European Network on New Sensing Technologies for Air Pollution Control and Environmental Sustainability - *EuNetAir*

COST Action TD1105

Third Scientific Meeting – Istanbul, December 3-5, 2014

Action Start date: 01/07/2012 - Action End date: 30/06/2016

Year 3: 1 July 2014 - 30 June 2015 (***Ongoing Action***)

Plenary Session 1: Indoor Environment Quality Applications

Selective VOCs Detection in the ppb Range for Demand Controlled Ventilation

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COST is supported by the EU Framework Programme

ESF provides the COST Office through a European Commission contract

Why worry about indoor air?

- Safety
  - Gas leak detection (combustible gases, e.g. CH_4)
  - Fire detection (various gases)
  - Hazardous gas detection (e.g. CO)
- Malodor detection (kitchen & bathroom ventilation)
- HVAC systems
  - Reduced air circulation for greatly reduced energy consumption
    - ➢ CO_2 monitoring for fresh air
  - Mold detection / prevention
  - Increased levels of VOCs lead to sick building syndrome
    - ➢ Selective (formaldehyde, benzene etc.) and sensitive (ppb level) detection
  - Systems have to be adapted to the specific room use scenario

VOC-IDS: Volatile Organic Compound Indoor Discrimination Sensor

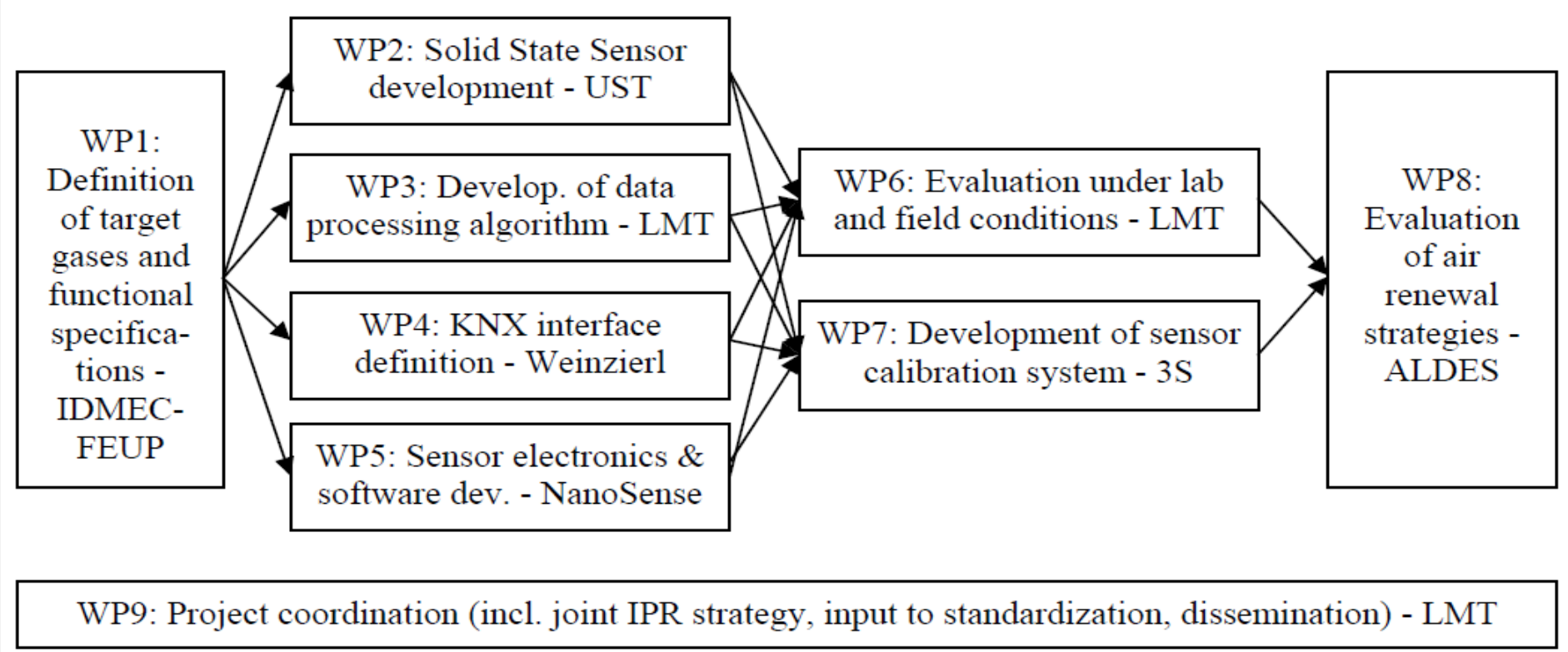
- Transnational project funded within MNT-ERA.net
- Selective VOC detection, primarily formaldehyde, benzene
- Novel ceramic nanomaterial metal-oxide semiconductor gas sensors
- Intelligent signal processing based on temperature cycling
- Networked systems connected to KNX bus

SENSIndoor: Nanotechnology based intelligent multi-SENsor System with selective pre-concentration for Indoor air quality control

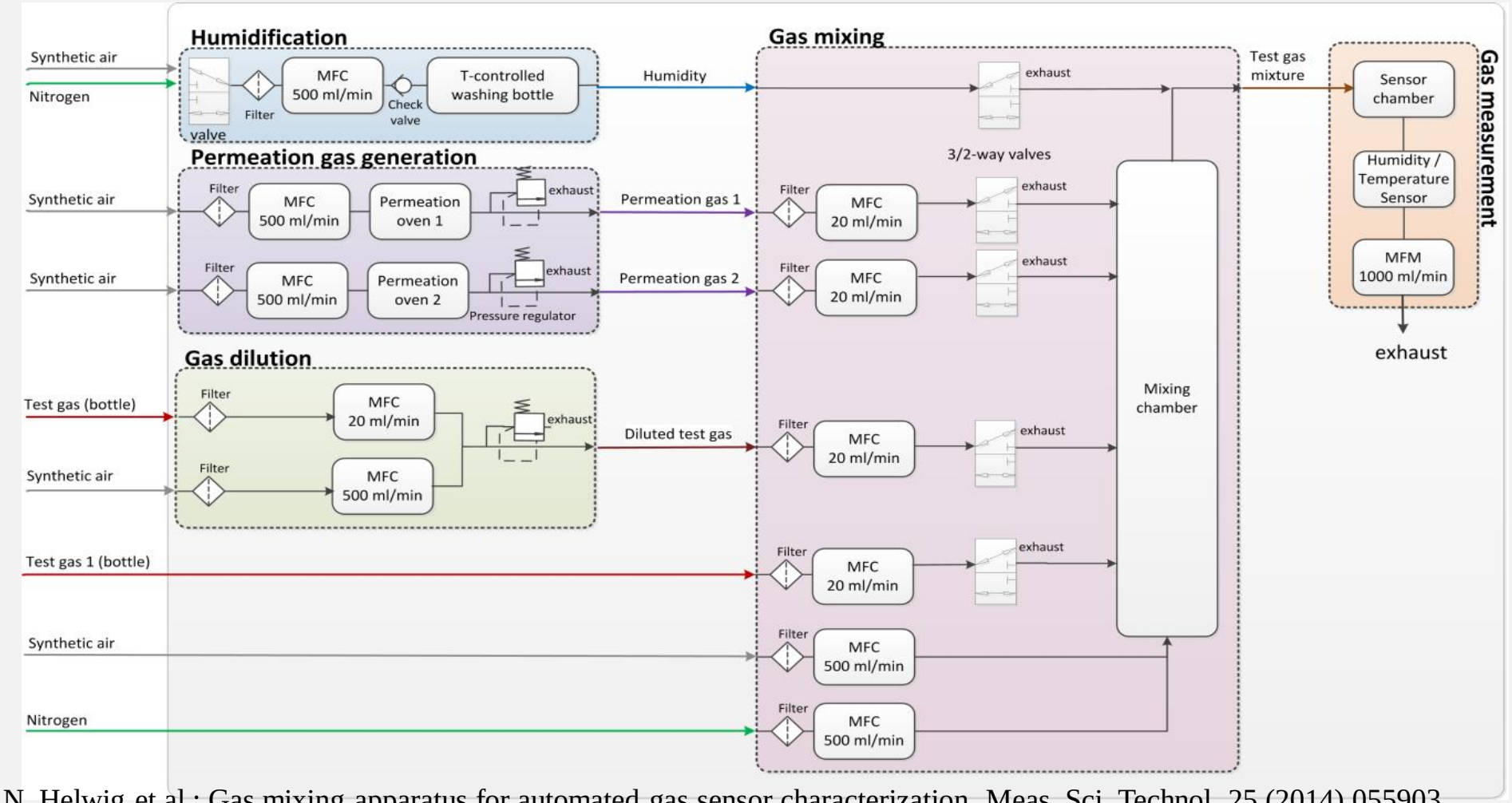
- EU-FP7 project NMP.2013.1.2-1:
  Nanotechnology-based sensors for environmental monitoring
- Microtechnology based approach for MOS and SiC-GasFET sensors
- Pre-concentration to boost sensitivity and selectivity
- Integrated multi-sensor approach
- Application specific priorities and field tests

MNT-ERA.net project VOC-IDS

- Volatile Organic Compound Indoor Discrimination Sensor
- Scenario specific detection of hazardous VOC
- Integration of sensor system into KNX building automation networks



First step: novel gas mixing system for VOC testing/calibration @ (sub) ppb-level



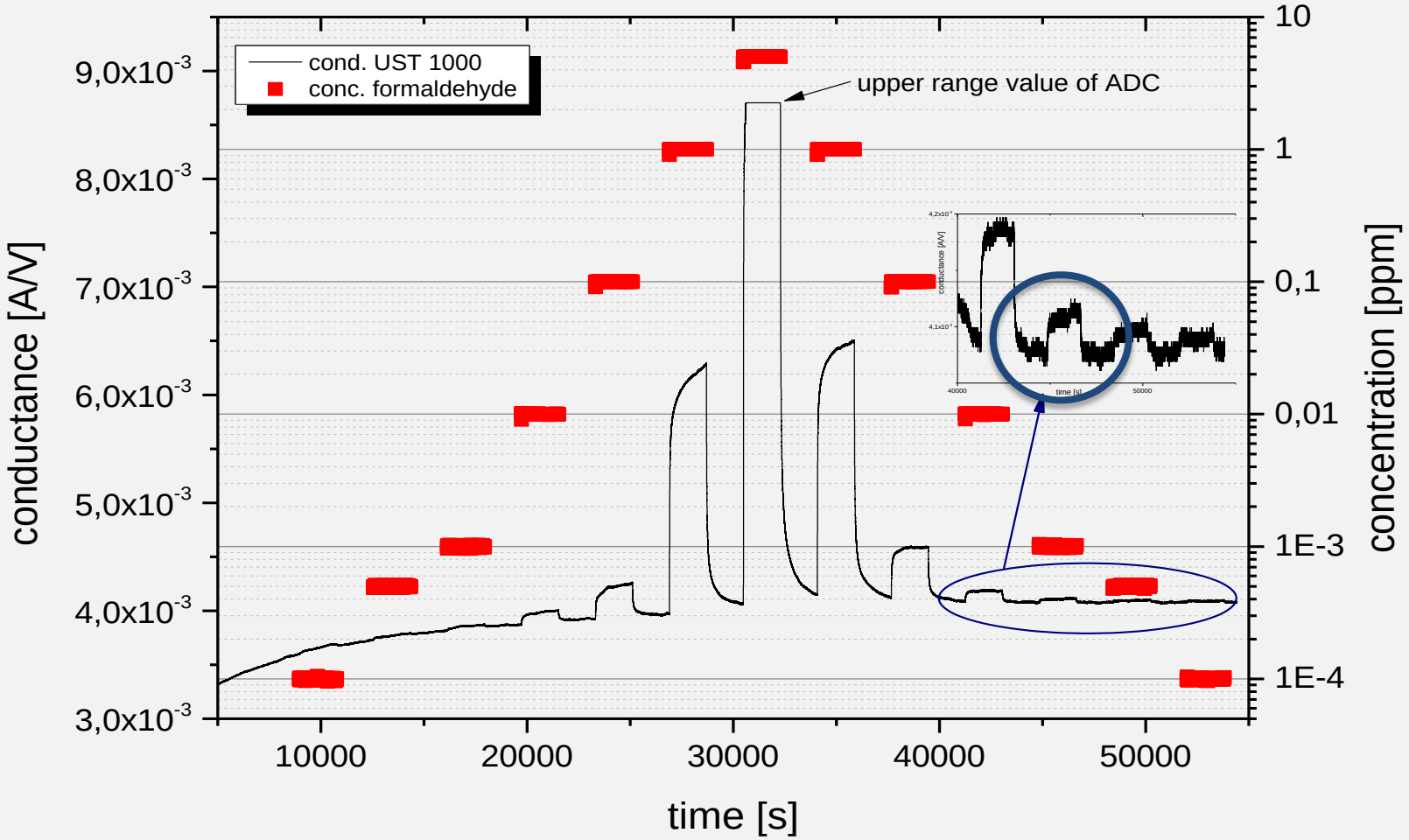
N. Helwig et al.: Gas mixing apparatus for automated gas sensor characterization, Meas. Sci. Technol. 25 (2014) 055903

Gas mixing system: results of reference measurements (zero air)

compound	CAS no	c [µg/m³]	c [ppb]
benzene	71-43-2	0.17	0.053
toluene	108-88-3	0.06	0.016
chlorobenzene	108-90-7	0.26	0.056
camphene	79-92-5	0.29	0.052
benzaldehyde	100-52-7	0.2	0.046
phenol	108-95-2	0.3	0.06
benzonitrite	100-47-0	0.61	0.144
octanal	124-13-0	0.1	0.019
benzyl alcohol	100-51-6	0.19	0.043
acetophenone	98-86-2	0.62	0.126
naphthalene	91-20-3	0.24	0.046
bicyclol[2.2.1]-heptane,2-chloro-2,3,3-trimethyl	465-30-5	16.2	2.6
TVOC		24.3	

N. Helwig et al.: Gas mixing apparatus for automated gas sensor characterization, Meas. Sci. Technol. 25 (2014) 055903

Novel gas mixing system: results of first sensor tests



Sensor reaction to 1 ppb formaldehyde

Relevance? Legal limits in France for indoor air: Formaldehyde 25 ppb in 2015; Benzene 0.6 ppb in 2016

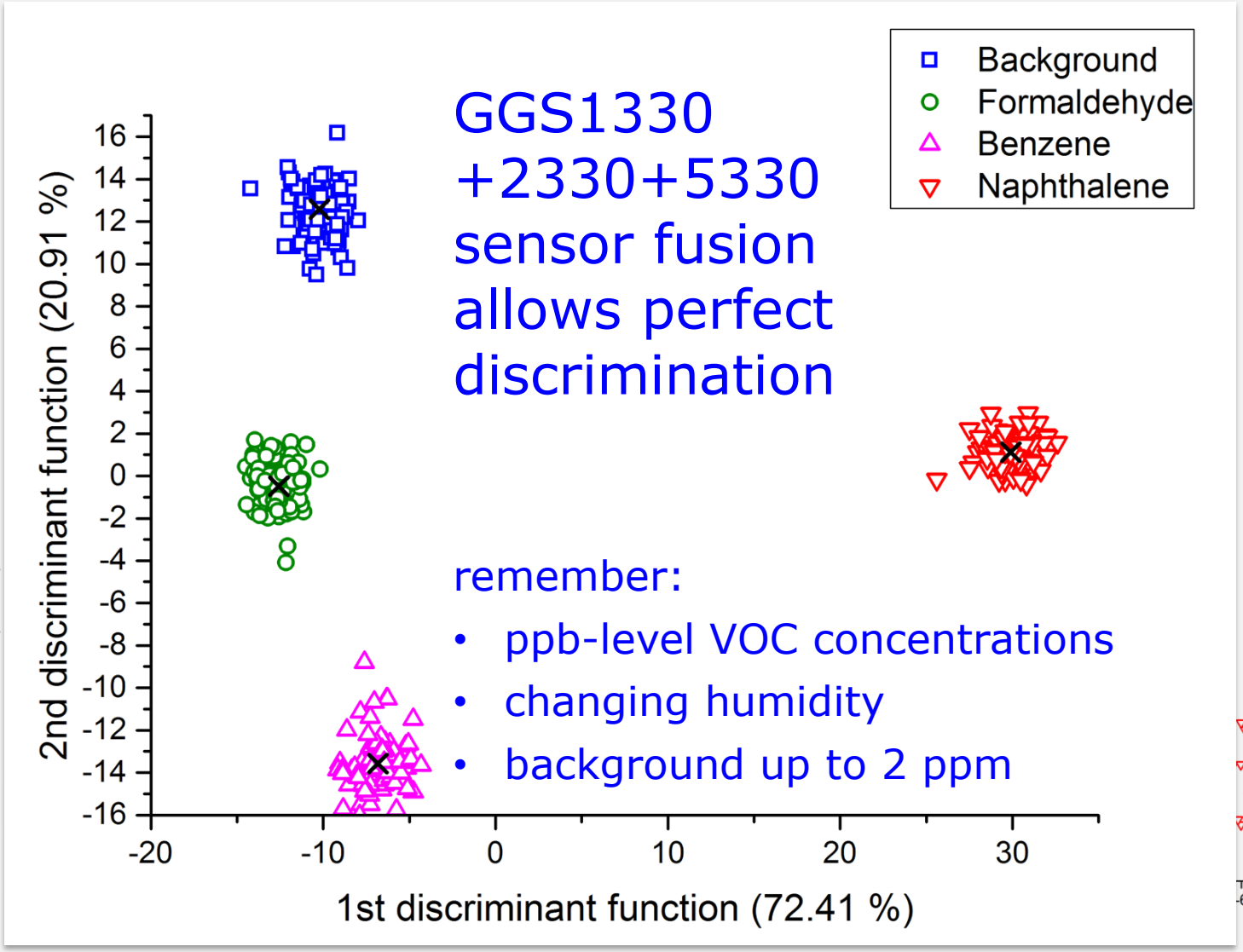
N. Helwig et al.: Gas mixing apparatus for automated gas sensor characterization, Meas. Sci. Technol. 25 (2014) 055903

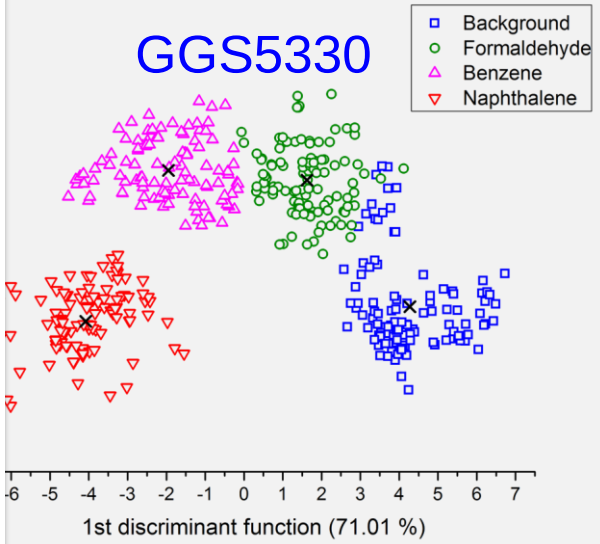
MNT-ERA.net project VOC-IDS

- Example for selective detection of VOCs in interfering background
- Classification of formaldehyde, benzene, naphthalene in the presence of ethanol

target gas	Concentration (ppb)	humidity	Interferents (EtOH ppm)
Air	NA	40%, 60%	none, 0.4, 2
Formaldehyde	10, 100	40%, 60%	none, 0.4, 2
Benzene	0.5, 4.7	40%, 60%	none, 0.4, 2
Naphthalene	2, 20	40%, 60%	none, 0.4, 2

Classification target	interferent concentrat.	relative humidity	number of LDA steps for charac.	Estimated # of LDAs
generalized classification	0, 0.4, 2	40%, 60%	1	1
classification w known r.h.	0, 0.4, 2	known	1 (2)	(1+) 5*1
classification w known EtOH	known	40%, 60%	2	1+10(?)*1


Background
Formaldehyde
Benzene
Naphthalene
GGS1330
+2330+5330
sensor fusion
allows perfect
discrimination
remember:
• ppb-level VOC concentrations
• changing humidity
• background up to 2 ppm
2nd discriminant function (20.91 %)
1st discriminant function (72.41 %)
2nd discriminant function (36.7 %)

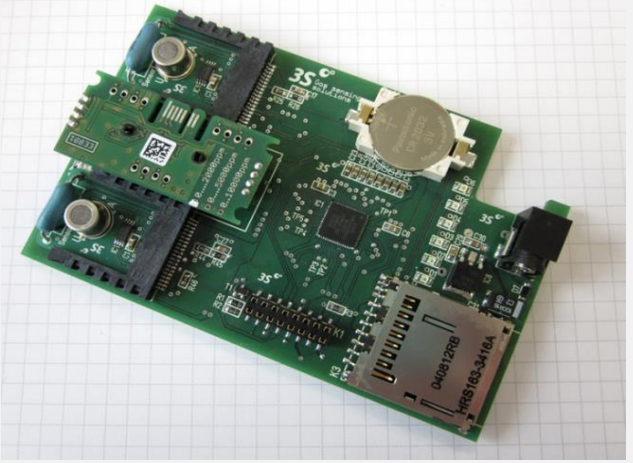

GGS5330
Background
Formaldehyde
Benzene
Naphthalene
1st discriminant function (71.01 %)

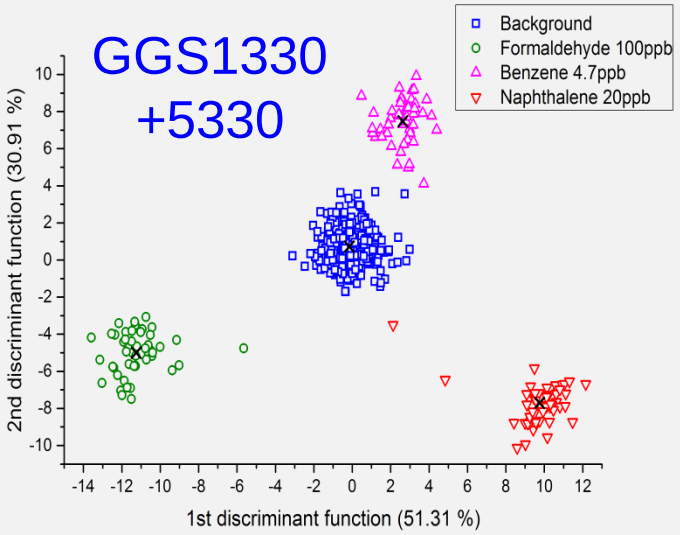
LEHRSTUHL FÜR MESSTECHNIK

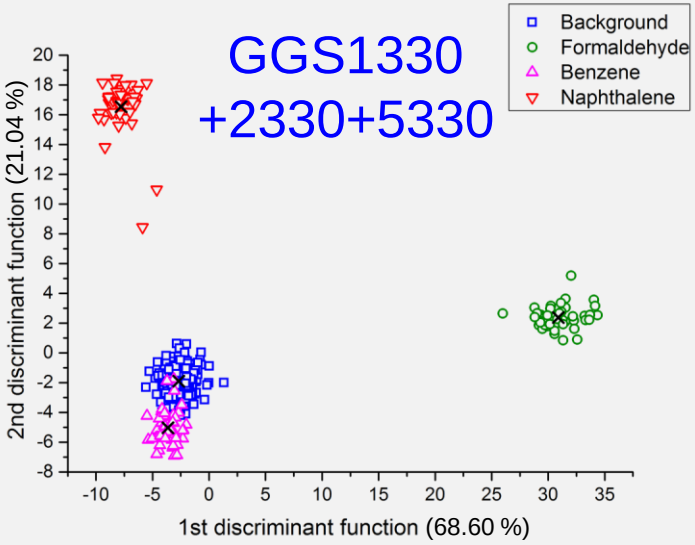
mnt-era.net

- Stand-alone field test systems by 3S GmbH (Saarbrücken, Germany)
- 2 MOS gas sensors (+ CO_2 + humidity) with independent temperature control
- Data storage on SD card
- Same test gas profile as for sensors only

Setup for system calibration

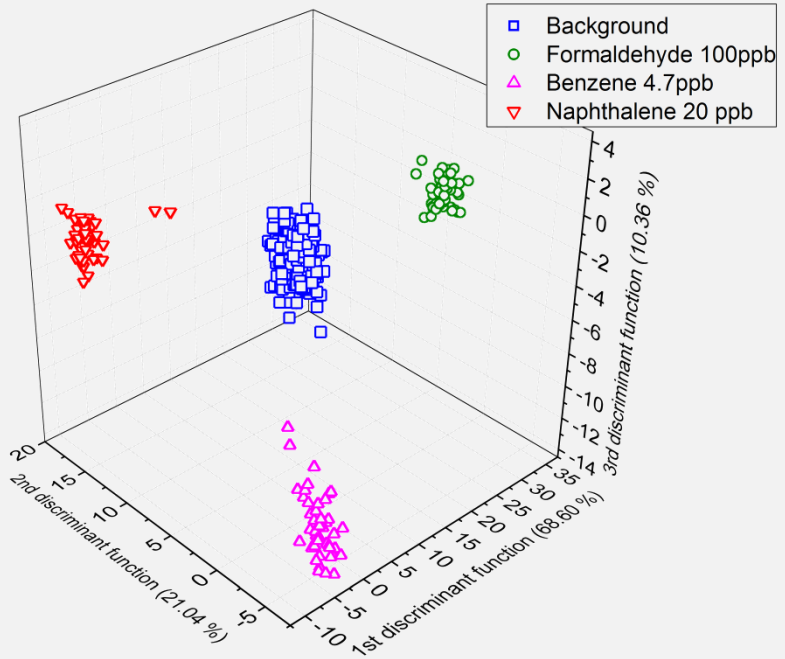






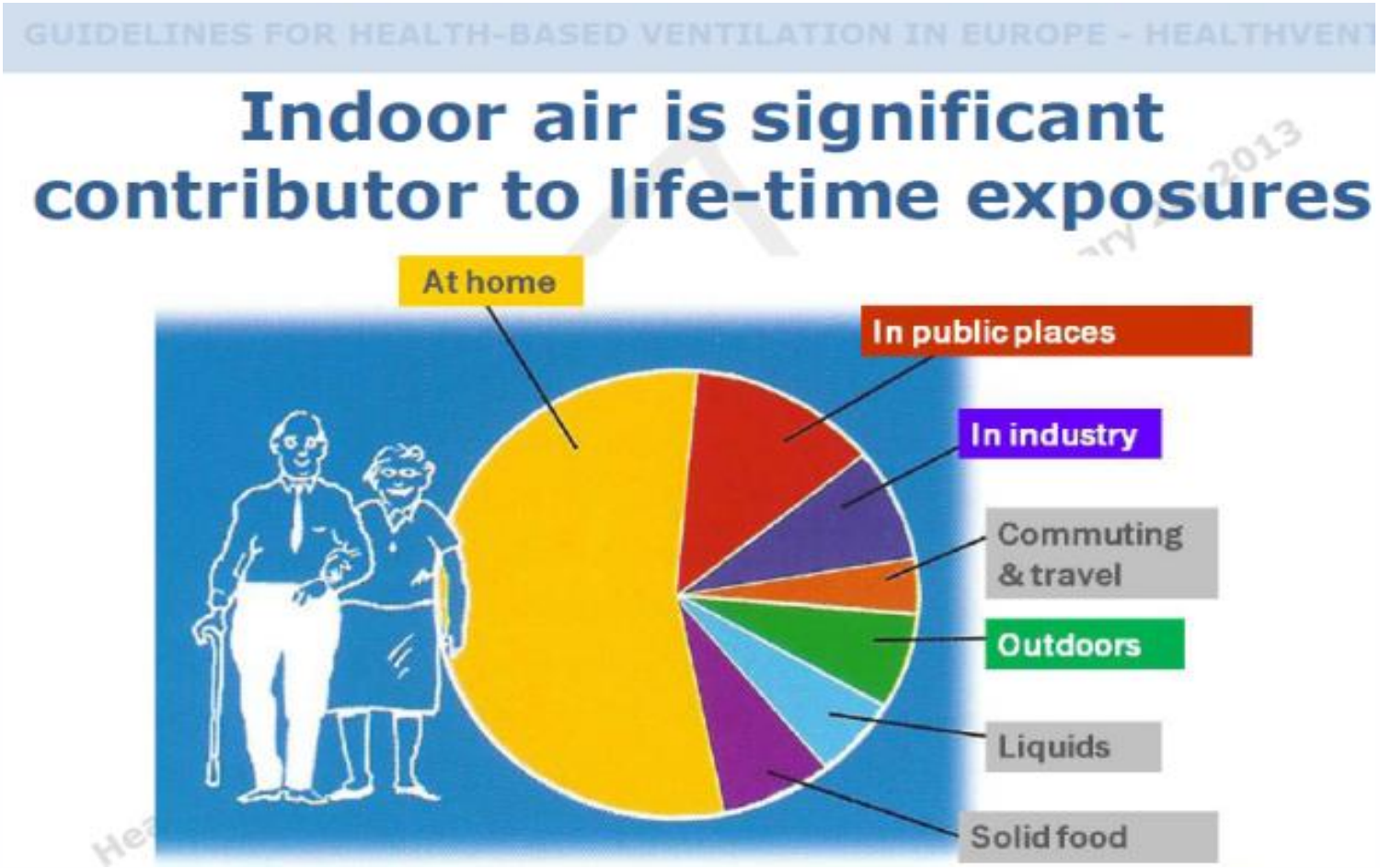
- Reduced discrimination due to VOC background from sensor systems, i.e. PCB, plastic housing
- Good discrimination of higher VOC concentrations
- Sensor fusion improves results considerably
- Further improvement with 3D LDA
- Promising results of initial field tests

3D



Motivation

- Core motivation for the SENSIndoor project



http://www.healthvent.byg.dtu.dk/

Motivation

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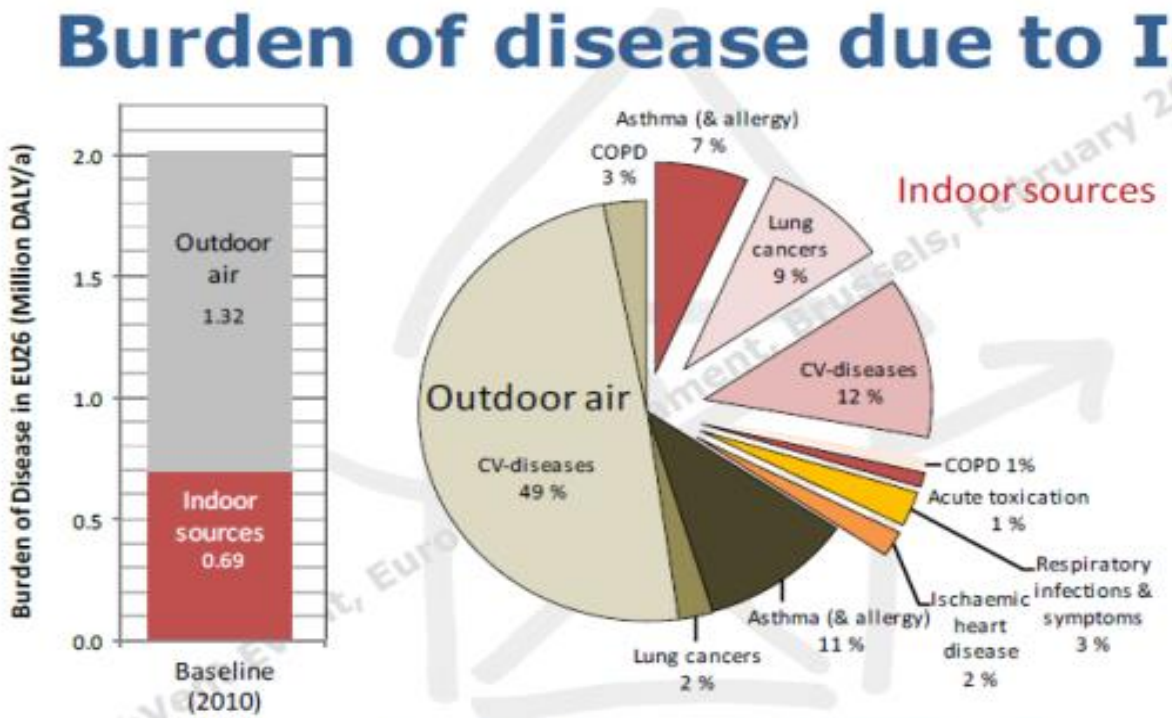


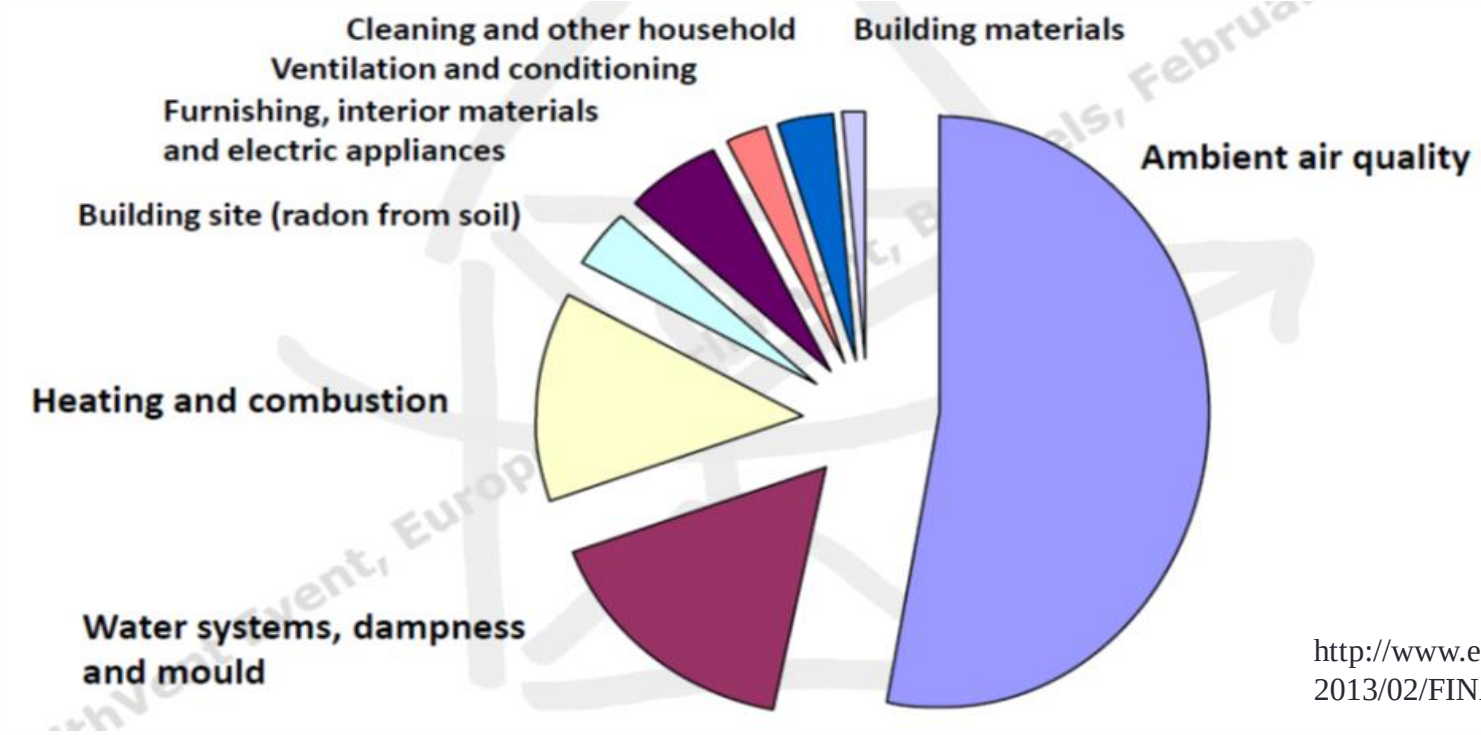
Figure 1. Burden of disease at the baseline (2010) in EU-26 divided into indoor and outdoor source components (left) and fractions associated with different diseases (right).

http://www.healthvent.byg.dtu.dk/

Motivation

Core motivation for the SENSIndoor project

2 Mio healthy life years are lost every year in the EU due to indoor exposure according to an analysis in the EU project EnVIE



http://www.efanet.org/wp-content/uploads/2013/02/FINAL-Presentation-all.pdf

Motivation

- People spend more than 80 % of their time indoors where fresh air exchange is increasingly limited to reduce energy consumption.
- Indoor air pollution contributes significantly to the global burden of disease.
- Continuous ventilation would greatly increase energy consumption for HVAC (heating, ventilation, air conditioning) systems.
- Low-cost sensor systems are required to provide ubiquitous Indoor Air Quality (IAQ) monitoring.

➢ **Core motivation for the SENSIndoor project**

Sensor system requirements 1

- Detection of hazardous indoor air pollutants at relevant levels
  - key target pollutants are VOCs, i.e. formaldehyde, benzene,…
  - target concentrations are ppb and sub-ppb level

➢ **extremely high sensitivity required**

	2012							2013			2015			2016			2023		
	MAK work place (8 hours)		TRK work place (15 mn)		Domestic (MAK/3) 24h/24h			French decree n° 2011-1727 of 2/12/2011 long-term guide value for public buildings											
	ppm	mg/m3	ppm	mg/m3	ppm	ppb	mg/m3	ppm	ppb	µg/m3	ppm	ppb	µg/m3	ppm	ppb	µg/m3	ppm	ppb	µg/m3
Formaldehyde	0.5	0.615	1	1.23	0.17	166.67	0.21				0.024	24.39	30.00				0.008	8.13	10.00
Benzene	1	3.25	1	3.25	0.33	333.33	1.08	0.00154	1.54	5.00				0.00062	0.615	2.00			

- In addition: many other interfering gases/VOCs
  - benign, e.g. ethanol, air freshener (much higher concentrations!)
  - unpleasant, but not hazardous, e.g. isovaleric acid
  - other background gases, e.g. CO, O_3, NO_x, ammonia, …

➢ **extremely high selectivity required**

Sensor system requirements 2

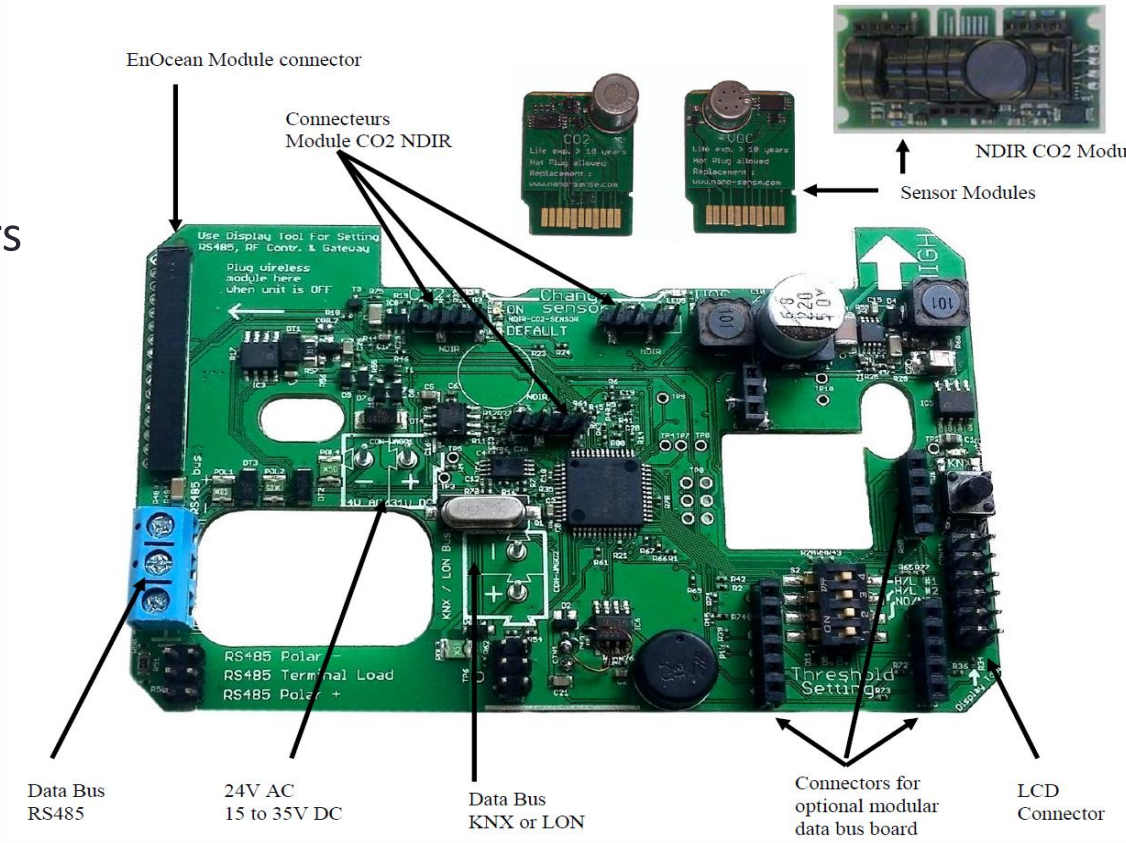
- Demand controlled ventilation to achieve optimal compromise between energy efficiency and health benefits adapted to specific application scenarios
  - **room-specific measurements required**
- Significant contribution to EU 20-20-20 goals and health aspects of IAQ targeted
  - **ubiquitous measurements required**

- **Core challenges addressed with micro- and nanotechnologies**
  - **microtechnologies for low cost mass production (and low power consumption)**
  - **nanotechnologies for unrivalled sensitivity and selectivity**

State-of-the-art

- Demand controlled ventilation today
  - mostly CO_2 monitoring, at best total VOC (TVOC)
  - CO_2 based on IR absorption or solid state electrolyte
  - TVOC based on metal oxide semiconductor (MOS) sensors

E4000 Air Quality Probe
(NanoSense SARL)

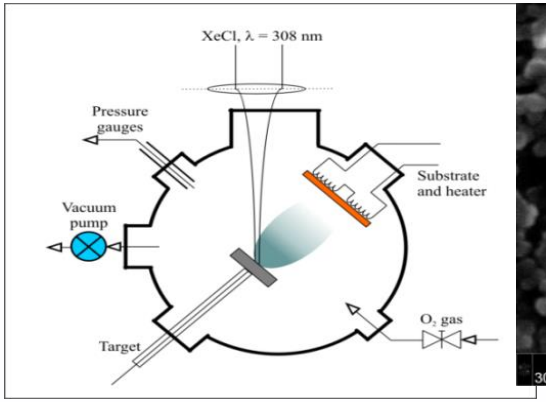


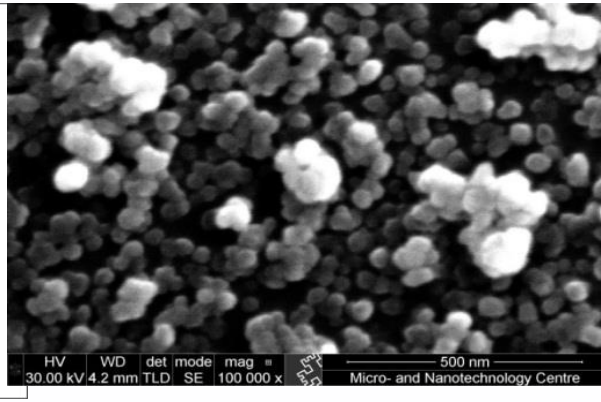
SENSIndoor origins

- **VOC-IDS** (MNT-ERA.net collaborative project)
  Volatile Organic Compound Indoor Discrimination Sensor
  - Partners: USAAR-LMT, IDMEC-FEUP - Instituto de Engenheria Mecânica, University Porto (P), UST Umweltsensortechnik GmbH (D), 3S GmbH (D), NanoSense SARL (F), Weinzierl Engineering GmbH (D), CIAT - Compagnie Industrielle d'Application thermique S.A. (F), ALDES Aéraulique S.A. (F)
- COST action TD1105 **EuNetAir**
  European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability
  - Partners: U Linköping (A Lloyd Spetz: vice chair of action), U Oulu, USAAR, 3S GmbH, SenSiC AB, SGX Sensortech S.A.
  - Several topics identified to be addressed in call **NMP.2013.1.2-1 Nanotechnology-based sensors for environmental monitoring**

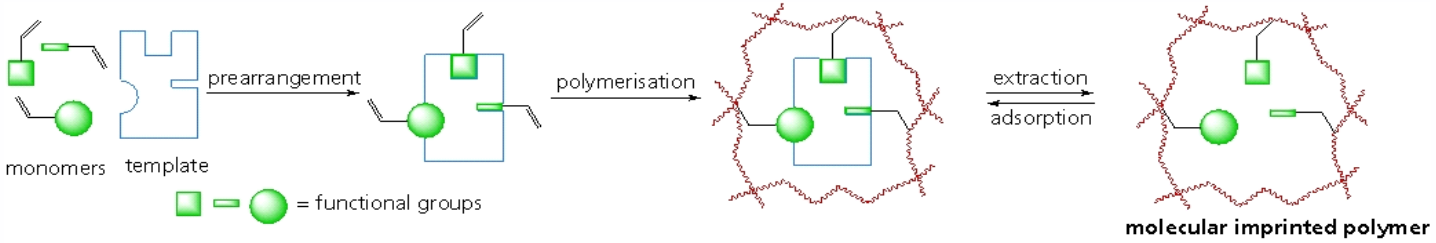
SENSIndoor technologies 1

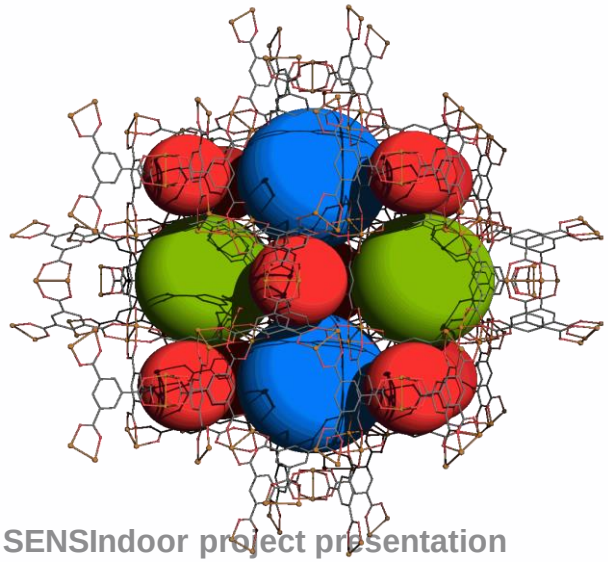
- Nanotechnology for improved sensor elements
  - **Pulsed Laser Deposition** (*U Oulu, Picodeon*)
    for novel, highly sensitive gas-sensitive layers suitable for wafer level mass production





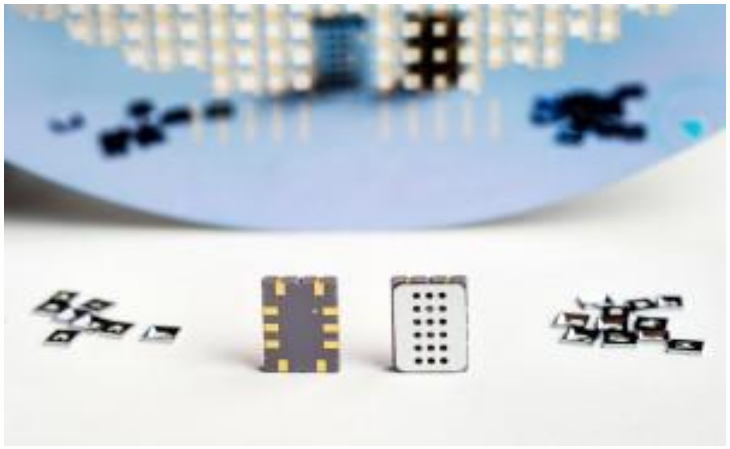
  - **Selective pre-concentration** (*FhG-ICT*)
    based on MOFs (metal-organic frameworks) → and MIPs ↓ (molecular imprinted polymers)

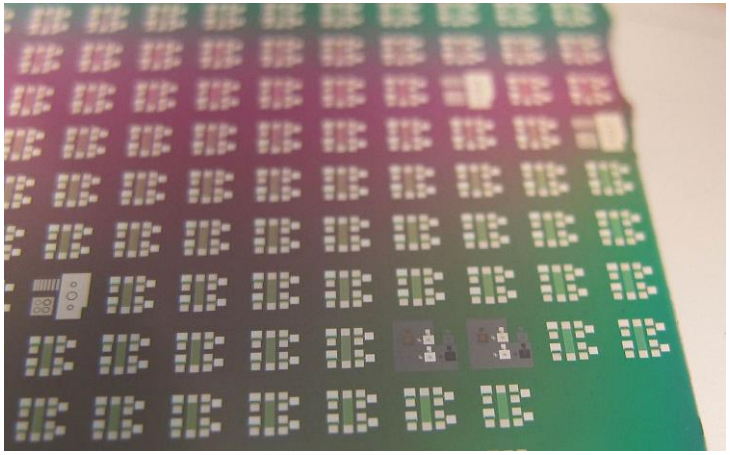




SENSIndoor technologies 2

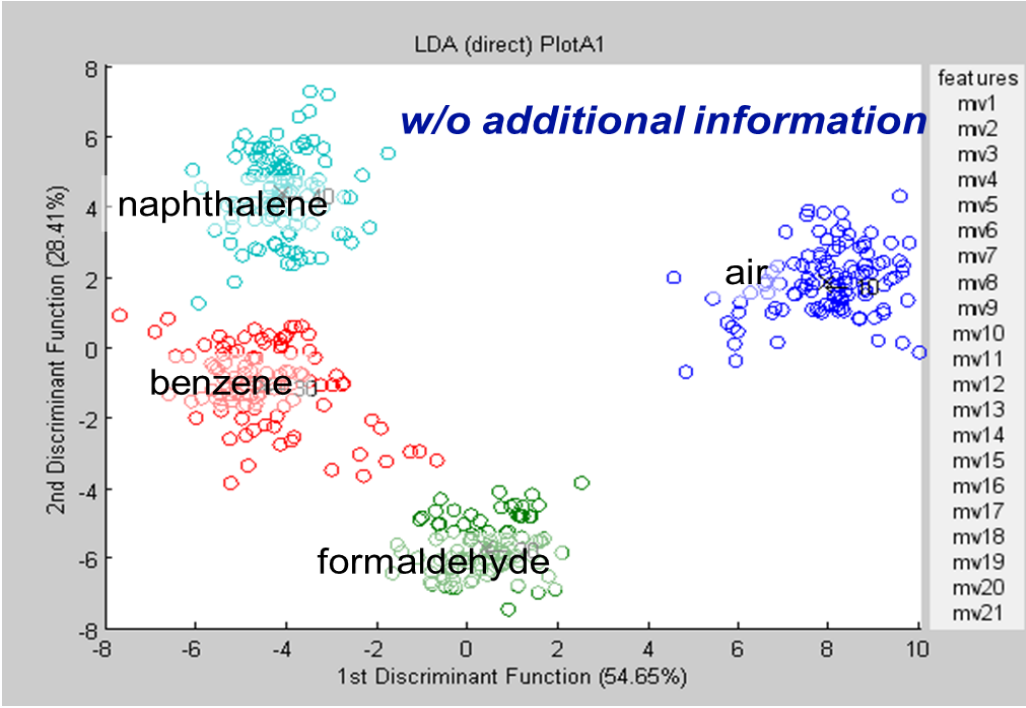
- Sensor technologies
  - **MOS – Metal oxide semiconductor** (*SGX Sensortech, USAAR-LMT*)
    - well known for high sensitivity and robustness @ low-cost
    - MEMS technology for mass production and low power consumption
  - **GasFET – Gas-sensitive Field Effect Transistors** (*LiU, SenSiC*)
    - complementary technology (polarity ⇔ reaction)
    - SiC technology for chemical robustness and high operating temperatures

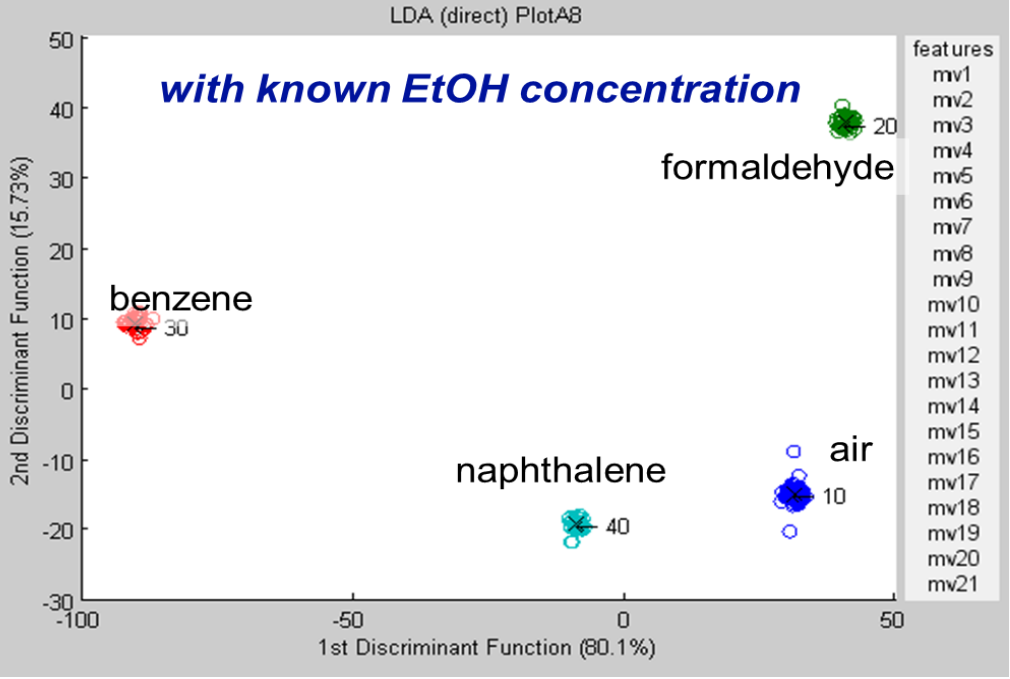




SENSIndoor technologies 3

- Dynamic operation and intelligent signal processing
  - **Temperature Cycled Operation** (*USAAR-LMT, NanoSense, 3S*) to increase selectivity ("virtual multisensor") and stability

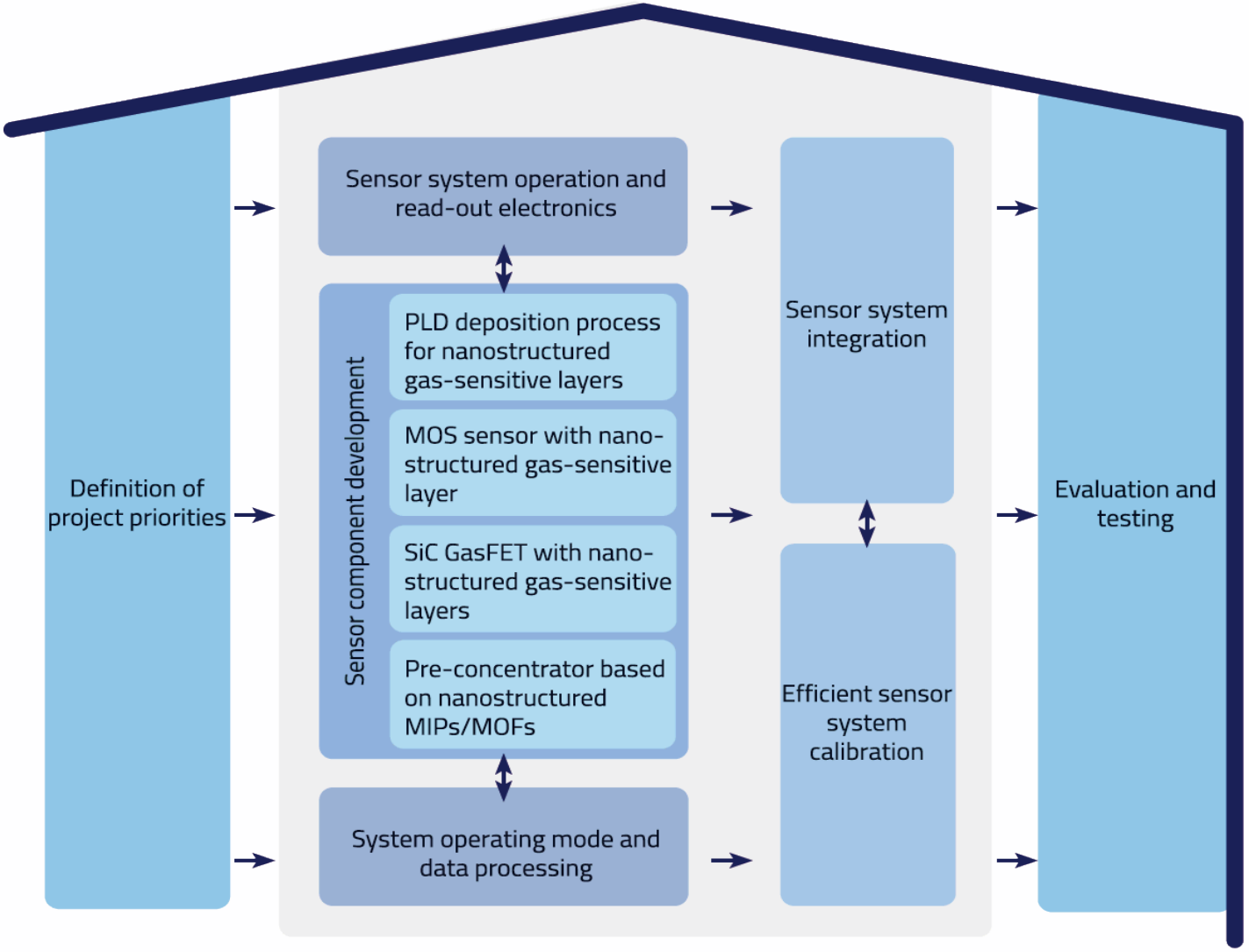




SENSIndoor overview

Project structure:

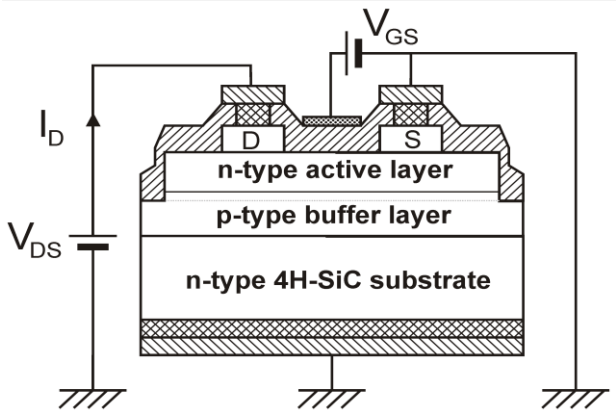
A clear road from application requirements to field evaluation

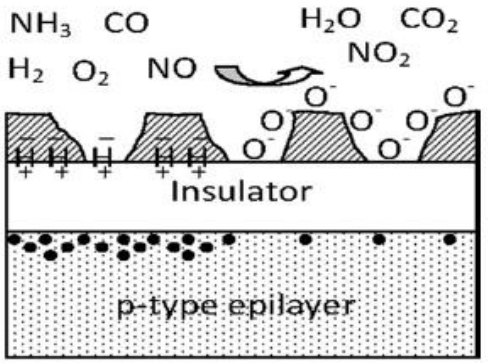


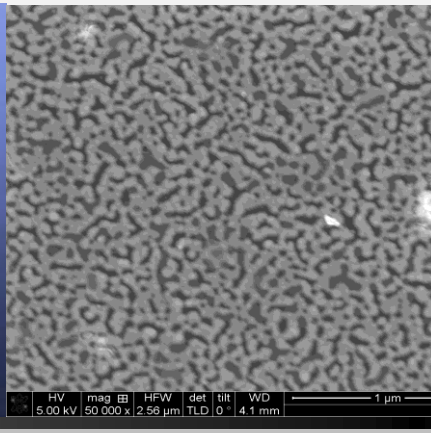
> IAQ monitoring w GasFET sensors

- SiC – Field Effect Transistors
  - Porous gate contacts (Pt, Ir)
- Gas interaction with the gate and insulator
  - Additional (internal) gate bias
- Shift in IV curve
  - Measured at constant current ID or voltage VDS
- Selectivity enhancement by dynamic operation
  - Temperature Cycled Operation (TCO)
- Goals: VOC discrimination and quantification

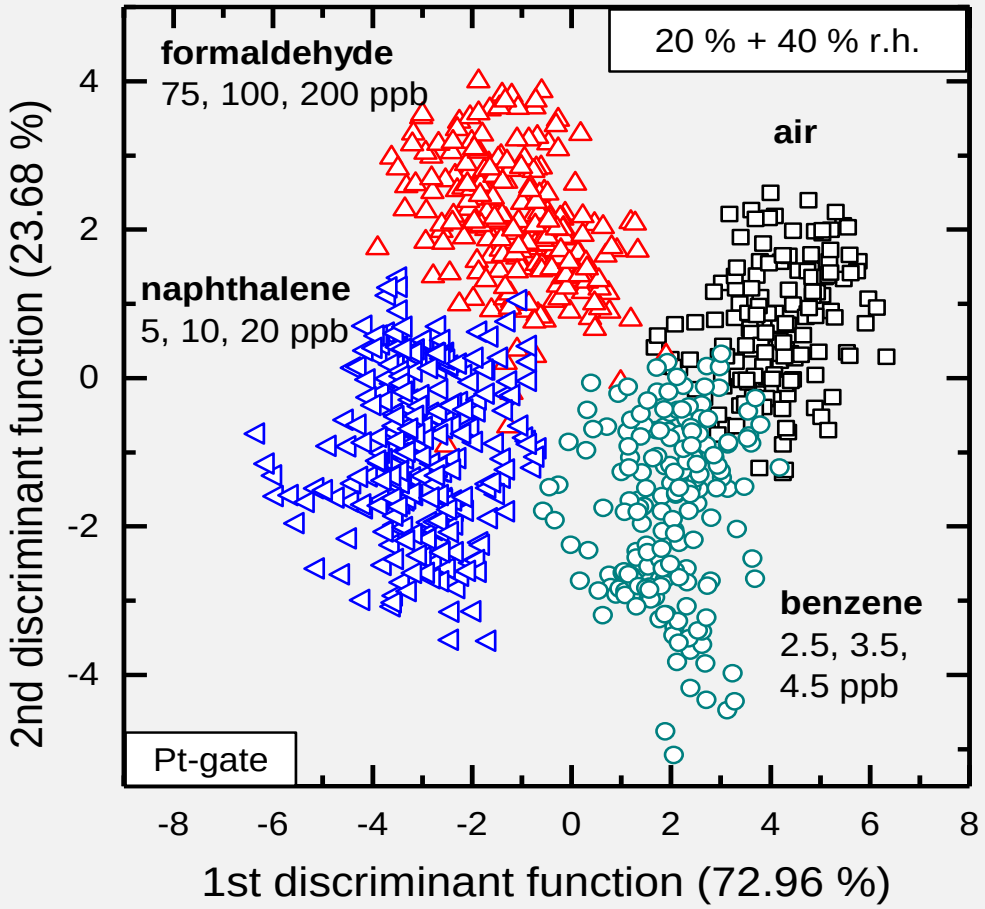
Joint PhD project of Christian Bur in collaboration with Linköping University, Prof. Anita Lloyd Spetz







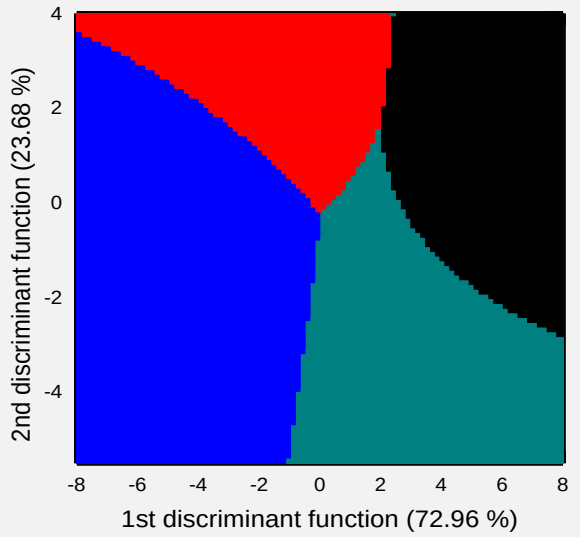
- **Discrimination** tested with 3 concentrations per VOC
- Tests performed at 20 % + 40 % r.h.



C. Bur et al.: Discrimination and Quantification of VOCs in the ppb-Range with Gas Sensitive SiC-FETs EUROSENSORS 2014, talk B1L-A02

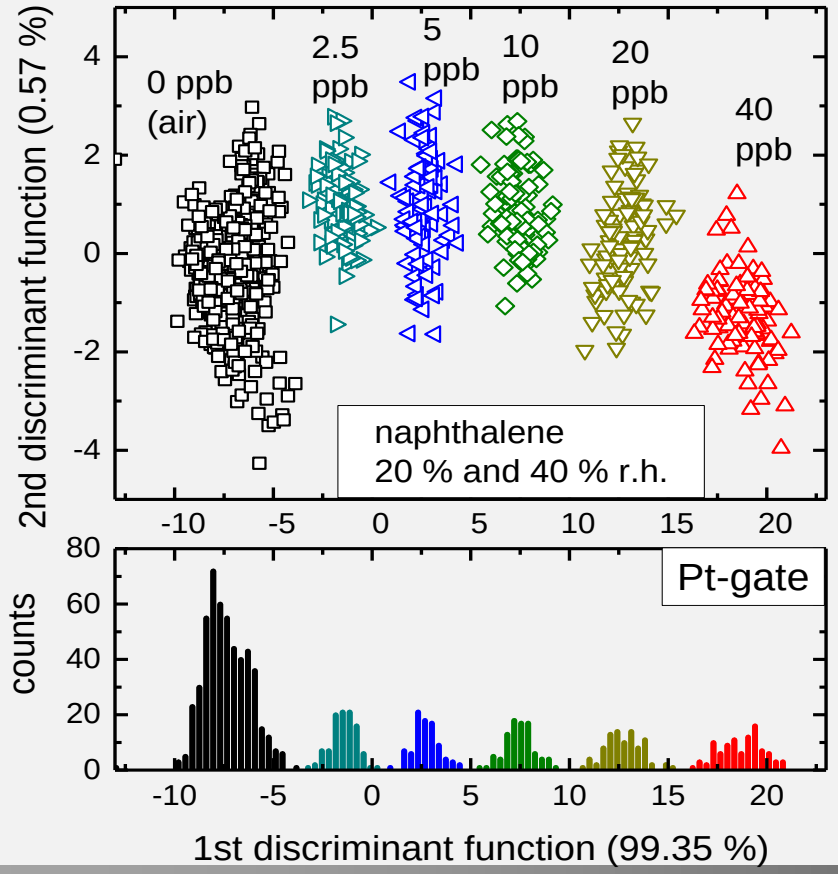
10-fold cross validation yields an overall classification rate of 94.7%

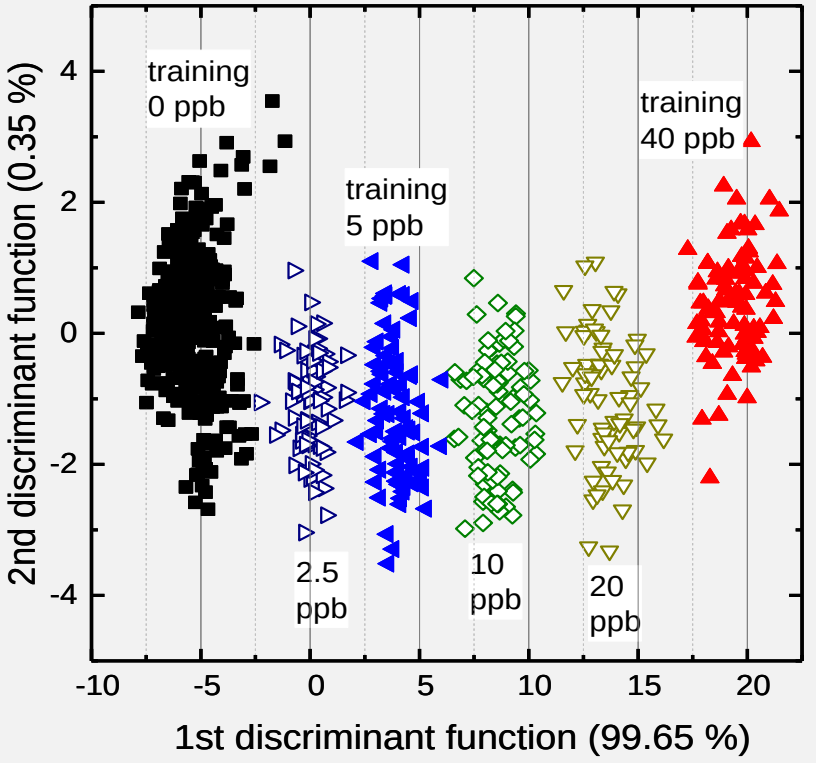
Mahalanobis distance classifier



> IAQ monitoring w GasFET sensors

- **Quantification** tested with Naphthalene
- 5 concentrations 2.5 to 40 ppb @ 20% and 40% r.h.
- Calibration based on 2 conc., evaluation with 3 others

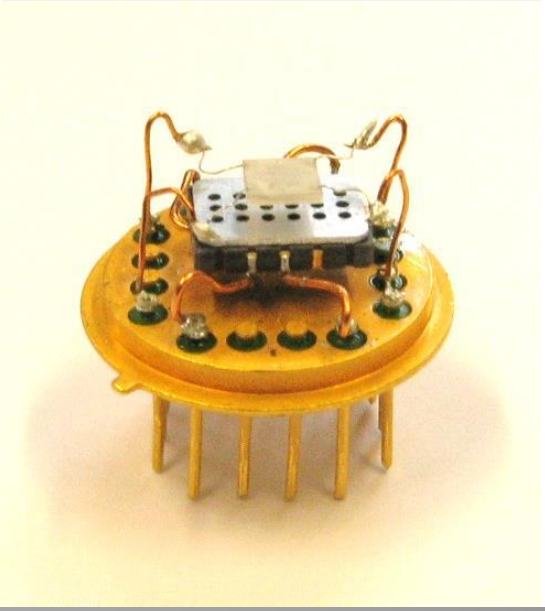


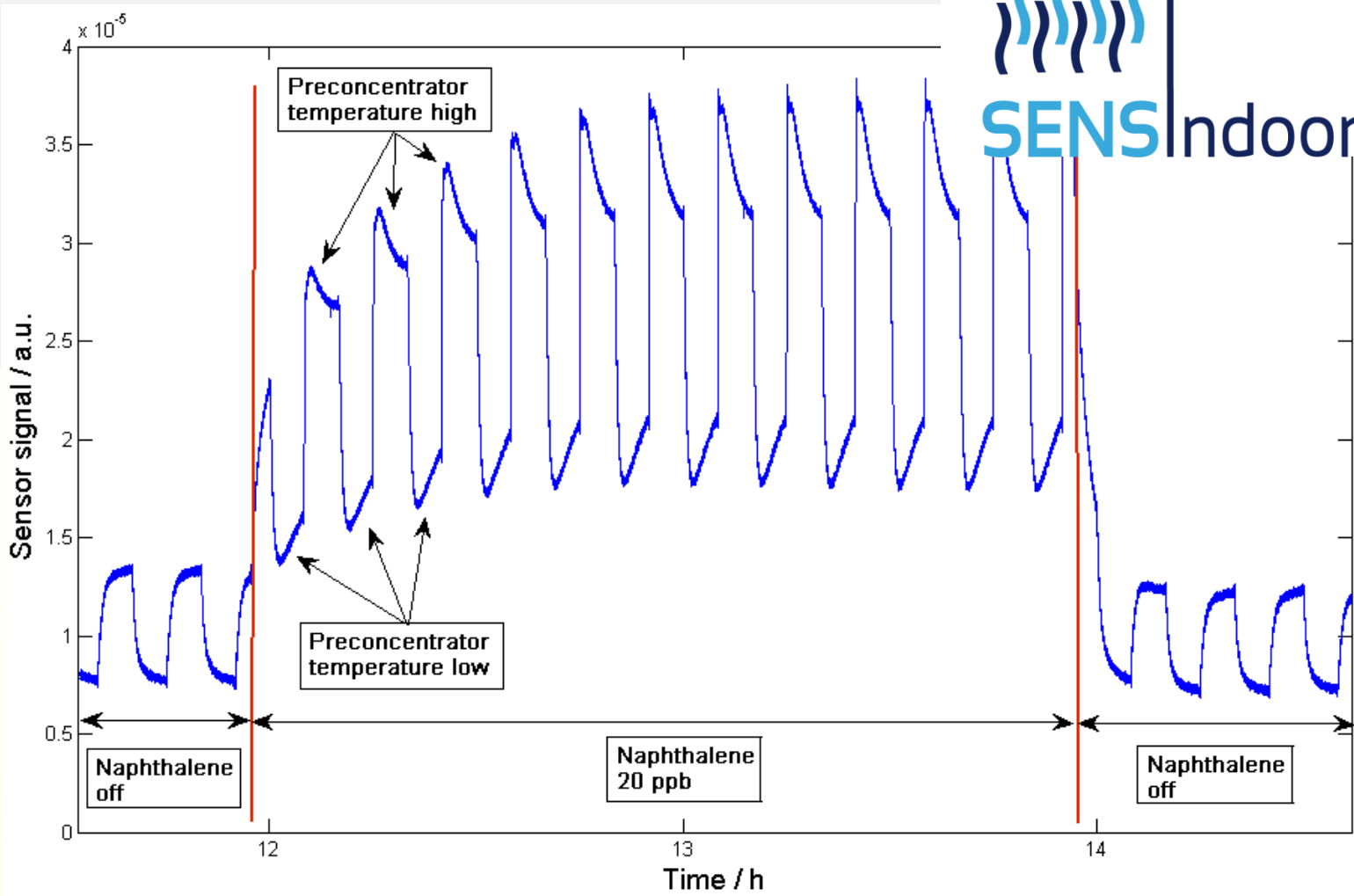


C. Bur et al.: Discrimination and Quantification of VOCs in the ppb-Range with Gas Sensitive SiC-FETs EUROSENSORS 2014, talk B1L-A02

First proof-of-principle measurements

- preconc. off: signal low, then increases
- preconc. on: signal high, then decreases





CONCLUSIONS

- **CONCLUSIONS:**
- Both MOS and GasFET sensors highly sensitive for VOC
- TCO allowing discrimination and quantification
- Micro- and nanotechnologies for excellent functionality at low cost
- µ-pre-concentrator promising concept for IAQ applications
- Ubiquitous low-cost sensor systems for IAQ realistic

- **OUTLOOK:**
- Extensive field testing required: calibration and reliable operation
- Priority application scenarios: schools/kindergarten, refurb. homes

European Network on New Sensing Technologies for Air Pollution Control and Environmental Sustainability - *EuNetAir*

COST Action TD1105

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