COST Action TD1105 – EuNetAir
WG Meeting: New Sensing Technologies and Methods for Air-Pollution Monitoring

Gas Sensor Systems for Indoor Air Quality Monitoring

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

Outline

- Introduction: indoor applications and air quality
- Gas measurement systems – more than just sensors
  - The three “S”
  - Gas measurement systems
  - Signal processing and evaluation
  - Calibration and field testing
- Indoor Air Quality monitoring
  - Target gases and concentrations
  - Potential sensor solutions
- Novel developments
  - Novel sensors: versatile GasFETs
  - System self monitoring
  - Multifunctional multisensor systems
- Conclusions

Introduction: Indoor Air Quality

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
  - 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

Introduction: Indoor Air Quality

Sensor requirements

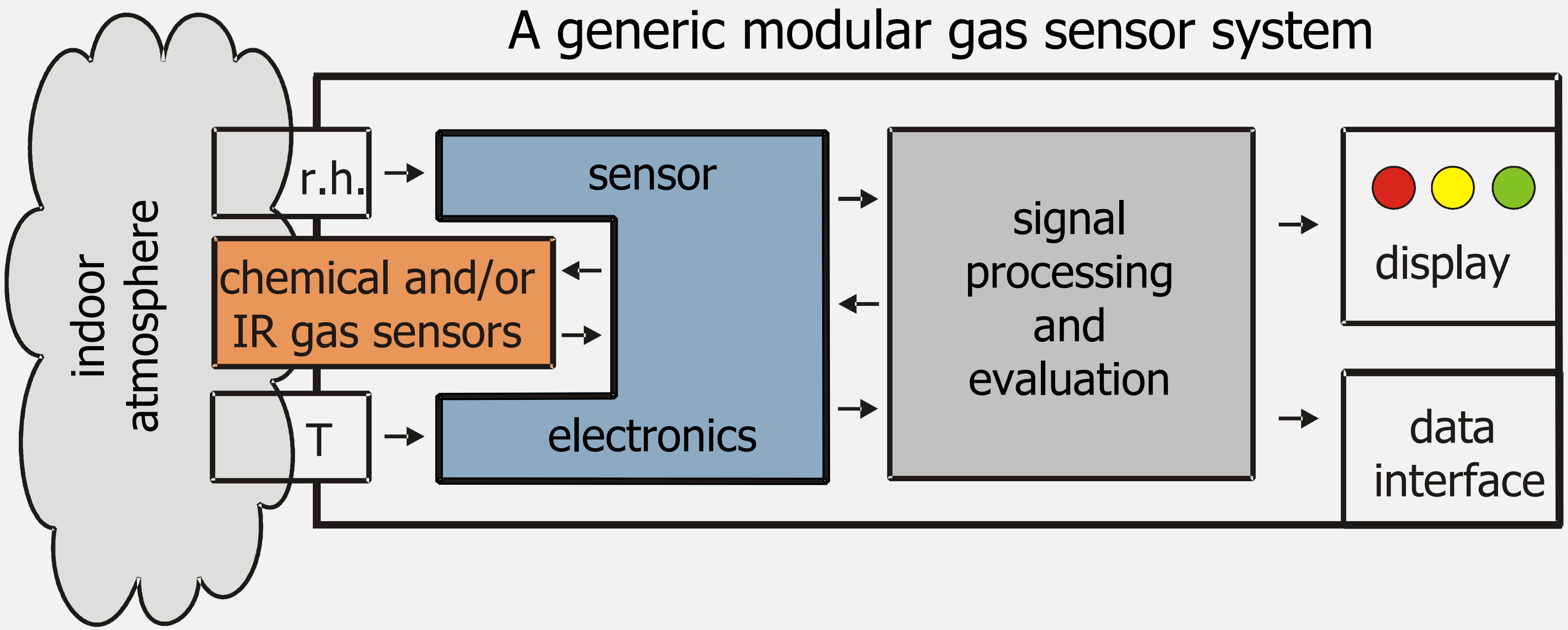
- Low cost
- Networked systems (in major buildings, but also private homes)
- Long lifetime: >10 years without maintenance for private homes

Which sensors are used today?

- Safety
  - Gas leak detection: pellistors (ind.), human nose (in Japan: MOS)
  - Fire detection: various sensors, mostly optical;
    gas sensor systems under development (EC, MOS, GasFET)
  - Hazardous gas detection: EC, MOS
- Malodor detection: MOS
- HVAC systems
  - CO_2 monitoring: NDIR (in major rooms/buildings), EC, GasFET
  - VOCs: MOS (total VOC), GasFET (emerging)

The three "S"

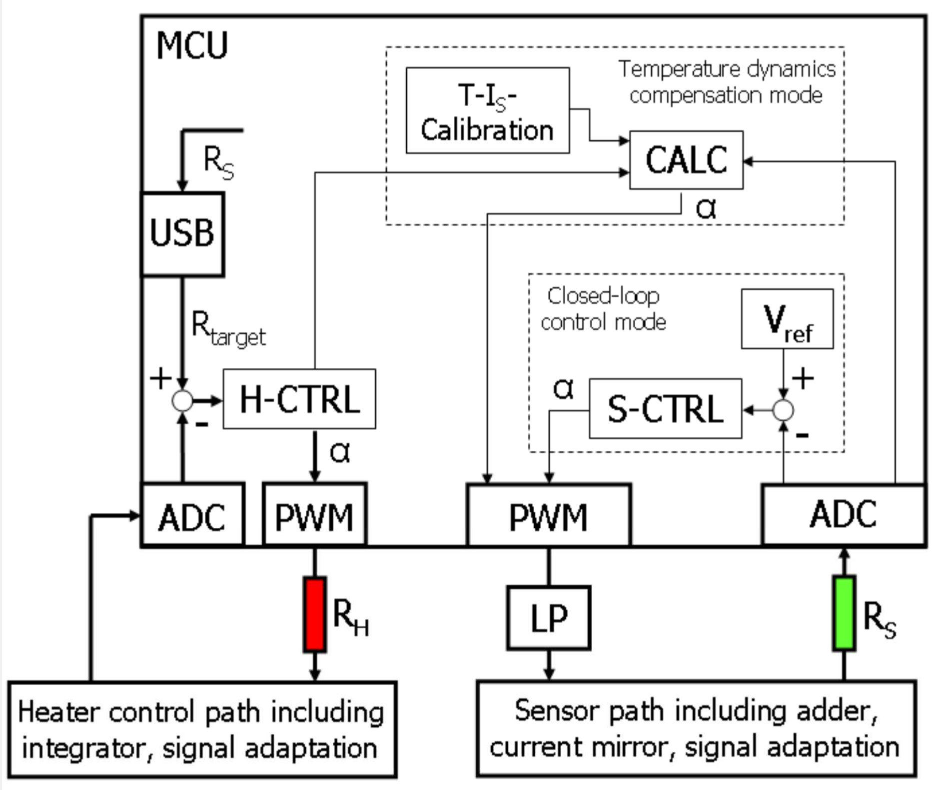
- Sensitivity
  - Broad spectrum
    from ppb (for malodors, ozone, hazardous VOCs)
    up to 1000 ppm (gas leak, CO_2)
- Selectivity
  - False alarms are primary concern for fire detection (ratio 10:1)
  - VOC detection: hazardous (formaldehyde) vs. neutral (alcohol vapor, cleaning agents) vs. wanted (odorants)
- Stability
  - Industrial applications: maintenance interval < 6 months
  - Public buildings: annual or bi-annual tests (if that)
  - Private homes: 10 years lifetime w/o regular maintenance?


A generic modular gas sensor system
indoor atmosphere
r.h.
chemical and/or IR gas sensors
T
sensor
electronics
signal processing and evaluation
display
data interface

Hardware platform PuMaH for exact temperature control and large dynamic range data acquisition - Pulse-width-modulated Measuring and Heating Unit

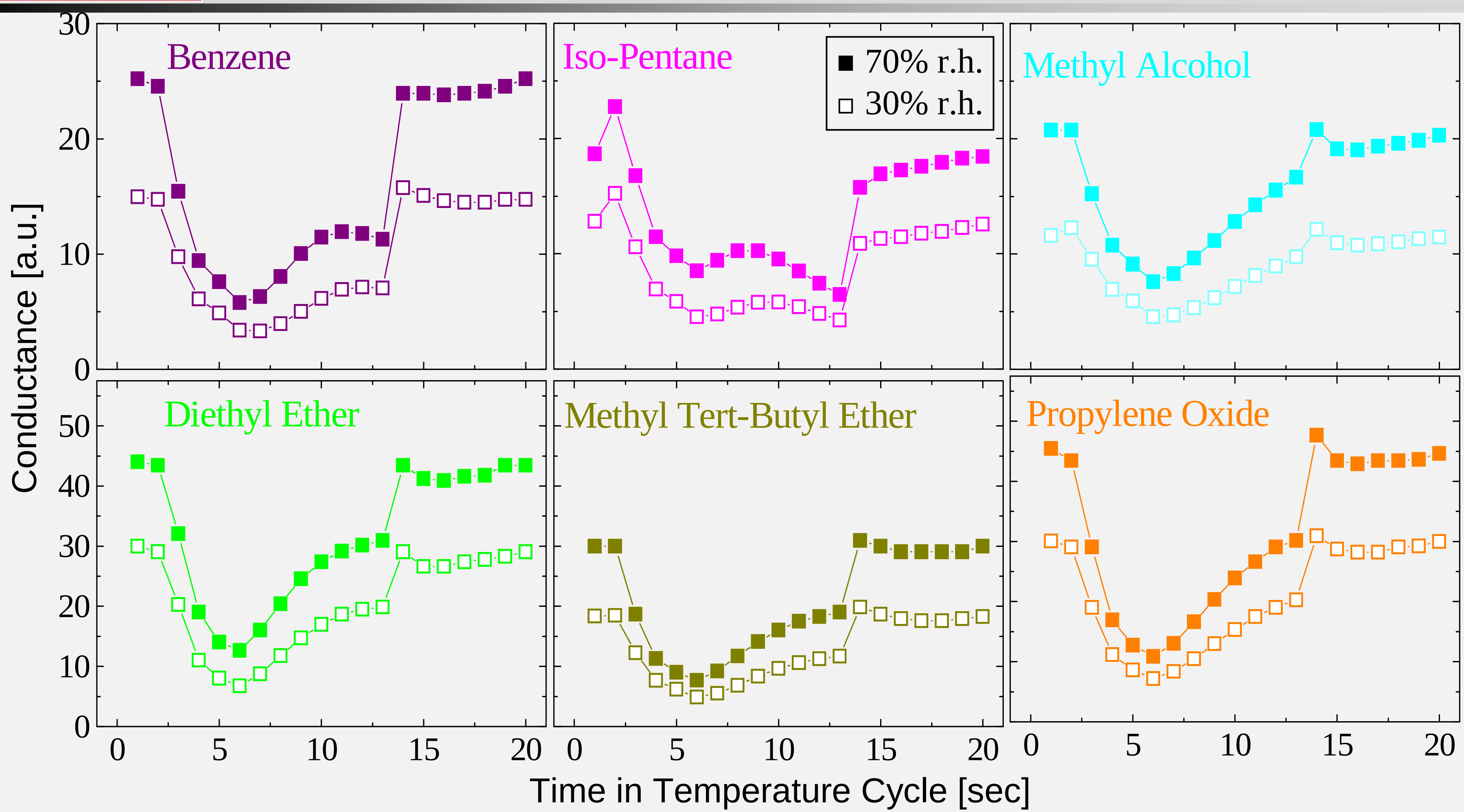
- Heater temperature control
  Heater resistor $R_H(T)$ controlled for exact temperature control of (micro-)hotplates
- Sensor resistance read-out
  Gas sensitive layer: R_S(gas)
  - Closed-loop control mode
    → constant voltage drop across R_S
  - Temperature compensation mode
    → large dynamic range of 26 bits
- Software controlled
- 16 bit PWM outputs used to apply signals to R_H and R_S

➢ **now commercialized "OdorChecker"** by 3S GmbH



Th. Conrad et al., IEEE Sensors Conference 2005

Temperature Cycled Operation (TCO) – software



A. Schütze, A. Gramm, T. Rühl
IEEE Sensors Journal, Vol. 4, No. 6, 2004

Signal evaluation:

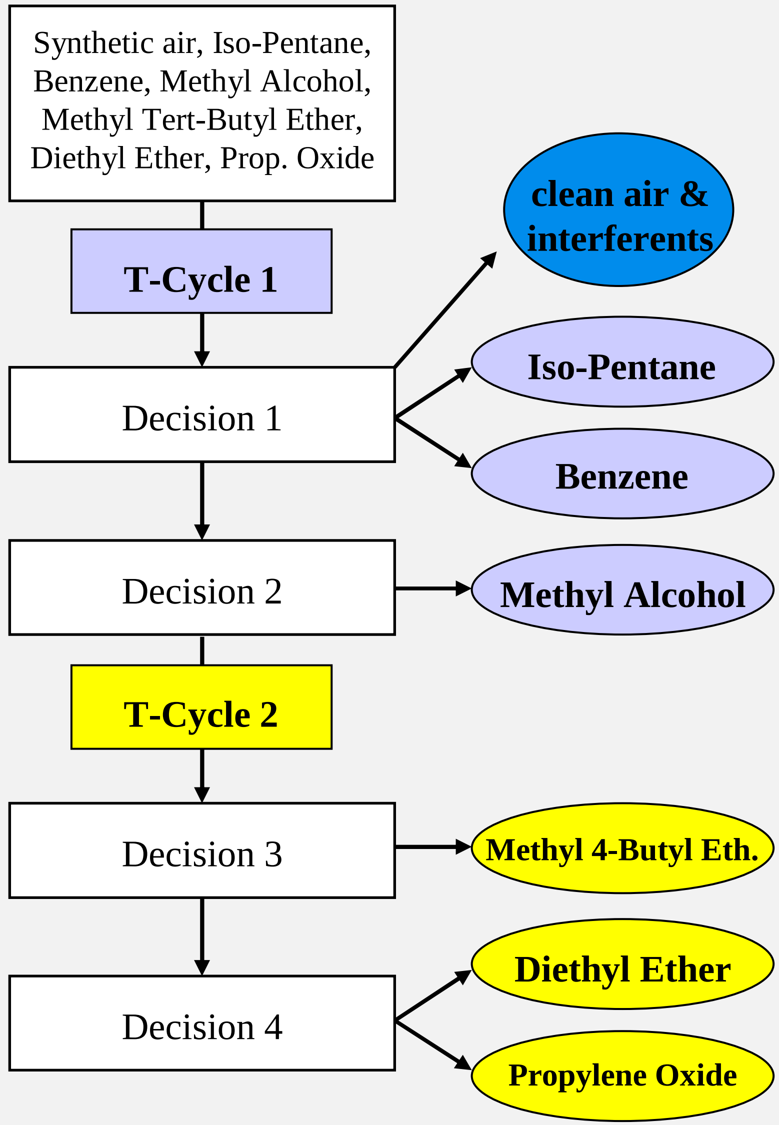
1. Normalization of the response curves ⇒ reduces sensor drift
2. Generation of secondary features, i.e. levels, slopes etc.
3. Suitable patterns are extracted for further evaluation

Evaluation of sensor data based on temperature cycling (example)
→ **Virtual multisensor**

Characteristic features of the curve shapes (i.e. ***slope at the end of the high temperature phase*** and ***curvature during the low temperature phase***) are evaluated, to discriminate between different gases in several steps.

Note: the decision tree reflects the chemical composition of the solvents starting with the alkane pentane and the aromatic benzene (both pure CH-compounds), then the alcohol (R-COH) and finally the three ether compounds (R1-O-R2). This indicates that an expansion might be possible to classify many different molecules.

Source: A. Schütze, A. Gramm, T. Rühl
IEEE Sensors Journal, Vol. 4, No. 6, 2004

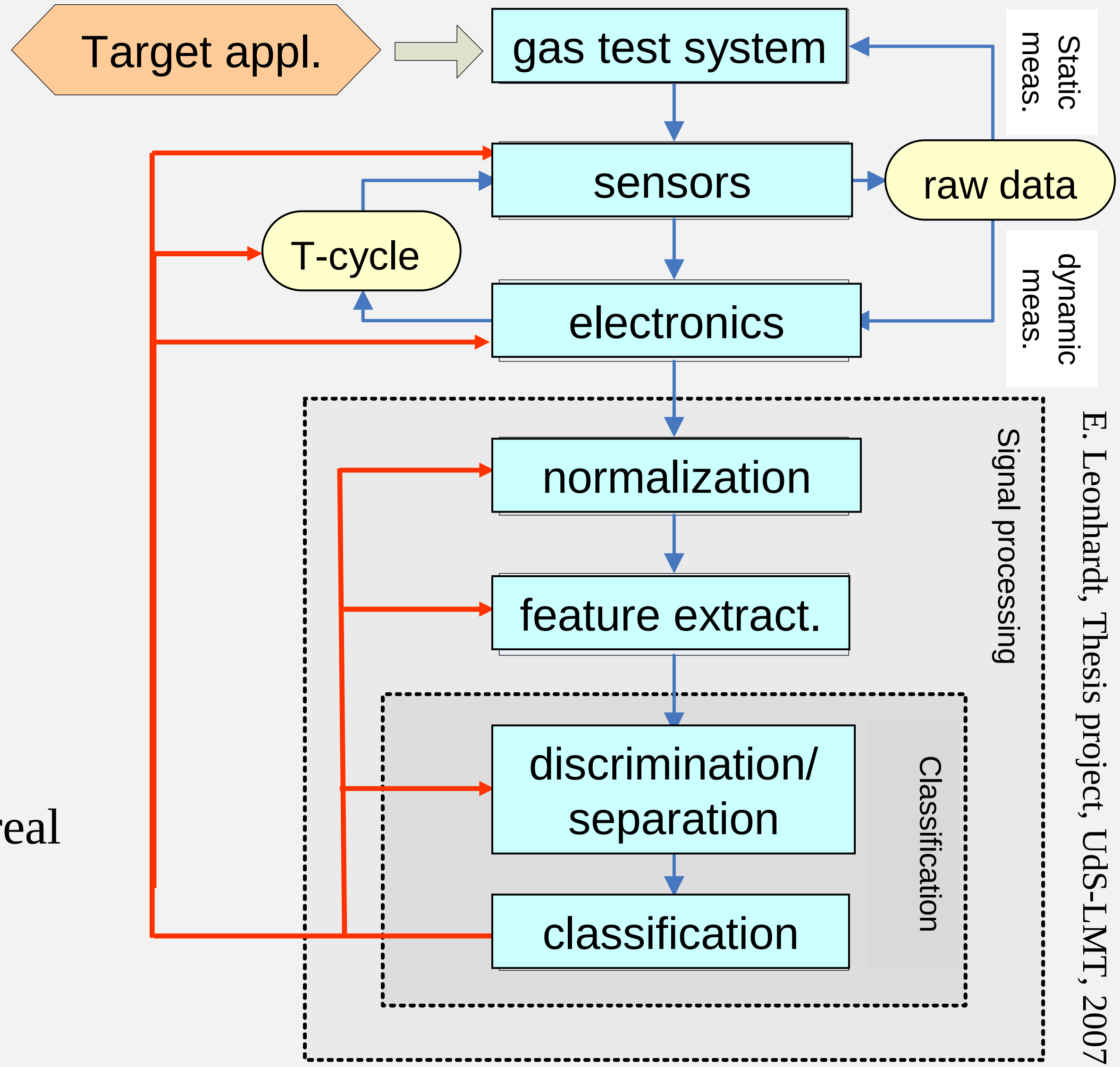


Gas measurement systems – more than sensors
Temperature Cycled Operation – system design

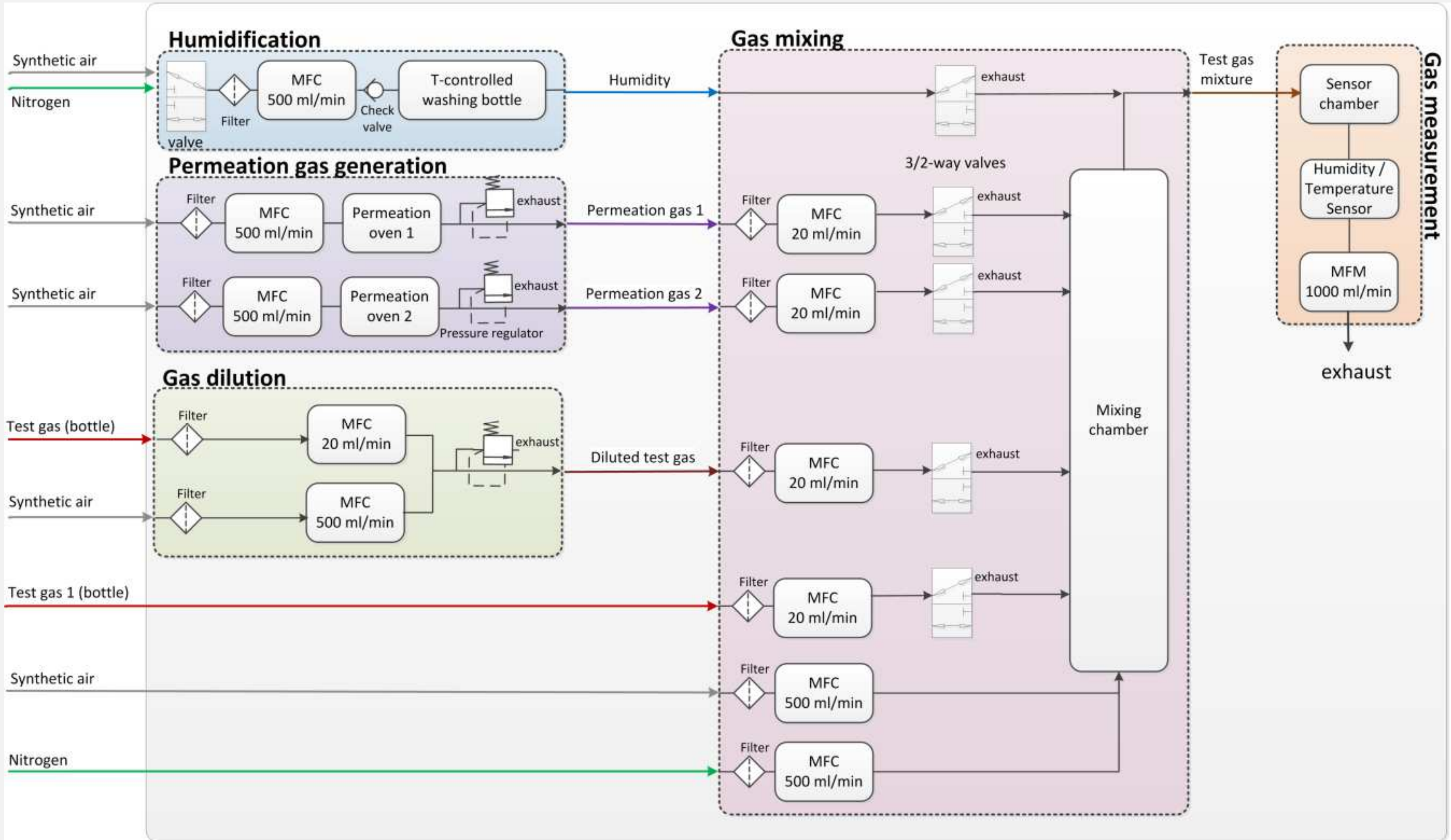
Many possibilities for optimization:

- Sensor selection
- Operating mode
- Data acquisition
- Signal preprocessing
- Feature extraction
- Separation
- Classification

…and **always** testing under real application conditions (field testing)!



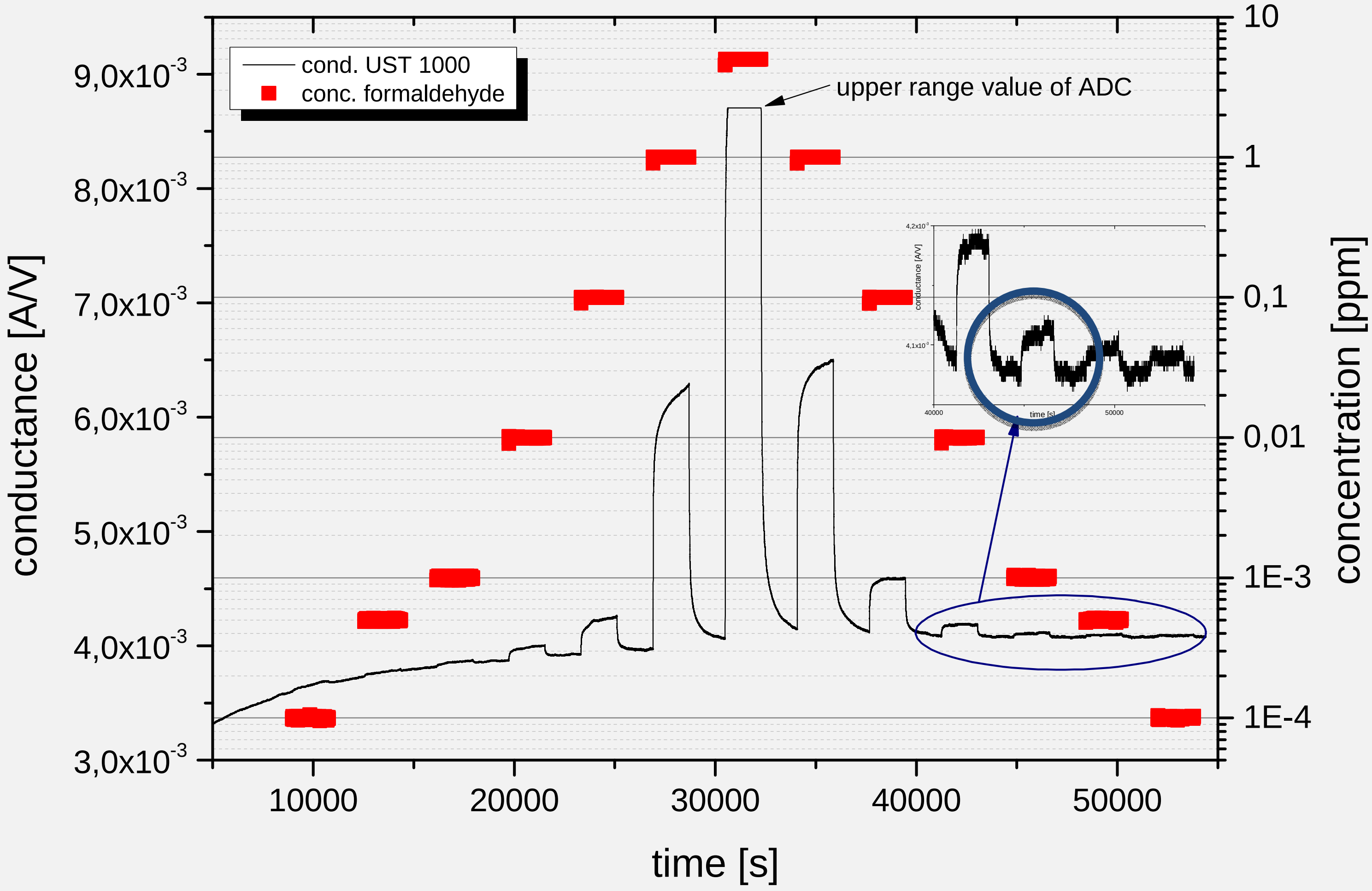
Calibration: novel gas mixing system for VOC testing down to sub ppb-level



Novel gas mixing system: results of reference measurement (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	

Novel gas mixing system: results of first sensor tests



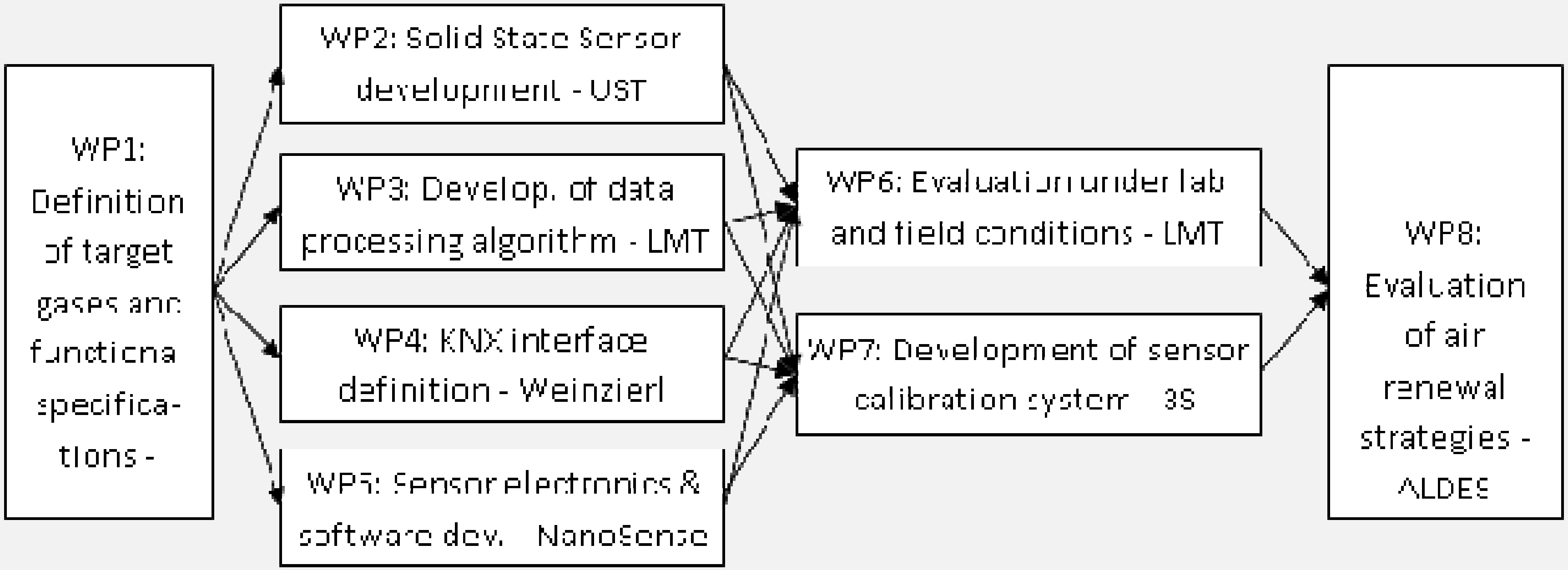
Sensor reaction to **1 ppb formaldehyde**

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

Indoor Air Quality monitoring

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



WP9: Project coordination (incl. joint IPR strategy, input to standardization, dissemination) - LMT

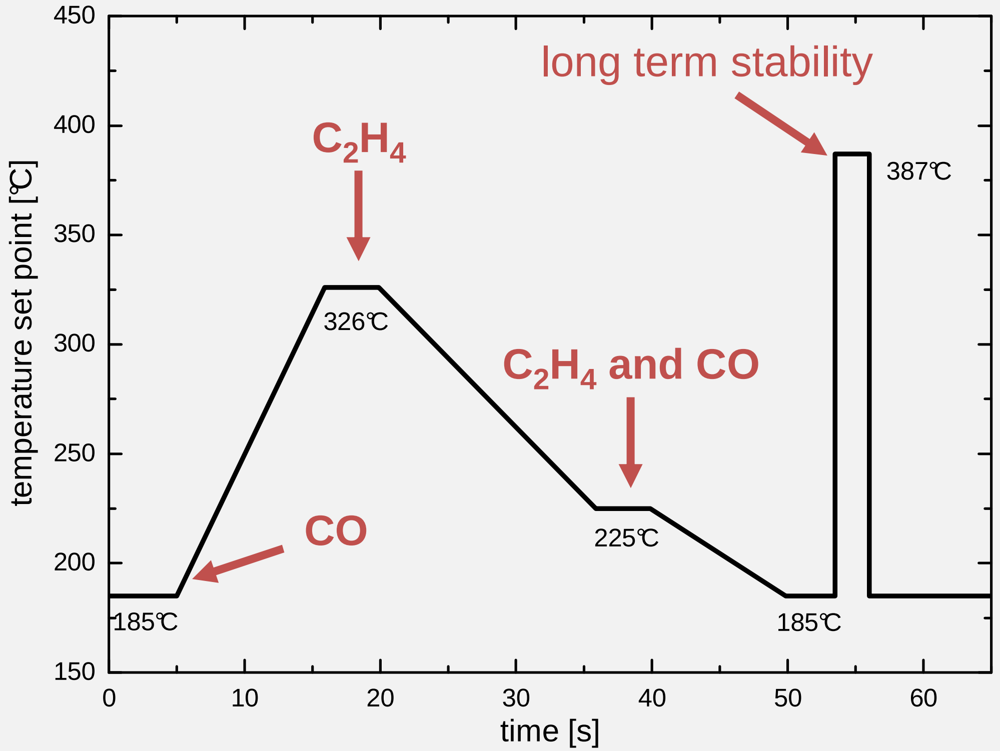
Indoor Air Quality monitoring

VOC-IDS: ppb-level detection of VOCs against background gases?

Similar requirements: Fire detection in coal mines

- CO/C_2H_4 mixtures at 10 ppm/100 ppb respectively
- Background: up to 1% methane + interfering gases: r.h., CO, H_2, NO_2 etc.

P. Reimann, PhD thesis, UdS-LMT, 2011



different temperature levels for the target gases

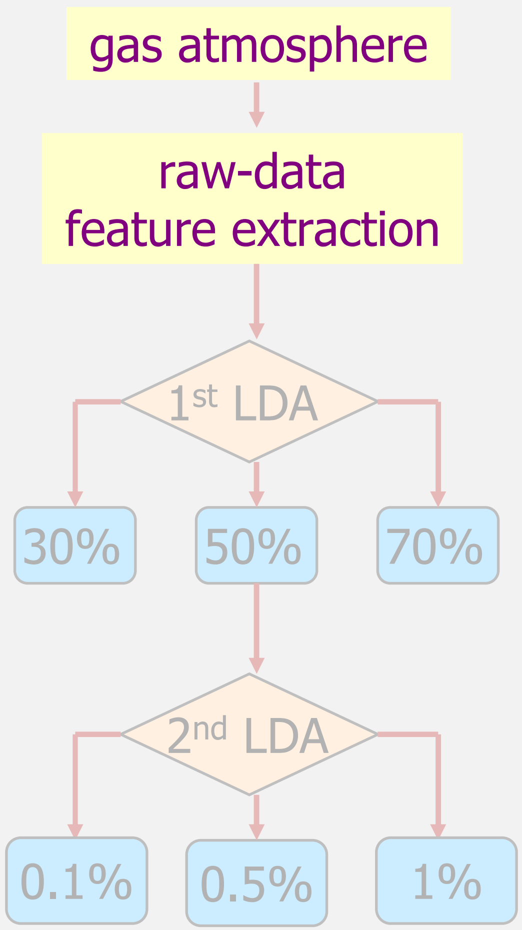
ramps between these levels allow max. reproducibility

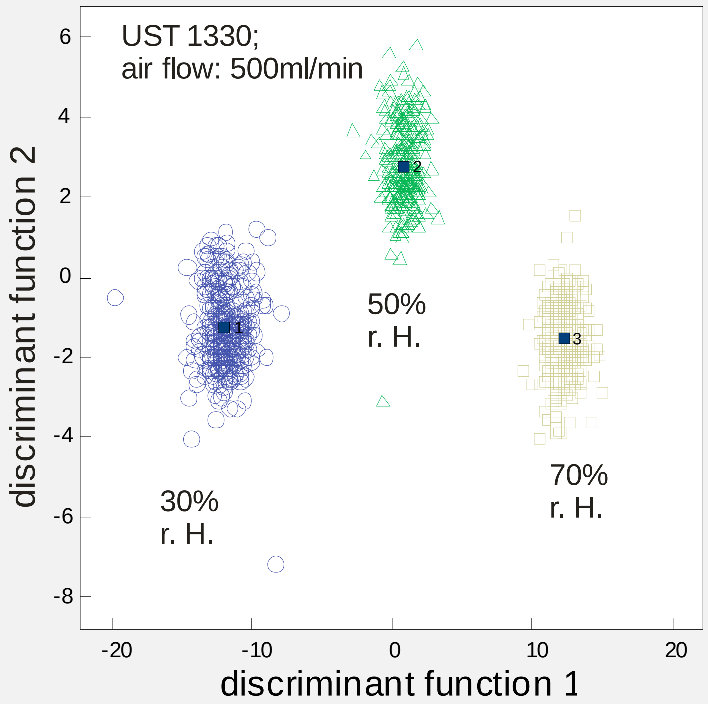
feature extraction

slopes and mean values from these sections

Application examples

P. Reimann, A. Schütze:
Sensor Review Vol. 32 Iss: 1, 2012

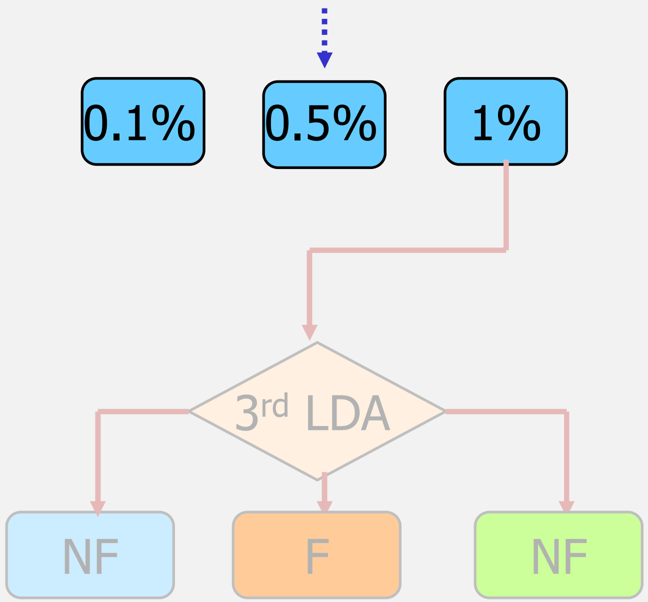


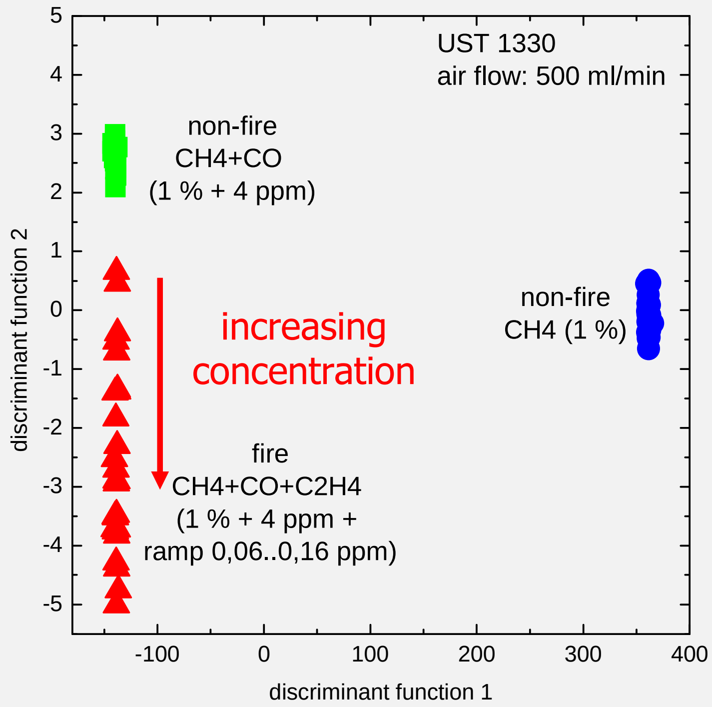


- discrimination along function 1
- similar for CH_4

Application examples

P. Reimann, A. Schütze:
Sensor Review Vol. 32 Iss: 1, 2012





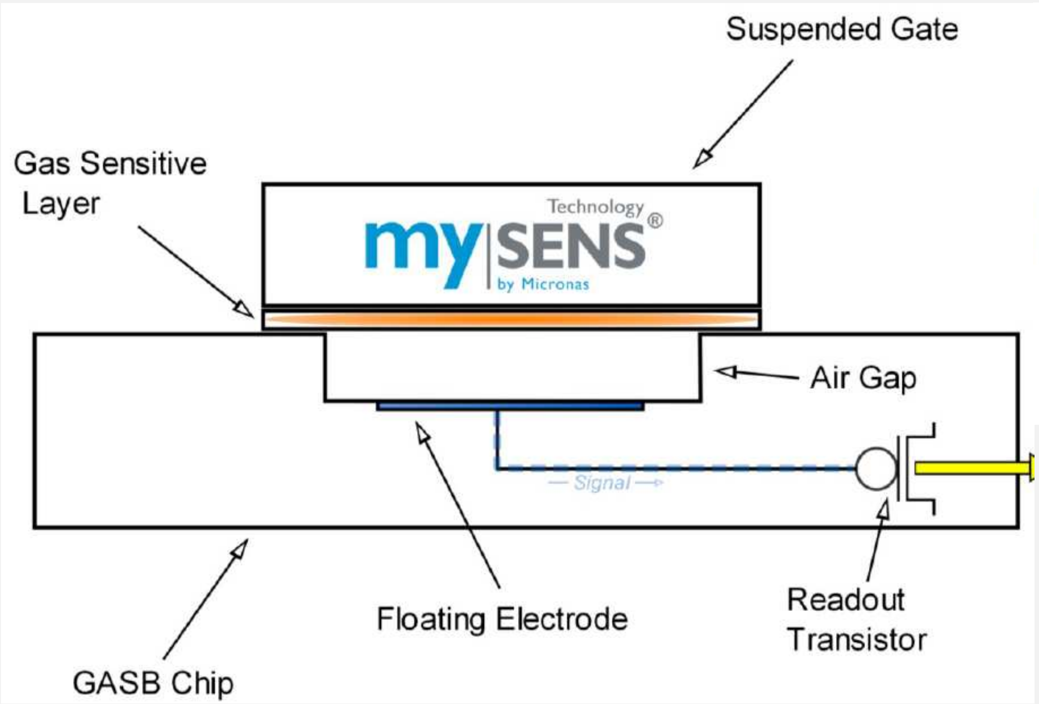
- alarm decision
- discrimination along function 1 & 2
- additional step(s) for interfering gases

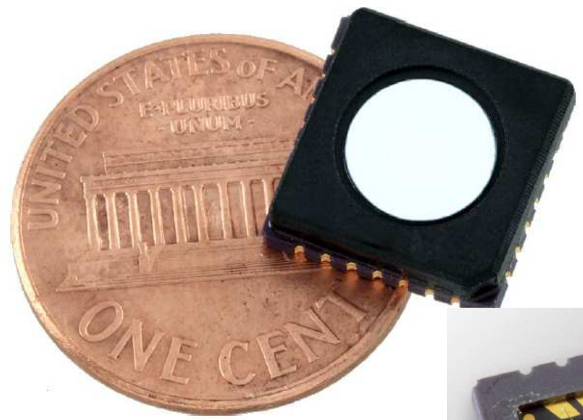
Field test: correlation with existing sensors shown, stability needs to be improved

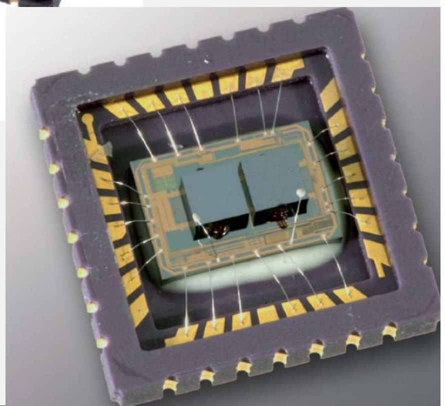
Novel developments

Novel sensor materials and transducer principles

- Nanotechnology for improved gas sensitive layers
- Novel transducer principles
  - Gas ionization (can be electronically controlled!)
  - GasFETs commercially available



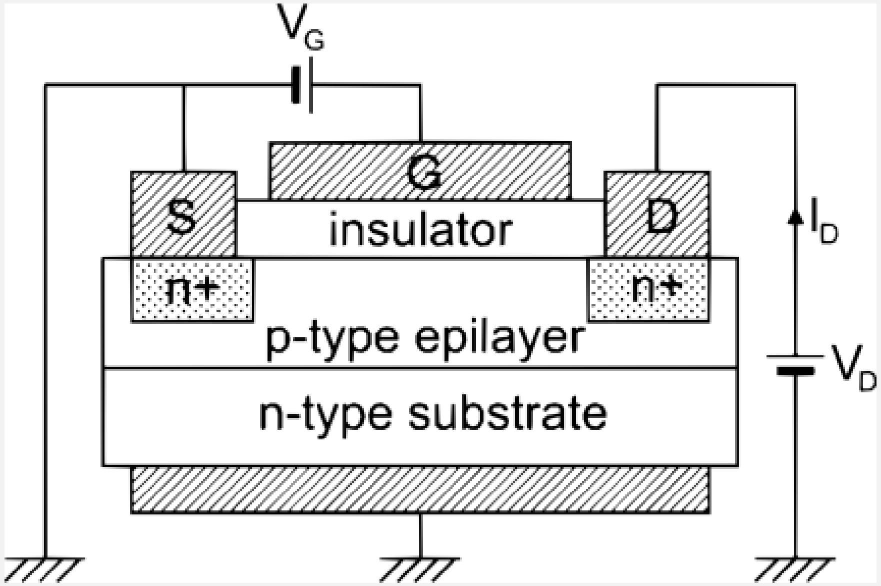


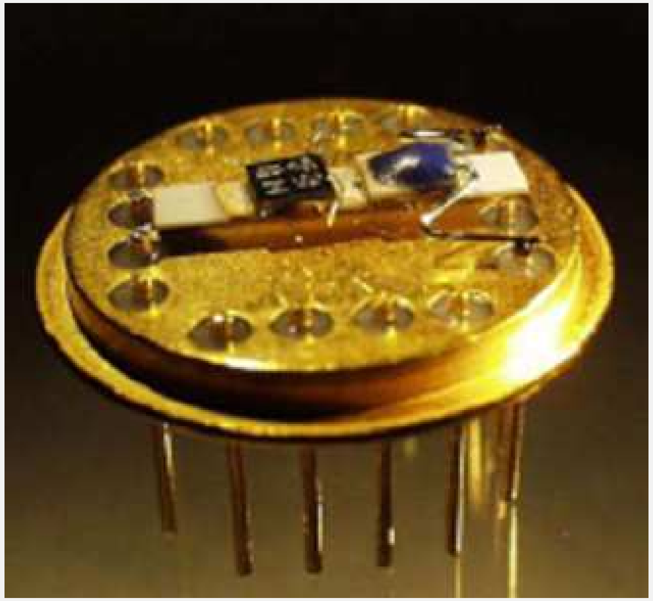


Source: Micronas

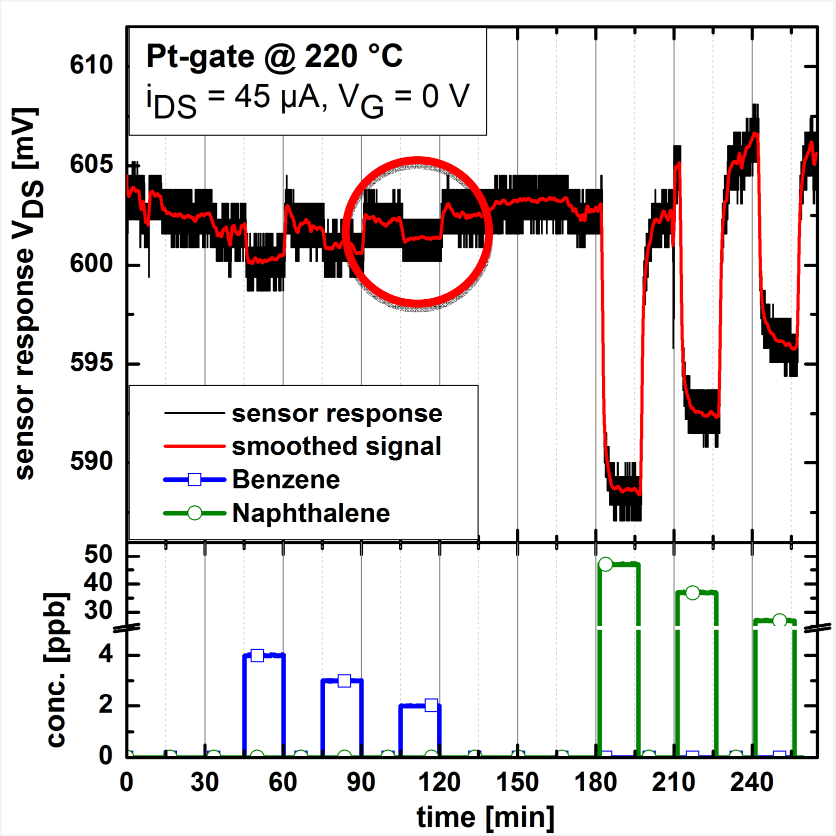
SiC Gas-sensitive Field Effect Sensors (Linköping U, SenSiC)

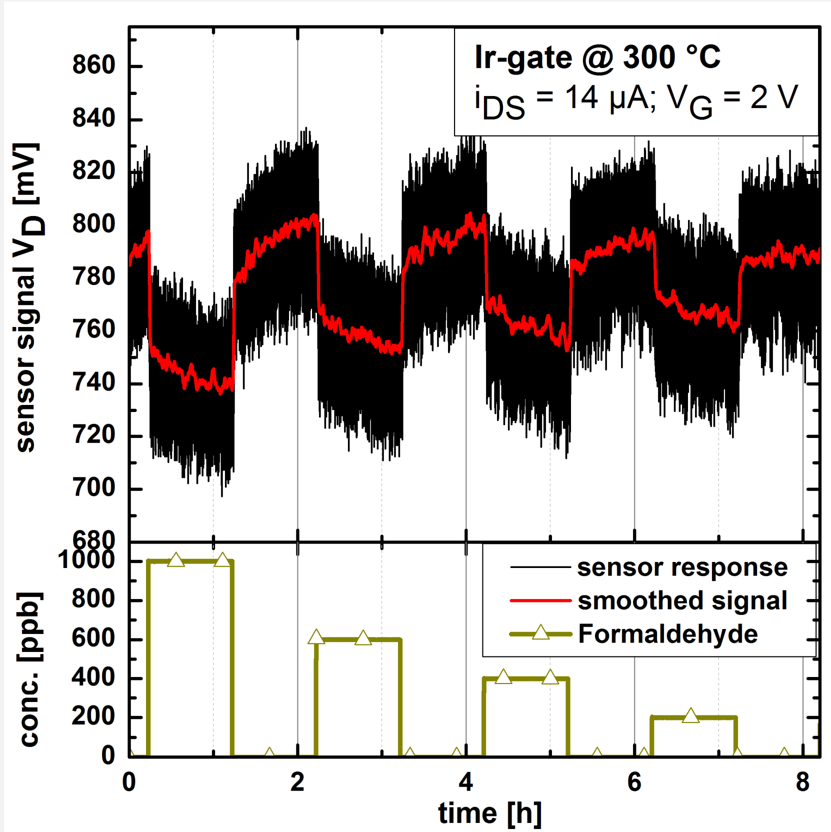
- high temperature operation
- allows temperature cycled operation as for MOS
- (nano-)porous platinum and iridium gate materials





SiC GasFETs (Linköping U, SenSiC): high sensitivity

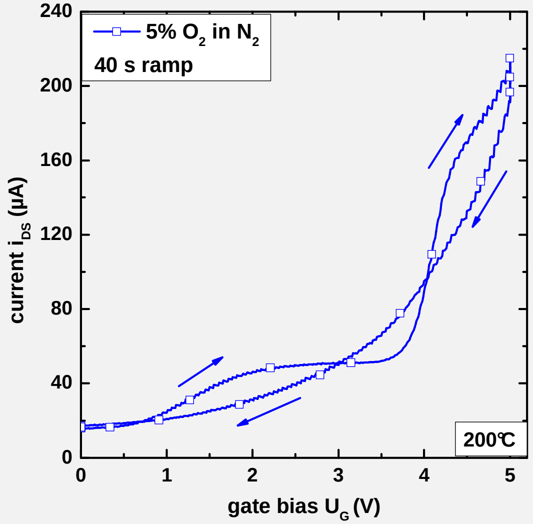


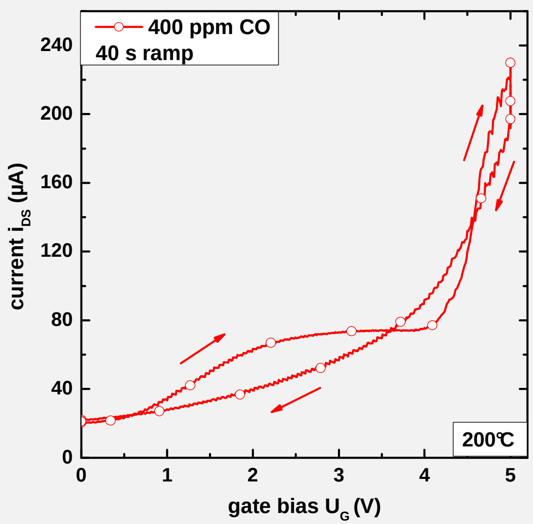


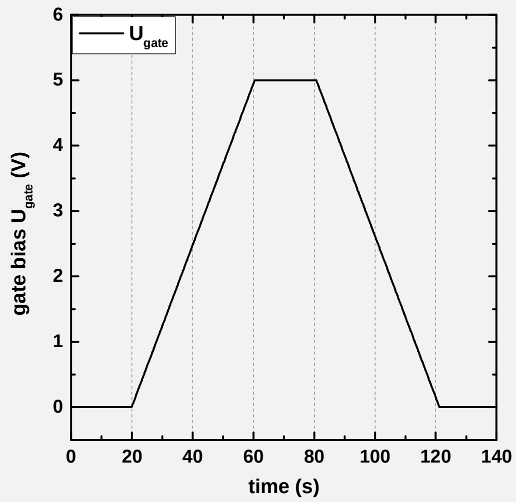
Sensor reaction to **2 ppb benzene**

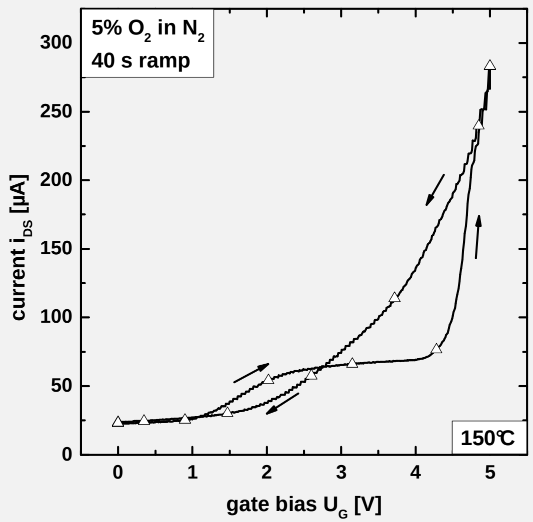
Novel developments

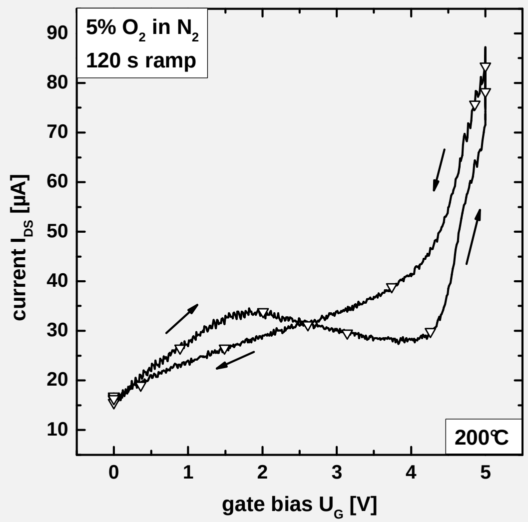
System integration: temperature and gate bias variation for SiC-GasFETs







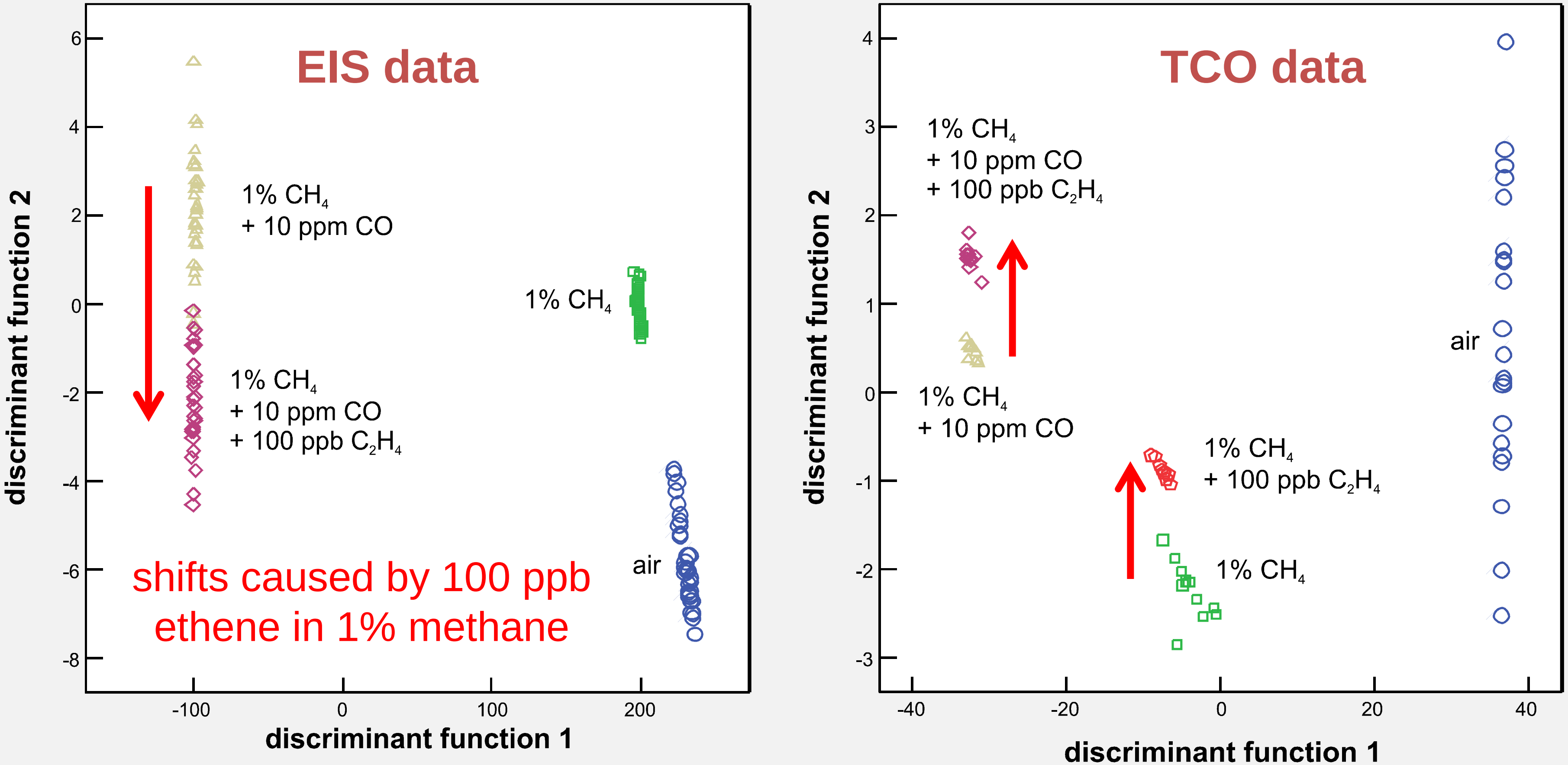




C. Bur et al.: Influence of a Changing Gate Bias on the Sensing Properties of SiC Field Effect Gas Sensors, IMCS 2012

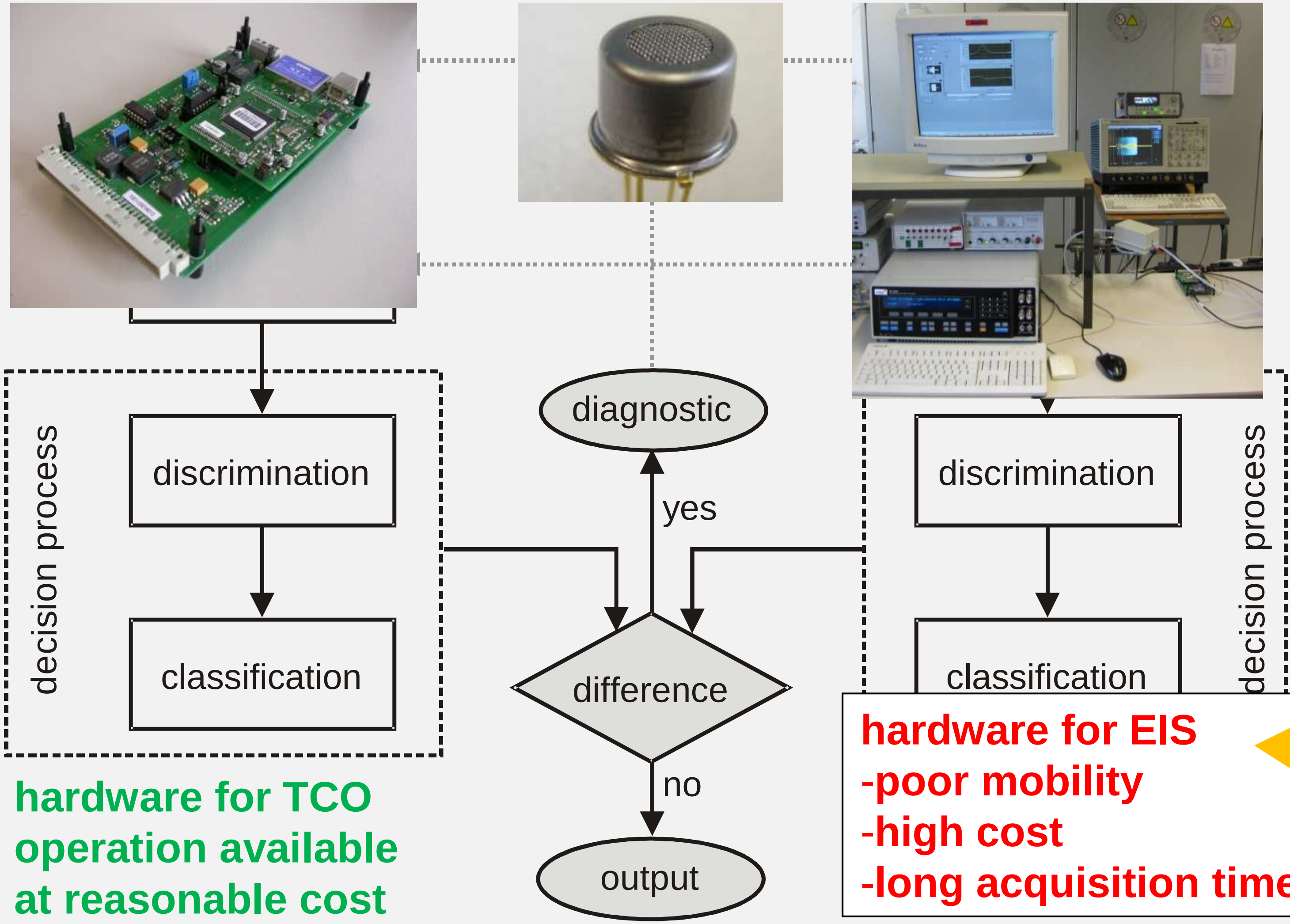
Novel developments

- Electrical Impedance Spectroscopy yields similar improvement in selectivity as Temperature Cycled Operation (but time scale is completely different)



A. Schütze et al.: Improving MOS Virtual Multisensor Systems by Combining Temperature Cycled Operation with Impedance Spectroscopy, ISOEN 2011

Sensor self-monitoring with combination of TCO and EIS



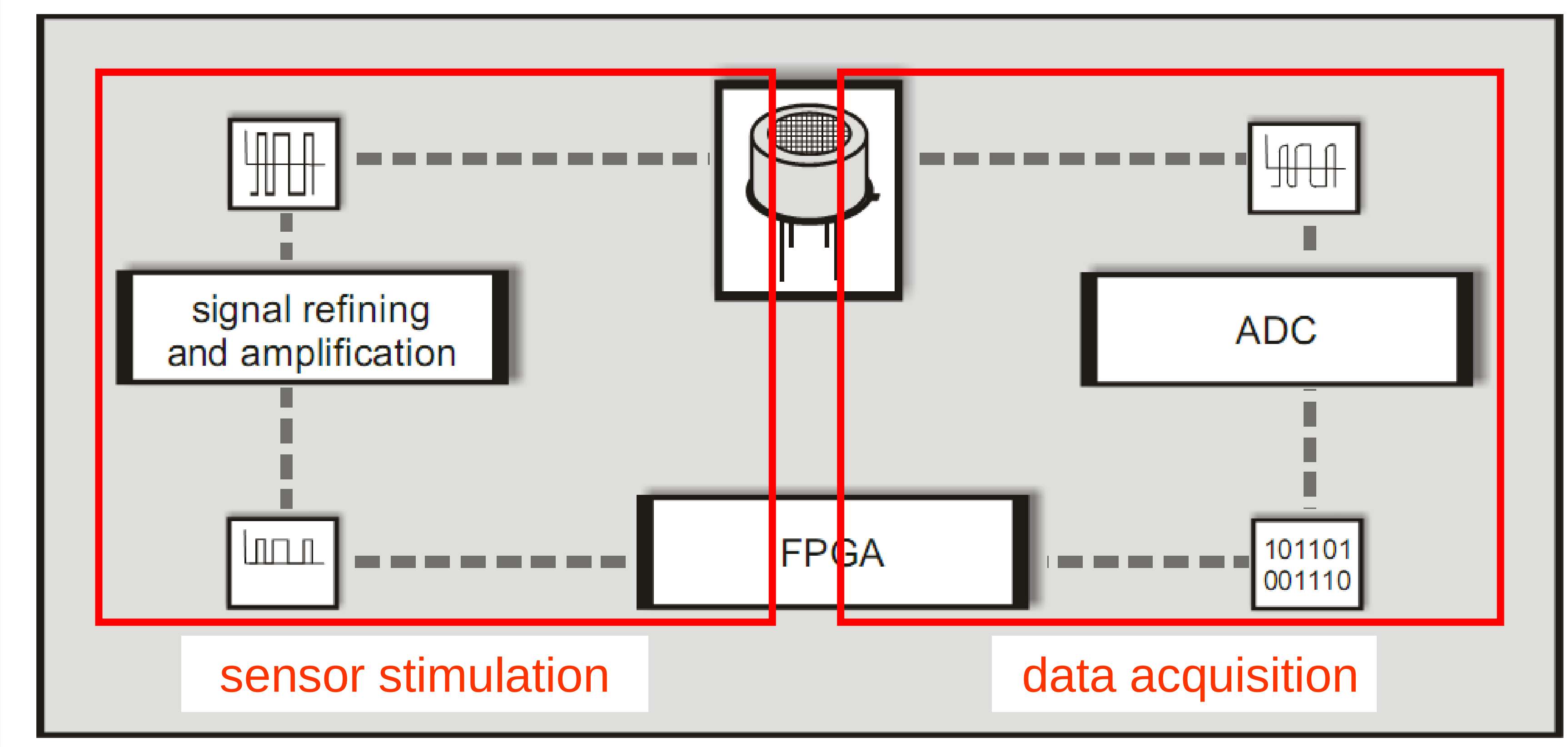
hardware for TCO operation available at reasonable cost

hardware for EIS
-poor mobility
-high cost
-long acquisition time

A. Schütze et al.: Improving MOS Virtual Multisensor Systems by Combining Temperature Cycled Operation with Impedance Spectroscopy, ISOEN 2011

Low cost EIS hardware realization: general approach

- Implementation using an FPGA (field programmable gate array)
- MLS signal refined with variable amplification using dedicated circuit
- Data acquisition using high speed ADC (sample rate 200 MHz)



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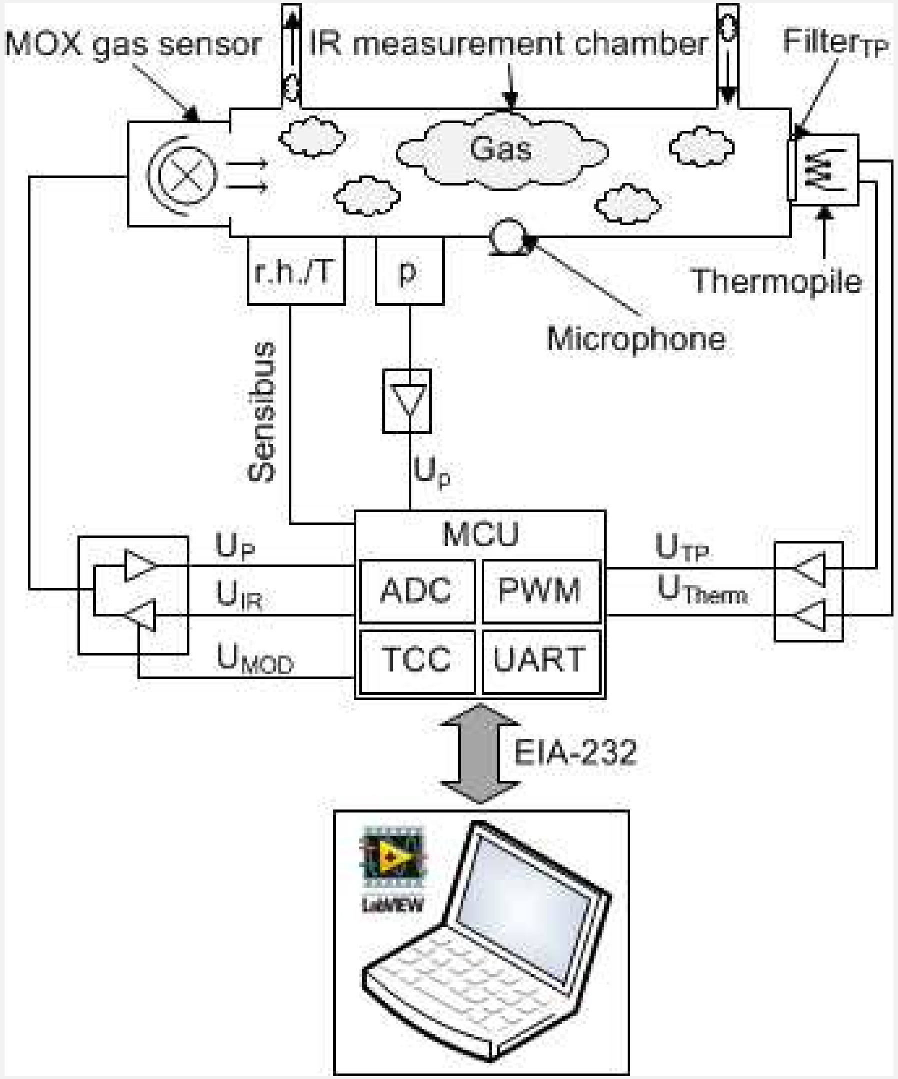


MOS-IR measurement system:

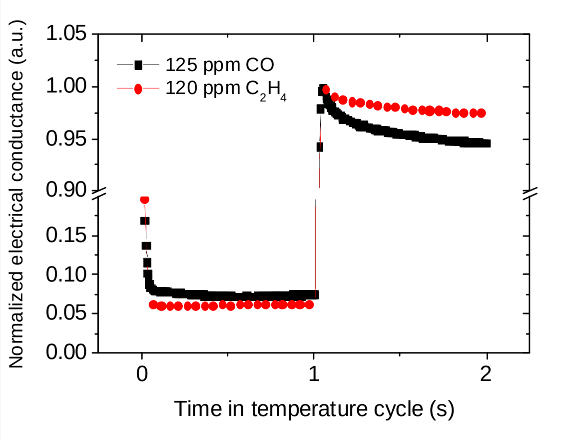
- Gas filled chamber (9 cm length)
- MOS gas sensor (MICS 5131, e2v)
- Transmission: Thermopile (HIS A21 F4.26, Heimann Sensors)
- Ambient condition monitoring (p, r.h./T)
- Electronics controlled by a microcontroller
- Configuration settings set by a GUI (LabVIEW)
- Data evaluation offline using Matlab

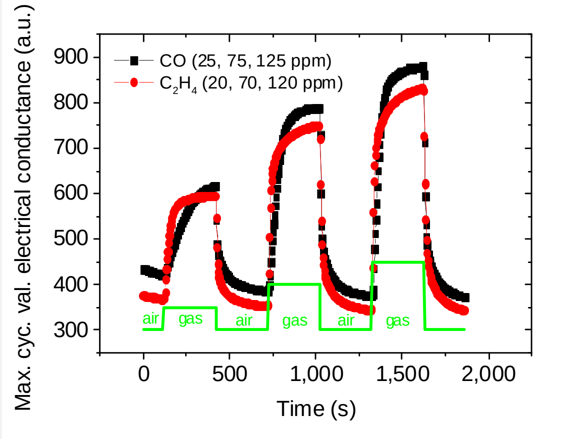
K. Kühn et al.: Investigations on a MOX Gas Sensor as an Infrared Source for an IR-based Gas Sensing System, IMCS 2012

Novel developments

MOS signal:

Raw data DC resistance → Shape of the response curve from temperature cycle

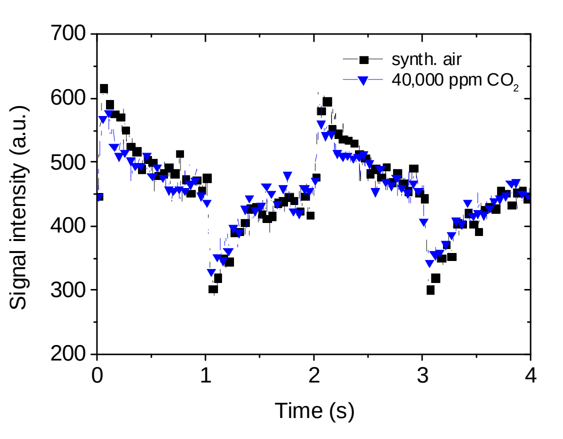


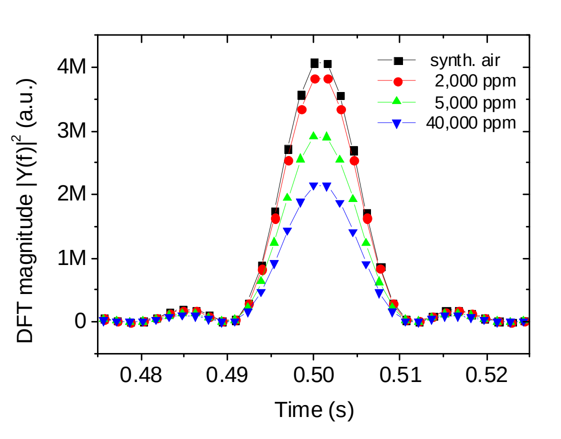


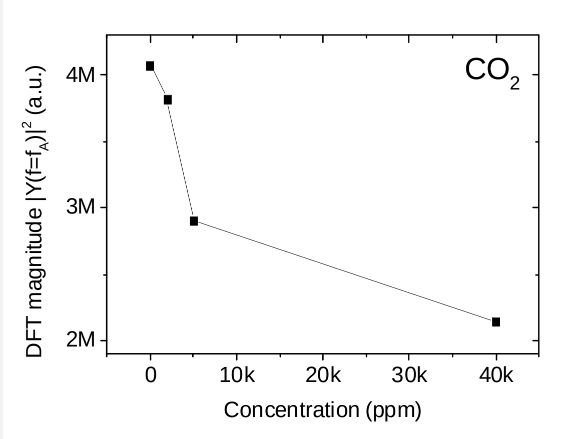
K. Kühn et al.: IMCS 2012

Transmission signal:

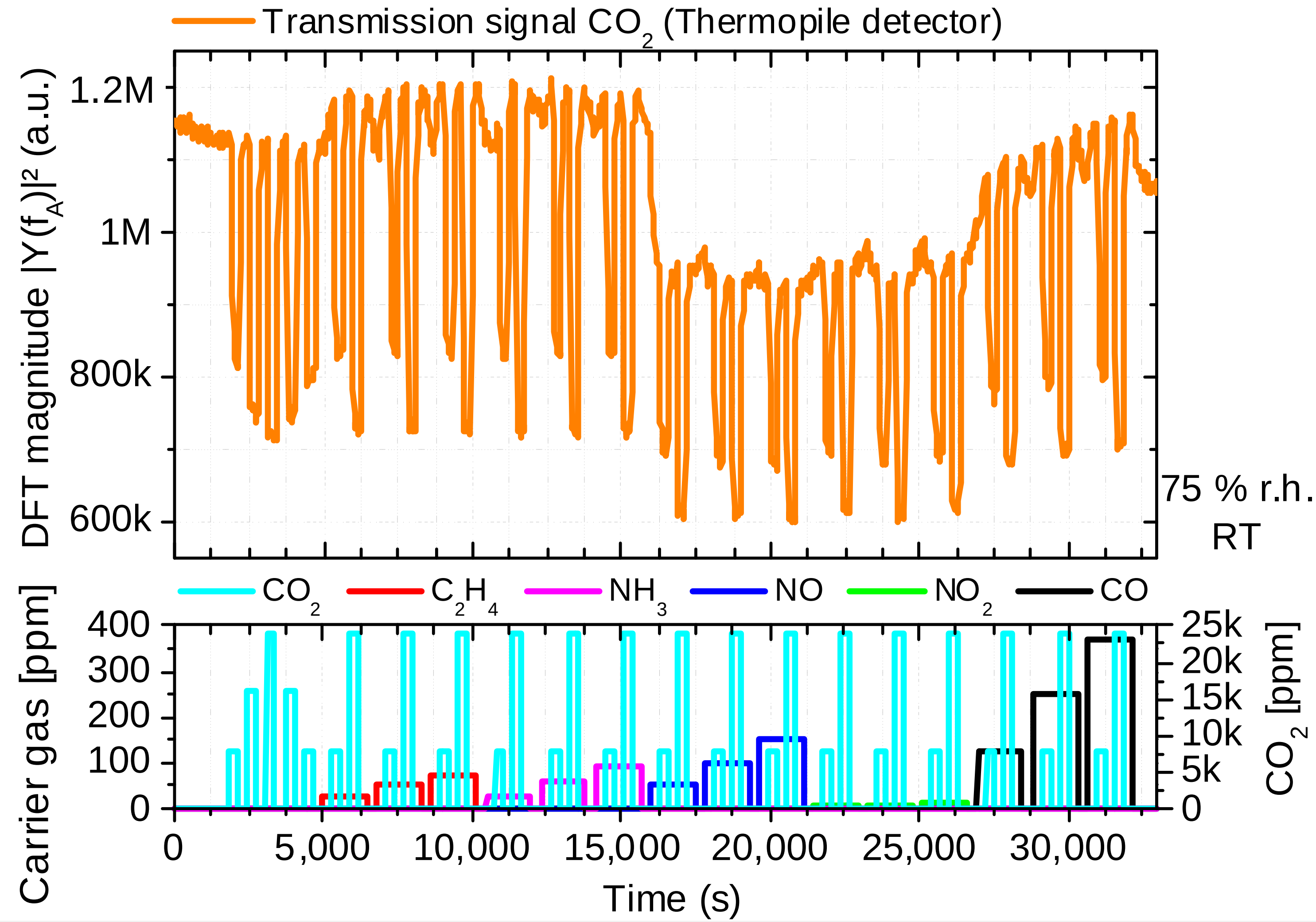
Raw signal (thermopile) → DFT analysis of raw data (90 ON/OFF cycles) → $|Y(f=f_A)|^2(c)$







Transmission signal, f_A = 6 Hz square wave mod. of the MOS gas sensor (MICS 5131, SGX)



K. Kühn et al.: Investigations on a MOX Gas Sensor as an Infrared Source for an IR-based Gas Sensing System, IMCS 2012

Conclusion

- **Indoor applications are of increasing interest, especially for improving energy efficiency and health**
- **Gas measurement systems are more than just sensors**
- **Multifunctional, intelligent multisensor systems can address emerging applications**
- **Application specific development still required**
- **Field testing is an absolute must for any chemical sensor system**
  - **Field tests of VOC-IDS sensor systems are starting now**
- **Chemical sensor systems can become ubiquitous in modern building environments and a key to Indoor Air Quality**

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Thank you for your attention.

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