Gas Sensors for medical - Healthcare

Jerome Mouly – Team Lead Analyst, Sensing & actuating

SEMICON® EUROPA

YOLE *Développement*

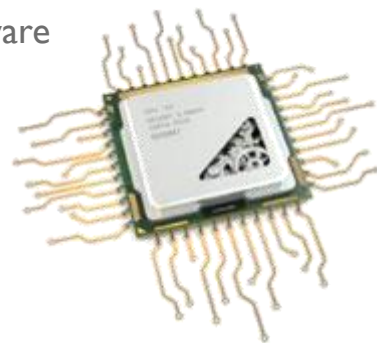# FIELDS OF EXPERTISE COVERING THE SEMICONDUCTOR INDUSTRY

Photonics & Sensing

- Photonics
- Lighting
- Imaging
- Sensing & Actuating
- Display

Semiconductor, Memory & Computing

- Semiconductor Packaging and Substrates
- Semiconductor Manufacturing
- Memory
- Computing and Software

Power & Wireless

- RF Devices & Technologies
- Compound Semiconductors & Emerging Materials
- Power Electronics
- Batteries & Energy Management

A COMPLETE SET OF PRODUCTS & SERVICES TO ANSWER YOUR NEEDS

YEARLY REPORTS

Insight
› Yearly reports
› Market, technology and strategy analysis
› Supply chain changes analysis
› Reverse costing and reverse engineering

Format
› PDF files with analyses
› Excel files with graphics and data

Topics
› Photonics, Imaging & Sensing
› Lighting & Displays
› Power Electronics & Battery
› Compound Semiconductors
› Semiconductor Manufacturing and Packaging
› Computing & Memory

115+ reports per year

QUARTERLY MONITORS

Insight
› Quarterly updated market data and technology trends in units, value and wafer
› Direct access to the analyst

Format
› Excel files with data
› PDF files with analyses graphs and key facts
› Web access (to be available soon)

Topics
› Advanced Packaging
› Application Processor
› DRAM
› NAND
› Compound Semiconductor
› CMOS Image Sensors
› Smartphones

7 different monitors quarterly updated

WEEKLY TRACKS

Insight
› Teardowns of phones, smart home, wearables and automotive modules and systems
› Bill-of-Materials
› Block diagrams

Format
› Web access
› PDF and Excel files
› High-resolution photos

Topics
› Consumer: Smartphones, smart home, wearables
› Automotive: Infotainment, ADAS, Telematics

175+ teardowns per year

CUSTOM SERVICE

Insight
› Specific and dedicated projects
› Strategic, financial, technical, supply chain, market and other semiconductor-related fields
› Reverse costing and reverse engineering

Format
› PDF files with analyses
› Excel files with graphics and data

Topics
› Photonics, Imaging & Sensing
› Lighting & Displays
› Power Electronics & Battery
› Compound Semiconductors
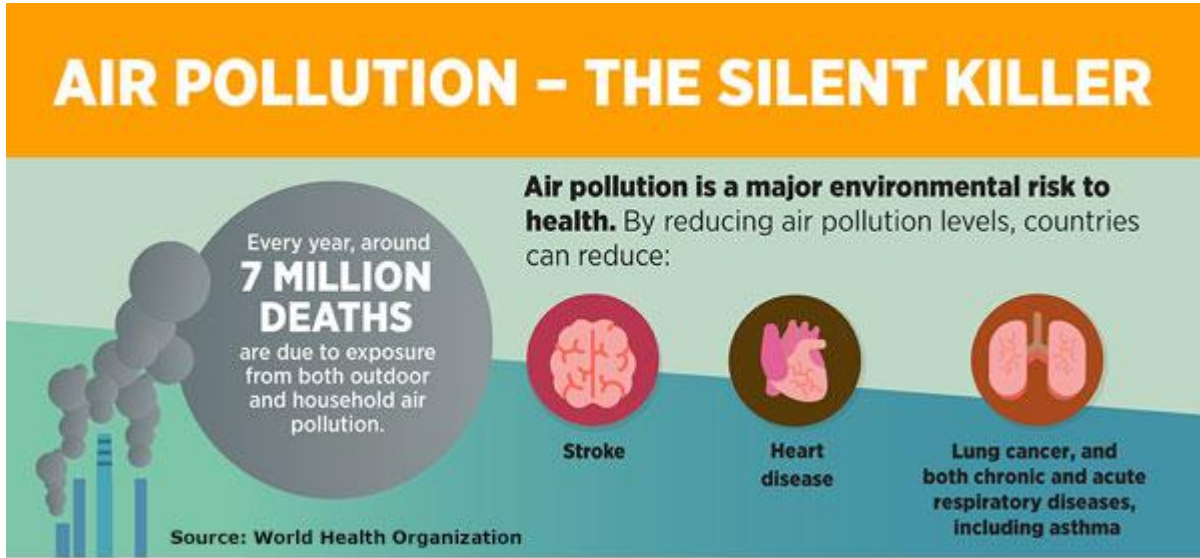› Semiconductor Manufacturing and Packaging
› Computing & Memory
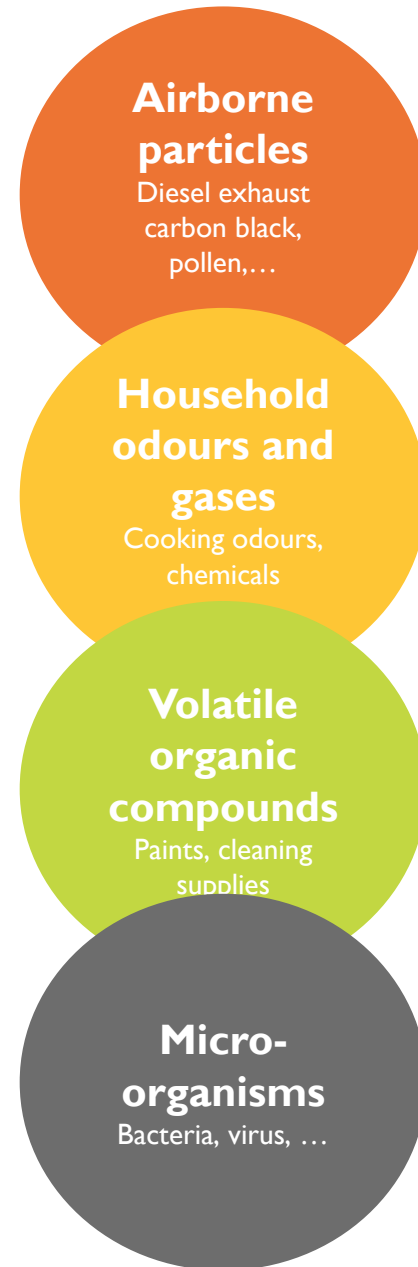
190 custom projects per year
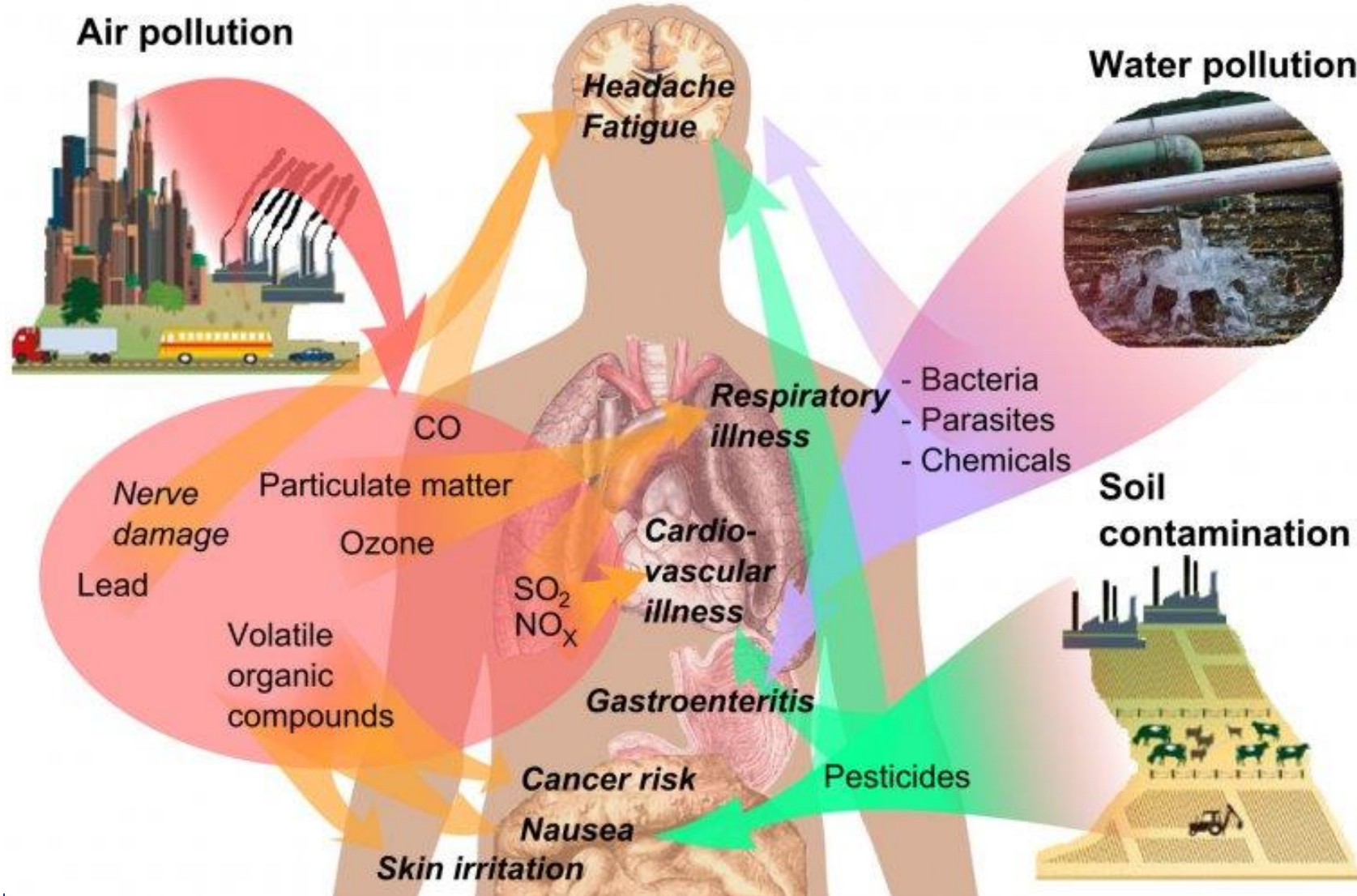
A bit of context

AIR POLLUTION – THE SILENT KILLER

AIR POLLUTION – THE SILENT KILLER

Air pollution is a major environmental risk to health. By reducing air pollution levels, countries can reduce:

Every year, around **7 MILLION DEATHS** are due to exposure from both outdoor and household air pollution.

Stroke

Heart disease

Lung cancer, and both chronic and acute respiratory diseases, including asthma

Source: World Health Organization

World Health Organization

Outside pollution

Better there?

Airborne particles
Diesel exhaust carbon black, pollen,…

Household odours and gases
Cooking odours, chemicals

Volatile organic compounds
Paints, cleaning supplies

Micro-organisms
Bacteria, virus, …

Health effects of pollution

Air pollution

Water pollution

Headache
Fatigue

Nerve damage
Particulate matter
CO
Ozone
Lead
SO_2 NO_X
Volatile organic compounds

Respiratory illness

Cardio-vascular illness

Gastroenteritis

Cancer risk

Nausea

Skin irritation

- Bacteria
- Parasites
- Chemicals

Soil contamination

Pesticides

Air pollution could have many different impacts on health:

- Immediate impact with headache, fatigue and even asphyxia (with **CO** or **CO_2**)
- Medium to long term impact with **VOC** or particulate matter, leading to cancer or respiratory diseases

PARTICULATE MATTER
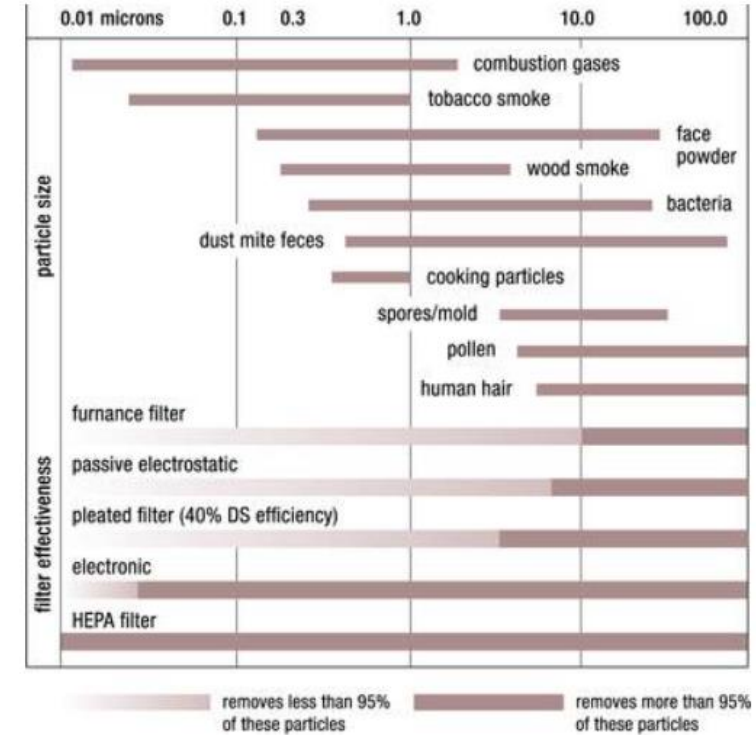
Complex mixture of solid particles and liquid droplets

Nose and mouth can stop **>10µm** diameter particles
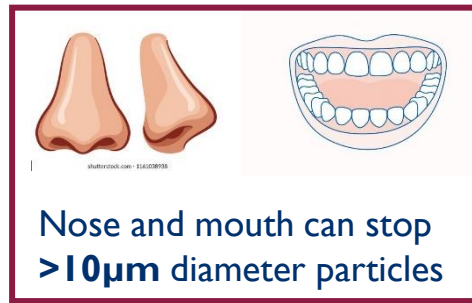
Suspended particulate matter with a diameter **<10µm** → **BREATHABLE !**

PM_{10}

$PM_{2.5}$

$PM_{1.0}$

$PM_{0.1}$
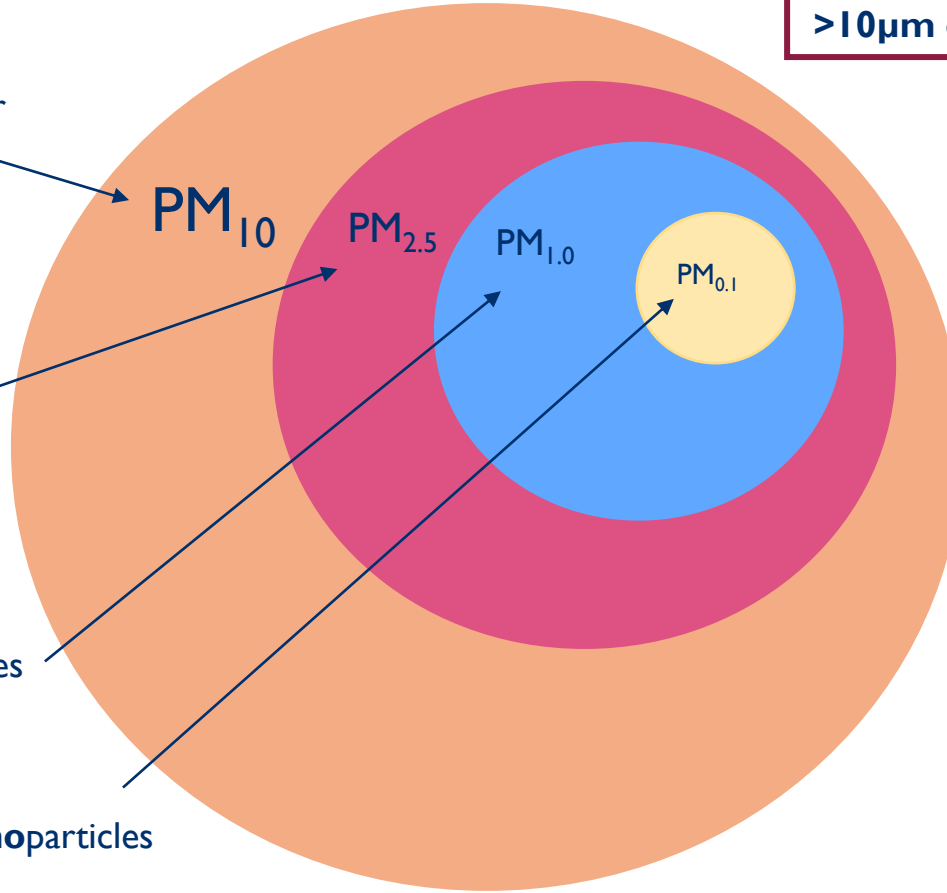
Fine particles : can enter the pulmonary alveolus

Ultrafine particles can enter the bloodstream

Nanoparticles

Figure 1: Size range of common pollutant sources (adapted from John Wiley and Sons, Best Practices Guide to Residential Construction, 2006).

© 2006 John Wiley & Sons, Best Practices Guide to Residential Construction

Because of the different PM sizes and physico-chemical composition, the impacts on health and environment are numerous and varied.

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WHY DO WE NEED GAS SENSORS?

→ **Detect**

→ **Measure**

→ **Control**

Health

Cancer biomarkers in exalted gas

Asthma (pollen, …)

Virus presence (Covid-19,…)

Air quality (homes, in-cabin…)

Outdoor air quality

Capnography (CO2 level)

Food safety

Gas leakage

CO2 level

Anesthesia instruments (Mix of gas, ventilation, …)

Monitoring

Safety

Particle level

Ventilators (O2, CO2 level)
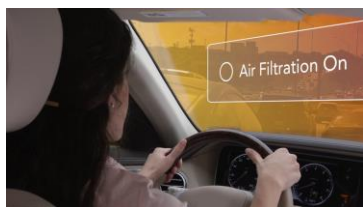
COVID-19 AND INDOOR AIR QUALITY
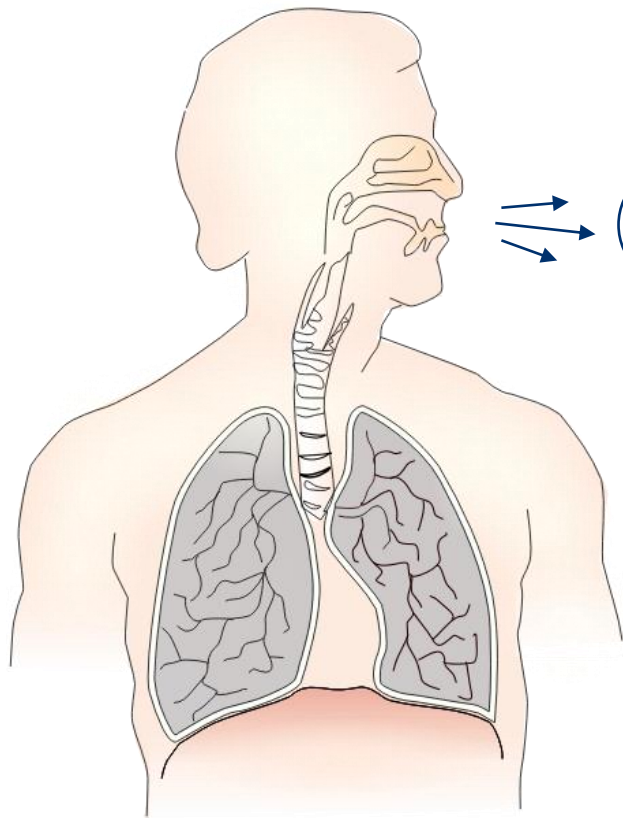
Covid-19 virion

Micro-droplet

INFECTED HUMAN

The size of the Covid-19 virion is approximately 100nm. So even with an accurate particle sensor, it can get quite difficult to measure the virus concentration in the air.

But when a covid-infected human sneezes, coughs, speaks or even breathes, Covid-19 virions are released into the air, as well as spit micro-droplets. Those tiny droplets are filled with Covid-19 virions and could potentially infect other people in the room.

The micro-droplets have different sizes :
- 100μm → they fall quickly onto the ground & surfaces as they are too heavy to propagate in the air
- 10μm and below → can propagate in an air flow and enter someone else's body

There are two ways to monitor the Covid-19 virion concentration is a room:

Particle sensors

The number of particles detected by a sensor is directly related to the number of micro-droplets in the air. Hence a particle sensor helps in managing the ventilation and indoor air quality, stopping the propagation of the virus. Particle sensors have been used in private and public facilities for:
- Air purifiers
- HVAC

CO_2 sensors

The more people exhale in a room, the more micro-droplets are spread in the air. And the more people exhale, the higher the CO_2 level is. So, there is a direct relation between the particle concentration, the level of CO_2 and the Covid-19 virion concentration in a room.
CO_2 sensors can therefore be used to monitor the level of CO_2 and warn users when it reaches a defined threshold.
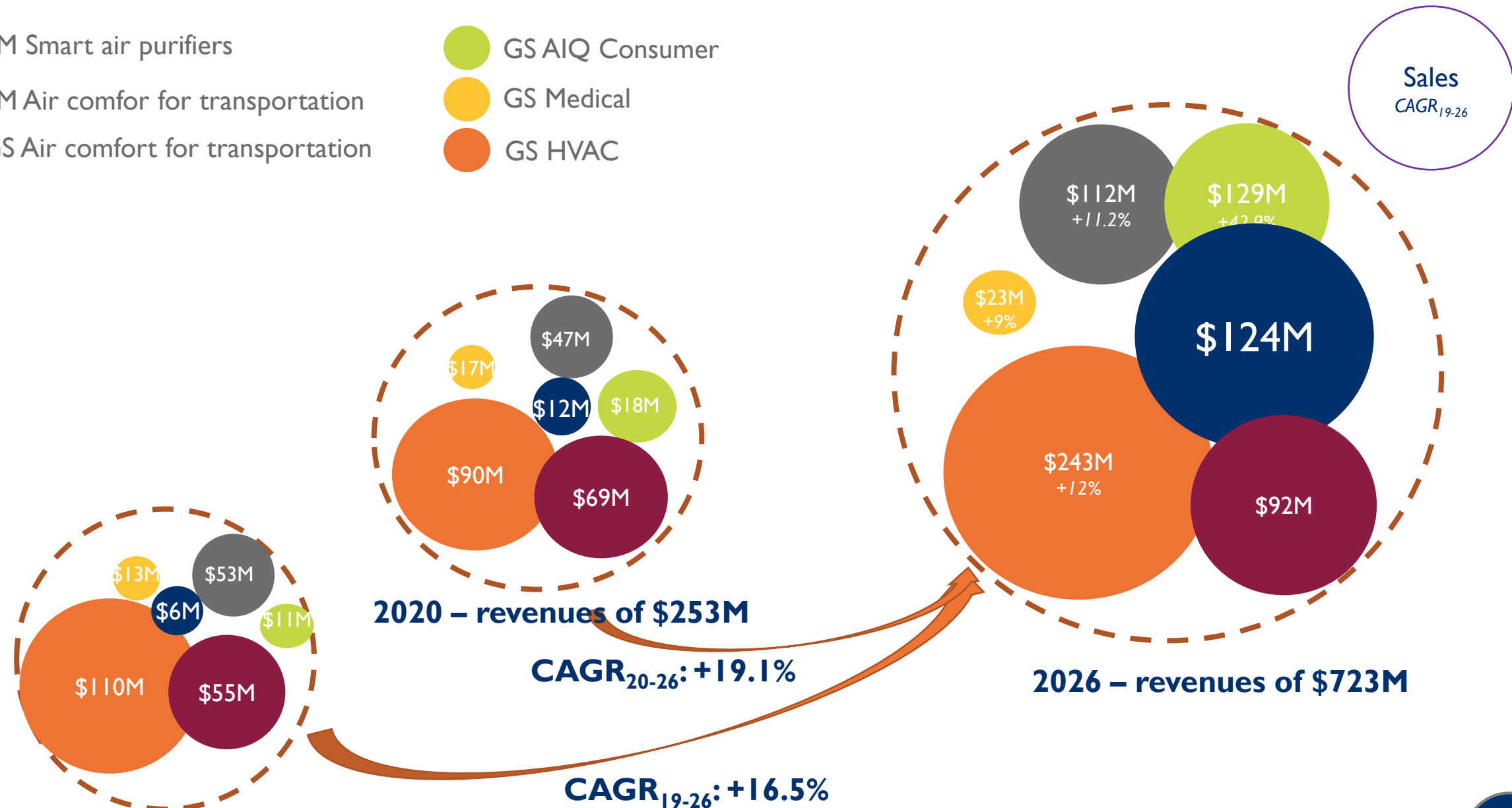
Market forecast and market trends
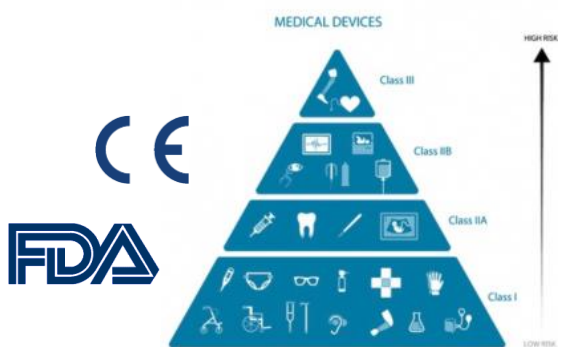
GAS SENSORS MARKET DYNAMICS BY APPLICATIONS

Legend:
- 🔴 PM Smart air purifiers
- 🔵 PM Air comfor for transportation
- ⚫ GS Air comfort for transportation
- 🟢 GS AIQ Consumer
- 🟡 GS Medical
- 🟠 GS HVAC

Sales
CAGR₁₉₋₂₆

2019 – revenues of $248M
- $110M
- $55M
- $53M
- $13M
- $6M
- $11M

2020 – revenues of $253M
- $90M
- $69M
- $47M
- $17M
- $12M
- $18M

CAGR₂₀₋₂₆: +19.1%

CAGR₁₉₋₂₆: +16.5%

2026 – revenues of $723M
- $243M *+12%*
- $124M
- $112M *+11.2%*
- $129M *+42.9%*
- $92M
- $23M *+9%*

Gas and particle sensor markets are highly regulated

Each market has different regulations

Medical
ISO 13485

Transportation
Emission standards

HVAC
Countries regulate CO_2 level

Environment
EU Commission
World Health Organization (WHO)

REGULATION

"To ensure proper ventilation is maintained throughout the school year, all classrooms shall be equipped with a carbon dioxide monitor"
Assembly Bill No. 841

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AIR QUALITY AND PEOPLE SAFETY

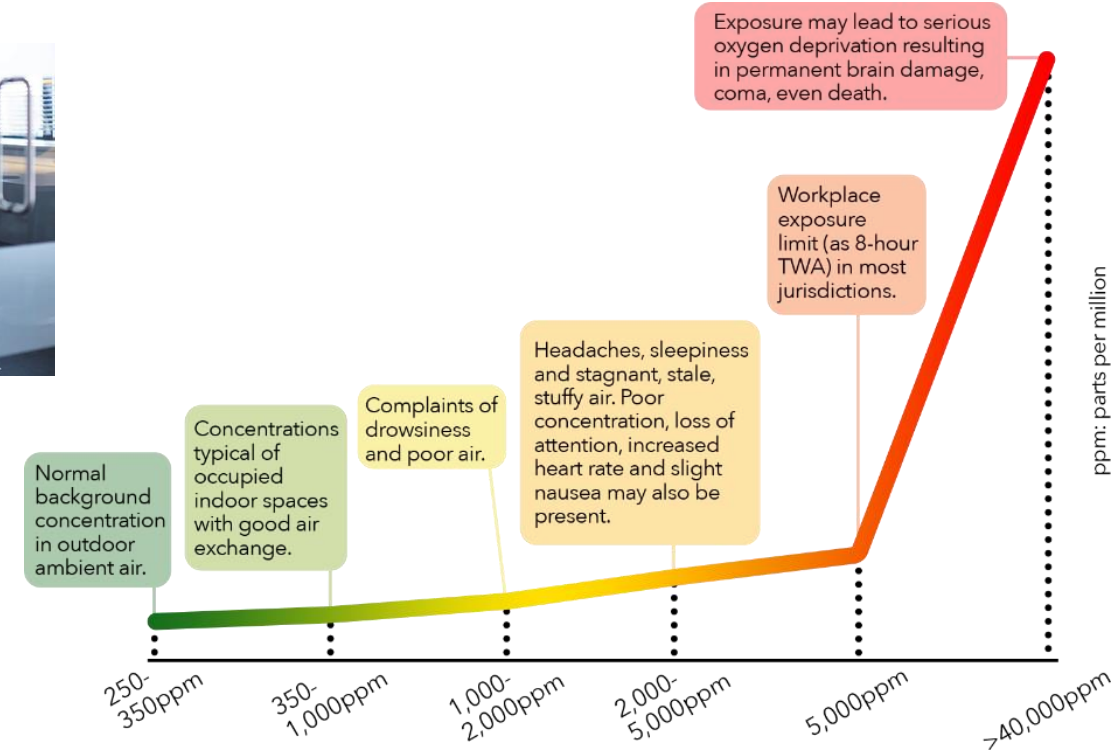## Air quality monitors in classrooms and offices

CALIFORNIA ENERGY COMMISSION

"To ensure proper ventilation is maintained throughout the school year, all classrooms shall be equipped with a carbon dioxide monitor"
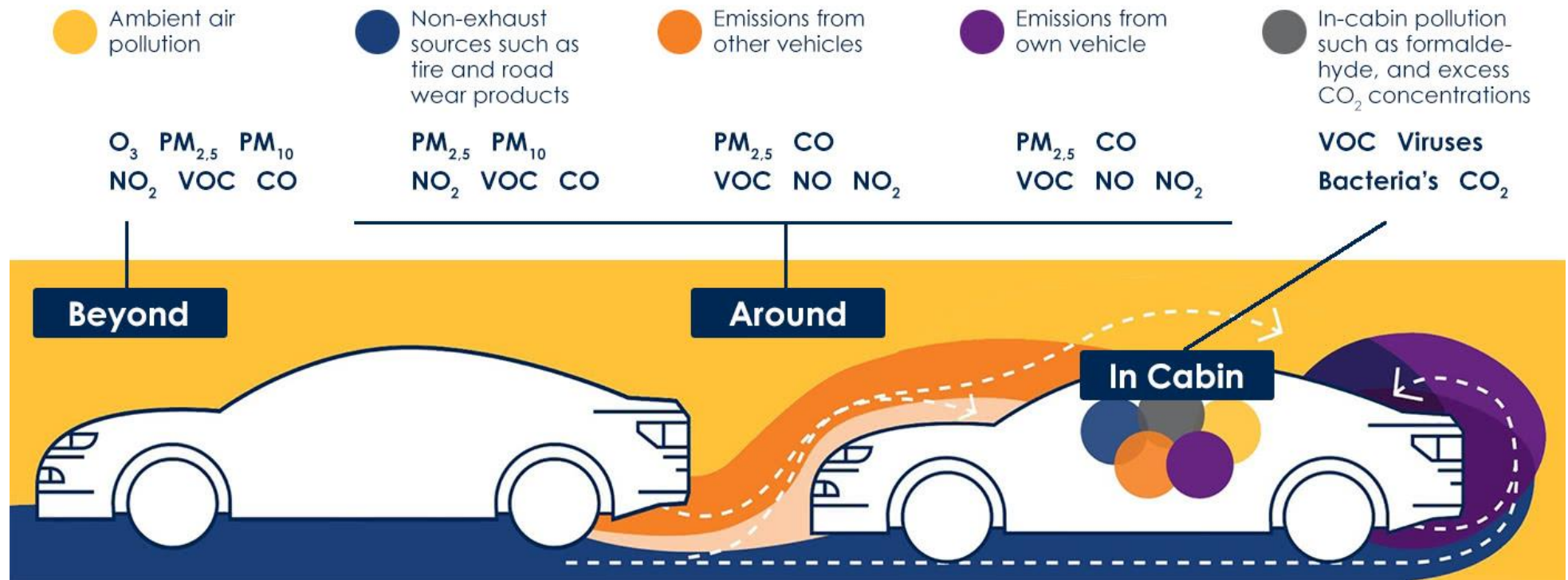**Assembly Bill No. 841**

Courtesy: Sensirion

ppm: parts per million

- **Normal background concentration in outdoor ambient air.** (250-350ppm)
- **Concentrations typical of occupied indoor spaces with good air exchange.** (350-1,000ppm)
- **Complaints of drowsiness and poor air.** (1,000-2,000ppm)
- **Headaches, sleepiness and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present.** (2,000-5,000ppm)
- **Workplace exposure limit (as 8-hour TWA) in most jurisdictions.** (5,000ppm)
- **Exposure may lead to serious oxygen deprivation resulting in permanent brain damage, coma, even death.** (>40,000ppm)

The more people / students there are, the higher the CO_2 concentration and the more micro-droplets are in the air
→ Reduced capability to focus on work, leading to headaches, nausea and blurred vision
→ Increased opportunity for viruses to infect many people rapidly. So, the Covid-19 crisis boosted the demand for air quality monitors in classrooms.

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AUTOMOTIVE - IN CABIN AIR QUALITY

Ambient air pollution

O_3 $PM_{2.5}$ PM_{10}
NO_2 VOC CO

Non-exhaust sources such as tire and road wear products

$PM_{2.5}$ PM_{10}
NO_2 VOC CO

Emissions from other vehicles

$PM_{2.5}$ CO
VOC NO NO_2

Emissions from own vehicle

$PM_{2.5}$ CO
VOC NO NO_2

In-cabin pollution such as formaldehyde, and excess CO_2 concentrations

VOC Viruses
Bacteria's CO_2

Beyond

Around

In Cabin

Source: CabinAir Sweden

Origin of gases entering the cabin are varied:

- From outside: air pollution, exhaust gas in traffic jams or in closed locations like basement car parks → leading to respiratory issues for drivers and passengers
    - Action from the gas sensors: inform driver, close ventilation flap automatically
- From inside: CO_2 level leading to headache and drowsiness. Odors, in the context of public transportation.
    - Action from the gas sensors: inform driver (to open windows)
    - Action from the gas sensors: early detection of cleanliness issues

CONSUMER ORIENTED PRODUCTS FOR AIR QUALITY

Air quality monitors for indoor applications
Stronger demand from the Covid-19 pandemic

Air purifiers and HVAC for home. More and more concerned by consumer to avoid CO_2 and VOC at home
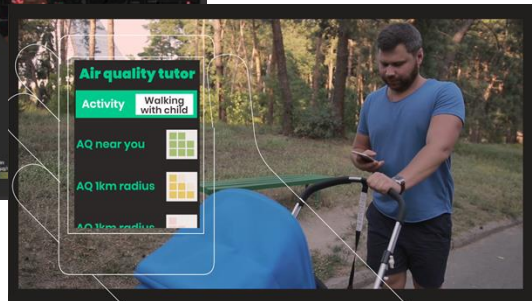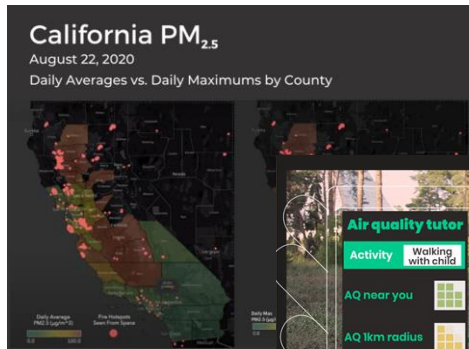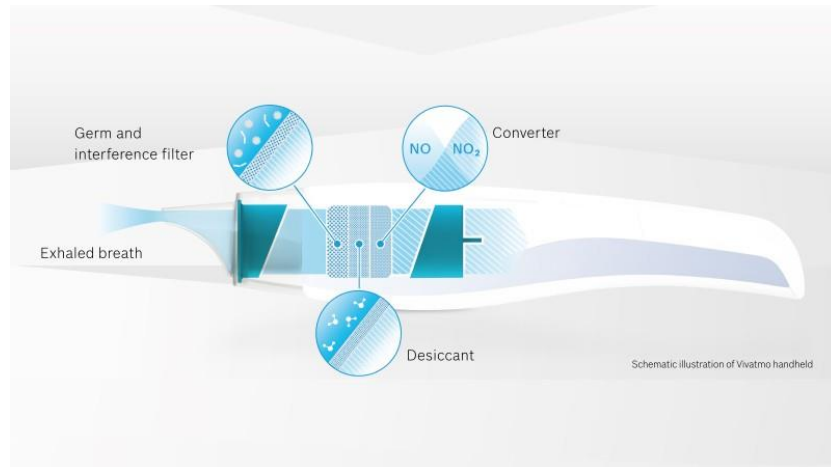
Wearables or smartphones - Personal mobile gas sensor station with data shared via apps & the cloud to get mapping of the air quality.

MEDICAL TRENDS – DIAGNOSTICS FROM EXHALED GAS

Vivatmo Me personal breath analyzer for asthma, detecting NO_2 with high specificity; Source: Bosch

Details on Vivatmo Me analyzer; Source: Bosch

Gases exhaled could contain a lot of information

- Bosch healthcare has developed breath analyzers to prevent from asthma attack using NO2 gas detection, sign of inflammation

- Several R&D centers and companies try to develop early and non-invasive diagnostic methods through VOCs exhaled

Human breath typically contains ~200 VOC's

Gas (Normal level)	Disease
Acetone *(480 ppb)*	Diabetes
Ammonia *(830 ppb)*	Kidney malfunction
Isoprene *(110 ppb)*	Cholesterol
Methylated Hydrocarbons	Breast cancer
Sulfur compounds	Liver disease
Toluene	Lung cancer
Nitrous Oxide (NO) *(40 ppb)*	Asthma
H_2S *(100 ppb)*	Helitosis (bad breath)
Ethanol *(200 ppb)*	Alcohol
Ethane	Inflammatory diseases
Methanol *(470 ppb)*	Liver Cirrhosis

Gas sensor technology and focus on MEMS

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Major focus

Non-exhaustive list
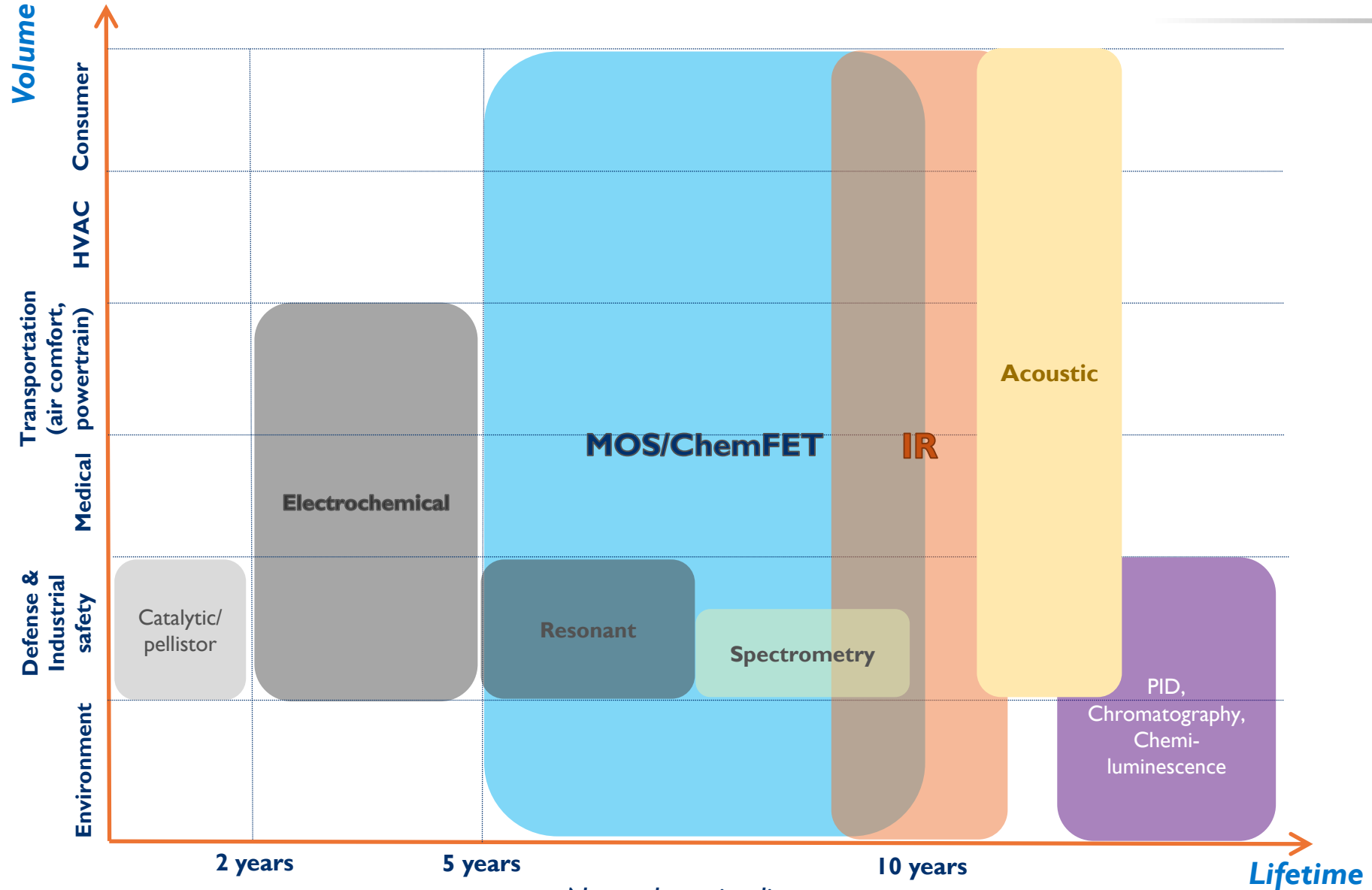
MAIN GAS DETECTED BY TECHNOLOGIES

MOS/ChemFET	Wide range of gases – VOCs, alcohol in breath, CO, CO_2, …
Catalytic/pellistor	Flammable, toxic gases, hydrocarbons, …
Electrochemical	Very wide range of gases, good for toxic gases, …
IR	CO_2, CH_4, explosive gases, …
Acoustic	CO_2 mainly, H_2S, explosive gas…
PID, Chromatography, Chemi-luminescence	Wide range, mainly VOCs, …
Spectrometry	Mainly VOCs, …
Resonant	CO, CO_2, Hydrocarbons, several industrial gases …

GAS-SENSING TECHNOLOGIES - COMPARISON

There is no "universal" solution for all possible applications

Sensitivity axis (ppb to ppm):
- Acoustic
- Resonant
- Pellistor
- μGC
- ChemFET
- NDIR
- Electrochemical
- MOS

Response time axis (10sec to 120sec):
- ChemFET
- Pellistor
- Resonant
- Electrochemical
- Acoustic
- μGC
- NDIR
- MOS

ASP axis ($1 to $10k):
- Resonant
- Pellistor
- Acoustic
- MOS
- Electrochemical
- ChemFET
- NDIR
- μGC
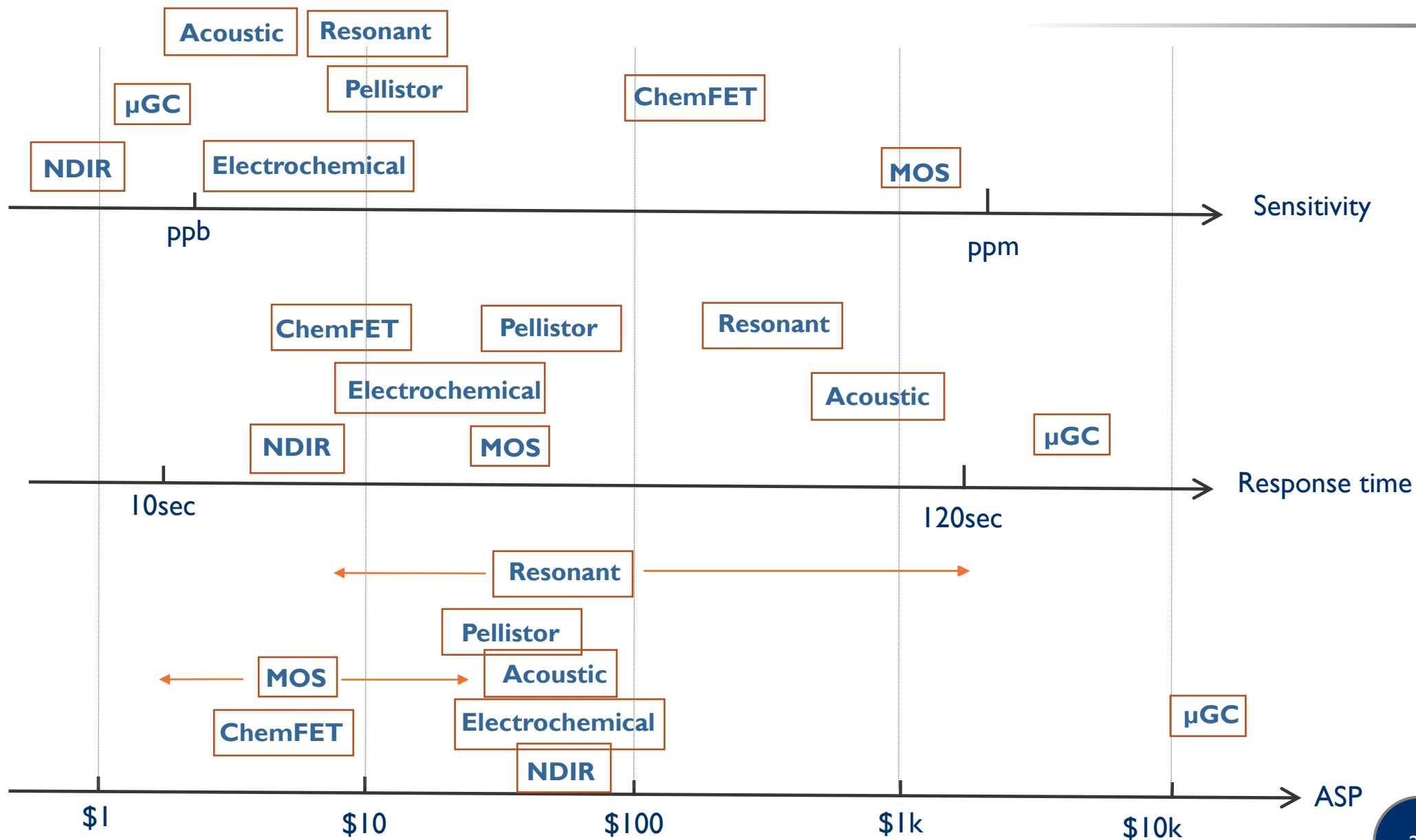
GAS SENSOR TECHNOLOGIES FOR MEDICAL APPLICATIONS

Medical machines like ventilators, anesthesia equipment or spirometers are mainly using electrochemical / galvanic fuel cell based gas sensors
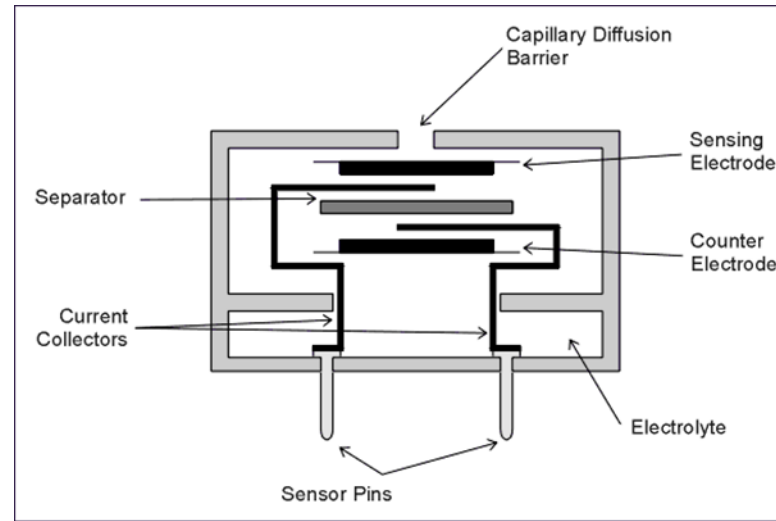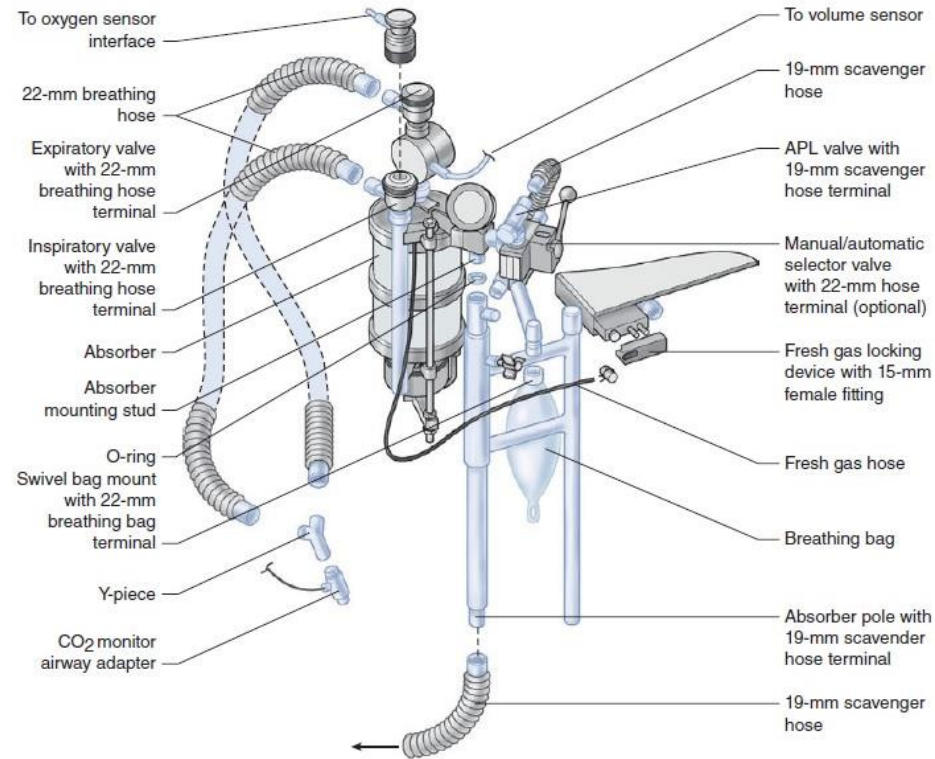
Pro:
- ppb sensitivity
- Good response time (<30s)
- Portable

Cons:
- Lifetime
- Drift issues

AI

Edge computing

Intelligence

Size (sub mm²) **& cost reduction**

Using Semicronductor and MEMS manufacturing for gas sensors and e-noses

Pressure

Humidity

Combo

VOC, CO_2

Temperature

CNT

Low power (10s of mW)

Printing process

Dual-channel for detection of multiple gases (NDIR)

Increased selectivity (to the ppb)

Multi-pixels for detection of multiple gases (MOS)

UFPM (<1μ)
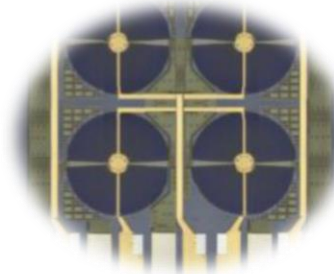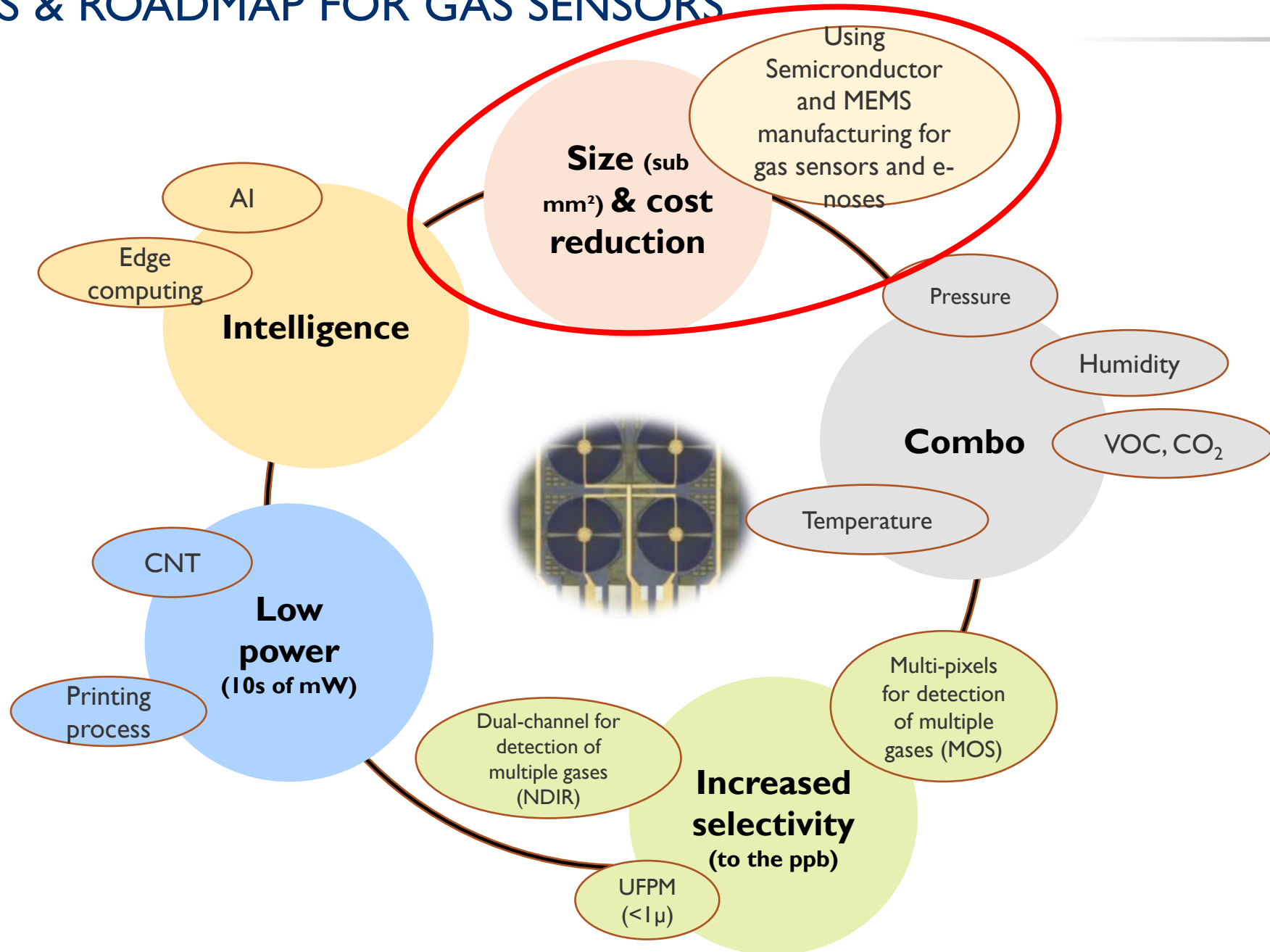
2020 GAS SENSOR STATUS - WHO IS DEVELOPING WHAT?

Major focus

Newcomers from the IC industry are entering the game
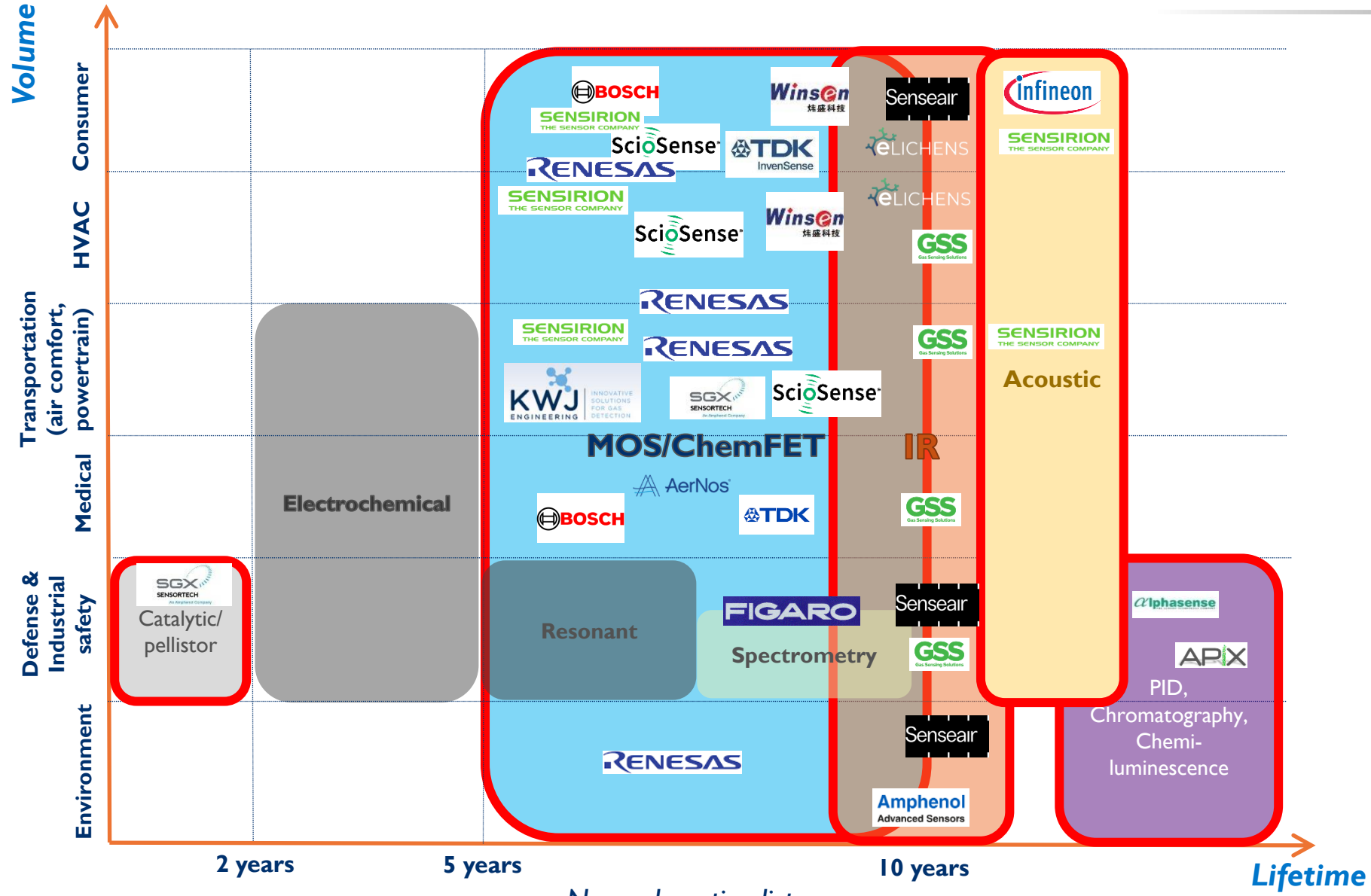
Non-exhaustive list

Semiconductor & MEMS

Principle of detection	MOS	PAS	NDIR (MEMS source)	BAW

Companies / Products

BOSCH — Invented for life
ScioSense
FIGARO
Winsen 炜盛科技
TOS8100

SENSIRION
Infineon

eLICHENS
Senseair
SenseAir S8

SOREXSENSORS

Non-exhaustive list of players

← Gas sensors →

← Particle sensors →
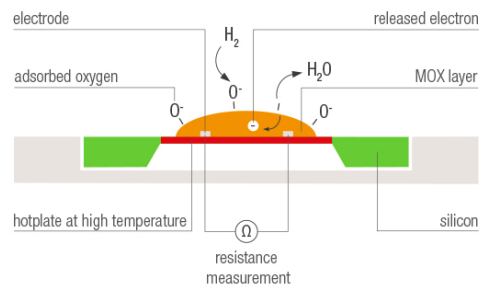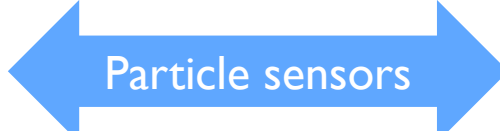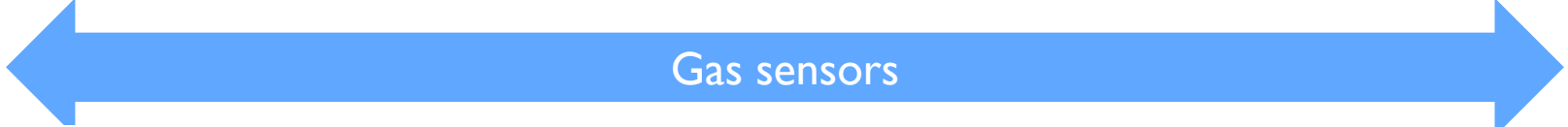
Courtesy of sensirion
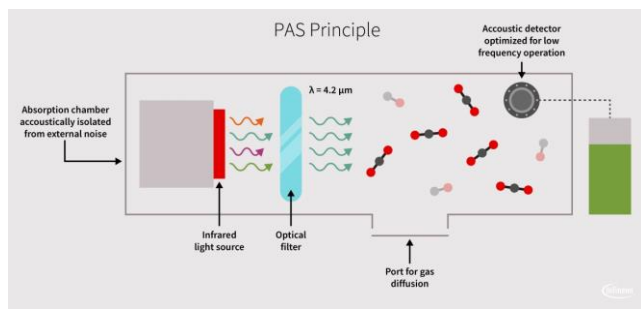
Courtesy of Infineon
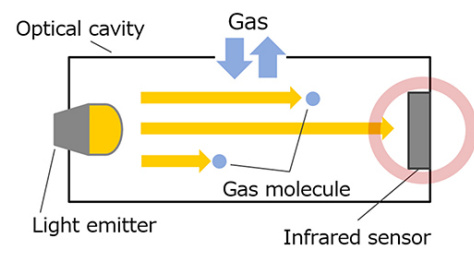
Courtesy of AKM
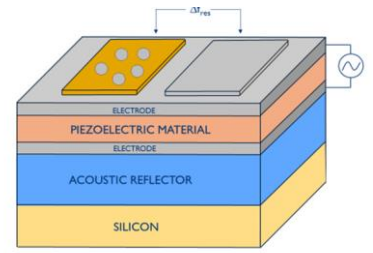
Courtesy of Sorex Sensors

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Microspectrometer for VOC detection
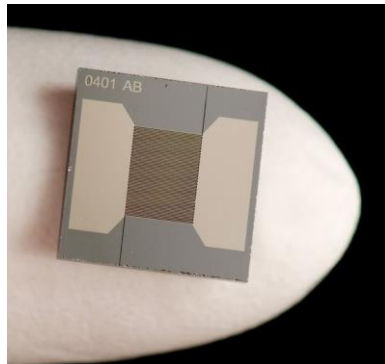

- The detection principle is based on FAIMS (Field-Asymmetric Ion Mobility Spectrometry) technology:
  - A silicon wafer is etched to form an inter-digitated ion separator
  - The UltraFAIMS chip is packaged in an HTTC package

- Specifications of UltraFAIMS chips:
  - Detection below part per billion (ppb)
  - FAIMS can be used to detect VOC in breath, urine and other clinical samples
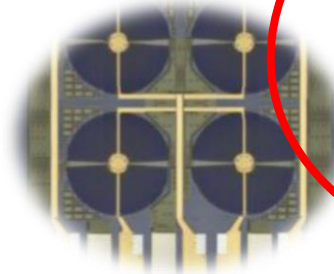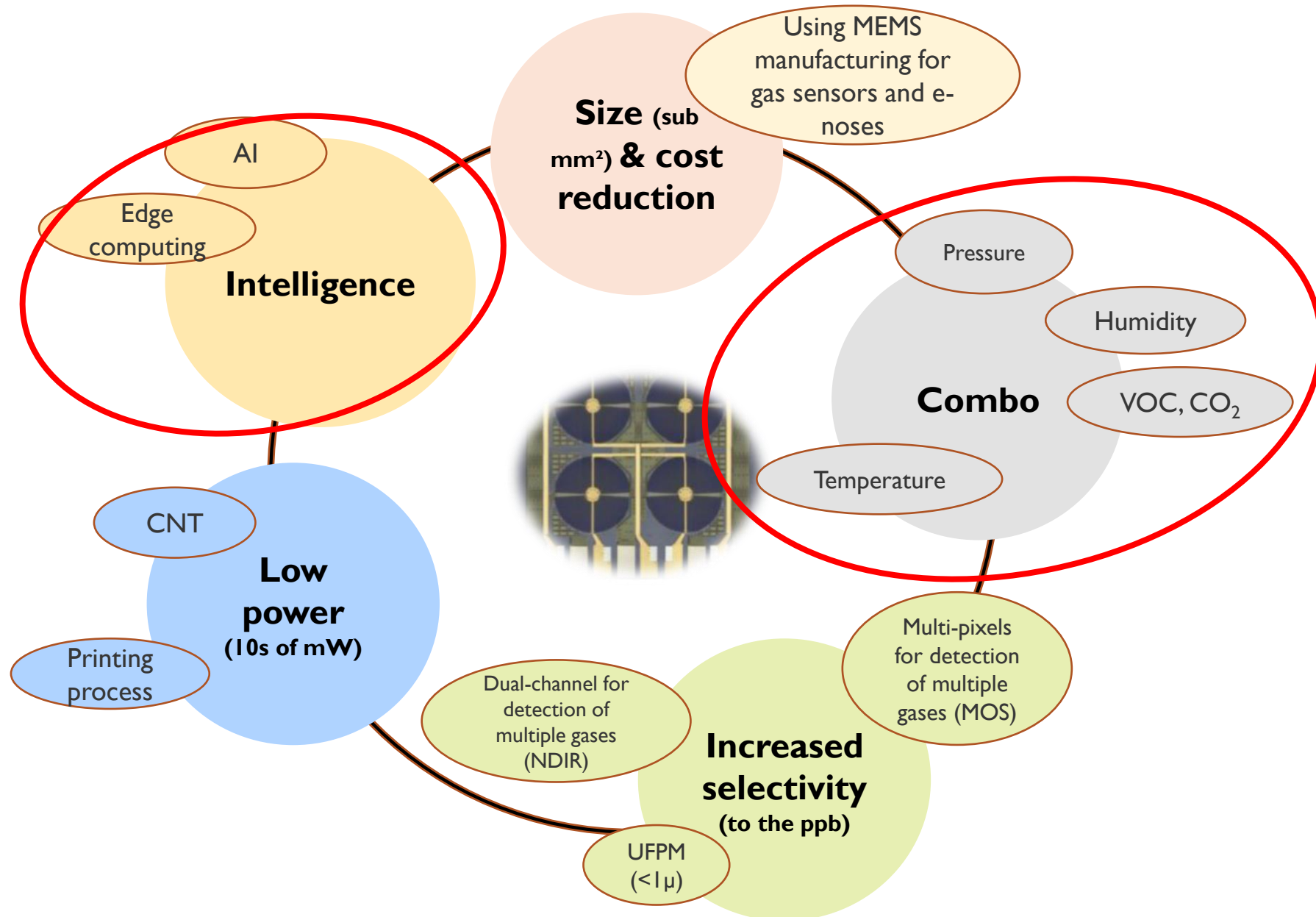 - High separation field: analytical width of 100µm.

UltraFAIMS chips

Detail on FAIMS chips
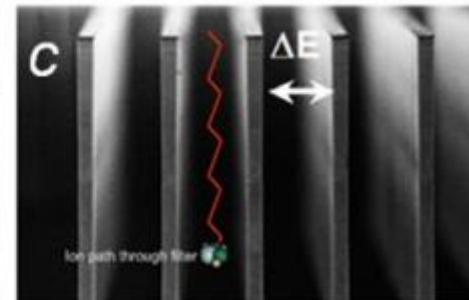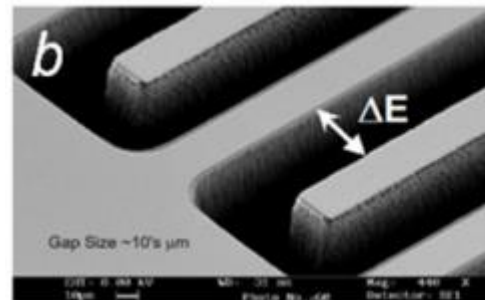
Inter-digitated structure

Credits: Owlstone Medical

Introduction to digital olfactometry

CHALLENGES & ROADMAP FOR GAS SENSORS

Size (sub mm²) & cost reduction

Using MEMS manufacturing for gas sensors and e-noses

Intelligence

AI

Edge computing

Combo

Pressure

Humidity

VOC, CO_2

Temperature

Low power (10s of mW)

CNT

Printing process

Increased selectivity (to the ppb)

Dual-channel for detection of multiple gases (NDIR)

Multi-pixels for detection of multiple gases (MOS)

UFPM (<1µ)

ENOSE TECHNOLOGIES

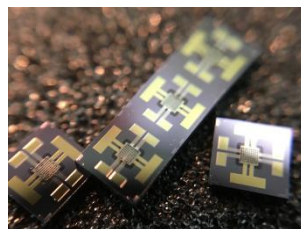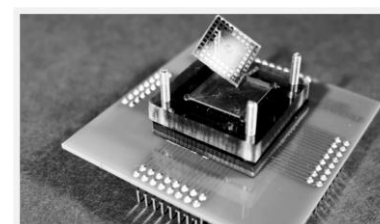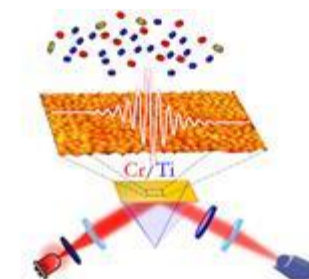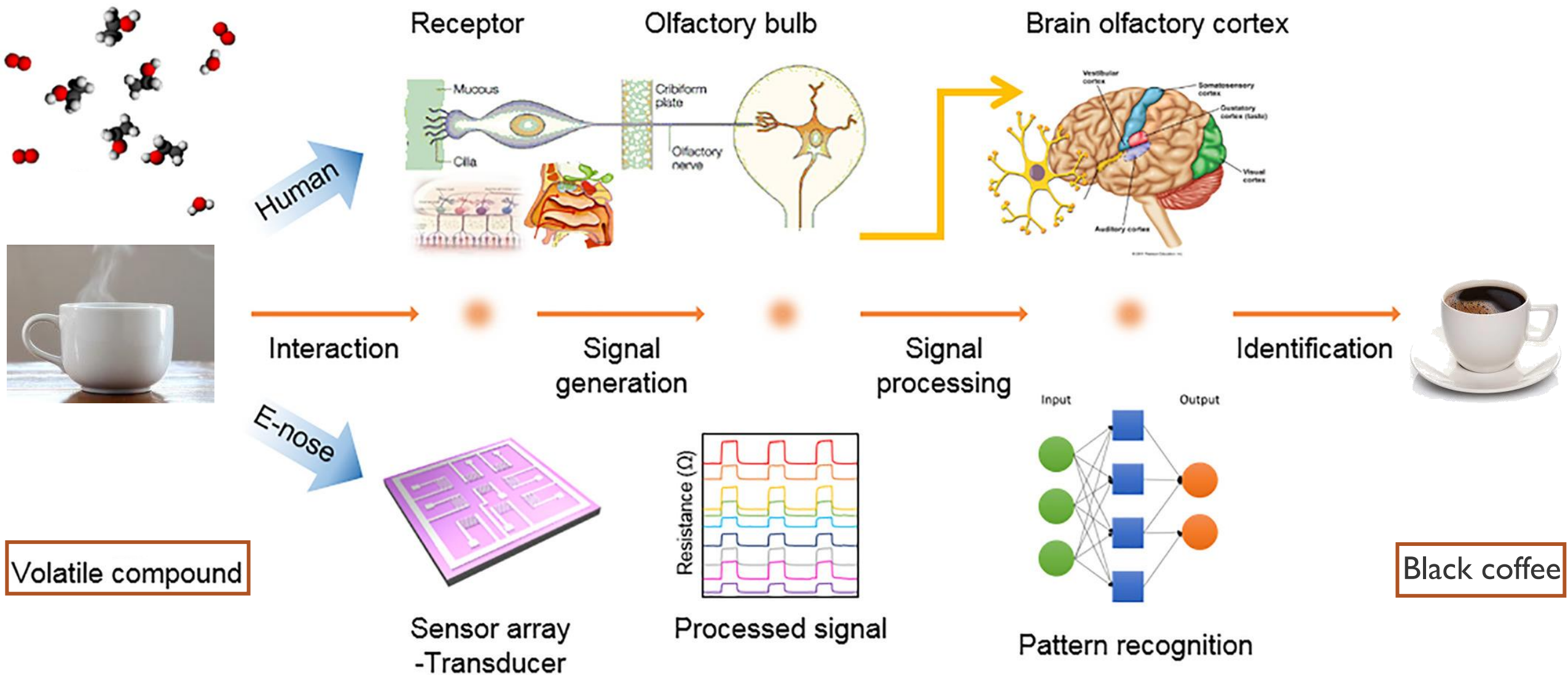| Chromatography & spectroscopy	Multi-sensors	Multi MOS sensors	Bio-based	Optical (Surface plasmon resonance)
• Laboratory equipment of high cost • Golden standard for VOC measurement • It requires time to perform analysis	• Typically integrating off-the-shelf sensors • Often combining T°C, humidity + specific gas • It gives a broad overview	• Typically using several sensors (less than 16) in a same system • Low number of sensors • Highly sensitive to humidity	• One of the latest technology for electronic noses • Use peptides, olfactory neurons,…	• Bio-based solution combined with an optical detection • Peptides are deposited on a prism • Odors captured form a pattern

DIGITAL OLFACTION PRINCIPLE

Receptor — Olfactory bulb — Brain olfactory cortex

Human

Interaction → Signal generation → Signal processing → Identification

E-nose

Volatile compound

Sensor array -Transducer — Processed signal — Pattern recognition

Black coffee

Source: National Research Foundation of Korea, readapted
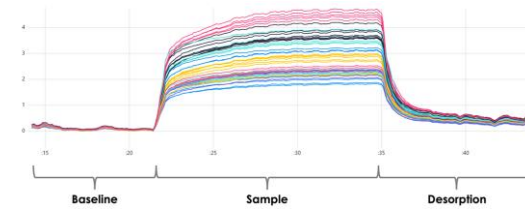
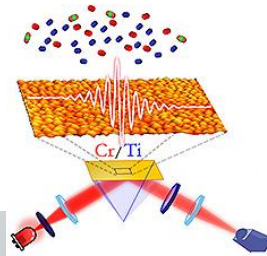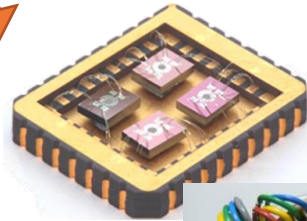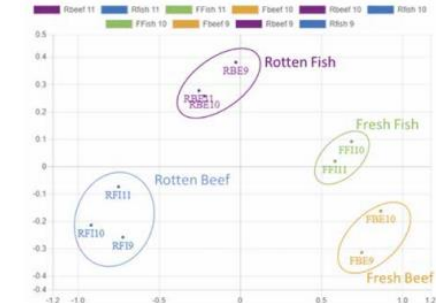# THE DIFFERENT PARTS OF DIGITAL ELECTRONIC NOSE

Hardware

Software

Sample

Processing: signature of gases

Courtesy of Aryballe

Results

Sensor arrays and detection principles are very different from one company to another:

- Array of multiple sensors
- Silicon photonic detection
- Protein based detection
- …

Data from sensors are processed to get gas fingerprints which are compared to a database (with pre-defined data), to translate it into results
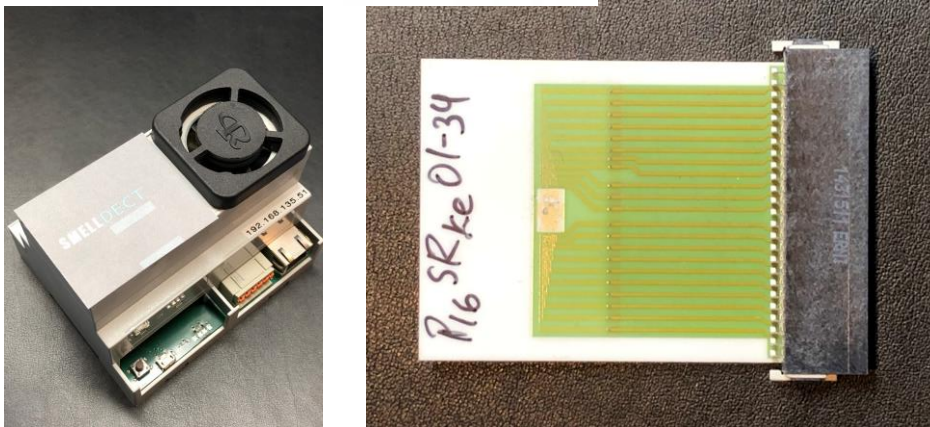
ELECTRONIC NOSE AND HEALTHCARE APPLICATIONS

Breathomix

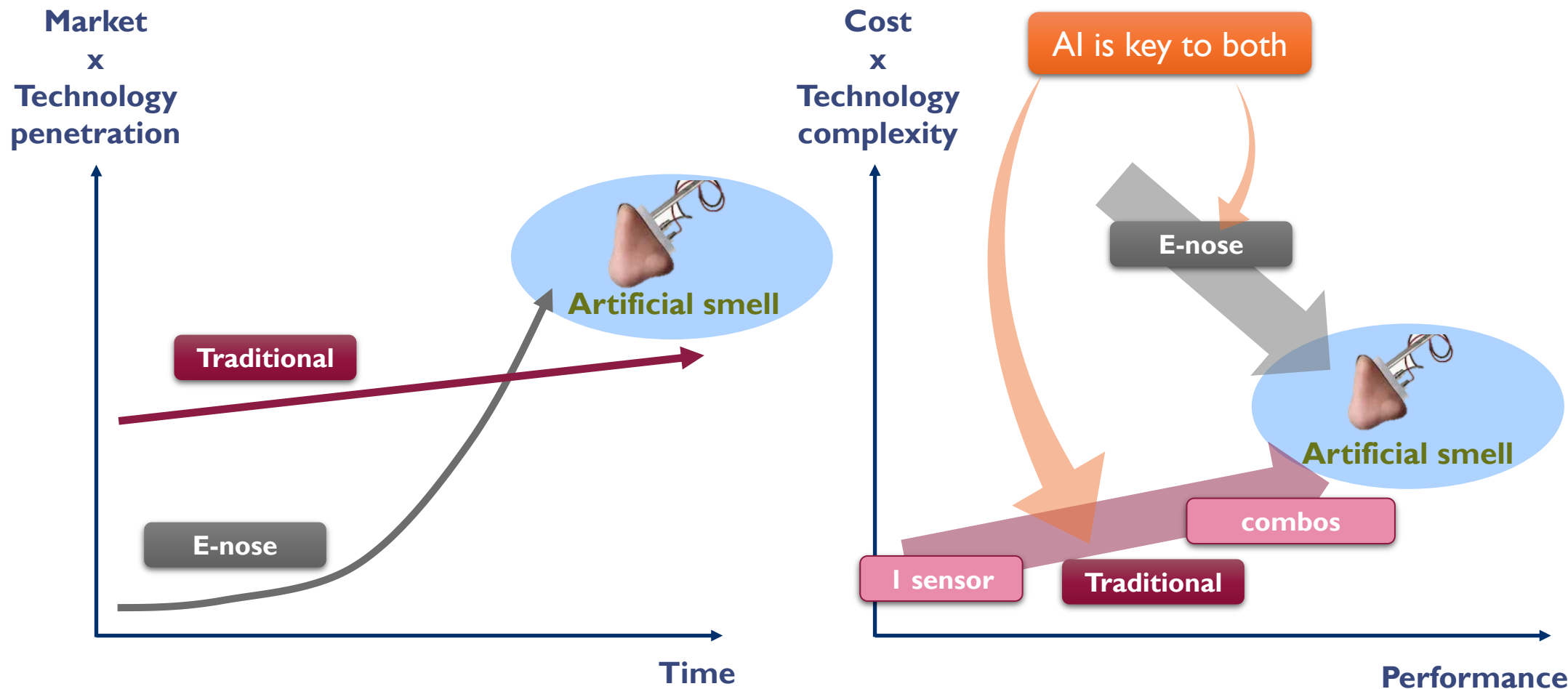- Spironose an e-nose to capture breath profiles (including diagnostic of Covid-19)
- 7 MOS sensors in the equipment (Arrows and circles)
- Direct measurement and results in less than 1mn

SMELLDECT

- Smelldect project is developing a portable odor analyzer.
- Sensor is based on inexpensive printed electronics (16 sub-sensors) + possible combination of other sensors
- Applications foreseen are Diabetes or liver/kidney issues

TWO PATHS FOR ARTIFICIAL SMELL

Market x Technology penetration

Traditional

E-nose

Artificial smell

Time

Cost x Technology complexity

AI is key to both

E-nose

Artificial smell

combos

I sensor

Traditional

Performance

Traditional — Moving from a sensor dedicated to one type of gas to combo sensors able to detect different types of gases

E-nose — E-noses are more complex than traditional sensors, using different technology (i.e., photonics), but also requiring more computing power

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Conclusions

CONCLUSIONS

- Air quality is still a major concern, with an acceleration at citizen level due to Covid-19 pandemic

- As gases and particles are sometimes difficult to detect, sensors are key devices to detect and measure presence and concentration

- We expect gas & particle sensor market related to air quality and medical applications to reach $723M in 2026 from $248M in 2019 with a $CAGR_{19-26}$ of +16.5%
  - The fastest segments are for indoor air quality in home and automotive.
  - Pure medical segment is more mature with regulation constraints

- Air quality systems at home, in cars or in wearables are benefiting from semiconductor- or MEMS-based technologies to reduce size, cost and power consumption

- Ecosystem of players is consolidating: new players in gas sensor market, strong merger and acquisitions

- Digital olfactometry is reaching more and more interest in medical field with the electronic nose approach or sensor combos. However, it is still a long way before using e-nose as standard tools.

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THANK YOU FOR YOUR ATTENTION!

Some slides from this presentation have been taken from the following reports:

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