Energy Autonomous Environmental Sensors

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GreEnergy Workshop

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MCL at a glance - History

- Founded 1999 MCL is one of the leading competence centres in material science in Austria with ~ 160 employees. The COMET K2 Centre for „Integrated Research in Materials, Processing and Product Engineering“ focuses on the full materials value chain in applications.
- In March 2012 the research area „Materials for Microelectronics“ was established:
  - Nanosensors and multi-sensor systems
  - CMOS integration of nanotechnology based sensor components
  - 3D-System Integration, Packaging and Reliability
  - Materials characterization from nano- to microscale.

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Outline

1. Motivation
2. Gas Sensor Devices
3. Smart System Integration
4. Chemical Sensors @ MCL
5. Multi-Gas Sensor Device
6. The FOXES Project
7. Summary & Outlook

1. Motivation

- ~90% of time is spent indoors; outdoor pollutants also found indoors, additional indoor pollutant sources add to disease burden
- > 400.000 premature deaths in EU27+UK every year (EEA); COVID-19 and influenza add further mortality

Air Quality Monitoring

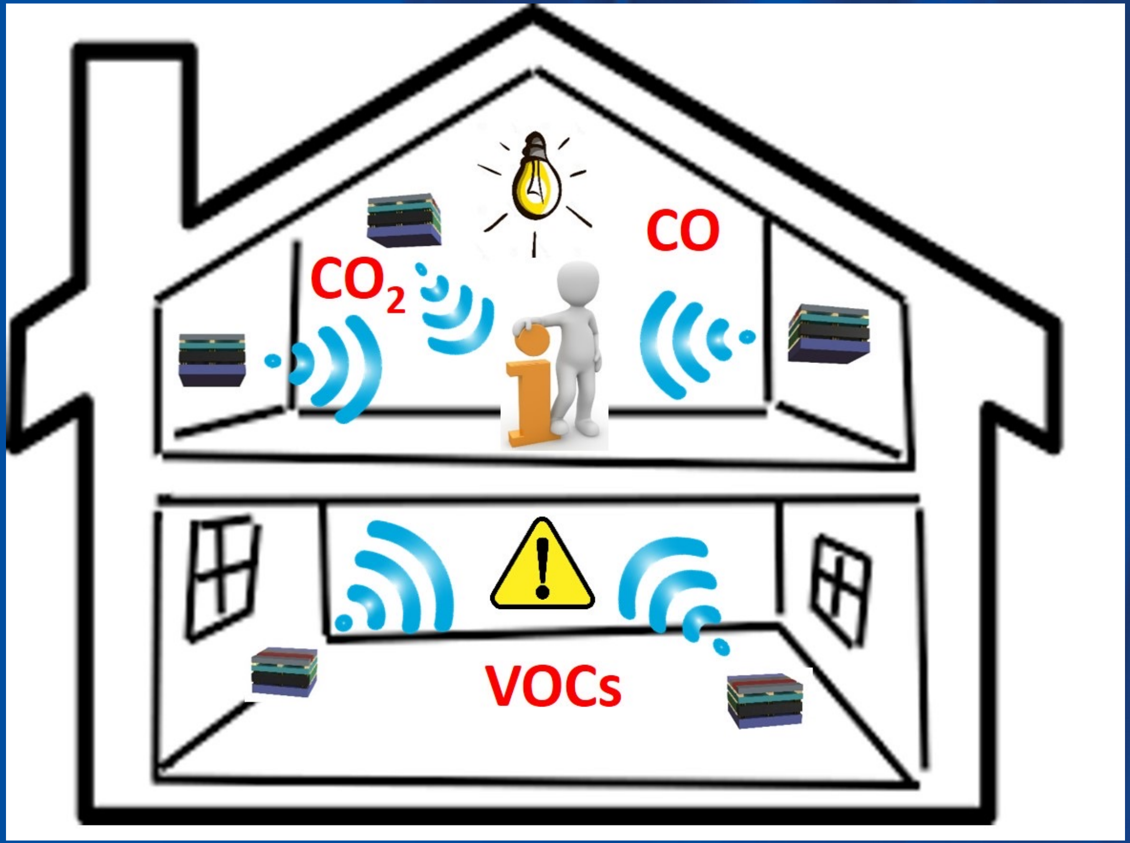
Indoors
CO, CO_2, VOCs, PM

Outdoors
NO_2, O_3, CO, PM_{10}, $PM_{2.5}$, UFPs

Air Quality Monitoring

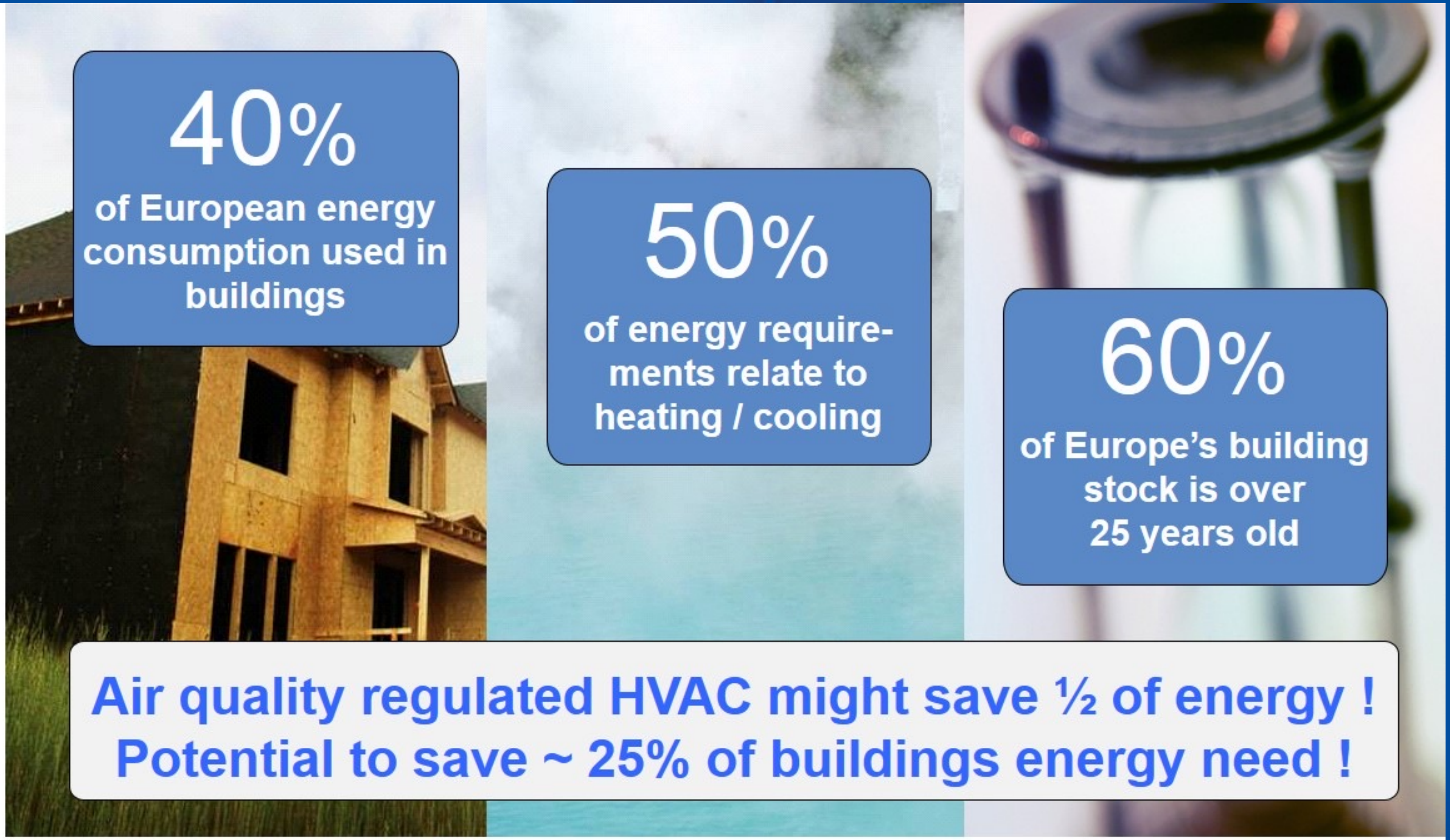
- ❑ Consumer Electronics: Individual monitoring of environmental conditions, for detection of potentially harmful situations, and for alerting people with health predisposition of upcoming afflicting environmental conditions (O_3, NO_2, …).
- ❑ Indoor environmental monitoring: Private homes, office buildings, hospitals or vehicle/airplane cabins.
- ❑ Outdoor environmental monitoring: Setting up sensor networks for area-wide monitoring of air pollutants (SO_2, NO_2, CO, CO_2, O_3 etc.) and greenhouse gas emissions.
- ❑ Smart medicine & smart health: Breath analysis for monitoring patients with chronical illness (e.g. diabetes) and screening of upcoming diseases (e.g lung infections).
- ❑ Agriculture and Food: Monitoring gaseous conditions in green houses, monitoring freshness of fruits and taking preventive actions when conditions potentially endanger crops.

- ❑ Indoor Air Quality (IAQ) Monitoring everywhere - in all rooms !
- ❑ Smart Homes, Smart Living,…
- ❑ Outdoor Air Quality Monitoring – pollution mapping,…



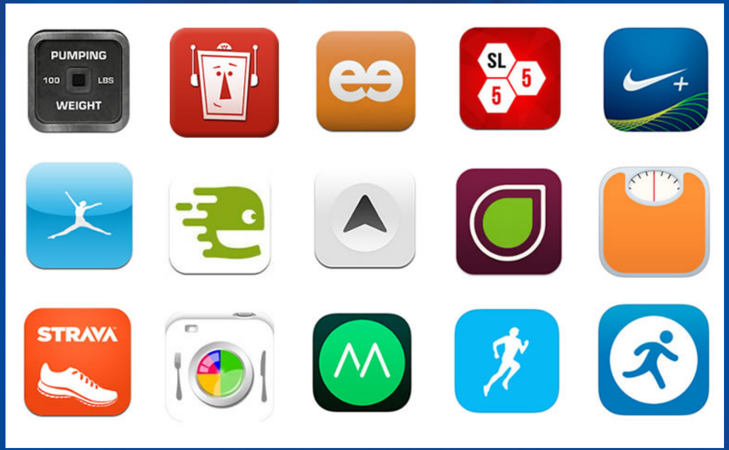
IoT Sensor Networks for indoor and outdoor air quality monitoring

- ❑ Air Quality Monitoring for Heating, Ventilation, Air Conditioning (HVAC)
- ❑ Smart Building Management: VOCs, CO_2,…

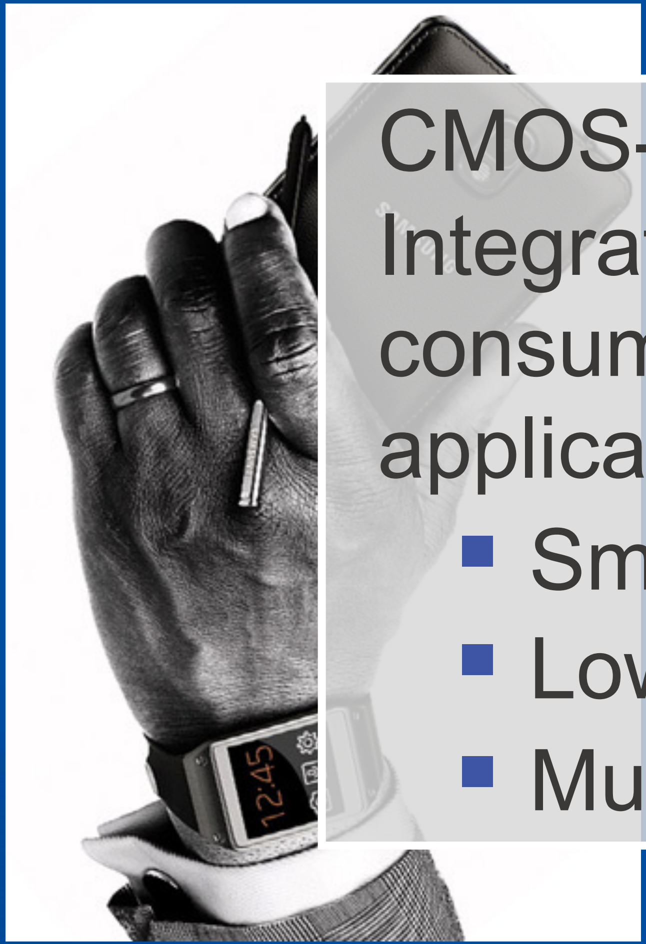


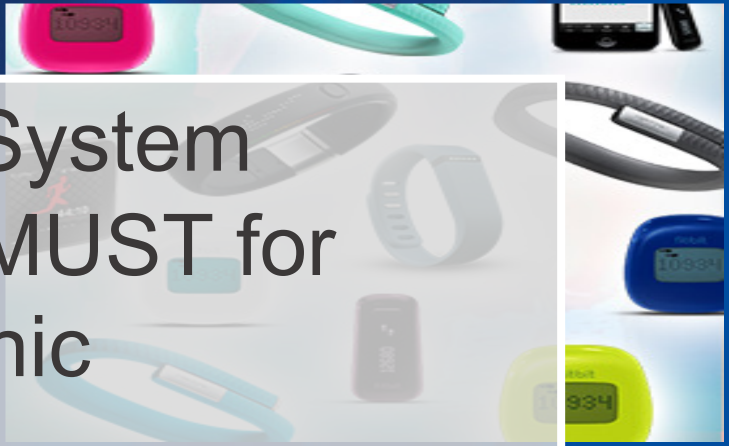
Energy Efficiency improvement potential in buildings in Europe (source: Siemens, 2011)

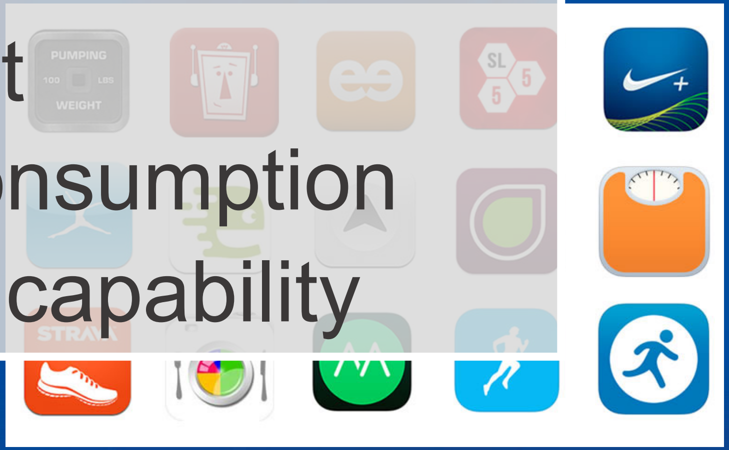
- New life style applications require chemical sensors in smart phones, smart watches,...
- Example: breath analyzes, individual monitoring of environmental conditions,…



- New life style applications require chemical sensors in smart phones, smart watches,...
- Example: breath analyzes (smart medicine: diabetes, upcoming diseases…)



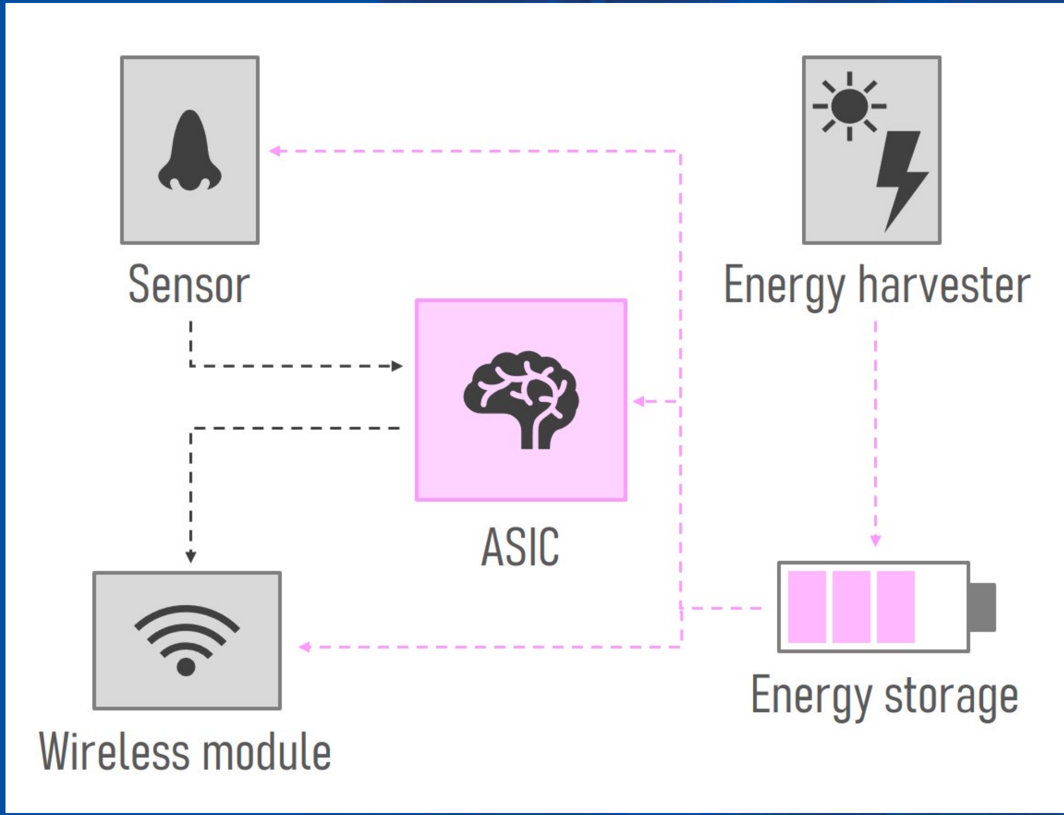




CMOS- & Smart System Integration are a MUST for consumer electronic applications !

- Small footprint
- Low power consumption
- Multi-sensing capability

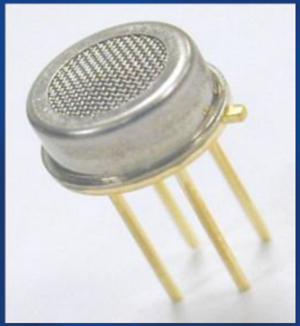
Vision: Energy Autonomous Sensor Systems

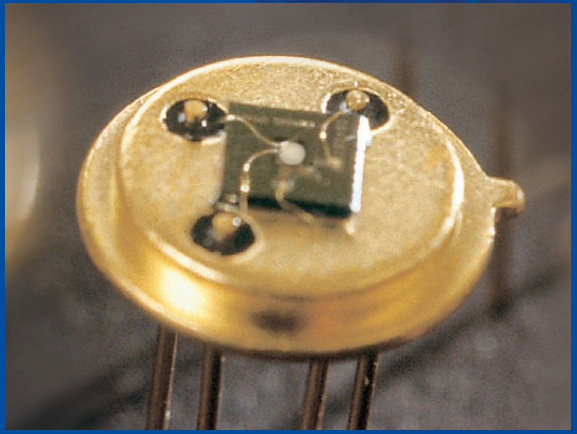


IoT Sensor Networks for indoor and outdoor air quality monitoring

2. Gas Sensor Devices

- ❑ Rather conventional devices
- ❑ Cross selectivities
- ❑ High power consumption
- ❑ Mostly for professional use only



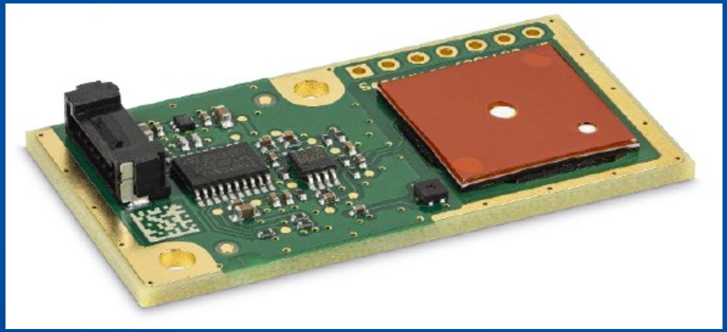


Sensor Solutions

- Rather conventional devices
- Cross selectivities
- High power consumption
- Mostly for professional use only

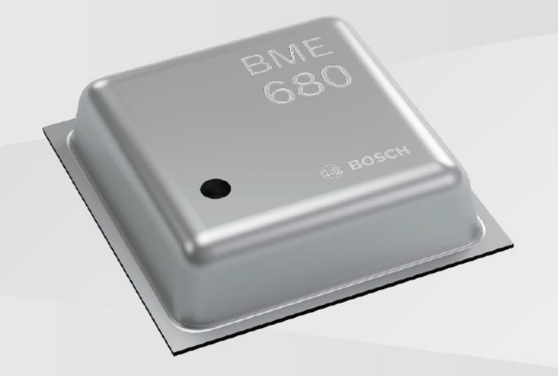
Datasheet Sensirion SCD30 Sensor Module
CO_2, humidity, and temperature sensor

SENSIRION



Data Sheet SFA30
Formaldehyde Sensor Module for HVAC and Indoor Air Quality Applications

BME680
Low power gas, pressure, temperature & humidity sensor



BOSCH

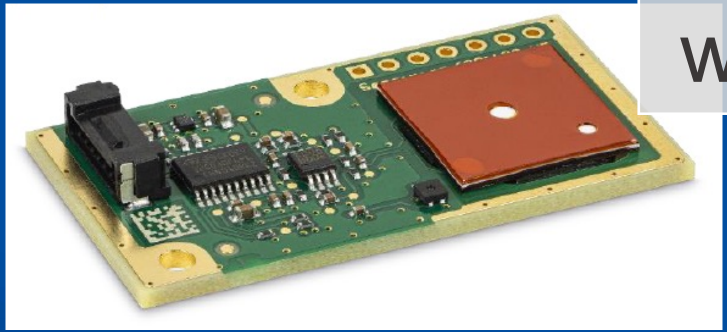
Datasheet Sensirion SCD30 Sensor Module
CO_2, humidity, and temperature sensor

SENSIRION

- ❑ Rather conventional devices
- ❑ Cross selectivities
- ❑ High power consumption
- ❑ Mostly for professional use only

Most of today‘s gas sensors are not smart devices – no integration with CMOS technology!

SENSIRION



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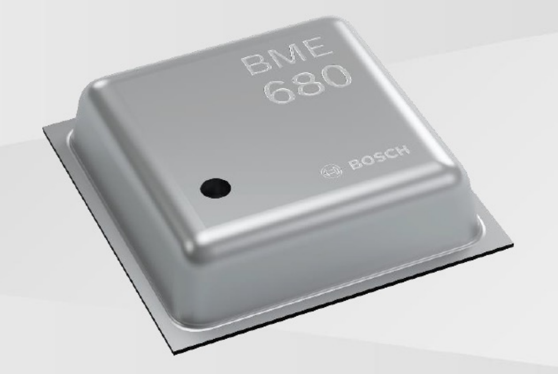


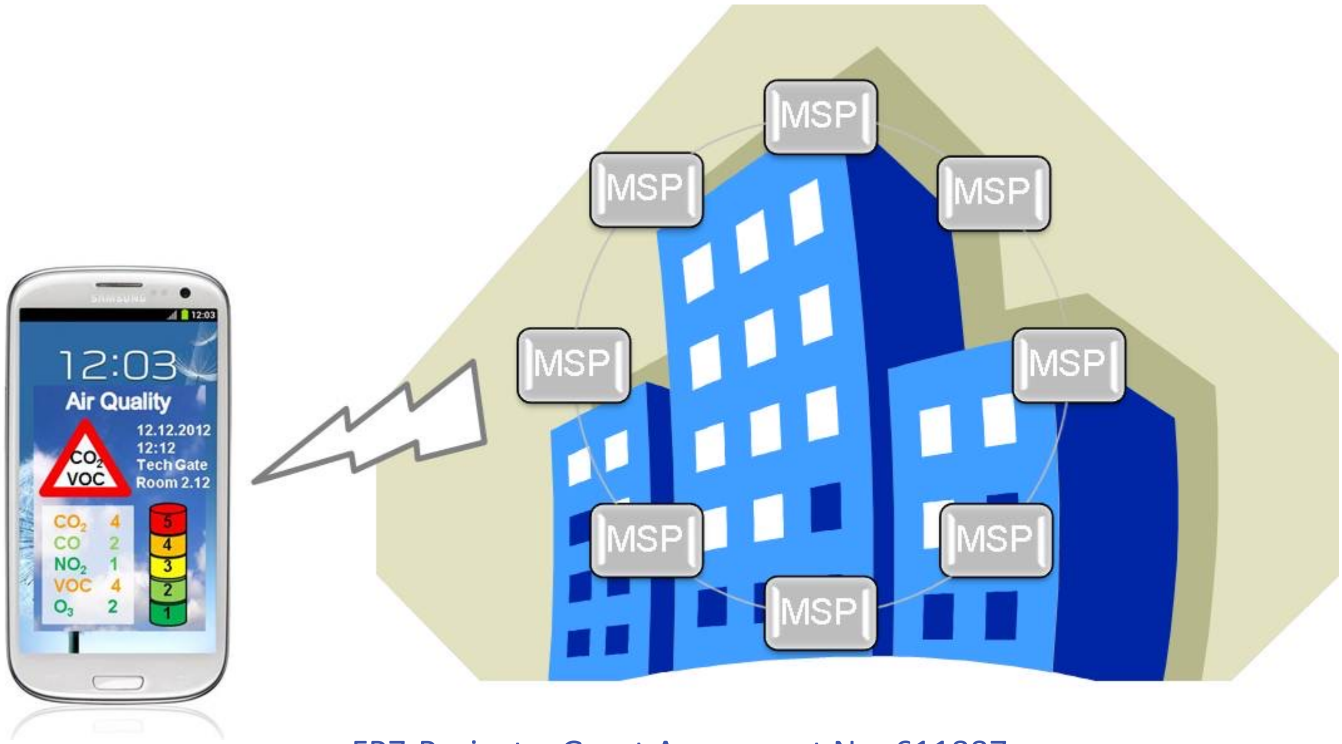
BOSCH

No Multi-Gas Sensor Devices !

	MATEAS Device	Bosch BME 680	Sensirion SFA30	Sensirion SGP41	Alphasense	Figaro TGS8100
Detection principle	conductometric	conductometric	conductometric	conductometric	electrolyte	conductometric
Size [mm x mm x mm]	< 4 x 4 x 2	3 x 3 x 1	17 x 17 x 1,5	2,4 x 2,4 x 0,85	32,3 x 32,3 x 16,5	3,2 x 2,5 x 1
Power consumption[mW]	< 0.5	11.9	10	10	not specified	15
Response time [sec]	< 5	not specified	120	120	30	not specified
Target gas						
"Air contaminants"		no	no	no	no	0 - 30 ppm
VOCs / Ethanol	100 ppb - 60 ppm	only quality index	no	500 - 10000 ppb	no	no
Nitrogen oxide	1 ppb - 10 ppm	no	no	50 - 600 ppb	no	no
Formaldehyde	10 ppb - 1 ppm	no	0 - 1000 ppb	no	no	no
Carbon monoxide	1 ppm - 1000 ppm	no	no	no	100 ppb - 10 ppm	no
Benzene	0 - 15 ppb	no	no	no	no	no
Toluene	50 ppb - 50 ppm	no	no	no	no	no
Ammonic	1 ppm - 500 ppm	no	no	no	no	no
Ozone	1 ppb - 1000 ppb	no	no	no	no	no
Sulfur dioxide	1 ppb - 1000 ppb	no	no	no	no	no
Hydrogen sulfide	50 ppb - 50 ppm	no	no	no	no	no

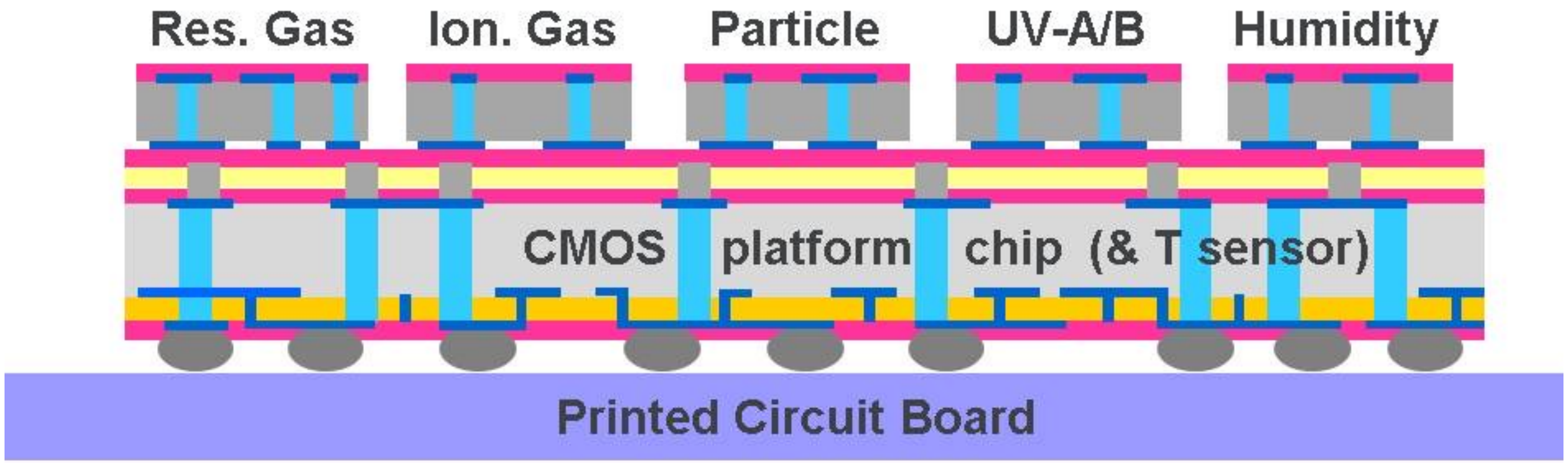
3. Smart System Integration

The MSP-Project - Multi Sensor Platform for Smart Building Management

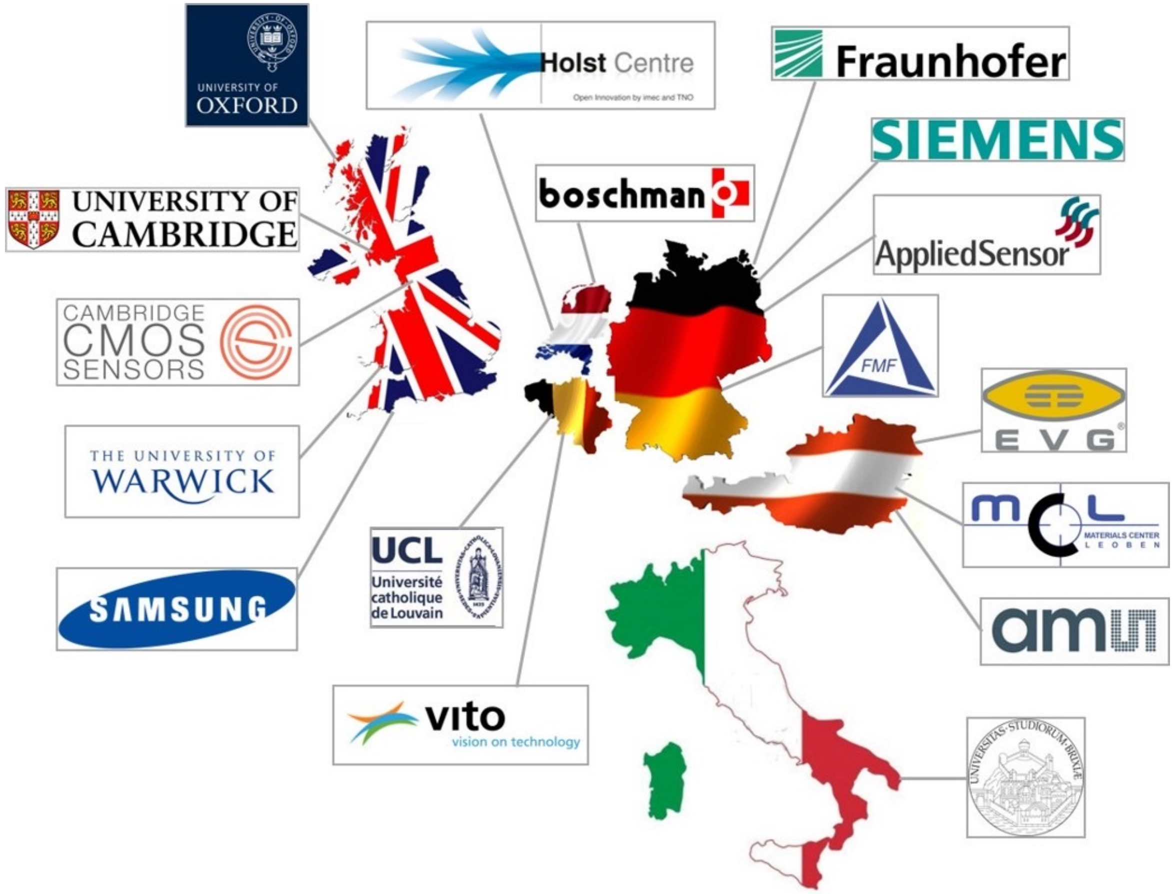


FP7-Project – Grant Agreement No. 611887

- Development of smart 3D-integrated multi-sensor systems enabling indoor and outdoor environmental monitoring !



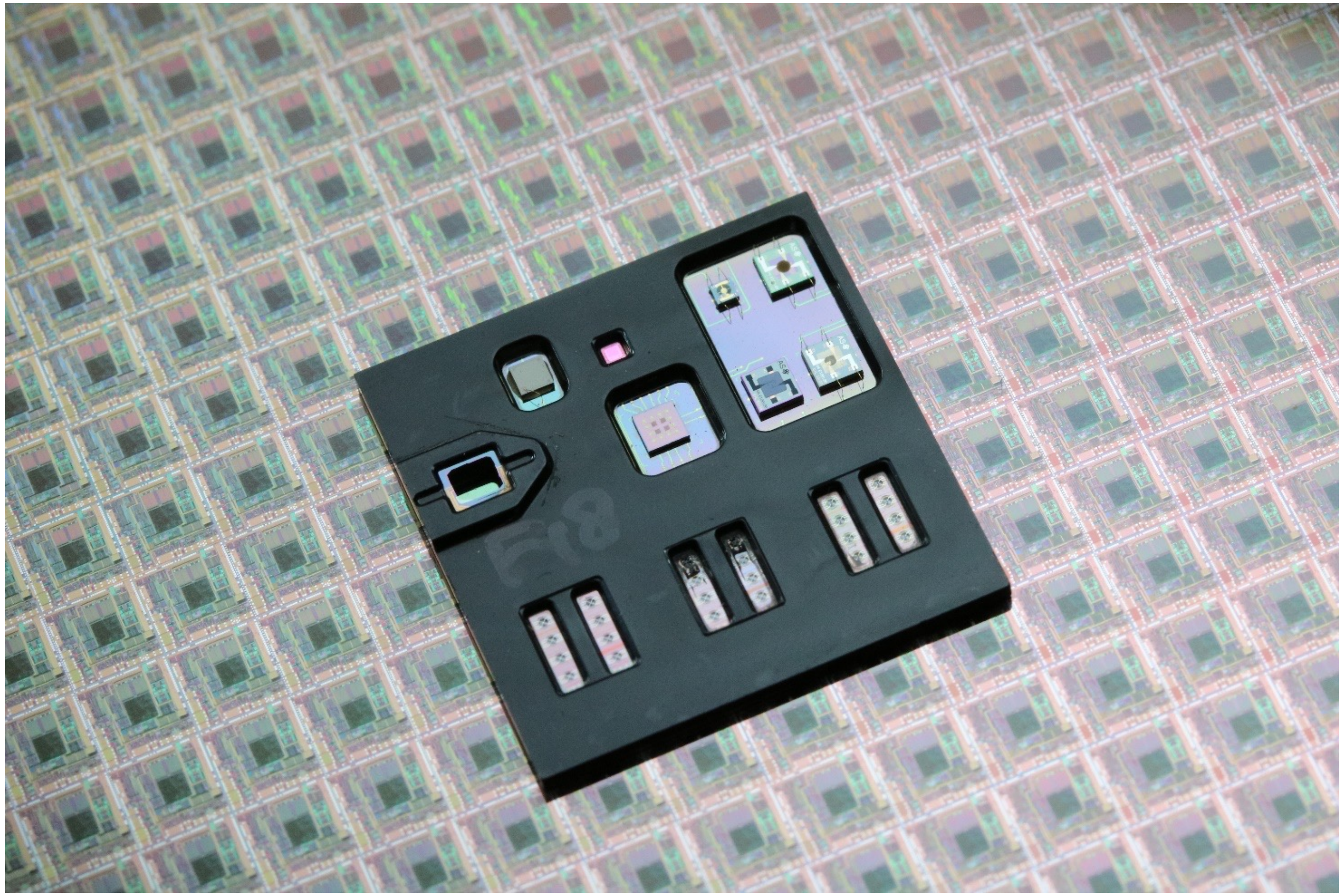
- 17 partners from 6 countries – 1/9/2013 – 30/4/2017
- 18.5 M€ budget and ~ 1300 Person Months effort

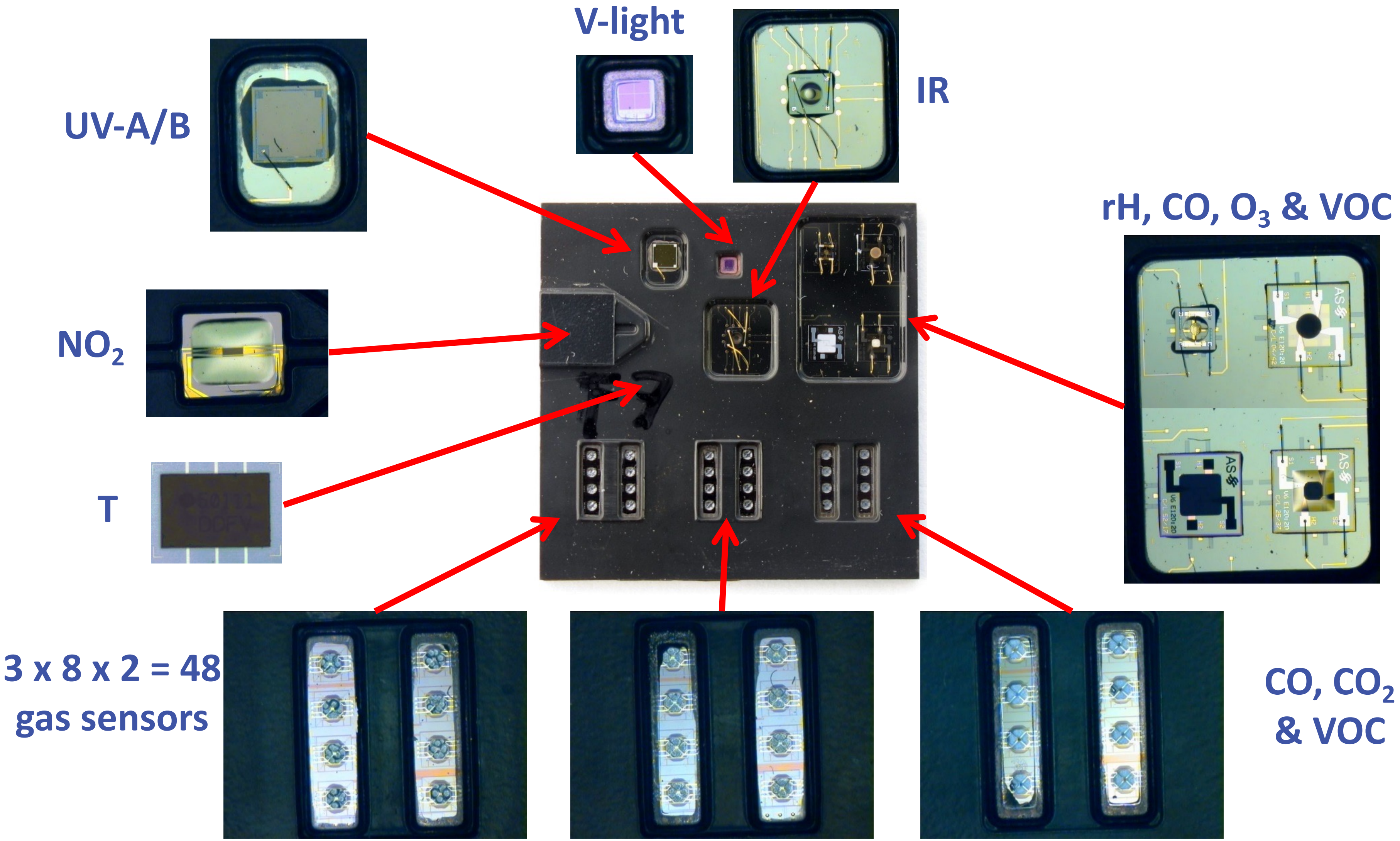


SEVENTH FRAMEWORK PROGRAMME

- 3D-integrated Multi-Sensor System !
- Worldwide unique Smart System - 57 Sensors!

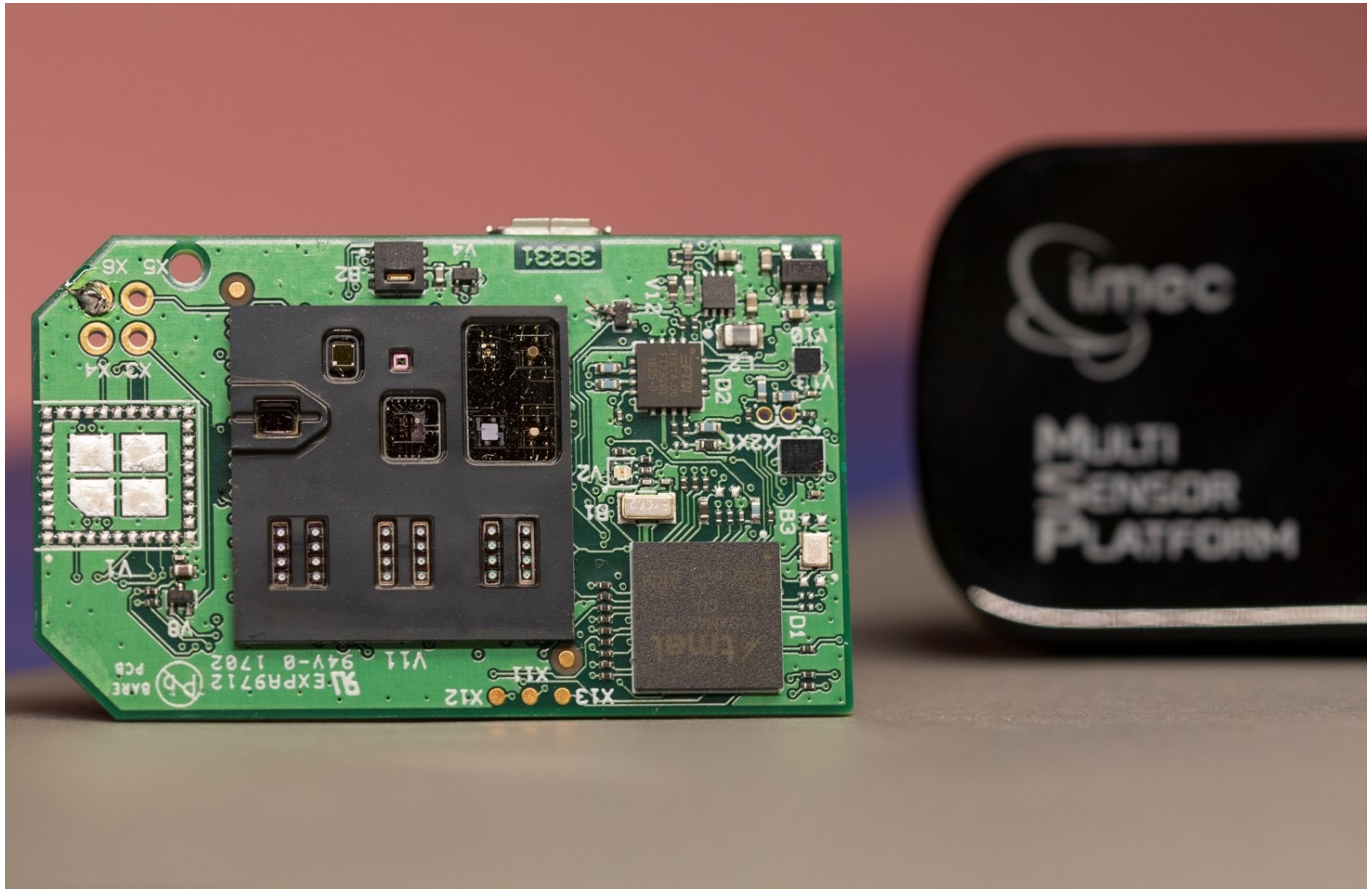
Energy harvesting: piezoelectric + photovoltaics





SEVENTH FRAMEWORK PROGRAMME

MSP WEARABLE DEVICE



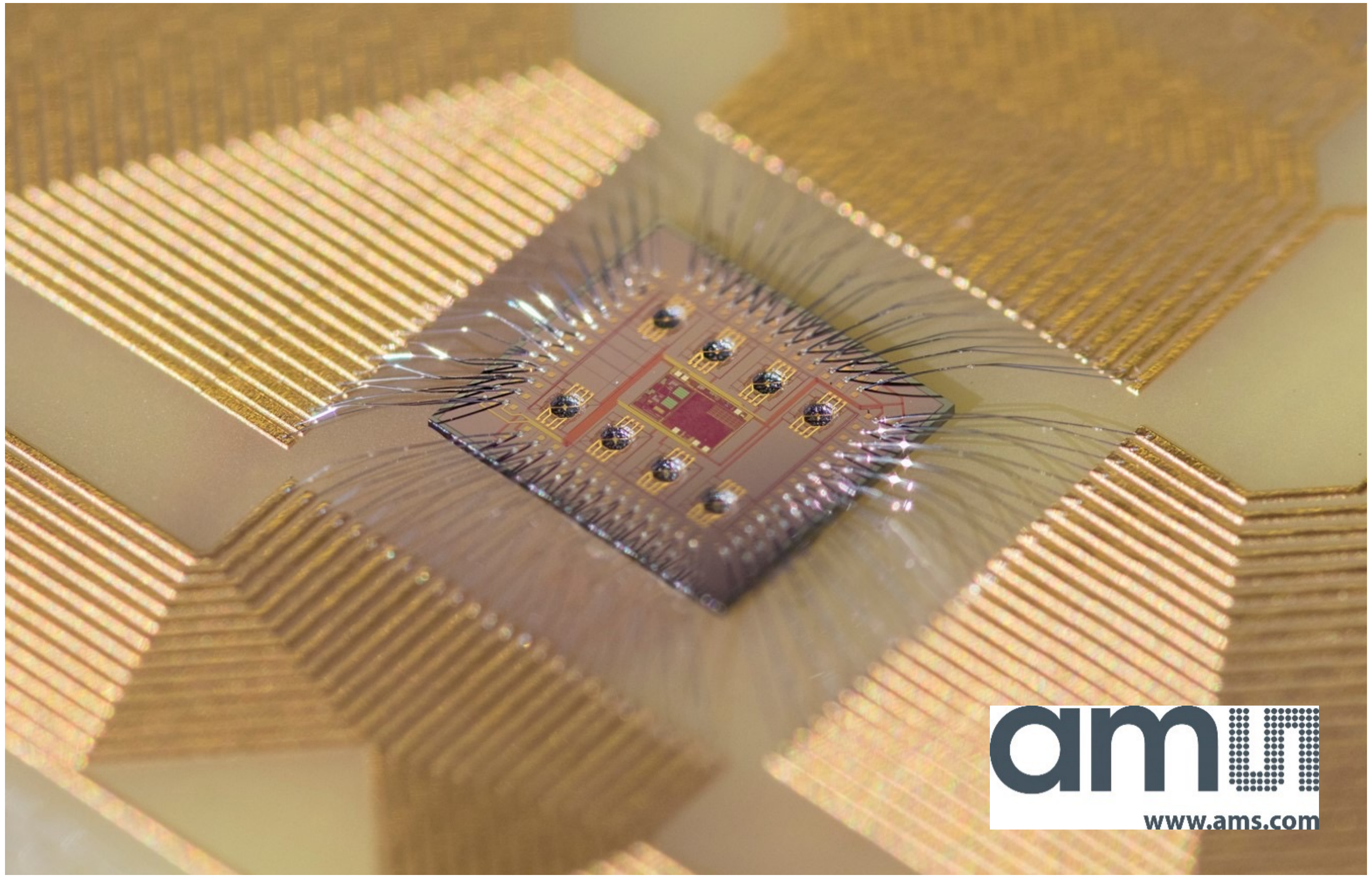
MSP WEARABLE DEVICE

SEVENTH FRAMEWORK PROGRAMME

MSP WEARABLE DEVICE

SEVENTH FRAMEWORK PROGRAMME

- Worldwide unique CMOS based micro-hotplate chip
- 8 micro-hotplates for 16 gas sensors



SEVENTH FRAMEWORK PROGRAMME

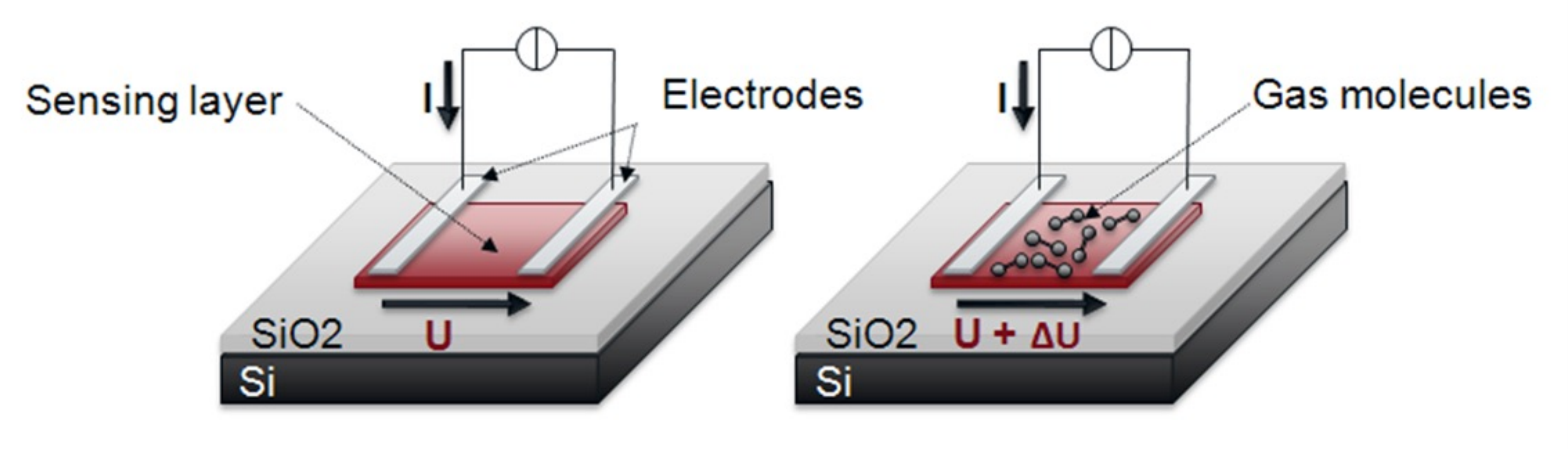
4. Chemical Sensors @ MCL

❑ Ultrathin MOx films, nanowires, and nanoparticles

- SnO_2-, ZnO,- CuO-films
- SnO_2-, CuO-, ZnO-NWs
- WO_3-NWs

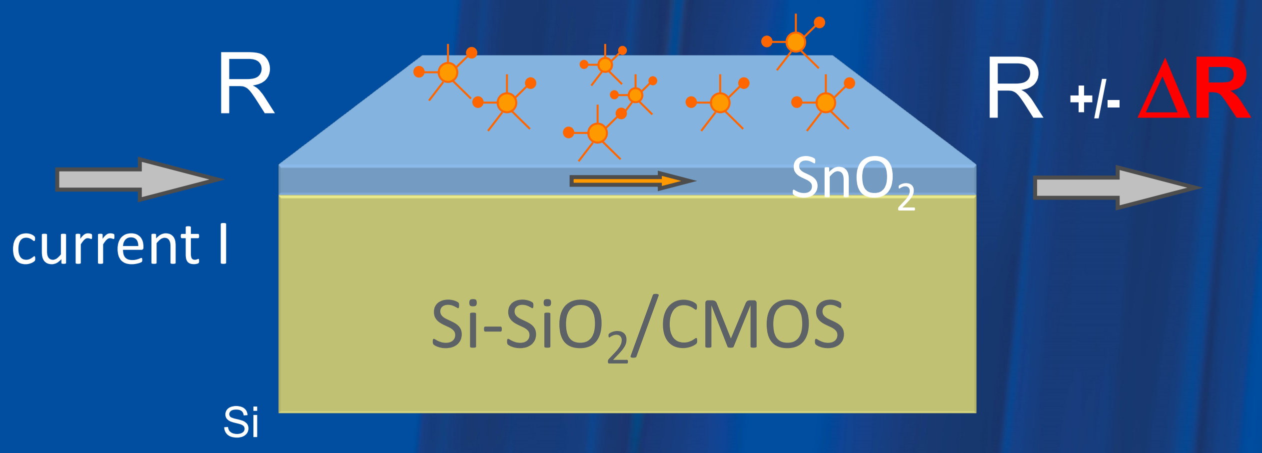
- Au, Pt, Pd
- AuPd, PdPt,…
- PdRuAg,...

- CO, CO_2, VOCs, HCmix
- H_2, H_2S, O_3 and NO_2
- In dry & humid air



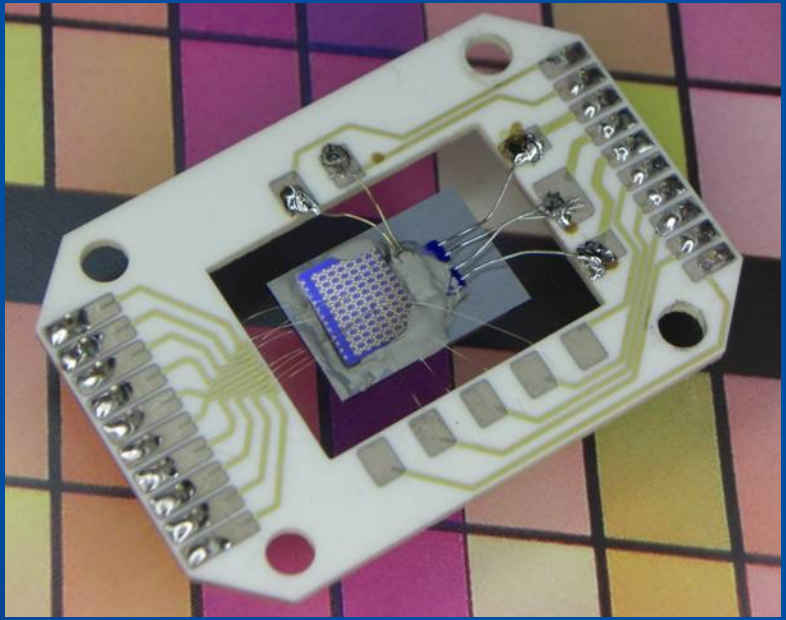
Sensor principle

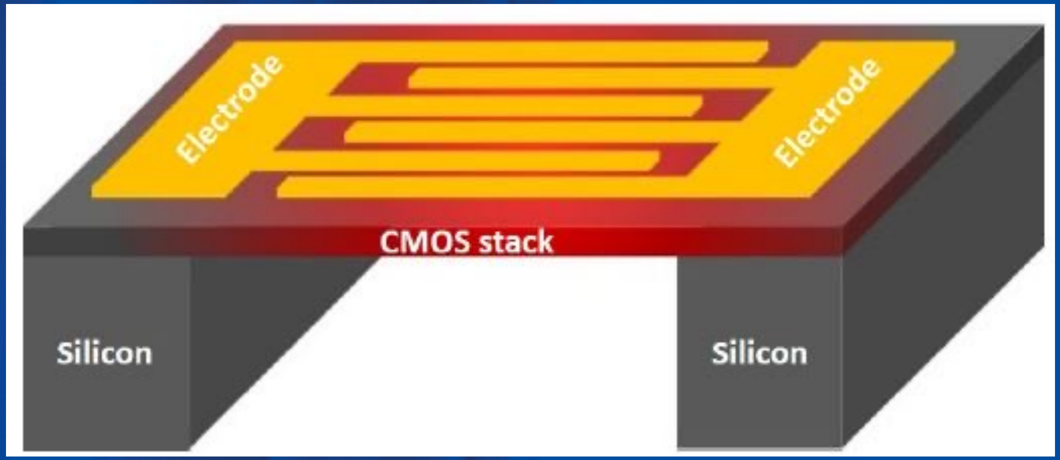
- Reducing gas: $CO + O^-$ ⟶ $CO_2 + e^-$
- Oxidizing gas: $NO_2 + e^-$ ⟶ NO_2^-
- Change of resistivity R ⟶ Sensor device !



Very thin films - nanosensor – big effect ΔR !

- ❑ MOx film sensors require heating up to 400°C and more !
- ❑ Macroscopic setup (power > 100 mW) for heating the sensor structures
- ❑ Integration on CMOS-based micro-hotplate (µhp) devices to minimize power consumption





- ❑ Gen 1: SiN-based microhotplate
- ❑ Gen 2: CMOS-integrated micro-hotplate devices

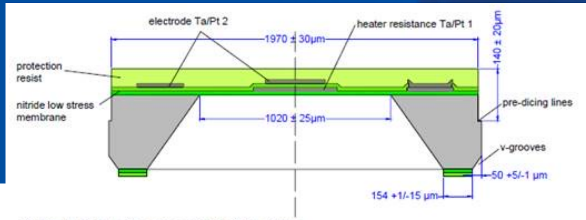
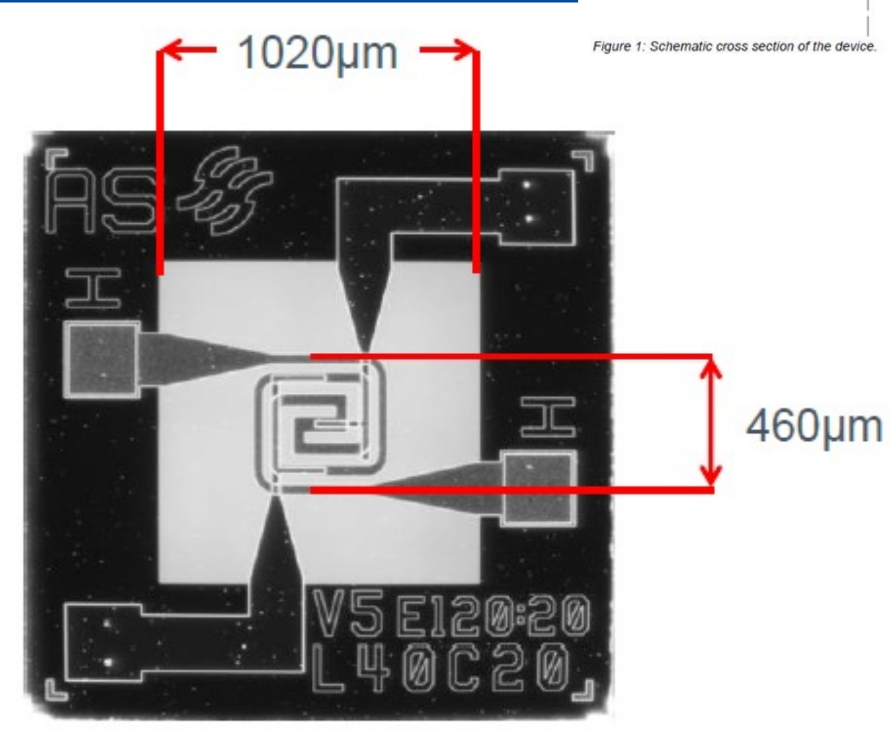
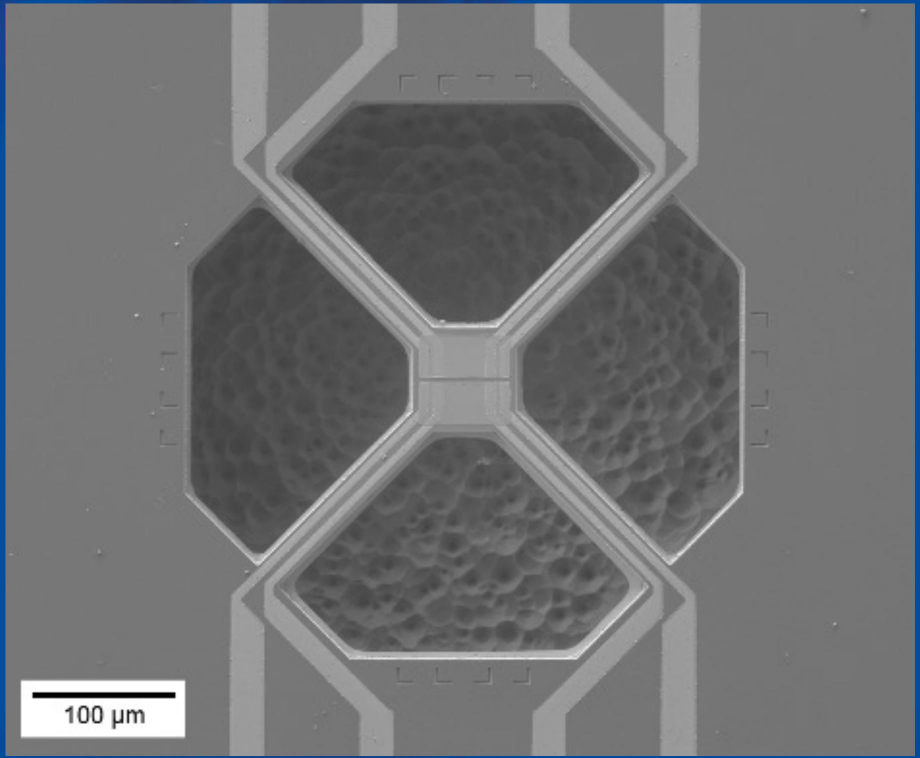
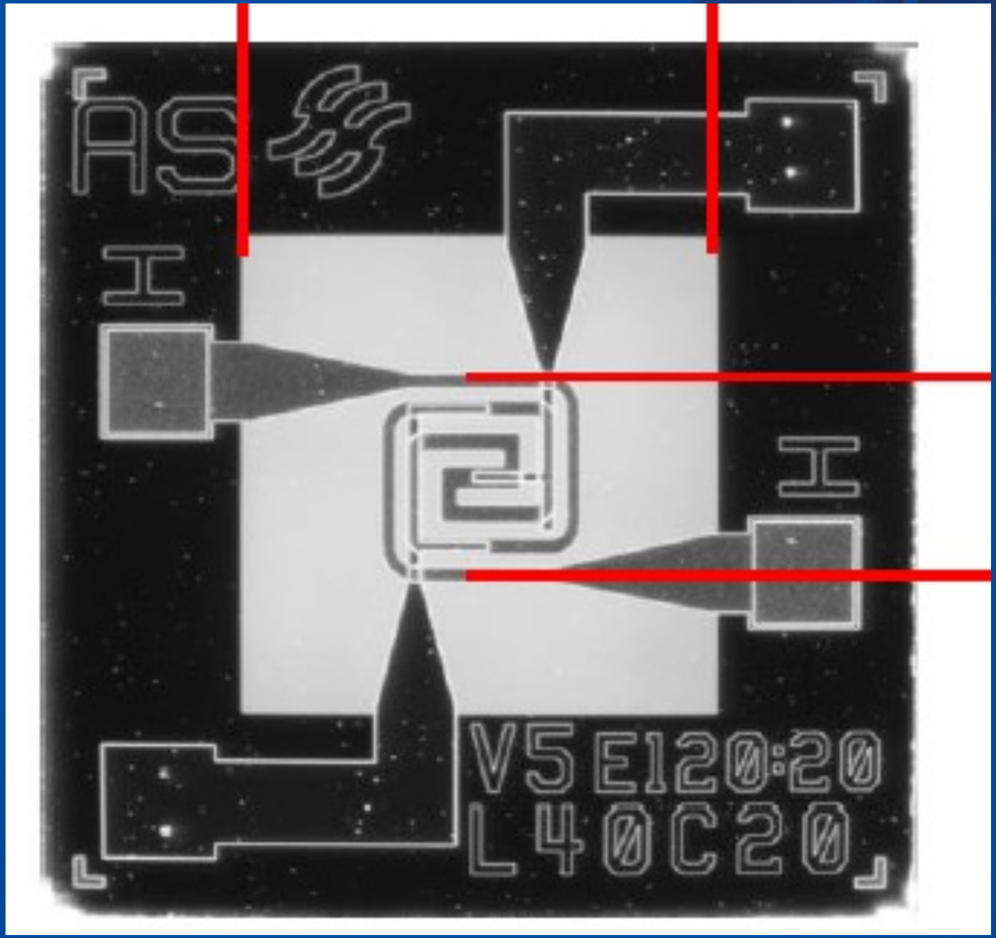


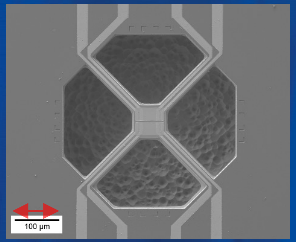
Figure 1: Schematic cross section of the device.





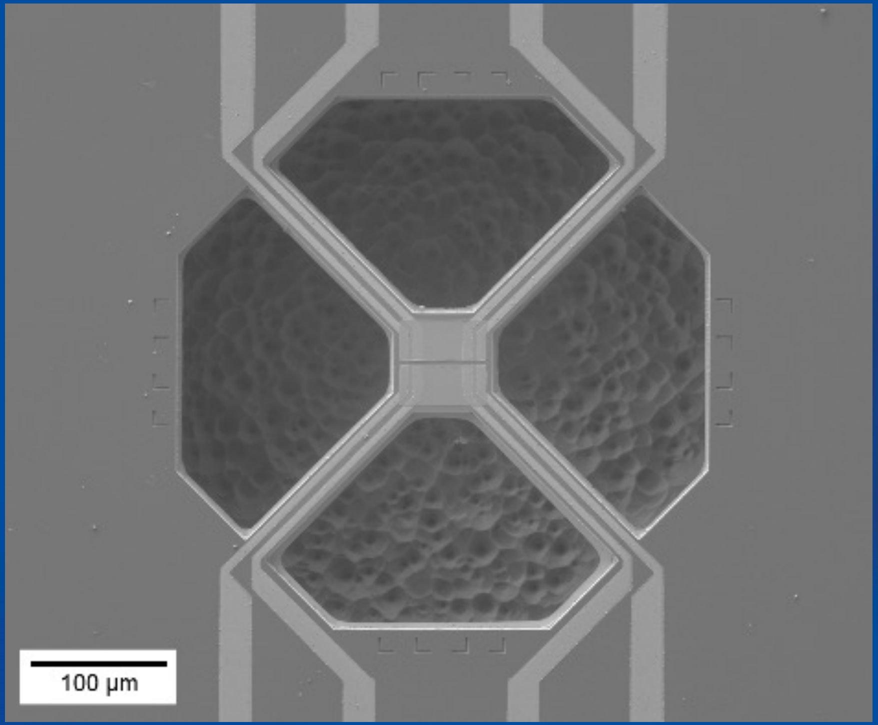
- Gen1: 1020 x 1020 x 0,8 µm = 832.320 µm^3
- Gen2: 80 x 80 x 8 µm = 51.200 µm^3

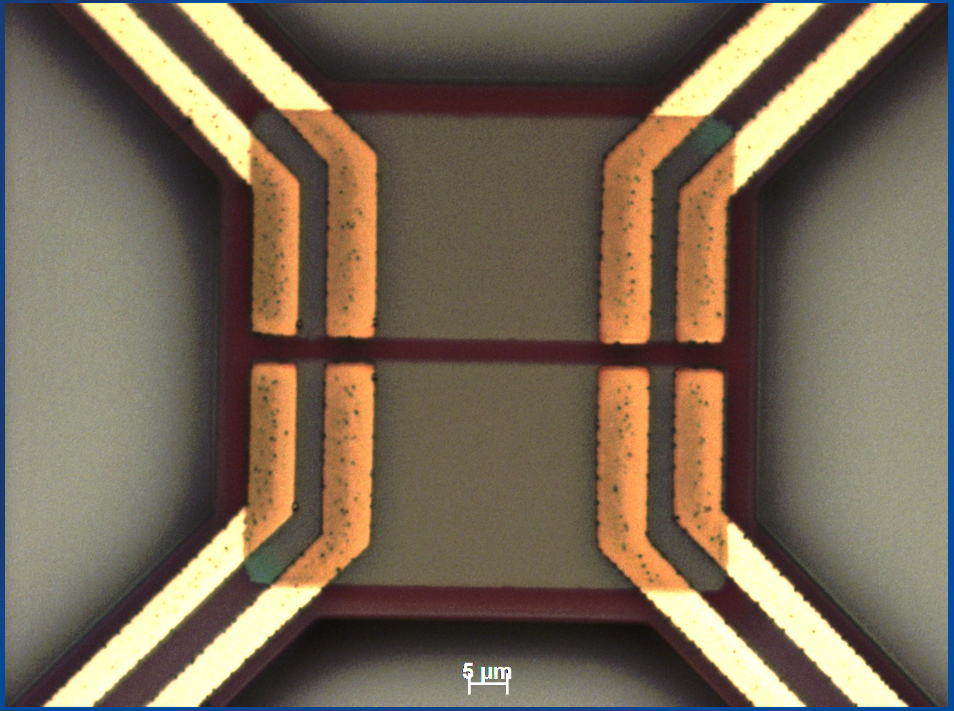




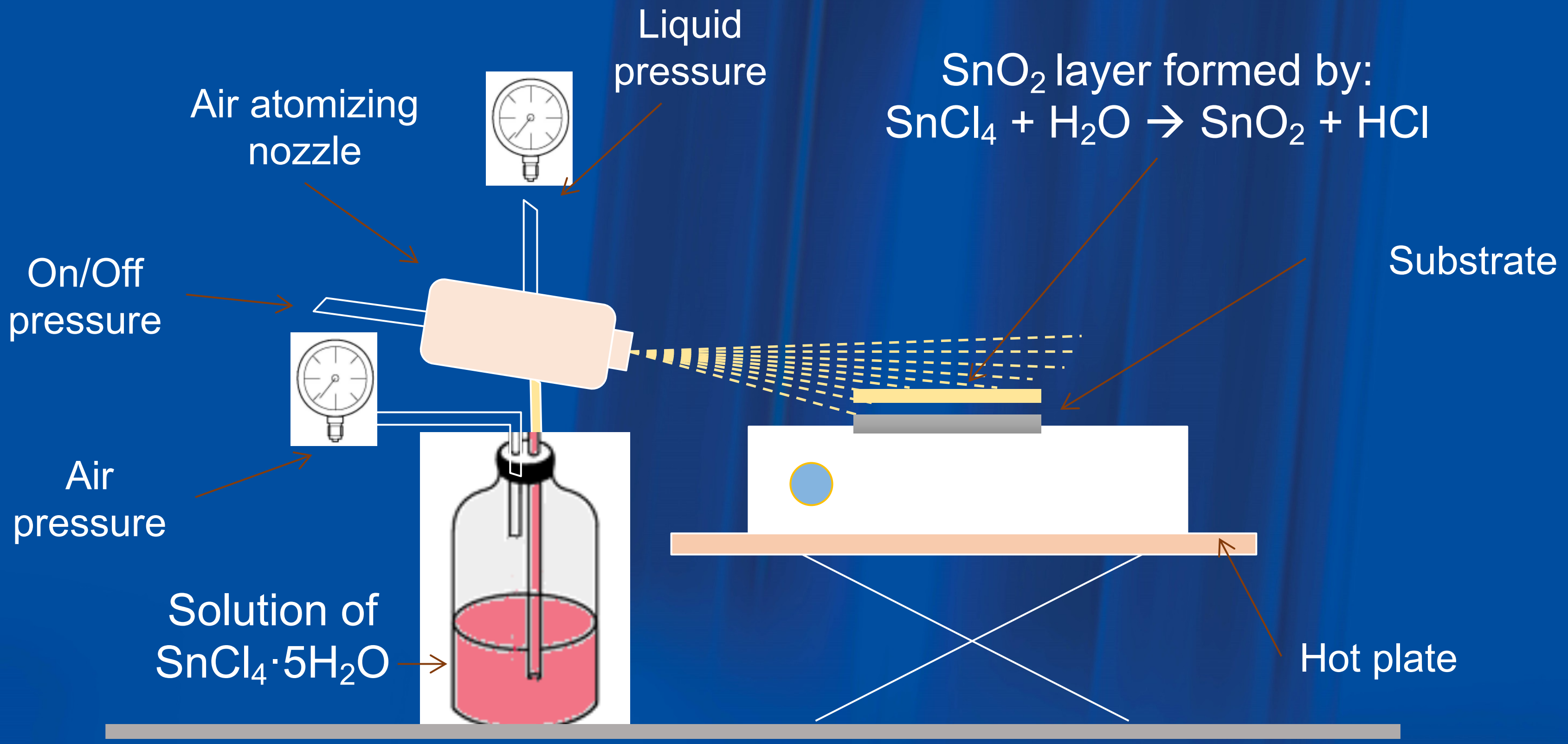
- Development of CMOS-integrated micro-hotplate devices for heating up to 400°C !
- Complex manufacturing chain (post-processing of nanomaterials on CMOS etc.) !

www.ams.com



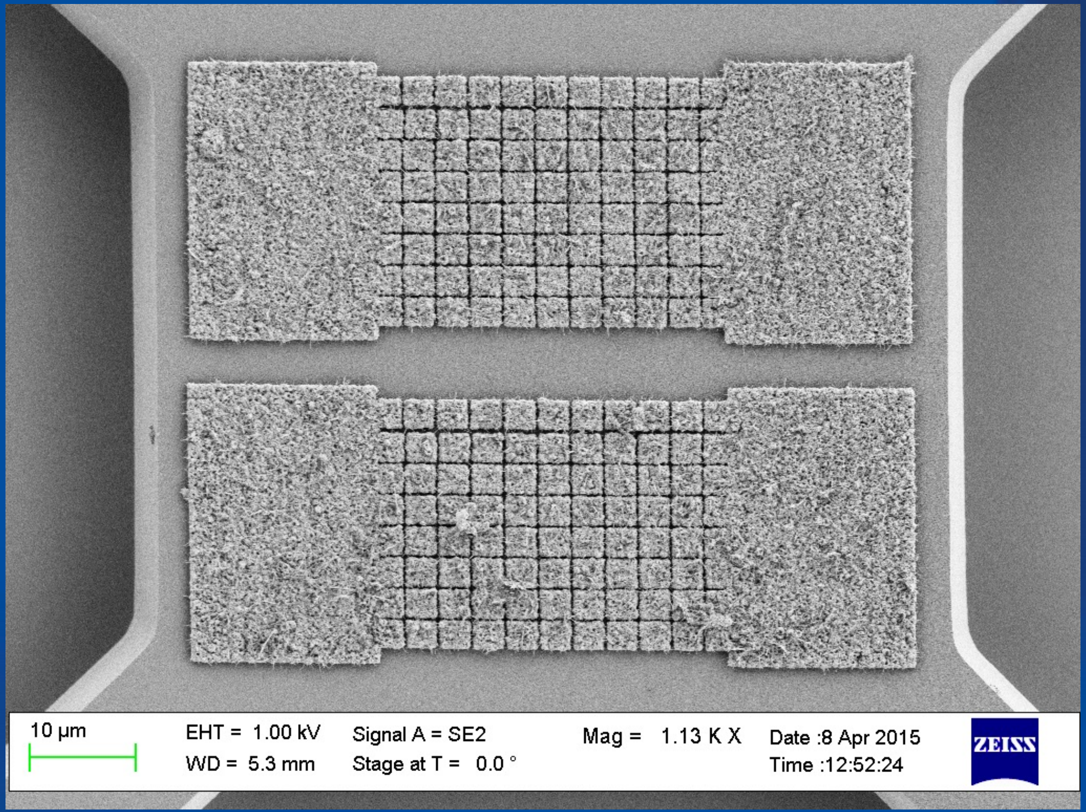


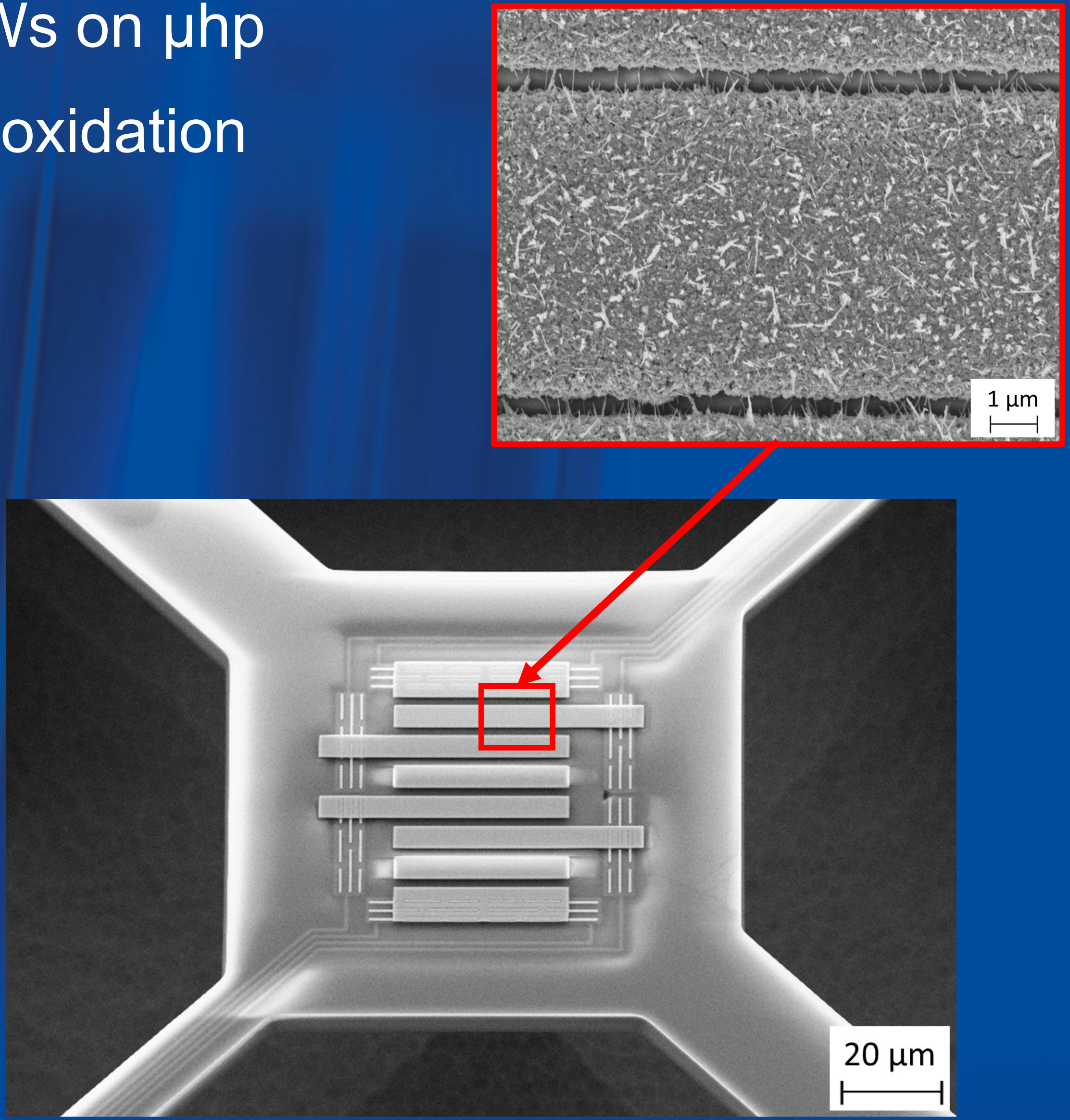
- ❑ SnO_2-thin film deposition by spray pyrolysis
- ❑ Nanocrystalline SnO_2-film ~ 50 nm thickness
- ❑ Photolithography and etching



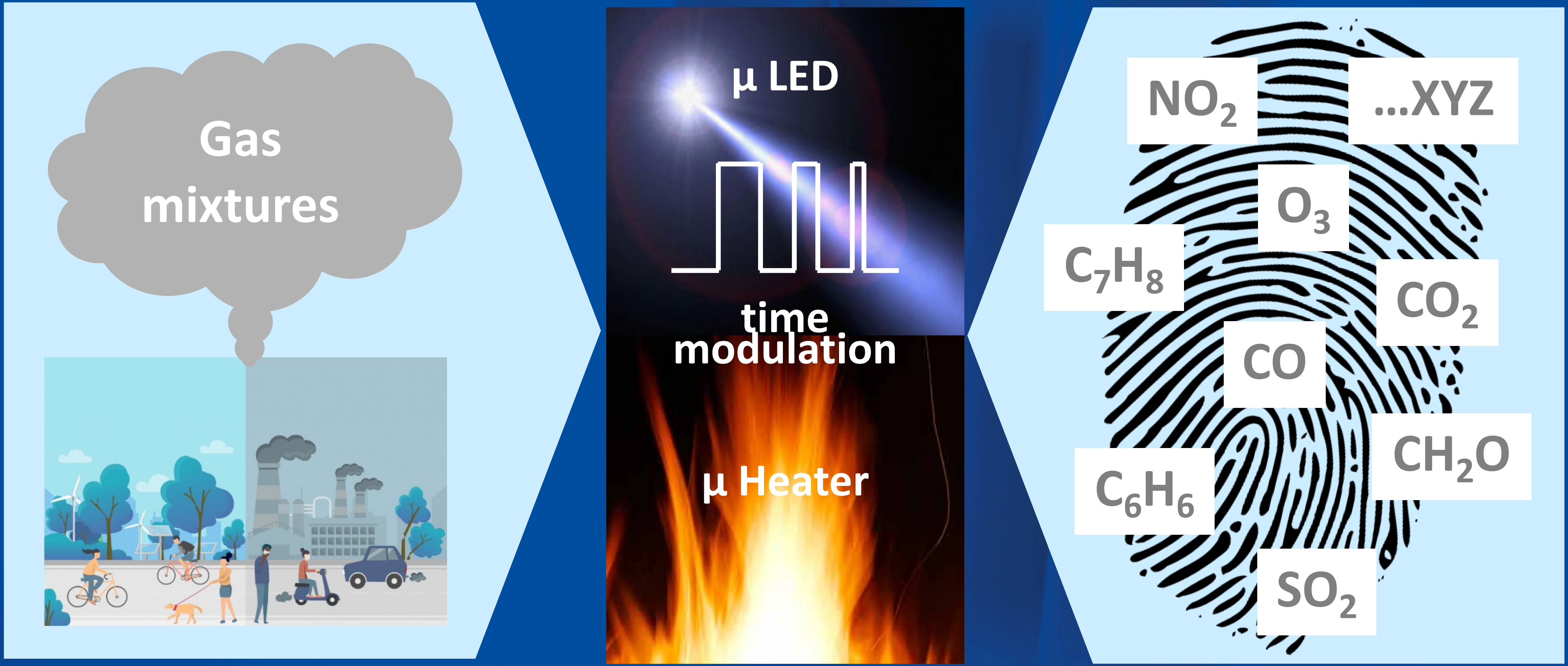
- Spray pyrolysis tool @MCL for MOx thin film deposition
- Up to 200 mm wafer size

- Local synthesis of ZnO- and CuO-NWs on µhp
- Evaporation of metal films & thermal oxidation

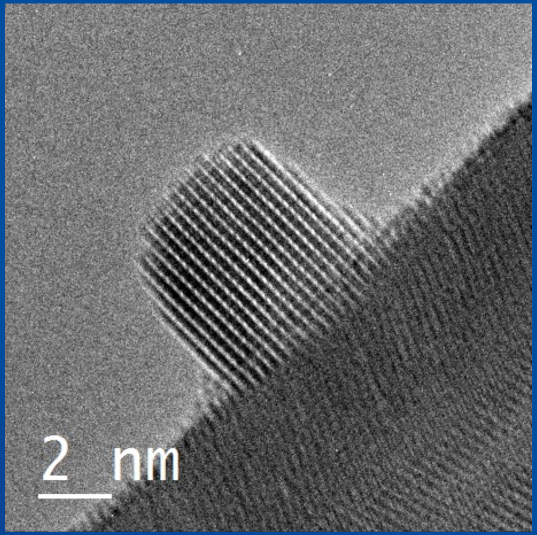


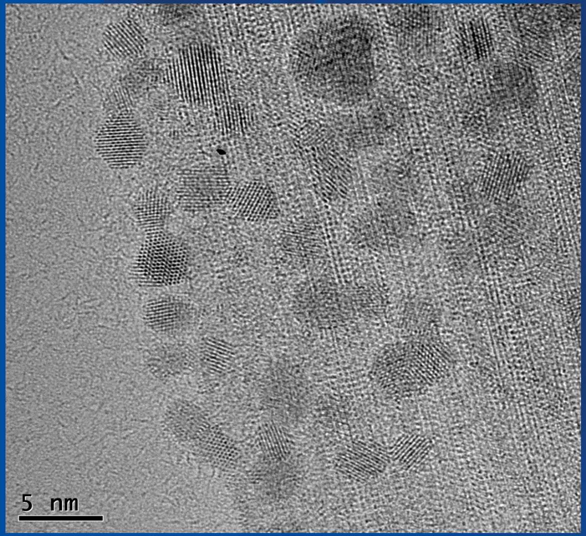


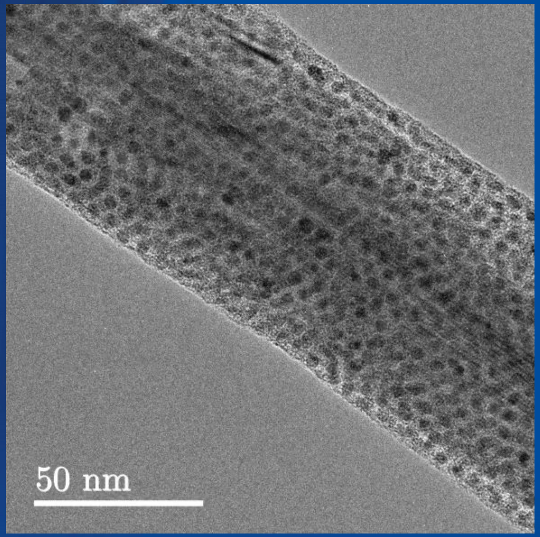
5. Multi-Gas Sensor Device



- ❑ Use of multi-functional NPs
- ❑ Mono-, bi, & trimetallic: Au, Pt, Pd, Ag, Ru, AuPd, NiPt, PdRuAg…
- ❑ NPs increase the response to specific target gas !
- ❑ NPs supress cross sensitivities to humidity !

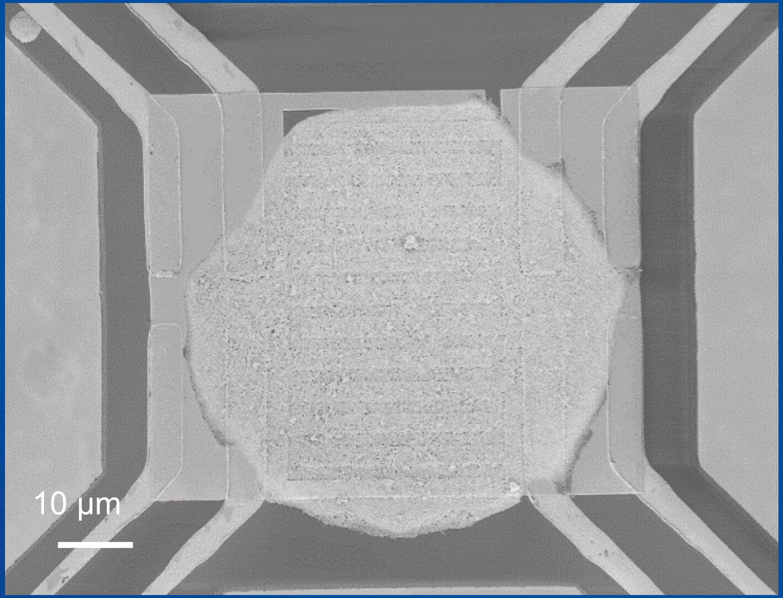


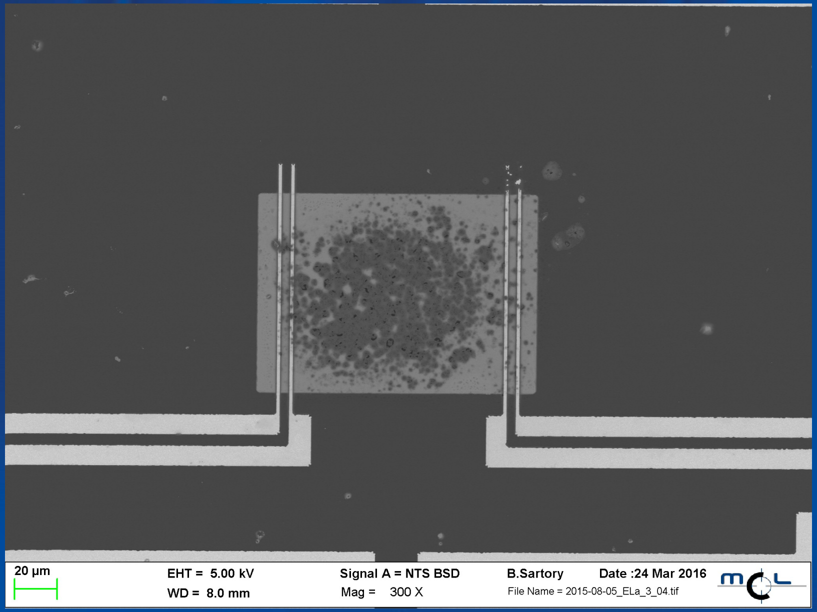




- „Organic approach“: Flow synthesis of (bi)metallic NPs und Ink-Jetting on CMOS devices

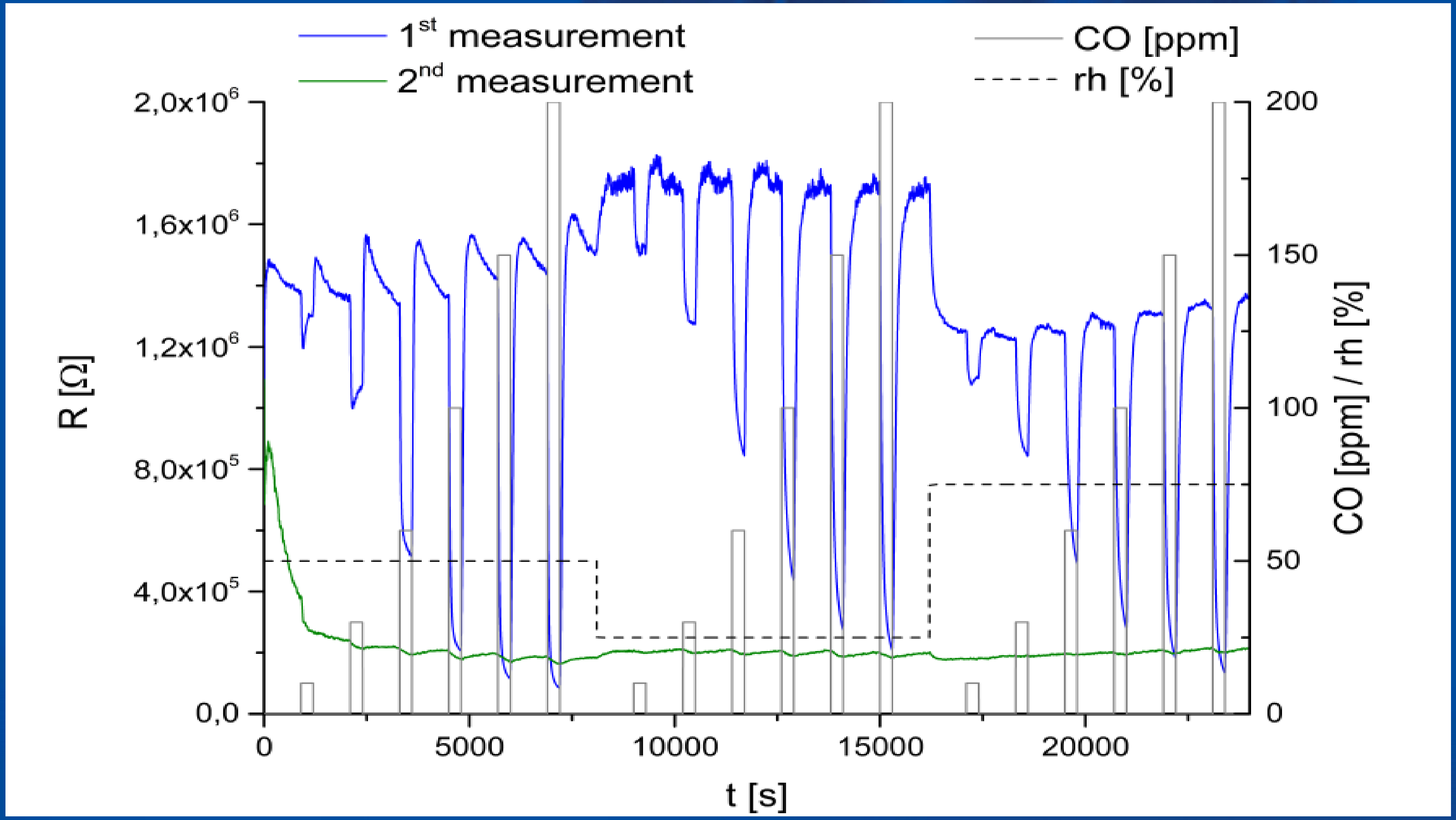
- „Anorganic approach“: Sputter deposition of (mono/bi/tri)-metallic NPs





Example 1:

- ❑ Response of SnO2-thin film + NiPt-NPs to CO
- ❑ Exposed to 10, 30, 60, 100, 150 and 200 ppm at different humidity levels



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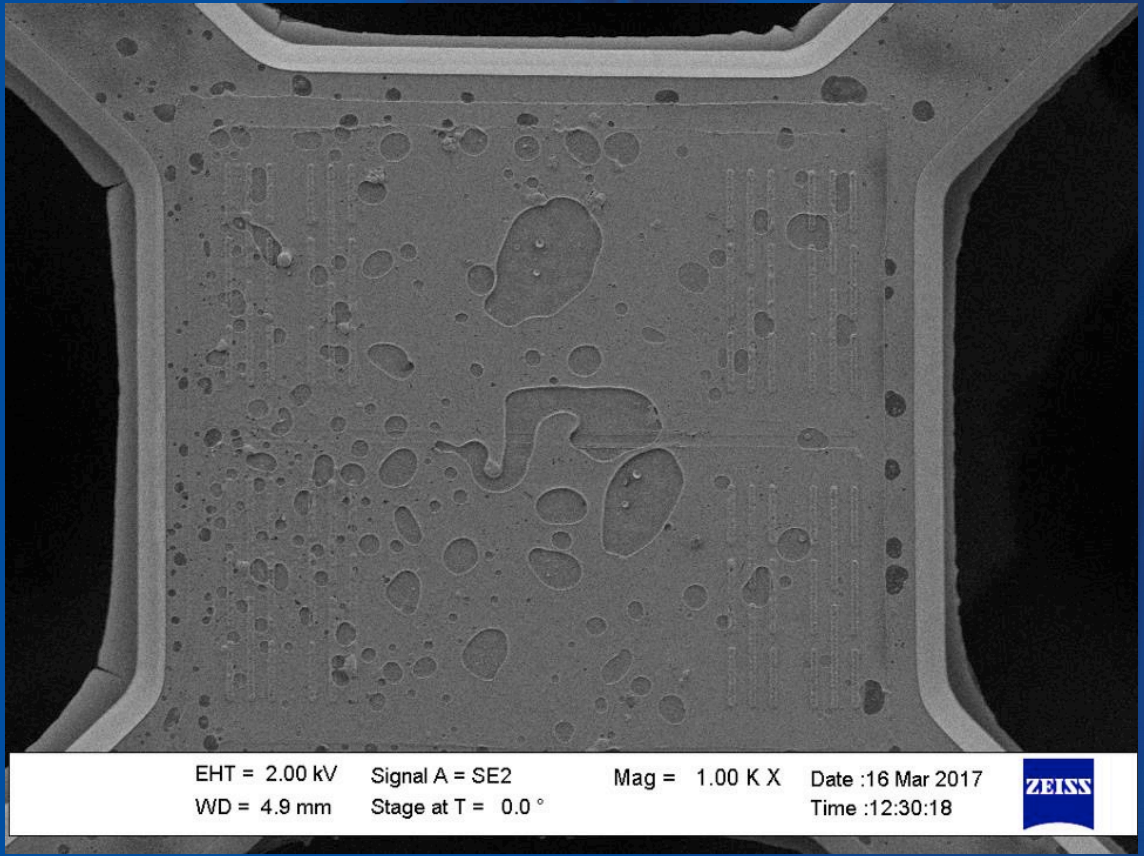
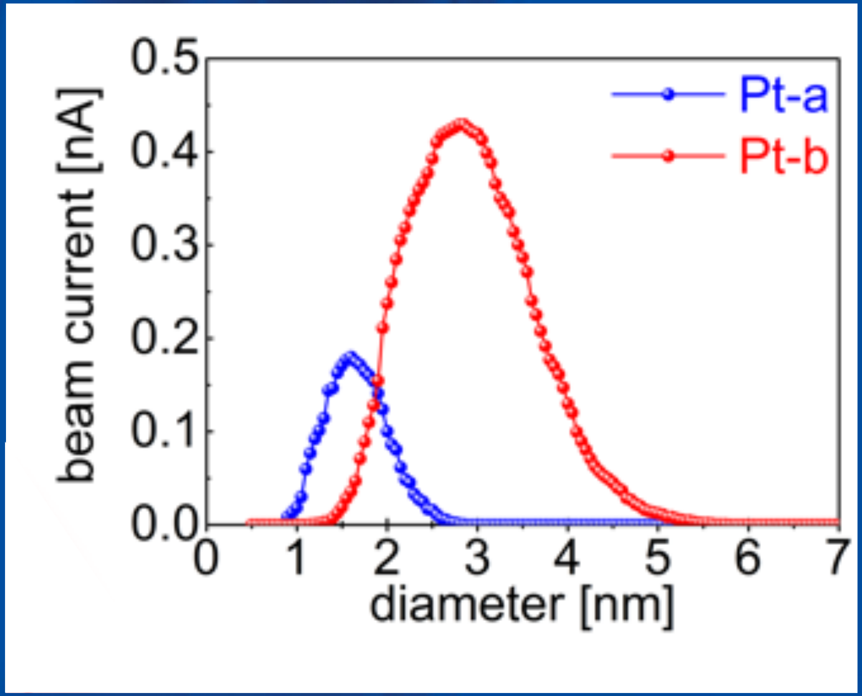
Example 1:

- Sensor „died“ at temperatures > 300°C !
- Obviousely the NiPt NPs melted and formed a metal alloy film covering the SnO_2 layer !



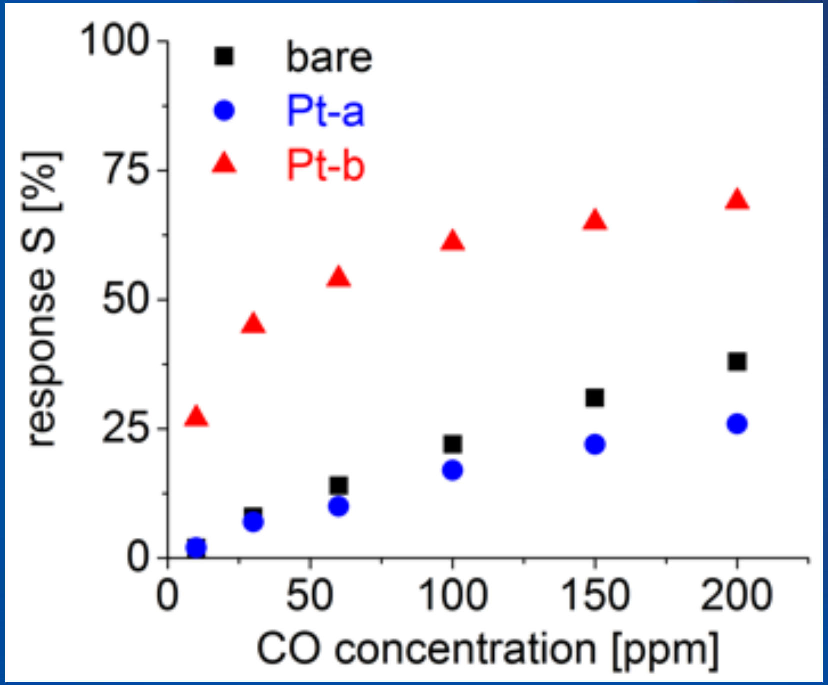
Example 2:

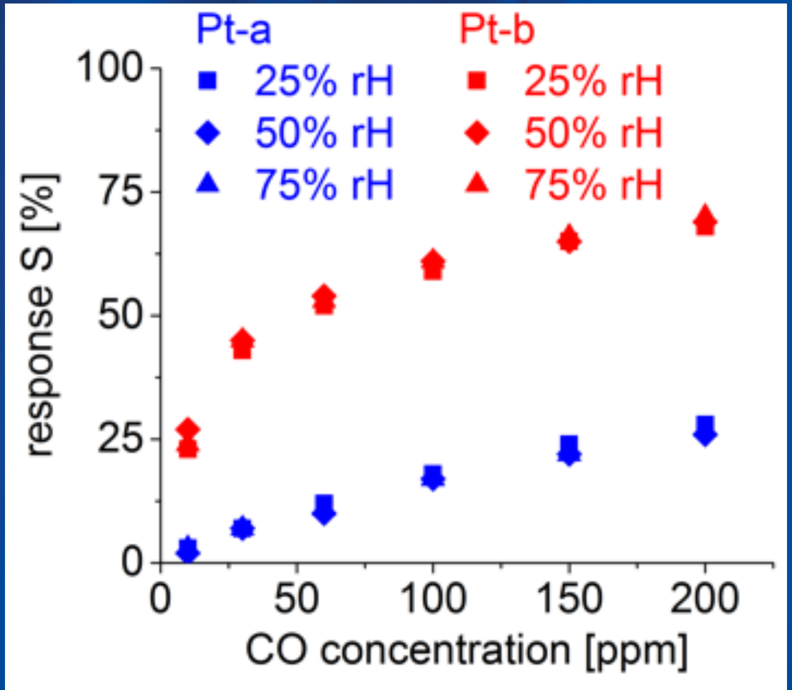
❑ Sputter deposition of Pt-NPs with different diameters



Example 2:

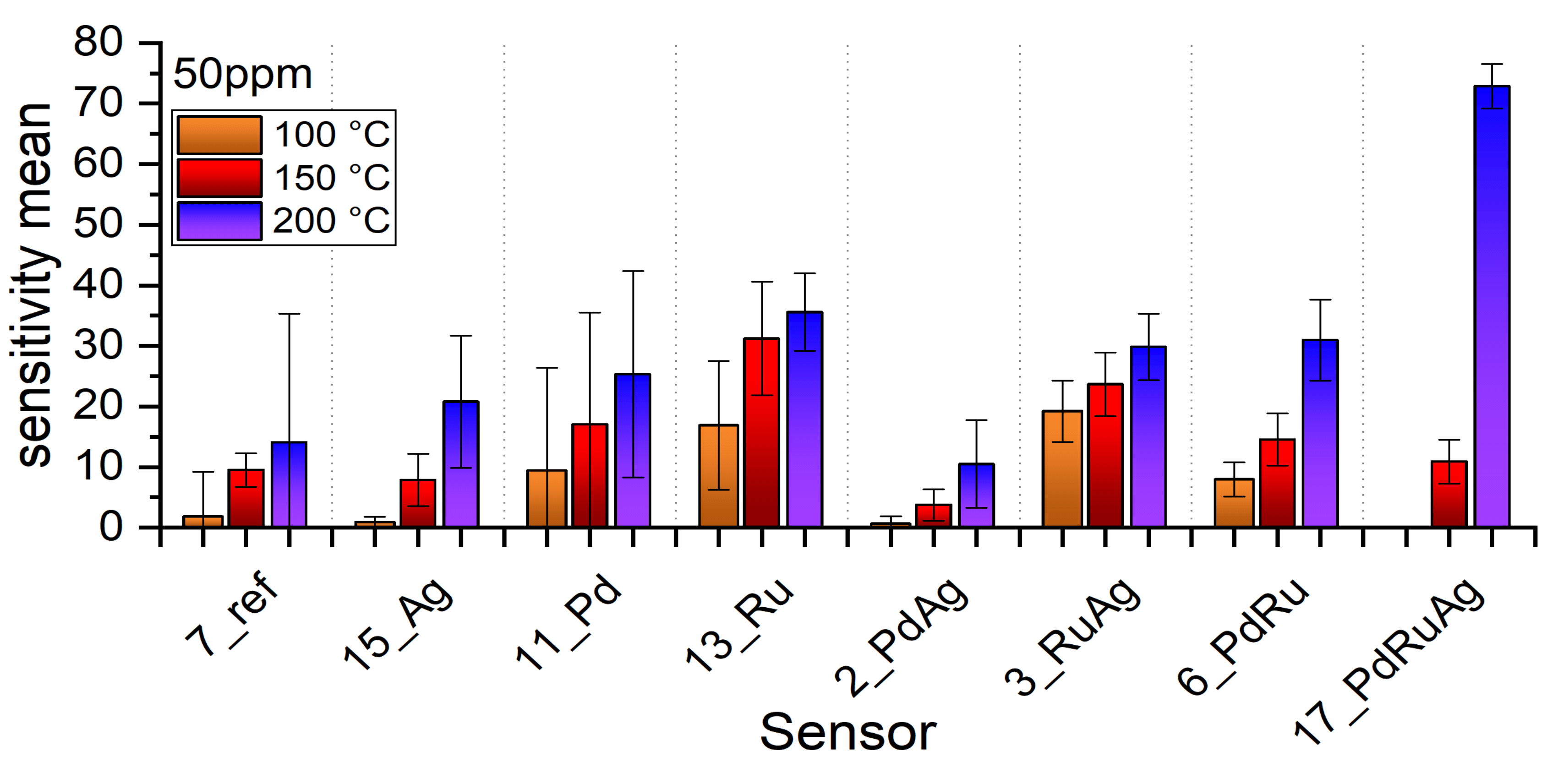
- SnO_2 thin film + Pt-NPs with different diameters
- Exposed to 10, 30, 60, 100, 150 and 200 ppm CO
- T = 375ºC



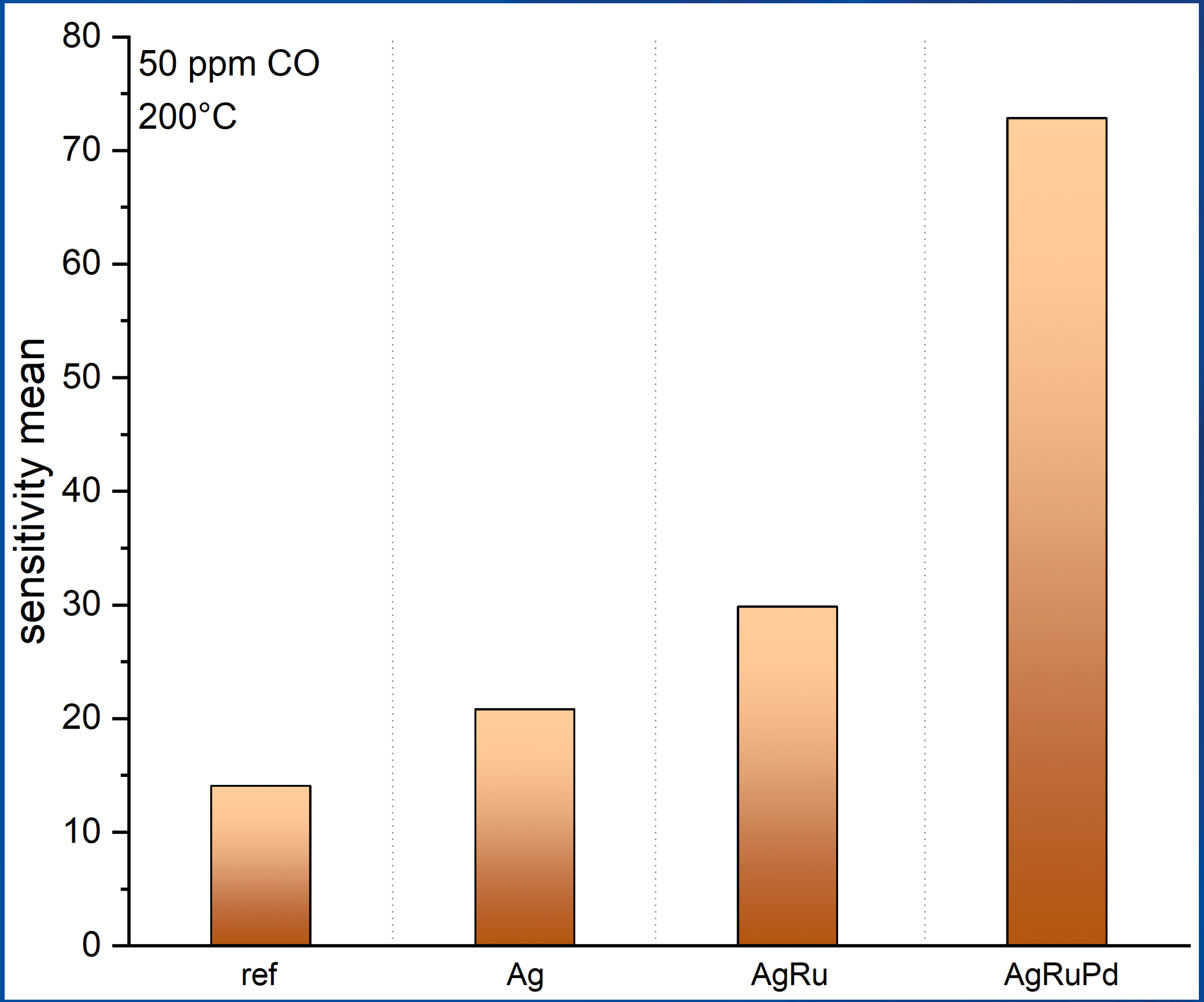


Example 3:

- ❑ SnO_2 thin film + mono-, bi-, & trimetallic NPs (Ag, Pd, Ru)
- ❑ Exposed to 50 ppm CO (50% rH)

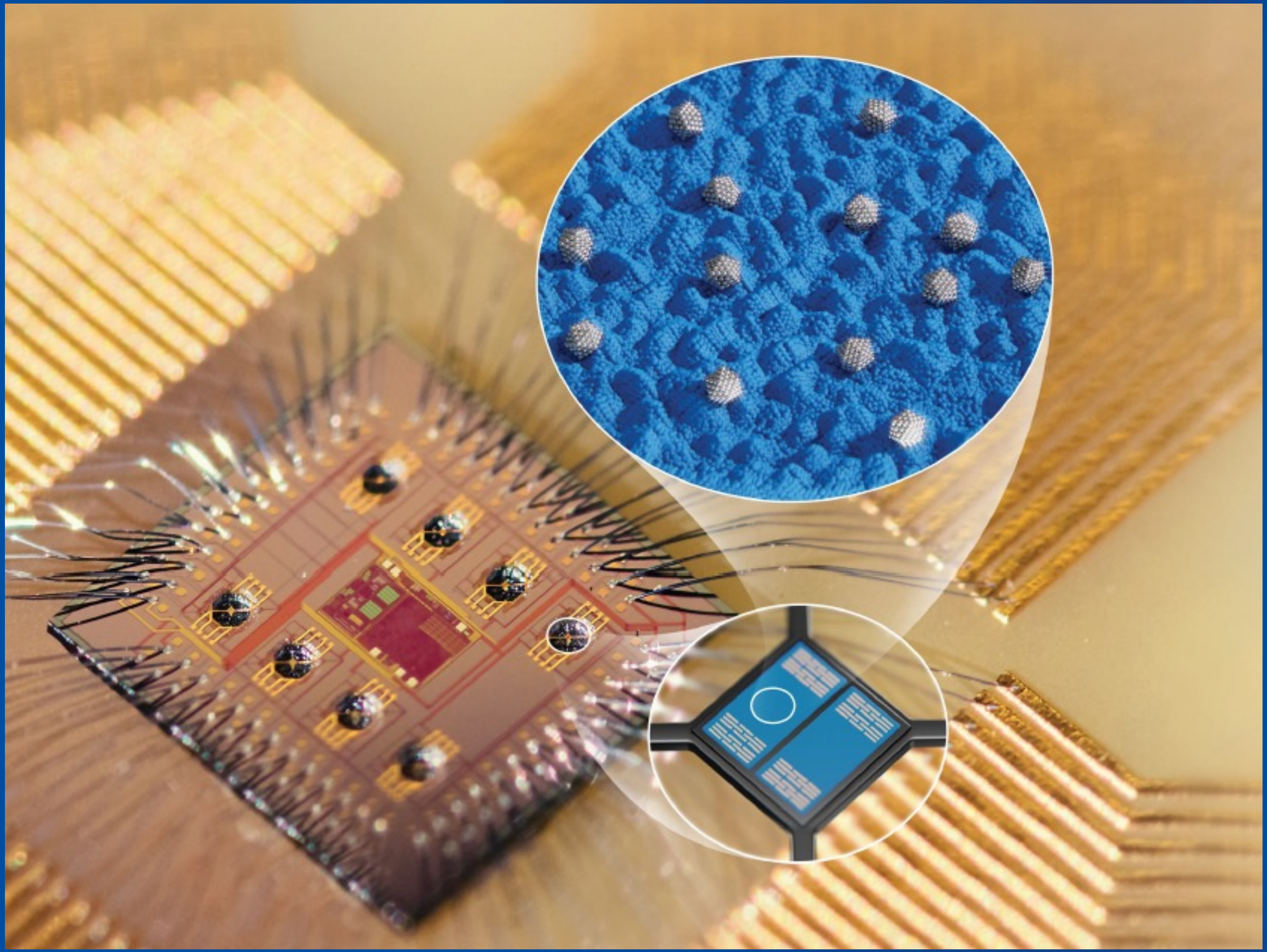


Example 3:



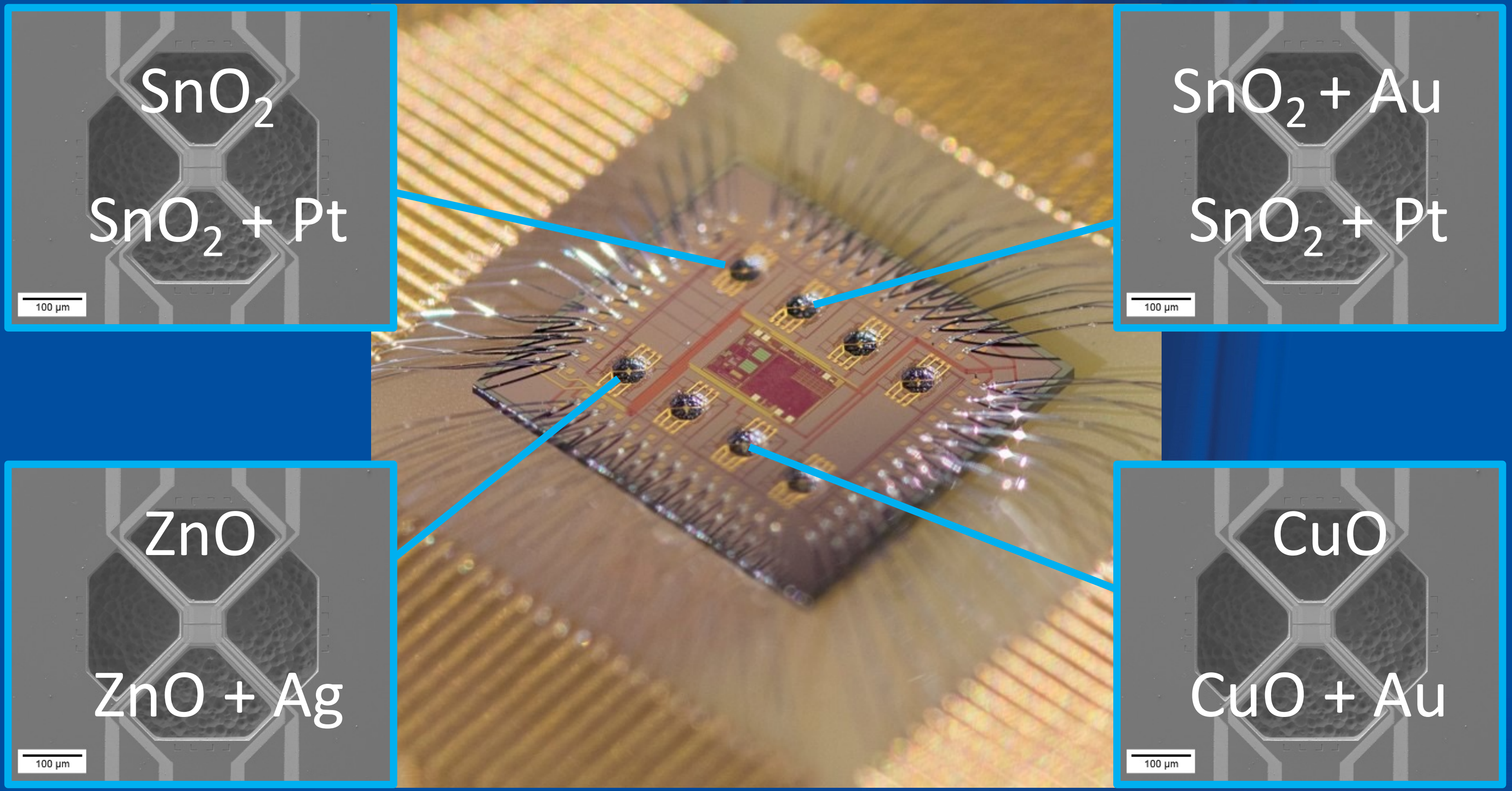
OIST

Next steps towards multi-gas sensor device



Next steps towards multi-gas sensor device

- ❑ Integration of different MOx on CMOS
- ❑ Functionalization with NPs



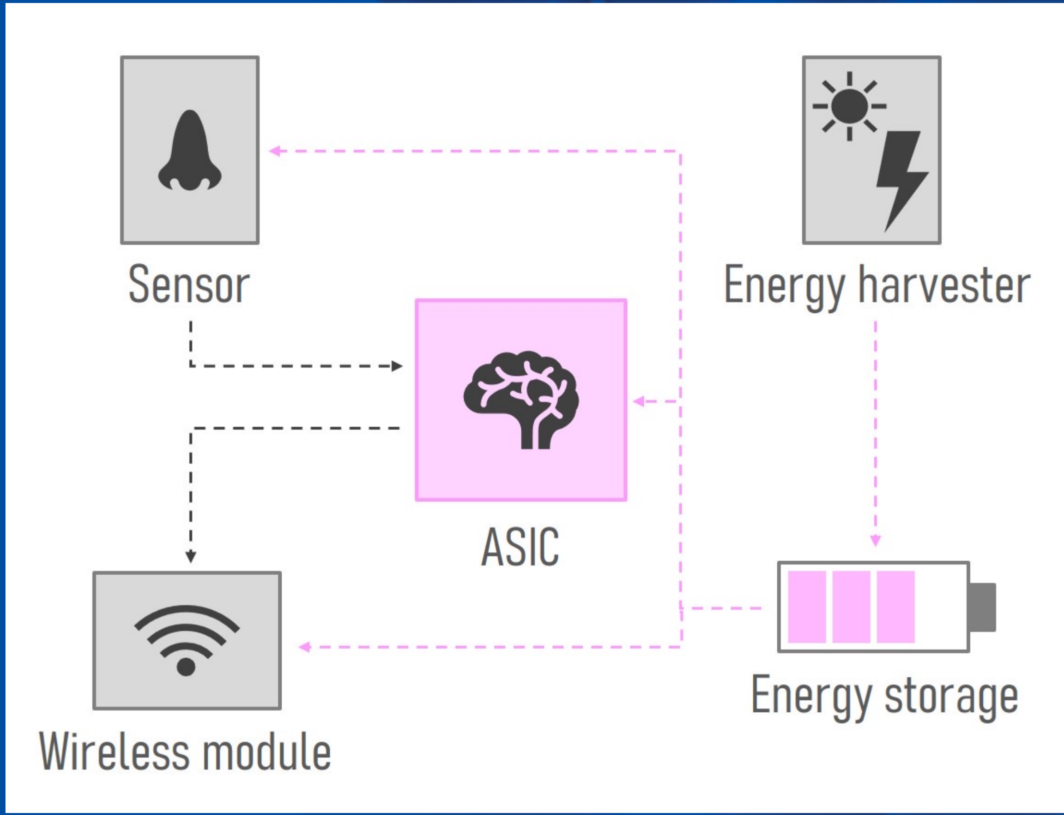
Intermediate Summary

- ❑ Successful realization as CMOS-integrated devices !
- ❑ Multifunctional NPs are key for optimization of chemical sensor devices !
- ❑ Many open questions - How does NP size/shape influence the response ? Chemical reaction in case of NP-combinations or alloys etc. ?
- ❑ Reasonable approach towards integrated multi-gas sensor device !

BUT:

- ❑ Power consumption ~ 15 mW (400°C) per sensor in DC operation !
- ❑ How to realize an **energy autonomous** multi-sensor system ?

Vision: Energy Autonomous Sensor Systems



IoT Sensor Networks for indoor and outdoor air quality monitoring

Power budget – rough estimation

- ❑ Power consumption ~ 10 mW (300°C) per sensor in DC operation !
- ❑ 8 x 10 mW ~ 100 mW (DC)

Photovoltaic energy harvesting

- ❑ Solar constant 1361 W/m^2
- ❑ 200 W/m^2 ~ 5 cm^2 solar cell area for 100 mW (24 hours)
- ❑ (4h/day & night) x 6 ~ 30 cm^2 solar cell (plus energy storage) to supply 4 x 4 mm^2 sized sensor chip (Smart System? IoT?)
- ❑ + Circuitry + AI-based data evaluation + data transmisssion…

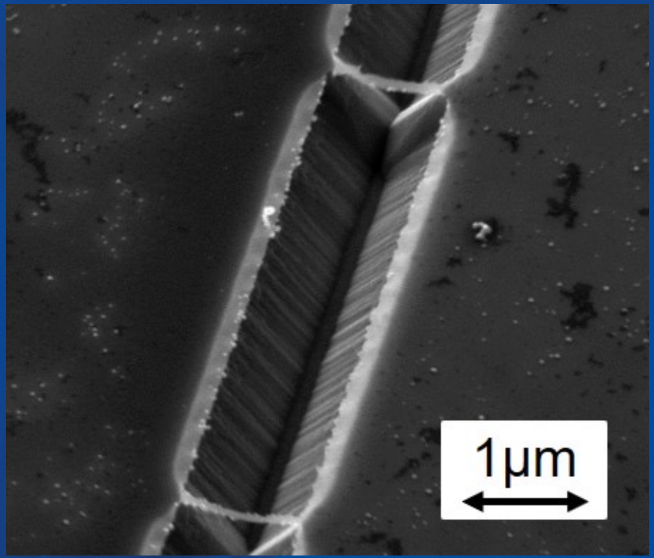
Energy harvesting & energy storage is a huge challenge!

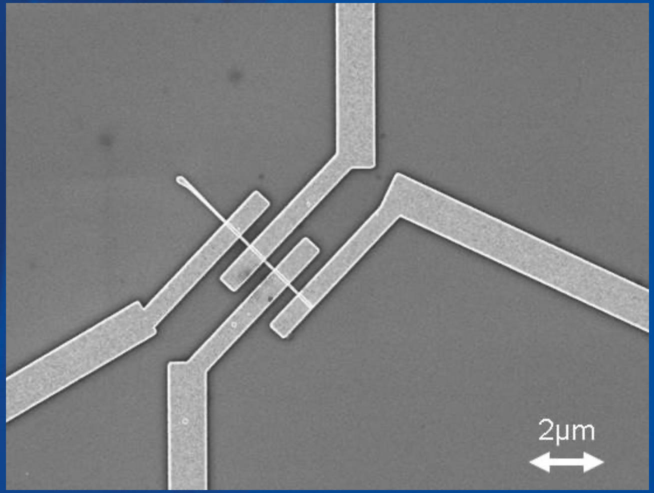
Ultra-low-power chemical sensor arrays

<< 1mW

Various approaches:

- ❑ Switching between the sensor array (10 mW)
- ❑ AC-operation - 1:10 (1 mW)
- ❑ Radical scaling of micro-heater devices
- ❑ Self heating of single nanowires
- ❑ Employment of time domain (AC operation)
- ❑ Combination of thermal & optical excitation





6. The FOXES Project

H2020-EIC-FETPROACT-2019 GA 951774

FOXES

Fully Oxide-Based Zero-Emission and Portable Energy Supply

www.foxes-project.eu

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Anton Köck (MCL)

Consortium

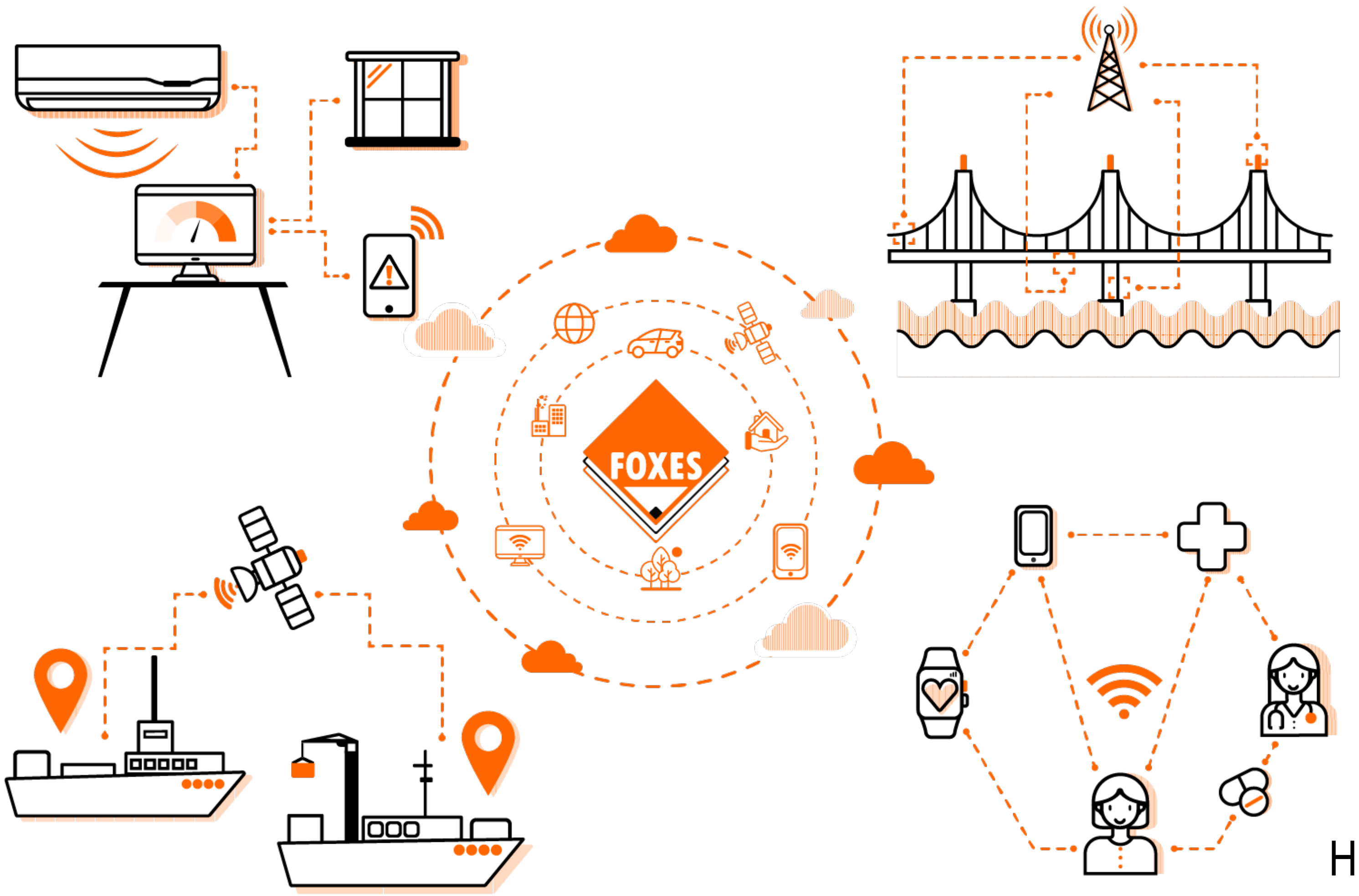
FULLY OXIDE-BASED ZERO EMISSION AND PORTABLE ENERGY SUPPLY (FOXES)

Participant No.	Participant organisation name	Country
1 (Coordinator)	Materials Center Leoben Forschung GmbH (MCL)	AT
2	Bergische Universität Wuppertal (BUW)	DE
3	AMO GmbH (AMO)	DE
4	Instituto de Desenvolvimento de Novas Tecnologias (UNOVA)	PT
5	Universitat de Barcelona (UB)	ES

Realization of an Energy Harvesting & Storage Solution for Wireless Sensor Nodes

Air quality monitoring

Structural health monitoring



Condition monitoring

Healthcare

Realising greenhouse gas emission reduction goals

- Realization of a novel stand alone zero emission solid state power generating and storage system (Power Cube)
- Combination of photovoltaic energy harvester with a multilayer capacitor
- Oxide based 3D-integrated system exploiting eco-friendly materials – no negative impact for end-of life
- Energy supply and storage system for an air quality monitoring system
- Demonstration of capability for supplying autonomous IoT devices installed in remote locations - field test campaign in Barcelona urban area (2024)

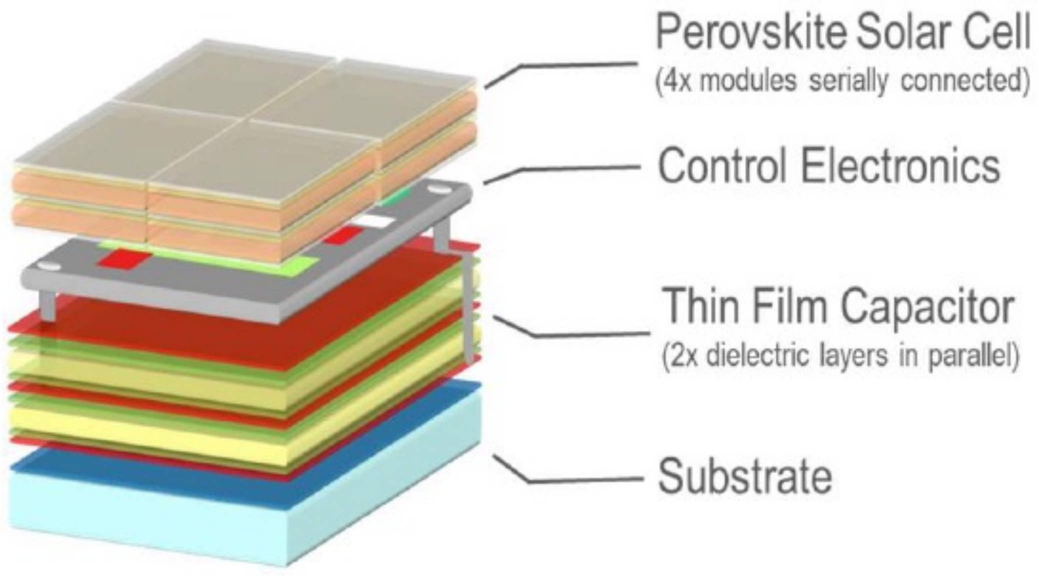
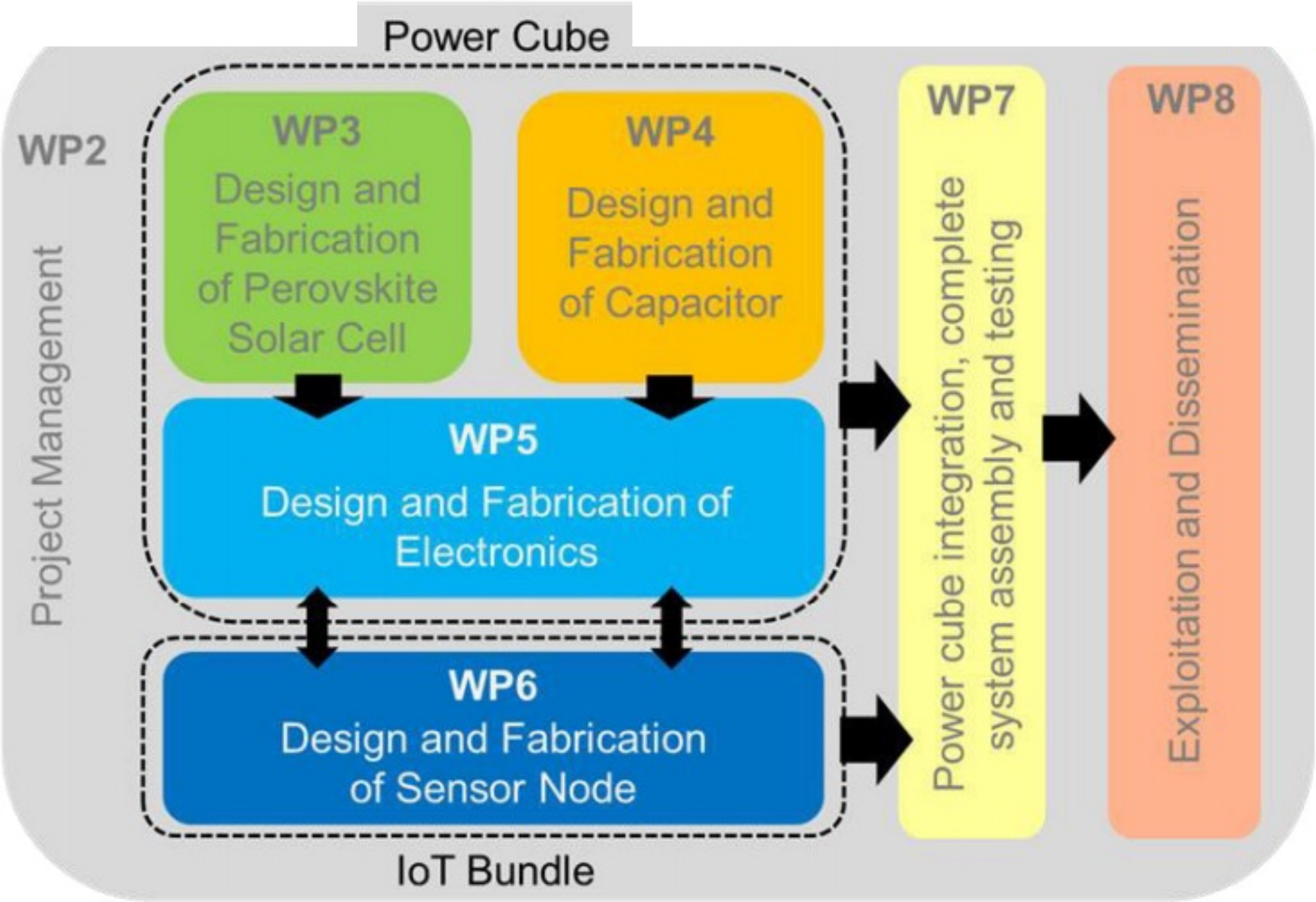


***Figure 1.1**: The FOXES Power Cube is constituted by:*
- *Fully lead-free PSC with > 10% efficiency (mini-module, voltage > 4V).*
- *Lead-free perovskite multilayer TFC with high energy density (> 50 J/cm^3).*
- Metal-oxide based electronics (integrated circuits) coupled with graphene electrodes for the energy management circuit.


Power Cube
WP2
Project Management
WP3
Design and Fabrication of Perovskite Solar Cell
WP4
Design and Fabrication of Capacitor
WP5
Design and Fabrication of Electronics
WP6
Design and Fabrication of Sensor Node
IoT Bundle
WP7
Power cube integration, complete system assembly and testing
WP8
Exploitation and Dissemination

WP Leaders:

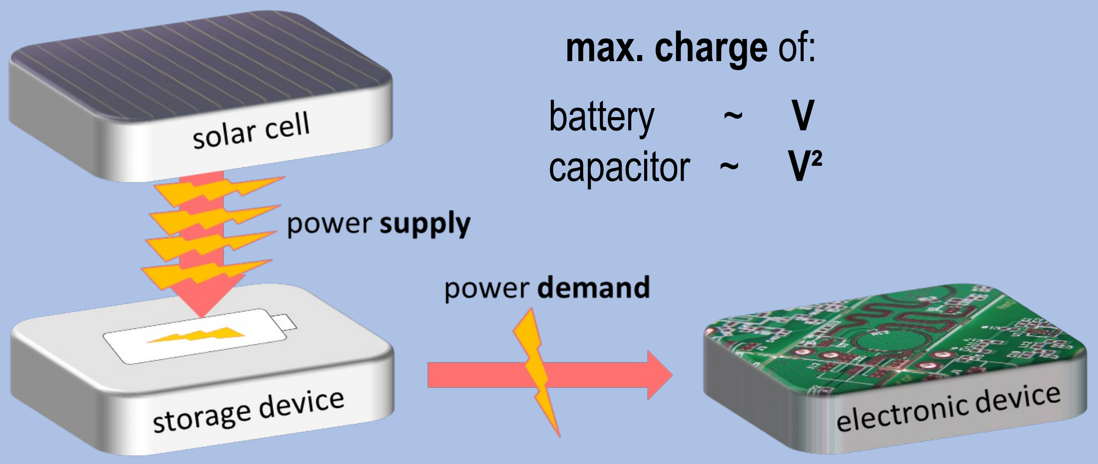

BERGISCHE UNIVERSITÄT WUPPERTAL
NOVA SCHOOL OF SCIENCE & TECHNOLOGY
DEPARTMENT OF MATERIALS SCIENCE
UNIVERSITAT DE BARCELONA
AMO

BERGISCHE UNIVERSITÄT WUPPERTAL

Pb-free Tandem Perovskite-Based Tandem Solar Cells with High Voltage for Microelectronics and Efficient Module Integration

High operation voltage

- **Efficient module integration** = high geometric fill factor
- **Increase chargeable energy** of storage devices



max. charge of:

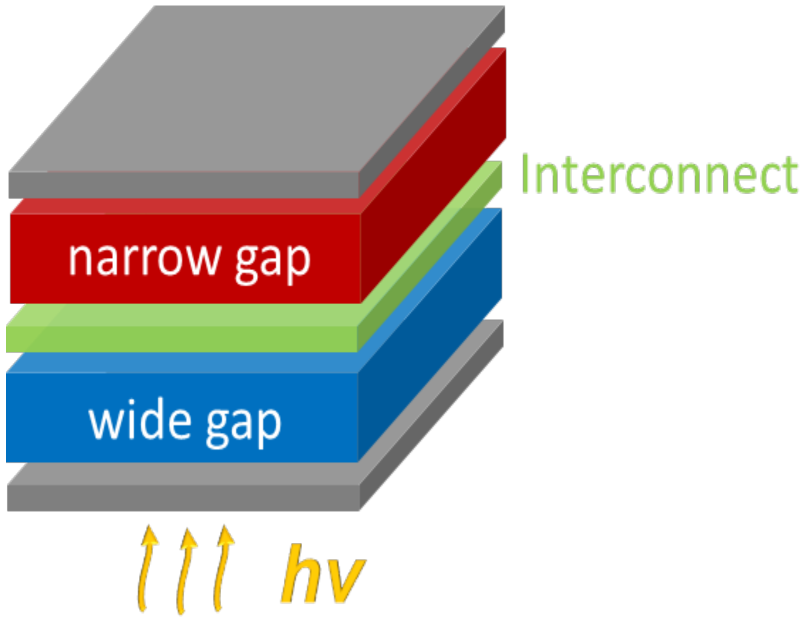
battery ~ **V**
capacitor ~ **V²**

Perovskite tandem cell

Environmentally friendly

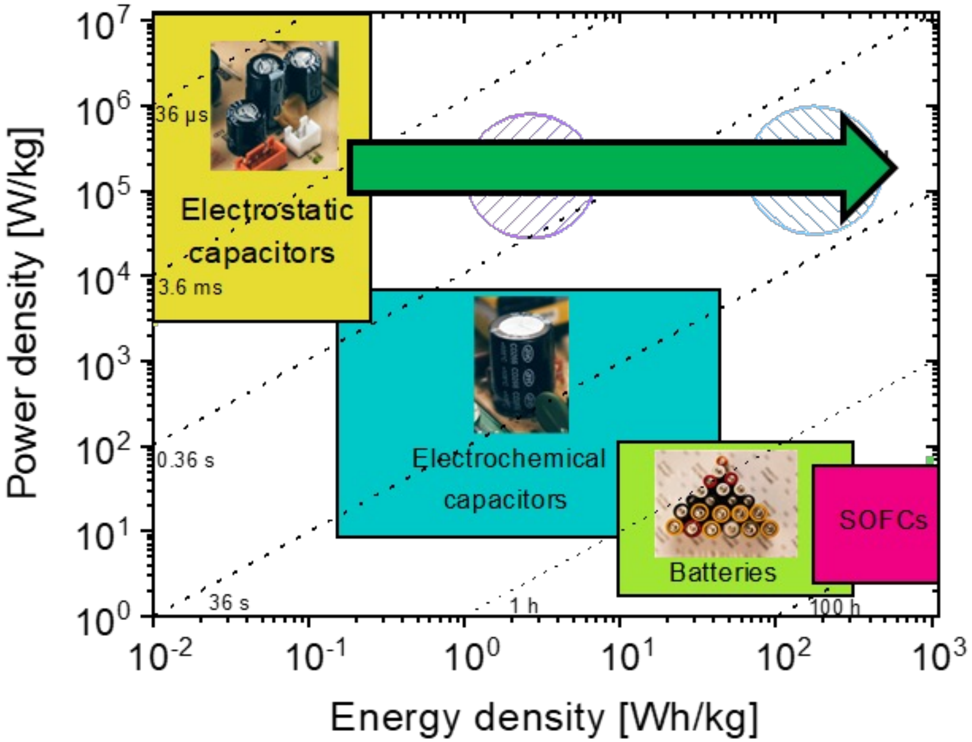
narrow gap cell
(Sn-based or organic)

wide gap cell
(Pb- and Sn-free)



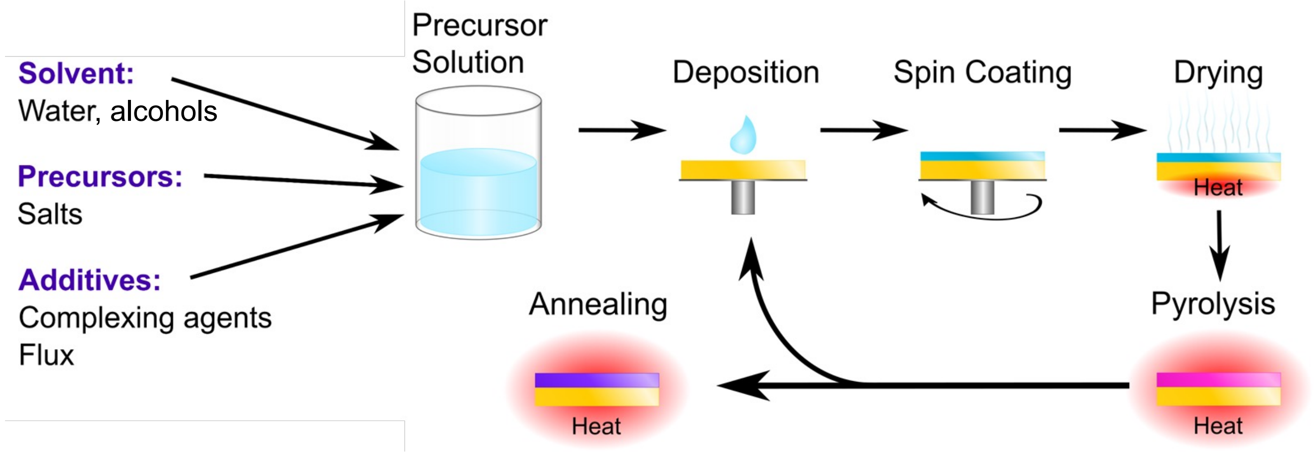
Challenges:

- Currently no energy storage system can provide at the same time high power density and energy density, with sufficient stability and environmental friendliness, and the potential to be integrated on flexible substrates



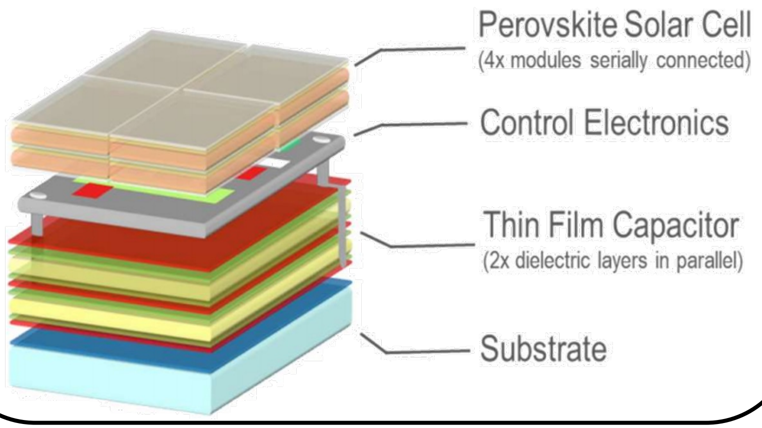
FOXES Innovation:

- Multilayer or stacked **thin film electrostatic capacitors** based on ceramic perovskites with **high energy density** and conductive metal oxide electrodes, produced using **nontoxic materials and methods**
- **$BaZr_xTi_{1-x}O_3$**
- **$LaNiO_3$ electrodes**.

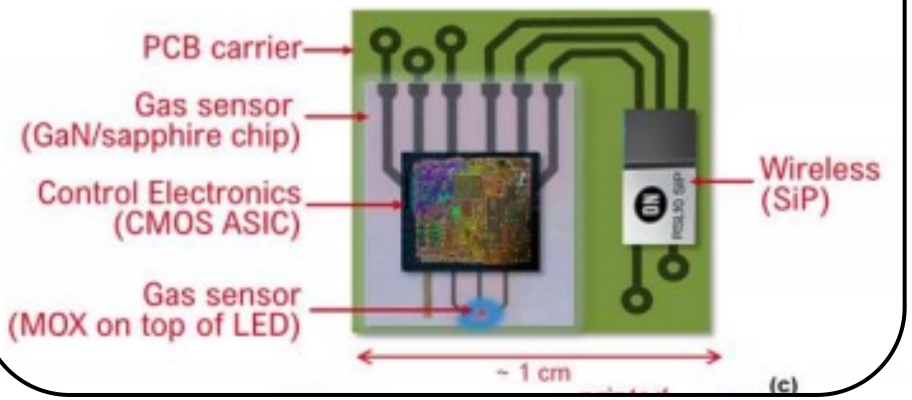


FOXES Goals

Power Cube



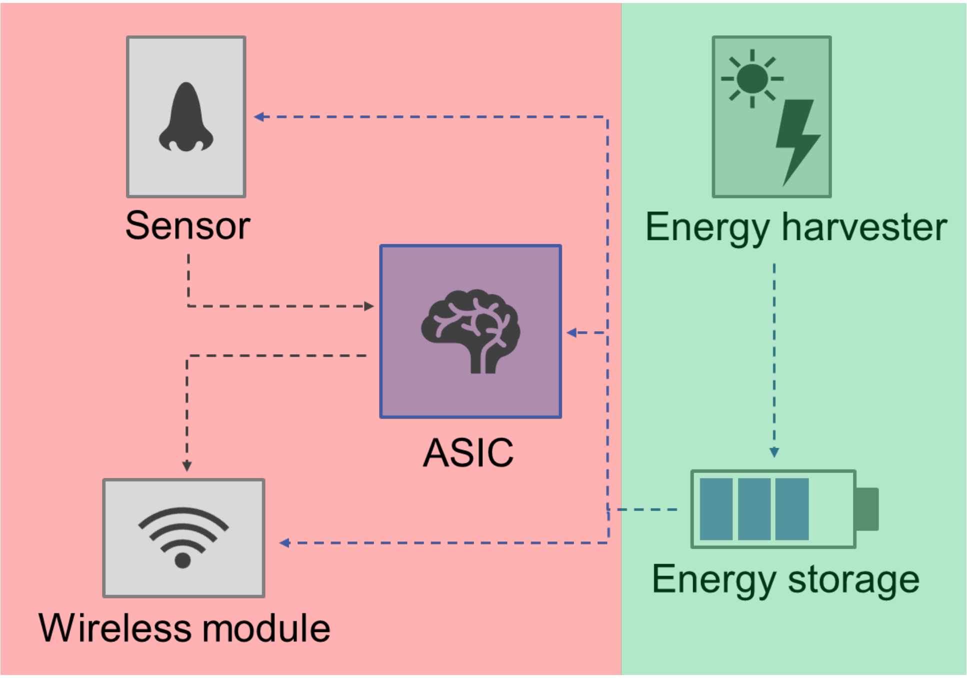
IoT Bundle



Goal: Realise an *integrated* Power Cube to power an IoT Bundle containing a gas sensor, and testing it!

KPIs:

- Pb- and Sn-free perovskite multi-junction solar cell with 4 V output **(WP3)**
- Pb-free multilayer thin film capacitor with 0.6 mJ stored energy @4 V **(WP4)**
- Energy management circuit with > 50% efficiency **(WP5)**
- Sensor node sensitive to < 1 ppm NO_2/O_3 and IoT Bundle power budget < 50 µW **(WP6)**



Ceramic ultracapacitors

Power consumption/day

per event	**0.5 mJ**
per 1 h sleep	**1.8 mJ**
4 x events/h	**91.2 mJ/day**

Gas sensor - 1 mW
AC-operation (1:10) – 86,4 J/day

Energy harvesting/day

260 mJ/12 h illumination

Energy storage

At least **45.6 mJ** energy storage capacity & ms charge/discharge capability

IC-MPPE 2022 Conference – 05.05.2022

7. Summary & Outlook

- ❑ Successful realization as CMOS-integrated chemical sensor devices !
- ❑ Performance has to be optimized (cross sensitivities !)
- ❑ We need many more chemical sensor devices with high selectivity
- ❑ Integrated multi-gas sensor devices
- ❑ Power consumption of sensor devices has to be drastically decreased
- ❑ Environmental-friendly technologies for energy harvesting and energy storage (sensor networks everywhere)
- ❑ Efficient 3D-integration technologies required !
- ❑ Energy autonomous IoT sensor devices – still a big challenge !