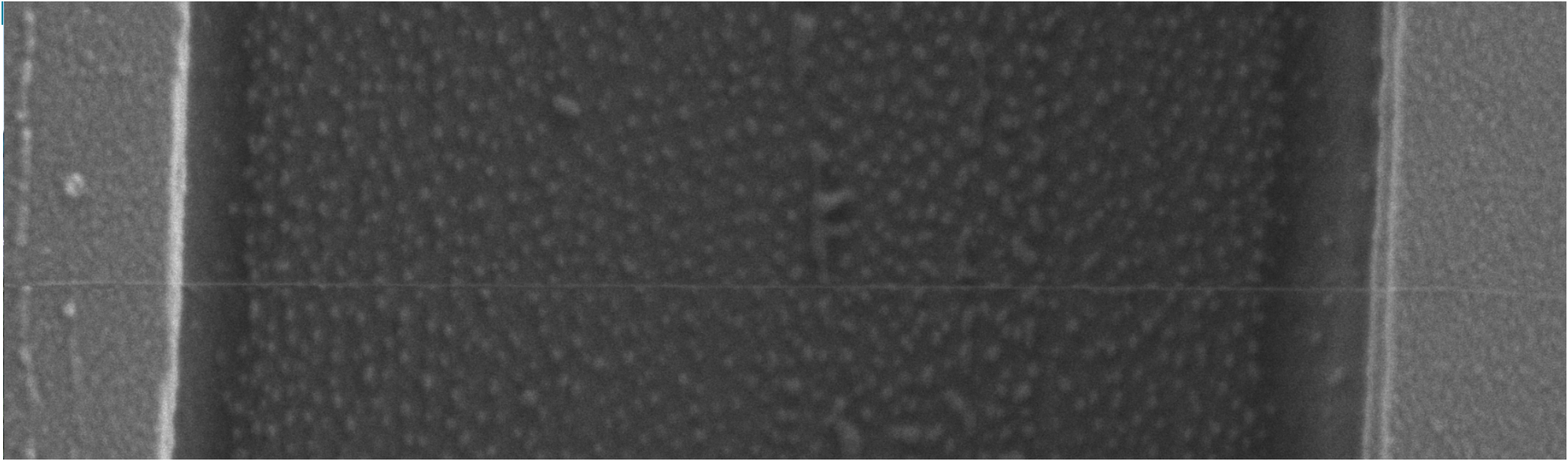
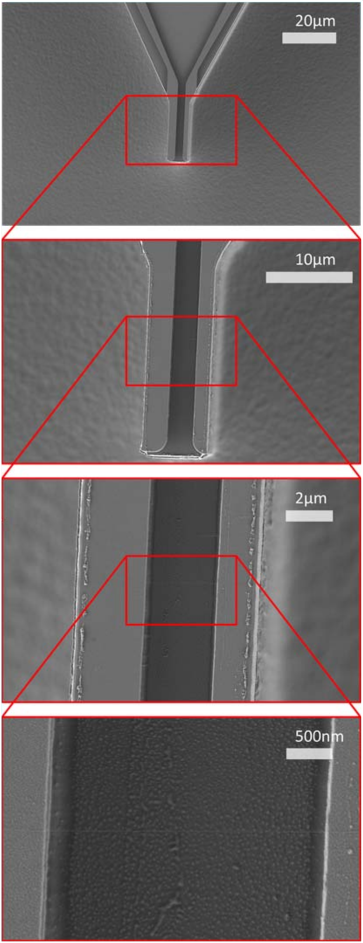




Integrated SWNT by Sebastian Eberle

Low power transducers for the IoT

Cosmin Roman
ETH Zurich

Wireless Sensor Node

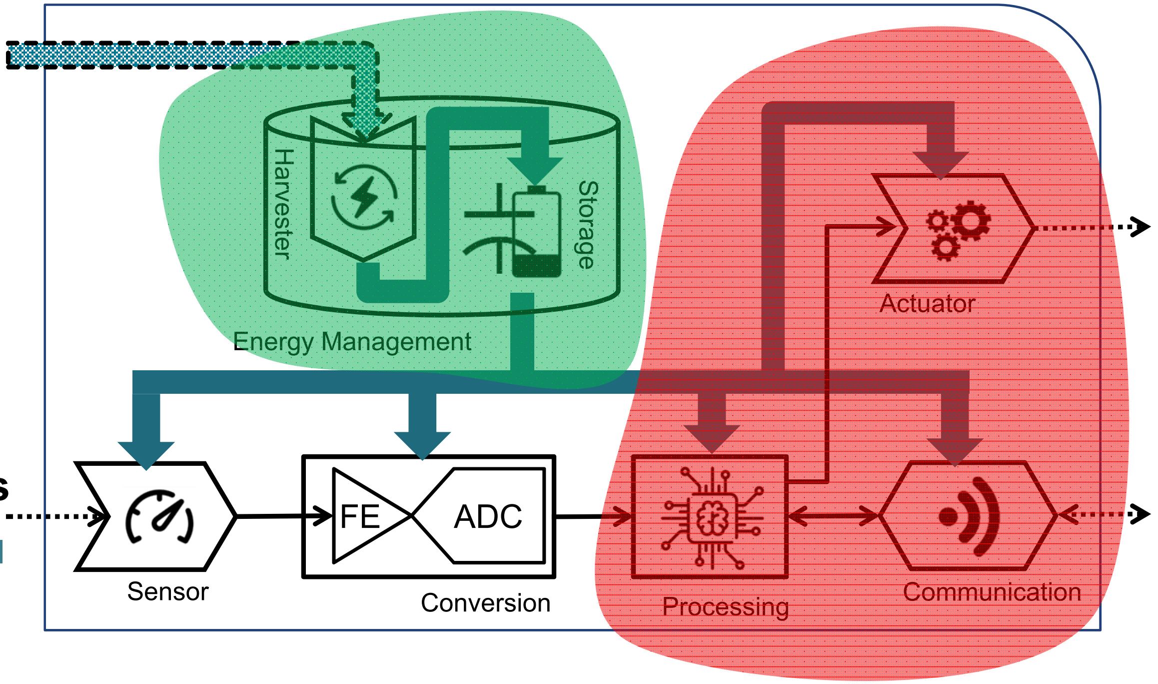
Energy Transducers

physical → electrical energy
e.g. photovoltaics,
thermoelectric,
tribo, piezo, inertia

Information Transducers

physical → electr(on)ical signal
e.g. inertia, pressure,
temperature, chemical, optical…)

Wireless Sensor Node



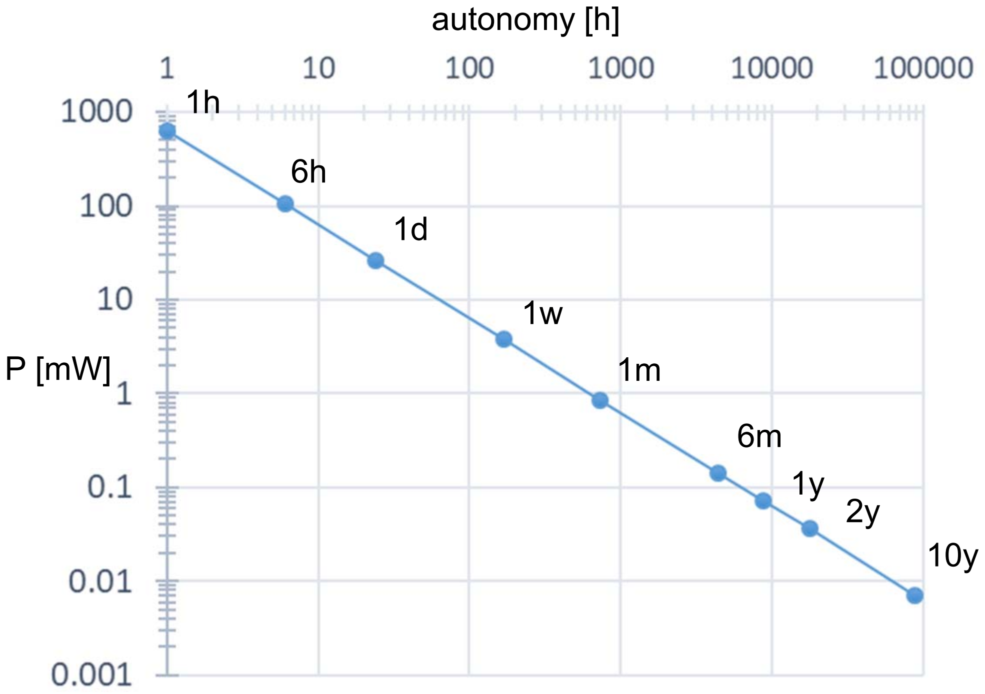
Communication, actuation and signal processing are significant power consumers

Domain *Pathway*	Electr(on)ical	Physical/Chemical External
Information	⟶	⇢
Energy	➡	⇨

Net power left for sensing =
+ Supplied power
- Processing and transmission power

Energy Budget

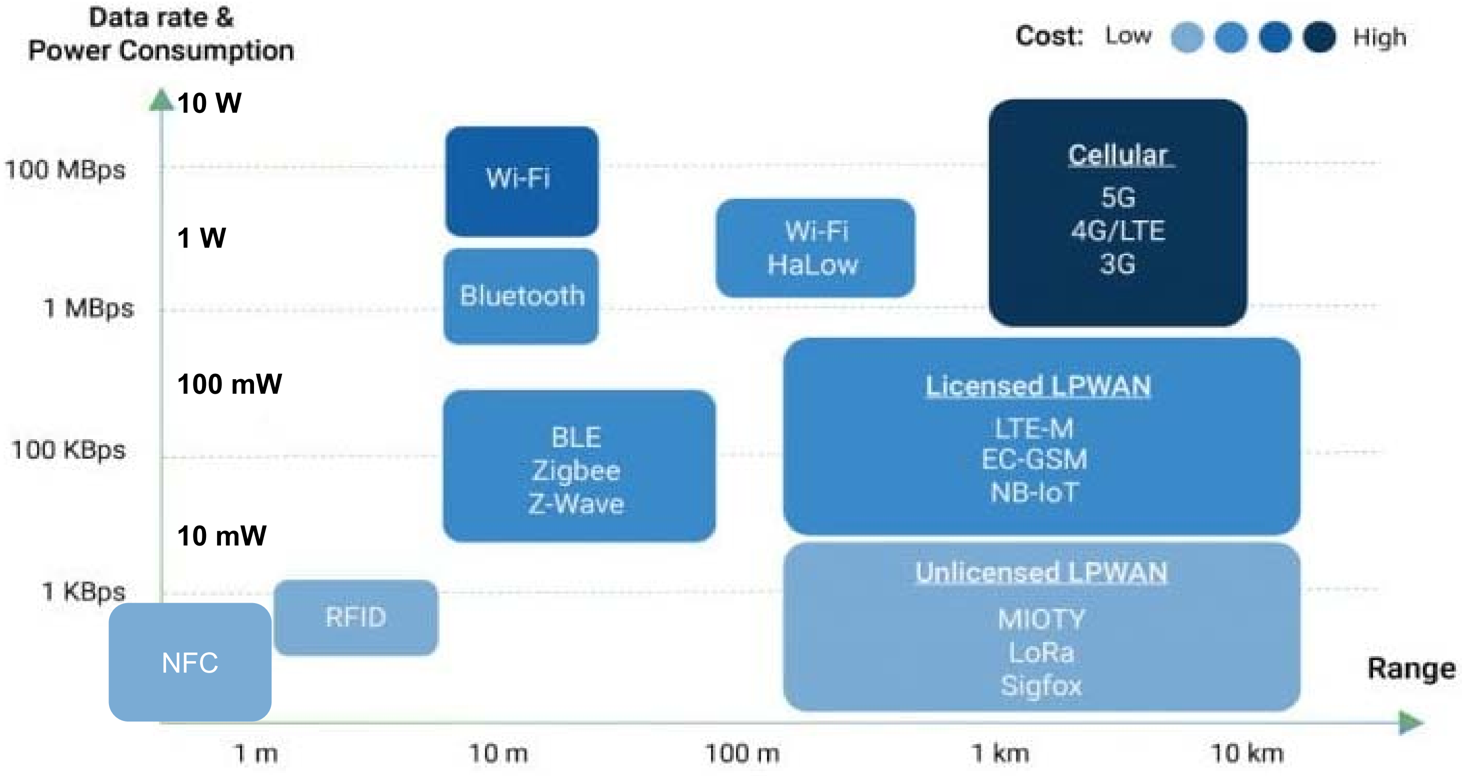
- A common CR2032 button cell (210mAh, 3V) stores 630mWh of energy
- The desired sensor node autonomy determines the average power budget



- With 1mW average power consumption, the autonomy cannot exceed 1month
- For an autonomy exceeding 1year the available budget is <100µW
- To reach 10years of autonomy, one needs to limit the average power consumption to <10µW

- The shelf-life (which considers the low self-discharge rate) of CR2032 is 10years

Wireless Communication Cost

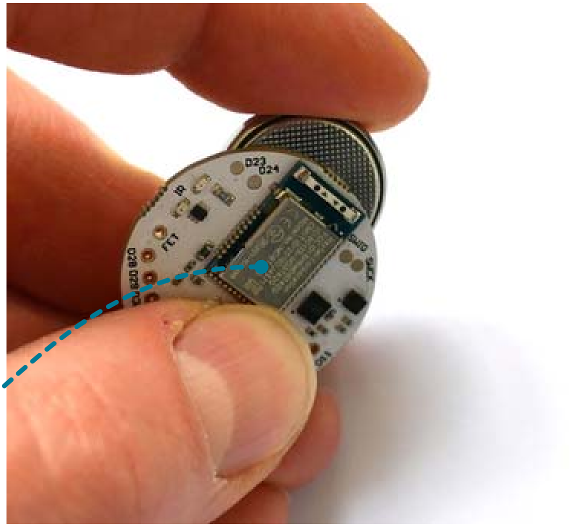


source: http://industrytoday.com/article/best-uses-of-wireless-iot-communication-technology/

- Speed (data rate) and distance (transmission range) are the two main factors determining power consumption for wireless communication
- At 100mW, using BLE, the autonomy of a sensor based on CR2032 is limited to 6h
- However, if the sensor bandwidth is 1kbps only, duty-cycling at 1‰, will extend autonomy to ~9mths

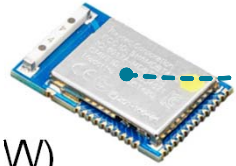
Example BLE sensor node

- Puck.js is a 20g programmable Bluetooth sensor powered by CR2032, offering:
  - Bluetooth Low Energy (nRF52832 SoC)
  - NFC programmable tag
  - IR Transmitter
  - Sensors: thermometer (PCT2075TP), magnetometer (LIS3MDLTR), inertial (incl. gyro) (LSM6DS3TR-C), light and battery level sensors, plus pin capable of capacitive sensing



http://www.espruino.com/Puck.js

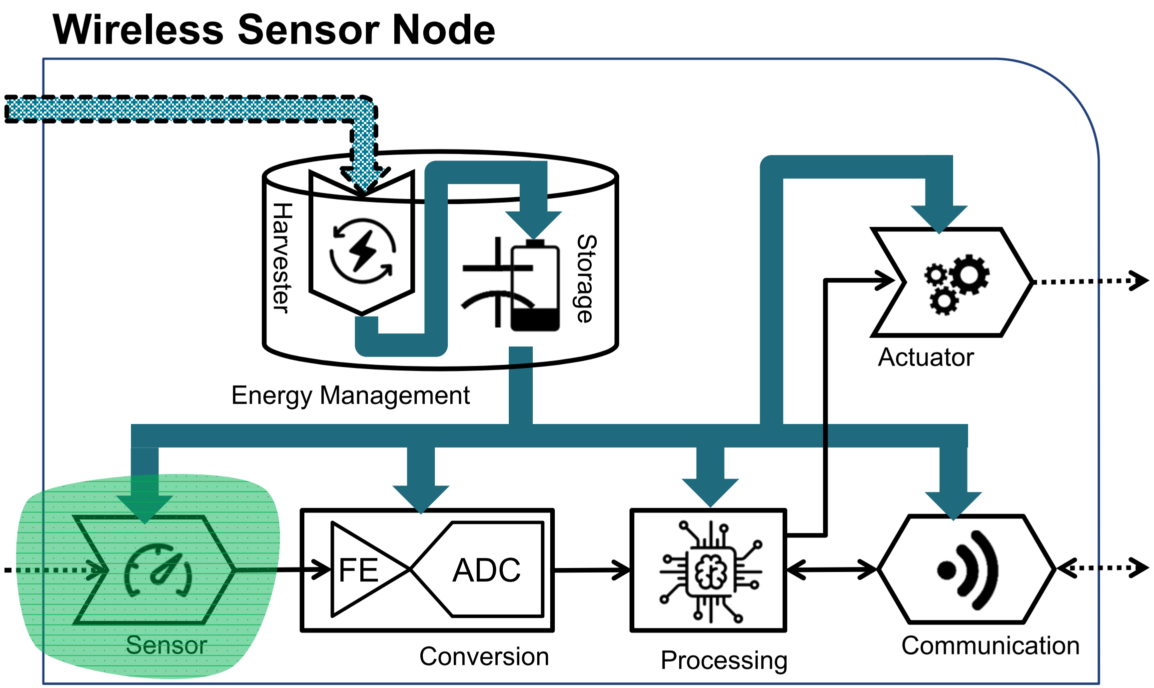
- The core is the nRF52832 SoC, that can send 2Mbps with 15.2mA (45.6mW) (for 1kbps projected power consumption 22.8μW)



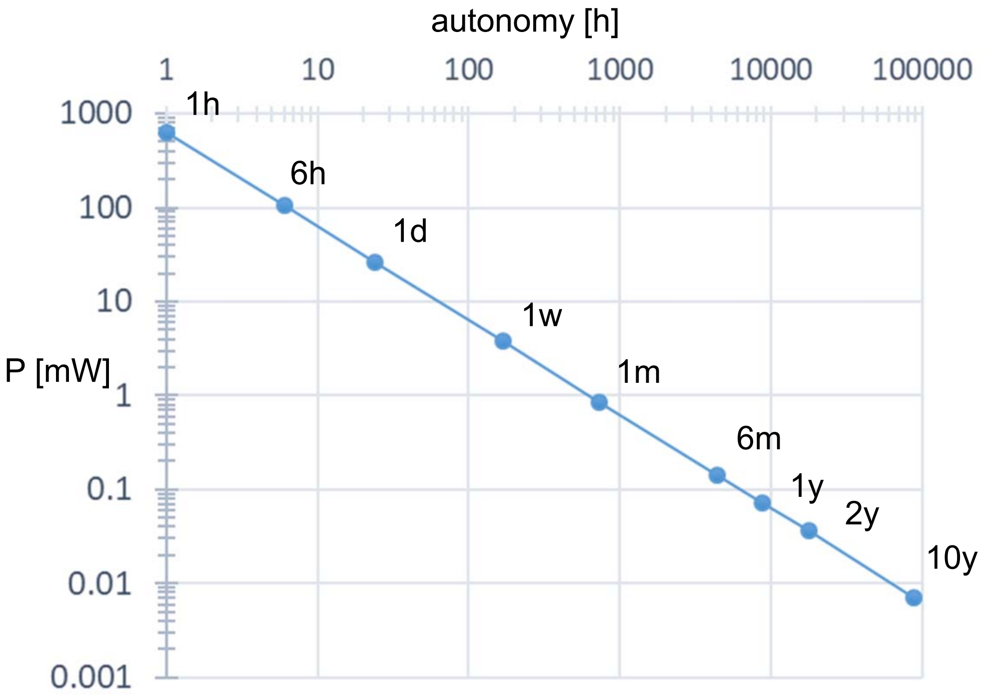
- The gyroscope is the LSM6DS3TR, which consumes 0.65mA (2mW) at 1.6kHz data rate (gyros are much more power hungry than BLE!)

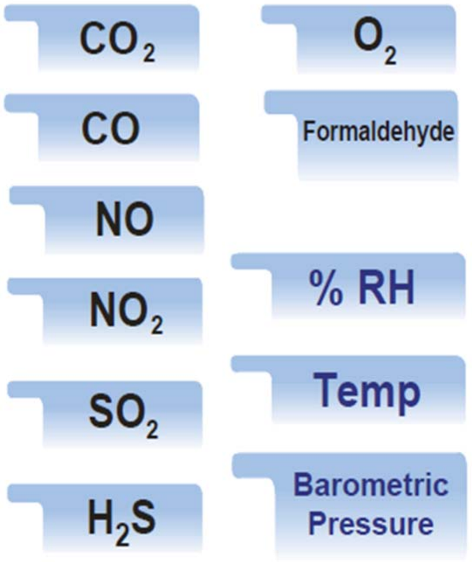
With duty-cycling, Puck.js can reach >1yr battery life!

Ultra-Low Power Sensors



Example Calculation for ULP Sensor Power Budget



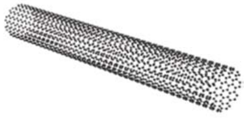


- For a battery lifetime of ~1yr the power budget is 100µW
- Because the data rate can be reduced to 0.1kbps, BLE would need ~2µW

- **The power budget appears to be: 10µW per (gas) sensor function!**

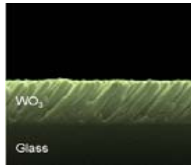
Motivation: Lowering Power Consumption

CNTs



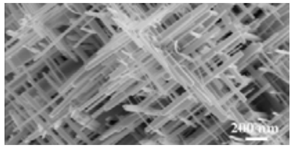
Self-heated nanowires

Prades et al., APL 2008

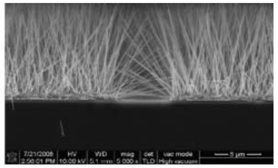


Moon et al., Sci Rep 2012

Nanostructures

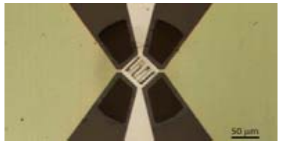


Ponzoni et al., APL 2006

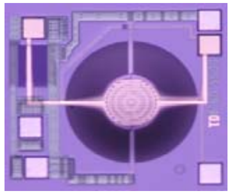


Ahn et al., SNB 2009

Microheaters



Courbat et al., JMM 2012



Cambridge CMOS Sensors, 2008

Commercial MOX sensors

e2v tech

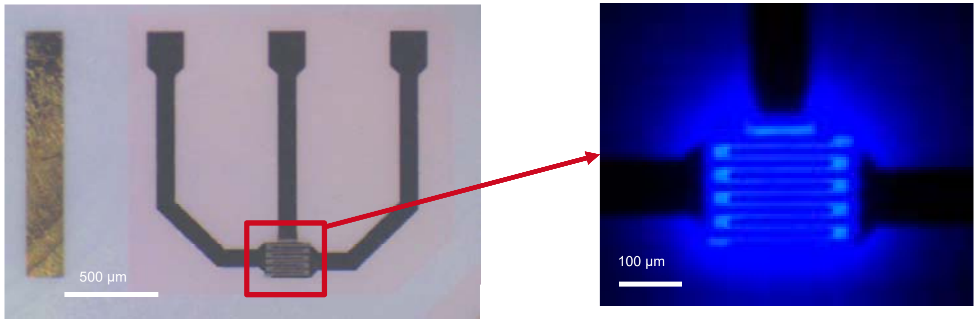
intlsensor.com

1 µW 10 µW 100 µW 1 mW 10 mW 100 mW

Operating power

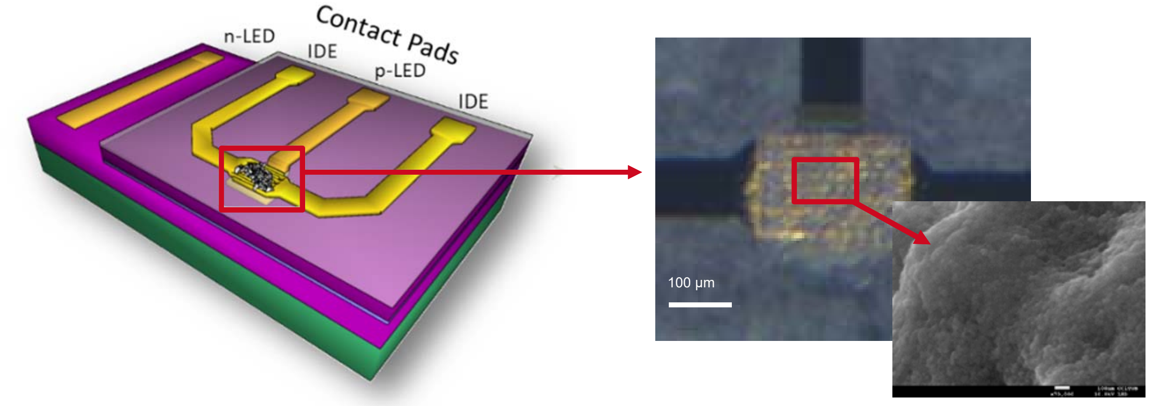
Ultra-low-power Gas Sensors Based on Nanostructures

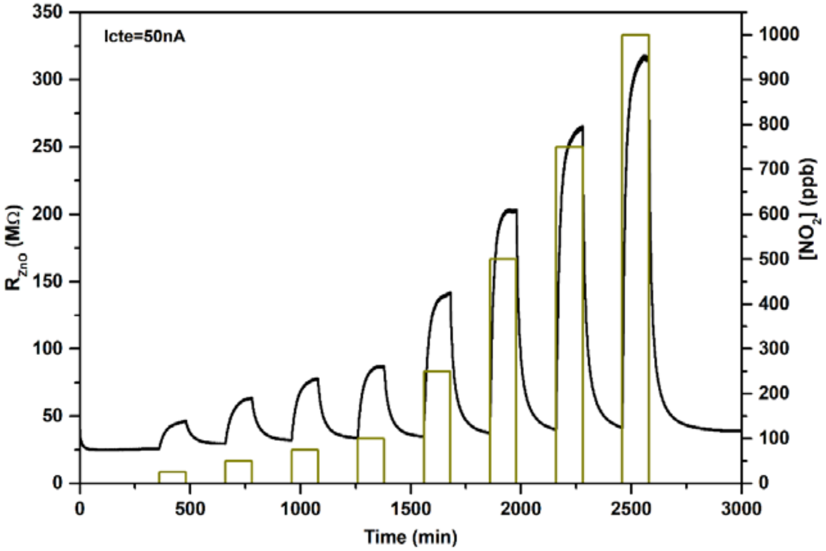
A ppb Sensor for NO_2 with µW Power Requirements Based on Micro Light Plates



UNIVERSITAT DE BARCELONA

ZnO nanoparticles $\phi \leq 130$ nm on IDE and InGaN μLP



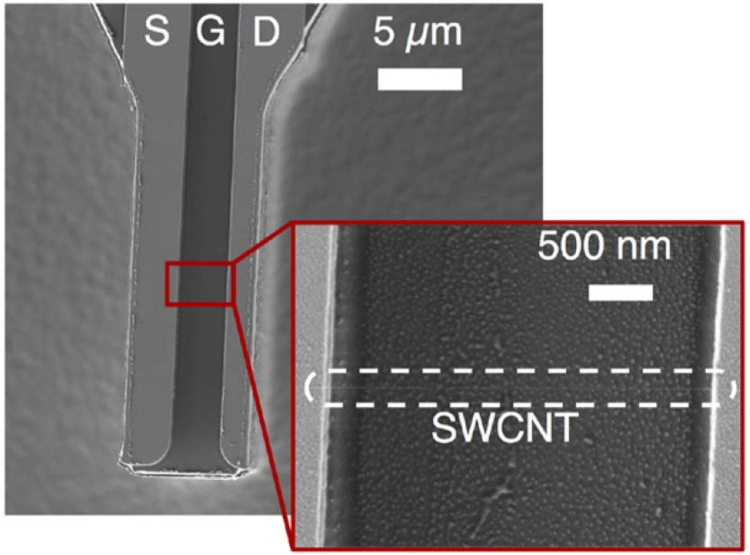


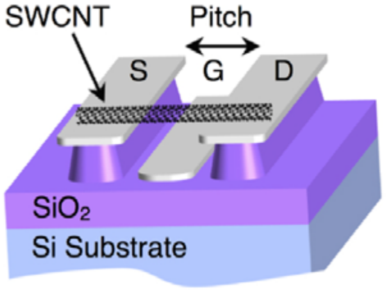
- **Limit of Detection 1 ppb NO_2 @ 200 μW**
- **Limit of Detection a few ppb NO_2 @ 30 μW**

O. Casals *et al. D. Prades* , ACS Sens., 2019, DOI: 10.1021/acssensors.9b00150
N. Markiewicz, et. al., D. Prades, Appl. Phys. Lett. 114, 053508, 2019, DOI: 10.1063/1.5078497

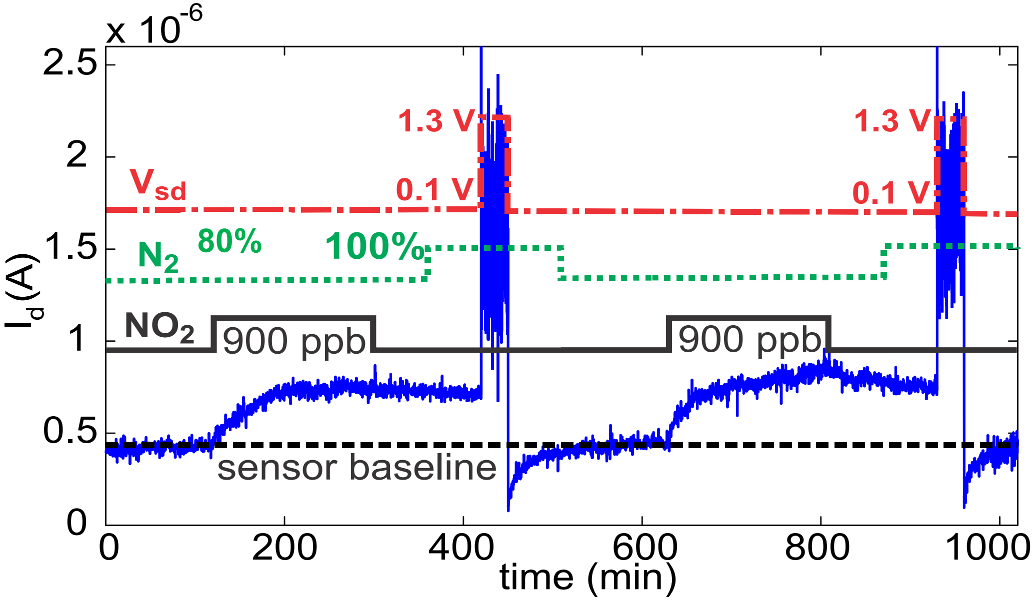
Ultra-low-power Gas Sensors Based on Nanostructures

Ultra-low power operation of self-heated, suspended carbon nanotube gas sensors





- Operating power: < 1 μW
- Resolution: < 50 ppb
- Ultra-low power recovery by self-heating possible: 2.9 μW

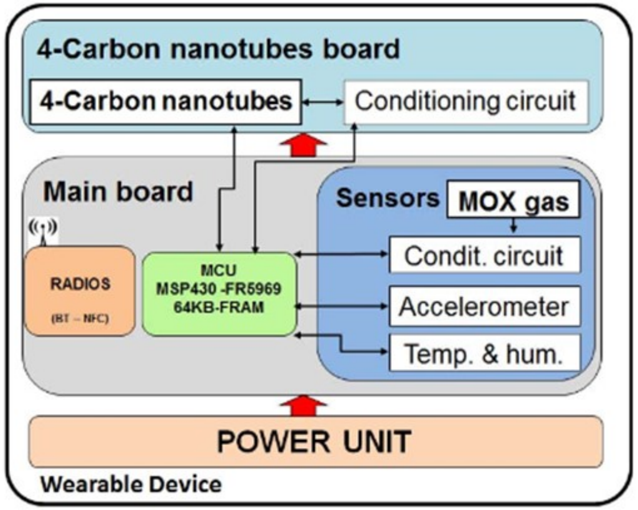


P.F. Satterthwaite et. al, C. Hierold, Sensors & Actuators: B. Chemical 297 (2019) 126674, https://doi.org/10.1016/j.snb.2019.126674

K. Chikkadi et. al, Appl. Phys. Lett. **103**, (2013) 23109 https://doi.org/10.1063/1.4836415

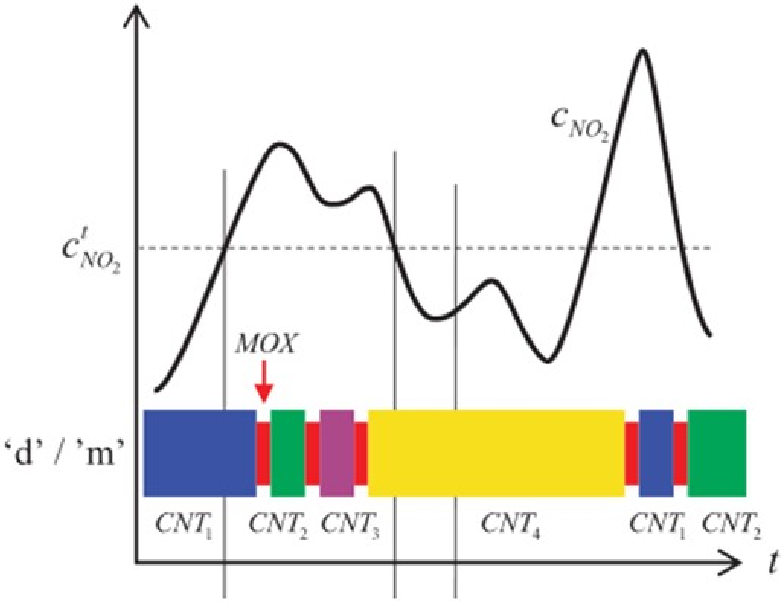
Two-Stage Gas Sensing using SWCNTs and MOX in Wearable Devices

A simulation study based on experimental data: Four single-walled carbon nanotubes are proposed as trigger-detectors for an energy-hungry metal–oxide semiconductor gas sensor.



SWNT wake-up
~20 µW, long des. time constants

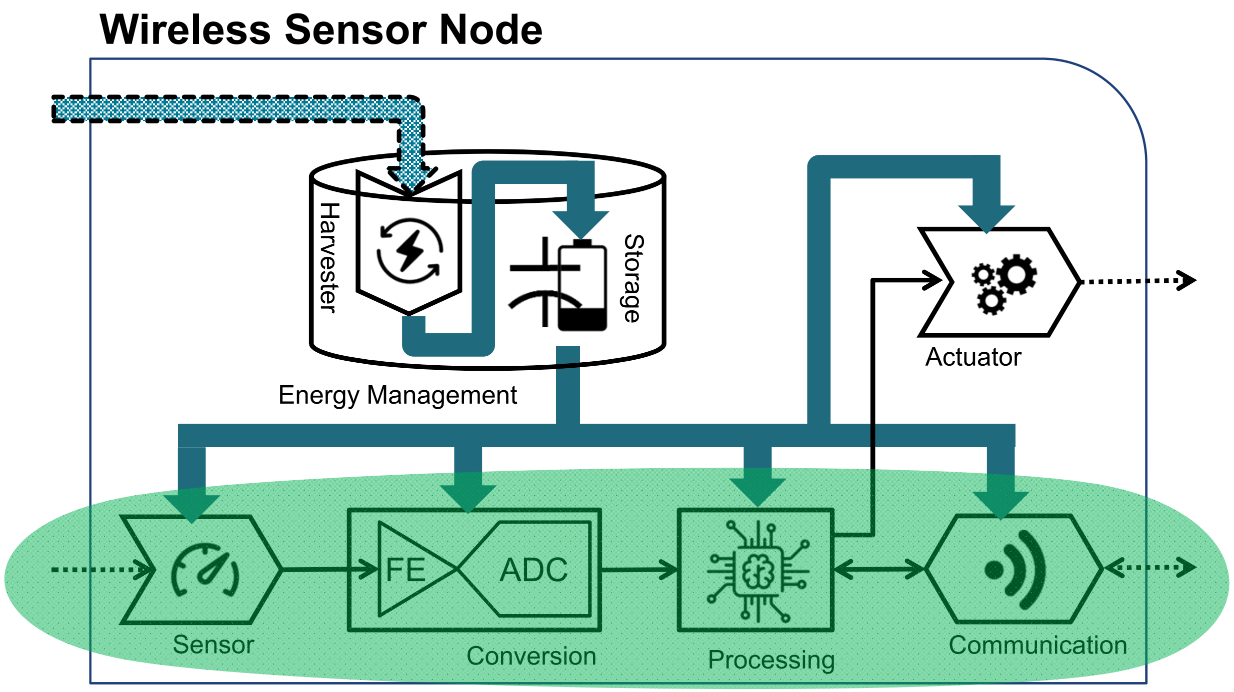
MOX sensor
~50 mW, short time constants



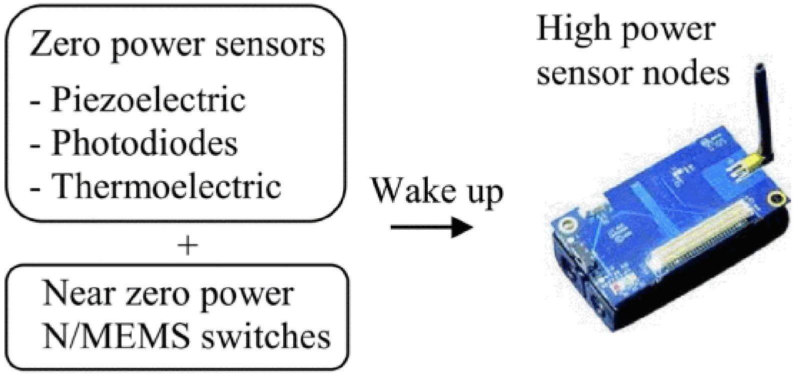
--> from days to weeks of operation:

30 times longer - scenario dependent - **operation time** by SWNT wake-up trigger compared to duty cycling

(Near) Zero-Power Sensors



PZT Bimorphs for Wake-up Sensors



Zero power sensors
- Piezoelectric
- Photodiodes
- Thermoelectric

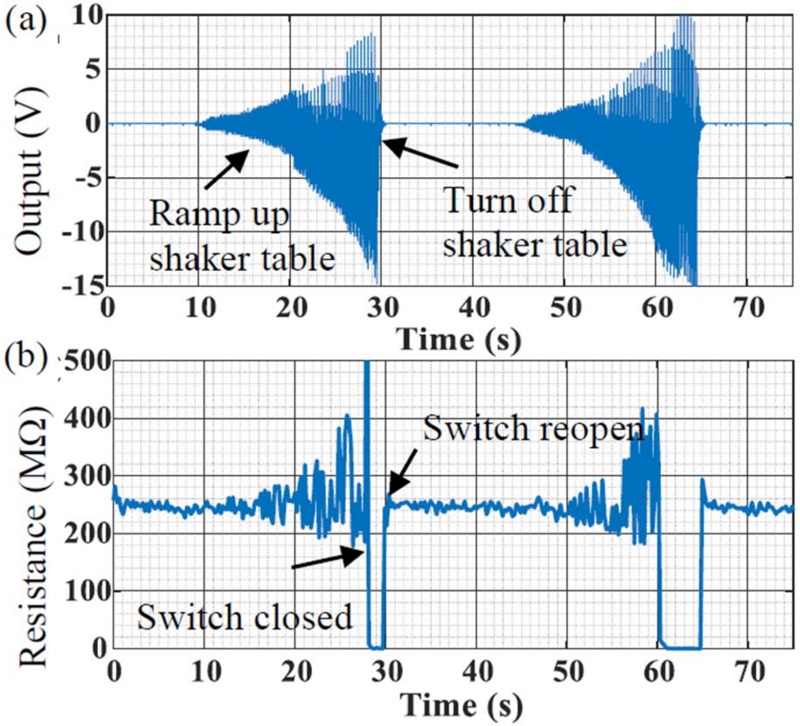
\+

Near zero power N/MEMS switches

Wake up →

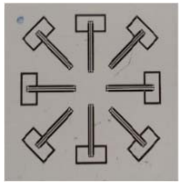
High power sensor nodes

Cornell University



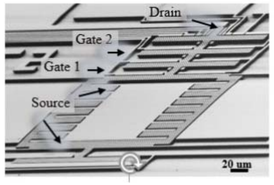
accelerometer

rotation



magnetometer

NEMS switch



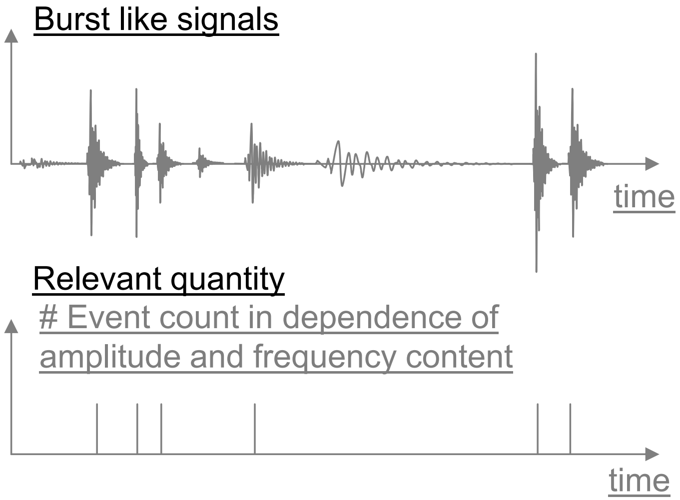
- PZT bimorphs to generate voltages from lateral motion
- Voltages from sensors combined to trigger a NEMS switch

V. Pinrod, et al., MEMS 2017, Las Vegas, NV, USA, Jan 22-26, 2017, DOI: 10.1109/MEMSYS.2017.7863640

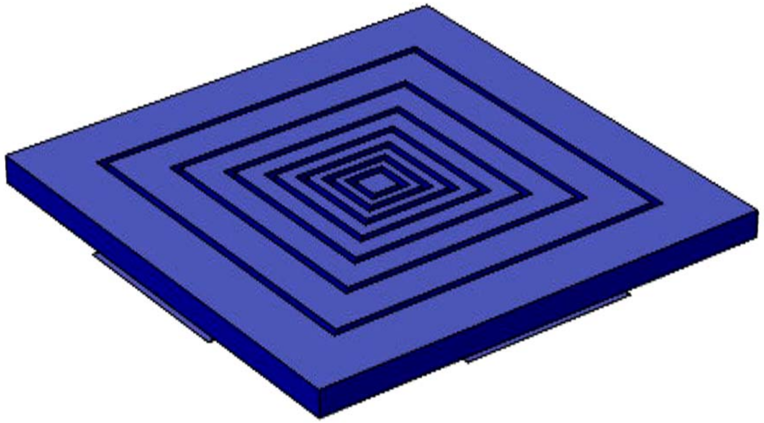
Environmental Sensing: Acoustic MEMS Trigger

In collaboration with
Computer Engineering and Networks Laboratory

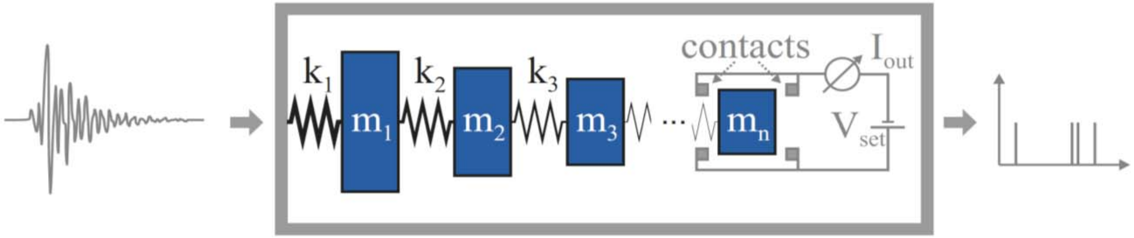
Objective:
MEMS Acoustic emission trigger
for rock fall early warning systems



Environmental Sensing: Acoustic Emission



FloWave Ocean Energy Research Facility, Edinburgh, 2014.

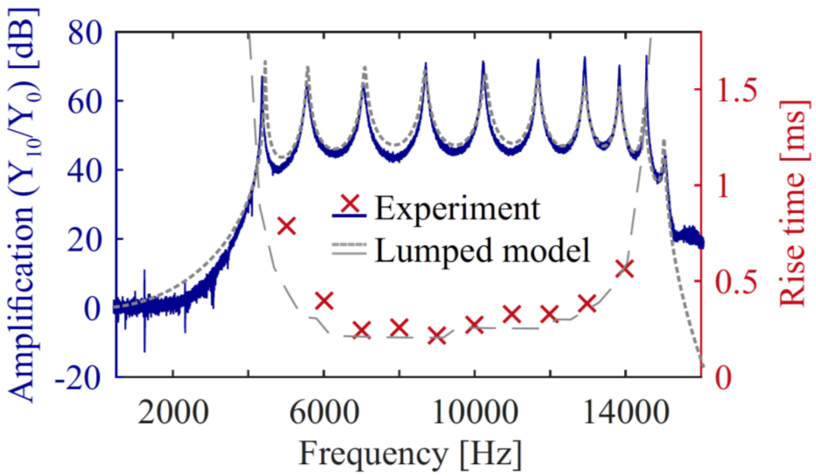


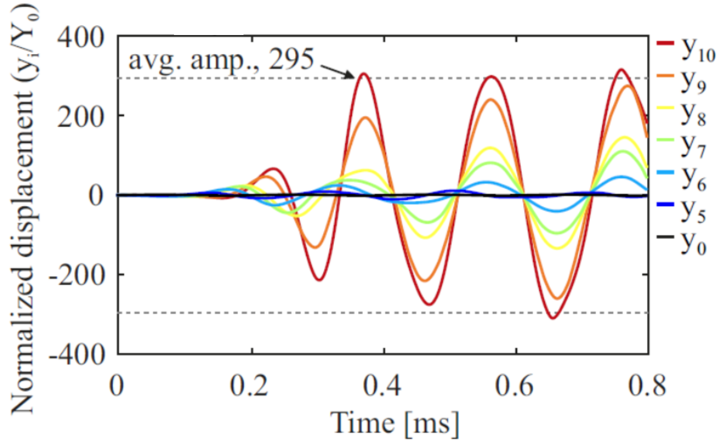
Microseismic / acoustic signals ▶ Frequency selective amplification ▶ Pull-in detection ▶ Events

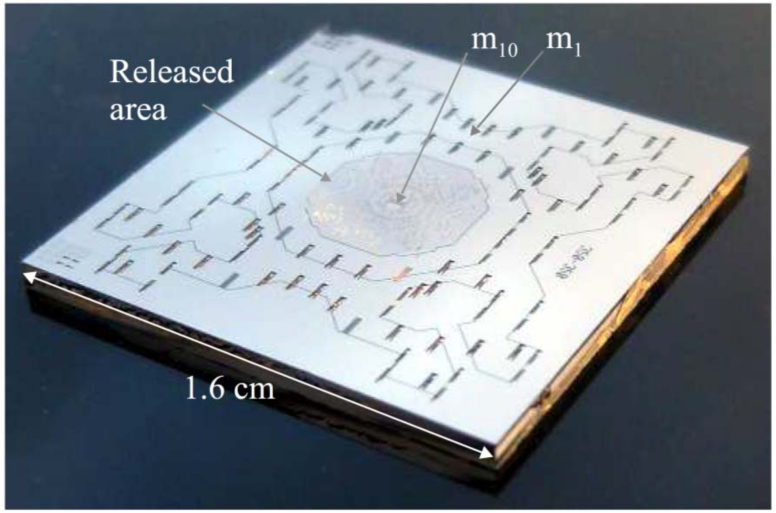
V. Maiwald, et al, Cosmin Roman, J. Microelectromechanical Systems, 26, 6, 2017, p. 1345
https://doi.org/10.1109/JMEMS.2017.2745051

M. Müller et al, C. Hierold, 2018 J. Micromech. Microeng.28 045009
https://doi.org/10.1088/1361-6439/aaabf6

Environmental Sensing: Acoustic Emission





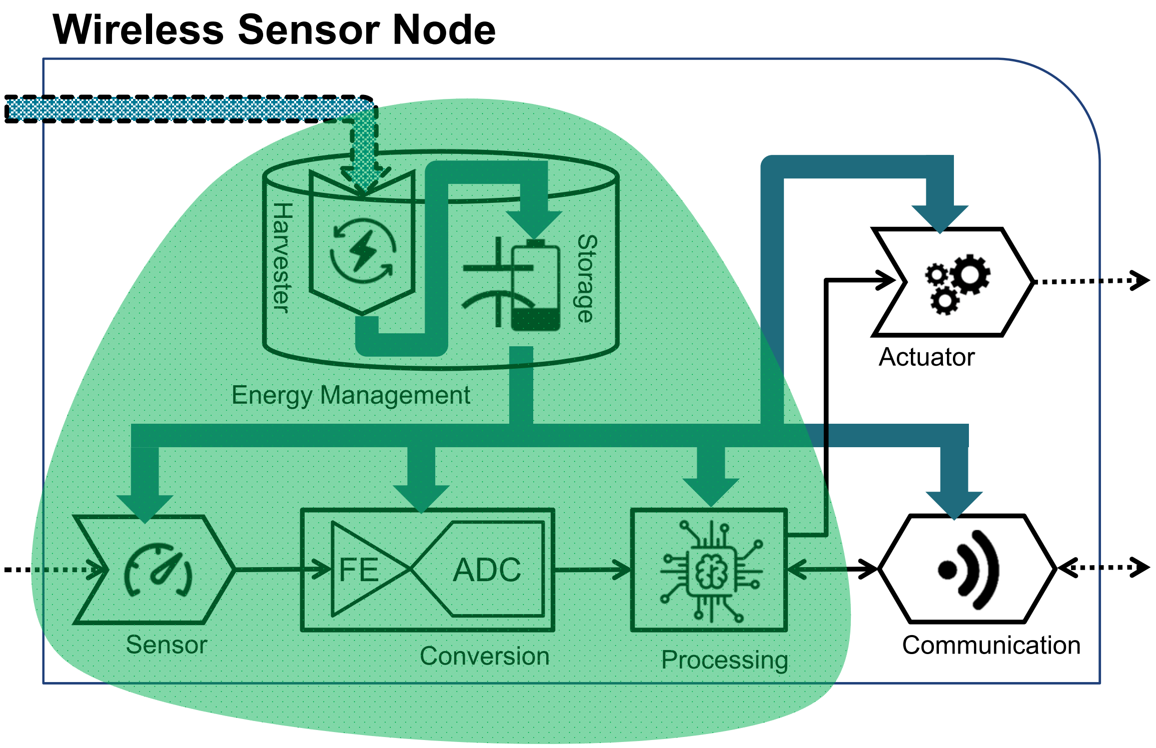


- Broadband amplification of 295 has been achieved with 10 masses coupled in series
- Frequency response flattened by damping
- Signal rise time < 0.5 ms

V. Maiwald, et al, Cosmin Roman, J. Microelectromechanical Systems, 26, 6, 2017, p. 1345
https://doi.org/10.1109/JMEMS.2017.2745051

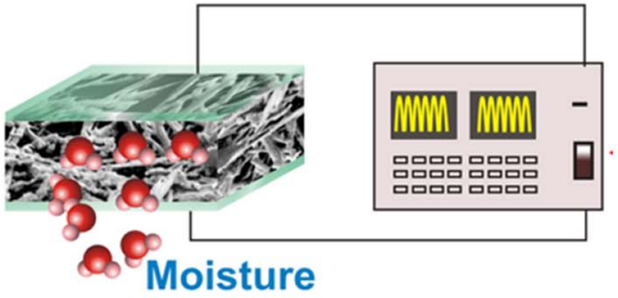
M. Müller et al, C. Hierold, 2018 J. Micromech. Microeng.28 045009
https://doi.org/10.1088/1361-6439/aaabf6

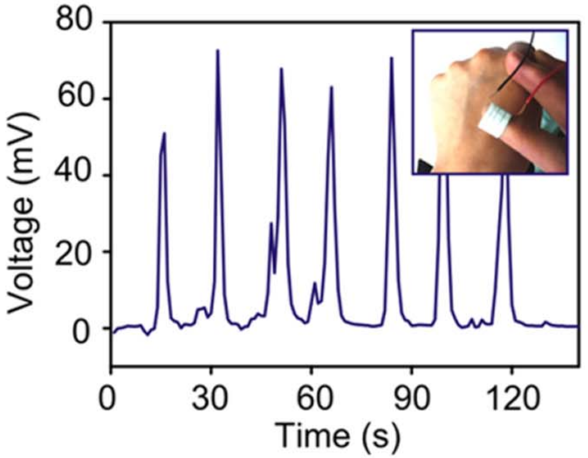
Emergent Self-Powered Sensors



Self-powered Humidity Sensors based on TiO_2 Nanogenerators

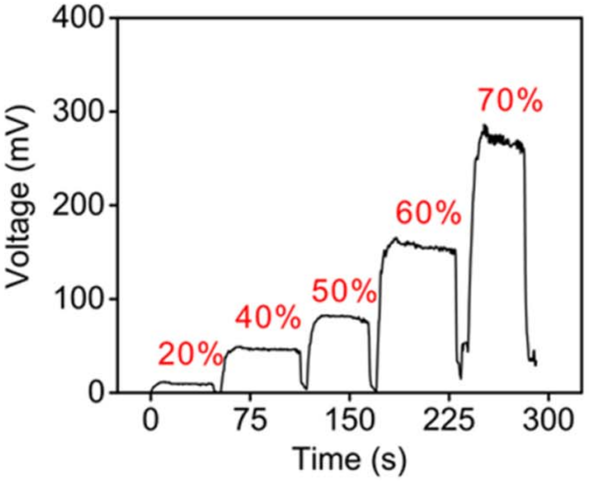
- TiO_2 nanowire networks
- Output voltage dependent on relative humidity
- Fast response (4.5s) and fast relaxation (2.8s)

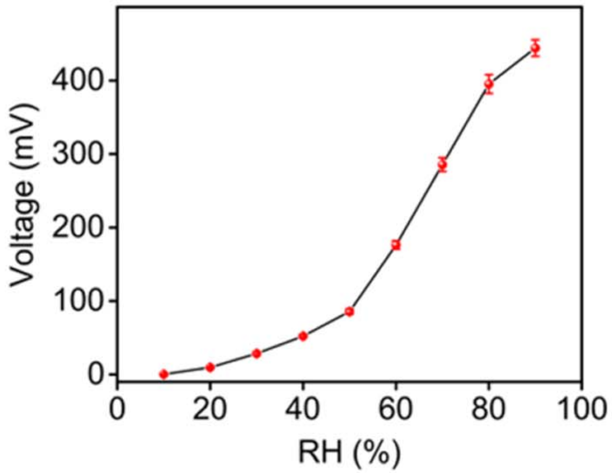




清華大學
Tsinghua University

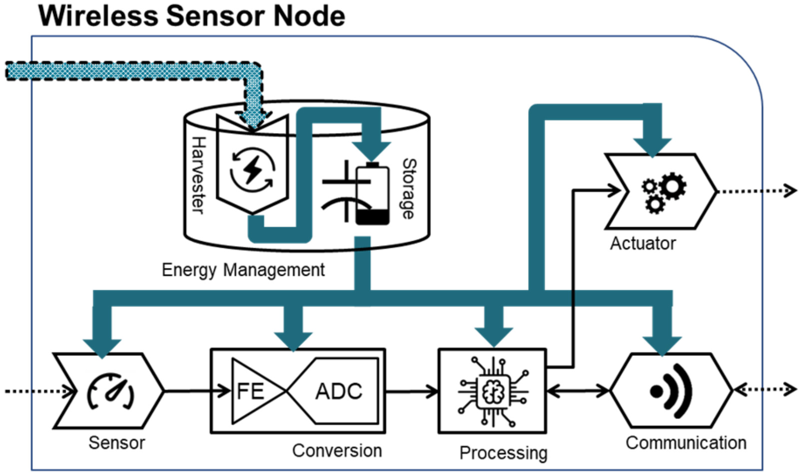
UNIVERSITY OF WATERLOO





D. Shen, et al., ACS Appl. Mater. Interfaces 2019, 11, 14249−14255,
DOI: 10.1021/acsami.9b01523

Conclusions



Ultra low power sensors enabled by

- Physical and electronic system optimization
- RT operated nanostructures (chemical)

Challenges

- High electronic noise in nanostructured sensors
- RT operation may cause long time constants (chemical)

Opportunities

- (Near) Zero-power sensors working as wake-up triggers for even-driven sensing (lower idle-power)
- Self-powered sensors based on piezoelectric, thermoelectric, mechanical, electrochemical, photo-generators
- Combined information and energy transducers
- Energy harvesters replace batteries or extend time of operation for IoT applications

Acknowledgments

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- **Profs Daniel Prades, Uo Barcelona, and Taekwang Jang, ETH Zurich**
- **FIRST, FIRST-CLA, BRNC and ScopeM, ETH Zurich**

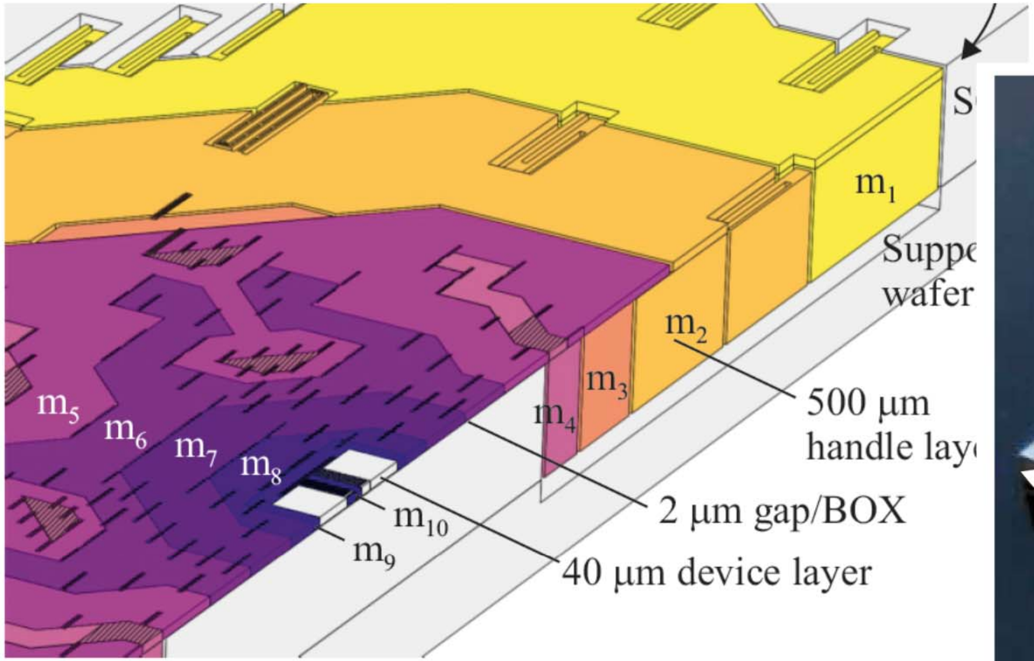
- **Swiss National Science Foundation**
- **FLAG ERA project CONVERGENCE**
- **Innosuisse**
- **Gebert Rüf Stiftung**
- **nano-tera.ch**
- **SFA Advanced Manufacturing**

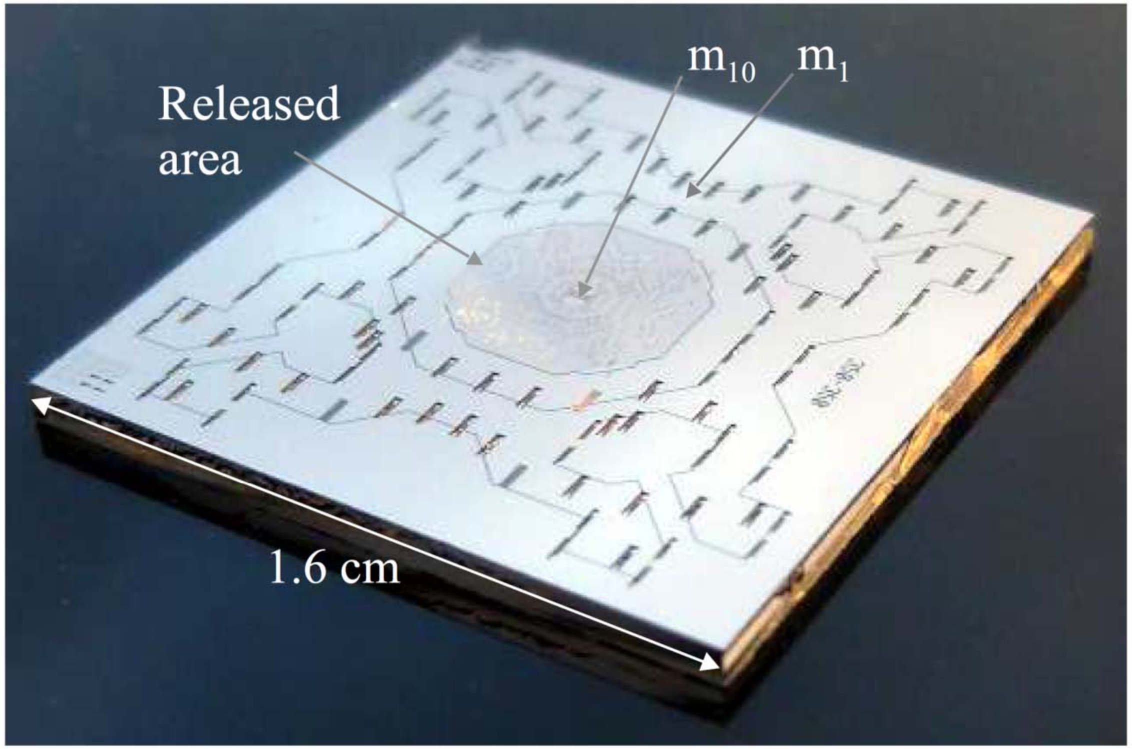
- **European Projects, COST actions**

Daniel Bachmann, Cancan Blaser, Clementine Boutry, Norbert Burger, Emine Cagin, Hengky Chandrahalim, Kiran Chikkadi, Diana Davila, Valentin Döring, Mathias Dupuch, Lukas Durrer, Sebastian Eberle, Felix Gattiker, Wulf Glatz, Ronald Grundbacher, Miro Haluska, Thomas Helbling, Jochen Hötzel, Laura Jenni, Seoho Jung, Alain Jungen, David Juncker, Katrina Klösel, Stefan Kuehne, Lalit Kumar, Shih-Wei Lee, Yunjia Li, Wei Liu, Ryan Linderman, Verena Maiwald, Moritz Mattmann, Ian Mihailovic, Michelle Müller, Matthias Muoth, Stefan Nedelcu, Christian Peters, Cosmin Roman, Debajoti Sarangi, Silvan Schmid, Bernd Schöberle, Etiennne Schwyter, Christoph Stamper, Silvan Staufert, Tobias Süss, Marcel Suter, Moritz Thielen, Stuart Truax, Florian Umbrecht, Signe-Li Vehusheia, Morten Vollmann, Johannes Weichart, Nina Wojtas, Christina Wouters, Eeva Köpilä, Manuela Kägi

Thank You

Environmental Sensing: Acoustic Emission





Michelle Müller et al 2018
J. Micromech. Microeng. 28 045009

V. Maiwald, et al, Cosmin Roman, J. Microelectromechanical Systems, 26, 6, 2017, p. 1345
https://doi.org/10.1109/JMEMS.2017.2745051

M. Müller et al, C. Hierold, 2018 J. Micromech. Microeng.28 045009
https://doi.org/10.1088/1361-6439/aaabf6