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

COST Action TD1105

4th International Workshop *EuNetAir* on

Innovations and Challenges for Air Quality Control Sensors

FFG - Austrian Research Promotion Agency - Austrian COST Association

Vienna, Austria, 25 - 26 February 2016

"Environmental Sensors and Miniaturization"

Martin Schrems

Vice President Technology R&D

Martin.Schrems@ams.com

ams AG

Austria

COST is supported by the EU Framework Programme

European Science Foundation ESF provides the COST Office through a European Commission contract

About ams

Shaping the world with sensor solutions

Focus

- Designing and manufacturing advanced analog sensor solutions
- Markets: communications, consumer, industrial, automotive and medical
- Solutions: intelligent light sensors, CIS, RFID/NFC, chemical sensors, active-noise-cancelling ICs, position sensors, ultra-low power management, and more
- Standard products & custom solutions (ASICs & foundry services)

People:

- More than 2,100 employees in 20 countries
- 18 design centers
- 20 sales offices
- 30+ channel partners

Manufacturing

- IDM with 30+ years of experience
- Advanced processes: CMOS, HV-CMOS and SiGe, 3D TSV
- Certified for automotive & medical production
- Full service foundry including packaging and testing options
- 8 inch wafer fab in Austria (180k wspa)
- Test facility in Calamba, Philippines
- Strong relationships with global manufacturing partners

Financials

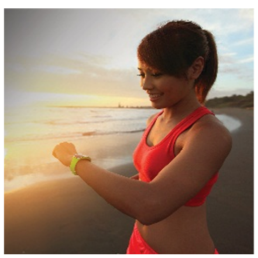
- Revenues 2015 EUR623m/$691m (2014: EUR 464m/$614m)
- Revenues Q4 2015 EUR147m/$161m (Q4 2014: EUR139m/$141m)

The world of sensors

Smart Phones & Tablet

- Ambient light, color & proximity sensors
- Gesture recognition
- NFC-based contactless payment solutions
- Environmental sensors
- Active Noise Cancellation
- Spectral sensors

Wearables



- Biosensors, heart rate monitoring
- Power management
- NFC-based contactless payment solutions
- Active Noise Cancellation
- Environmental sensors

Smart Home & Buildings

- Gas sensors
- Temperature sensors
- Smart light sensors
- Humidity sensors
- Pressure sensors
- Flow sensors
- Lightning sensors

Automotive

- Position sensors
- Sensors for advanced driver assistance
- Air quality sensors
- Hydrogen sensors

Industrial

- Position sensors
- CMOS sensors for machine vision and drones
- Industrial/building automation
- Flow sensors (Heat, Water, Gas Metering)
- NFC Sensor Tags

Medical

- Image Sensors for:
  - Computed tomography
  - Digital x-ray
  - Ultrasound
  - Surgical robots
- CMOS image sensors for endoscopy (miniature cameras)

Overview

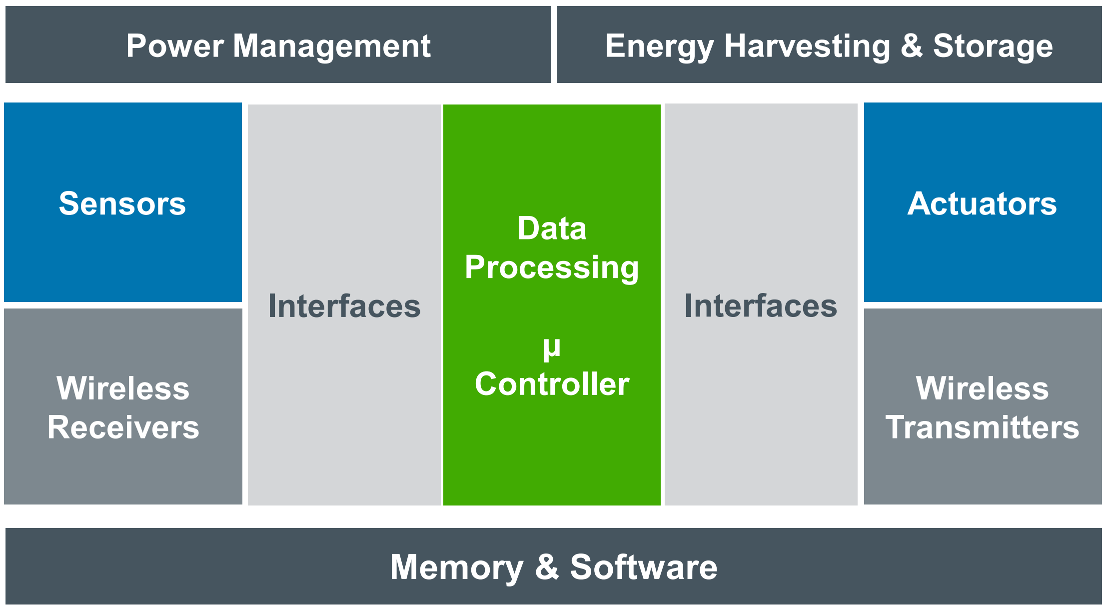
1. Sensors and Smart Systems
2. Environmental Sensor Market Needs and Applications
3. Environmental Sensors and Technologies
4. Miniaturization
5. Conclusions

Overview

1. Sensors and Smart Systems
2. Environmental Sensor Market Needs and Applications
3. Environmental Sensors and Technologies
4. Miniaturization
5. Conclusions

Smart Systems

<u>Smart System Block Diagram</u>



<u>Examples</u>

Wearable/Fitness 

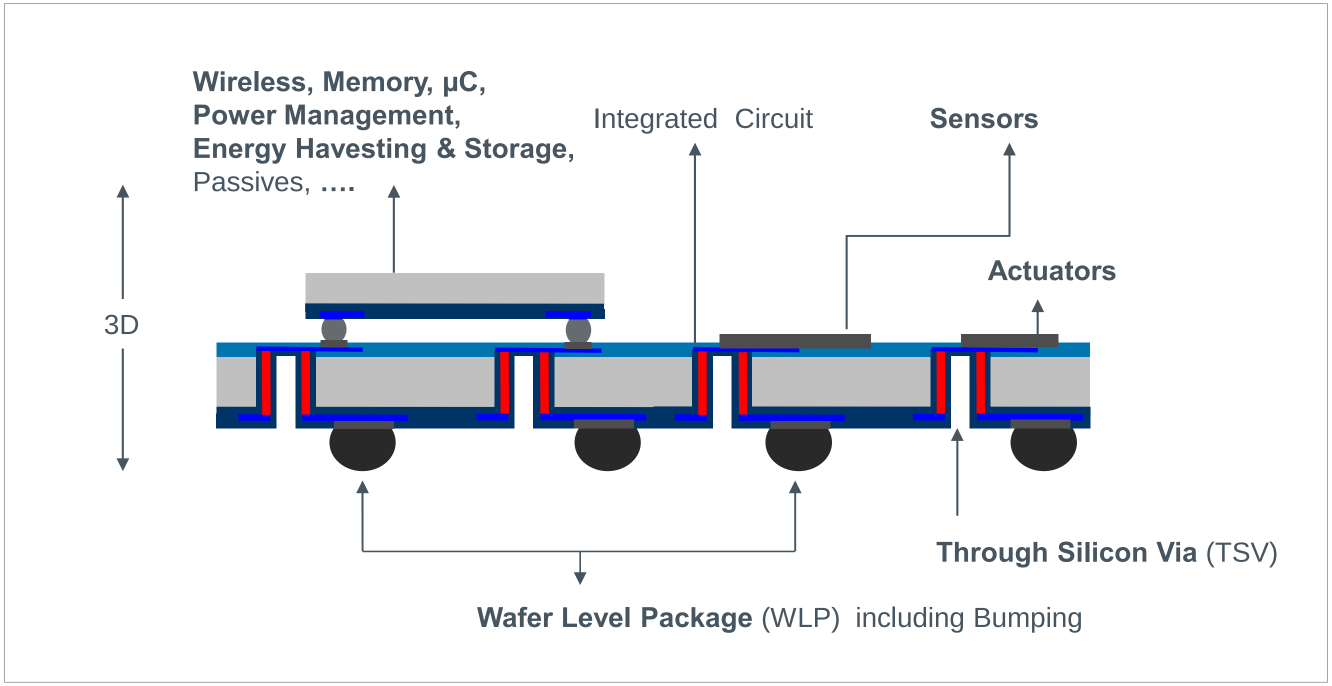
Smart Watch 

Smartphone 

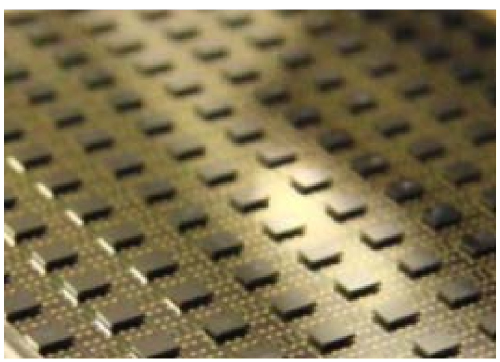
Smart Home 

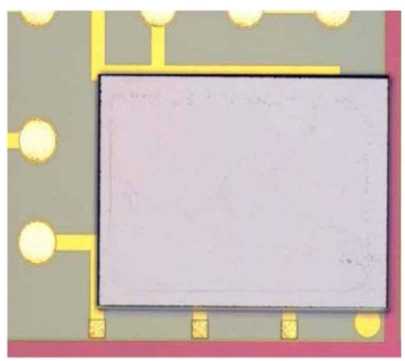
…
Smart Everything

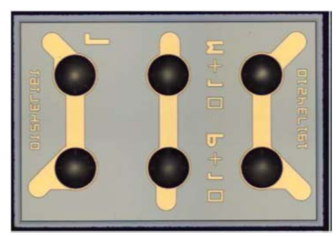
Miniaturized Smart Systems

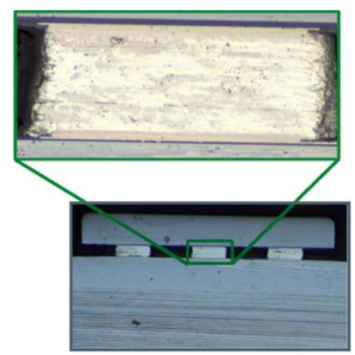


- Active Interposer
- TSV
- WLP
- D2W
- FO WLCSP
- PCB Die Embedding





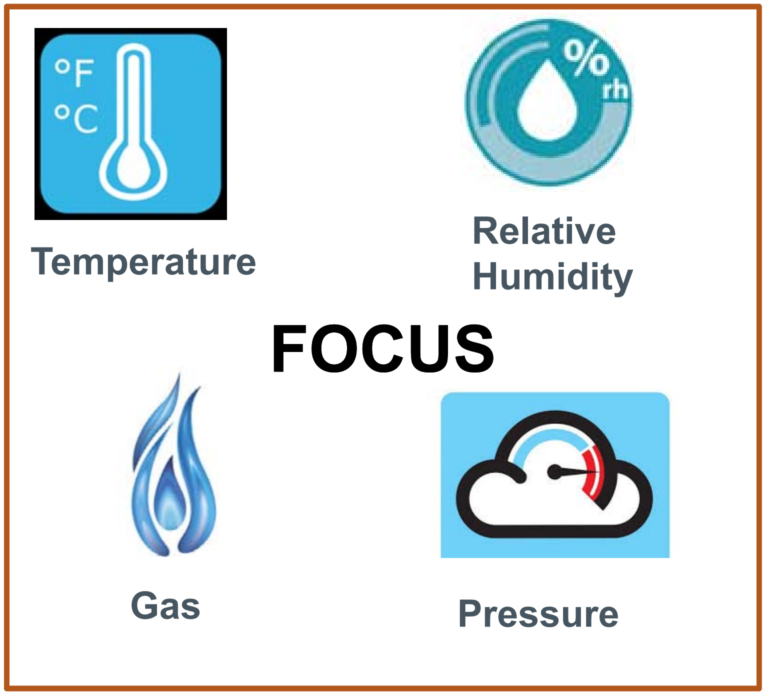


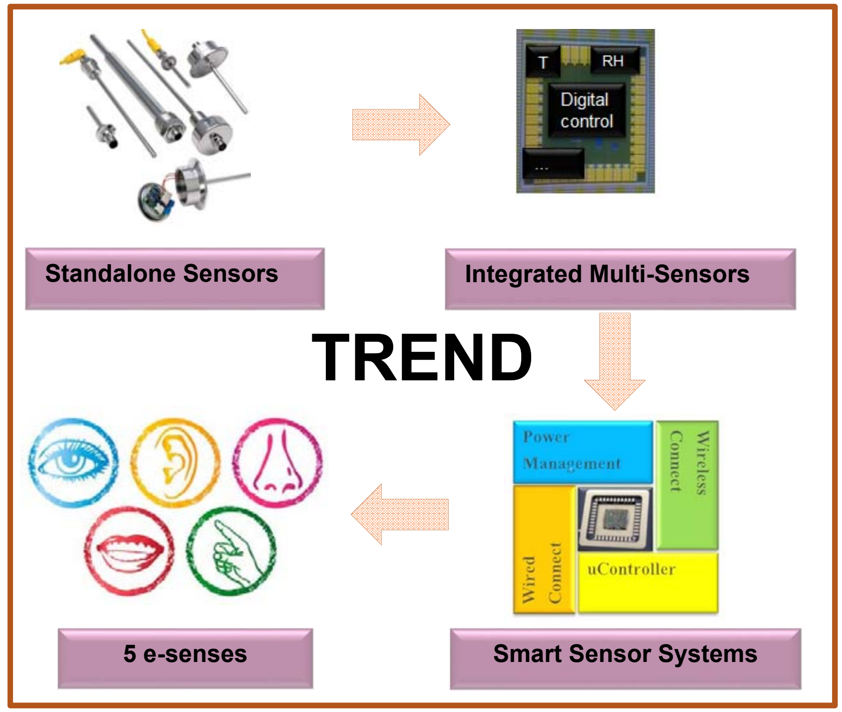


Source: F.Schrank et al. (2015)

Environmental Sensors

- Provide environmental information to people
- EM radiation, sound, pressure, temperature, gas, particles





Overview

1. Sensors and Smart Systems
2. Environmental Sensor Market Needs and Applications
3. Environmental Sensors and Technologies
4. Miniaturization
5. Conclusions

Market Drivers

- Human comfort and safety
- Environmental awareness and indoor navigation
- Fitness
- Health monitoring

Mobile
Wearable
Consumer

- Human comfort, safety and health
- Energy Efficiency
- Cost reductions (maintenance, energy, …)
- Security

Home and
Building
Automation

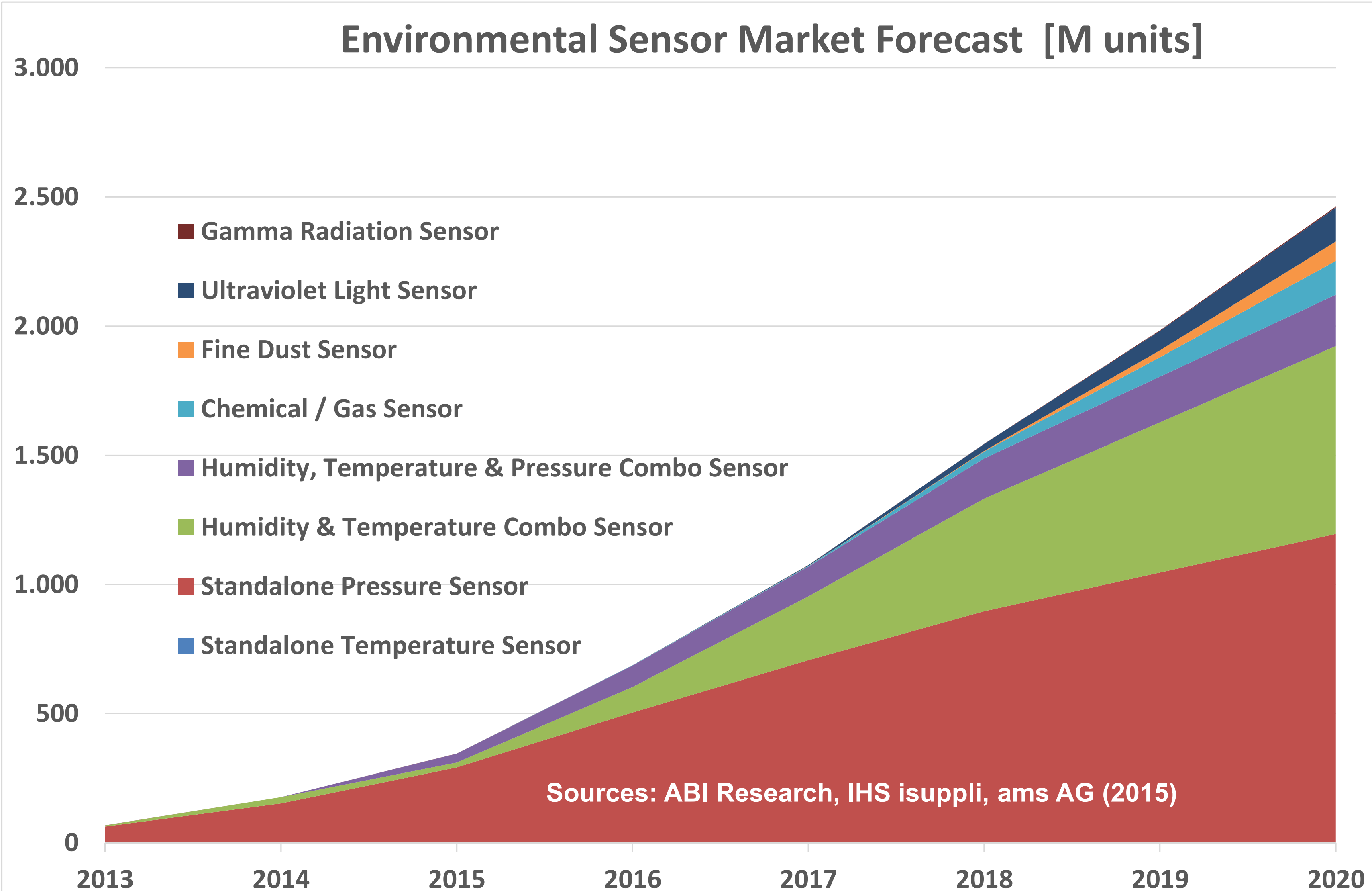
- Cost reduction
- Yield increase
- Safety
- Security

Industrial & Agriculture

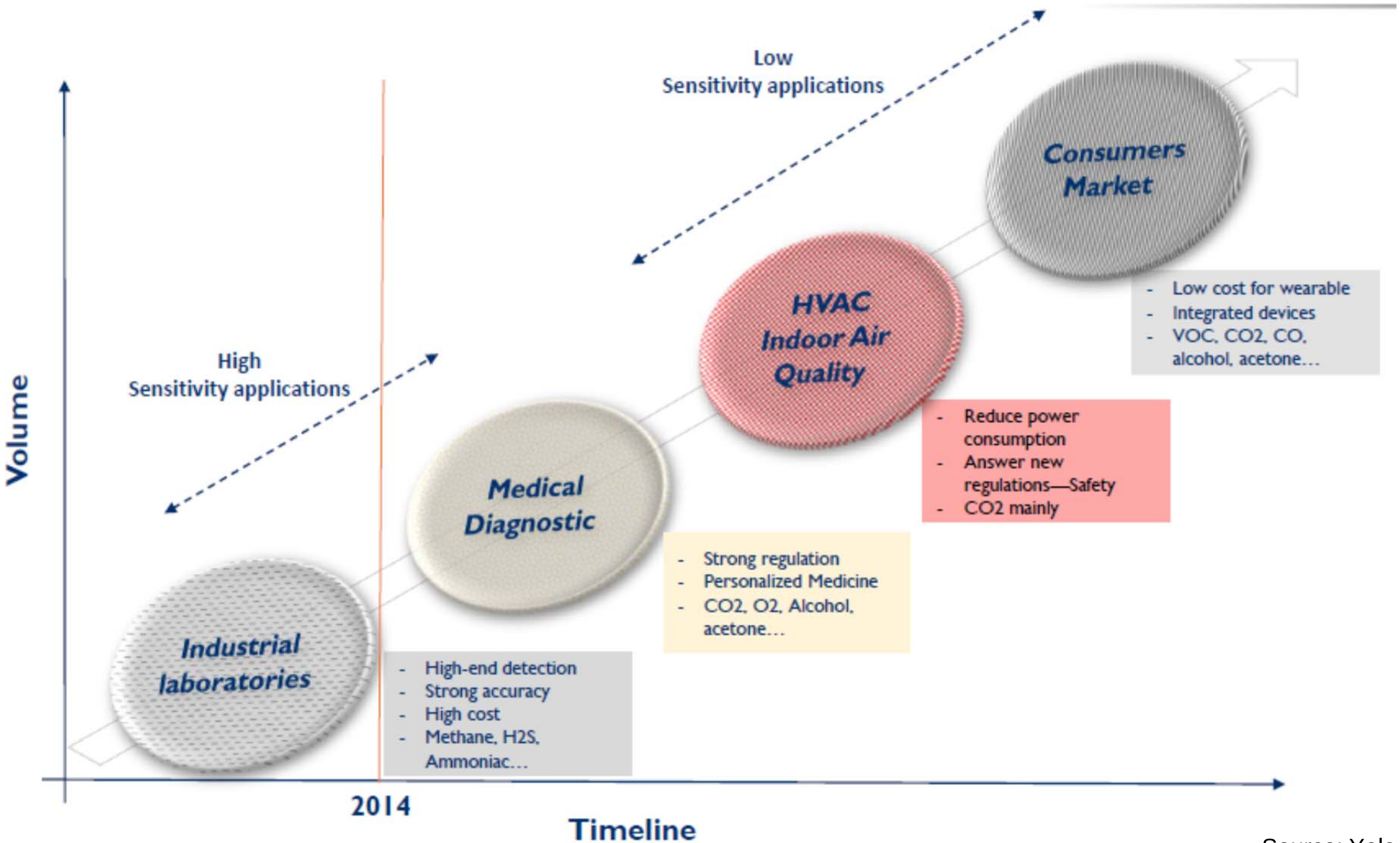
- Improve human comfort
- Pedestrian and passenger safety
- Security

Automotive

Environmental Sensor Market



Gas Sensor Applications



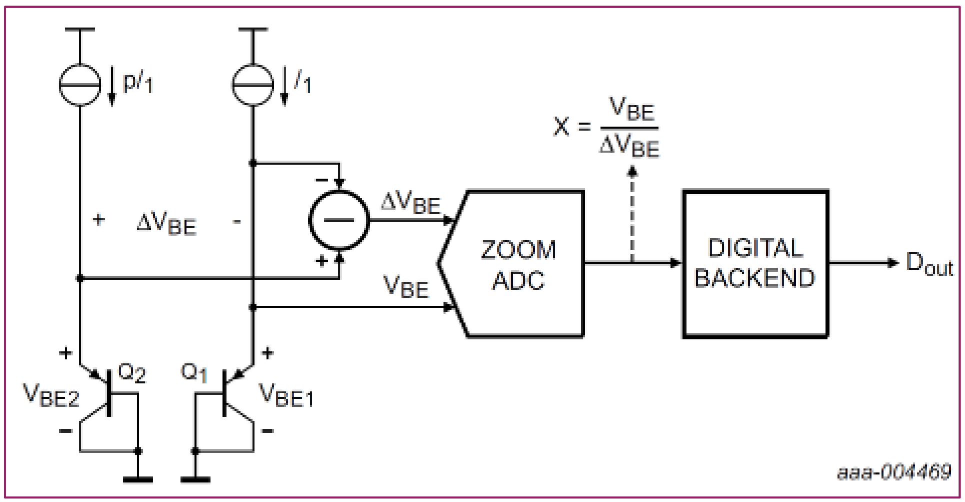
Source: Yole (2016)

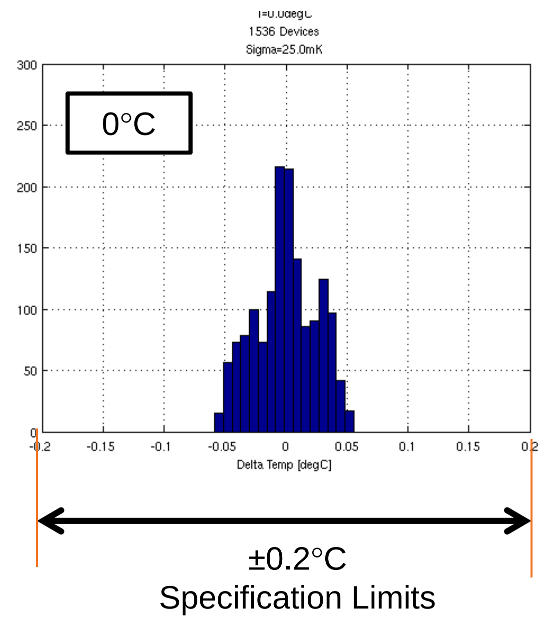
Overview

1. Sensors and Smart Systems
2. Environmental Sensor Market Needs and Applications
3. Environmental Sensors and Technologies
4. Miniaturization
5. Conclusions

Temperature

- CMOS-based design block (Bandgap)



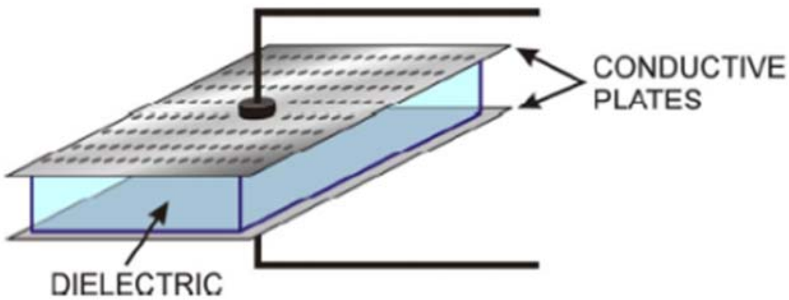


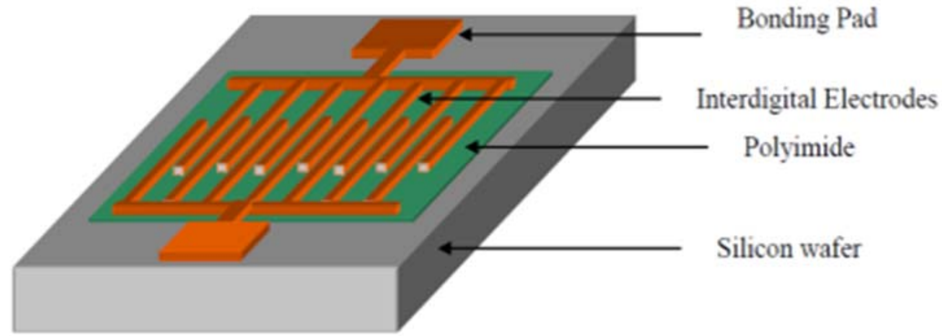
Source: ams AG (2015)

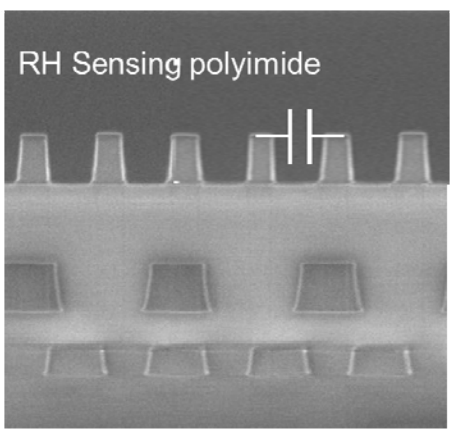
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Humidity

- SoC integrated humidity sensor (CMOS postprocessing)







DRY POLYIMIDE (RH=0%):

$$C_{RHS} = \varepsilon_{PI,Dry} \times \frac{A}{d}, \quad \varepsilon_{PI,Dry \approx (3-4)}$$

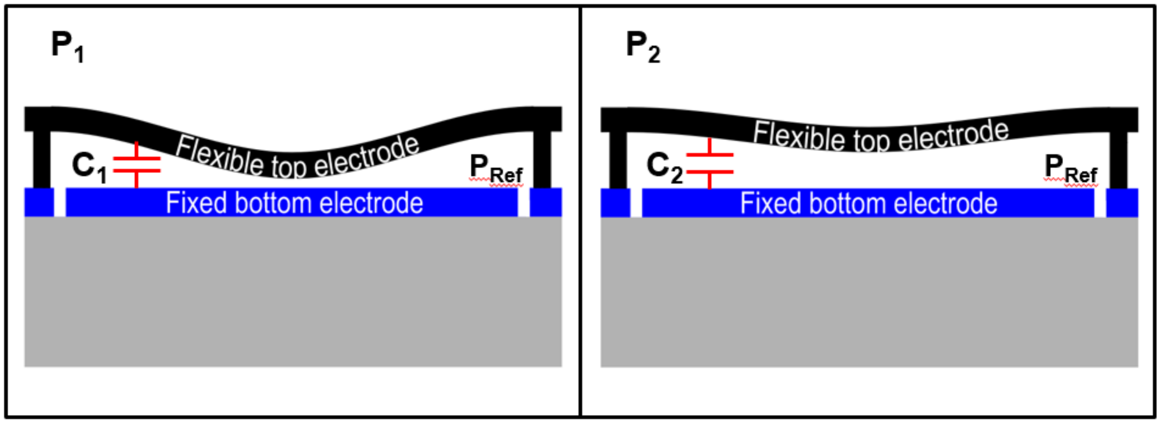
RH > 0%:

$$C_{RHS} = f(\varepsilon_{PI,Dry}, \varepsilon_{H_2O}) \times \frac{A}{d}, \quad \varepsilon_{H_2O \approx 78}$$

Source: ams AG (2015)

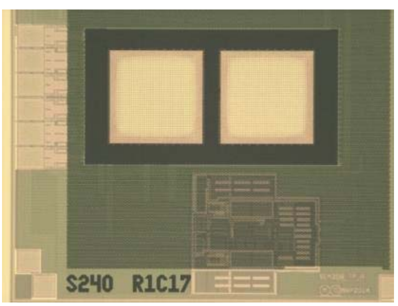
Pressure

- SoC integrated pressure sensor (CMOS postprocessing)

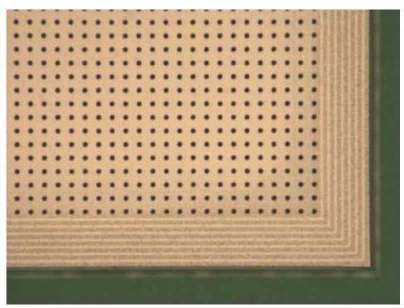


$$P_1 > P_2 > P_{ref}$$

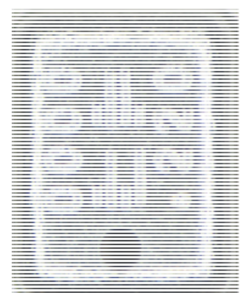
$$C_1 > C_2$$



Top view ASIC with two membranes on CMOS



Top view membrane showing release etch holes

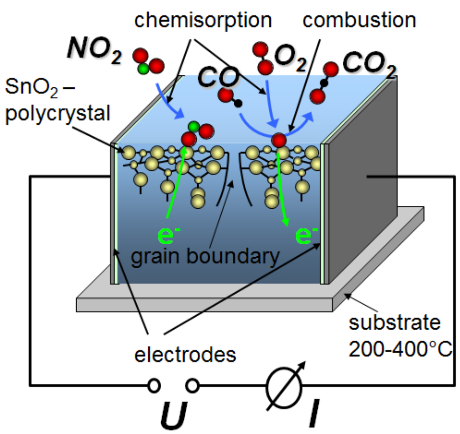


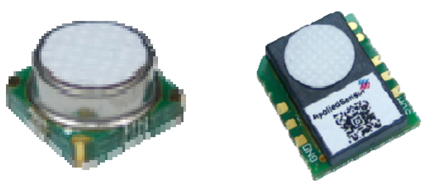
Top view Packaged Product

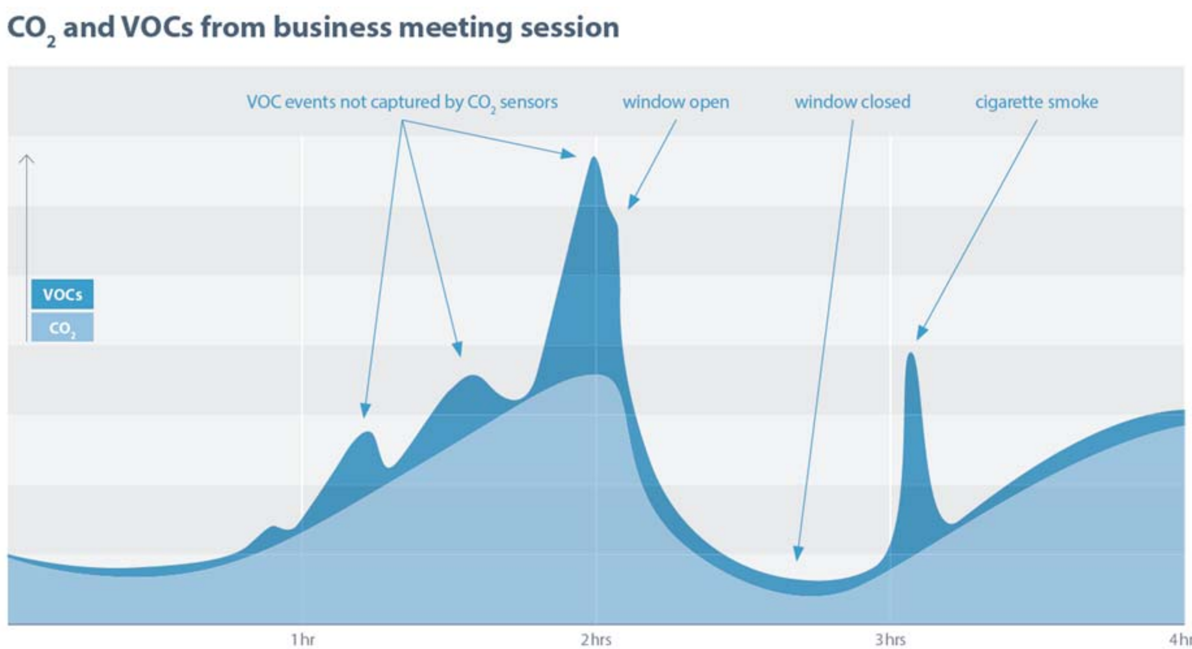
Source: ams AG (2015)

Gas

- Volatile Organic Compounds

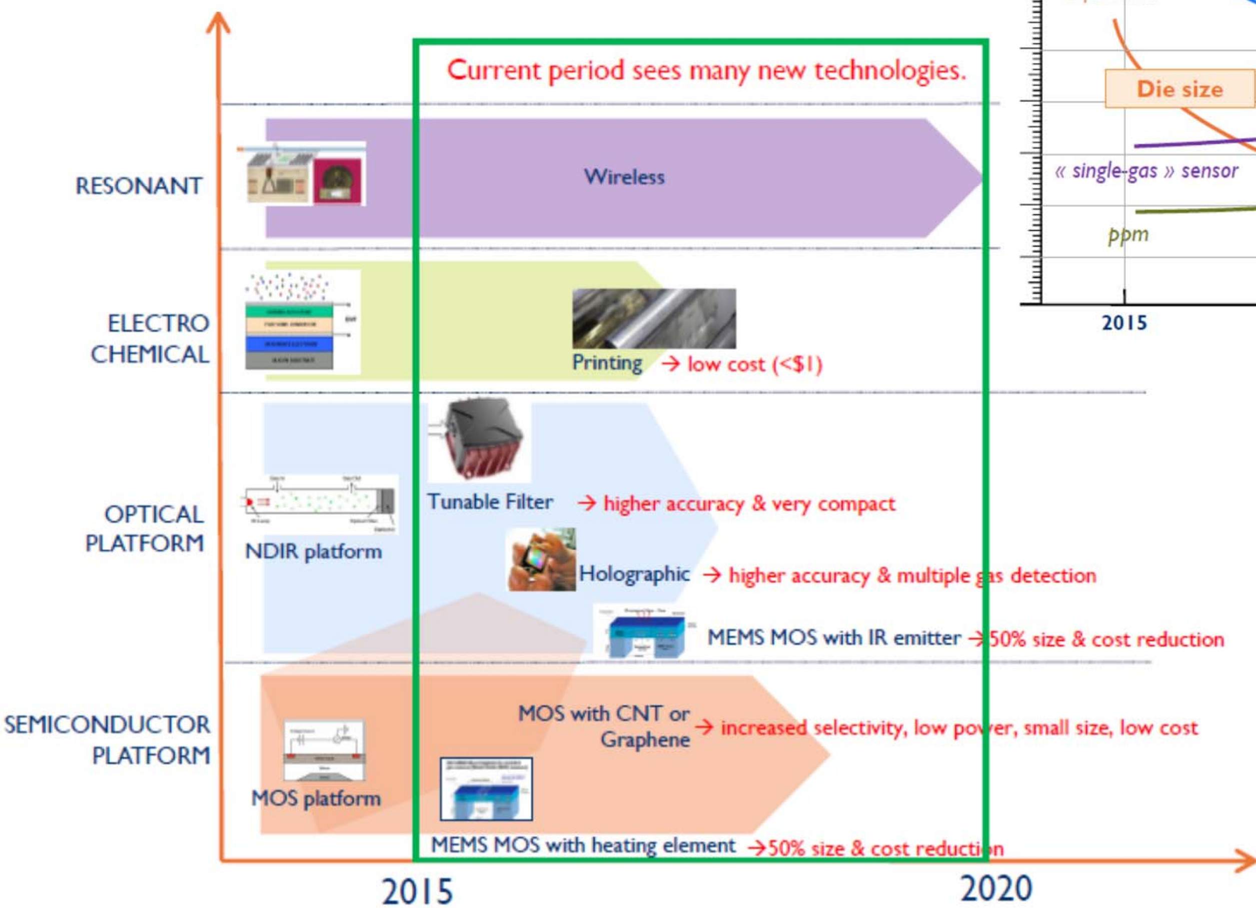


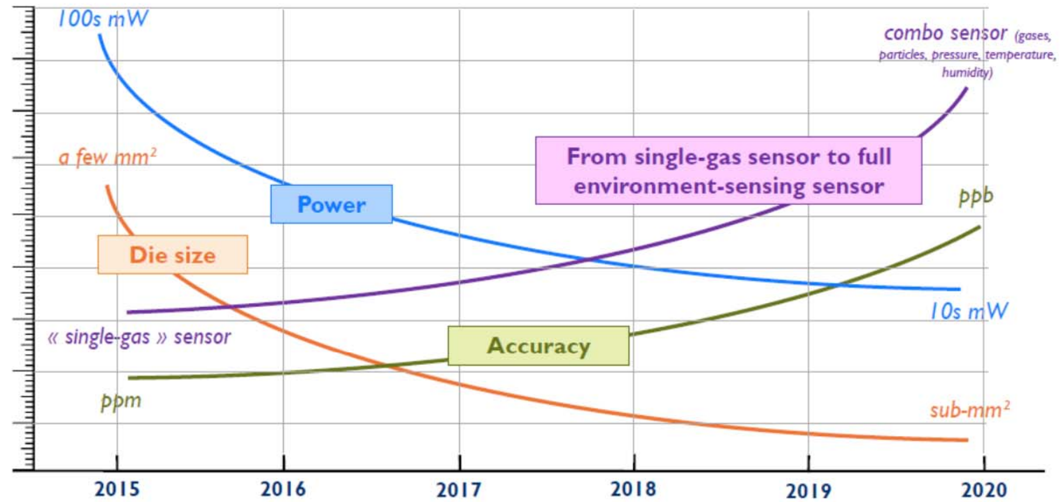




Source: ams AG (2015)

Gas Sensor Trends





Source: Yole (2016)

Gas Sensor Technologies

Gas sensing technologies	Principles	Chip size	Power consumption	ASP
NDIR	*IR light passes through the gas & an IR detector measures the transmitting light (MWIR is used to detect CO and CO2)*	• ~ cm² range	• 100s mW for pyro (3.5 mW for COZIR from GSS) • 50µW with PD	• For CO2 HVAC: $30–$80 • Target ASP for wearable applications: $2–$3
FTIR	*An FTIR spectrometer simultaneously collects high spectral resolution data over a wide spectral range (different of NDIR which has narrow range of wavelengths).*	• many cm²	• 150–300 W	• $1000s
Holographic	*Uses a DOE with gratings, lens, splitters for higher accuracy & multiple gas detection (Optosense)*	• ~ 10x10 mm²	• mW	• $100–$500
Electrochemical	*Electrochemical reaction between sensing & counter electrodes creates a current proportional to target gas concentration*	• ~ 20 mm²	• 100s µW range	• $20
Printed electrochemical	*Same as above but using screen printing technology*	• 15x15x3 mm³	• Zero (based on energy harvesting)	• <$1 target
MOS	*Gas absorption at the surface of heated oxide (200–250°C) that results in change of electrical resistance related to sample gas concentration*	• 3.2 x 2.5 x 0.99 (mm3)	• 1–10s of mWs range	• $2 for very high volume to $60 for industrial applications • MEMS technology could achieved $0.20 (SGX)

Source: Yole (2016)

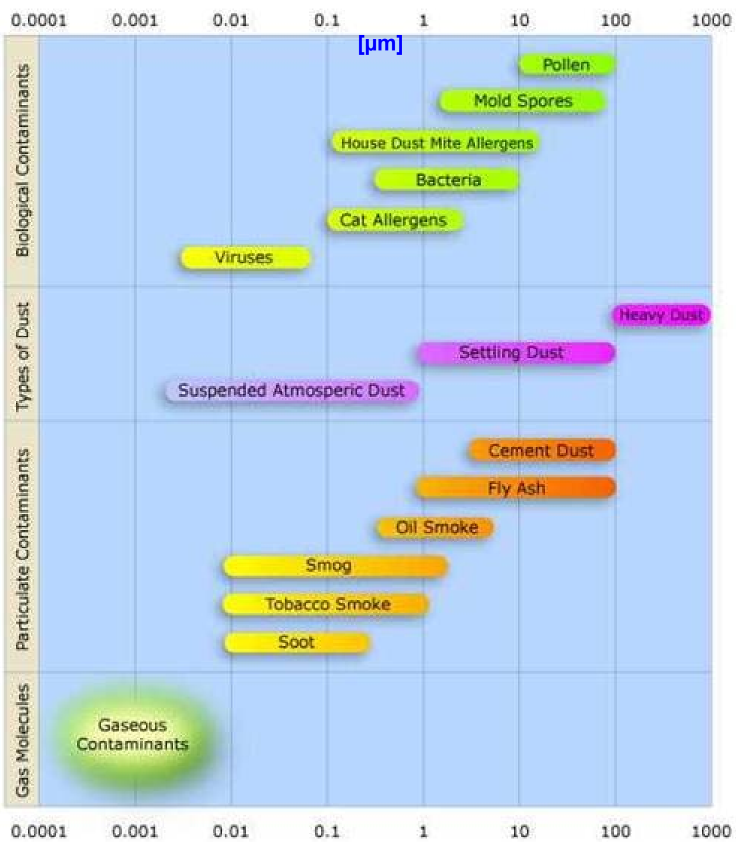
Gas Sensor Technologies contd.

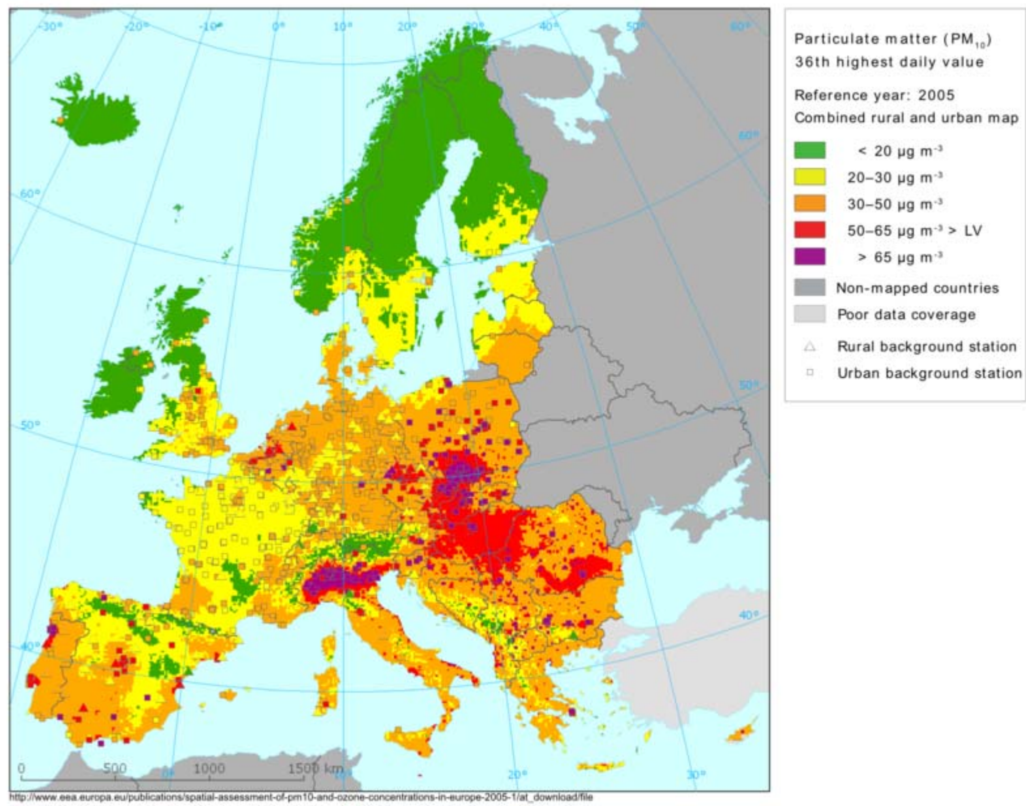
Gas sensing technologies	Principles	Chip size	Power consumption	ASP
Catalytic/Pellistor	*Resistance change through the increase of temperature of a Pt wire impregnated with a catalyst (thus promoting oxidation) compared to a second Pt wire with no oxidation.*	• ~ 1mm long	• 10–100s mW range	• $40–$60 (SGX)
Acoustic/Photo-acoustic	*Photoacoustic spectroscopy is the measurement of the effect of absorbed light by means of acoustic detection. The absorption depends on the wavelength. A microphone is used for detection.*	• ~cm² range	• W range	• > $1500
ChemFET	*Structure is similar to a MOSFET with an electrode replaced by a chemically sensitive membrane. There is NO heating compared to MOSFET.*	• ~mm²	• 10s of mW range	• Est < $10
Resonant	*Quartz resonators sensitive to adsorbed gas species*	• A few mm²	• Low (few mW)	• Est a few $ (a SAW filter is $0.10–$0.25)
PID / GC	*Photo-ionization (e.g., UV) breaks molecules into positive ions. The gas becomes electrically charged and the ions produce an electric current, which is the signal output of the detector.*	• Miniaturized system: 1 liter size (APIX)	• 1000W (lab tool)	• From $50k (3 gases) to $150k (13 gases) • Portable system cost: a few $100s is targeted
Chemiluminescence	*Emission of light as the result of a chemical reaction.*	• Not miniaturized	• 100s W	• $10k to $15k

Source: Yole (2016)

Fine Dust

- Fine Particles (< 2.5µm, < 10µm) pose health hazards (cancer,..)





Source: wikipedia (2015)

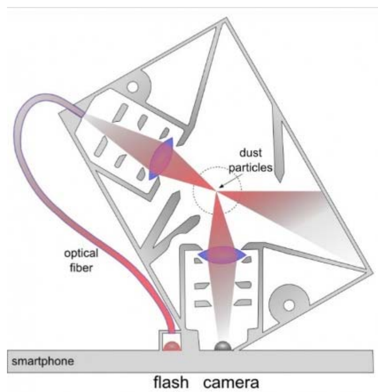
Fine Dust Sensors

Optical ~ m^3

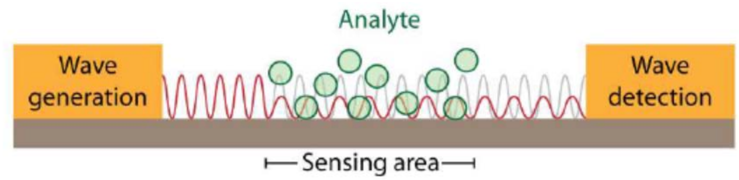
Optical ~ cm^3

MEMS ~ mm^3

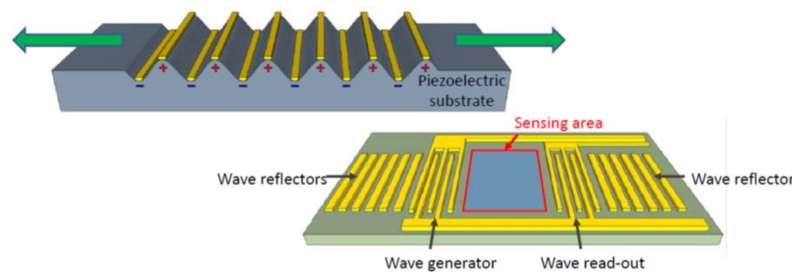
Fine Dust Measurement Station

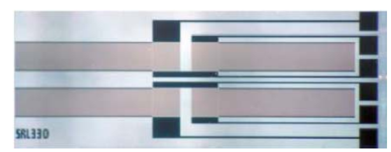


Optical Fine Dust measurement using Mobile phone functions (Budde et al. (2013))



Film Bulk Acoustic wave Resonator (FBAR)



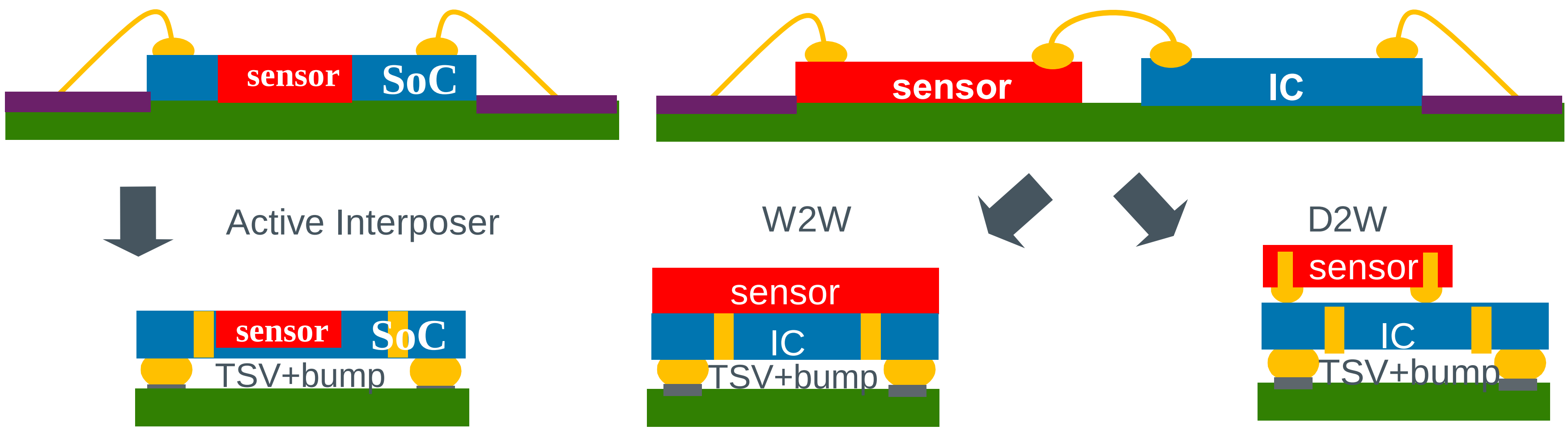


Fine Dust measurement e.g. by SAW / FBAR (S.Thomas et al. (2013))

Overview

1. Sensors and Smart Systems
2. Environmental Sensor Market Needs and Applications
3. Environmental Sensors and Technologies
4. Miniaturization
5. Conclusions

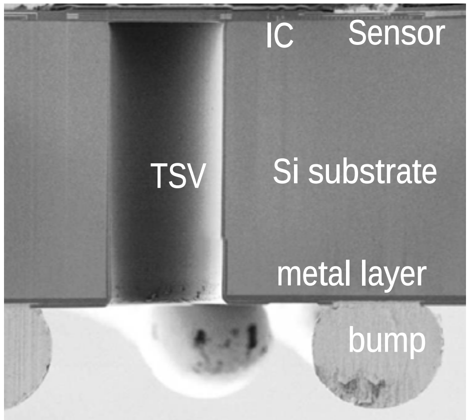
Sensor IC Minaturization using 3D

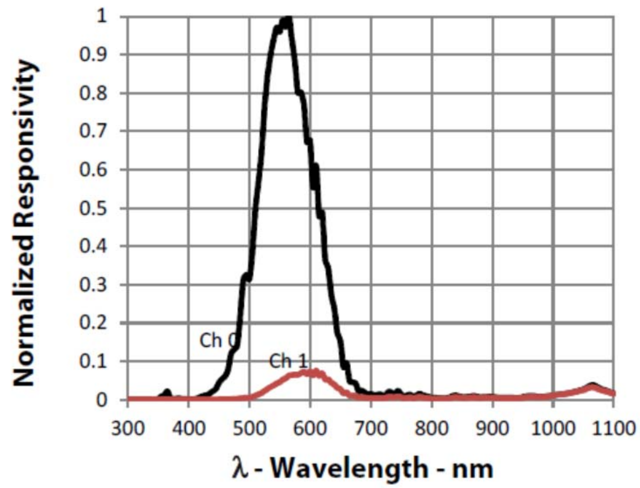


- System on Chip (SoC) with TSV and RDL
- Wafer to Wafer (W2W) bonding for matched sensor and IC die sizes
- Die to Wafer (D2W) bonding if sensor and IC die sizes do not match

- Form factor reduction
- System cost reduction
- Better performance

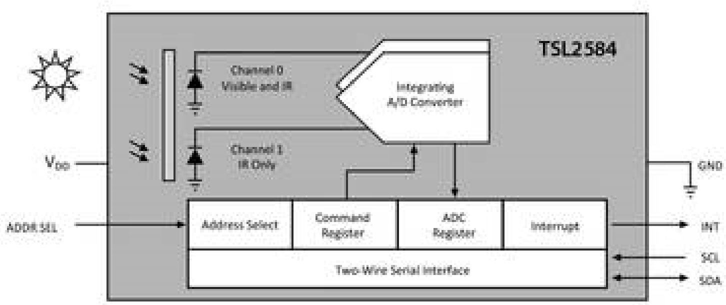
Light Sensor with 3D/TSV





Source: ams AG

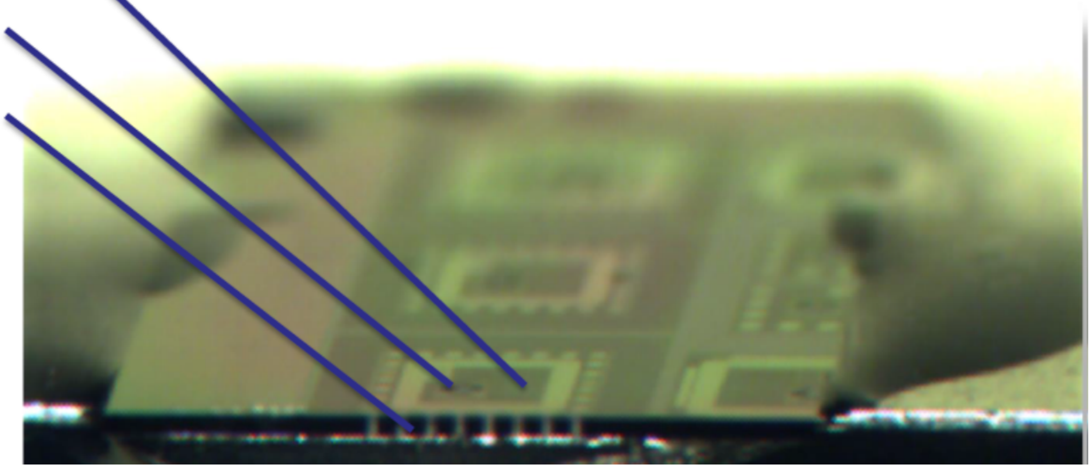
- World's smallest Ambient Light Sensor
- Using 3D/TSV
- Height of only 0.218mm w/o bumps



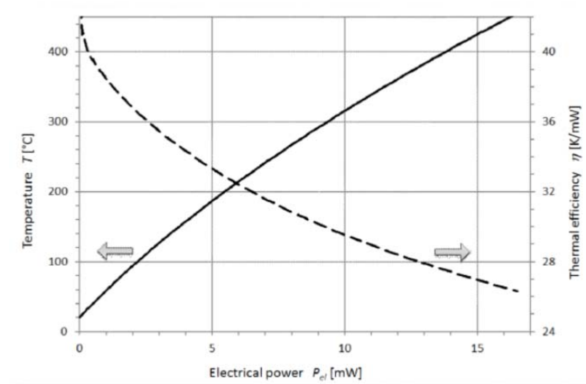
Benefits	Features
• Approximates Human Eye Response	• Dual Diode with Photopic Filter
• Flexible Operation	• Programmable Analog Gain and Integration Time
• Suited for Operation Behind Dark Glass	• 1,000,000: 1 Dynamic Range
• Low Operating Overhead	• Programmable Upper and Lower Thresholds • Programmable Persistence Filter
• Low Power	• 3.0 µA Sleep State
• Industry Standard Two-Wire Interface	• I^2C Fast Mode Compatible Interface • Data Rates up to 400 kbit/s • Input Voltage Levels Compatible with1.8–V Bus
• Ultra-Small Foot-Print	• 1.145 mm x 1.660 mm TSV (Through Silicon Via) • 0.218 mm Height w/o Solder Balls
• Unlimited Manufacturing Floor Life	• MSL1 Rated

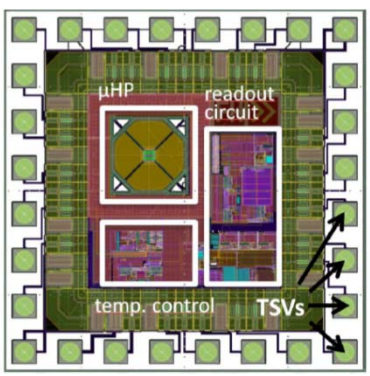
3D Gas Sensor IC

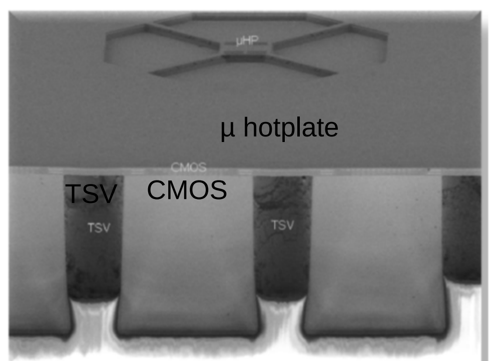
- System on Chip (SoC) integration with 3D/TSV

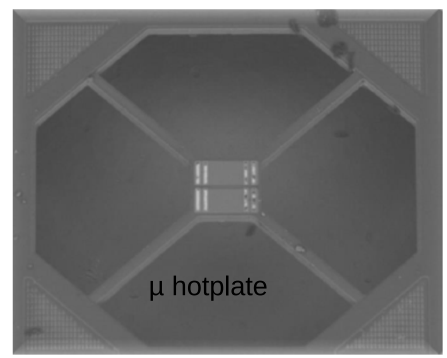


poly-silicon heater
power consumption *9 mW*





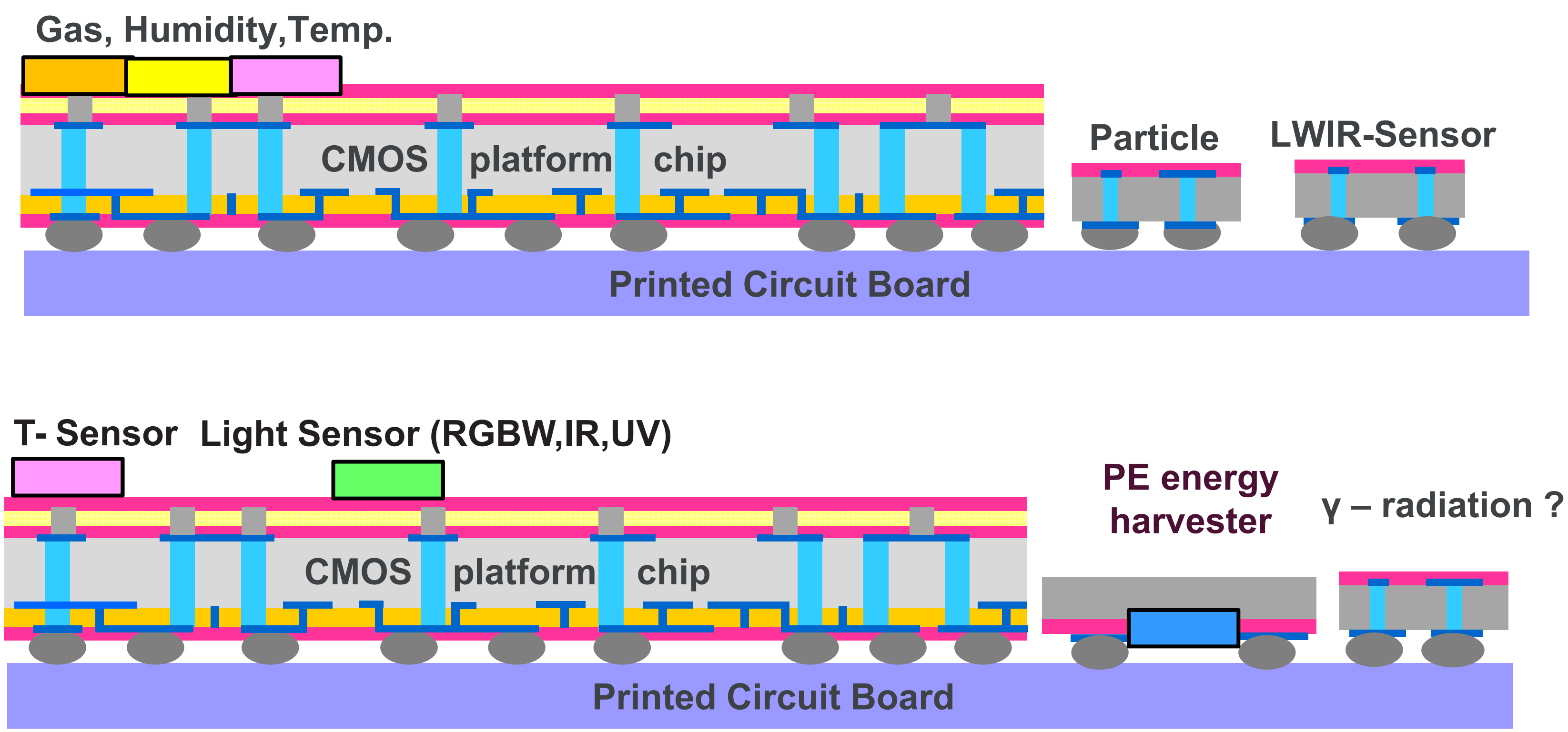




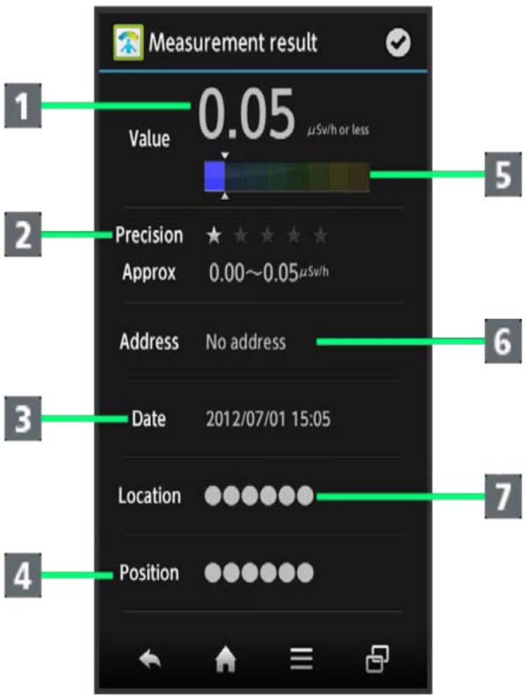
Source: A.Nemecek et al., Semicon Europe (2014) ; ams AG

EU project “Multi-Sensor Platform”

- Ambition: Integration of multiple sensor functions



Gamma Radiation



1 Measured amount of radiation

2 Measurement accuracy (more ☆s indicate higher accuracy)

3 Measurement date

4 Measurement position

5 Level (longer color bar indicates greater amount of radiation)

6 Address (based on GPS, encrypted)

7 Measurement location

Sharp Pantone 5 107SH
0.05µSv/h (min)
(dedicated semiconductor sensors 2x100mm2)
Source: Sharp (2012)

iPhone 4s using camera covered with black tape & SW app
1µSv/h (min)
Source: ansto (2014)

CONCLUSIONS

- Sensors for environmental parameters such as gas, humidity, temperature and pressure as well as EM radiation have become available with increasingly smaller form factors.
- Chemical and fine dust sensing are particular areas where further R&D is needed for identifying the optimum sensing technologies with respect to sensitivity, size and cost.
- Cost reduction and the use of small form factor mobile devices drive the further miniaturization of sensors and electronics as well as the combination of multiple sensor functions
- Miniaturization is enabled by recently developed Wafer Level Packaging and 3D integration technologies with Through Silicon Vias and Die to Wafer Stacking
- Not all sensing parameters need dedicated sensors (T, gamma)

Gas Sensing Technologies

- XXX

Technology	Principle	Output
Optical detection (FTIR, NDIR, photoacoustic)	It is based on wavelength absorption of the gas: NIR to MWIR sources are used for IR sensing; UV source is used for photo acoustic.	A shift in wavelength is measured, correlated to the target gas.
Calorimetric/Pellistor	It is based on burning target gases (it is mainly for combustible gases).	A shift in temperature/resistance is measured.
Electro chemical	It is based on a RedOx chemical reaction between sensor electrodes.	Current intensity is measured.
Metal Oxide Semiconductor	It is mainly based on gas adsorption at the sensor surface.	A resistance change is measured.
ChemFET	It is based on a change in mass/dielectric properties of a specific layer.	A change in mass/dielectric constant is measured.
Acoustic	It is based on the measure of travel time of ultrasound at a given distance to calculate propagation velocity of ultrasonic waves. Concentration is linked to velocity.	Gas velocity is measured.
Chromatography	Gas is electrically charged.	Output is electrical current.
Chemiluminescence	Chemiluminescence (sometimes "chemoluminescence") is the emission of light (luminescence), as the result of a chemical reaction.	Output is light.