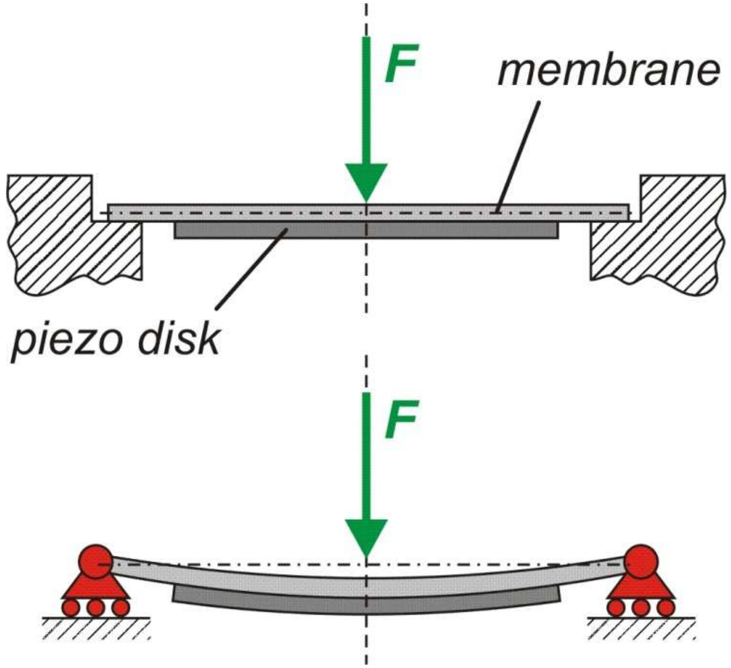


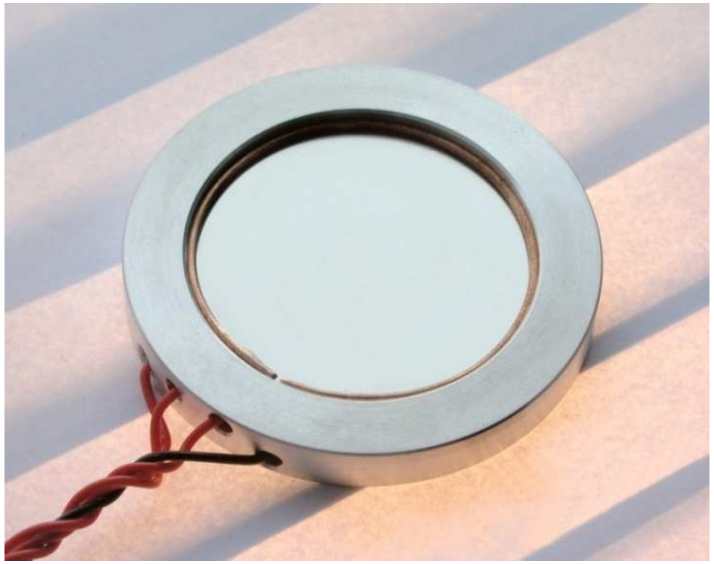


Advantages

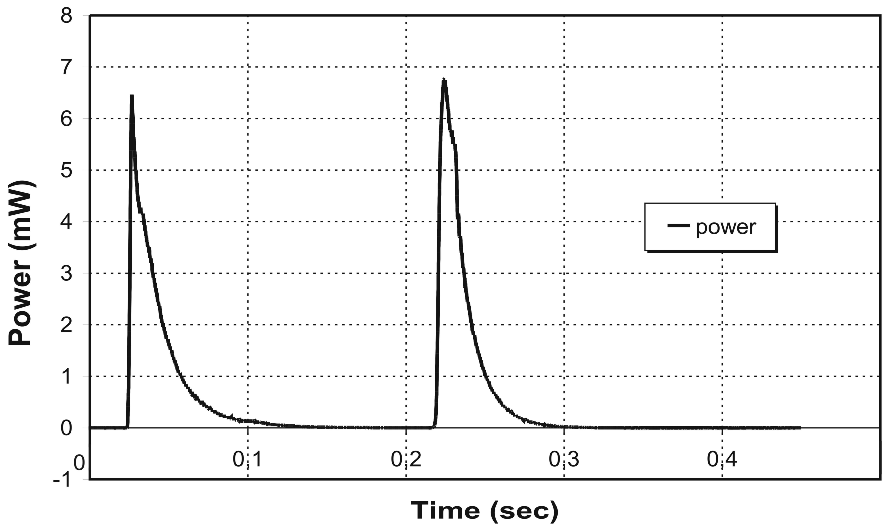
- structure definition and piezo integration in one single step
- low-cost perspective via inject molding
- extremely high design flexibility
- actuators and generators in one single technology

Impact-type piezo generator (2005)





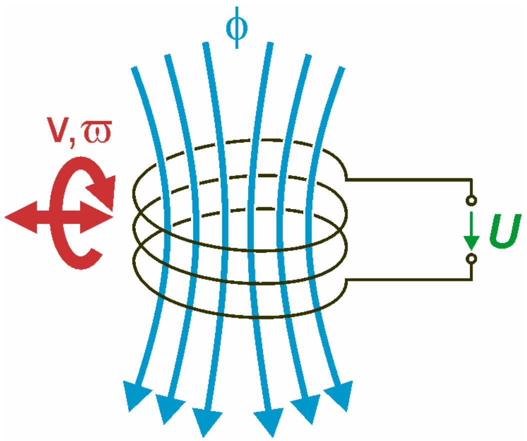
6 mW$_p$ @ 36N pulse (100 ms)



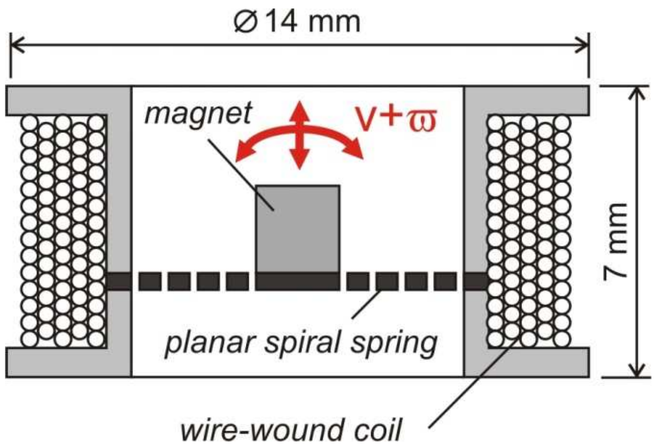
Advantages

- stress-homogenized hinge design for a maximal output power
- non-resonant operation
- high output power
- high output voltage
- stacked devices for power multiplication

Electromagnetic generators: Principle and examples

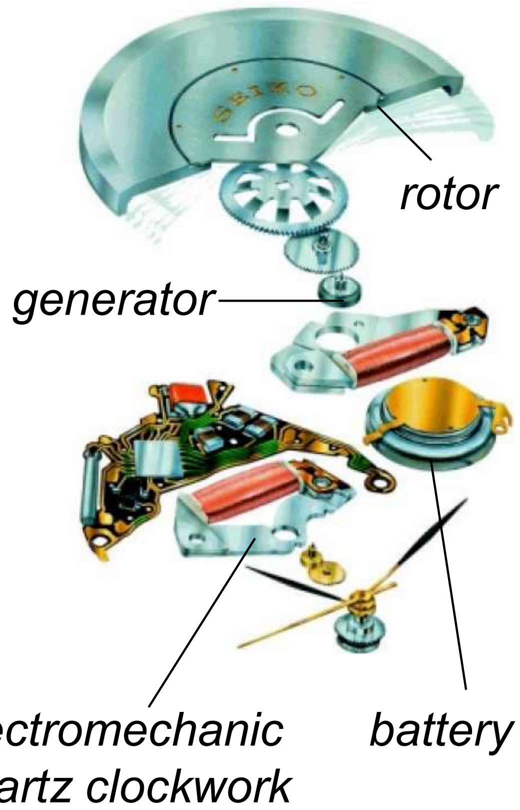


$$U = -N \cdot \frac{d\Phi}{dt}$$



***P* = 800 μW**

multi-resonant generator
Univ. Hongkong, 2002



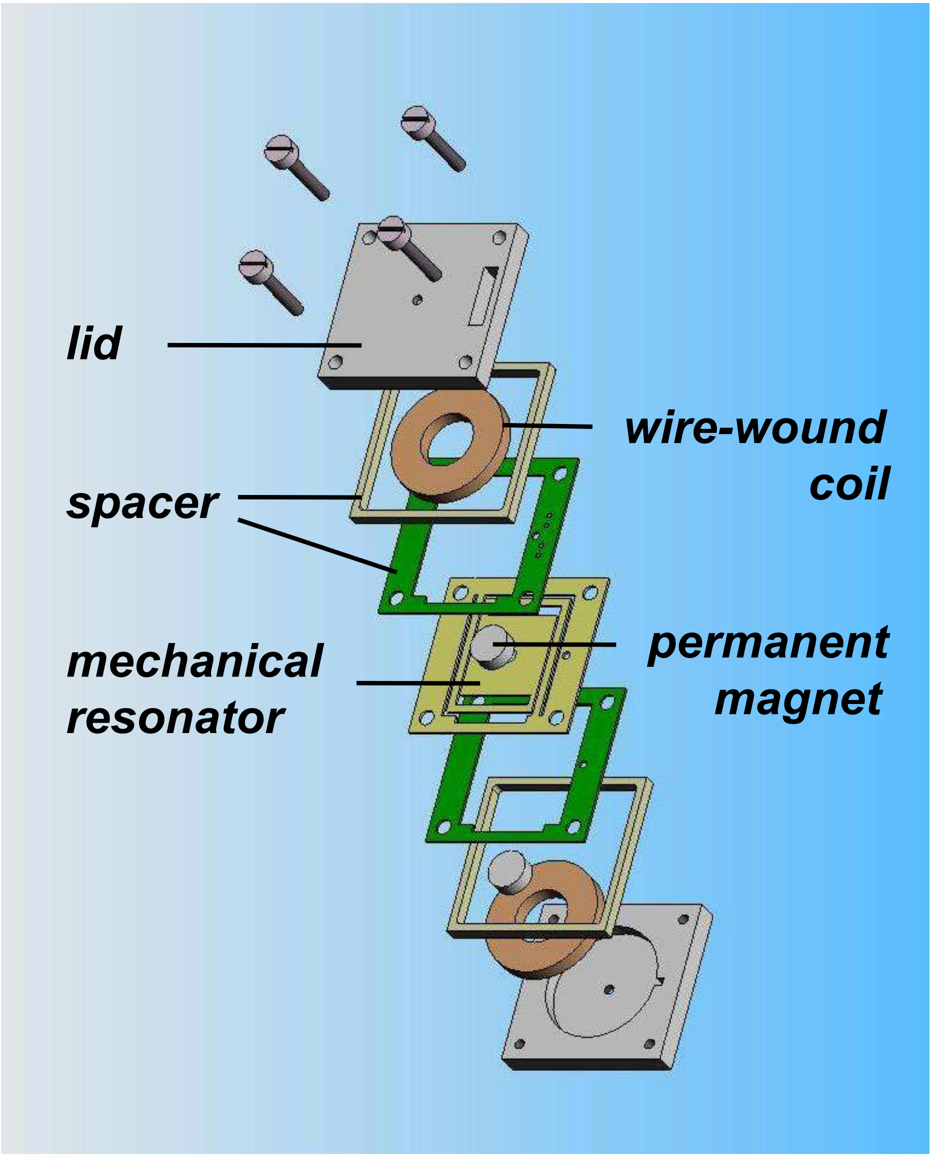
***P* = 5 μW**

rotatory generator of the
Seiko Kinetic™ wrist watch

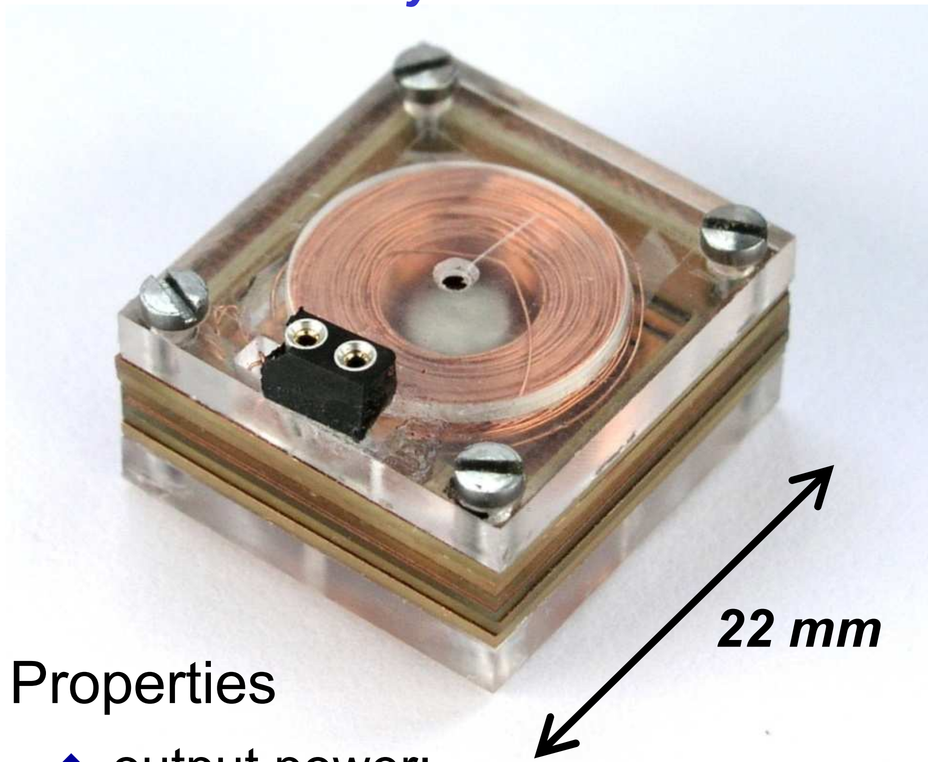
Properties

- AC currents from motion or induced AC fields
- bad to fair voltage range (mV…V)
- moderate source impedance (<10 kΩ)

Electromagnetic generator in PCB technology



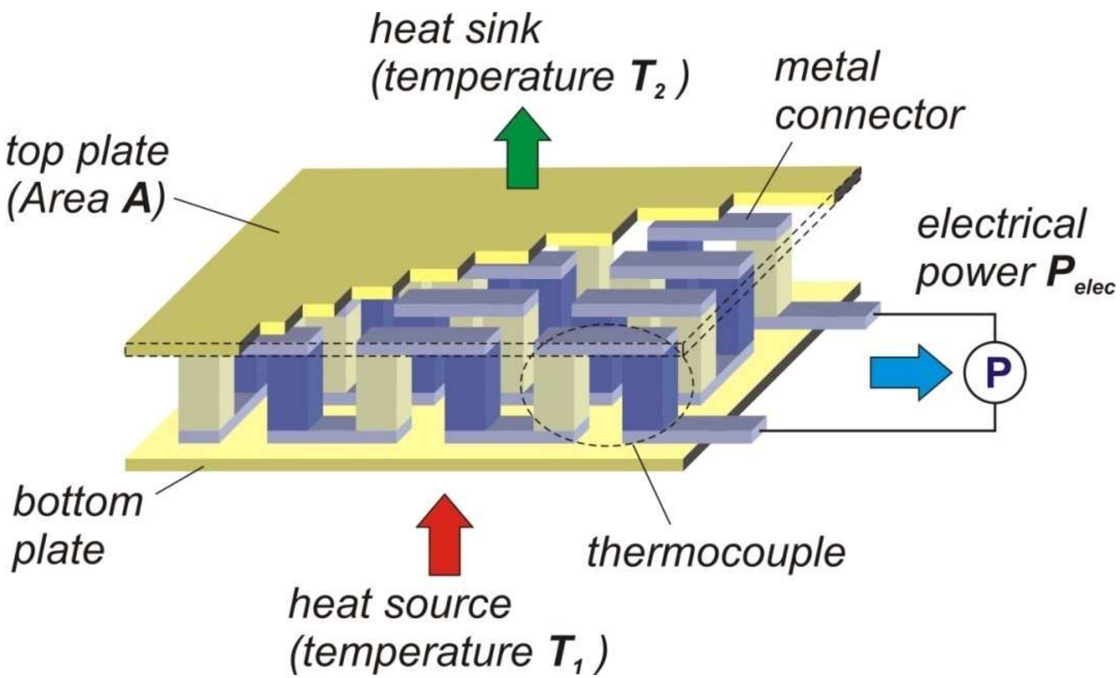
E. Bouendeu, J. Kovink,
IMTEK – Laboratory for Simulation



Properties

- output power:
  330 µW @ 102 Hz and 1G
- no-load voltage: 210 mV
  (improved via modified coil design)

Thermoelectric generators (TEG): Principle



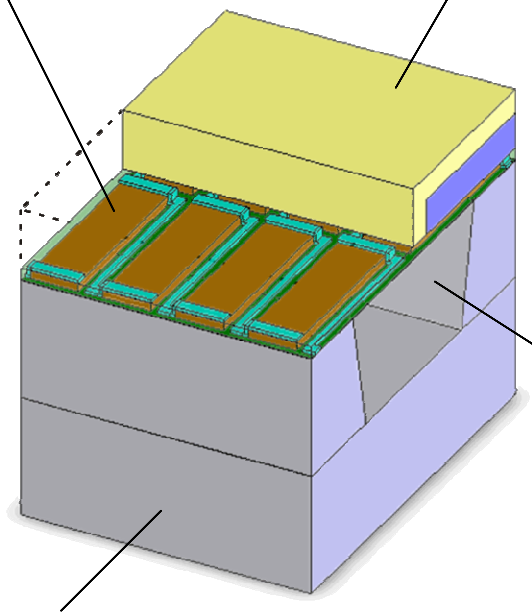
relevant material combinations	α [µV/K]
Al / p-Poly-Si	195
Al / n-Poly-Si	110
p-Poly-Si / n-Poly-Si	190...320
p-$Bi_{0,5}Sb_{1,5}Te_3$ / n-$Bi_{0,87}Sb_{0,13}$	200...420

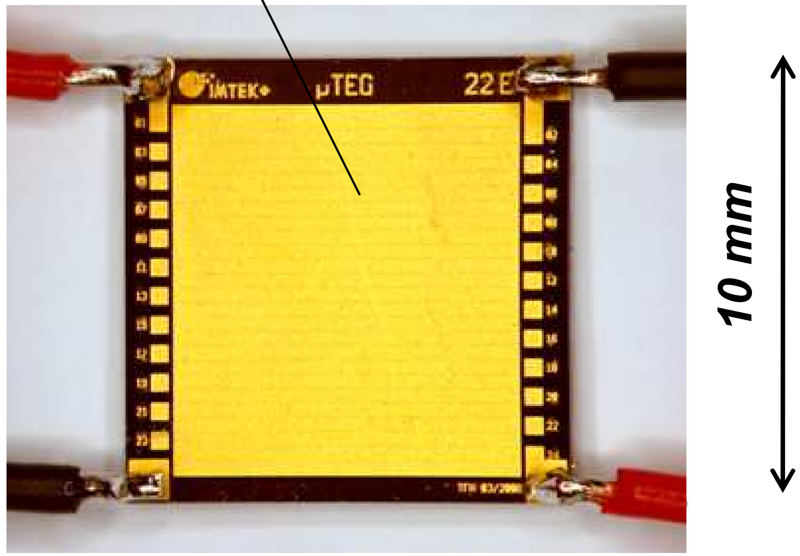
Seebeck voltage

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

Specific output power

$$p = \frac{P_{electric}}{A \cdot \Delta T^2}$$





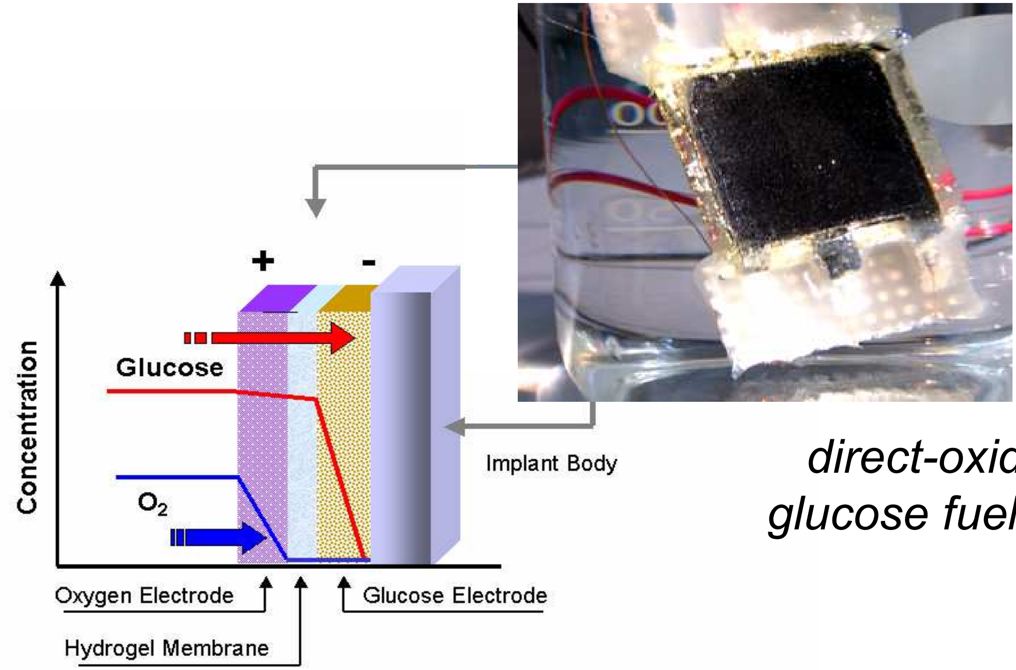
Output power and no-load voltage @ 10K

- measured: 1.612 μW
  6 V
- optimization potential: 36.3 μW

T. Huesgen *et al., Sensors & Actuators* A 145-146, 2008, 523-429.

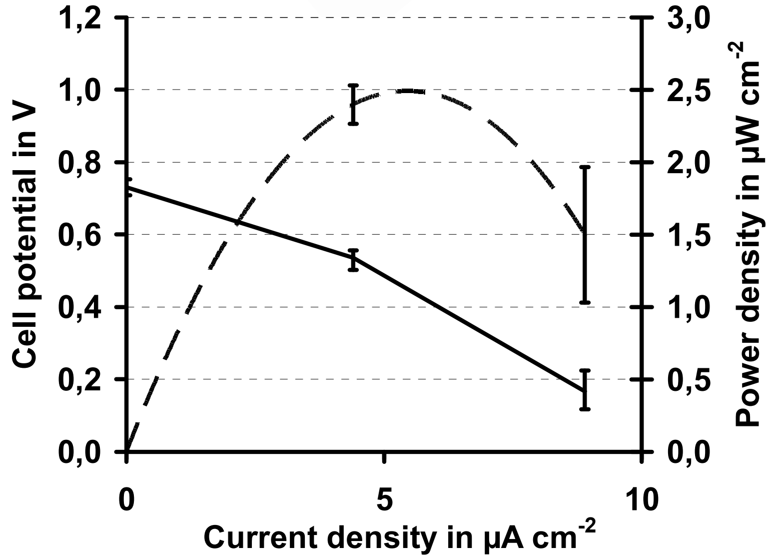
Bio fuel cells: Principle and application

IMTEK – Laboratory for MEMS Applications



direct-oxidizing glucose fuel cell

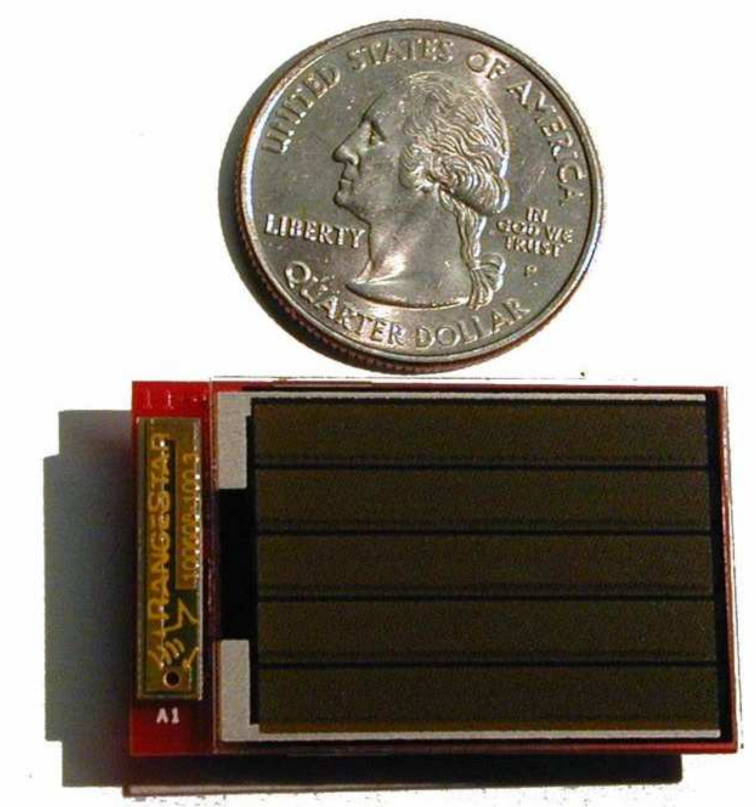
S. Kerzenmacher et al., Journ. Power Sources, 2008
A. Kloke et al., Proc. Biosensors 2008, Shanghai



Properties

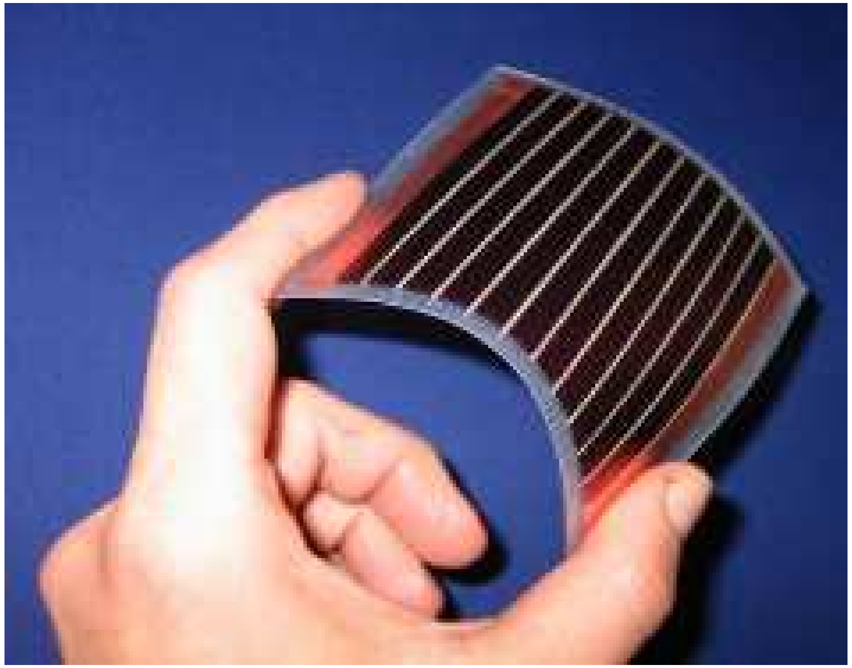
- output power: 2.3 … 3.3 µW /cm²
- open cell voltage: 0.5 … 0.3 V
- power requirement of a pacemaker: 10 µW

Photovoltaic generators



flexible Si thin film cell on a polymer carrier

© Flexcell



„Pico Beacon“ with rigid Si thin film cell on glass © UC Berkeley

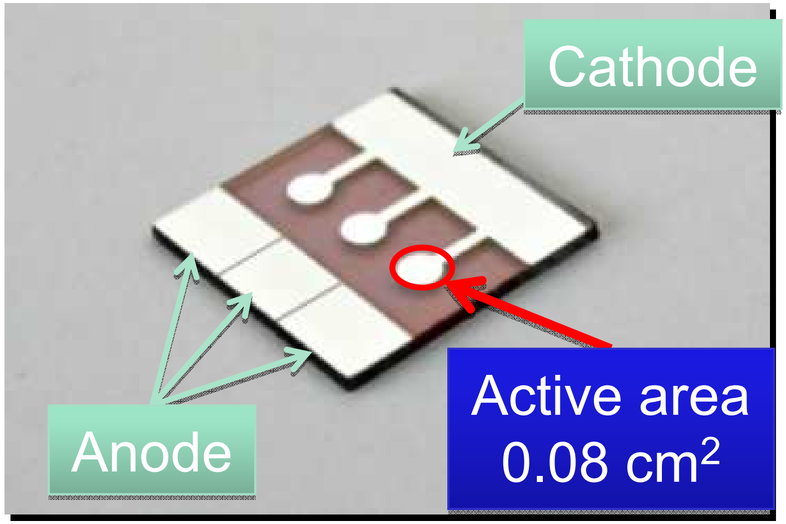
Properties

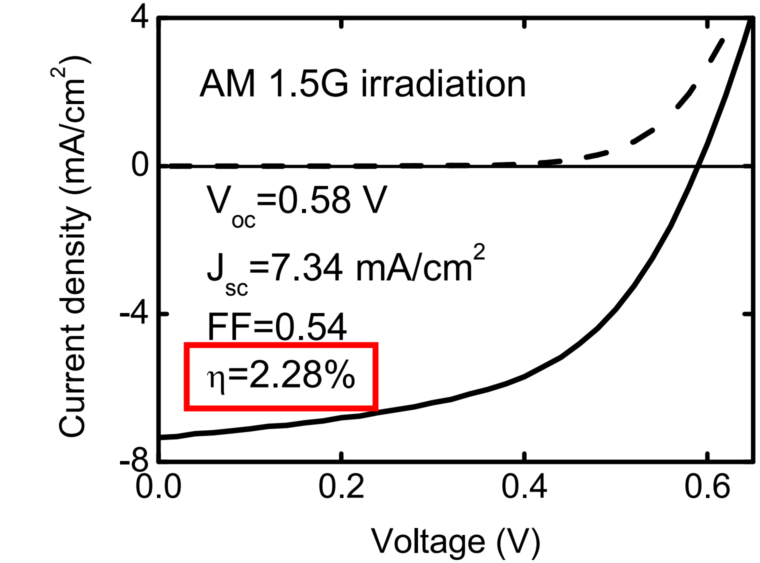
- delivers DC voltages
- thickness: 0.3...0.6 mm
- flexible and washable
- effiziency: 3%
- *sunlight:* $\approx$ *3.0 mW/cm²*
- *in-door:* $\approx$ *0.1 mW/cm²*

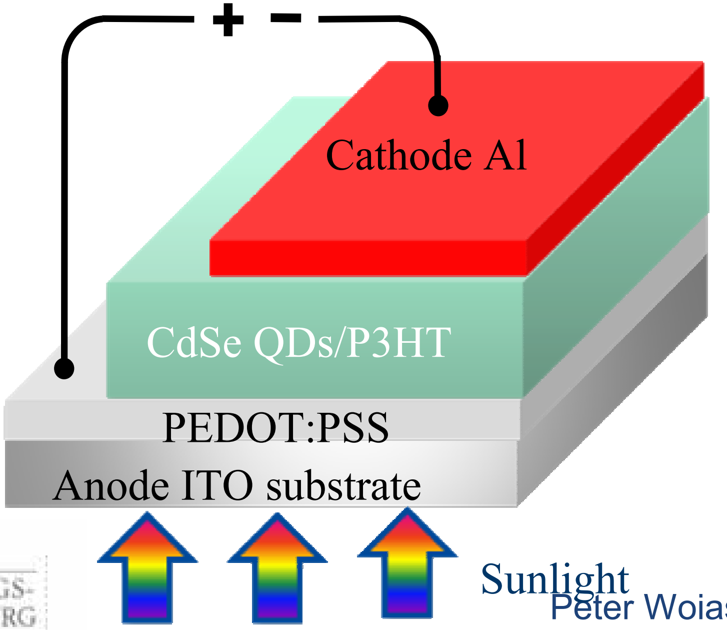
Polymer PV cells

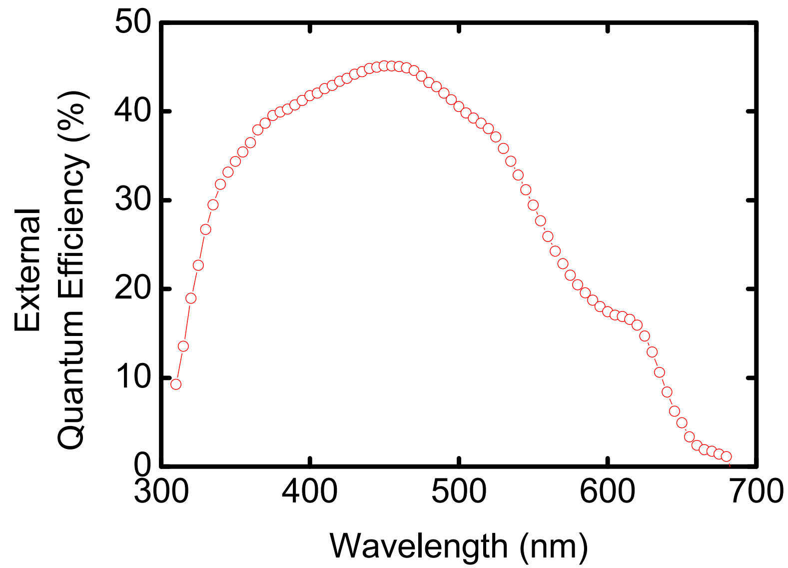
Y. Zhou, M. Krüger, G. Urban, IMTEK, Laboratory of Sensors and FMF

Summer 2009: Highest reported efficiency value* based on CdSe QDs!

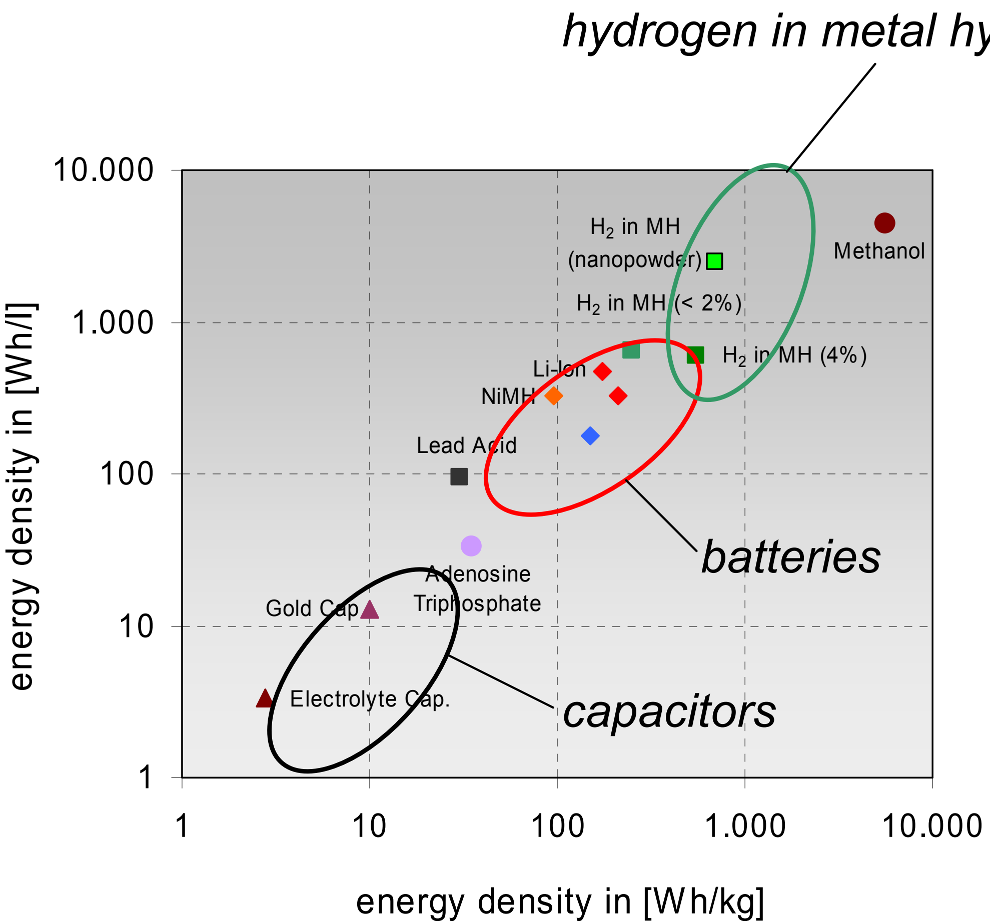


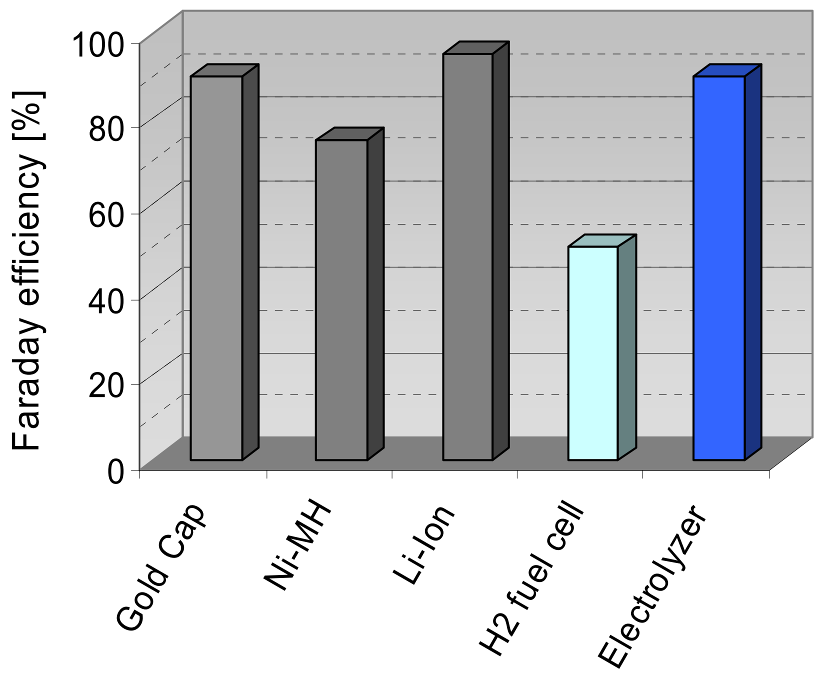






Energy densities of various storage concepts



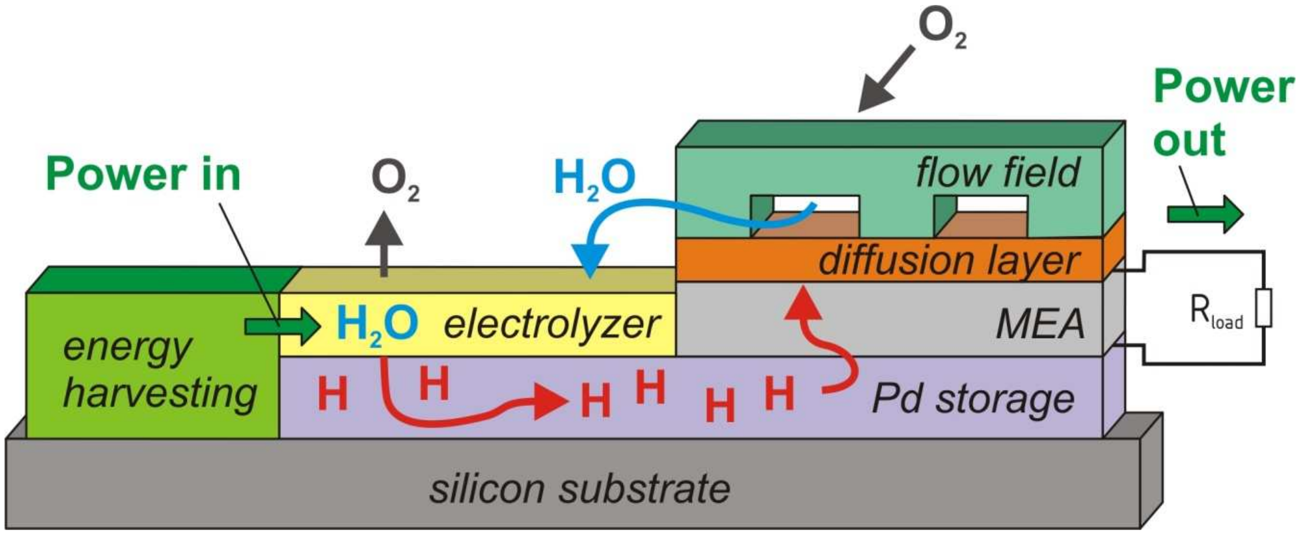


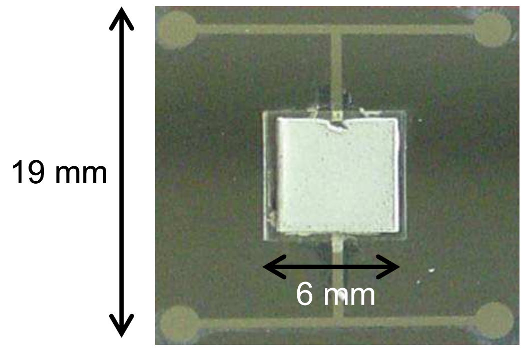
- high storage density of H_2 in MH
- acceptable (and improving) efficiency of H_2 fuel cells

➨ **Would a „hydrogen battery“ make sense ?**

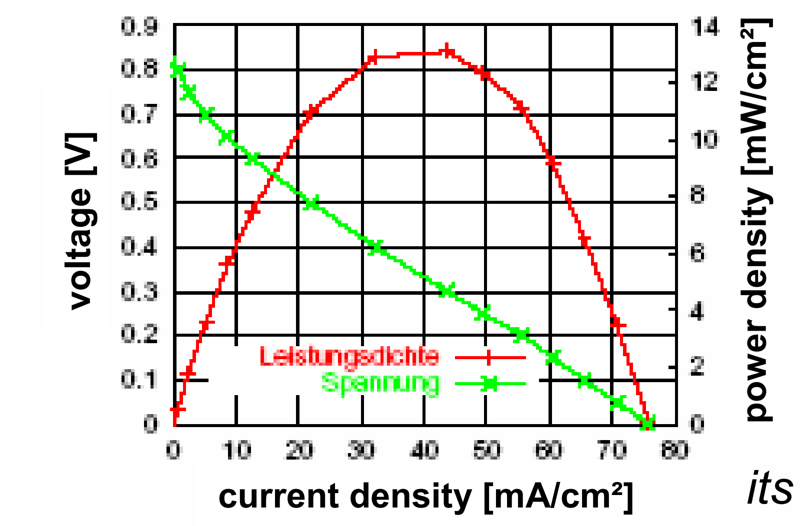
Refs: J. Brodd et al, J. Electrochem. Soc., 151 (3), 2004, K1-K11 and HERA Hydrogen Storage Solutions, Germany

Hydrogen-based energy storage

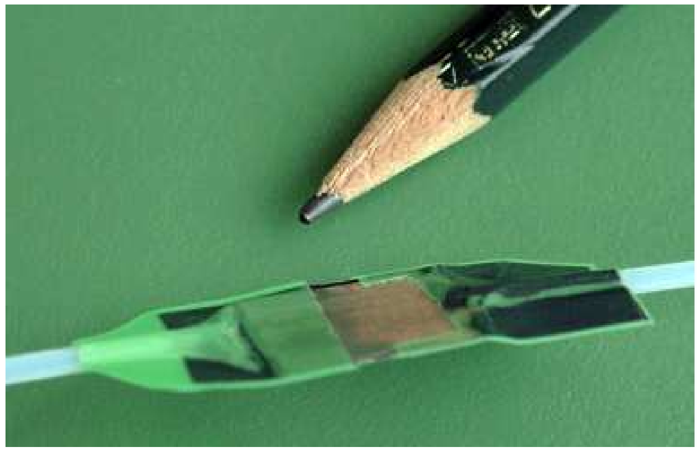




chip-integrated fuel cell with Pd storage



0.5 mm thick fuel cell: photograph (right) and its electrical characteristics



G. Erdler, M. Frank, M. Lehmann, H. Reinecke, C. Mueller, Sensors & Actuators A 132/1 (2006), 331-336.

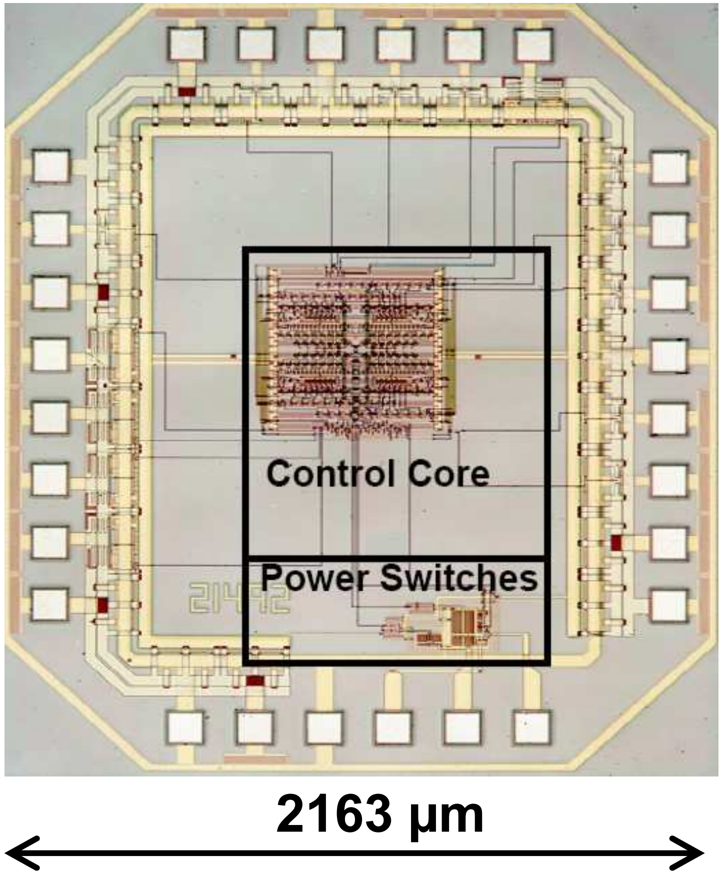
Energy management

Requirements

- start-up control
- optimal impedance match between generator, battery and load
- voltage level transformation
- active generator control
- active rectification
- supply voltage: < 1 V
- power consumption: a few µW

Solutions, microchips ?..... ~~not available today (2004).~~

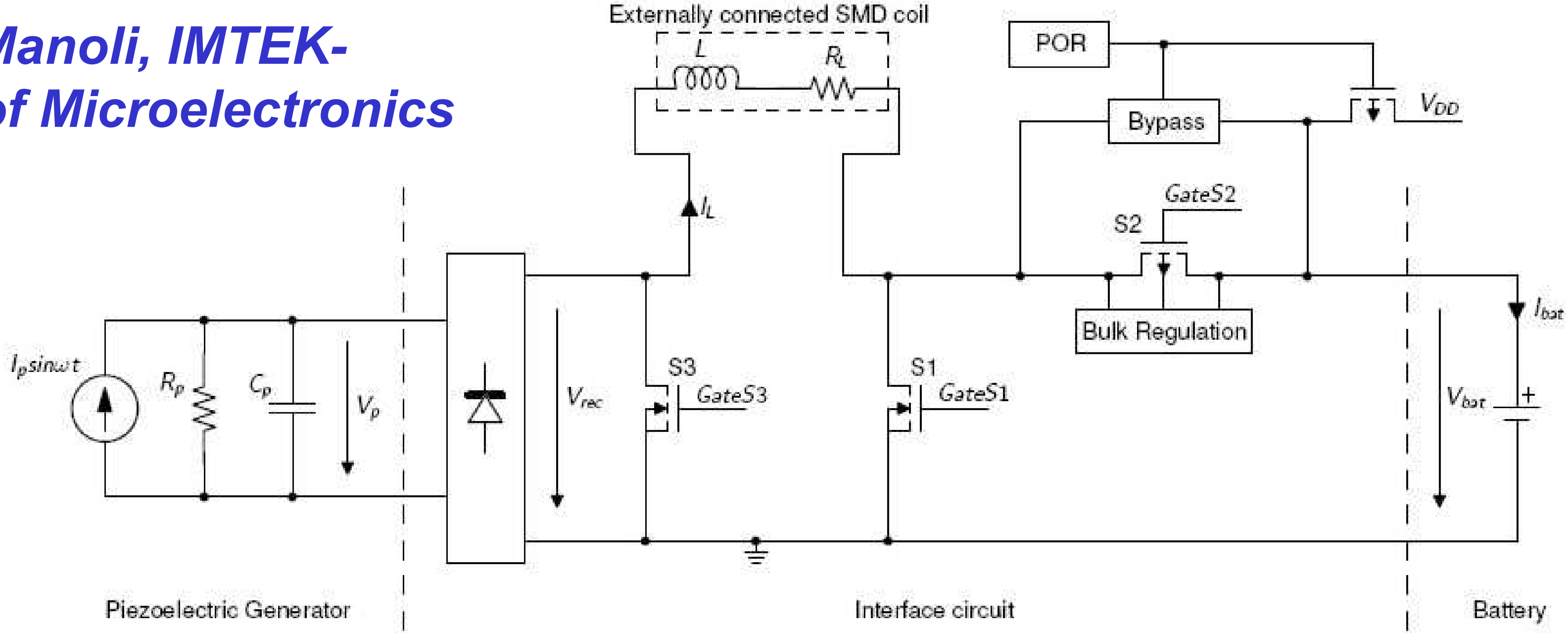
….eventually coming along (2007).

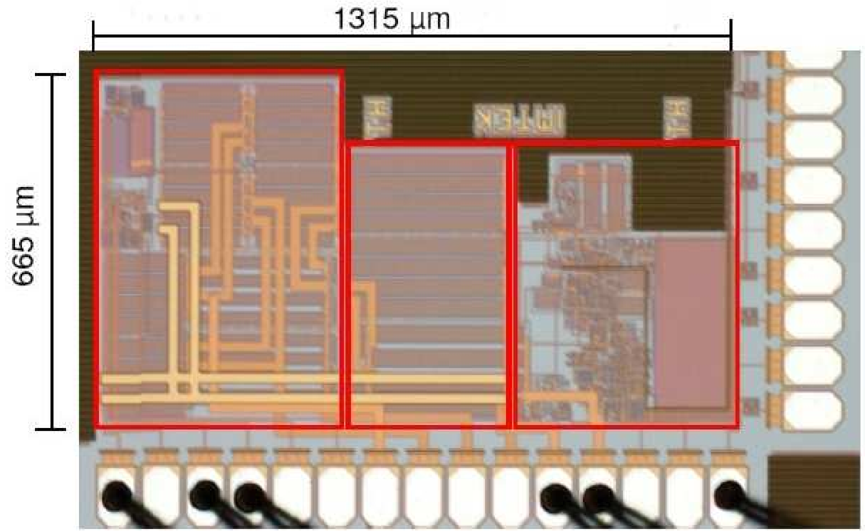


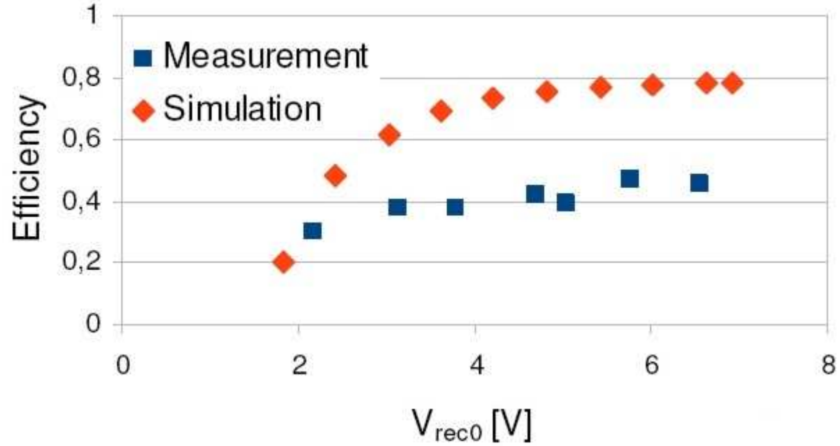
control ASIC for a capacitive micro converter, Medinger, Ph. D. thesis, MIT, and Analog Devices, 1999

Adaptive voltage converter for piezogenerators

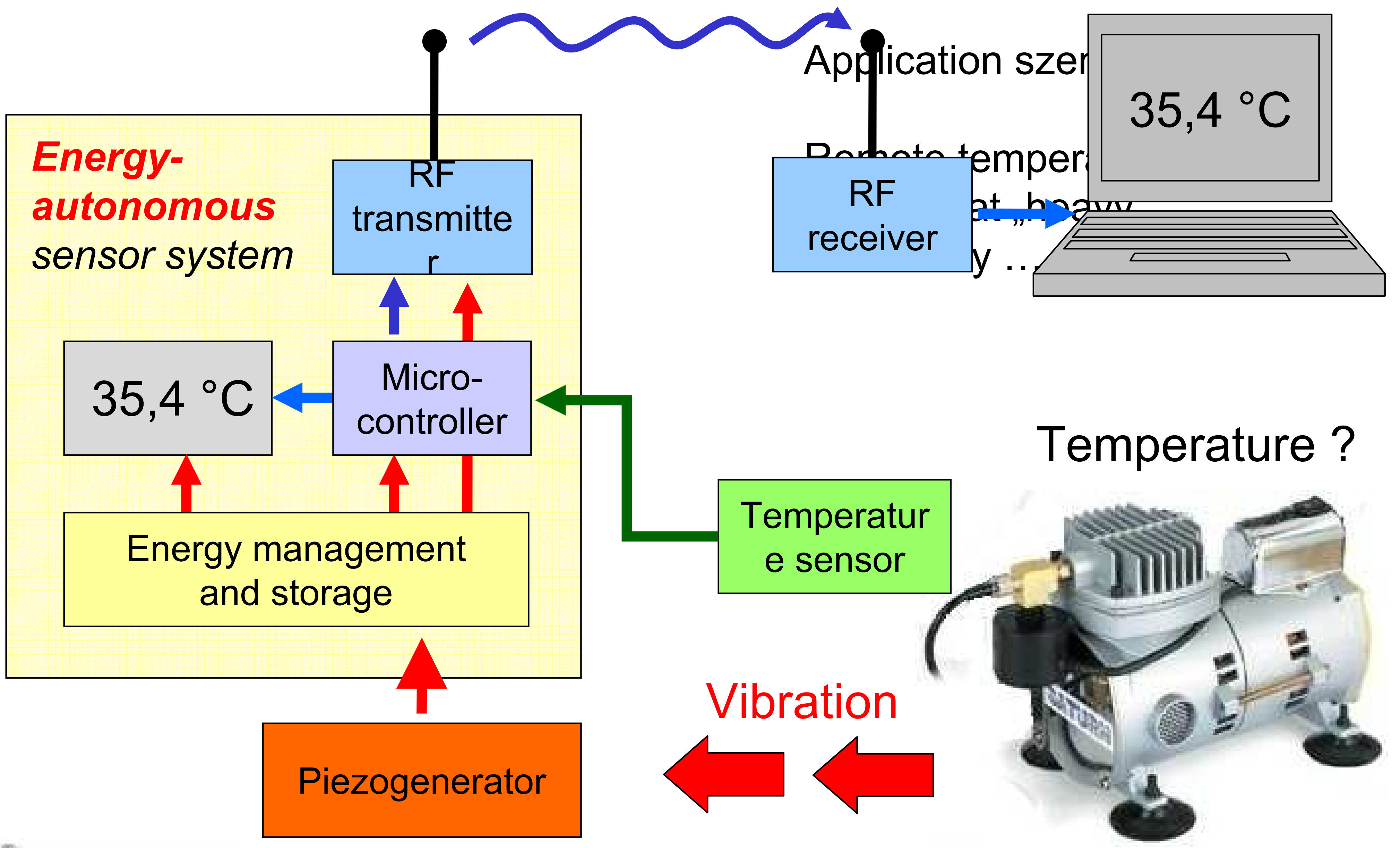
T. Hehn, Y. Manoli, IMTEK-
Laboratory of Microelectronics



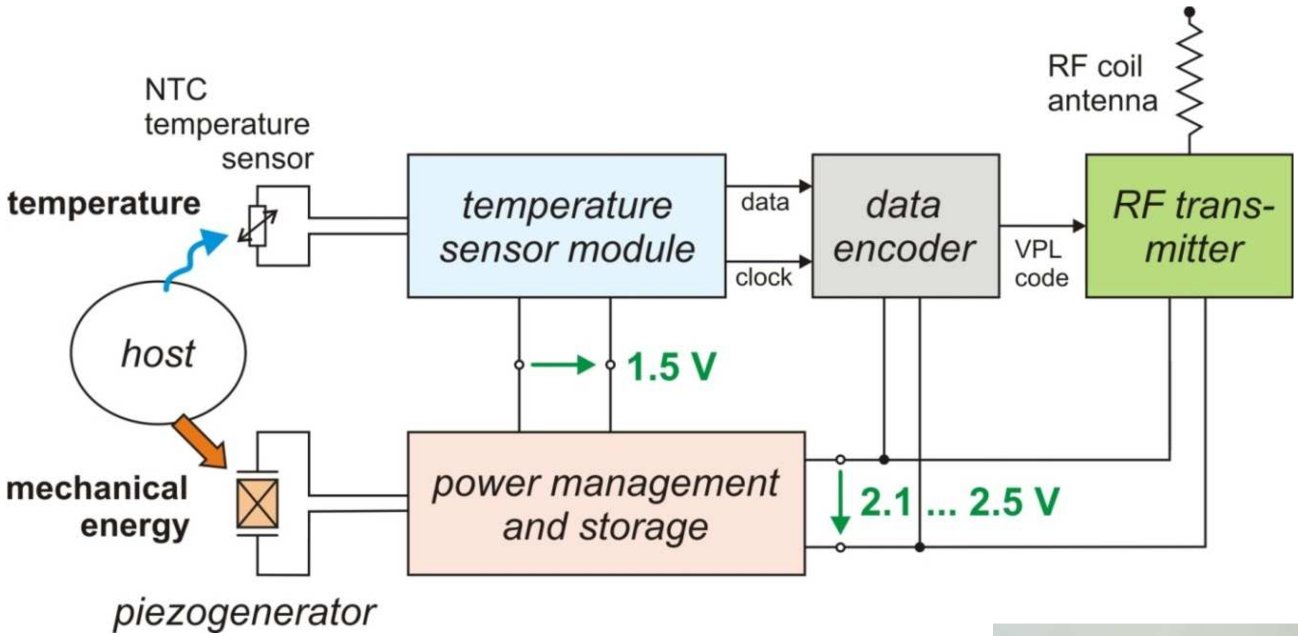




Demonstrator: Remote Temperature Monitoring



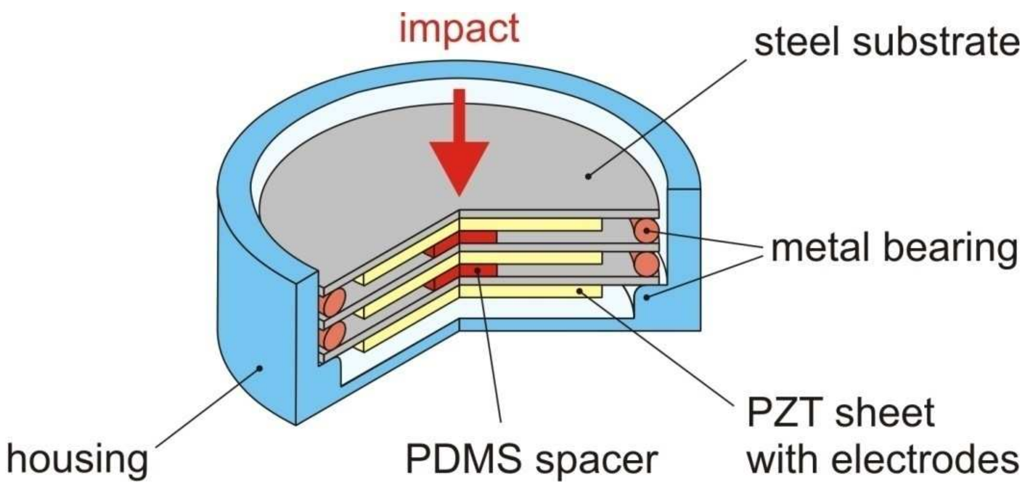
System set-up

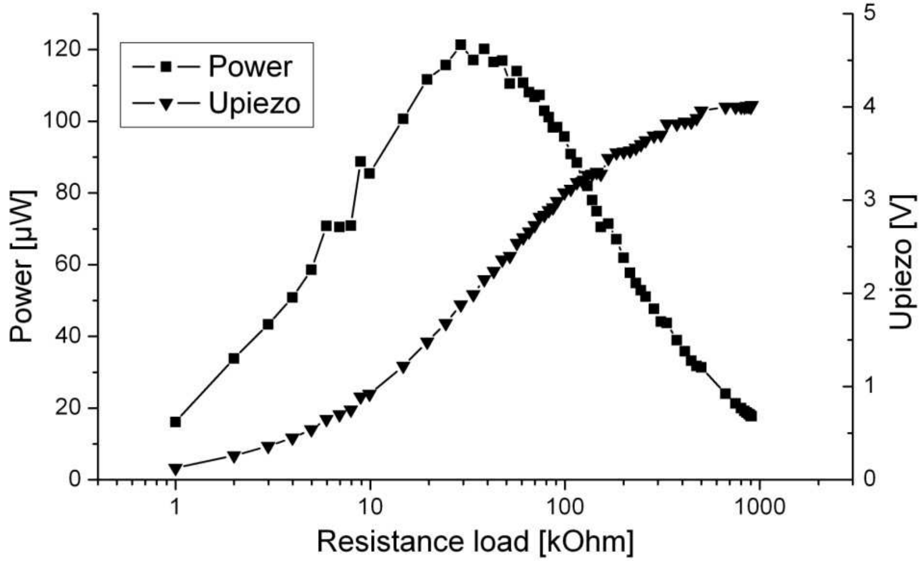


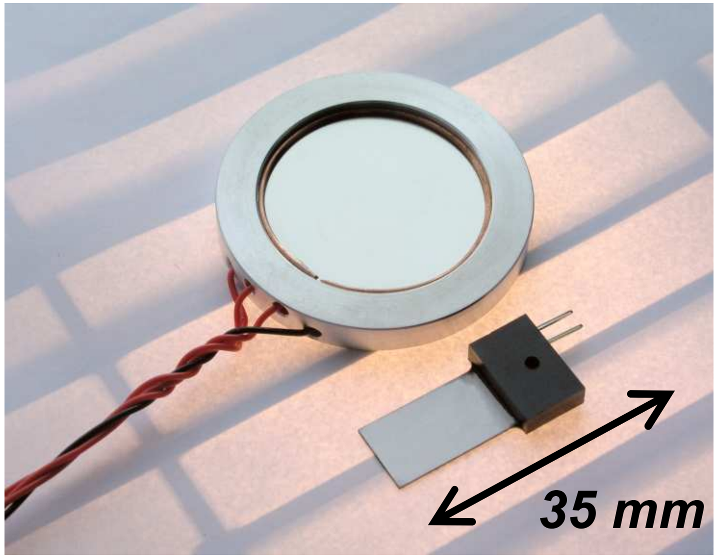
Requirements

- well-defined turn-on and turn-off
- low-voltage operation
- low-power operation

Stacked impact-type piezogenerator





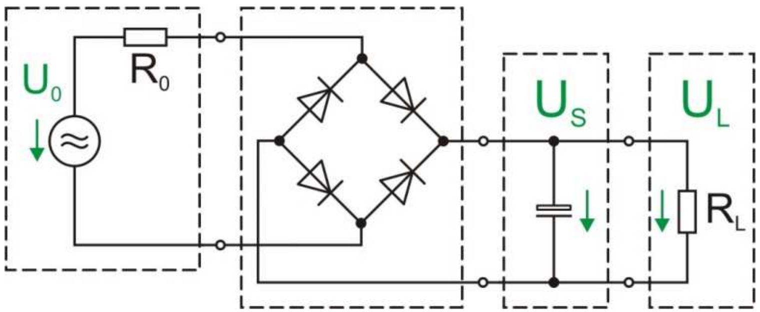


Technical data

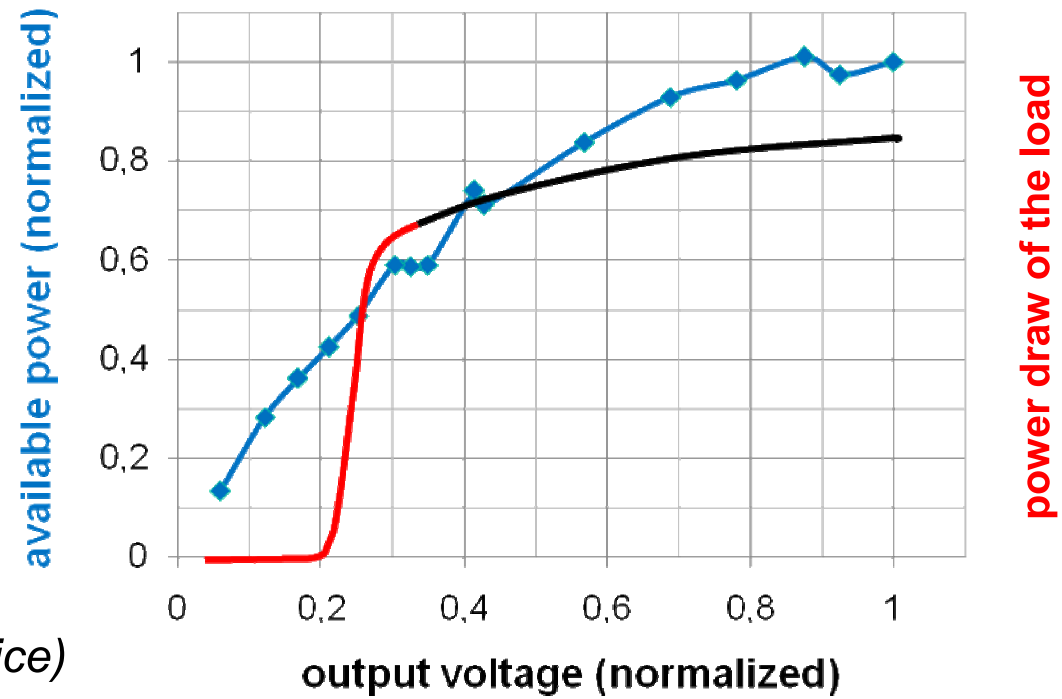
- maximum output power: 120 µW
- optimal output voltage: 2.15 V
- tolerance band: ± 0.2 V

Micro power management

A frequently used concept …



piezo-generator *storage* *load (CMOS device)*



… with inherent problems

- overall bad efficiency
- **no** safe start-up from zero power (danger of deadlock)

Solution: defined turn-on via power management

Why not buy … ?

Note 1. Exceeding the absolute maximum rating may damage the device.

Note 2. The device is not guaranteed to function outside its operating rating.

Note 3. Devices are ESD sensitive. Handling precautions recommended. Human body model, 1.5k in series with 100pF.

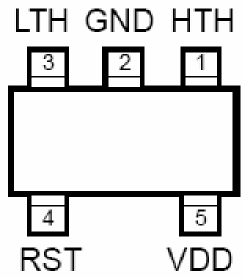
Note 4. V_{DD} operating range is 1.5V to 5.5V. Output is guaranteed to be held low down to V_{DD} = 1.2V.

MIC2779

Voltage Monitor with Adjustable Hysteresis

Features

- Optimized for PDAs, cellular telephones, pagers, and other battery-powered devices
- Independently adjustable high- and low-voltage thresholds
- Internal logic prevents battery-voltage-fluctuation chatter
- High ±2% voltage threshold accuracy; 1% available
- Built in 140ms (minimum) delay deglitches output
- Extremely low 1µA typical supply current
- For applications requiring open-drain output, see MIC2778/MIC833
- Immune to brief power supply transients
- 5-pin SOT-23 package

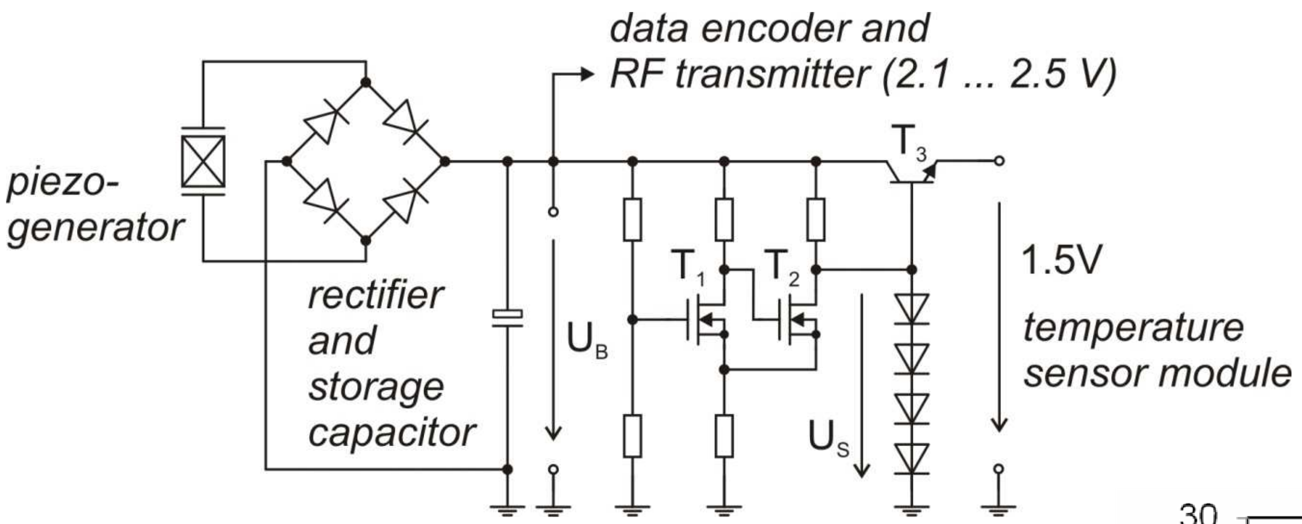


SOT-23-5 (M5)
“H” Version

Problems with today‘s ICs

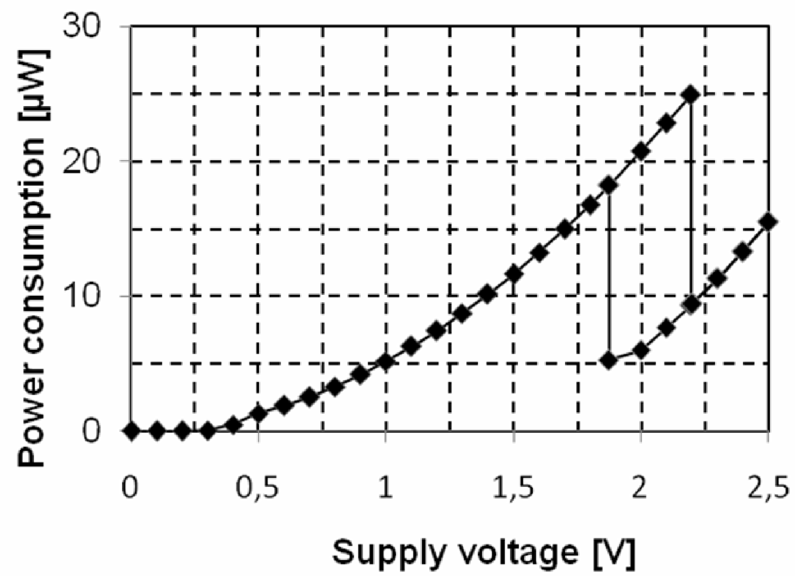
- no „real low voltage“
- undefined sub-threshold behaviour
- limited functionality (not specific for energy harvesting)

Low-voltage regulator with sharp turn-on



Characteristics

- **mimimum transistor count (3)**
- **safe-operation** supply voltage: 0.4 V ☺
- max. power consumption: 25 µW ☹
- optimization potential: 1…3 µW ☺



Demonstration

Conclusions

Embedded systems are an essential part of our current and future living.

Their power supply can not be done by batteries and power grids alone.

➡ **We will depend on Energy Harvesting.**

However, its successful application will require an optimum interplay of …

- ➡ energy conversion
- ➡ energy storage
- ➡ energy management
- ➡ system hardware and operation

… i.e. a thorough and application-specific **system design**.

Thank you very much for your attention !