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

COST Action TD1105

Final Meeting at PRAGUE (CZ), 5-7 October 2016

New Sensing Technologies for Air Quality Monitoring

Action Start date: 01/07/2012 - Action End date: 30/06/2016 - EXTENSION: 15/11/2016

WG2 - Sensors, Devices and Systems for AQC
Key achievements over four years of EuNetAir

UNIVERSITÄT DES SAARLANDES

Lehrstuhl für LMT Messtechnik

Andreas Schütze

WG2 leader

Lab for Measurement Technology, Saarland University, Germany

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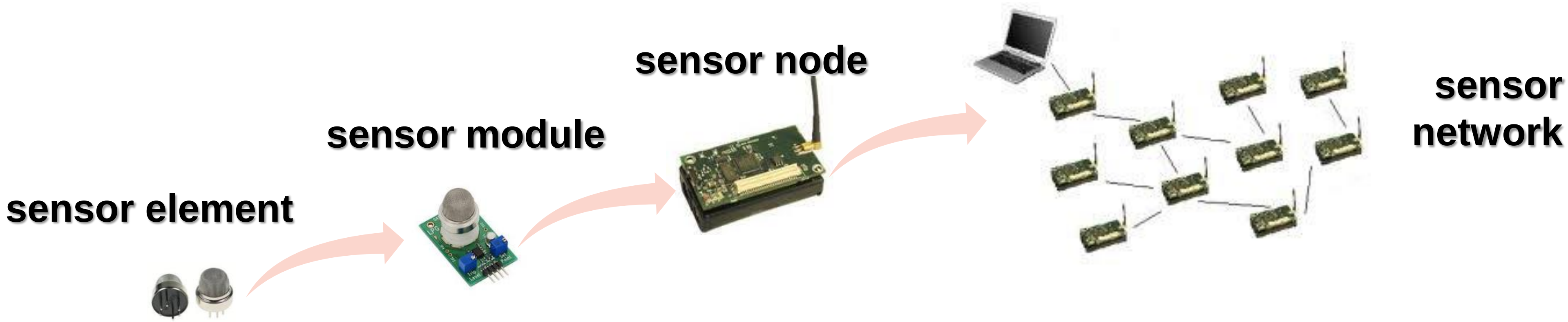
Scientific context and objectives in the Action

- **Sensors and sensor systems for Air Quality Control**
- **WG2: from nanomaterials to sensor networks** (Sensors, devices and sensor systems for AQC)
- **WG2 objectives:**
- Protocols for fabrication of gas sensors; specifically
  - integration of nanostructures and -materials in AQC gas sensors;
  - design and implementation of new transducers for AQC sensors;
  - device characterization for AQC gas sensors;
- Report for integration of portable gas sensor-systems for AQC;
- Report on integrated intelligence of AQC systems & distr. computing;
- Protocols for development of wireless sensors network for AQC;
- Report on IP Rights of gas nanosensors for AQC.

Scope: from nanomaterials to sensor networks



- Investigation of the integration effect of novel sensor element level materials and techniques on AQC sensor systems
  - Closely linked to WG1 activities
- Study of sensor elements active control techniques on all levels:
  - Sensor module ➔ enhanced electronics (i.e. for self-monitoring)
  - Sensor node ➔ improved selectivity and stability via information correlation
  - Sensor network ➔ enhanced reliability, auto-configuration/calibration

Research Priorities (1/5): sensor elements

- Versatile µ-transducers for integration of various (nano)materials
  - Allow application specific adaptation and **low cost**
  - **Low power** (down to µW for single nanowire)
- **Selective filters** integrated in sensors or sensor modules
- Be open for novel sensing methods
  - e.g. dosimeter approach: integrated sensor response
- MEMS and beyond:
  - low cost microstructured sensors
  - other sensor technologies, i.e. printed electronics
- **Nanoparticle detection** for dust and aerosols!

Research Priorities (2/5): sensor systems (1)

- **Combination of sensor principles**
  - Temp., r.h., barometric pressure **plus** sensor correlation
- **Dynamic operation/self referencing of sensors** to obtain more than one signal from a single sensor (better selectivity and stability, self-monitoring/self-calibration) **at the sensor module level**
  - Well known, but not standard: temperature cycling, EIS
  - New methods: gate bias variation for GasFETs, RF, optical excitation (gas sensitive solar cell!), pulsed polarization, surface ionization, mass and dissipation in QCM
  - Modelling and simulation of interaction between sensor/ sensing layer and gas/dust/aerosol

Research Priorities (3/5): sensor systems (2)

- **Optimized calibration**
  - Simple calibration for manufacturers
  - Ideally no re-calibration in the field (self-calibration, cross referencing in networks
- **User and network interface** optimization
  - Simple and easily understood feedback for citizen use
  - Qualitative display
  - Quantitative data with uncertainty estimate for sensor networks
  - Feedback channel for data input from the user
  - **Complex but easy to use systems**

Research Priorities (4/5): applications

- **Outdoor air quality monitoring** (imission control)
  - ➢ Better information for citizens and awareness of pollution
- **Indoor air quality monitoring** (imission control)
  - ➢ Controlled ventilation due to monitoring of hazardous VOC
  - ➢ Reduced health hazards plus improved energy efficiency
- **Outdoor monitoring of pollution sources** (emission control)
  - ➢ Identification of sources and minimizing of emissions
- **Closed loop process control** (industrial, transport, home use)
  - ➢ Minimizing emissions at source incl. active countermeasures

➢ **Identification of reference applications**

➢ **Sensors on/in smartphones with open data interface**

Research Priorities (5/5): overall target

- Intelligent sensor modules for NO_x, O_3, NH_3, H_2S, SO_2, VOC, PM
  - Electronics combined with sensor elements
- Intelligent sensor nodes and (heterogeneous) networks
  - Data pre-processing and processing (in node and/or in network: parallel and distributed computing)
  - Energy efficient communication

Goal:

Demonstrate the potential of (micro) sensor systems in the context of environmental sensing (complementarity, added resolution – spatial and temporal, improved information to and feedback from citizens), **including an assessment of performance**

Current research activities of in WG2 (1)

- Gas Sensors for Environmental Monitoring (Sadullah Ozturk)
  - Overview of challenges: air, water, soil – gas sensors can be used for all
  - Low-power, i.e. low-temperature, low-cost sensors required
  - 3S: sensitivity, selectivity, stability
  - Example: room temperature hydrogen sensors
- Environmental Monitoring with RFID Tags (E. Llobet)
  - Semi-passive and passive tags (read-out with impedance analyzer?) - 2001
  - Low-cost paper/foil based devices, very simple sensor layout, short distance, but very low sensitivity (tested at 20% for ammonia) - 2009/2011
  - URIV: semi-passive tag with wake-up pulse and single measurement; tested with RT-measurement of ppm-level NO2 using CNT sensors; 10 years lifetime with a single 1000mAh battery @12 meas/h – 2014

Current research activities of in WG2 (2)

- New Sensor Principle w Graphene Nanoribbons (M. Voinova)
  - Main activity in WG2: modelling of QCMs, also for bacteria etc.
  - New project part of the flagship project graphene
  - Model of sensor nanosystem: suspended graphene membrane exhibits self-sustained oscillations due to non-linear effects (set-up published in 2008)
  - Could allow opto-mechanical transduction w external control for ammonia
- Particle detection w acoustic wave technology (F. Villa-López)
  - Target: particulate matter PM10, PM2.5, UFPs (<100nm)
  - Major concern for health (respiratory and cardiovascular)
  - SAW-Resonator, SMR (Solidly Mounted Res.) @ ~1GHz, diff. measurement
  - Mass loading: total number of particles with filters for size differentiation, tested with PM10: 580 kHz/ng
  - Challenges: reversibility, controlled deposition of particles

Current research activities of in WG2 (3)

- Modelling and Simulation Studies on IAQ (Ahmet Özmen)
  - Target: on-line evaluation of distributed sensor networks (i.e. in schools)
  - Sensor node with multisensor array; data transmitted to central server
  - Parallelized research: software simulator for distributed sensor network
- Automated Computational Model Selection (Roman Neruda)
  - Target: how to select the best performing method for a given problem?
  - No-free lunch theorem: no single method will outperfom all others!
  - Learn from previous experiments with statistical, NN, SVM, RBF models
  - Evolutionary search, combination (sum, product) of kernels

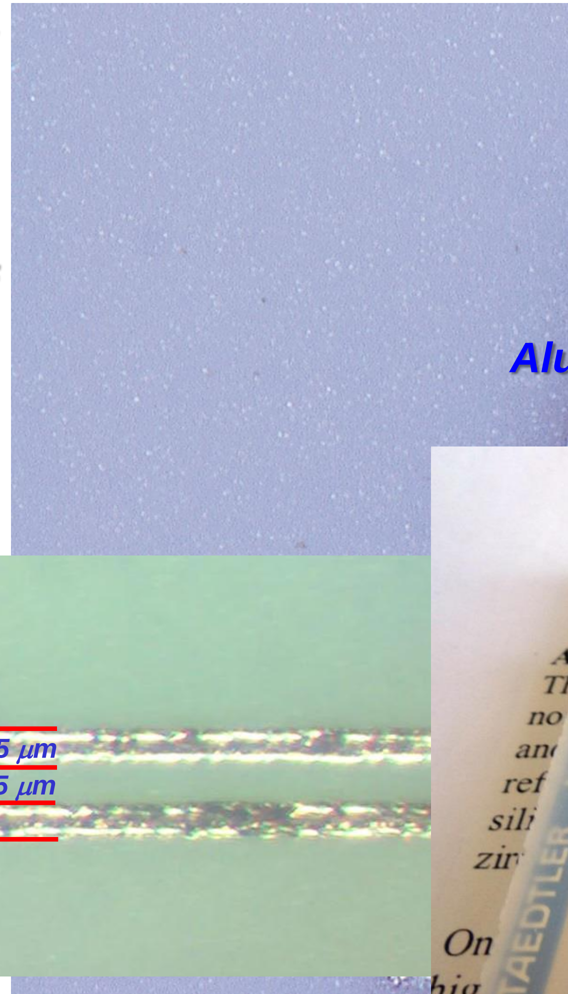
Suggested **R&I Needs** for future research to Action WGs/SIGs General Assembly

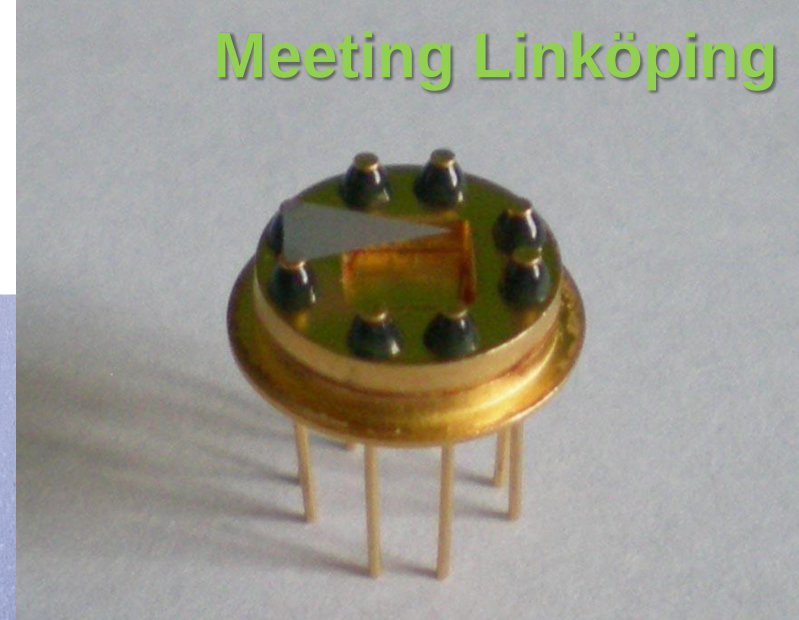
- **Low-cost particle sensors** are still elusive
  - But what do we measure: size, content, character (pollen, dust, ash, BC)?
- **Focus on health effects**: what is really important to measure?
  - Formaldehyde is often mentioned, but actually not critical
  - Avoid environmental hazards instead of measuring them
  - Study by VITO in Flanders; often super-critical individual houses
- **Compare indoor/outdoor AQ**: which hazard in more relevant?
- General: **ADVANCED HMI** for Environmental Sensor Data: Visualization of measurement (no ppb/ppm) and user feedback(!), e.g. for allergies, …

Session WG2

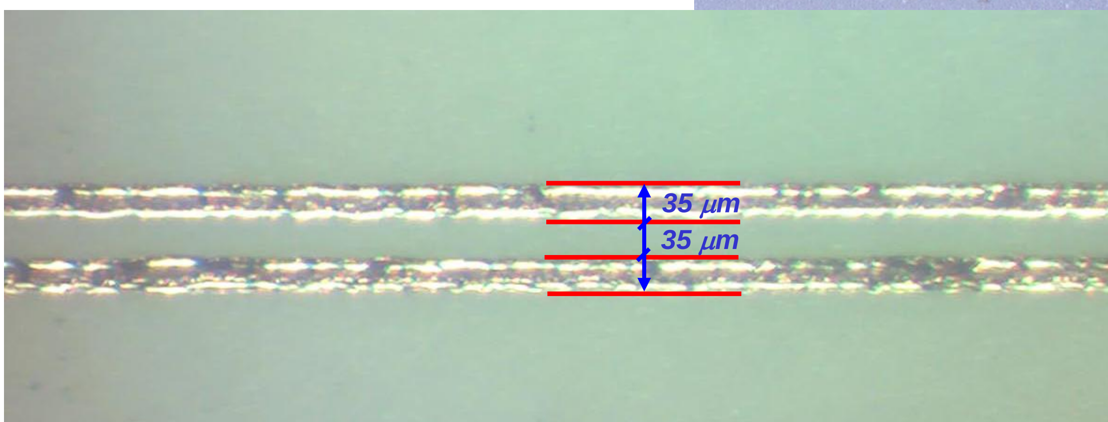
A.A. Vasiliev
NRC Kurchatov Institute,
Moscow, Russia

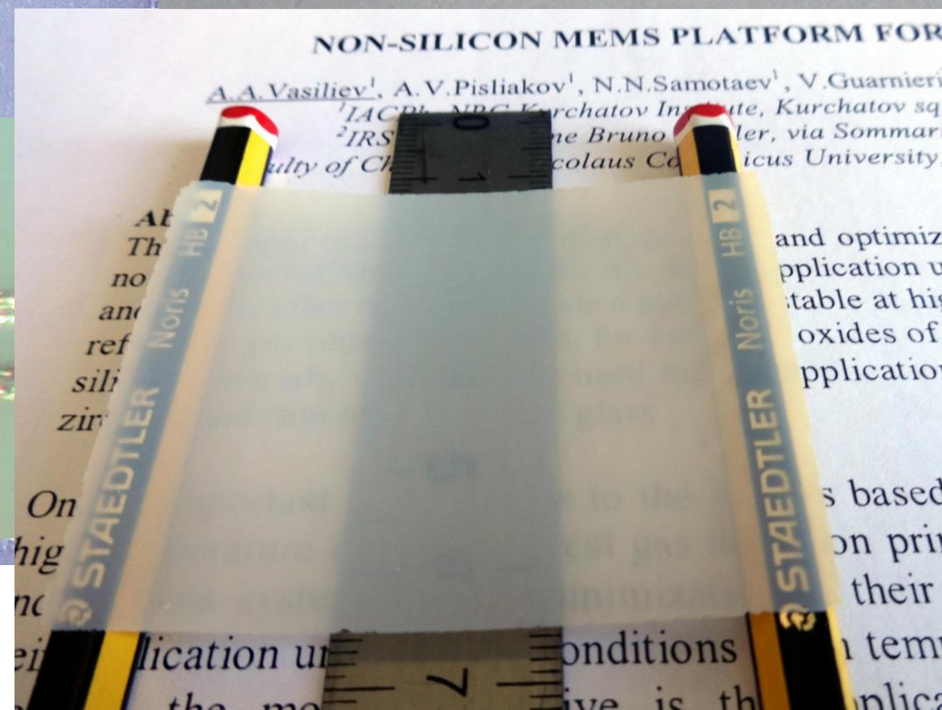
The Application of Additive Technologies for Ceramic MEMS Gas Sensors





Alumina cantilever chip in TO8 package.
Alumina film thickness 12 μm.

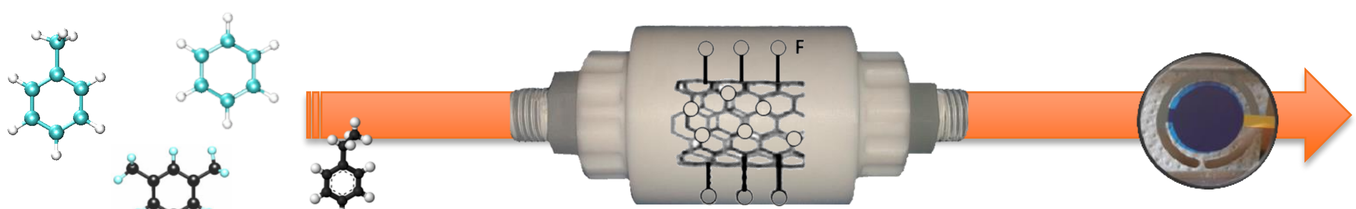




Session WG2

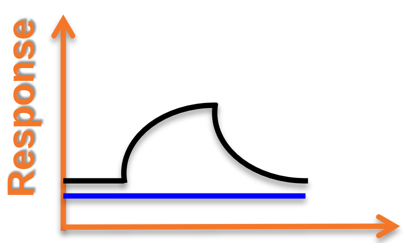
Jerome Brunet
Université Blaise Pascal, Aubiere, France

ASTHMAA exploratory project (granted)

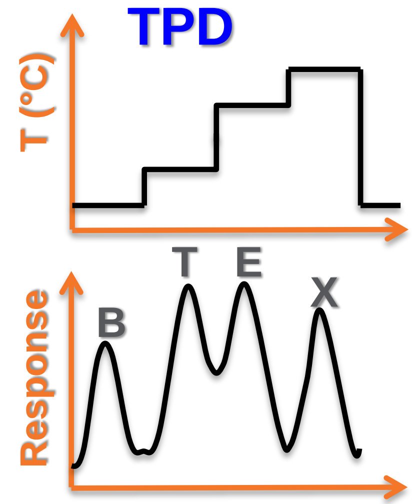


Discriminated responses

Selective filter



TPD



Partners:

IS2M

Institut de Chimie de Clermont-Ferrand

Session WG2

J.-M. Suisse
Université de Bourgogne,
Dijon, France

Views on Inter-Laboratory Reproducibility of Chemosensing Experiments

**Compare and verify sensor response on different test benches -
You might be surprised!**

Meeting Linköping

Session WG2

Calibration is a research topic for mass production,

but first needs to be better understood at lab level,

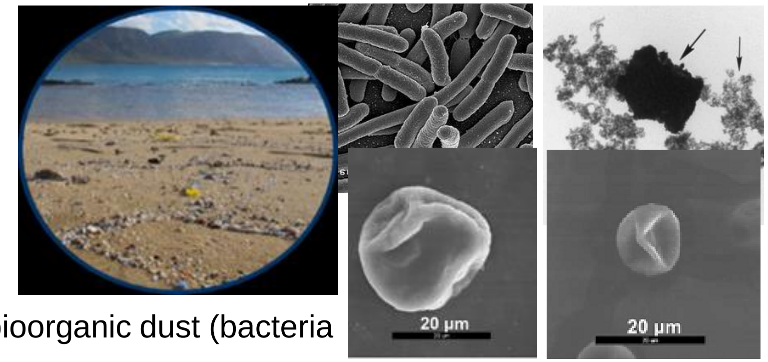
especially for ppb levels

- Interaction between tubing (materials) and gas
- Interaction between flow and sensor
- Flow-through system should be preferred due to reaction products

Predictive modeling of SAW-based and QCM-D sensors

Current research topics / Problem statement

- **Acoustic biosensors for healthcare (modeling)**
- **Acoustic sensors for environmental control (modeling)**
- **Goal1: Air quality control**
- **Goal2: Clean water control (precipitations; coastline sea water)**



Target pollutants :Microparticles and NPs dispersions, aerosols. Mineral,organic and bioorganic dust (bacteria and viruses), Pollen microparticles, microplastic fragments dispersed in water, marine aerosols

Pollutant model NPs

- **Gold NPs**
- **Fine sand grain**
- **Carbon NPs**
- **Polystyrene**
- **PVC**
- **E.Coli bacteria**

Figure 2

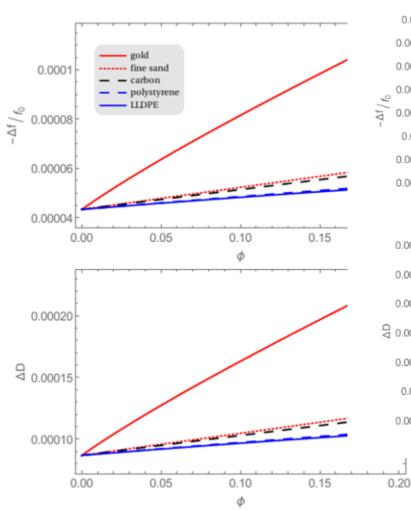
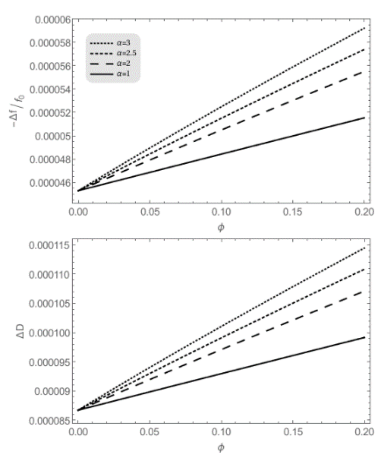


Figure 3



Plots. (to the left) A bare QCM-D, operating at a frequency *f*=1 MHz, in water containing by spherical (shape factor α=2.5) nanoparticles at different (low) concentrations ϕ. The nanoparticles affect the effective viscosity (as given by Einstein's expression) and density of the contaminated water. The plot shows the effect of spherical nanoparticles of different material.
(to the right): A QCM-D coated with a 10 nm PMMA-film, operating at a frequency *f*=1 MHz, in water contaminated by rigid PVC nanoparticles at different (low) concentrations ϕ. The density of rigid PVC is known, and the plot shows different shape factors α (α=2.5 corresponds to spherical nanoparticles).
(Voinova, Wikström, 2015, manuscript in preparation)

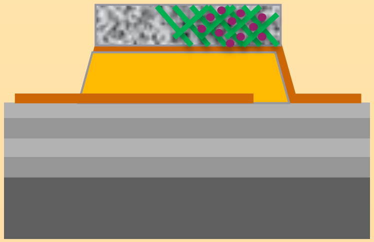
Pictures: plastic litter (MICRO2016 'Fate and Impact of Microplastics in Marine Ecosystems:From the Coastline to the Open Sea); E.coli (wiki);pollen micrographs (Tan,Friend,Yeo. Microparticle collection and concentration via a miniature surface acoustic wave device . Lab-on-a-Chip 7 (2007)); mineral particle and carbon aggregates(Kocbach, Li, Yttri, Cassee, Schrarze, Namork. Physicochemical characterization of combustion particles from vehicle exhaust and residential wood smoke. Particle and Fibre Toxicology 3 (2006)).

Romy Hoffmann:

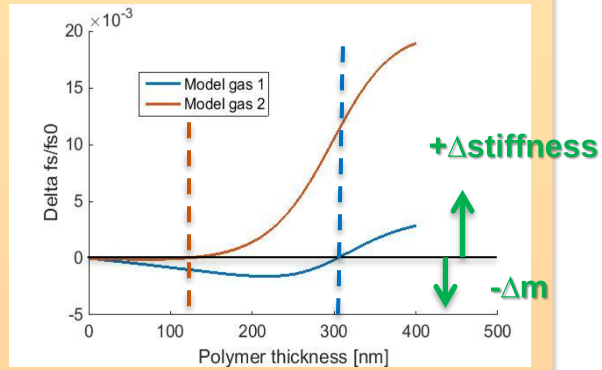
Siemens AG + TU Freiberg, Germany

Summary:

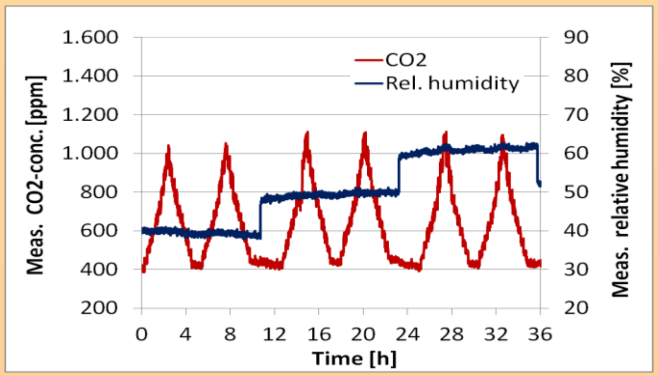
- FBAR has potential to be a low-cost, multi-gas sensor for AQM



- Due to its ability to detect Δmass and Δstiffness



- different polymer compositions, thicknesses and operating temperatures can be used to eliminate cross-sensitivity



- Stability still has to be evaluated

Romy Hoffmann
Siemens AG and TU Freiberg / Germany
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Poster presentations

M. Schüler, P. Gaudillat, J.-M. Suisse, T. Sauerwald, M. Bouvet, A. Schütze: Enhanced Selectivity of MSDI Sensors for Ammonia Monitoring by Illumination Cycled Operation
Laboratory for Measurement Technology, Saarland University, Saarbruecken, Germany; Institut de Chimie Moléculaire de l'Université de Bourgogne, Dijon, France

→ Result of 2 EuNetAir STSMs

S. Andreev, N. Nikolov, M. Holz, C. Iroulart
Dynamically Driven Multi-Gas Sensor
FACET LTD, Sofia, Bulgaria; Mikrosistemi LTD, Varna, Bulgaria; Nanoanalytik Gmbh, Ilmenau, Germany; Efficience Marketing, Vanves, France

→ EU-Project IAQSense

M. Davidovic, D. Topalovic, D. Suriano, V. Pfister, M. Prato, M. Penza, M. Jovasevic-Stojanovic: Measuring Tobacco Smoke Air Pollution using High-Quality and Low-Cost Optical Particles Sizers
VINCA Institute, Belgrade, Serbia; ENEA, Brindisi, Italy

→ Particle sensing is still a big challenge for low-cost sensors

Wednesday

Meeting Prague

10:30 - 11:00	**Gas and Particle Sensors in the Framework of EuNetAir** *Anita Lloyd Spetz*, Action Vice-Chair, Linkoping University (Sweden) and University of Oulu (FI)
11:30 - 12:00	**The SENSIndoor FP7 Project: Main Results, Lessons Learned and Outlook** *Andreas Schuetze*, Action MC Member, Saarland University, Saarbrucken, Germany
12:00 - 12:30	**The CITI-SENSE FP7 Project: From Sensor Technology to Citizen Engagement** *Nuria Castell*, Action MC Member, NILU - Norwegian Institute for Air Research, Kjeller, Norway
16:30 - 18:30	**WG2: Sensors, Devices and Systems for AQC** *Chairman: Andreas Schuetze, Action WG2 Chair - Saarland University, Saarbrücken, Germany*
16:30 - 17:00	**Disposable Sensors and Instruments for Air Quality Monitoring** *Danick Briand*, Action MC Member, EPFL, Neuchatel, Switzerland
17:00 - 17:15	**Multilayer Graphene Cantilever for Laser Photoacoustic Detection** *Zdenek Zelinger*, Action MC Member, J. Heyrovský Institute of Physical Chemistry, Academy of Sciences of the Czech Republic, Prague, Czech Republic
17:15 - 17:30	**A New Concept of Environmental Camera through Volatile Organic Compounds Sensing** *Thomas Walewyns*, *Nicolas Andrè*, *Laurent Francis*, Université Catholique de Louvain, Electrical Engineering Department, Louvain-la-Neuve, Belgium
17:30 - 17:45	**Dosimeter-Type Sensor for sub-ppm NO_x Detection** *Daniela Schoenauer-Kamin*, *I. Marr, Ralf Moos* Laboratory of Functional Materials, MC Substitute, University of Bayreuth, Bayreuth, Germany
17:45 - 18:00	**Theoretical Modeling of QCM-D and SH-SAW Sensors in Environmental Applications** *Marina Voinova*[1,2], *Anton Wikstrom*[2], [1]Chalmers University of Technology, Gothenburg, Sweden [2]National Technical University, Kharkiv, Ukraine
18:00 - 18:15	**Implementation of Complex Gas Sensor Systems - Ideas for a Structural Model** *Wolfhard Reimringer*, *T. Rachel, T. Conrad* 3S - Sensors, Signal Processing, Systems GmbH, Saarbrücken, Germany
18:15 - 18:30	**Vulnerability of Classifiers to Adversarial Examples** *Roman Neruda*, *Petra Vidnerova*, *Vera Kurkova*, MC Member/Substitute, Institute of Computer Science, Academy of Sciences of the Czech Republic, Prague, Czech Republic

Thursday

11:50 - 12:10

Mapping Urban Air Quality using Low-Cost Sensors: Opportunities and Challenges
Philipp Schneider, MC Member, NILU - Norwegian Institute for Air Research, Kjeller, Norway

12:10 - 12:30

Conclusions from One Year Operating a Low-Cost Sensor Network in Zurich
Michael Mueller, WG Member, EMPA, Zurich, Switzerland

12:30 - 12:45

Particulate Matter Smart Sensors Validation In Real-World Conditions
Mariacruz Minguillon, WG Member, CSIC-IDAEA, Barcelona, Spain

12:45 - 13:00

Towards Intelligent Air Quality Monitoring Networks: How Machine Learning Improve the Accuracy of Air Quality Multisensors Systems
Saverio De Vito, MC Substitute, ENEA, CR Portici, Italy

17:00 - 17:20

High Performance SiC-FET Gas Sensors for Highly Sensitive Detection of Hazardous Indoor Air Pollutants
Donatella Puglisi[1], *Mike Andersson*[1,3], *Jens Eriksson*[1], *Manuel Bastuck*[1,2], *Christian Bur*[1,2], *Joni Huotari*[3], *Jyrki Lappalainen*[3], *Andreas Schütze*[2], *Anita Lloyd Spetz*[1,3]
[1]Linköping University, Linköping, Sweden; [2]Saarland University, Saarbrücken, Germany; [3]University of Oulu, Oulu, Finland

17:20 - 17:40

Low Temperature-Low Power Gas Sensors based on Germanium Nanowires
J. Samà[1], *S. Barth*[2], *G. Domènech-Gil*[1], *M. Seifner*[2], *I. Gracia*[3], *C. Calaza*[3], *P. Pellegrino*[1] *and Albert Romano-Rodríguez*[1], Action MC Substitute, [1]Universitat de Barcelona, Barcelona, Spain; [2]Technical University of Vienna; [3]Consejo Superior de Investigaciones Científicas (CSIC), Institut de Microelectrònica de Barcelona-Centro Nacional de Microelectrónica, 08193 Bellaterra, Spain

17:40 - 18:00

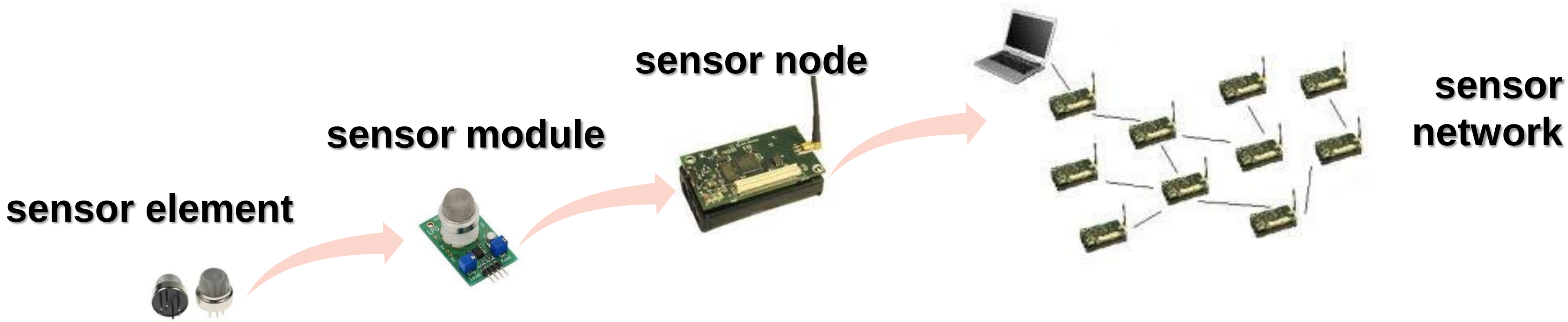
A Flexible Platform for Extremely Sensitive Gas Sensing: 2D Materials on Silicon Carbide
Jens Eriksson[1], *J. Bahonjic*[1], *D. Puglisi*[1], *R. Yakimova*[1,2], *A. Lloyd Spetz*[1]
[1] Department of Physics, Chemistry, and Biology, Linköping University, Sweden
[2] Graphensic AB, Linköping, Sweden

Friday

09:00 - 09:20

Low-Power Heating for Conductometric Gas NanoSensors: Self-Heating Effects
O. Monereo, C. Fàbrega, O. Casals, J. Samà, F. Hernandez-Ramírez, A. Cirera, A. Romano-Rodríguez, Juan Daniel Prades, ERC Starting Grant & Action WG Member, Universitat de Barcelona, Barcelona, Spain
ERC Starting Grant (no. 336917): *Nanodevice Engineering for a Better Chemical Gas Sensing Technology - BetterSense*

Take home messages



- Integrated approach from sensor to network incl. calibration required
- Many excellent examples over last years for potential of low-cost sensor systems in the context of environmental sensing
- Low-cost particle sensors (not counting, but health effect) still elusive
- Structured approach derived from target application required
- Standardization of test procedures, more cross-comparison

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Key achievements over four years of EuNetAir

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cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

EuNetAir

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

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