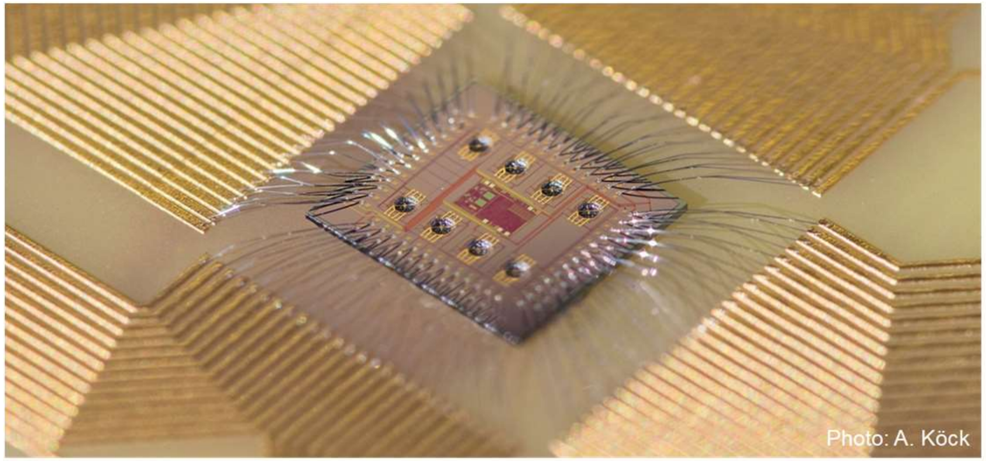
Materials-related challenges for autonomous sensor nodes



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European Research Council
Established by the European Commission
FWF Der Wissenschaftsfonds.
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
COMET Competence Centers for Excellent Technologies
FFG Österreichische Forschungsförderungsgesellschaft

Outline

- Wireless Sensor Networks for the Internet of Things (IoT)
- Autonomous sensor nodes
- Strategies to realise energy autonomy
    - Low-power gas sensors
    - Broadband piezoelectric harvesters
    - High-energy density dielectric capacitors
- Integration possibilities

Some definitions…

Digitalisation	**converting** information to a digital format and **making it available**	**improving business procedures** *(digital revolution)*

https://workingmouse.com.au https://en.wikipedia.org

Internet-of-Things (IoT)	network of physical devices that enables them to connect and exchange data	realising intelligent (smart) operation

Smart home

Smart cities

Smart vehicle

Smart industry *(Industry 4.0)*

Sensors

Actuators

CPU

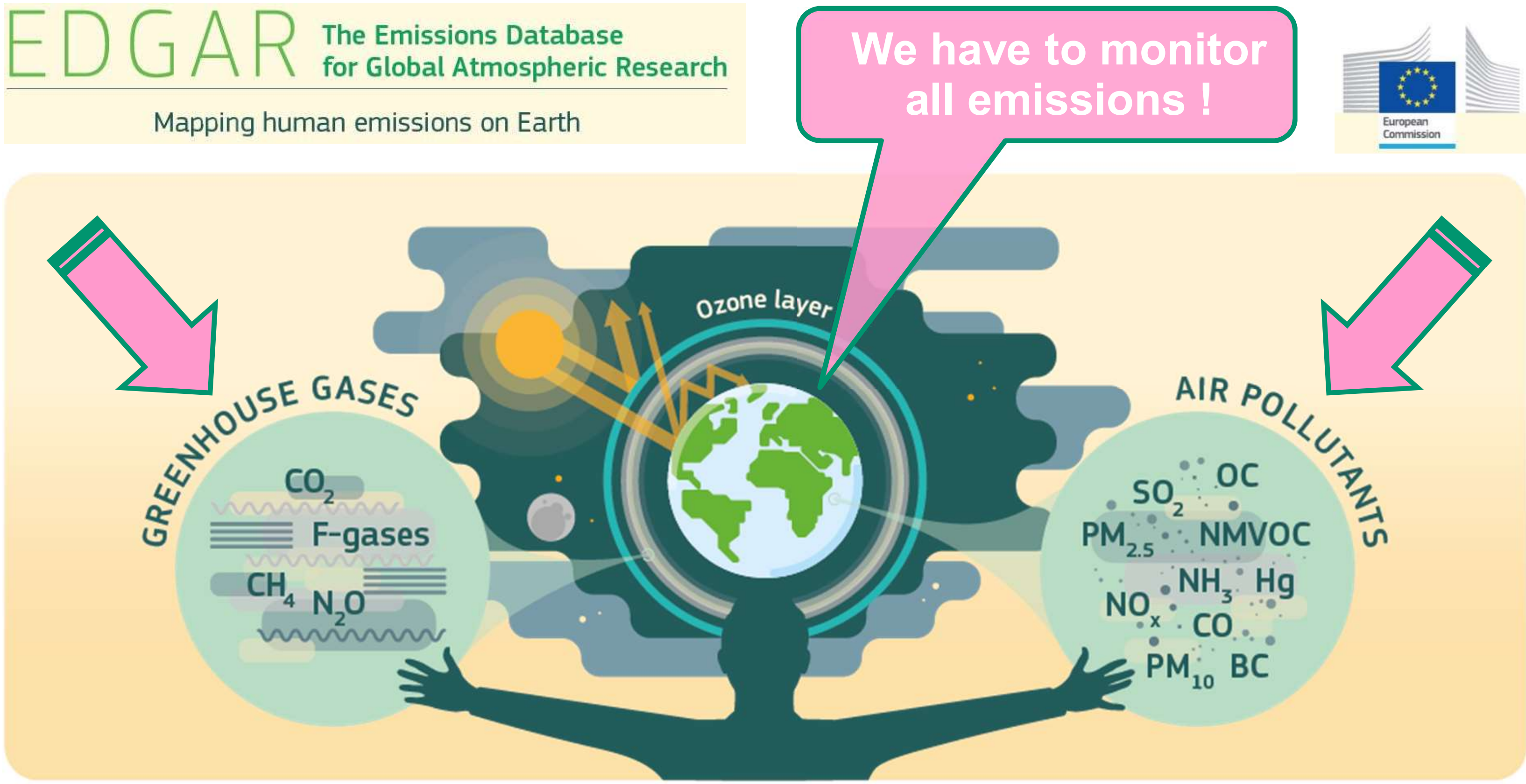
Network

Power supply

Smart device or system	system capable of analysing the environment and performing intelligent action on the environment.

www.speicherguide.de https://en.wikipedia.org

Environmental monitoring

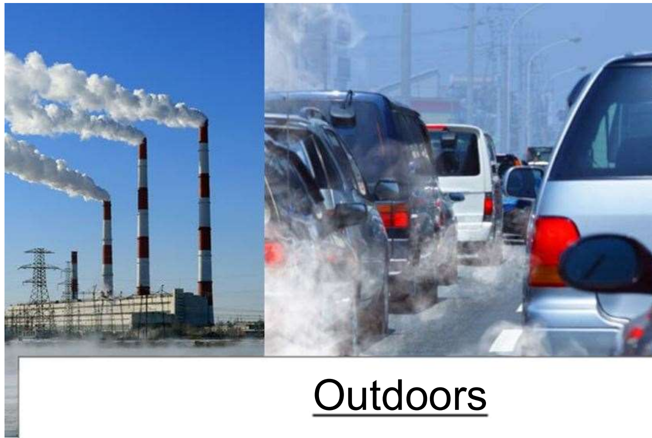


Source: The Emissions Database for Global Atmospheric Research (EDGAR): http://edgar.jrc.ec.europa.eu

Indoor and outdoor air quality monitoring

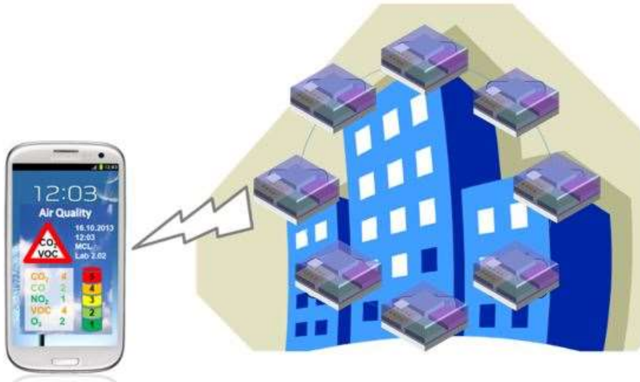
Indoors

CO, CO_2, VOCs, PM



Outdoors

NO_2, O_3, CO, PM10, PM2.5, UFPs

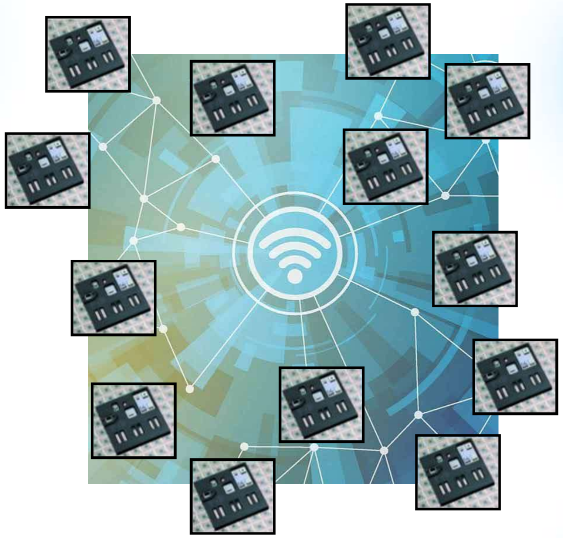


SENSOR NETWORKS ENABLING AUTOMATIC CONTROL AND REGULATION

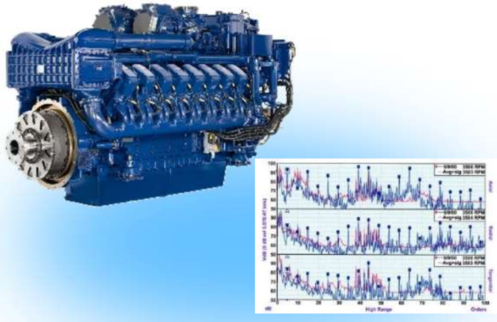
Wireless Sensor Networks

Air quality monitoring

Structural health monitoring



Condition monitoring



Predictive maintenance

Industry 4.0

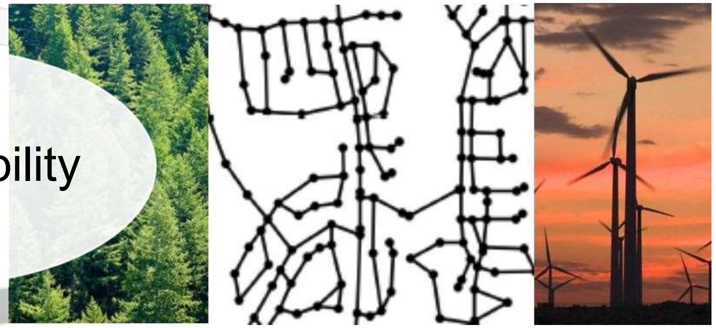
Realising GHG emission reduction goals

Challenges for sensor networks

Autoevolution.com DatSciAwards.com

Miniaturisation

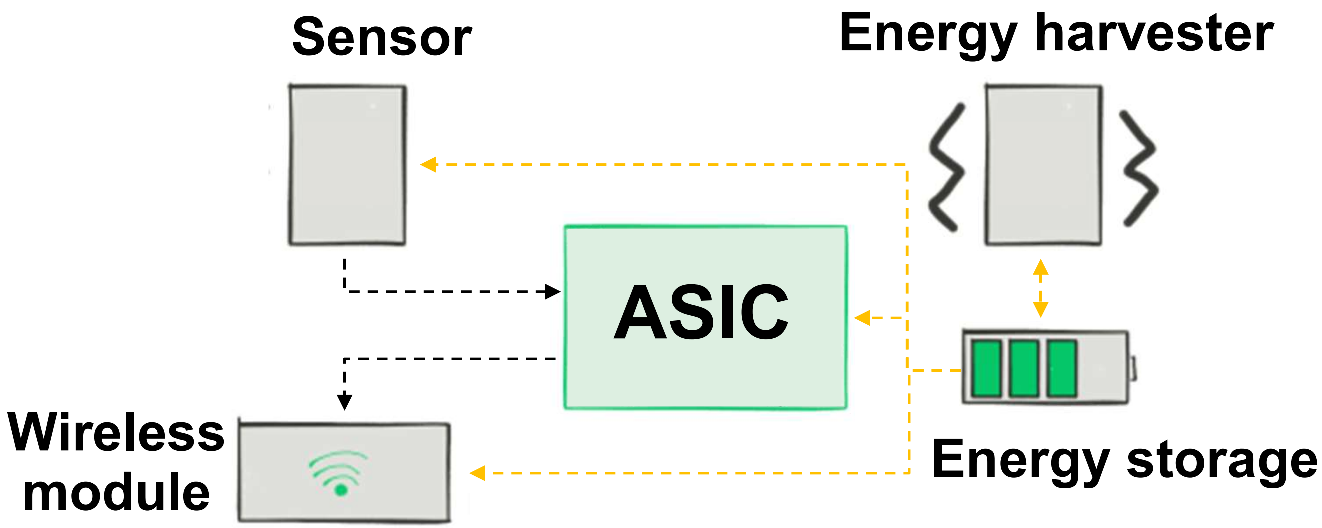
Inaccessibility



↓ Device footprint ↑ Energy efficiency

Miniaturised self-powered (energy autonomous) sensor nodes

Self-powered wireless sensor nodes



ENERGY CONSUMPTION

CMOS gas sensor: **144 J/d**

Temperature sensor: **0.47 J/d**

Self-heating gas sensor: **0.14 J/d**

Vibration sensor: **0.6 J/d**

ASIC/RFID (1 read/minute, ≤ 10 m transmission distance): **< 0.1 J/d**

ENERGY GENERATION

Photovoltaic harvester: **2.9 kJ/d**

Thermoelectric harvester: **5.2 J/d**

Piezoelectric vibration harvester: **~0.9 J/d**

ENERGY STORAGE

Ceramic multilayer capacitor: **$2.5*10^{-4}$ J/cycle**

Thin film multilayer capacitor: **$2.5*10^{-2}$ J/cycle**

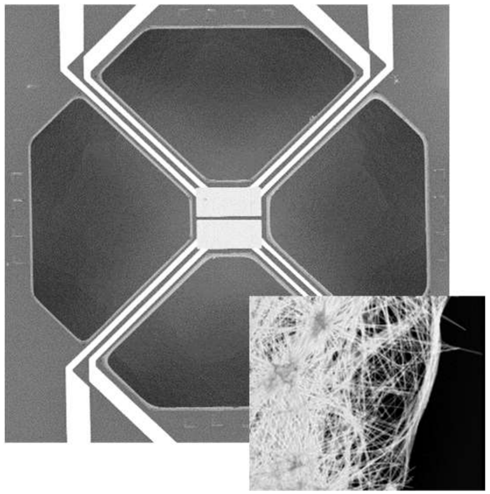
Supercapacitor: **$2*10^{-2}$ J/cycle**

Q. Wang et al., IEEE Explore, DOI: 10.1109/SAHCN.2006.288433 (2007)
M. S. Mahmoud et al., Adv. Inter. Th. 6, 19-29 (2016)
A. Baranov et al., Sens. Act. A 233, 279-289 (2015)
A. L. Gesing et al., Scientific Reports 8, 3920 (2018)

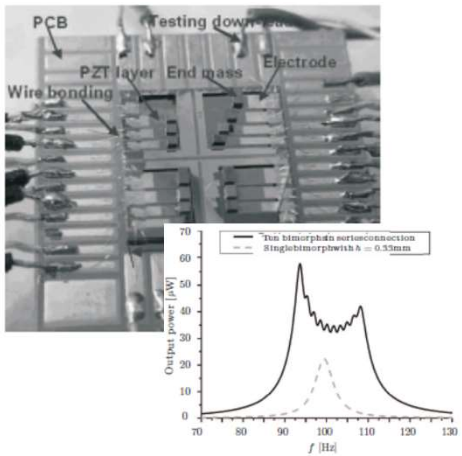
Materials-related challenges

Challenge	Requirement
Low power consumption	*sensor/harvester performance*
Variability of the energy source	*harvester + storage unit perf.*
Low cost per unit	*high-yield low-cost production*

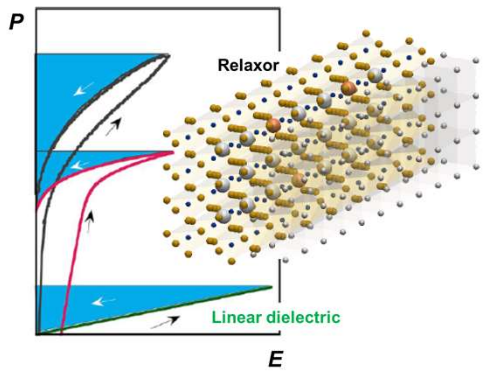
Low-power gas sensors



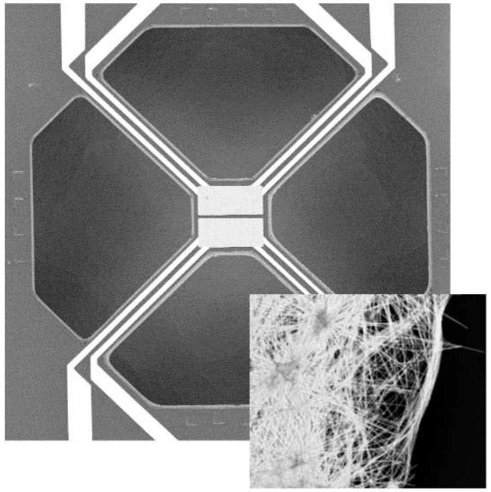
Broadband piezo-harvesters



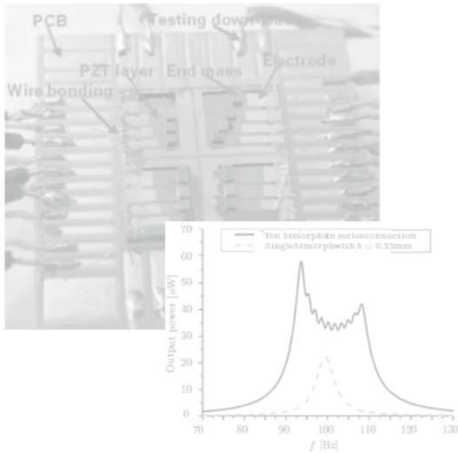
High energy-density capacitors



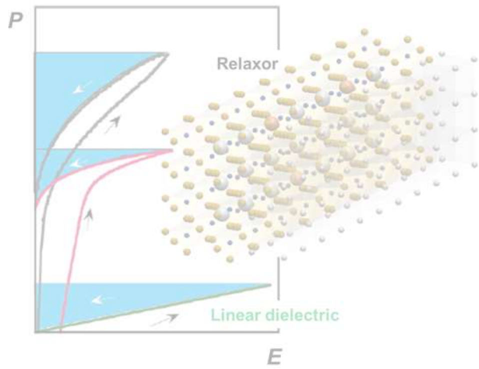
Low-power gas sensors



Broadband piezo-harvesters

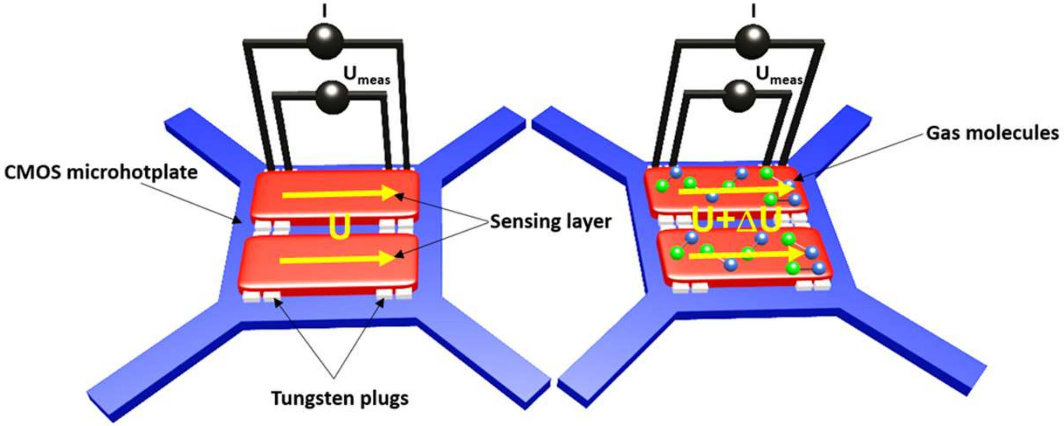


High energy-density capacitors

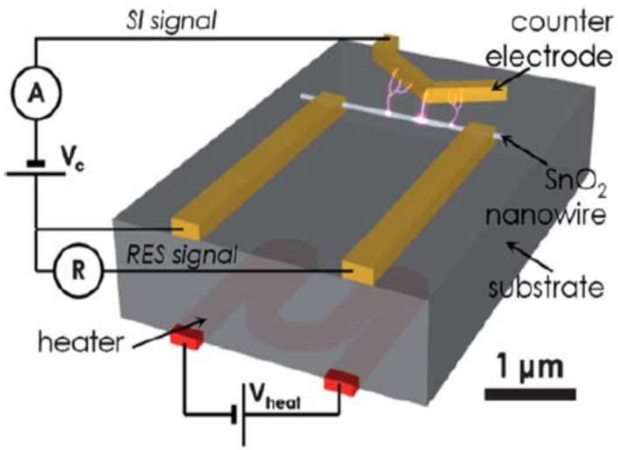


Metal oxide gas sensors

Conductometric (resistive)



Surface ionisation



Sensing Material	Functionalising Nanoparticles	Target Gases
▪ SnO_2 ▪ ZnO ▪ CuO ▪ WO_3 Thin films Nanowires	▪ Au, Pt, Pd ▪ AuPd, PdPt,… ▪ ZrO_2 ▪ $BaTiO_3$	▪ CO ▪ CO_2 ▪ VOCs ▪ NO_2 ▪ H_2S ▪ H_2, O_3 Dry and humid air

Metal oxide gas sensors

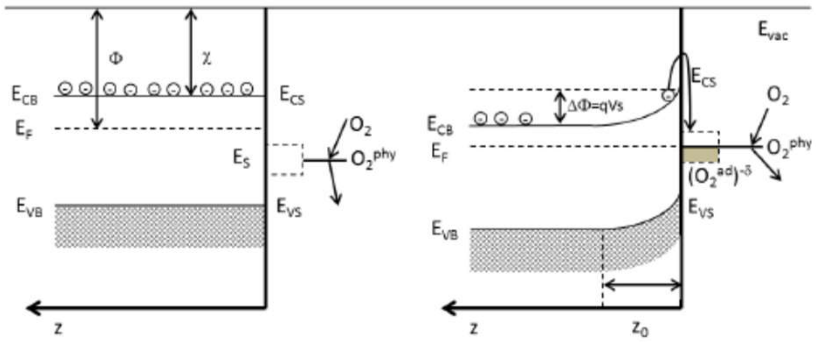
Conductometric Gas Sensor

C. Wang et al., Sensors 10 (2010) 2088-2106

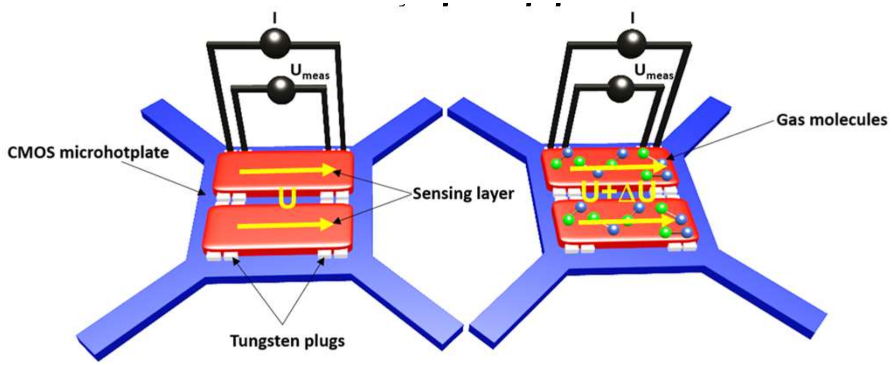
$$CO_{(g)} + O^- \rightarrow CO_{2(g)} + e^-$$

Reaction of gas with adsorbed O^- changes the resistance of the

n-type



W. Göpel, Prog. Surf. Sci 20 (1985) 9-103



- Optimal reaction T: 300° C – 450° C ⟶ Hotplate needed
- Decreasing particle size, surface/volume ratio of sensing surface layer increases

  ⟶ Nanocrystalline thin films and nanowires ⬆ Sensitivity
- Doping with noble metal particles is beneficial

⟶ Catalyses the reaction with gas

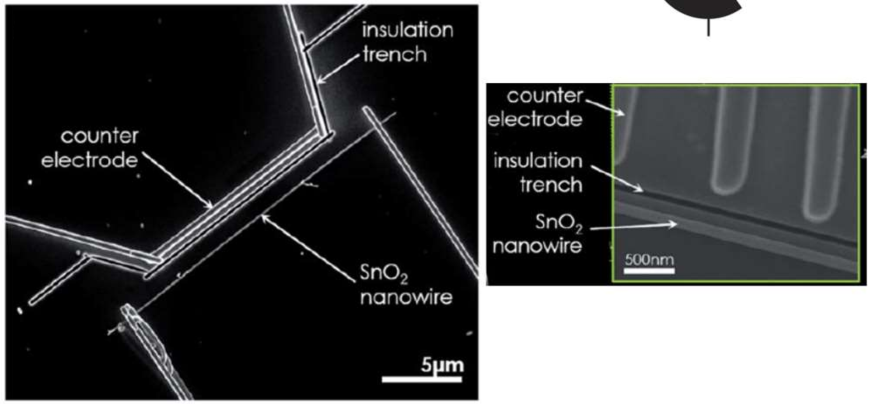
⟶ Improves electron exchange in sensing layer

⬆ Sensitivity

Metal oxide gas sensors

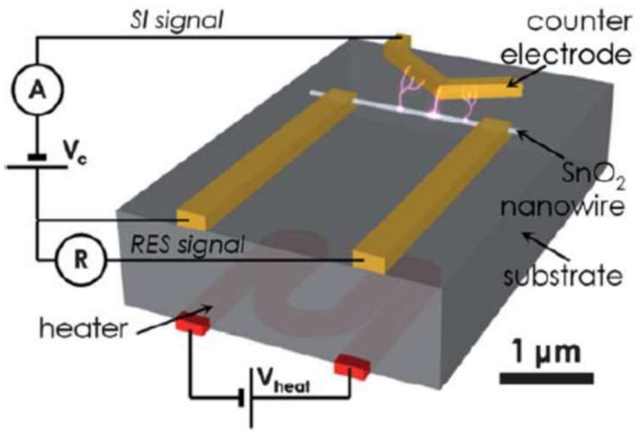
Ionisation Gas Sensor

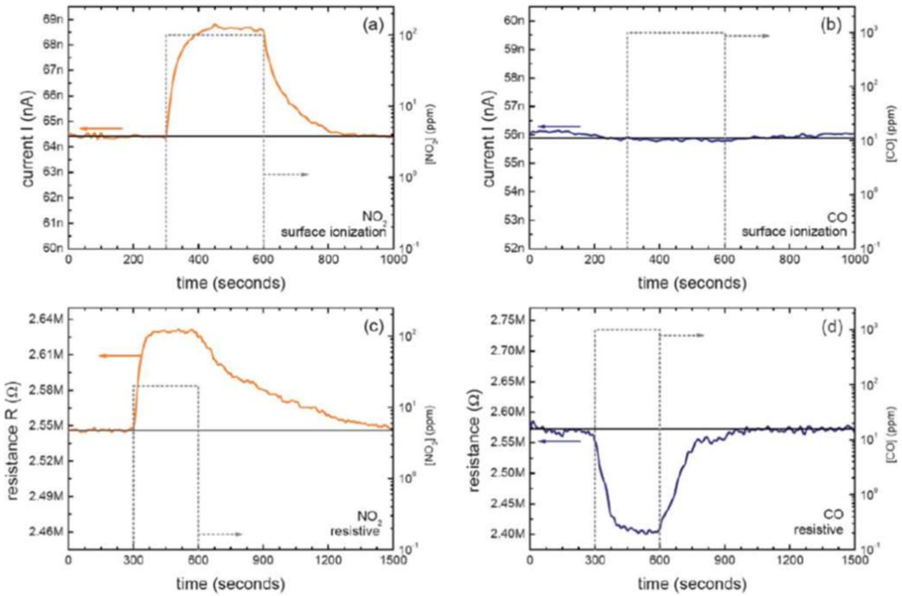
Adsorbed gas on metal oxide extracted by ionisation applying voltage to a counter electrode



Gap: 400 nm	Voltage < 1 V
E-Field > 15 kV/cm	

F. Hernandez-Ramirez et al., Nanoscale 3 (2011) 630-634





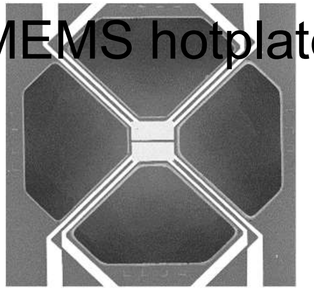
Sensitivity + Selectivity

Simultaneous ionisation (current) and conductometric (resistance) measurements at very low operating power

Fabrication of gas sensing nanostructures

Nanocrystalline Thin Films

MEMS hotplate



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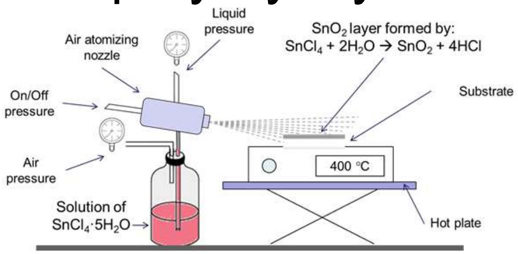
Spray Pyrolysis



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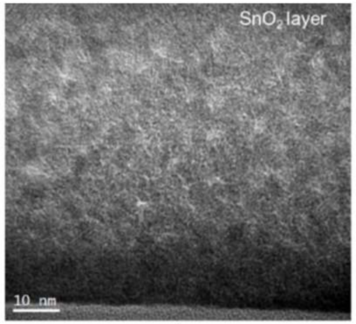

E. Brunet et al., Sens. Act. B 165 (2012) 110-118

Functionalising Nanoparticles

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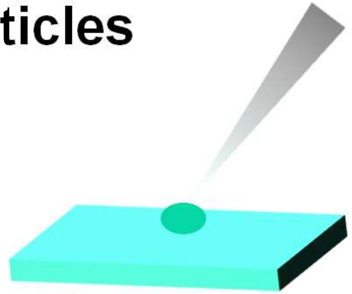

Drop Coating

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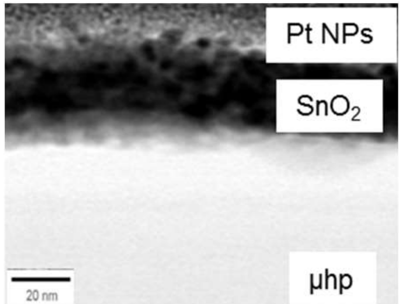
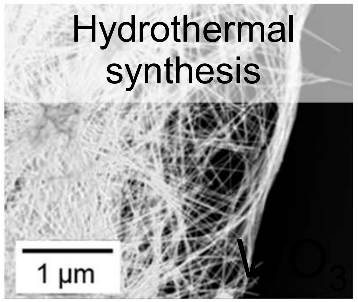
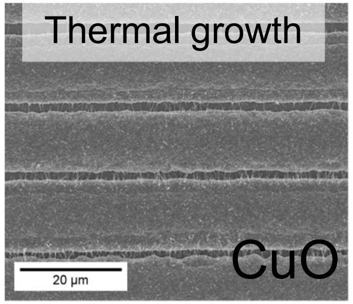


A. Köck, M. Deluca et al., Sensor+Test 2017

Nanowires





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Transfer printing

A. Carlson et al., Adv. Mater. 24 (2012) 5284-5318

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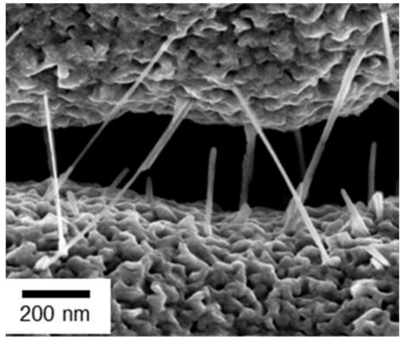
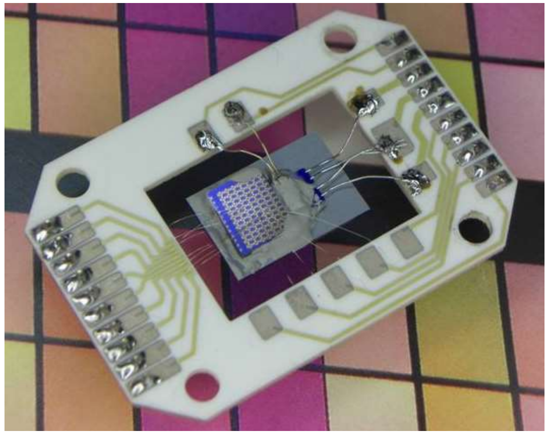
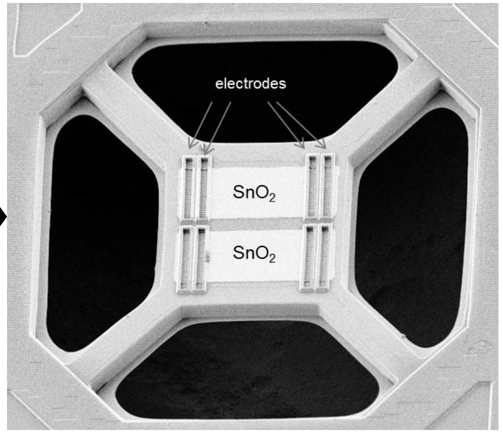
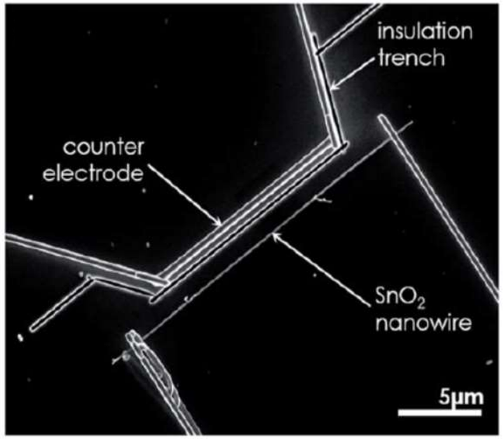


Low-power gas sensors

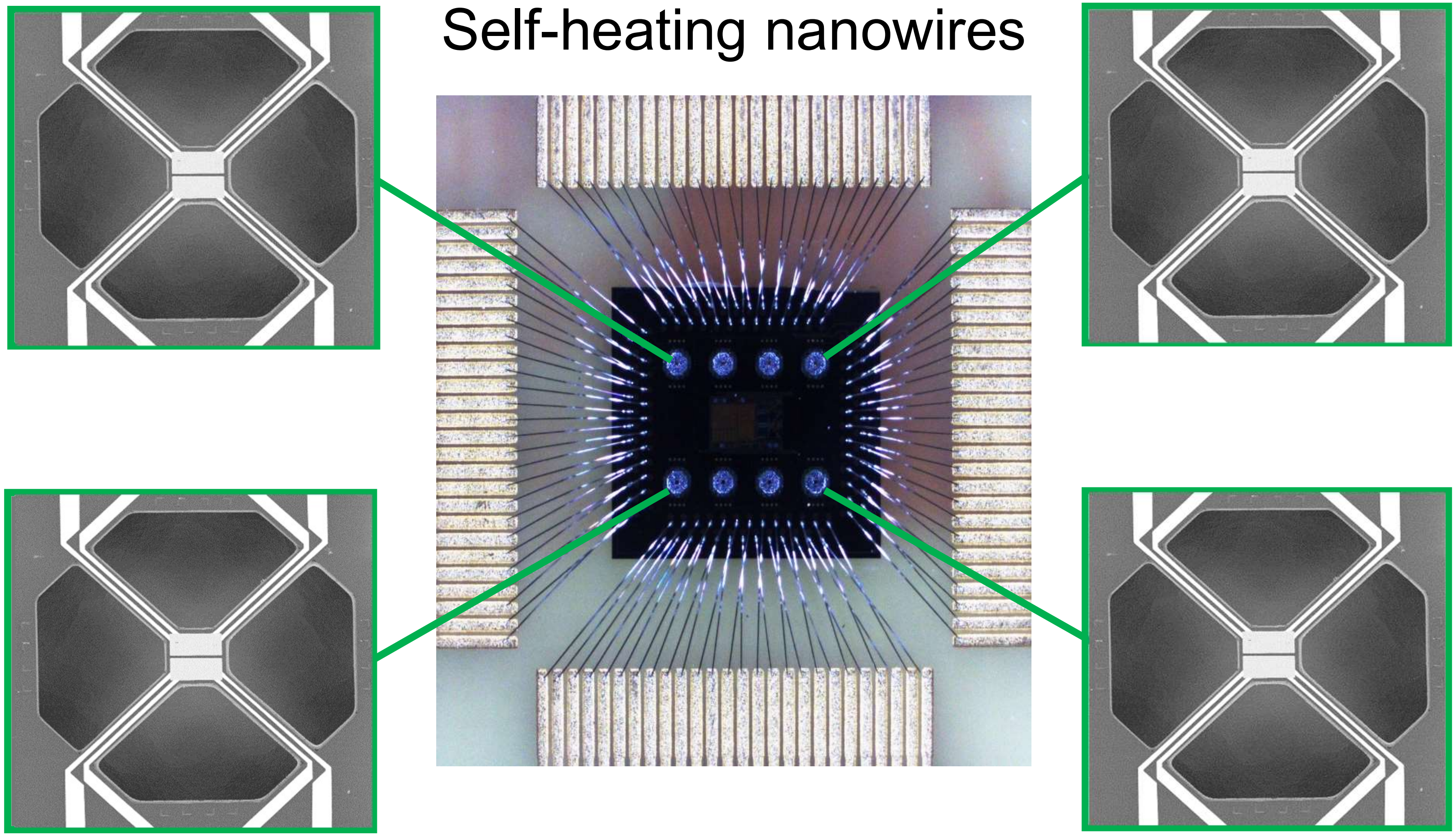
Bulk Conductometric	CMOS Conductometric	Self-heating
		
Bulky Pt-heater	MEMS polysilicon heater	Self-heating nanowires
Large size (> 15 cm^2)	Small size (< 5 mm^2)	Small size (< 1 mm^2)
No CMOS-integration	CMOS-integration	CMOS-integration
Large power consumption	Medium power cons.	Low power consumption
600 mW operation	20 mW operation	20 µW operation
4.3 kJ/day	**144 J/day**	**0.144 J/day**

A. Köck, M. Deluca et al., Sensor+Test 2017

Highly selective gas sensor arrays

MEMS resistive arrays

Self-heating nanowires



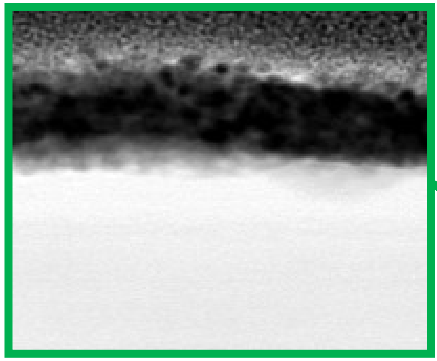
Power consumption: 20 µW **0.144 J/d**

Highly selective gas sensor arrays

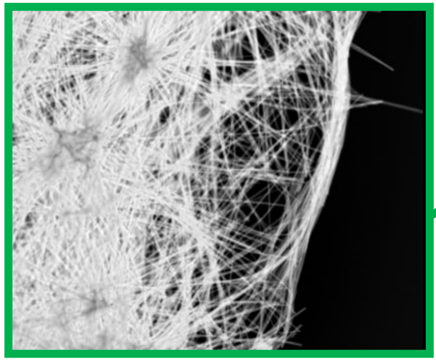
MEMS resistive arrays

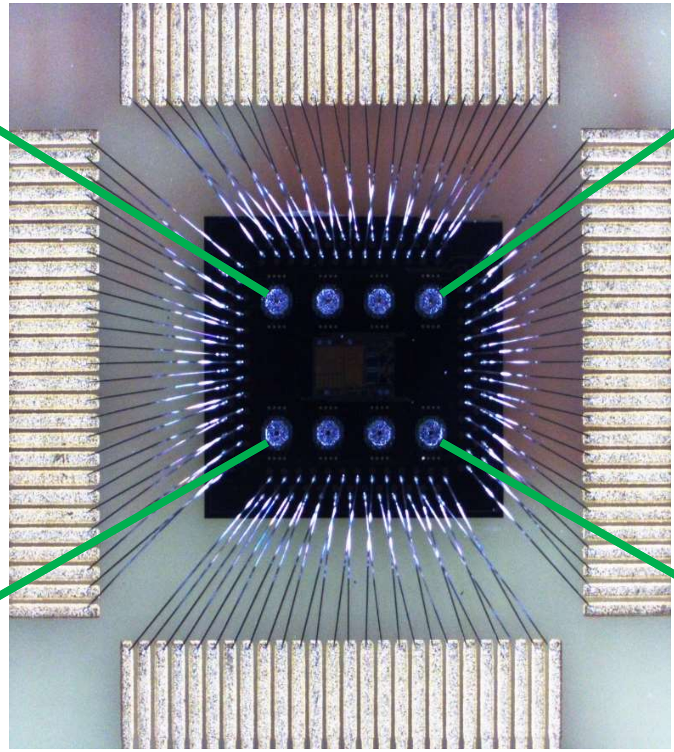
Self-heating nanowires

SnO_2 + Pt

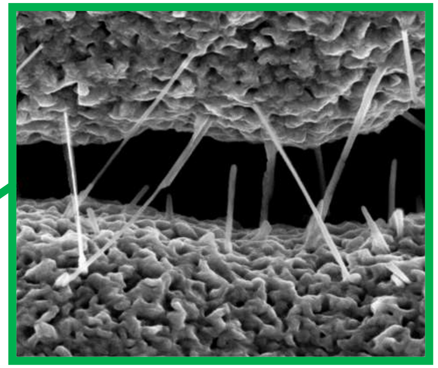


WO_3

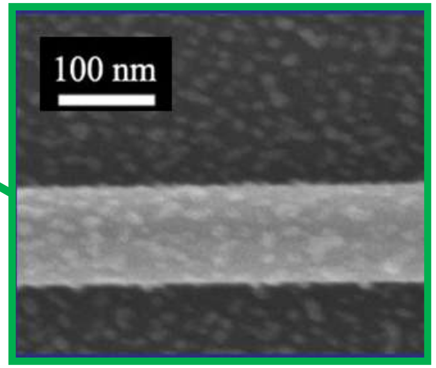




CuO-NWs



CuO-NWs + Au



Functionalised with different materials

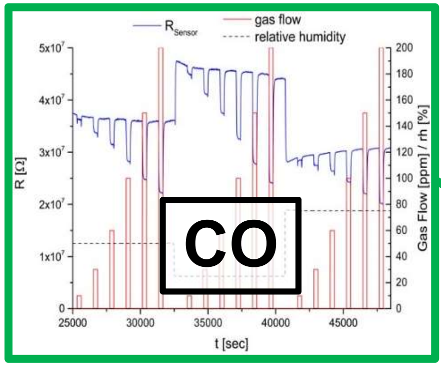
Selectivity to different gases

Highly selective gas sensor arrays

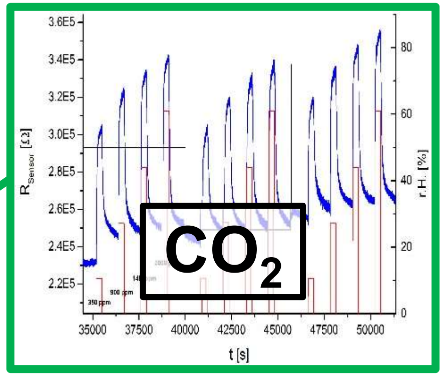
MEMS resistive arrays

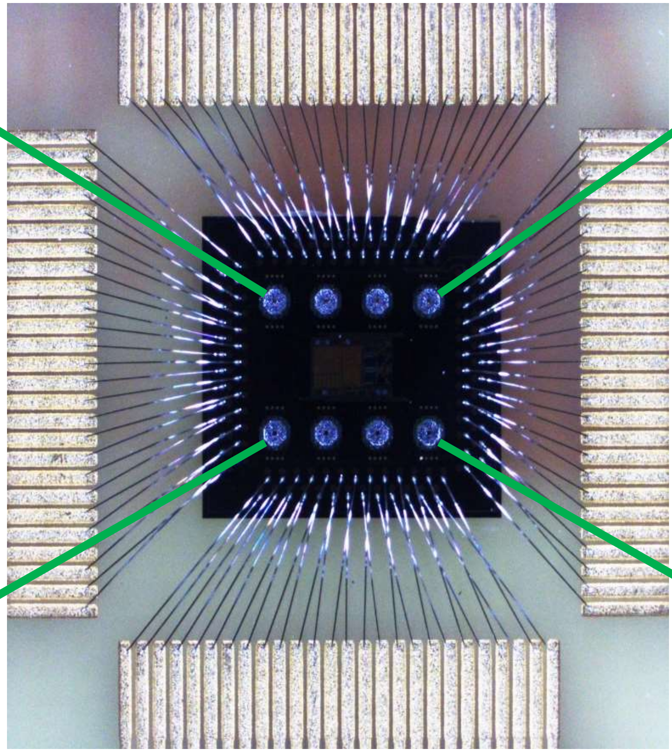
Self-heating nanowires

SnO_2 + Pt

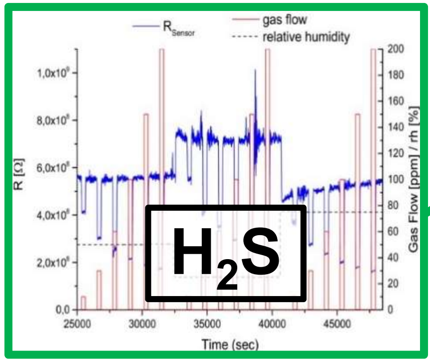


CuO-NWs

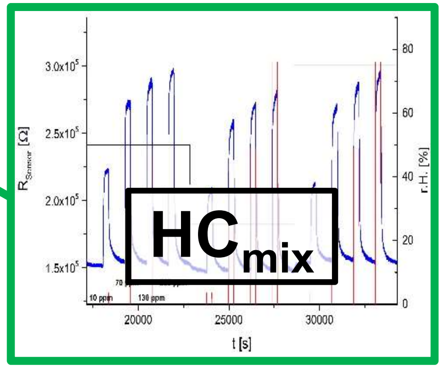




WO3

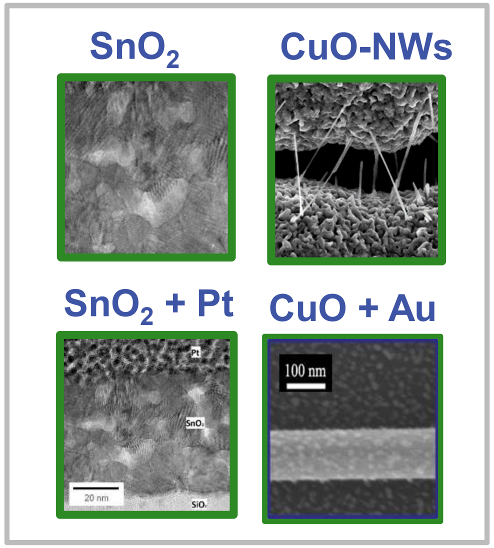


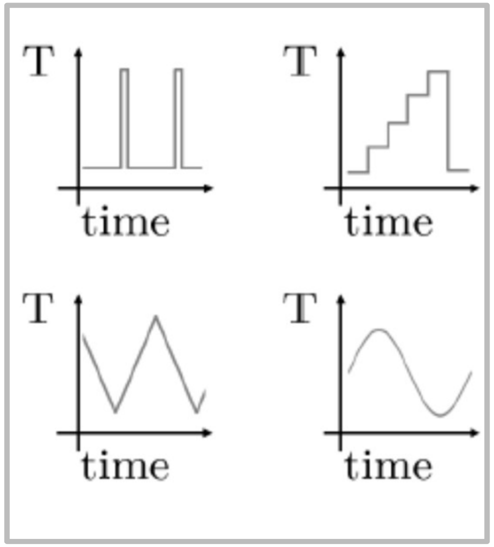
CuO-NWs + Au

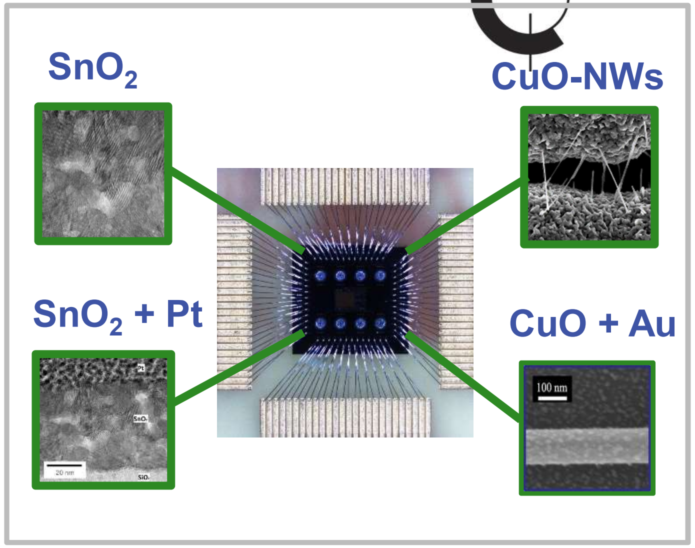


„Cross-Sensitivity“ problem

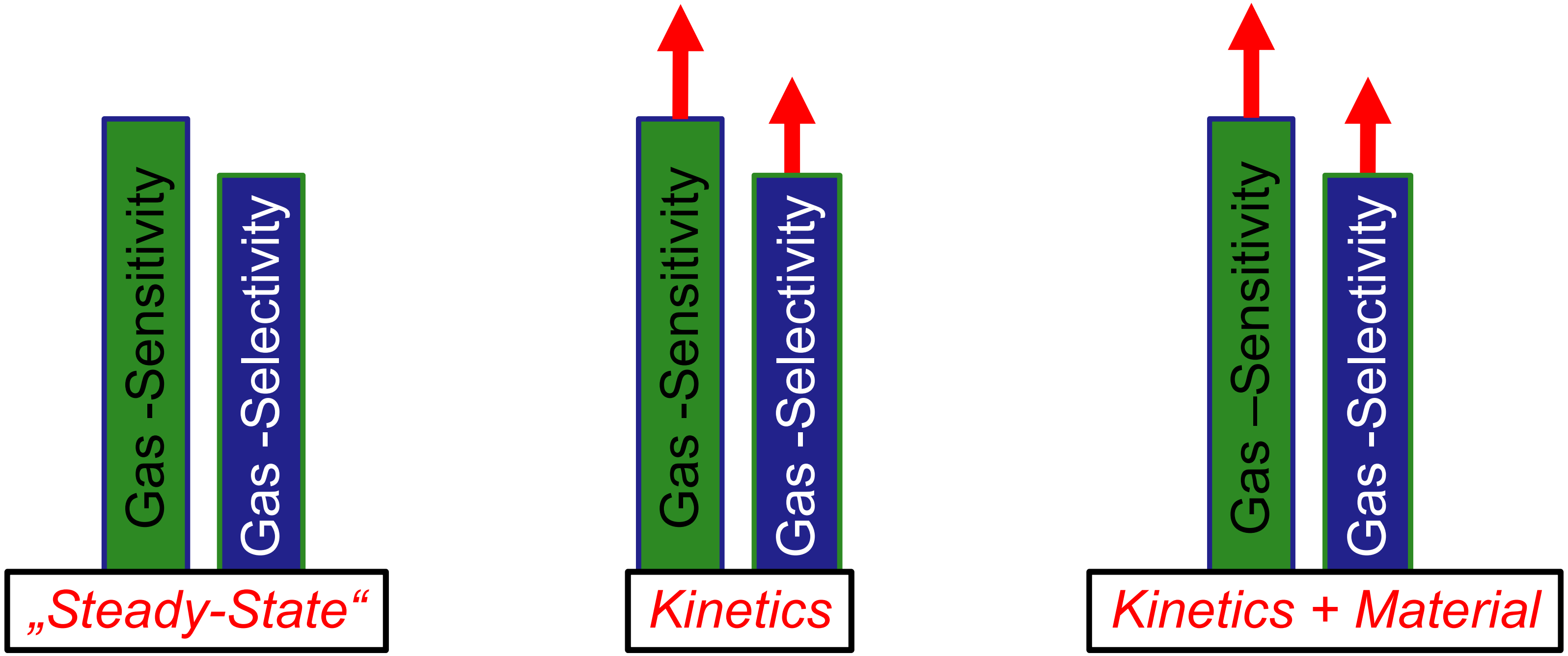
Multifunctional sensors





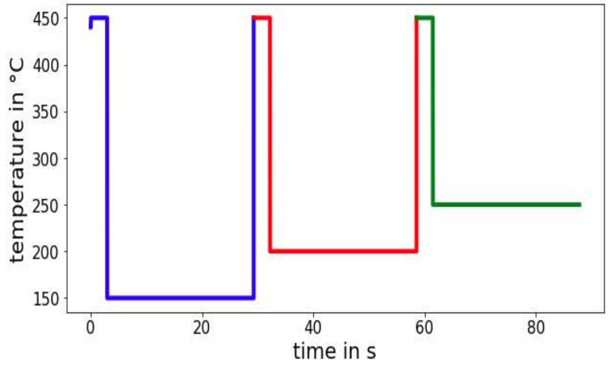


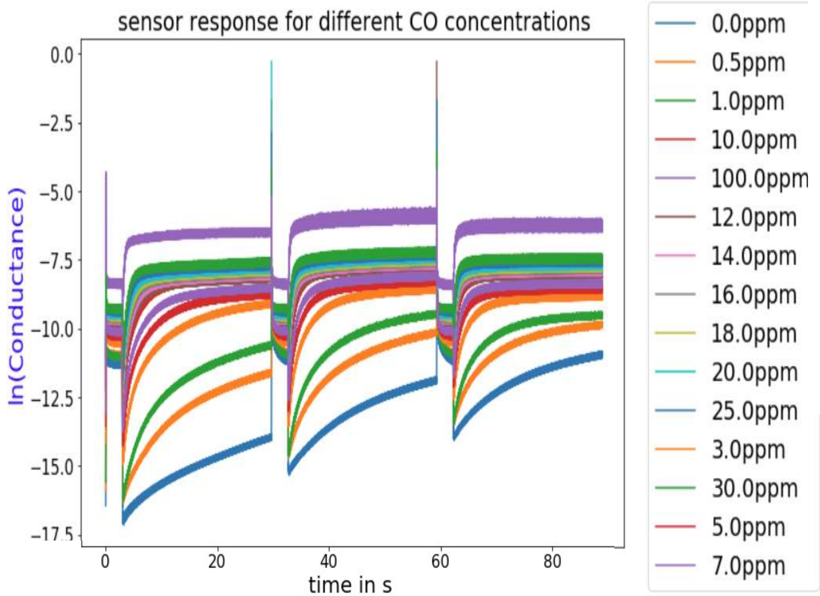
Single Sensors **Temperature Cycles** **Sensor Arrays**



Multifunctional sensors

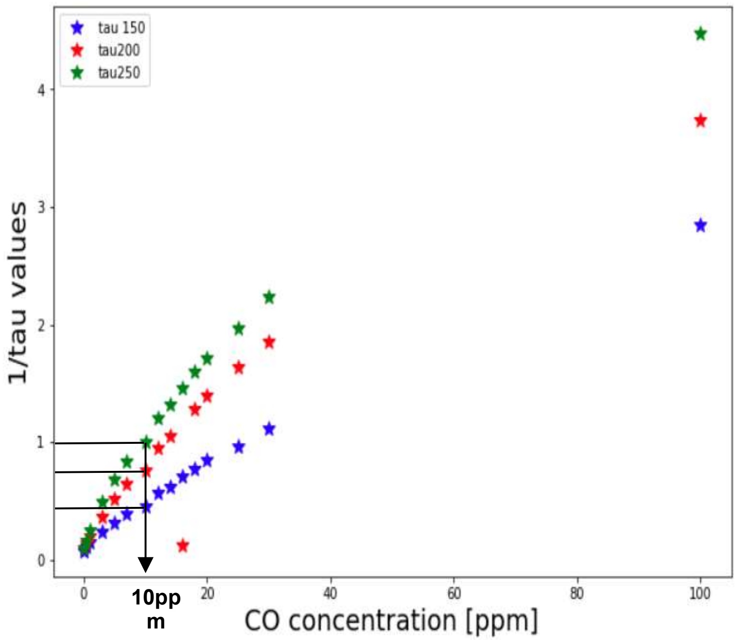
Temperature cycles for gas quantification





Kinetics: Slope change is dependent on gas concentration and temperature

τ-Evaluation for gas quantification

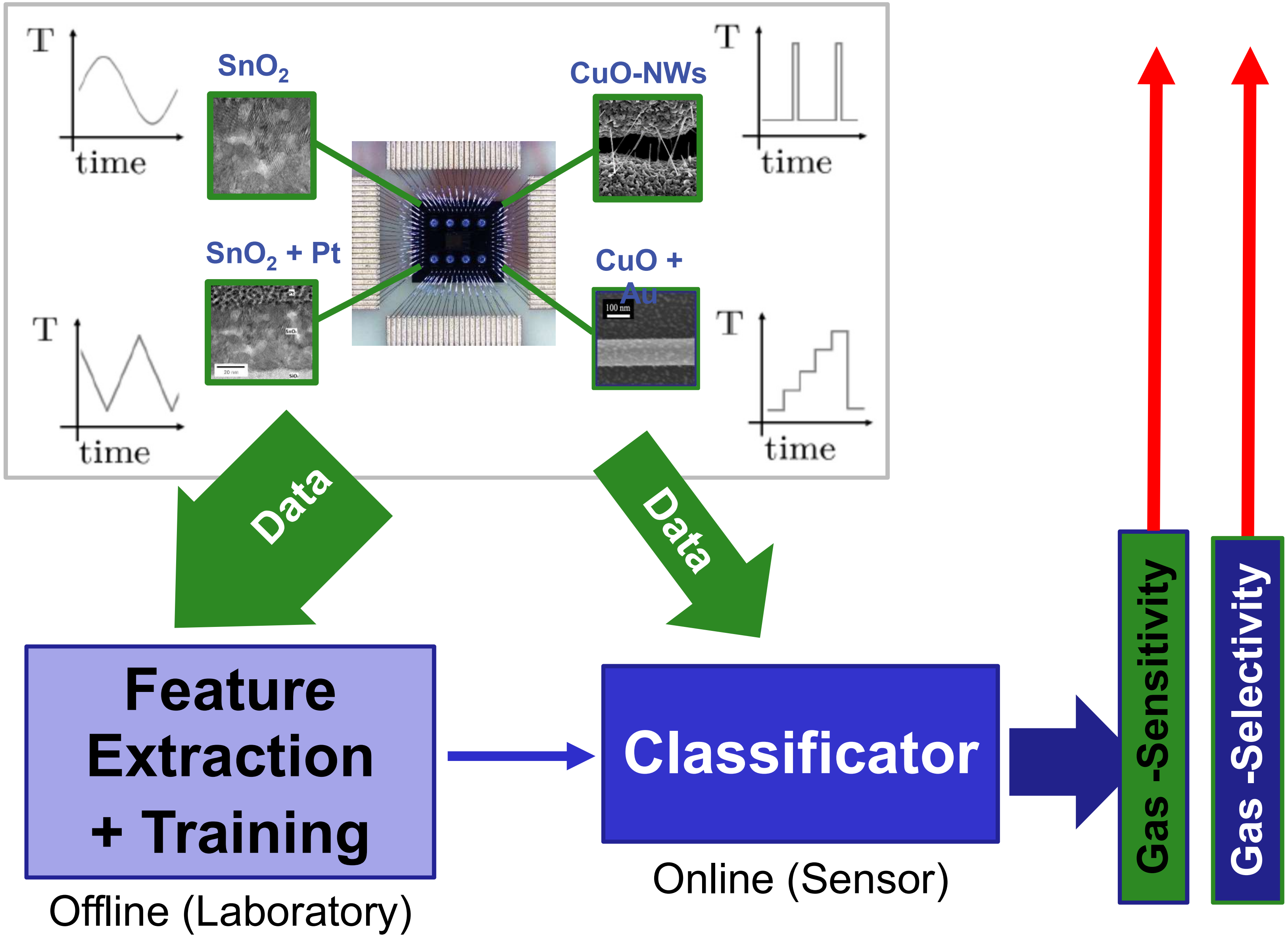


$$\tau = t\big(0.632(\ln(G_{max}) - \ln(G_{min}))\big) - t_{start}$$

Faster measurement!

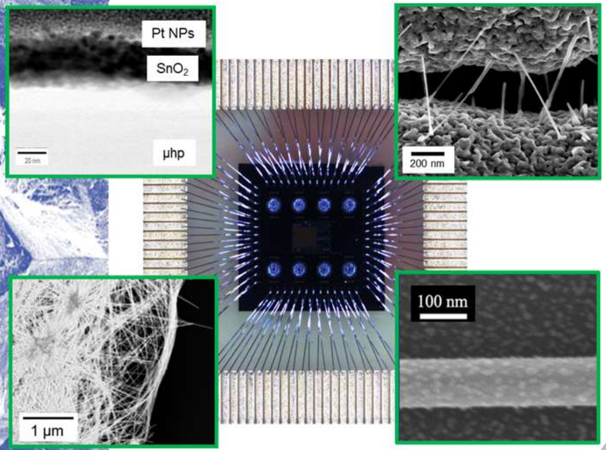
Multifunctional sensors

Sensor arrays + Temperature cycles



Highly selective gas sensor arrays

MEMS arrays



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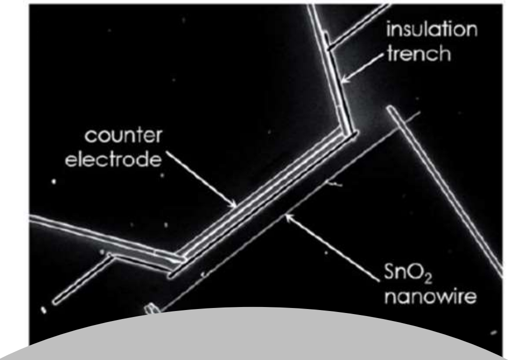
Ionisation sensor



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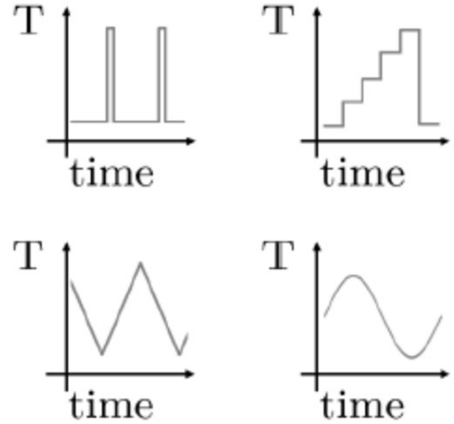
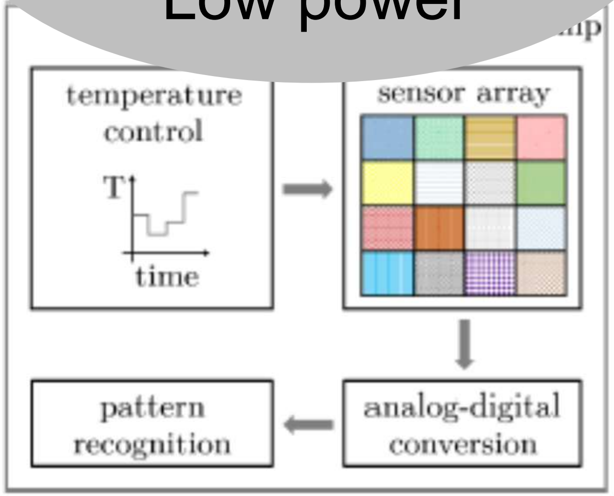
Thermal profiles



High sensitivity

High selectivity

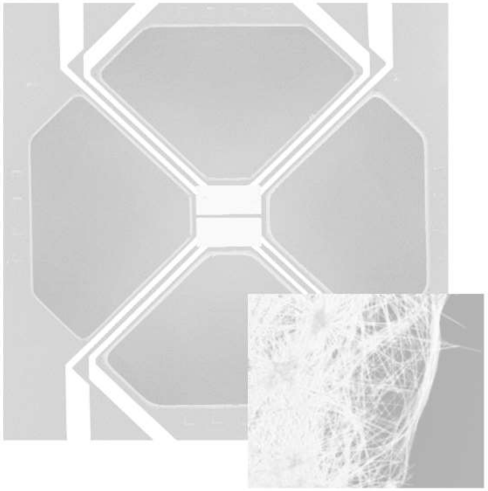
Low power



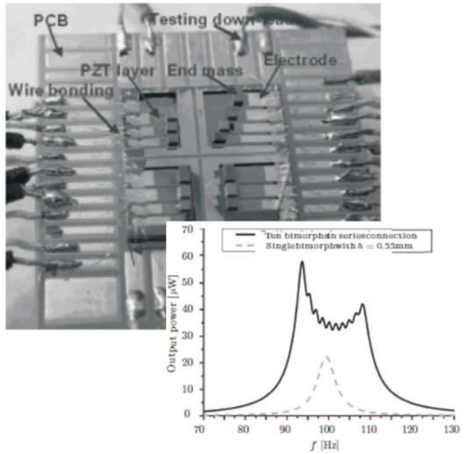
System-on-Chip
for gas detection

S.-W. Chiu and K. T. Tang, Sensors 13 (2013) 14214-27

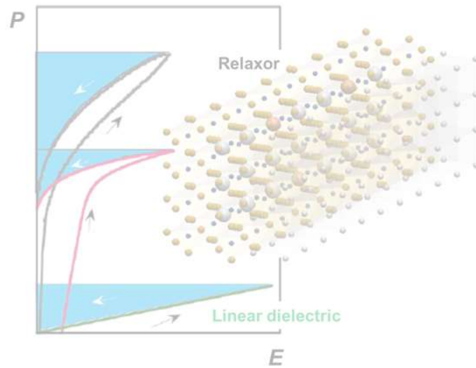
Low-power gas sensors



Broadband piezo-harvesters

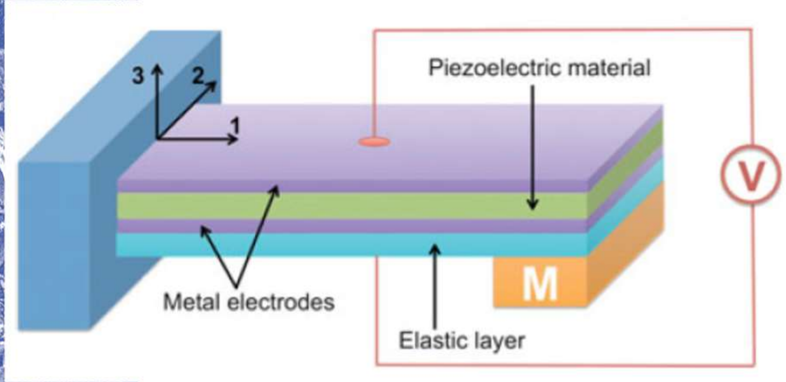


High energy-density capacitors

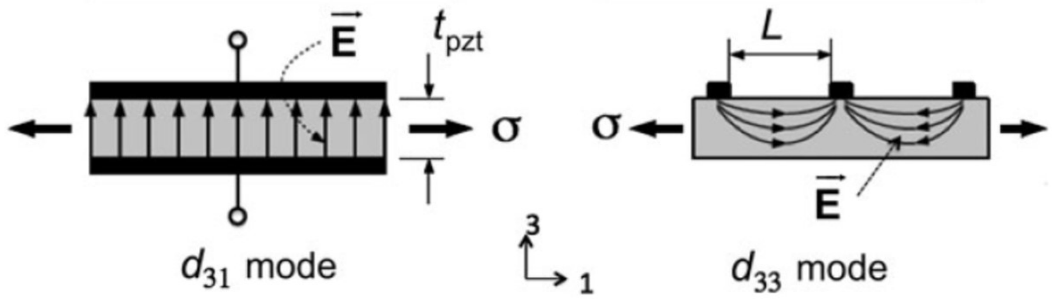


Piezoelectric energy harvesting

Linear piezoelectric energy harvesting



S.-G. Kim et al., MRS Bull. 37 (2012) 1039-1050



Mode of operation

Harvested energy

$$FOM = f\left(\frac{d_{ij}^2 E}{\varepsilon_{33}^{\sigma} tan\delta}\right)$$

↑ d_{ij} ↑ E (Young's modulus)

↓ ε_{33} ↓ $tan\delta$ (mech. losses – $1/Q_m$)

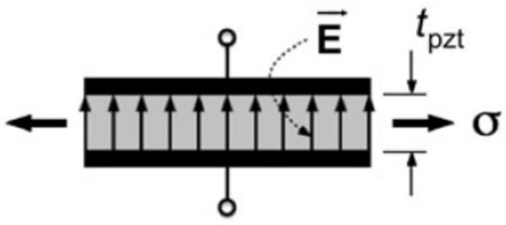
Material	d_{31} (pC/N)	ε_{33}	Frequency (Hz)	Power (µW/mm³)
PZT	170	3000	126	20.5
KNN	100	900	1036	6.5
AlN	3	9	214	0.2

Vibration Source	Frequency (Hz)
Ship engine	12
Numeric control machine	70
Office building, 2nd floor	100

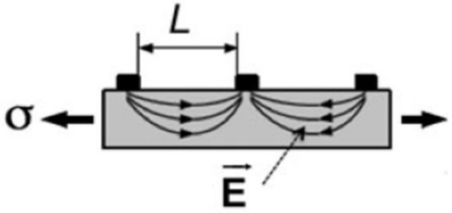
Piezoelectric properties

Maximise d_{ij}

$$FOM = f\left(\frac{d_{ij}^2 E}{\varepsilon_{33}^{\sigma} \tan\delta}\right)$$



d_{31} mode



d_{33} mode

Operational range

Frequency matching

Low-frequency operation

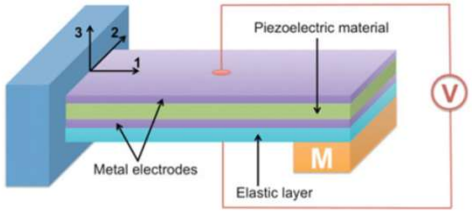
Broadband operation

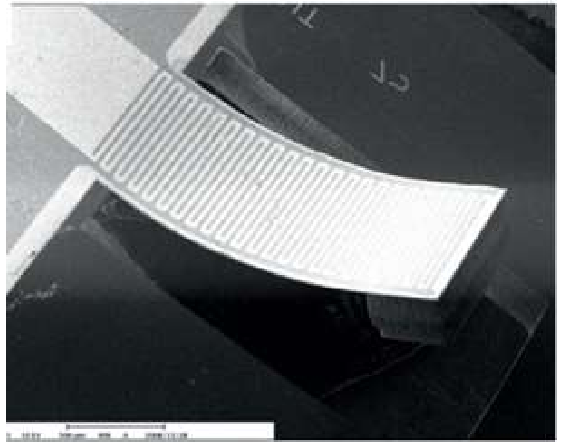
Trade-off ω_r , Q_m

Cost

Thin film deposition

MEMS structures





S. Priya et al., Energy Harvest. Syst. 4 (2017)

Low-frequency energy harvesting

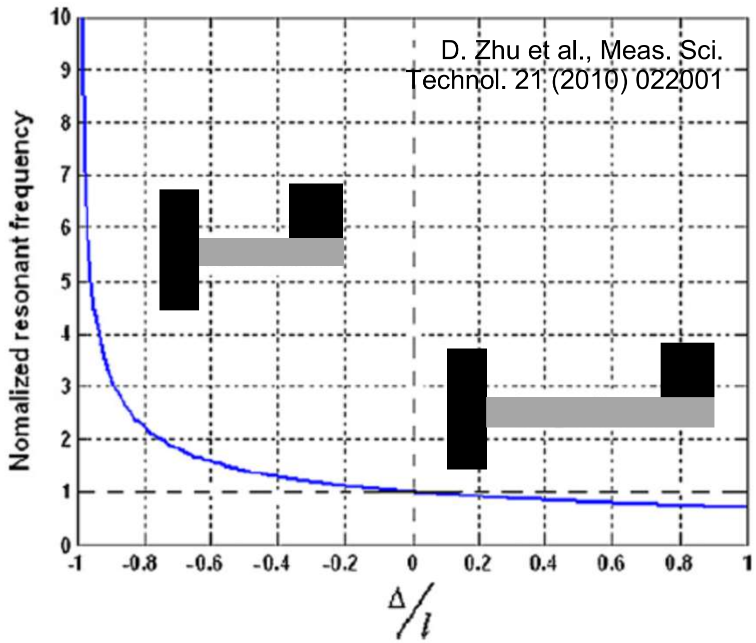
Resonance frequency of mass-cantilever system

$$f_r = \frac{1}{2\pi}\sqrt{\frac{Ewh^3}{4l^3(m+m_c)}}$$

D. Zhu et al., Meas. Sci. Technol. 21 (2010) 022001

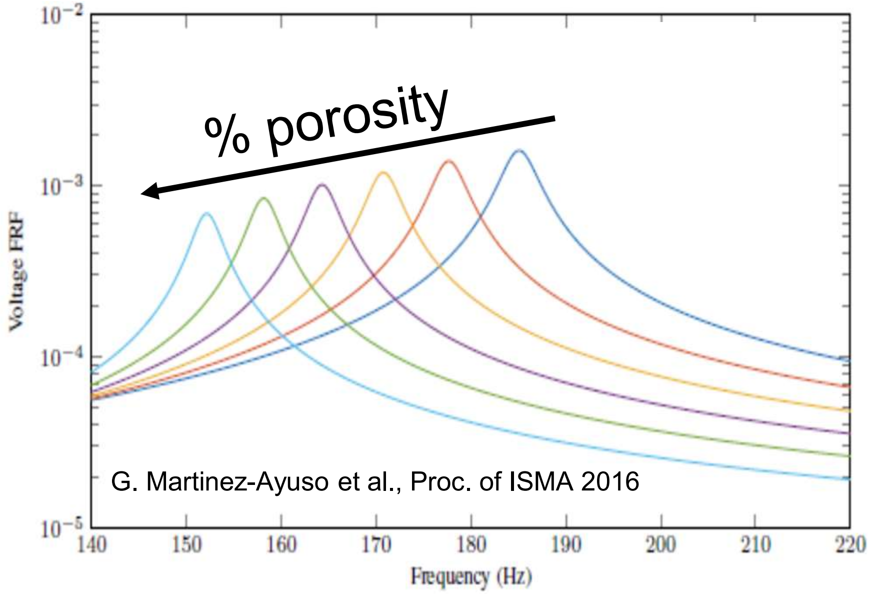
w, h, l	width, thickness, length of cantilever
E	Young's modulus of cantilever material
m, m_c	mass of proof mass and cantilever

Modify cantilever geometry



Q_m remains constant

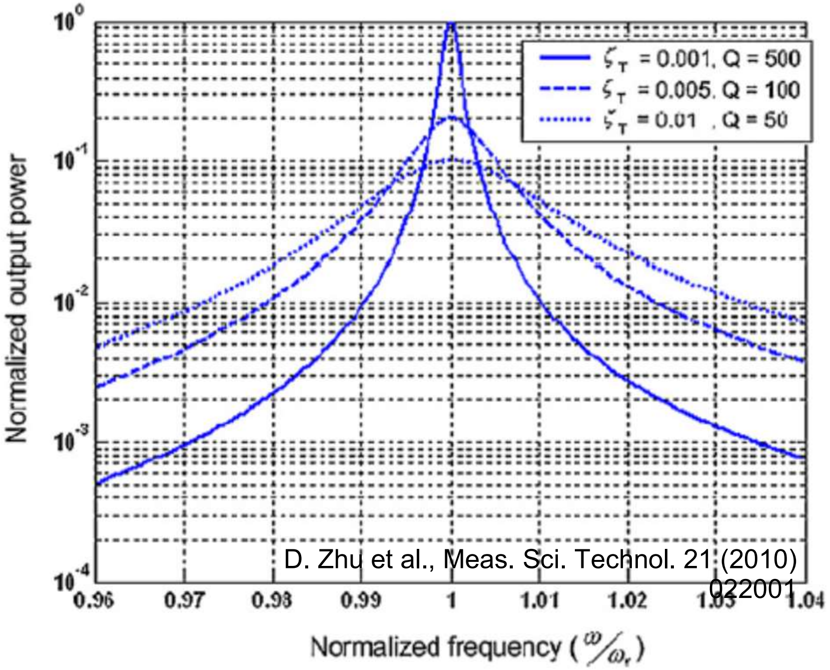
Modify Young's modulus



Q_m decreases

Broadband energy harvesting

Modify Q_m



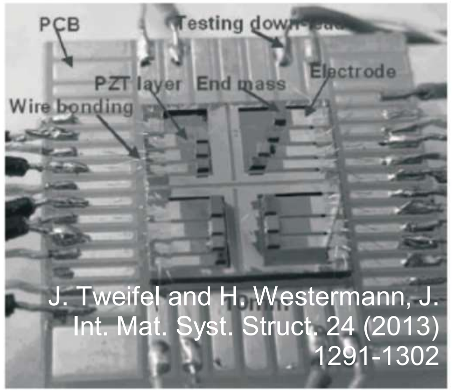
D. Zhu et al., Meas. Sci. Technol. 21 (2010) 022001

Suitable for low-power applications

↓ Q_m = ↓ Stiffness

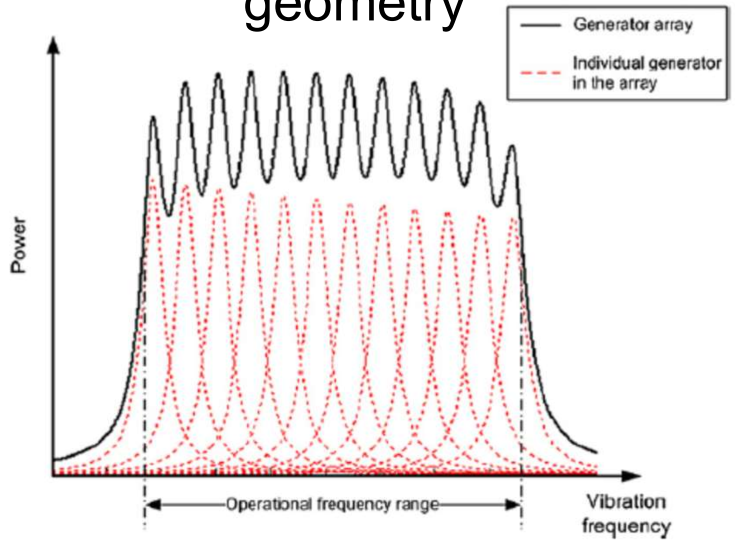
- Increase porosity
- Choose „softer“ material (polymer)

Modify Geometry



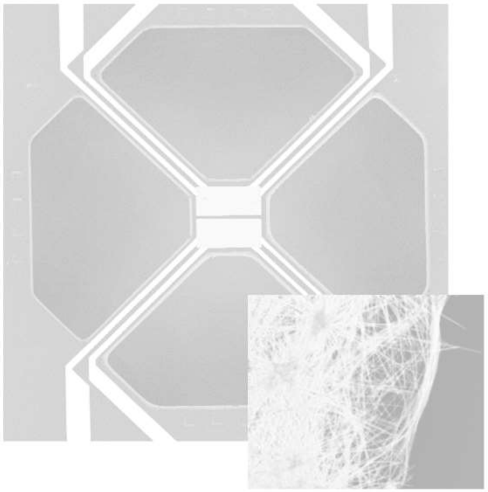
J. Tweifel and H. Westermann, J. Int. Mat. Syst. Struct. 24 (2013) 1291-1302

Cantilever array with variable geometry

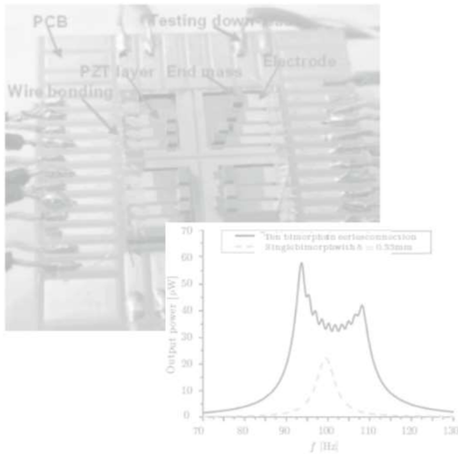


D. Zhu et al., Meas. Sci. Technol. 21 (2010) 022001

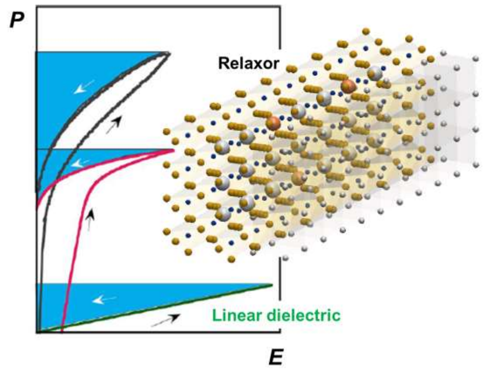
Low-power gas sensors



Broadband piezo-harvesters



High energy-density capacitors



Energy storage for wireless sensors

Energy sources change quickly

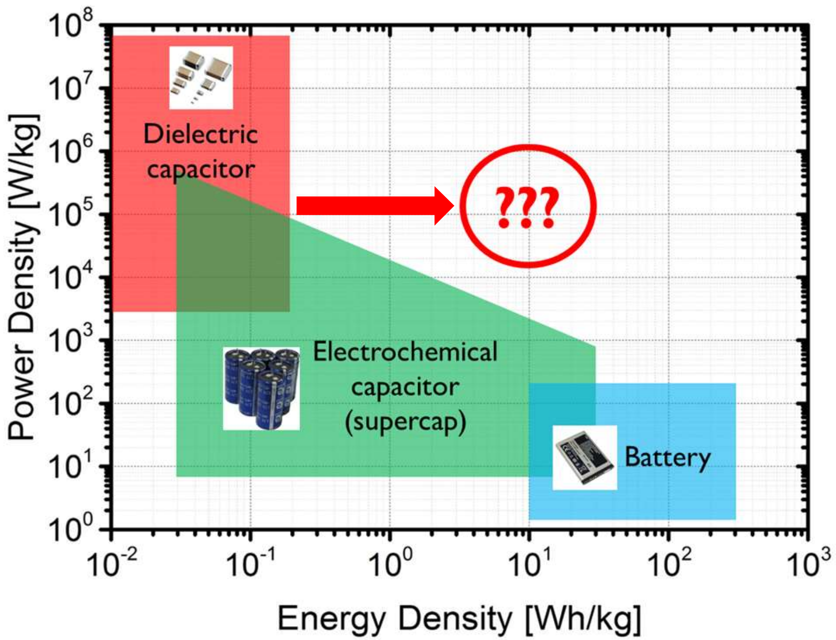
Need quick charge/discharge

High **power** density

Energy sources may be not available for long times

Need long-term energy supply

High **energy** density



Dielectric capacitors:

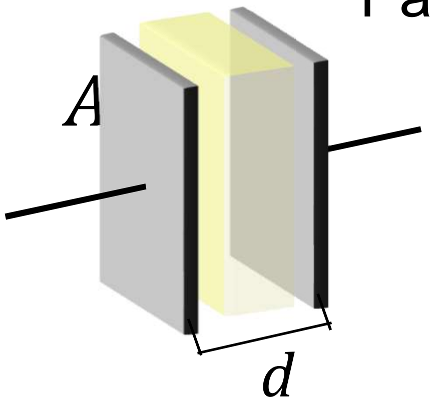
- High power density
- Temperature stability
- Cyclic stability

➡ Need high **energy** density

Adapted from X. Hao, J. Adv. Diel. 3[1] (2013) 1330001

Energy density of ceramic capacitors

Parallel plate capacitor with dielectric



$$U = \frac{1}{2} C V^2$$ El. potential energy

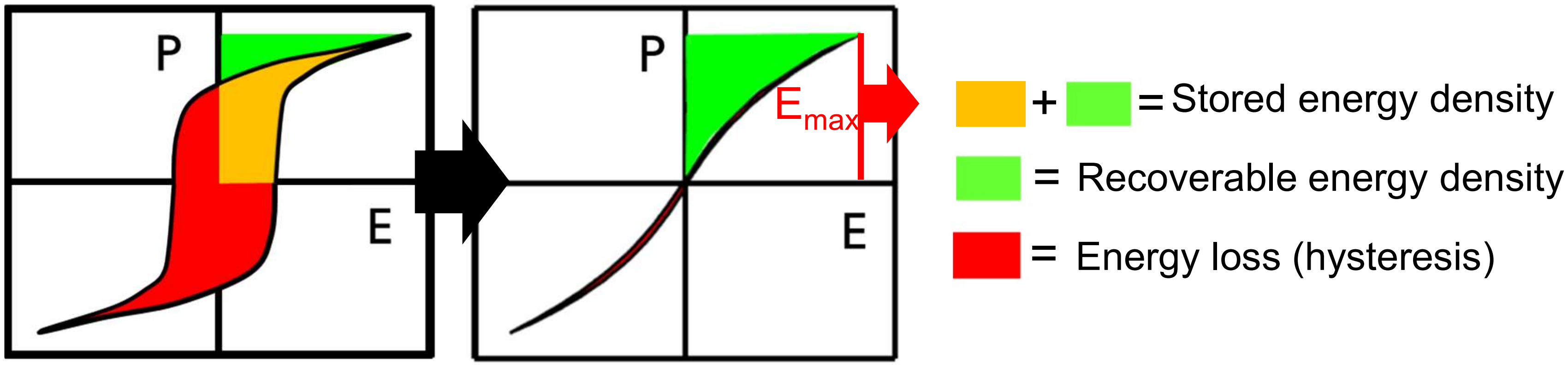
$$J = \frac{U}{Ad}$$ Energy density

$$J = \frac{1}{2}\varepsilon_0 \varepsilon_r E^2 = \int_{P_1}^{P_2} E dP$$

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

$$P = \varepsilon_0 \varepsilon_r E$$

Ferroelectric   Relaxor



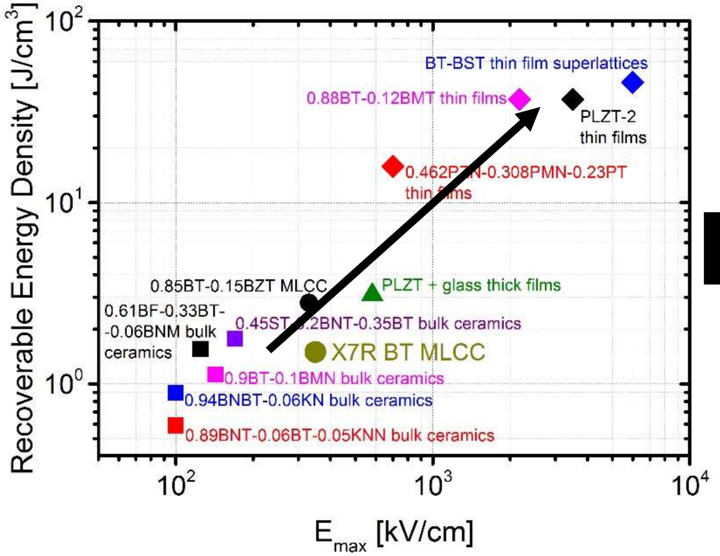
<u>Ways to increase energy density:</u>

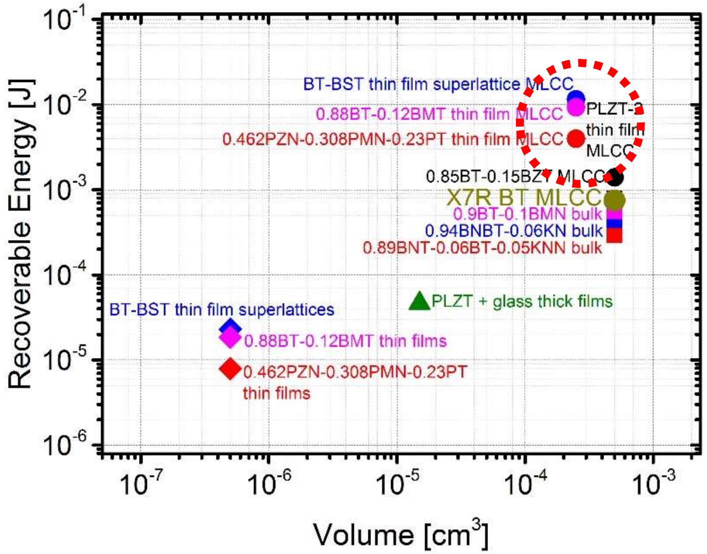
1. Reducing hysteretic losses *while maintaining high permittivity (i.e. P)*
2. Increasing dielectric breakdown strength (DBS) – enhancing E_{max}

A. J. Moulson, J. M. Herbert, *Electroceramics* (2003)

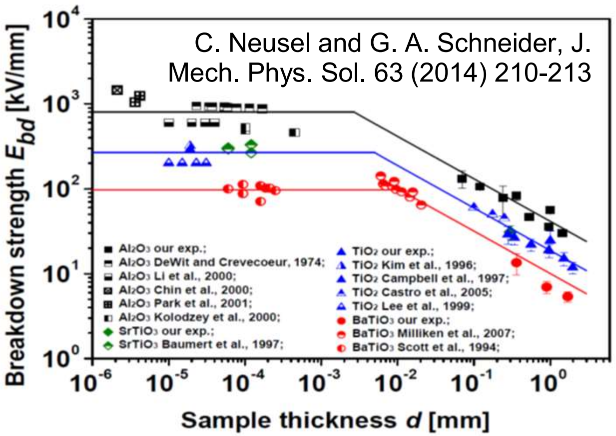
X. Hao, J. Adv. Diel. 3[1] (2013) 1330001

Increasing the DBS: Thin film processing



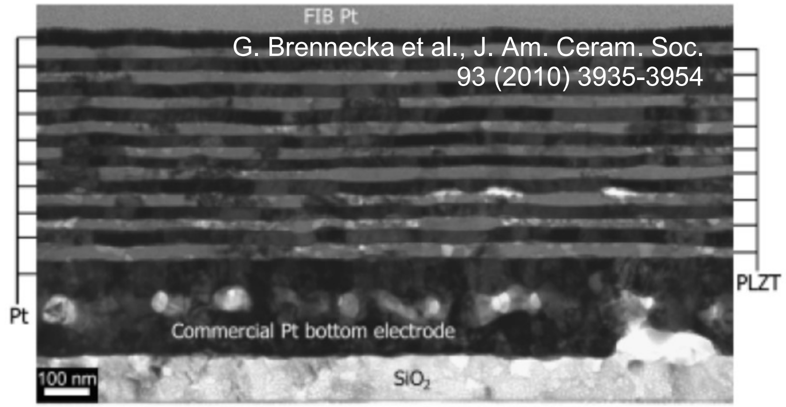


Reduced layer thickness



Less probability to find a critical defect

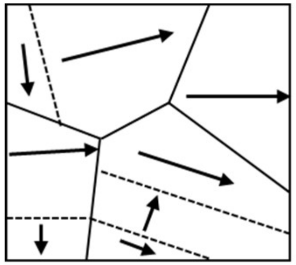
Chemical solution deposition

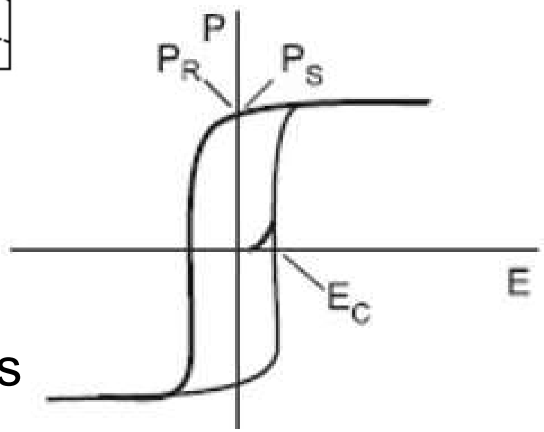


Low porosity and defect density compared to solid-state processing

Optimising the polarisation: Relaxors

Ferroelectric (FE)

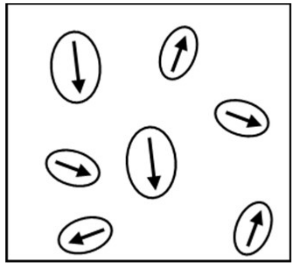


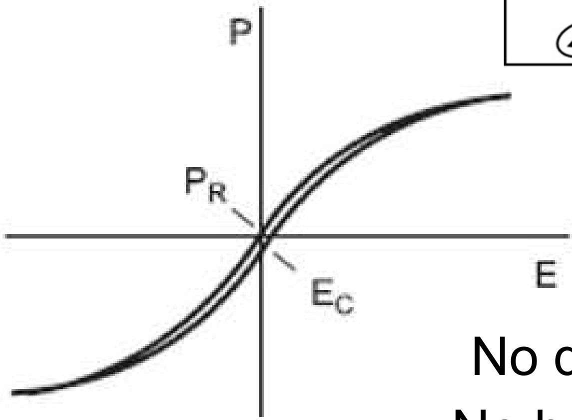


FE Domains

Hysteresis

Relaxor



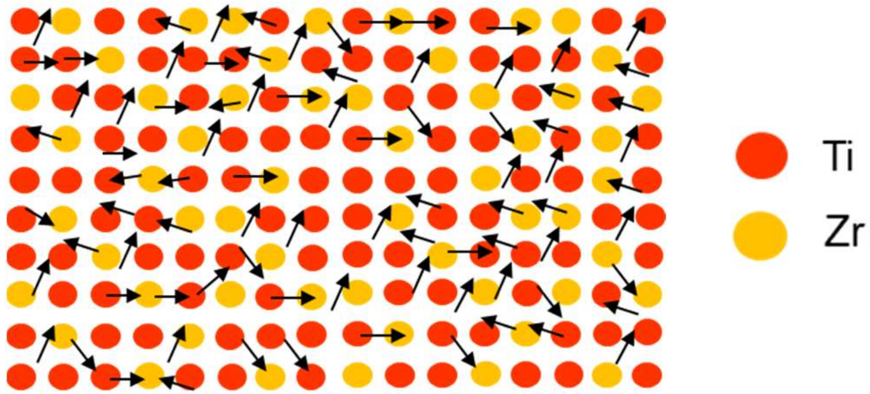


No domains

No hysteresis

$$BaZr_xTi_{1-x}O_3 \quad (Zr^{4+})$$

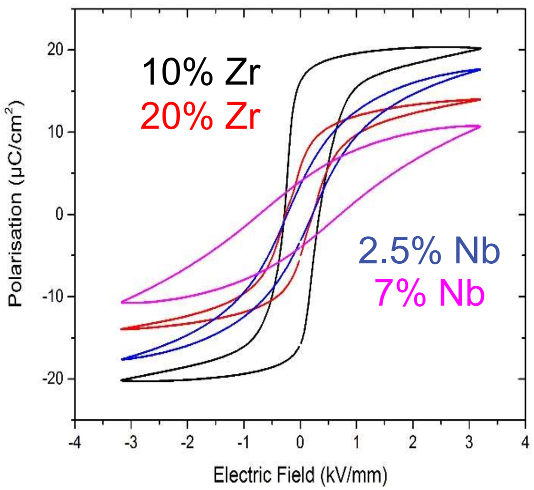
relaxor for x = 0.35



Relaxors: Chemical substitution breaks the long-range cooperative displacement of Ti cations and disrupts ferroelectricity

Optimising the polarisation: Relaxors

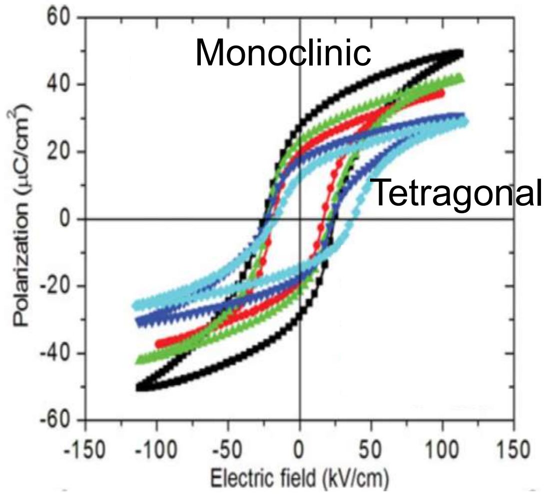
Composition



Substitution disrupts ferroelectricity

M. Deluca et al., unpublished (2019)

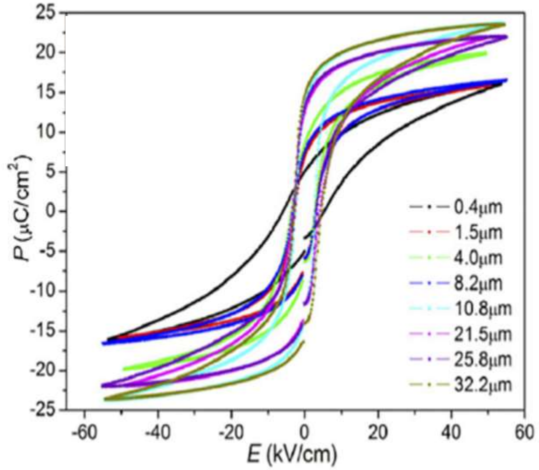
Symmetry



Monoclinic phase increases permittivity

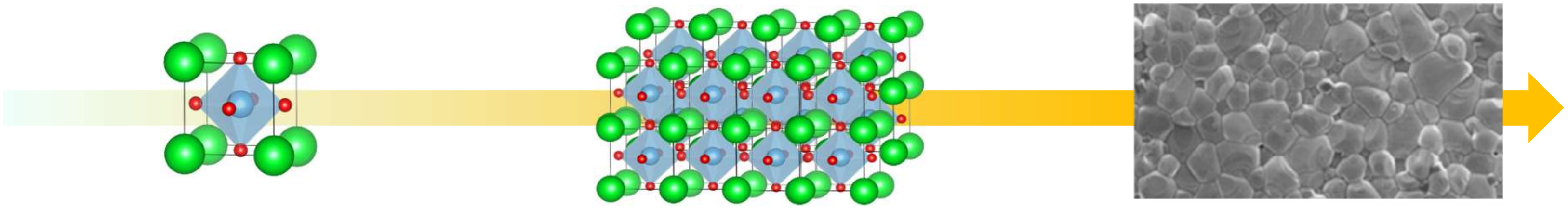
E. C. Lima et al., Ferroel. 465 (2014)

Grain size



Small grain size suppresses ferroelectricity

M. Acosta et al., Appl. Phys. Rev. 4 (2017) 041305

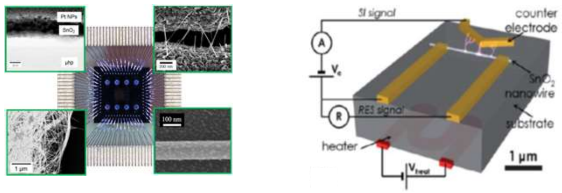


Atomic scale **Nanoscale** **Mesoscale**

Knowledge of relationship between chemical substitution and macroscopic polarisation is decisive for **optimising polarisation loops** in relaxors.

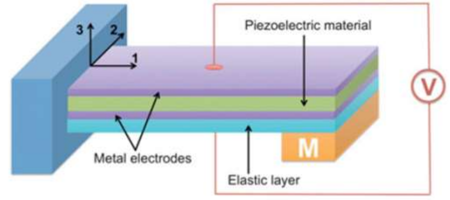
Self-powered wireless sensor nodes

MEMS resistive +
Ionisation gas sensor



0.145 J/day

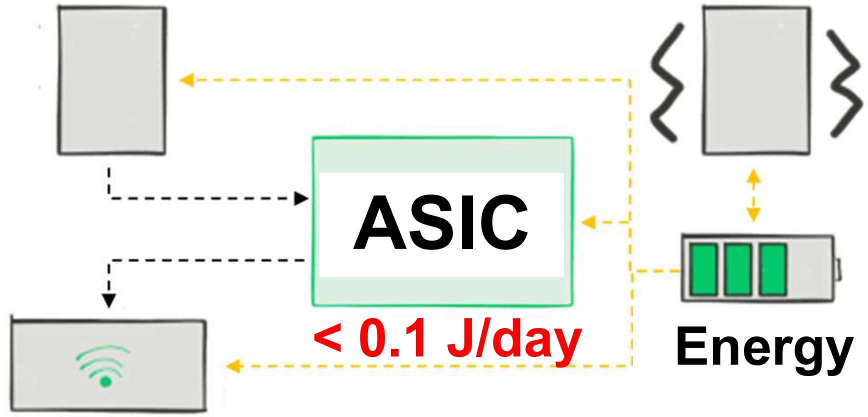
Piezoelectric energy harvester



0.9 J/day

Sensor

Energy harvester



< 0.1 J/day

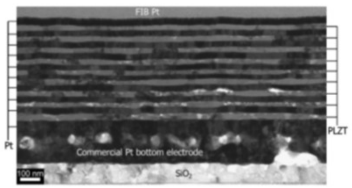
Energy storage

Wireless
module

< 0.1 J/day

Energy autonomous
operation possible!

Thin film ceramic MLCC



40 J/cm^3
8 cycles/hour
0.9 J/day

Take-home messages:

Autonomous IoT sensor nodes must combine the following elements:

- **Low-power sensors** including ASIC and network element
- **Resilient** energy harvesters such as **broadband** and **low-frequency piezoelectric energy harvesters**.
- **High-power** and **high energy density** energy storage.

Ionization or **self-heating gas sensors** may be a viable way to reduce power consumption and to improve selectivity.

Piezoelectric energy harvesting is suitable to low-power sensor nodes and works 24/7, but need broadband technology

High storage energy density is attained in **dielectric capacitors** using **thin film** technology and **relaxor systems**

Acknowledgements

FP7-ICT-2013-10 – GA. 611887

MSP – Multi Sensor Platform for Smart Building Management

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ERC-COG-2018 – GA. 817190

CITRES - Chemistry and Interface Tailored Relaxor thin films for Energy Storage capacitors

FWF Single Project – Nr. P29563-N36

Origin of relaxor behaviour in Ba-based lead-free perovskites

FFG „Production of the Future" – Nr. 858637

FUNKYNANO – Optimized Functionalization of Nanosensors for Gas Detection by Screening of Hybrid Nanoparticles

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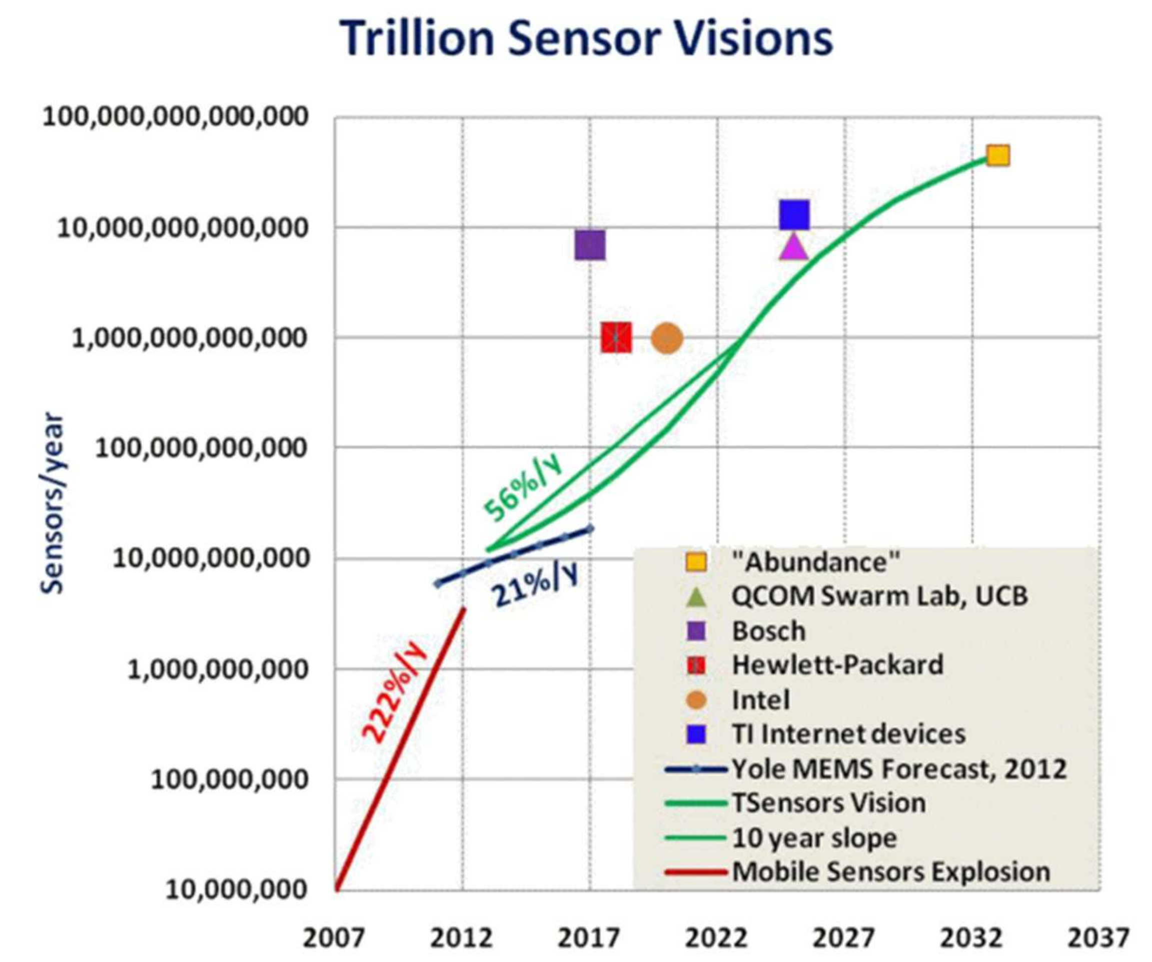

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