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COST Action TD1105

3rd International Workshop *EuNetAir* on

New Trends and Challenges for Air Quality Control

University of Latvia - Faculty of Geography and Earth Sciences

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CMOS SENSOR SYSTEMS FOR AIR QUALITY MONITORING

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Function in the Action (Partner)

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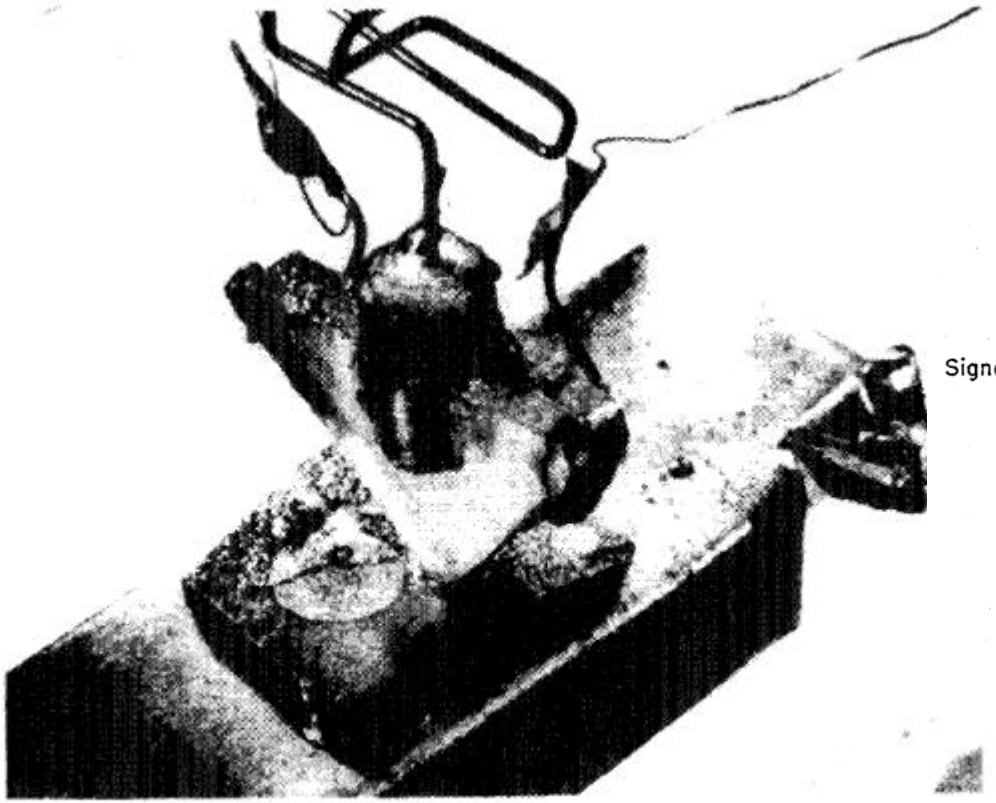
Contents

- Brief history
- Generation of MOX Sensors
- MOX sensor systems
- Potential of route to high AQM volume enablers
- Recent CMOS/MEMS MOX Sensors
- What’s next?
- Summary

First Transistor



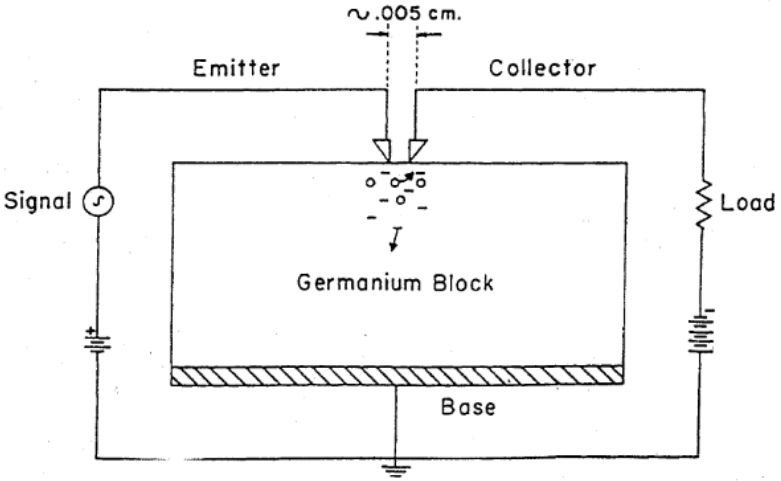
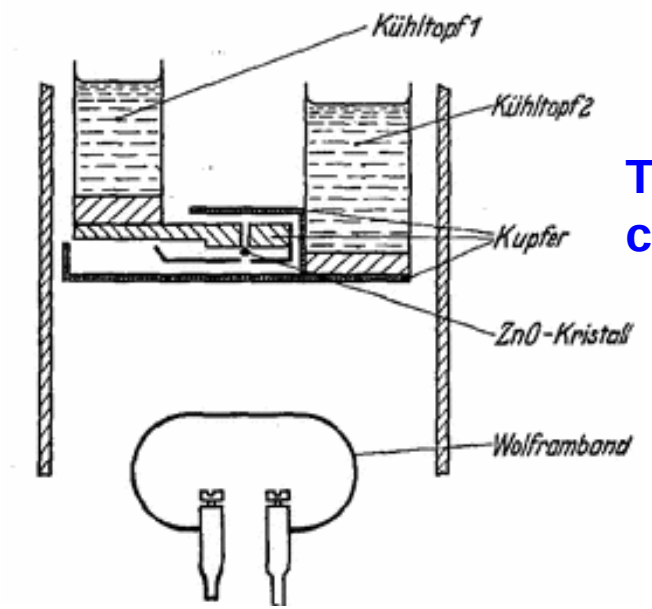


FIGURE 5. Bardeen and Brattain's point-contact semiconductor amplifier with the n-type polycrystalline germanium (note the ring electrode from the experiment performed on Dec. 15th) and two line-contacts of gold affixed to the plastic wedge [used with permission of the Estate of John Bardeen].

First Metal Oxide Gas Sensor

Metal oxide (MOX) gas sensor concepts were originally introduced by Brattein et al. and Heiland in early 1950's



The influence of hydrogen on the electrical conductivity on the surface of ZnO

Heiland, G. Zum Einfluss von Wasserstoff auf die elektrische leitfähigkeit von ZnO-kristallen. Zeit. Phys. 1954, 138, 459–464.

First Commercial Metal Oxide Gas Sensor

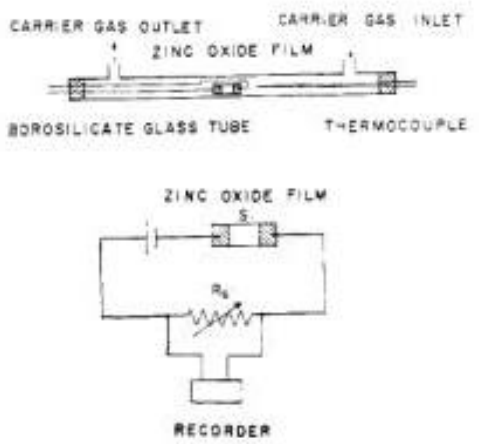


Figure 1. Experimental arrangement

Seiyama, T.; Kato, A.; Fujiishi, K.; 1962.

Who later formed Figaro Engineering, in 1971

Benchmarking is a critical step towards this process

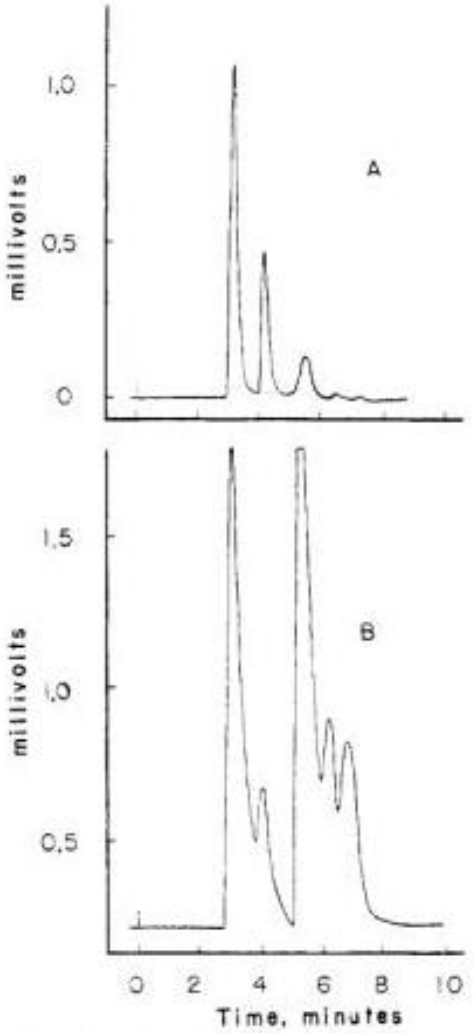


Figure 2. Results of commercial propane gas using thermal conductivity cell (A) and zinc oxide film (B).

MOS and CMOS Technology

In the same 1960's time frame with the advent MOSFET, MEMS and subsequent development of CMOS in 1963. a new dimension in sensors emerged for more innovative miniature sensors as an integral part integrated electronic components

Initiated with patent by Frank Wanlass.

This development enabled not only companies like IBM, Intel, Microsoft, Google, Facebook and others.

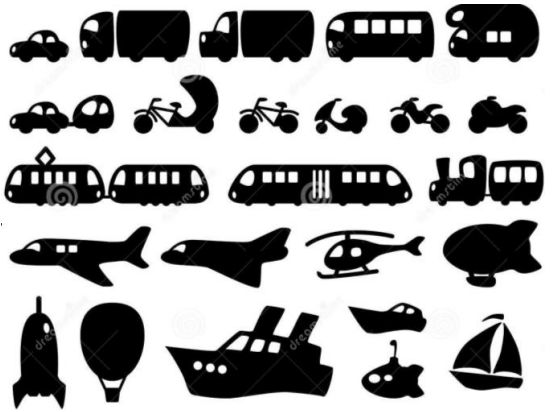
Behind the scene, you have foundries like TSMC, XFAB, AMS, and others.

And in the physical sensing world companies like …
…. ST, Freescale, Bosch, and others ..

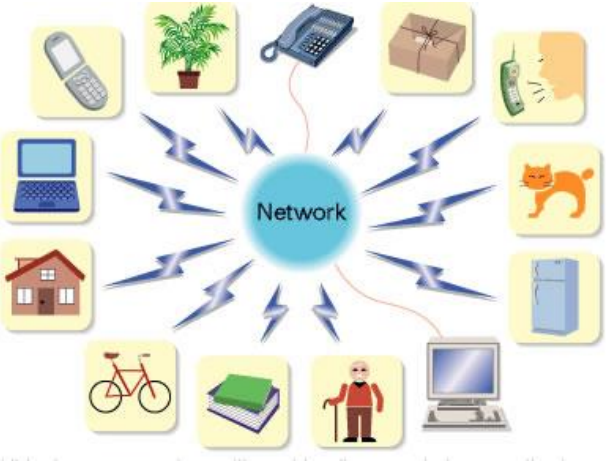
Innovations in CMOS MEMS sensors has lead to ..

Medical/ Home Healthcare

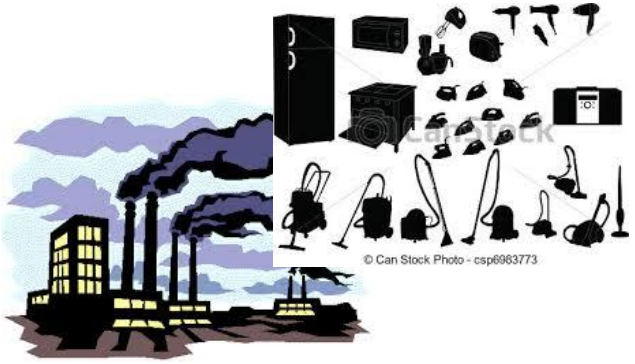
Consumer



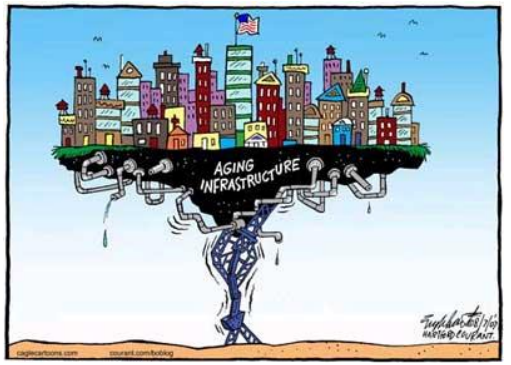
Transportation & Automotive



Network of sensors



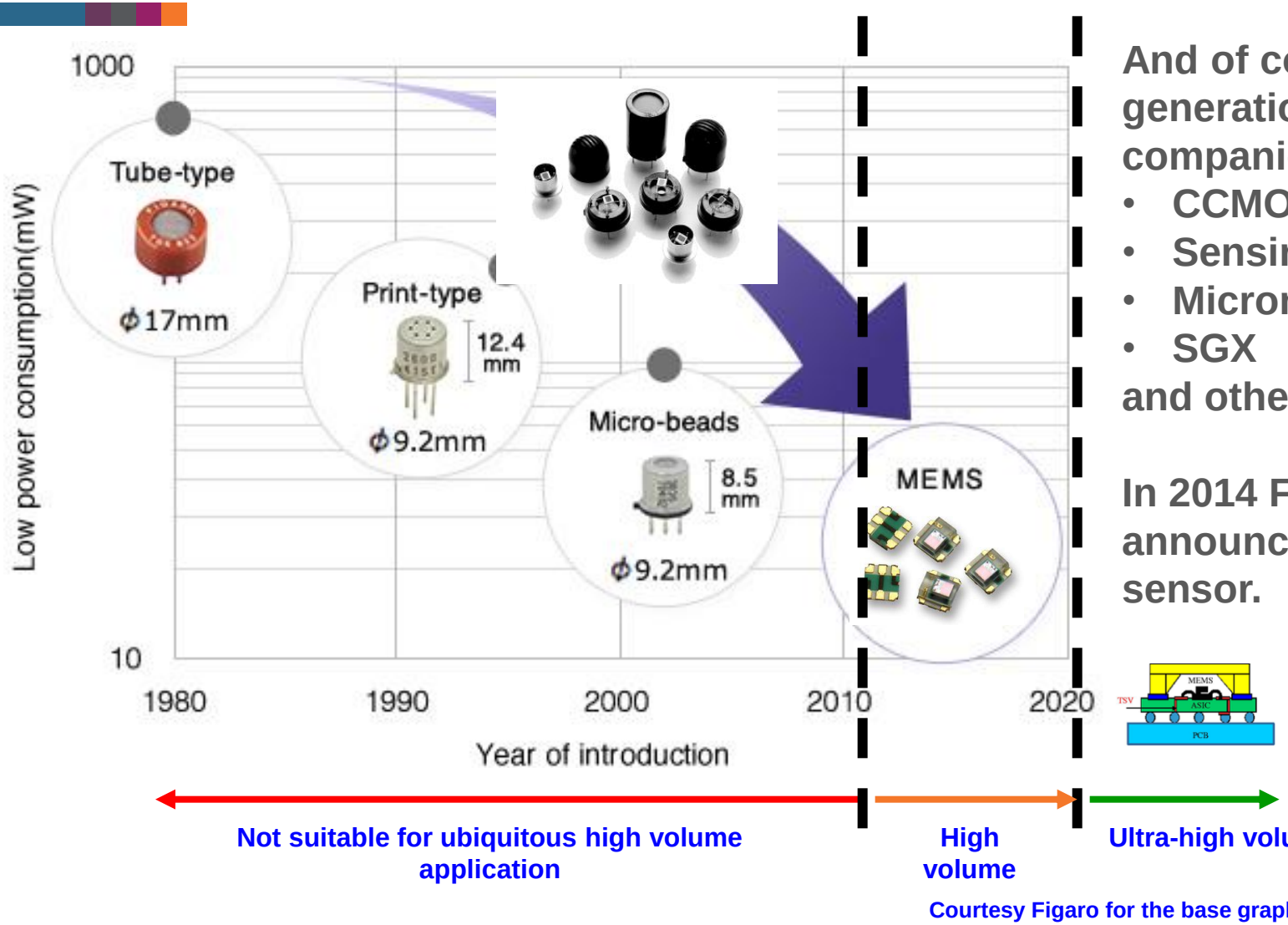
Domestic & Industrial Security



Infrastructures

ANYWHERE, ANYTIME, BY ANYONE AND ANYTHING

Generations of MOX Gas Sensors



And of course new generation gas sensing companies:

- CCMOSS
- Sensirion
- Micronas
- SGX

and others, for AQM

In 2014 Figaro, announced MEMS sensor.

Courtesy Figaro for the base graph

Progress in MOX has been slow, but with CMOS this is poised to change …

Portable Air Quality Monitoring System

- Personal Gas Monitors
- Portable Gas Monitors
- Fixed Gas Detectors
- Gas Sensor Control Systems

Single and Multi-point Safety Systems:
Asphyxiation and poison

- oxygen
- carbon monoxide
- hydrogen sulfide
- explosion (LEL)

Combination of EC, MOX, NDIR

Many companies, Honeywell, MSA, RAE-Systems, GMIUK, so on

Fixed AQM System with MOX

Especially for E-nose

PEN3

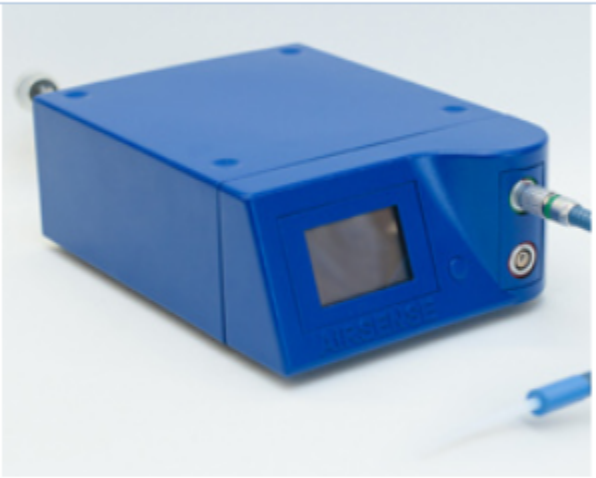
Portable Electronic Nose

AIRSENSE ANALYTICS

Intelligent chemical sensor for identification of gases and vapours

PEN3 is based on a metal-oxide gas sensor array. By using a specific dilution technique the system is protected from overloading with substances. This extends the life time of the sensors and shortens the cycle times. This gas-flow control makes it possible to stabilize the pattern under varying concentrations and analytical conditions.

Individual gases or gas mixtures are classified and recognized by their pattern. In this case, the unit provides a quick and simple quantitative answer as **good** or **bad**, **yes** or **no** ... .
Even qualitative answers can be given by training and comparison with the database.



Quality Control

Rancidity of oils, freshness of food, off odour in packaging materials, residual solvents in polymers, degradation of flavours, off odour in medicine, characterization of resins or aroma in beverages

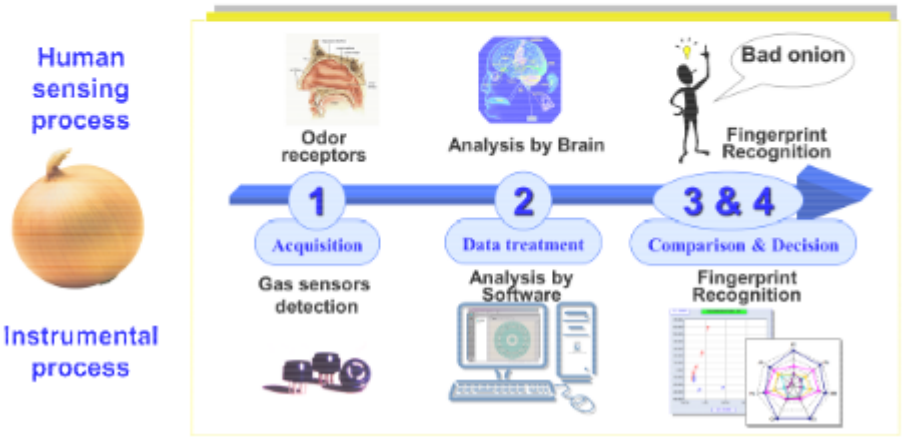
Fixed AQM System with MOX (cont)

Gas sensors Electronic Nose

1. Fully automated autosampler
2. Array of metal oxide sensors (detection system)
3. Electronic unit for acquisition & autosampler

Flavor assessment of food ingredients with FOX Electronic Nose

Working principle of Electronic Nose compared to human smell



Metal Oxide Sensors (MOS) of different types in arrays: 1 customized array of 6 sensors in GEMINI and 1 to 3 standard arrays of 6 sensors in FOX

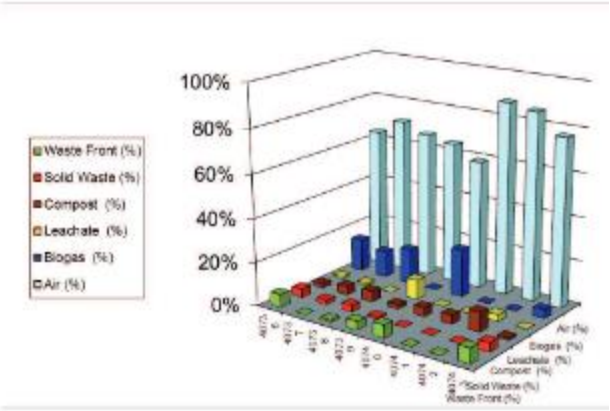
Fixed AQM System with MOX (cont)

No longer for sale

Dr. Födisch Umweltmesstechnik AG

Fixed AQM System with MOX (cont)

SACMI



Nest Sensor Teardown

- Freescale Kinetis K60
- Freescale K16
- EM357 ZigBee SoC
- Figaro TGS-5342 CO Sensor
- muRata Type ZX WiFi Module
- Passive IR Sensor

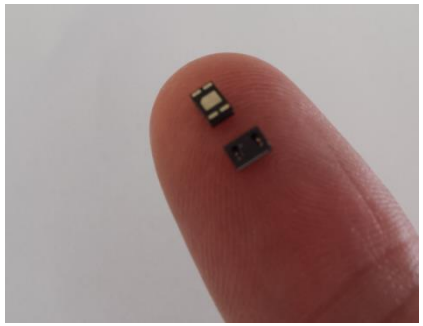
Still using bulky gas sensor devices on TO-type package.

Clever Way of Marketing …

- TEMPERATURE: Save money and be healthier with the right temperature for every room and every season.
- HUMIDITY: Monitor your humidity levels to keep mold, flu, virus and bugs away from your home or office.
- AIR QUALITY: Go beyond CO2. Learn about real indoor pollution based on VOC levels and open your windows when necessary to preserve your health and avoid a headache.
- NOISE: Reduce noise to reduce stress, sleep better, work smarter and be a more responsible neighbour.
- LIGHT: Know when it's too dark to work or too bright to sleep.
- PRESSURE: Predict weather changes and see if the headache you're having is weather related.

Both Nest and CubeSensors are playing an important role in this…

Where Next?

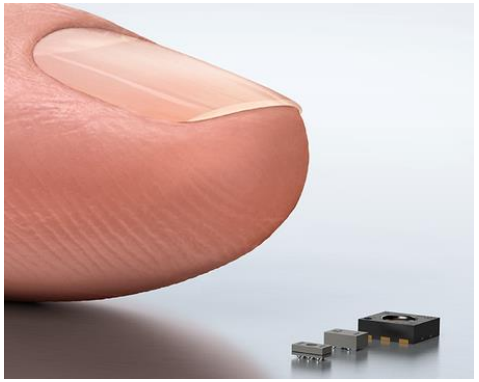


CCMOSS

- For VOCs, alcohol, CO, etc
- Single MOX sensor with multi-sensting
- For mobile and IoT apps
- Low power consumption
- Size: 3 x 2 x 1 mm (DFN)
- External ASIC Interface: I²C
- Supply voltage: < 1.8V

Figaro

- World's lowest* power consumption -- 15mW
- World's smallest size* – 3.2 x 2.5 x 0.99 (mm)
- Quick response
- High sensitivity to gaseous air contaminants



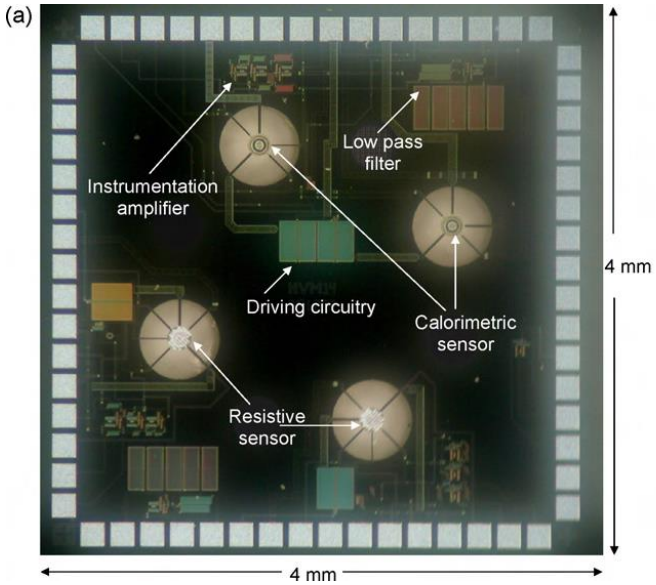
Sensirion

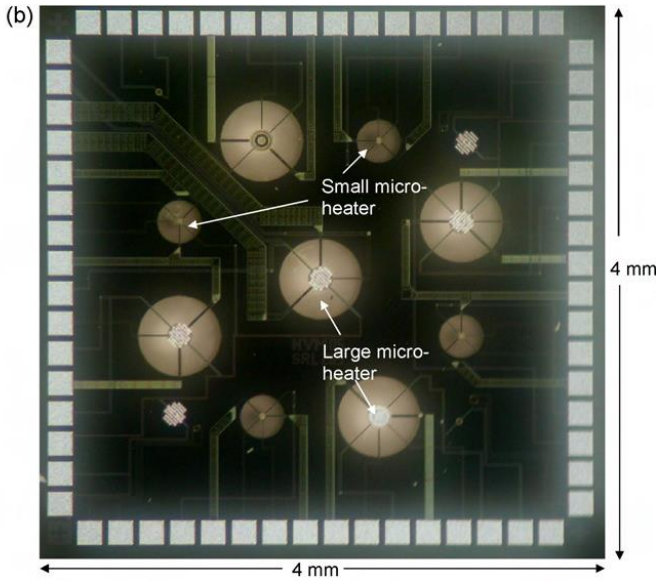
- Broad sensitivity to various gases including VOCs, alcohol, CO, etc
- MOX sensor with multi-Pixel technology for unique selectivity
- For mobile and IoT apps
- Low power consumption
- Size: 2.45 x 2.45 x 0.75 mm (DFN)
- Interface: I²C
- Supply voltage: 1.8V

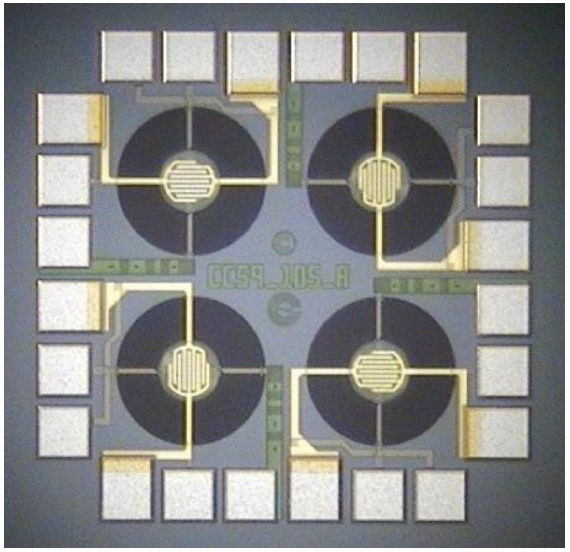
This will lead to a new generation of sensors in

- Indoor Air Quality (IAQ) monitor to detect a wide range of indoor air pollutants
- Toxic Gas Detector to alarm the user to dangerous levels of Carbon Monoxide (CO)
- Alcohol Breathalyser to provide ethanol levels on breath as indicator of Blood Alcohol Content (BAC)

To do this reliably it will need Sensor Array





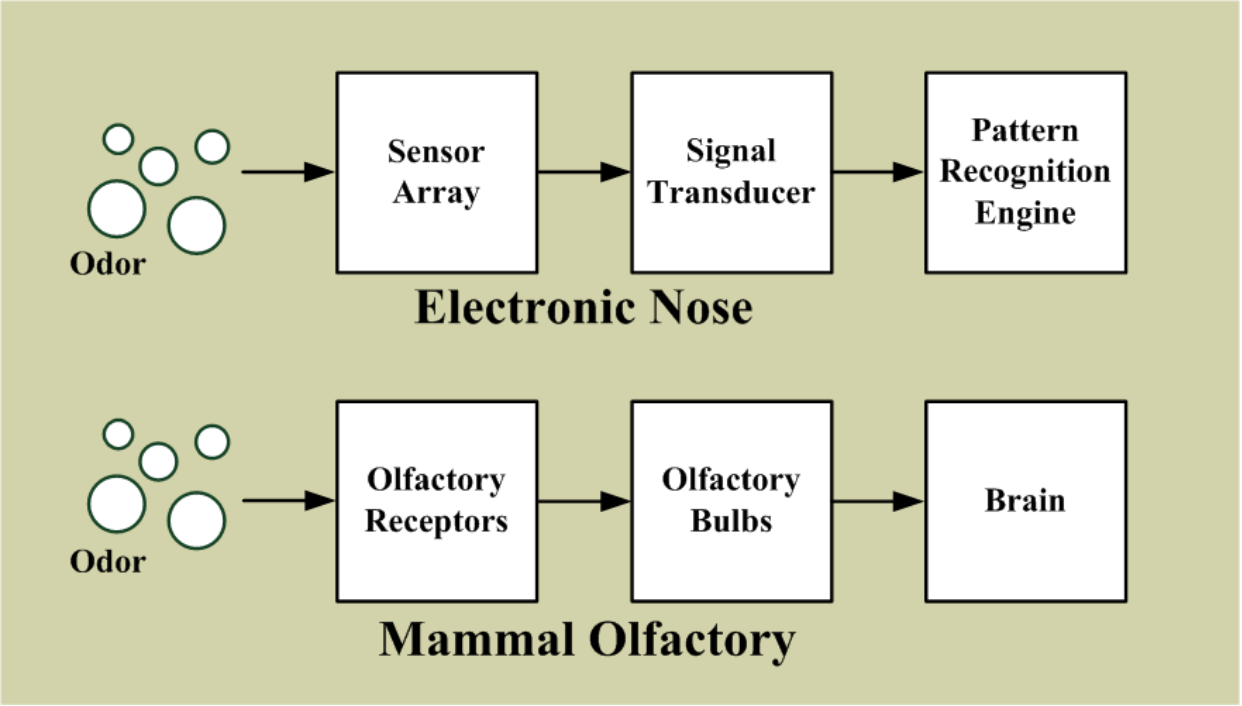


Quad Chip on 1mm x 1mm die with gold electrodes

With CMOS and MEMS next obvious step is to enable truly high volume AQM sensors in smartphone and wearable devices.

With arrays and combined with on-chip pattern recognition and algorithmic approaches, log awaited issues of SSS's is poised to be solved!

Why Sensor Array?

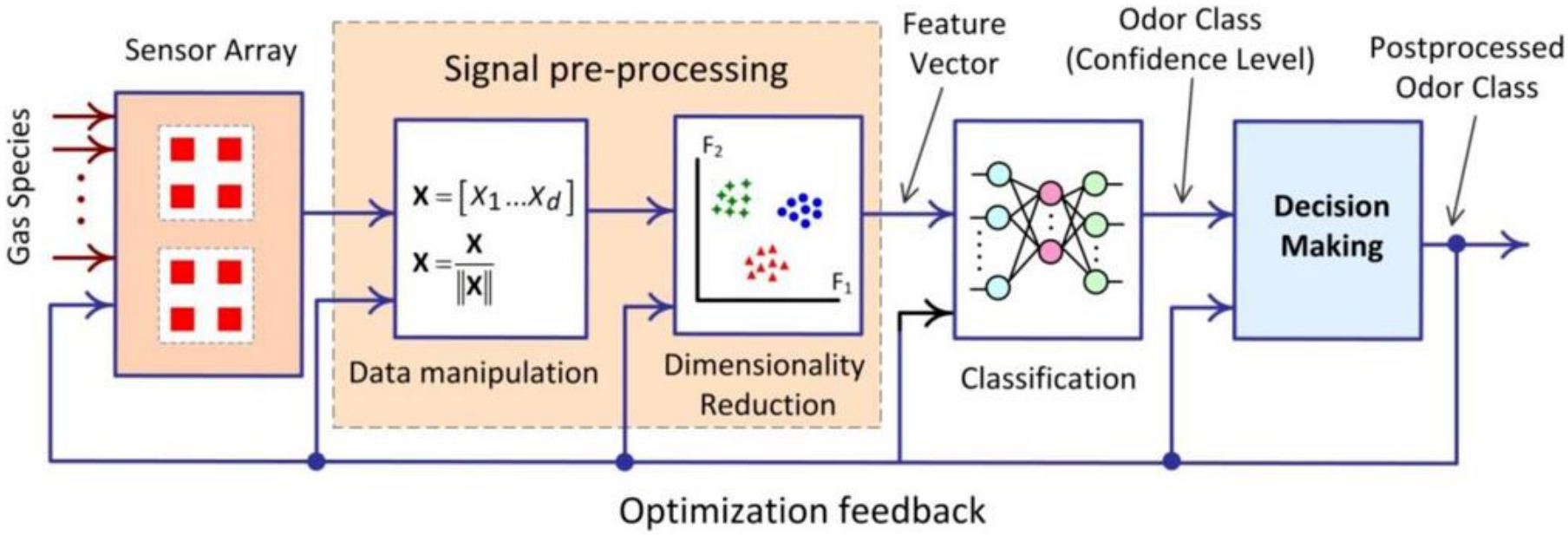


*

To imitate animal, human or insect sensory, but need to be better!

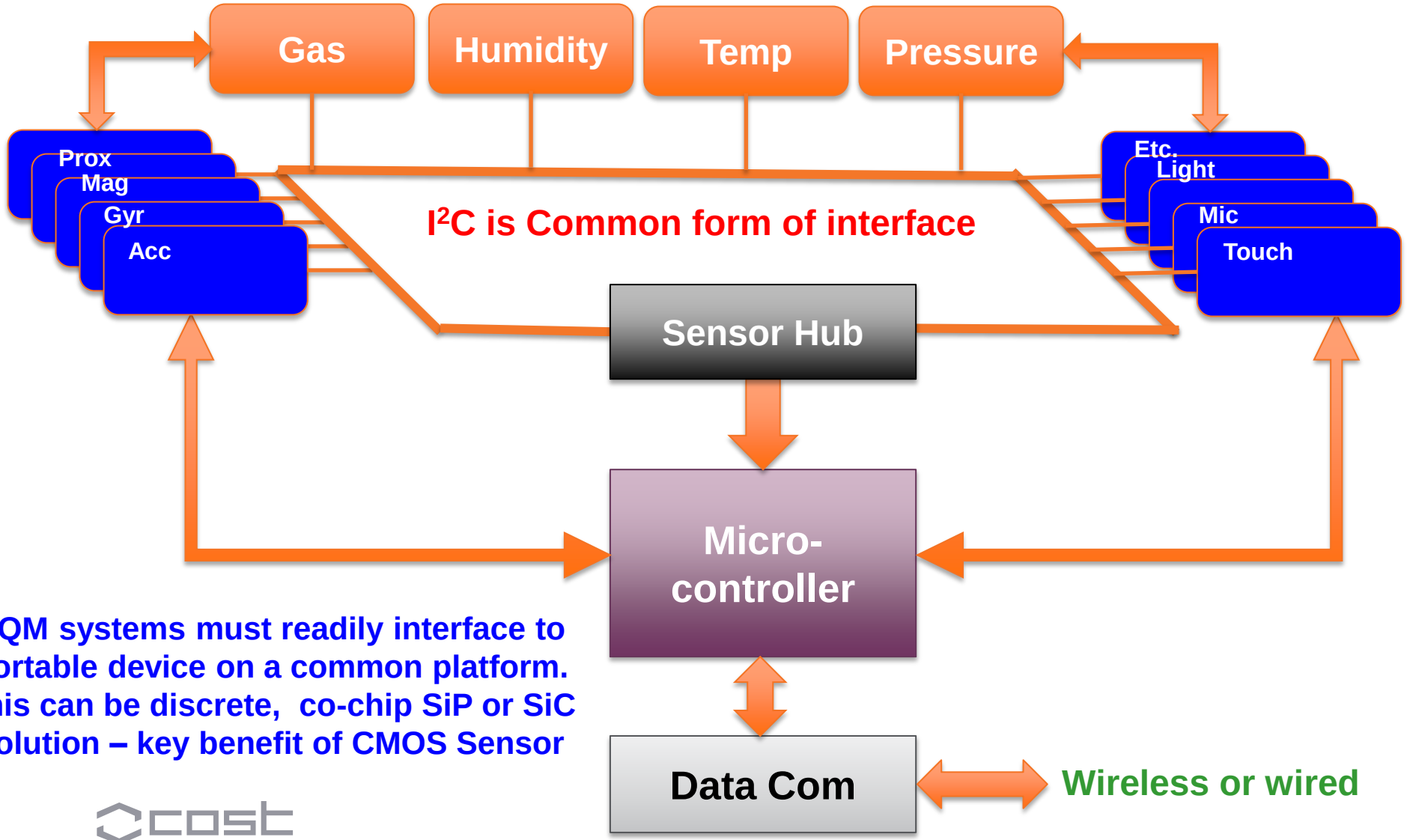
- ***Shih-Wen Chiu et al "Towards a Chemiresistive Sensor-Integrated Electronic Nose: A Review" Sensors 2013, 13, 14214-14247;***

Example of Sensor Array Implemetation



Fayçal Benrekia et al "Gas Sensors Characterization and Multilayer Perceptron (MLP) Hardware Implementation for Gas Identification Using a Field Programmable Gate Array (FPGA).", Sensors 2013, 13(3), 2967-2985

Will need common interface



AQM systems must readily interface to portable device on a common platform. This can be discrete, co-chip SiP or SiC solution – key benefit of CMOS Sensor

Data interpretation

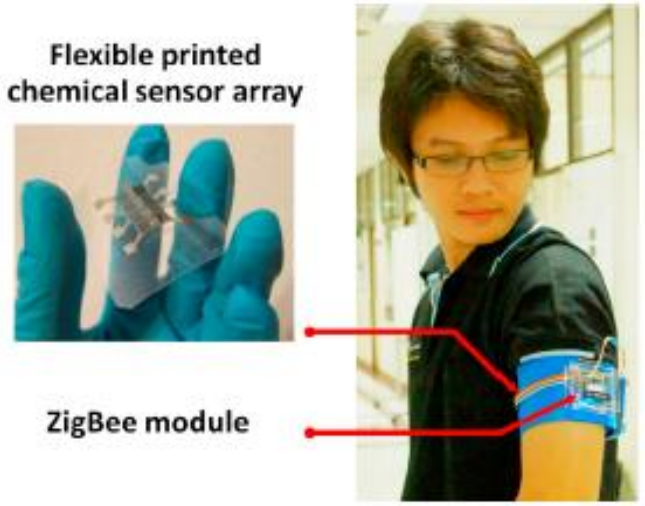
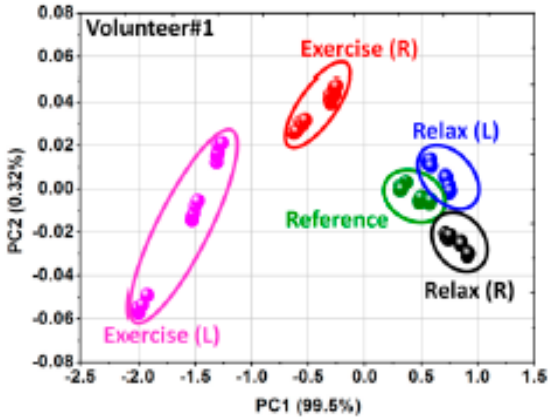


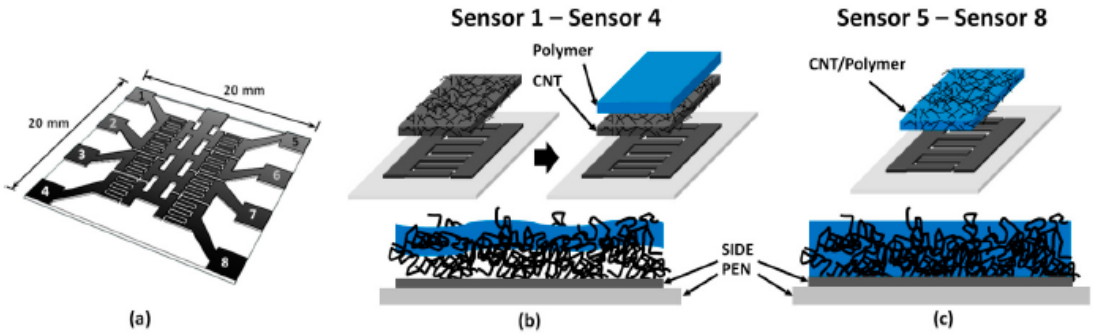
Figure 7. PCA scores plot of underarm odor under different activities: (**a**) volunteer#1; (**b**) volunteer#2 and (**c**) volunteer#3.

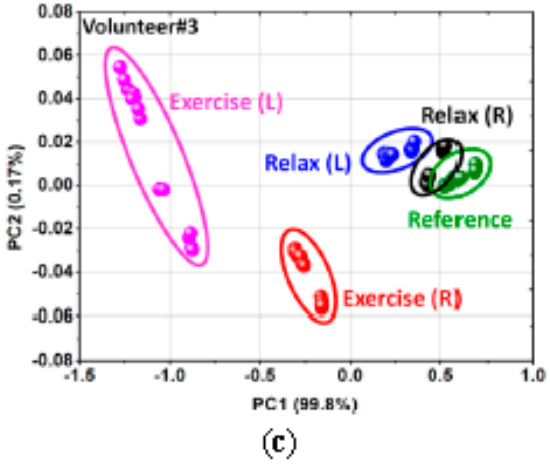


(a)

(b)

Figure 1. Architectures of (**a**) the silver interdigitated electrode (SIDE); (**b**) the double printed layers (DPLs) sensor and (**c**) the blended single layer (BSL) sensor.





(c)

Panida Lorwongtragool, A Novel Wearable Electronic Nose for Healthcare Based on Flexible Printed Chemical Sensor Array, Sensors 2014, 14, 19700-19712

Beyond CMOS

TFET

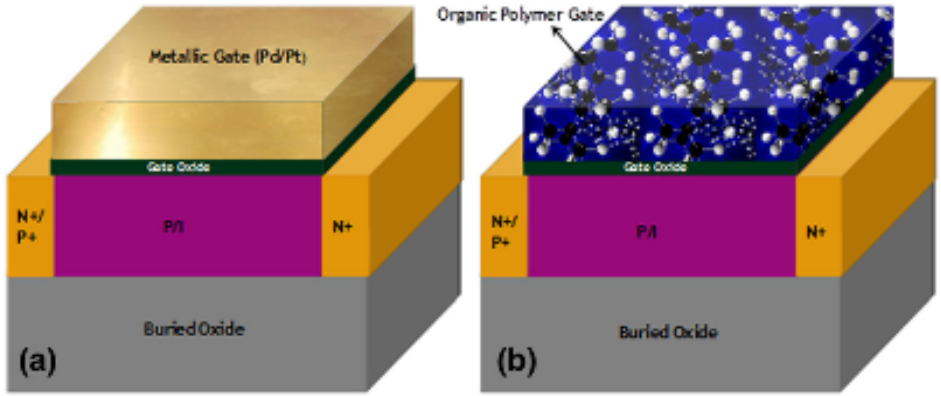


FIG. 1. The schematic diagram of a field-effect-transistor gas-sensor based on silicon-on-insulator (SOI) structure with (a) metallic gate and (b) organic conducting polymer gate as the sensing element. For conventional n-type MOSFET based sensor, the doping in source, channel, and drain are N+, P, and N+, respectively, while for that based on n-type TFET, the sequence is P+, I, and N+, respectively. Continuous Pd and Pt film is explored for metallic gates, while polyaniline and polypyrrole are discussed for polymer gates. Semiconductor material is taken to be silicon. Note that we use the term MOSFETs generically to specify conventional FETs even in case of a polymer gate. For all simulations the channel length is taken to be 50 nm, effective gate oxide thickness is 0.5 nm and thickness of SOI is 5 nm for both MOSFET and TFET.

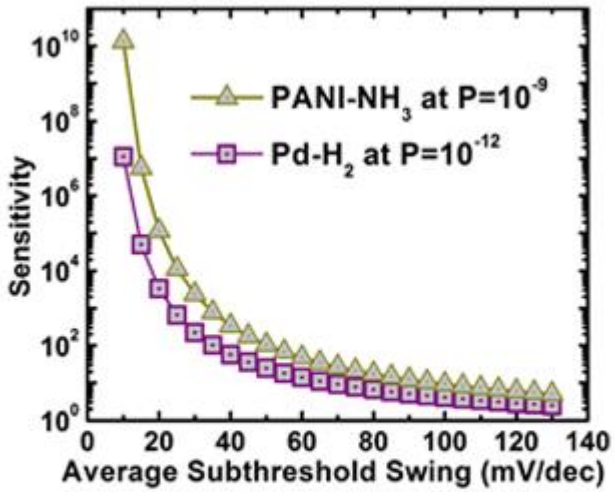


FIG. 5. Sensitivity as a function of average subthreshold swing for both metallic gate (Pd for sensing hydrogen at pressure of 10^{-9} Torr) as well as polymer gate (PANI for sensing ammonia at pressure of 10^{-12} Torr) as the sensing element.

Also Vt shift is used to measure concentration level

Claimed TFET can achieve 10000 x sensitivity compared to MOSFET!

With MOSFET and TFET combined with sensor arrays, ultimate goal is it achieve RT ultra-low power AQM sensors

Deblina Sarkar, et al, Tunnel-field-effect-transistor based gas-sensor: Introducing gas detection with a quantum-mechanical transducer, APPLIED PHYSICS LETTERS 102, 023110 (2013)

Summary

- MOX sensors for AQM is making slow progress
- With players in CMOS MEMS solutions this is changing
- Still a long way to as behind the scene, commercial CMOS foundries need to be actively involved … and they are now!
- Array based sensors with pattern recognition is potential to solve SSS's issues.
- Gas sensors for beyond CMOS has already started

Acknowledgements

CCMOSS Team

CCMOSS Investors

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SEVENTH FRAMEWORK PROGRAMME

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