# MEMS based sensors for indoor environment applications

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SINTEF

# ”The future is up to YOU!”

Thanks for your attention!

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# MiNaLab (Micro Nano Lab)

- Clean room area:
  SINTEF: 800 $m^2$
  University of Oslo: 600 $m^2$
- Micro environments, class 10
- A full silicon processing line for MEMS and radiation detectors
- Capacity of 10.000 6” wafers/year
- 35 employees at SINTEF
- Located at the campus of University of Oslo
- 240 MNOK invested in scientific equipment and laboratory infrastructure
- Funded by Norwegian Research Council and SINTEF

# MiNaLab offer

- One of two silicon processing lines in Norway. The only *independent one*.
- Offers the complete range from *design, process and device development through flexible prototyping and production*.

- **Production:**
  - Contract production of MEMS using processes not commercially available in industrial foundries.
  - Contract and foundry production of radiation detectors.
- **MEMS design center:**
  - SensoNor process = multiMEMS/microBUILDER
  - Other available foundry processes (TRONICS, pMUMPS)
  - In-house MEMS processes

# Key parameters for IAQ control

- Temperature
- $CO_2$
- Humidity
- Other gases (e.g. CO)

There is a strong demand for (networks of) low cost, low power, miniaturized multi sensors

# Solid state gas sensors

- Catalytic
- (Solid) Electrolyte Sensors
- Semiconductor
- Chemical sensors
- ISFET

CAPTEUR SENSORS

# Solid state sensors

Advantages: Low cost and small size

Disadvantages:
- Cross sensitivity
- Poisoning
- Influence by humidity
- Long term drift

CITY TECHNOLOGY

# Infrared (IR) gas sensing

**Advantages:**

- Selective
- Sensitive
- Non contact
- Reliable

**Disadvantages:**

- Inherently expensive (at least two components)
- Large size
- Requires drift compensation
- Complex packaging

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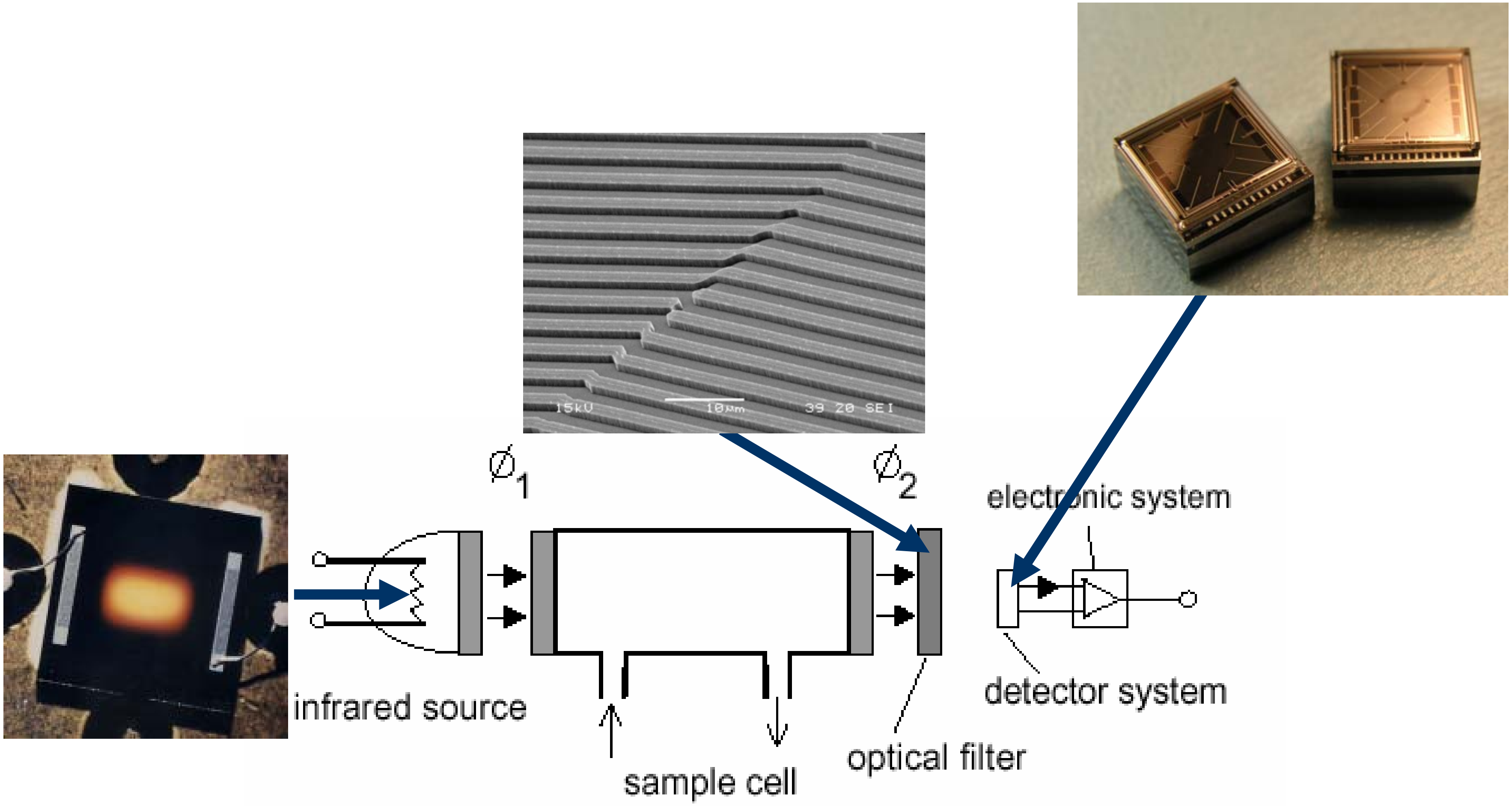
# MEMS components to complete sensors

- State-of-the-art IR examples (Nordic)
  - SenseAir-
  - Vaisala
  - Simrad Optronics
  - (OptoSense, kT Sensor)

- R & D examples (SINTEF)
  - PhotoAcoustic
  - ElectroAcoustic
  - Diffractive Optical Elements (CO-sensor)
  - Wireless
  - (Networks of ) Autonomous, wireless sensors

# MEMS devices for infrared gas sensing

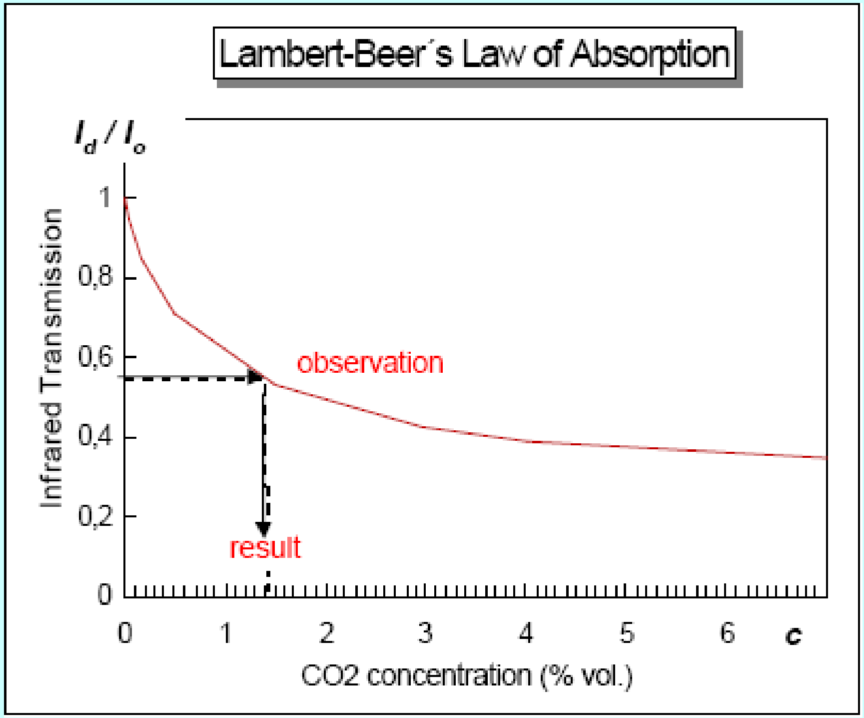


# SenseAir infrared IAQ sensors


Housing for industrial environments
150 x 86 x 46 mm


$CO_2$ sensor for embedded solutions

# SenseAir infrared IAQ sensors



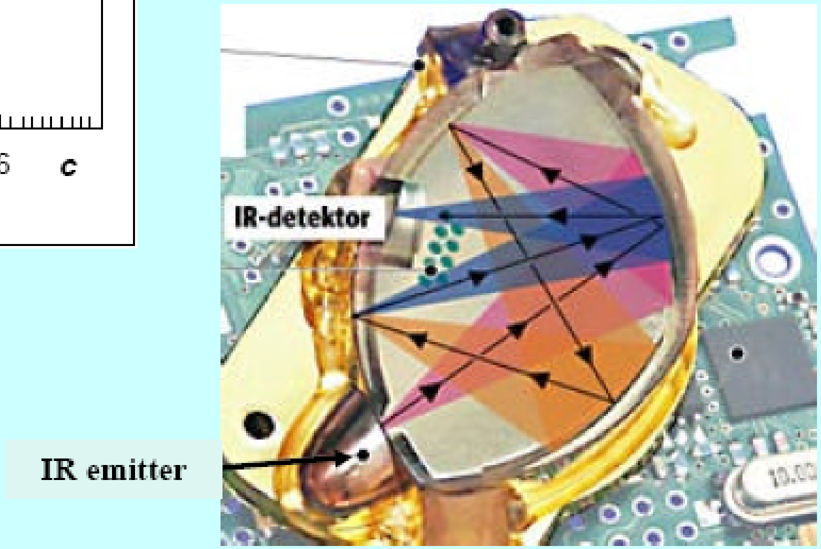

***Lambert-Beer's law:*** $I_d = I_o e^{-cds}$

$I_o$ is the incident light intensity,

$I_d$ the transmitted light intensity,

***d*** the optical path length

***s*** the molecular transition strength




The folded optical path results in a very long path length and a very sensitive, yet quite small, device!

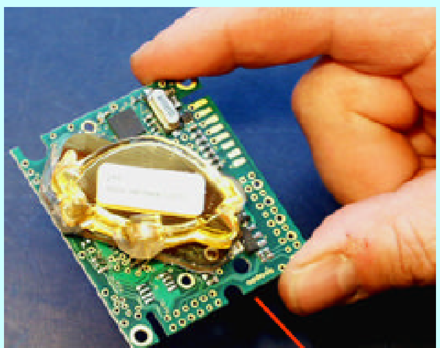
$CO_2$ ”engine” for embedded solutions

# SenseAir infrared IAQ sensors

## *Plug-in $CO_2$ sensor OEM modules*

LindinVent AB

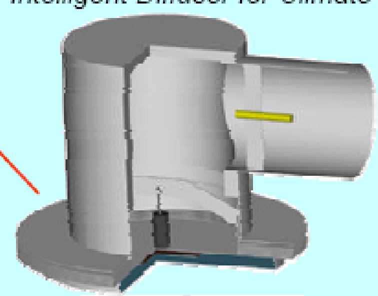
STORA ENERGIPRISET 2004



$CO_2$Engine®

Variable Air Volume supply

*IDCC - Intelligent Diffuser for Climate Control*



STORA INNEKLIMATPRISET

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# Autonomous Sensors

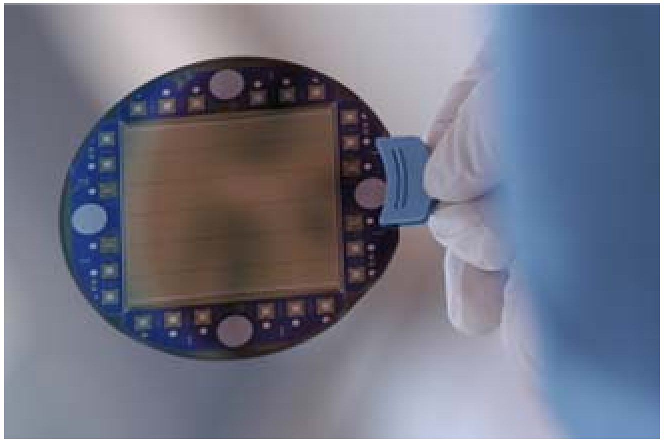
- Low power multi-sensor (MASCOT development)
- Low power, efficient nodes (EYES, e-CUBES)
  - Infineon, Thomas Lentsch et al. (*montie)
  - Chipcon/Texas Instr., Tunheim et al. (*montie)

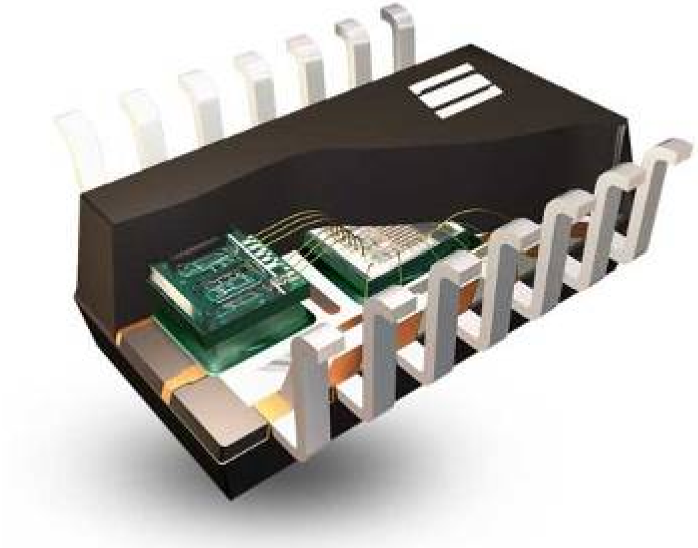
- Integrated System of Systems
  - IAQ/IEQ
  - Energy and Asset Management
  - Continuous Commisioning
  - Safety and Security
  - Built-in ”Smart Components”

# Micro ElectroMechanical Systems (MEMS)

Miniaturized systems that carry out several operations.
Typically: sensing, singnal conditioning and actuation

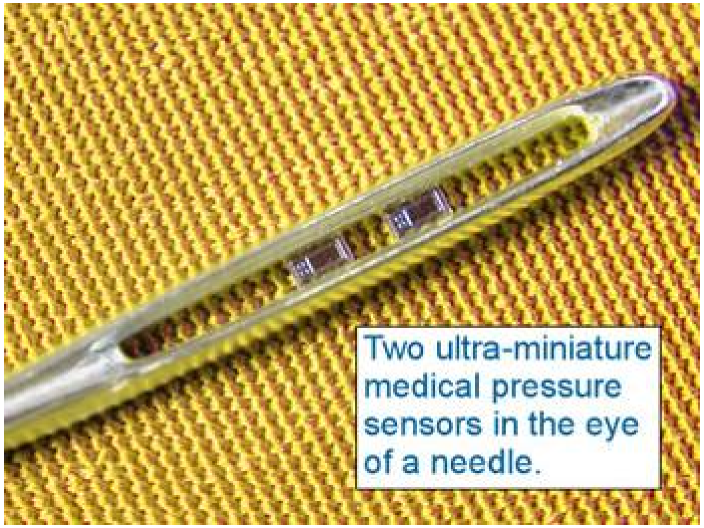
- **Micro sensor and/or actuator**
- **ASIC**
- **Packaging**



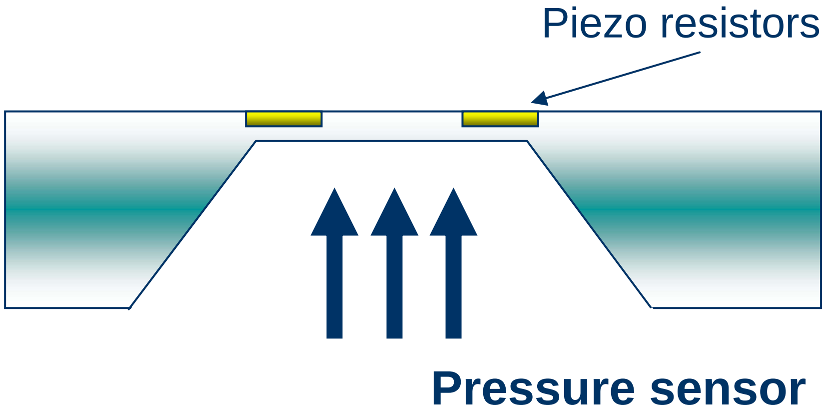


# Microsystem technology

- Utilizes the production technology developed for microelectronics to make sensors **(MEMS)**
  - Miniaturization
  - High volume, low cost production
  - Integration with electronics

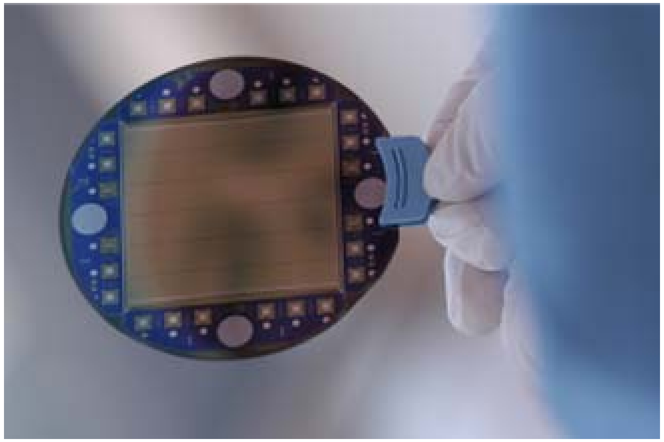



- Special processes
  - Micromachining
  - Functional thin films
  - Wafer stacking

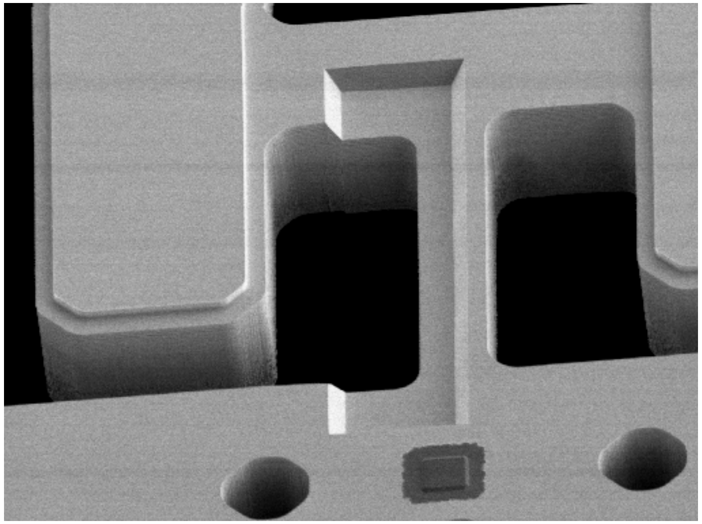


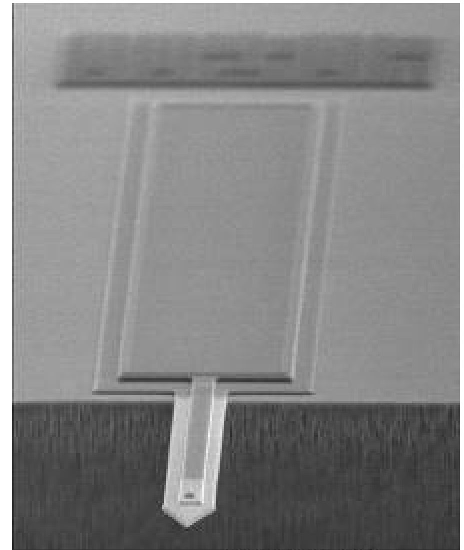
# Why silicon technology

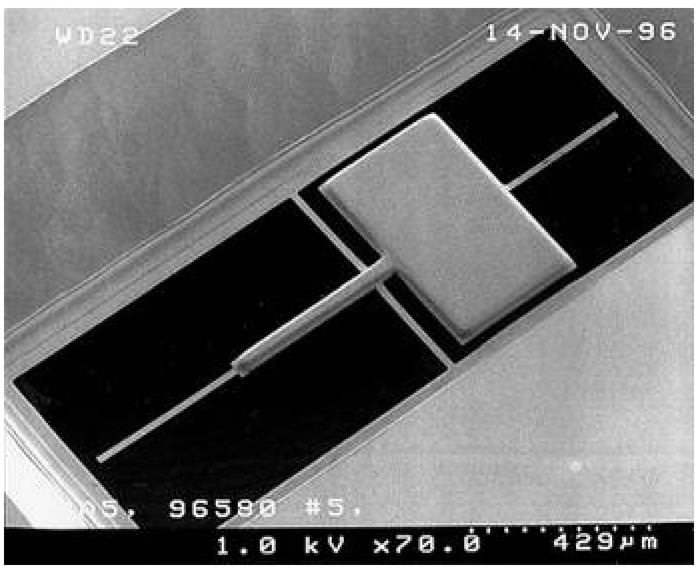
- Batch processing => low cost, high volume
- Well established production technology
- Advanced infrastructure, materials and design tools available
- Wide range of sensor principles available
- Silicon has attractive mechanical properties
- Integration is possible

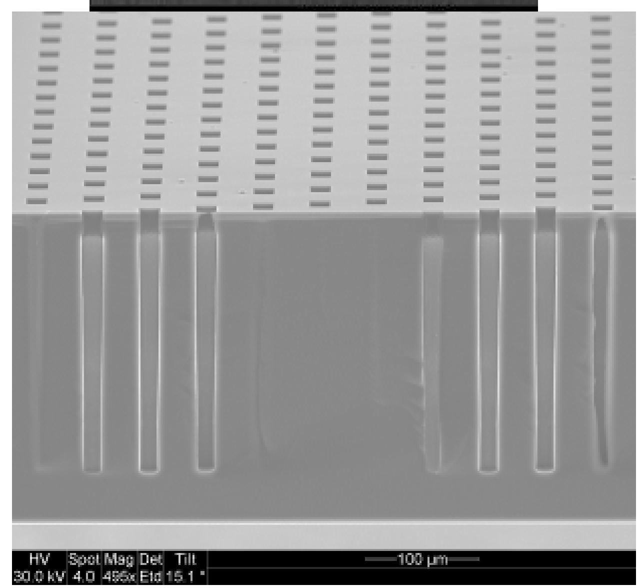


# Micromaching of 3D structures for mechanical sensors

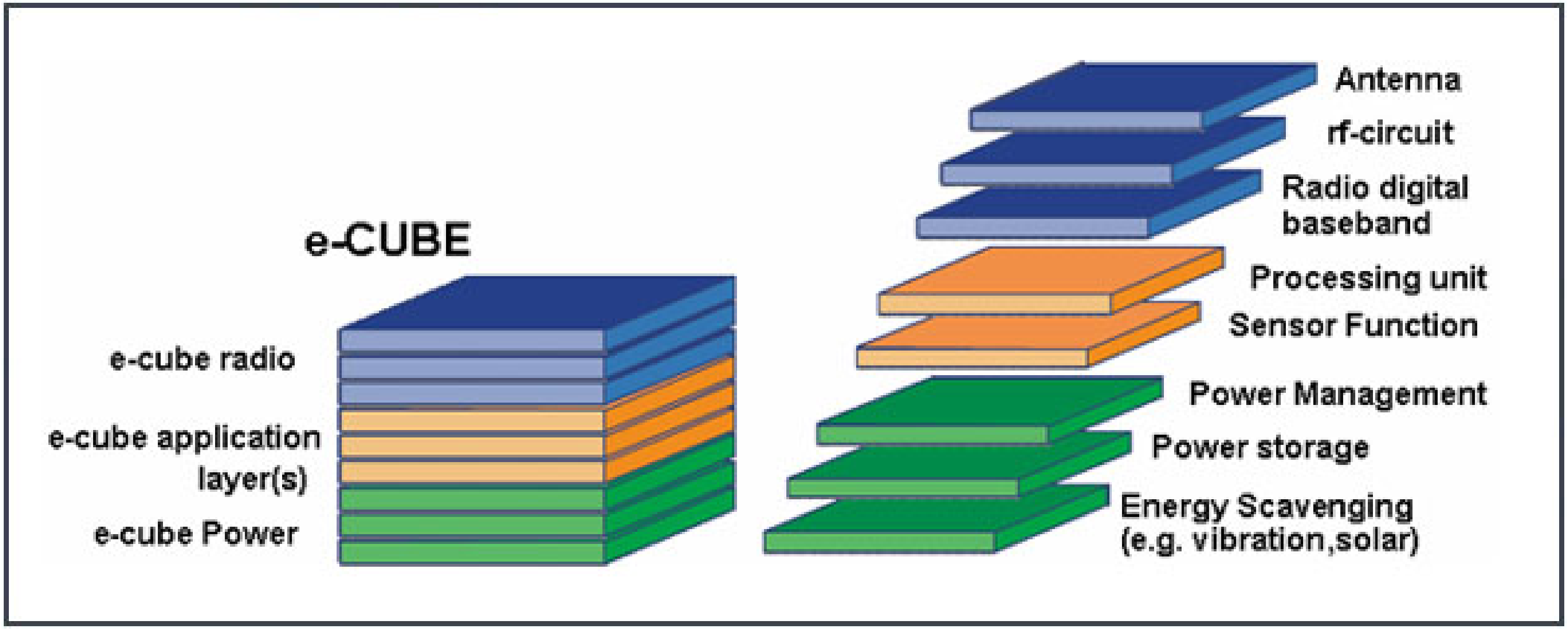




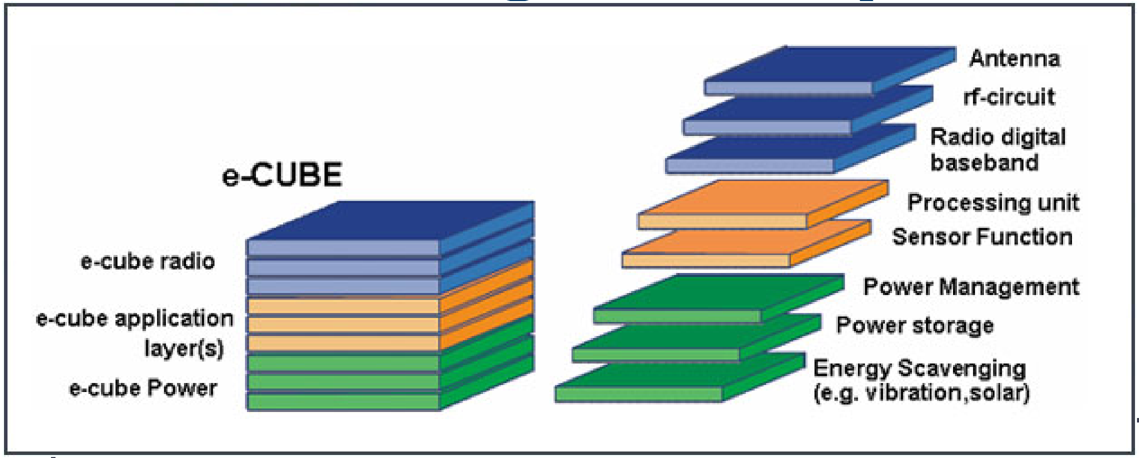


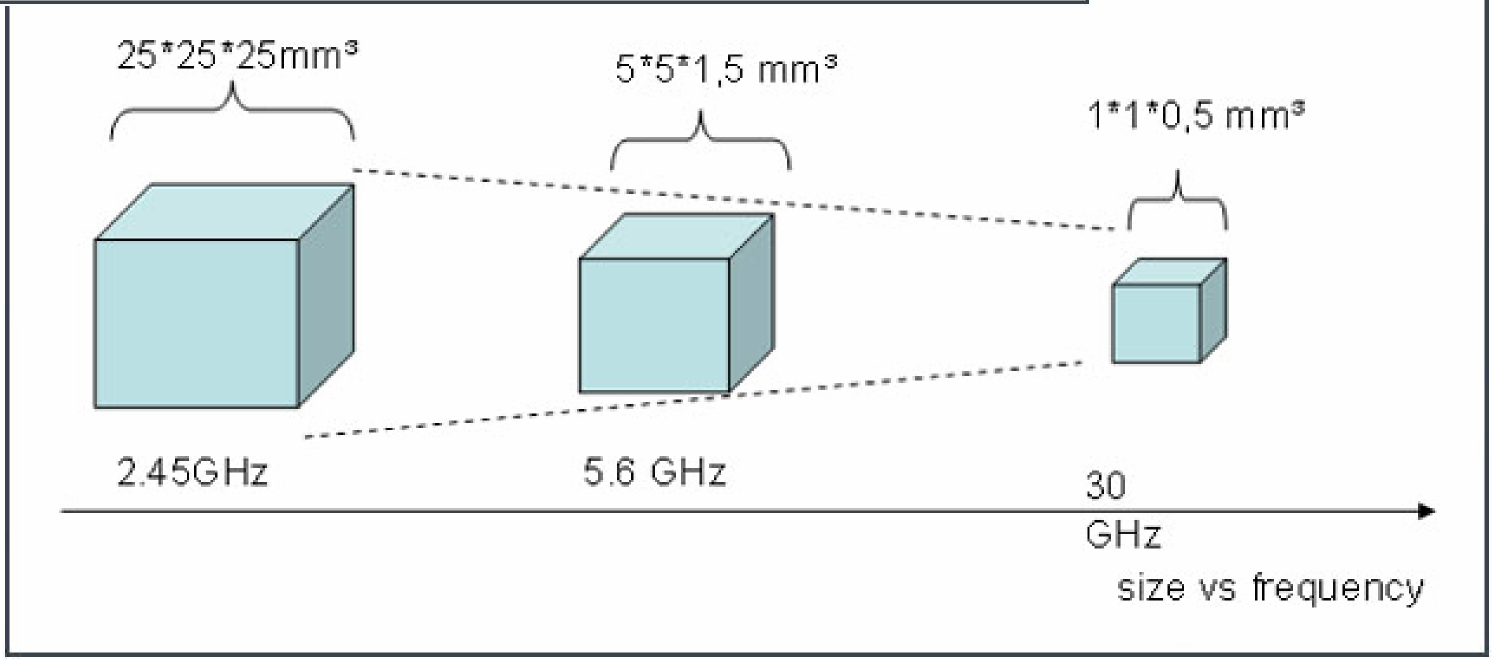



# MEMS-integration (e-CUBES)
## Wafer stacking



# MEMS-integration (e-CUBES)



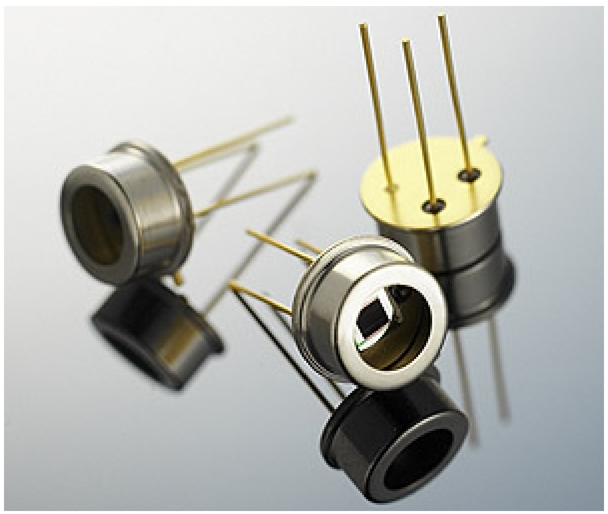
# IR sources

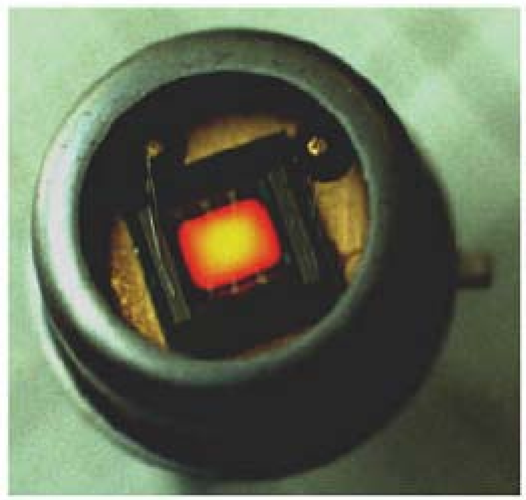
- Thermal sources
  - Conventional “light bulbs”
  - MEMS based IR sources
- IR LEDs
- IR LASERS

# MEMS based IR sources

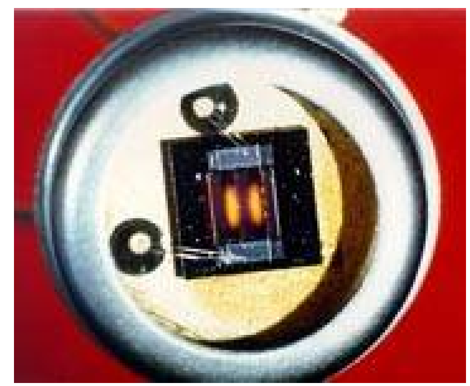
LEISTER

intex





PATINOR

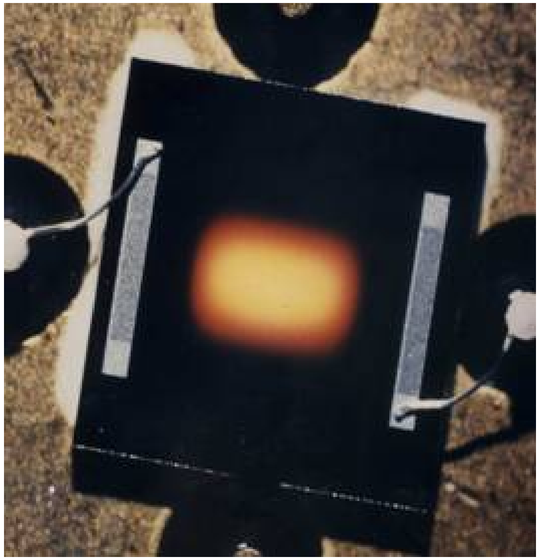


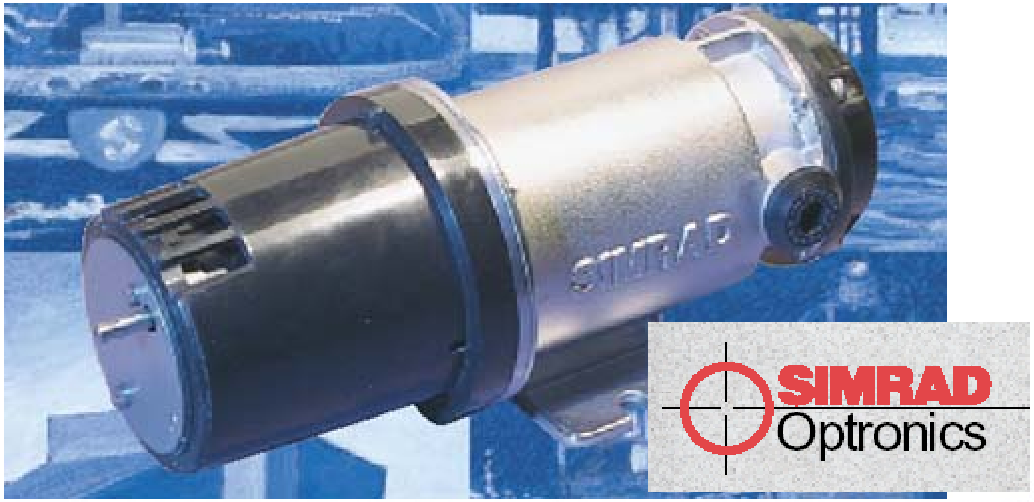
Ion Optics, Inc.

*Innovators in Sensor Design and Manufacturing*

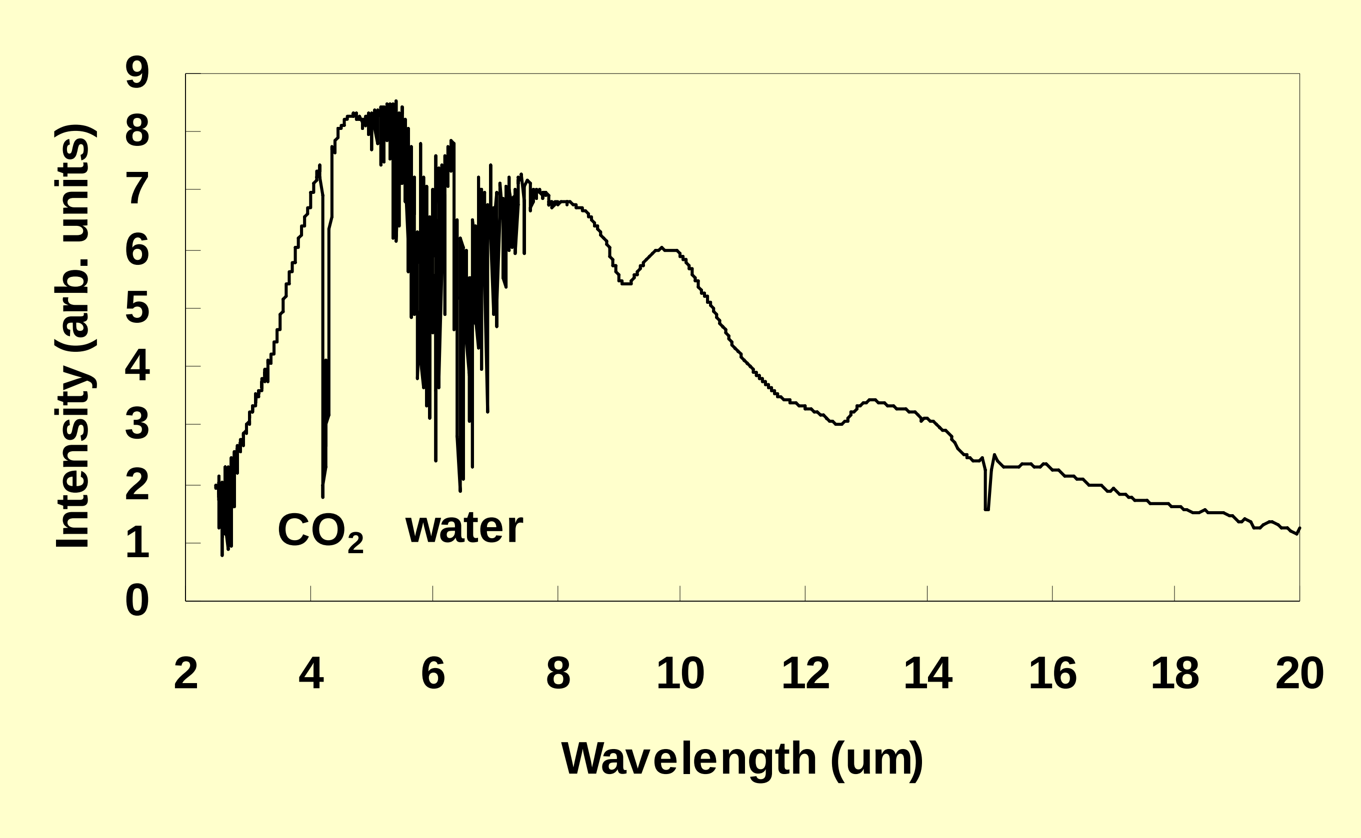
# The SINTEF infrared emitter

- Produced by silicon micromachining
- Grey body spectrum
- Electronically controlled modulation
- Modulation depth: 20 % @ 50 Hz
- Power consumption: ~ 1 Watt
- Application example:
  SIMRAD Optronics Gas Detector
  for methane (CH4)
  More than 15 years of
  continuous operation
  in the North Sea





# Emission spectrum from the IR source in air

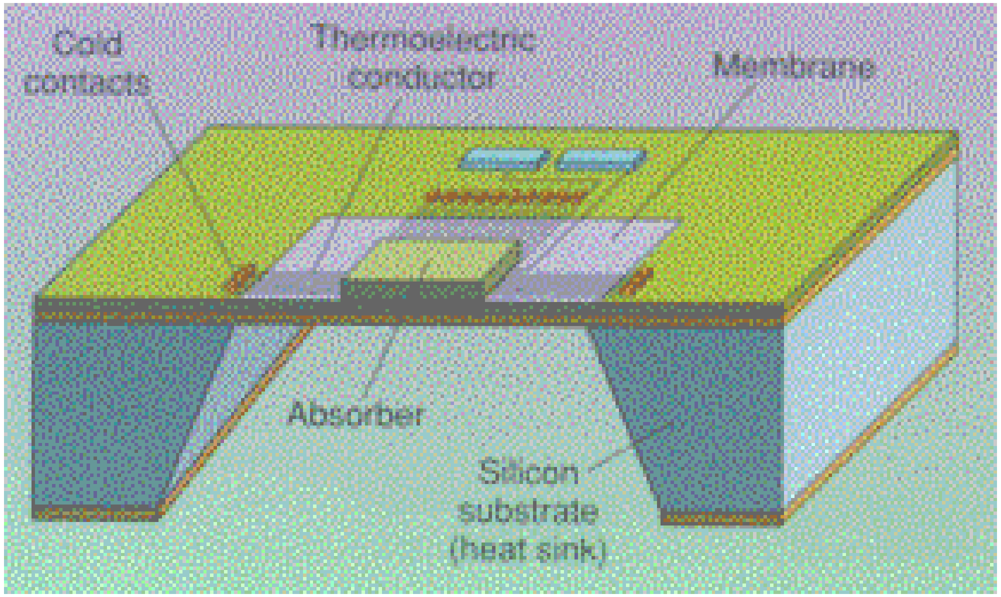


# Infrared detectors

- Photon detectors
  - Photoconductive
  - Photovoltaic
- Thermal detectors
  - Thermopile
  - Bolometer
  - Pyrolectric
  - Golay cells

# MEMS based IR detectors

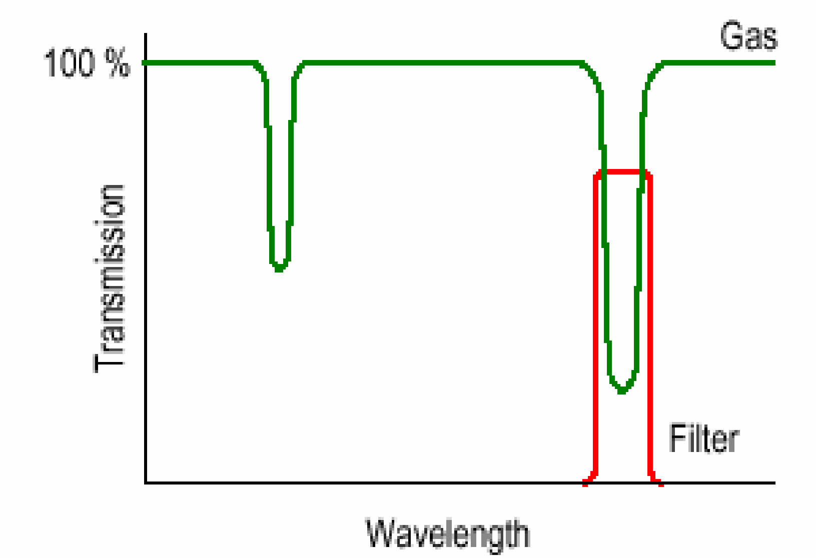
## Thermopile detector

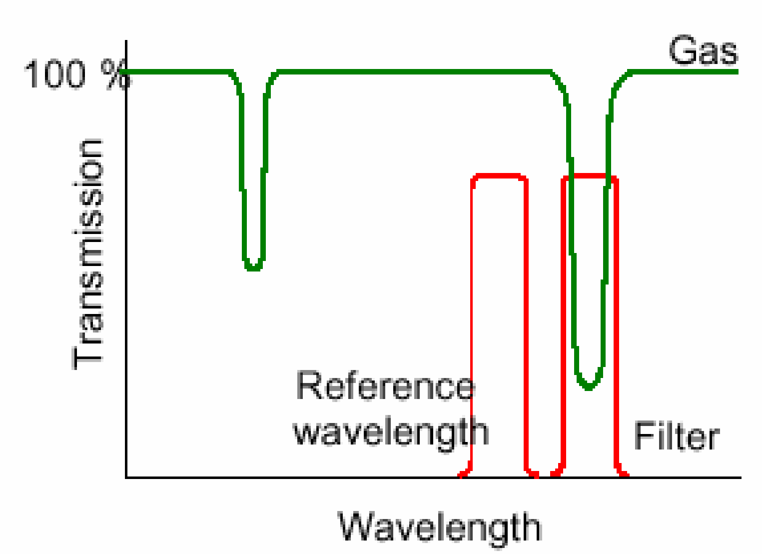



*Wolfgang Schmidt and Jörg Schieferdecker*

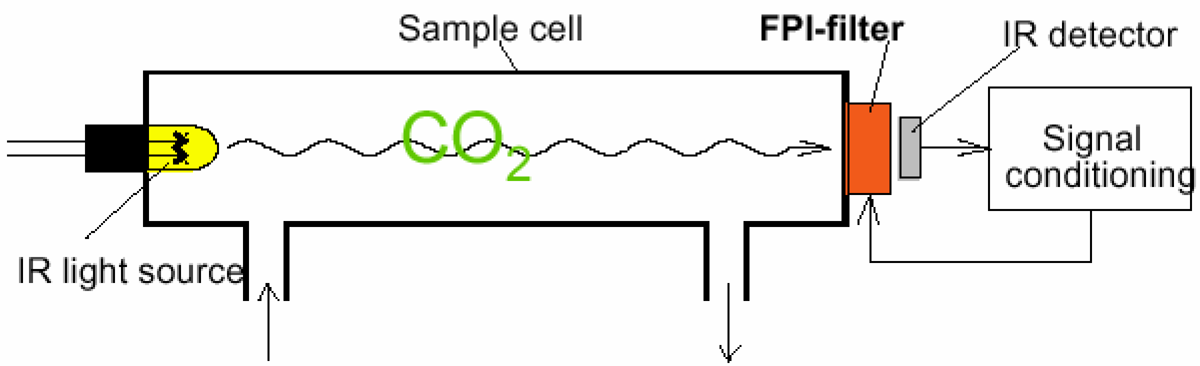
# Filters

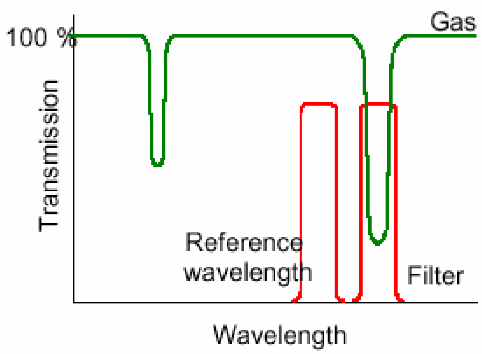
- Single gas selectivity
- Compensation
- Multi gas detection (CO, humidity)



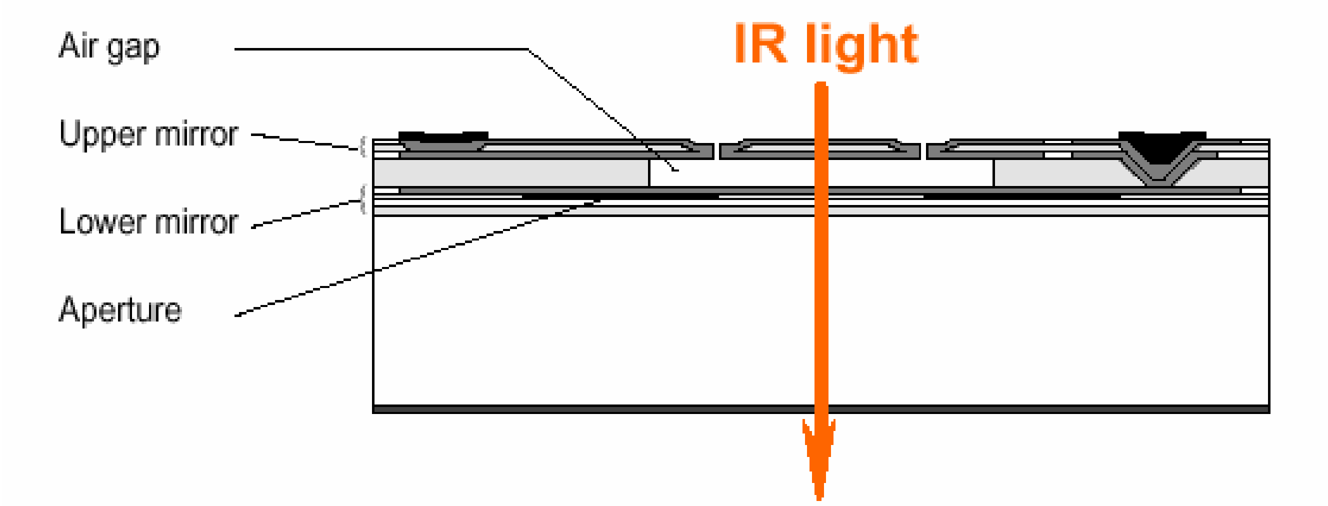
# The Carbocap® technology from VAISALA

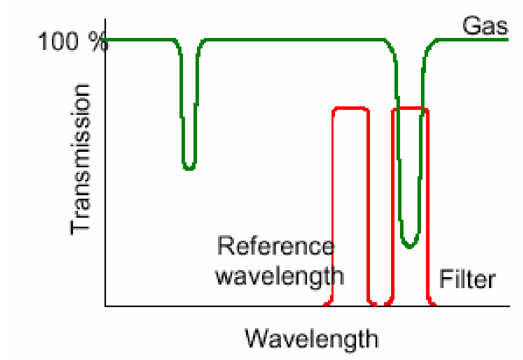


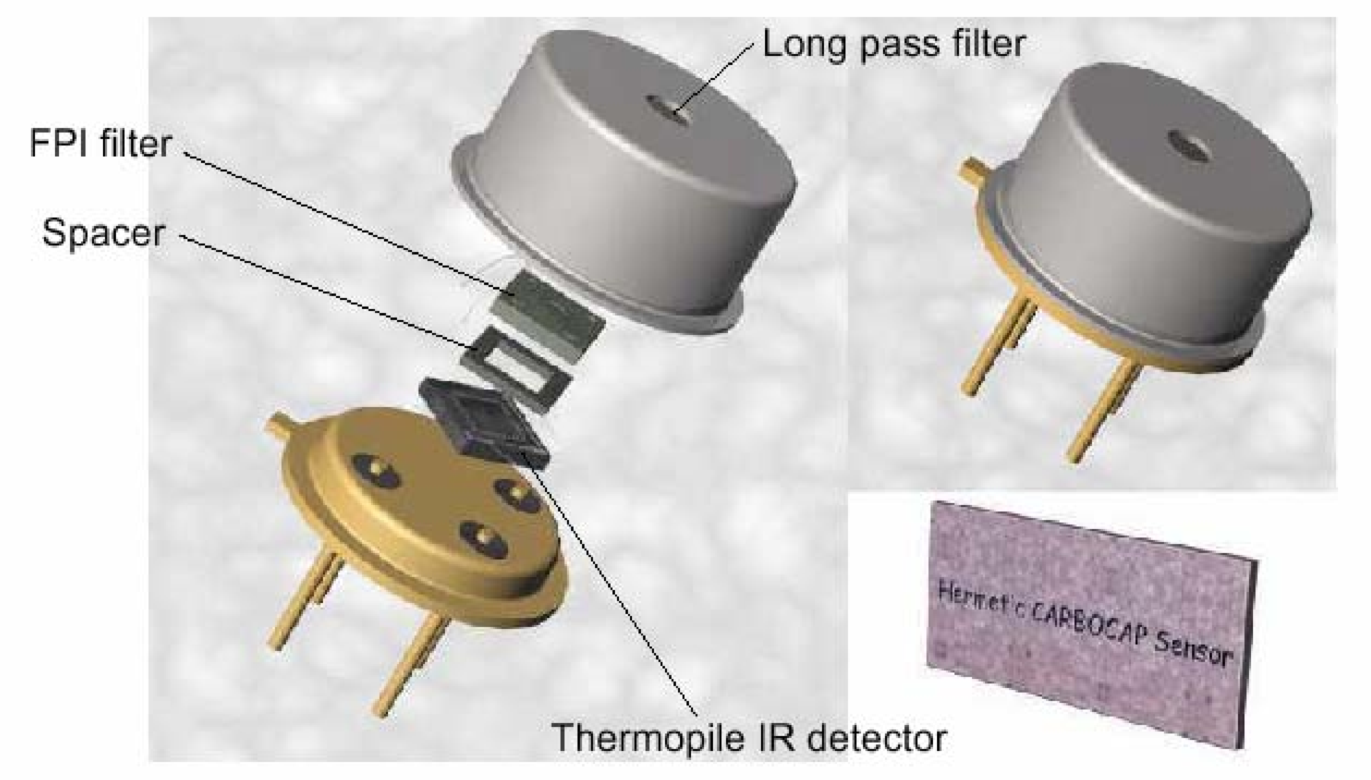

VAISALA

# The Carbocap® technology from VAISALA

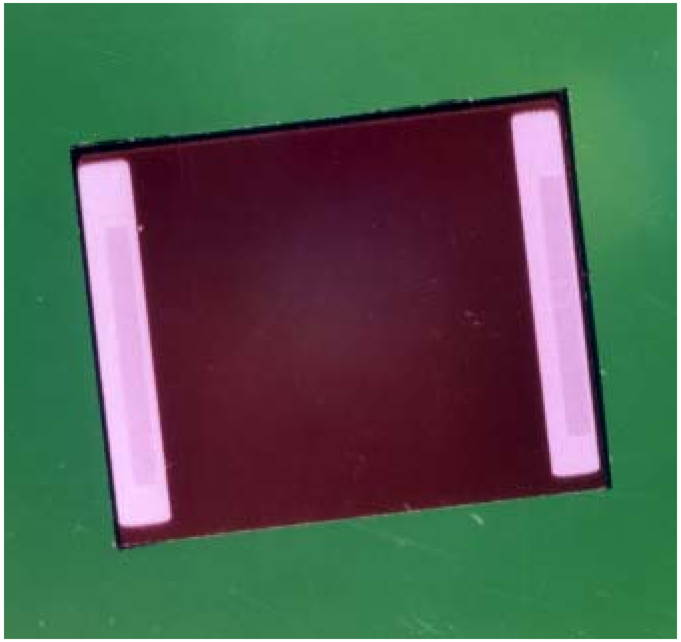


# The Carbocap® technology from VAISALA



# A CO and methane sensor based on a thermally tuned Fabry-Perot filter

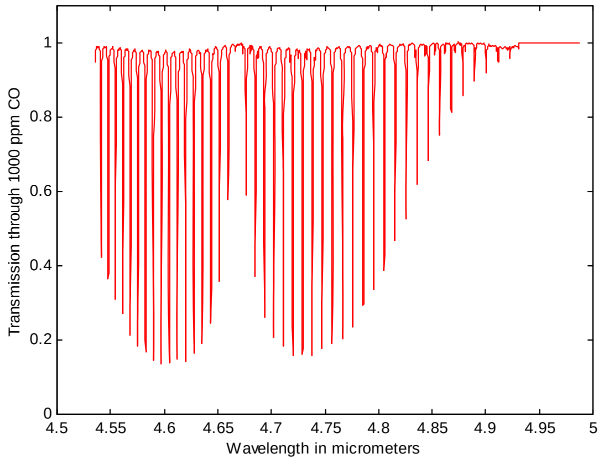


- **Micromachined in silicon**
- **Based on the thermo-opto effect**

$\Delta T \sim 25^{o}$ C

- **Designed to synthesize a characteristic gas spectrum**
- **Electrically modulated 10 nm**
- **Wavelengths from 1.2 µm ->**
- **Modulation frequency: 1 Hz**
- **Simple design, low cost**

**Rogne, Bernstein, Avset, Ferber, and Johansen**
**MOEMS ’99, Heidelberg**

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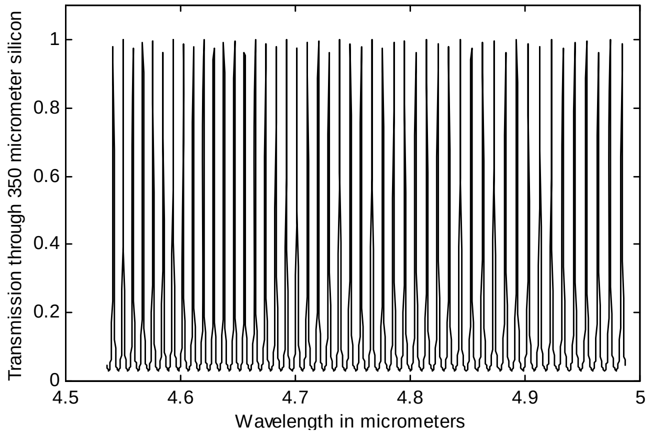
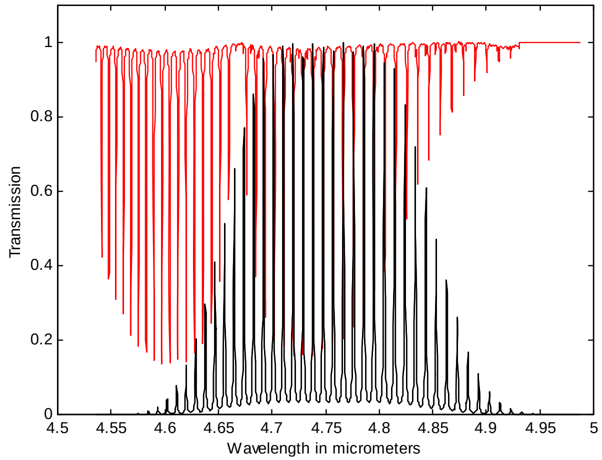
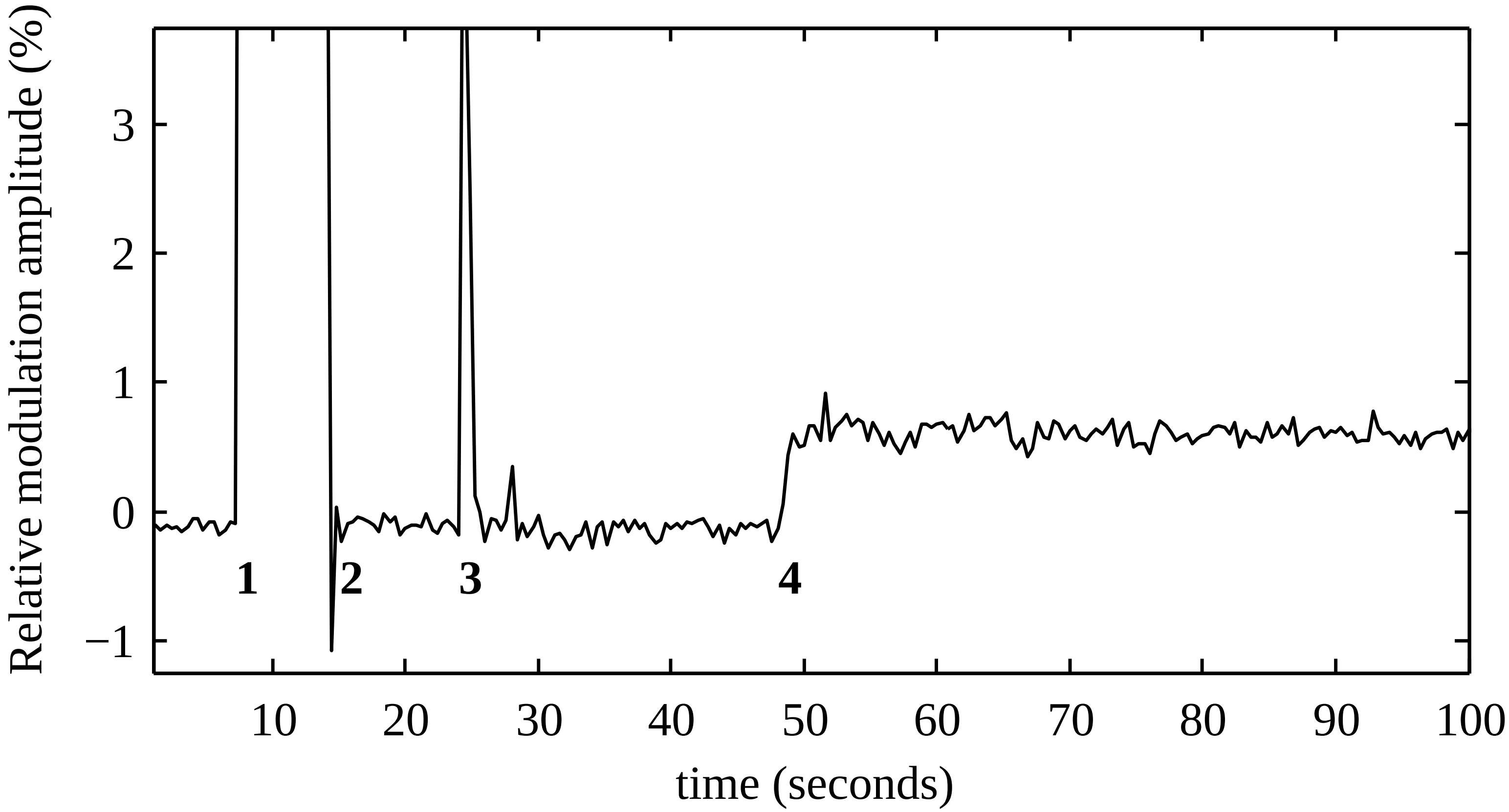



CO absorption pattern

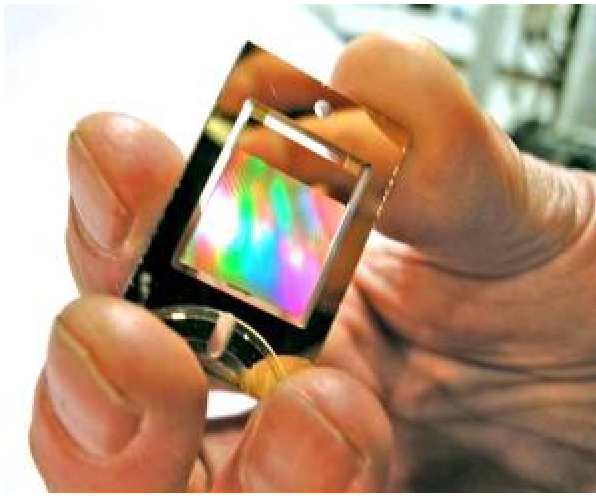
Absorption pattern synthesized by multi-line filter

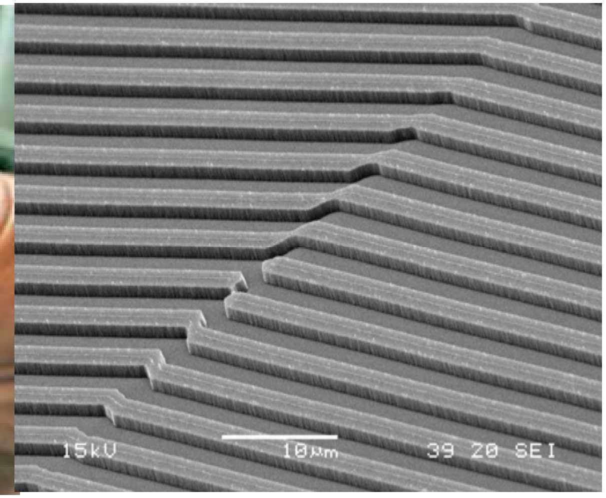


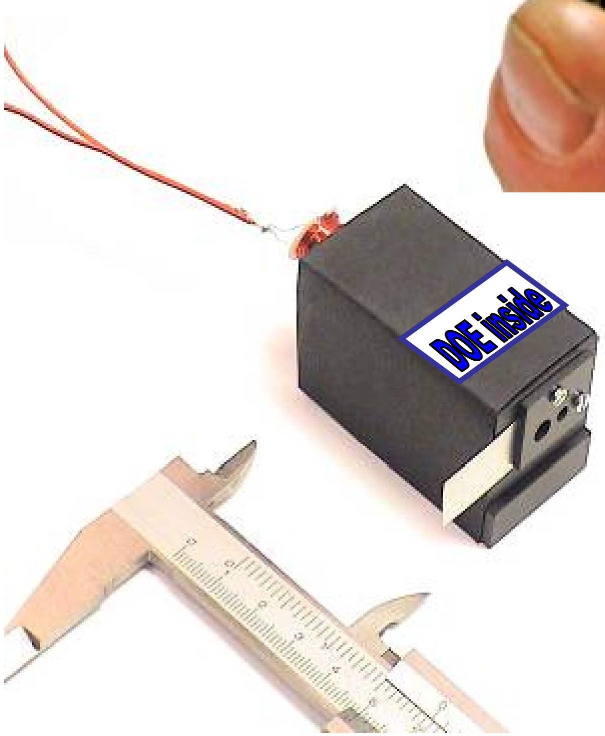
# CO measurments with the slab sensor

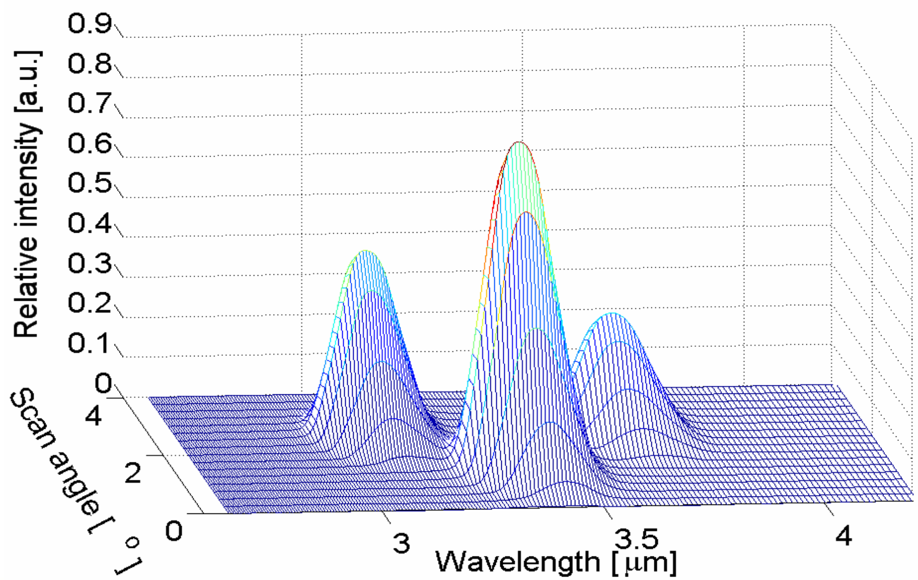


# Diffractive optics for gas sensors



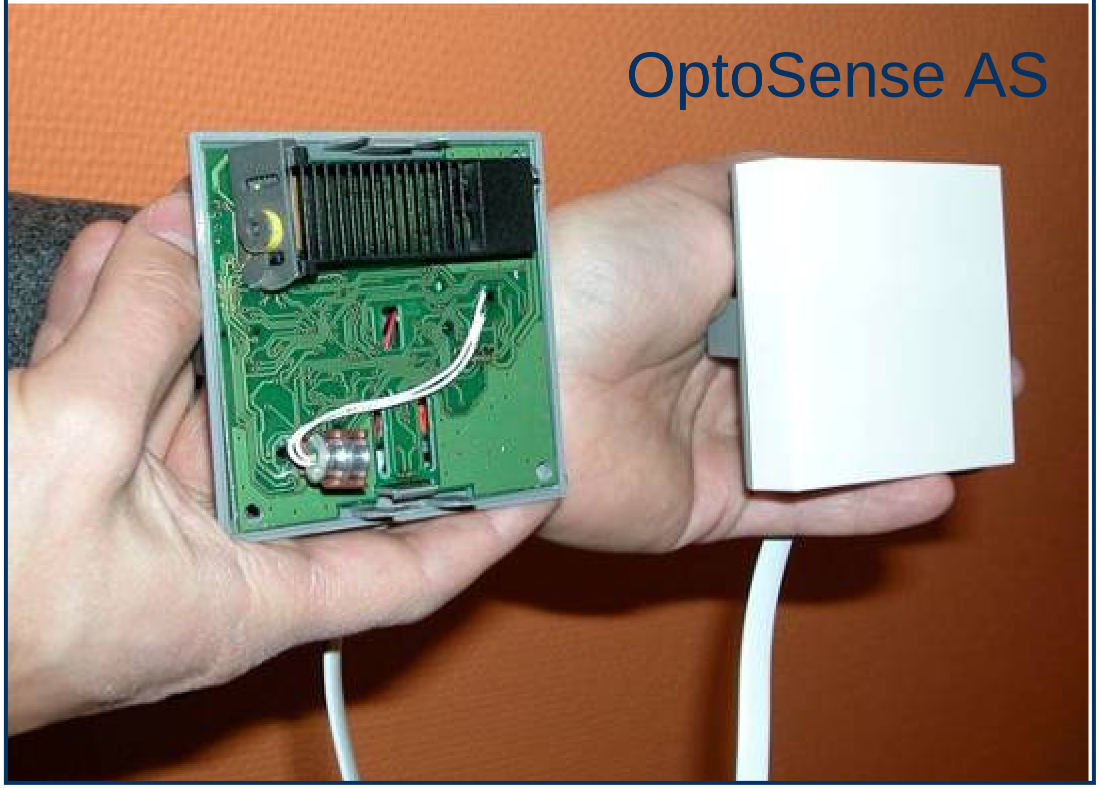


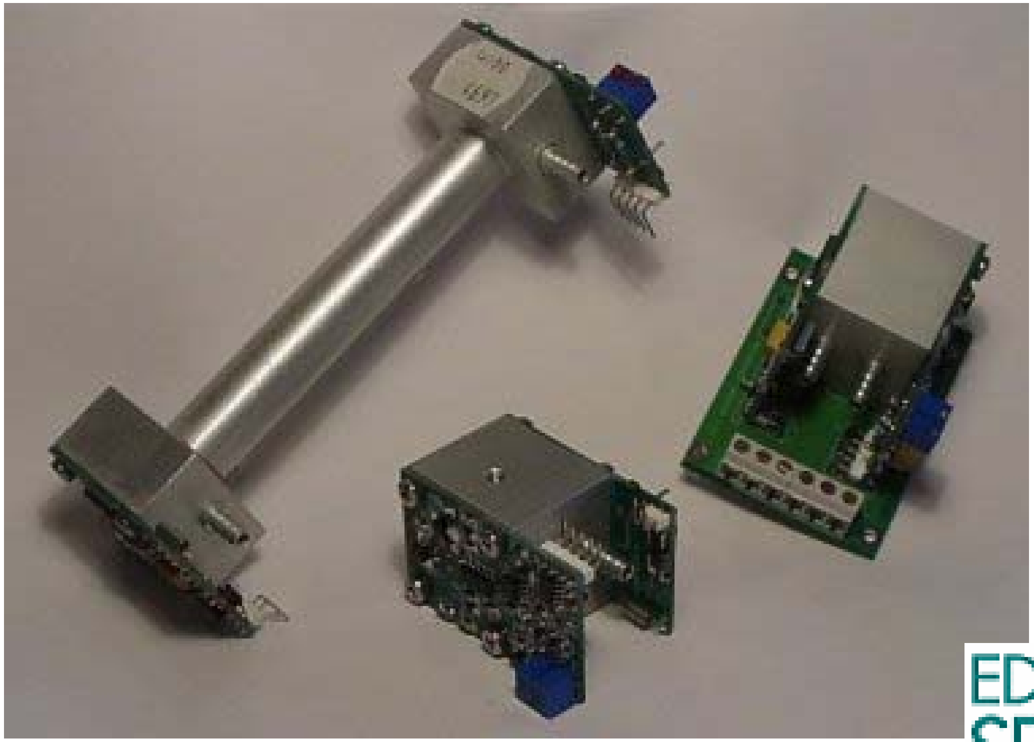



# $CO_2$ and hydrocarbon sensor based on DOE

$CO_2$-sensor for
ventilation control



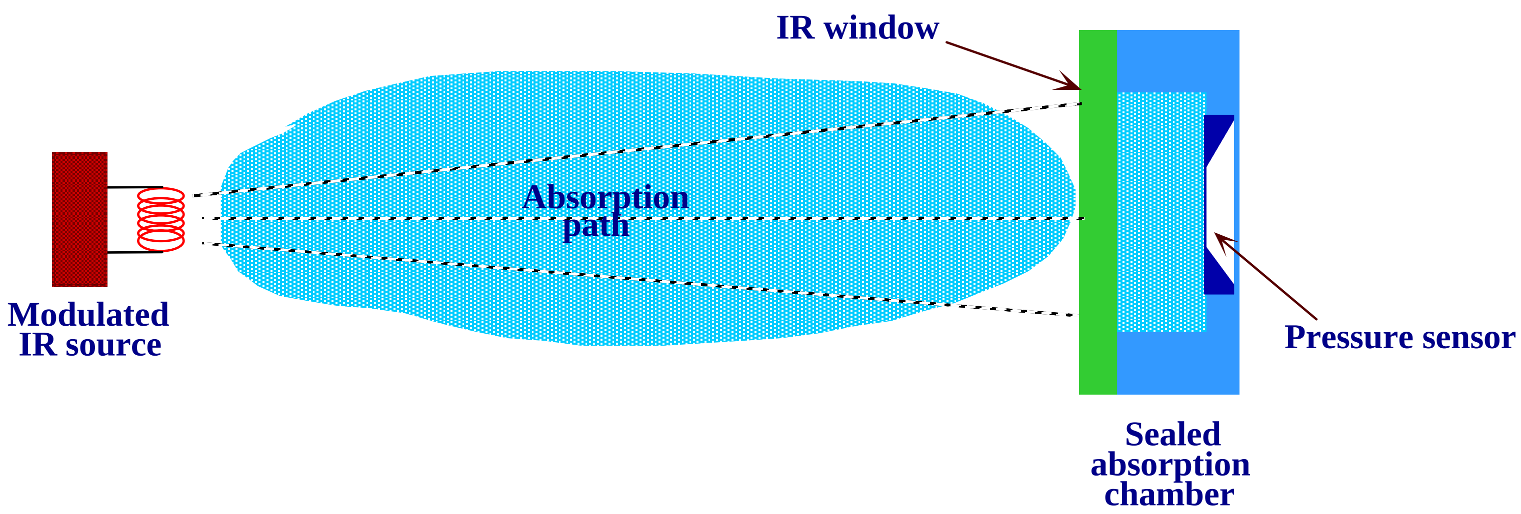
# Typical commercial IR gas sensor



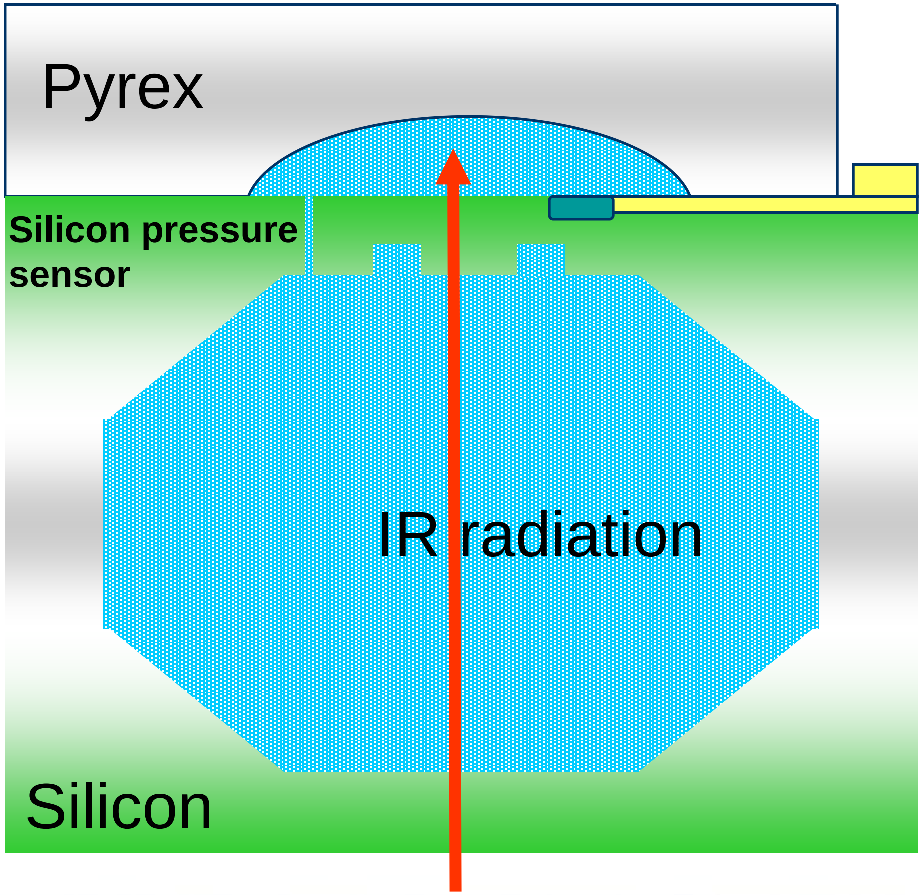
Typically 5 - 10 cm size

EDINBURGH SENSORS

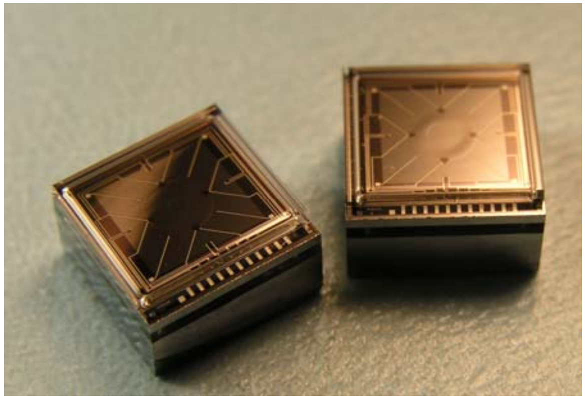
# Filter and detector in one chip: The SINTEF photoacoustic gas sensor



# The photoacoustic detector chip




- Wafer level gas filling
- High precision piezoresisive pressure sensor
- Transferred to the SensoNor MPW foundry process



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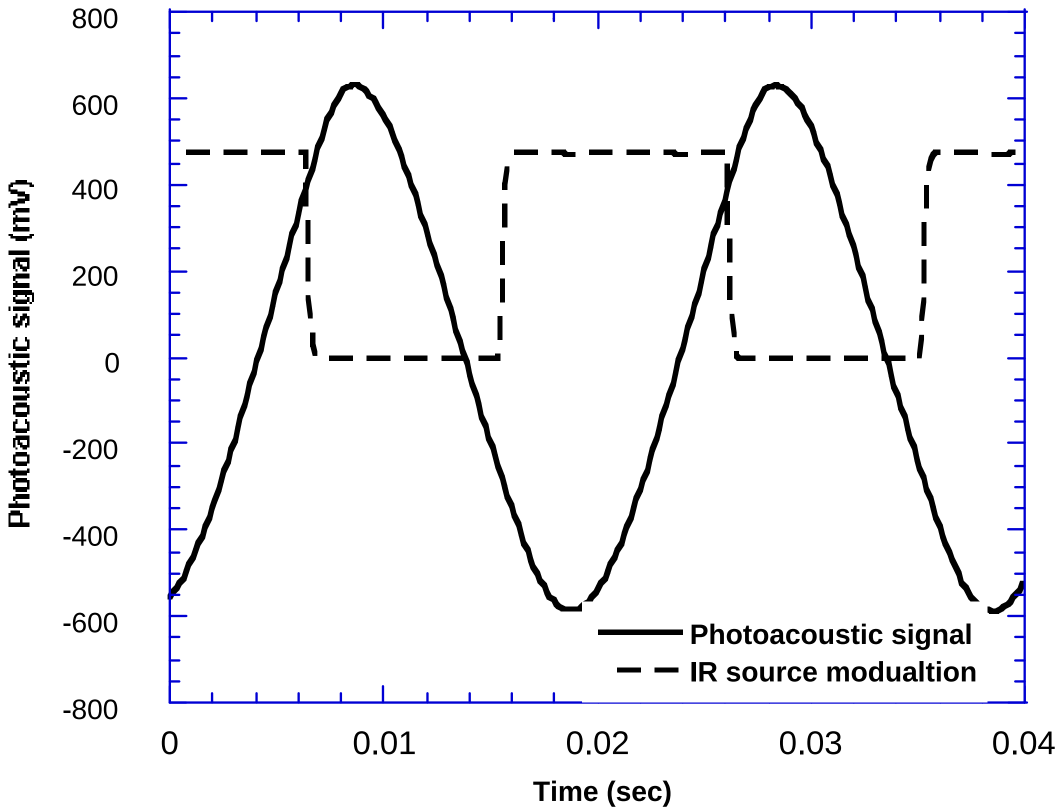
# The photoacoustic signal



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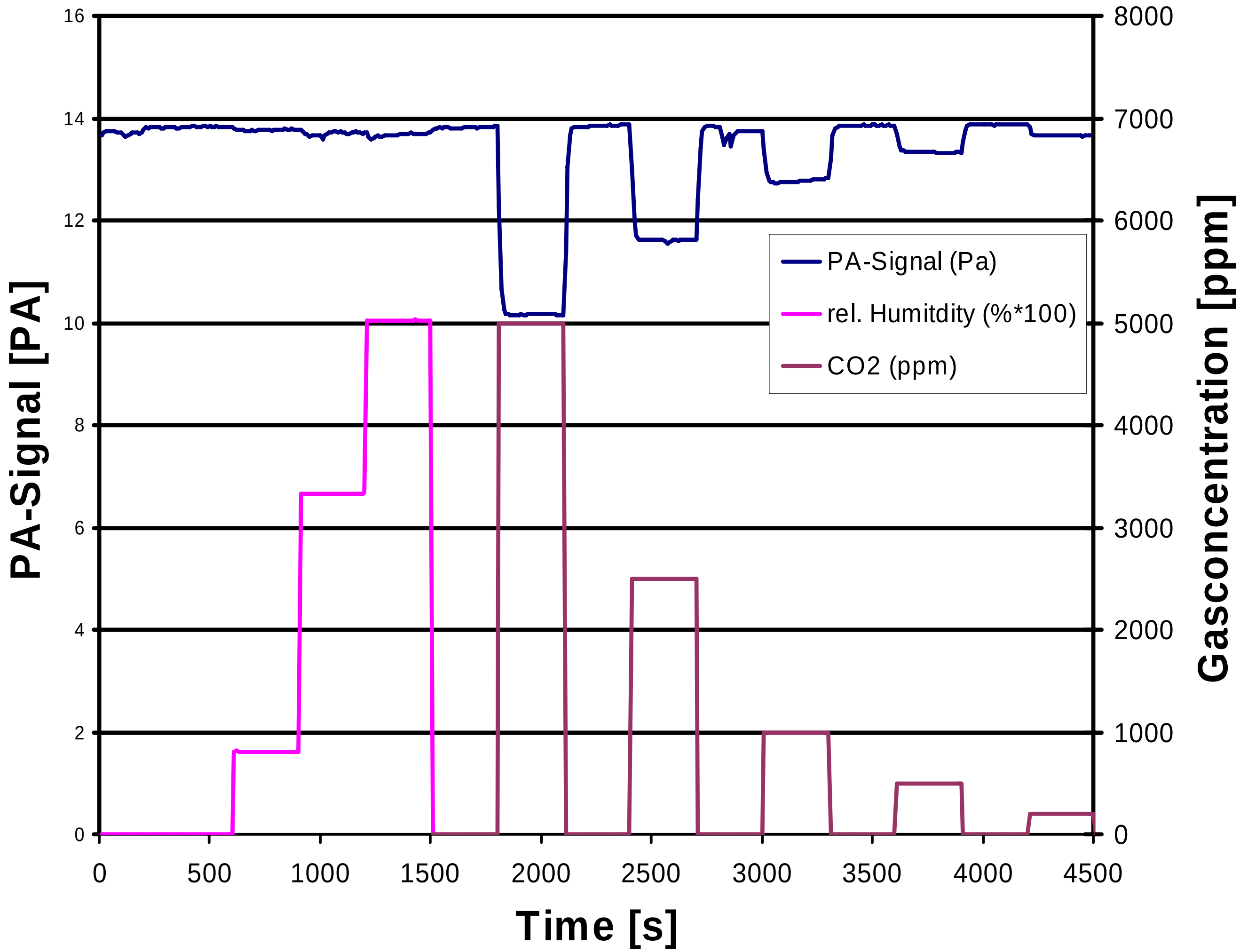
# $CO_2$ Measurement with the PA sensor:




**200-100 ppm resolution**

# Characteristics

- High selectivity without additional filters
- High sensitivity => small size
- No pumps and valves
- Easily implemented in MEMS technology => low cost

- High volume production and packaging technology required
- Long term drift compensation has to be implemented

# MASCOT: Micro-Acoustic Sensors for $CO_2$ Tracking


Per Gerhard Gløersen, SensoNor AS
Bertil Hök, Hök Instrument AB
Niels Peter Østbø, SINTEF



The MASCOT project was co-financed by the IST programme of the European Commission under grant number IST-2001-32411

# Electro-acoustic IAQ sensor

Q air

Hök instrument ab

# Device modelling basics

Relationship between velocity of sound c and molecular mass M of a gas:

$$c = \sqrt{\frac{RT\gamma}{M}}$$

R: universal gas constant (=8.314 J/mol K),
T: absolute temperature (K)
$\gamma$: Ratio of specific heat at constant pressure and volume

Resonant frequency and Q of a Helmholtz resonator:

Neck effective length *l* and area A (radius a)

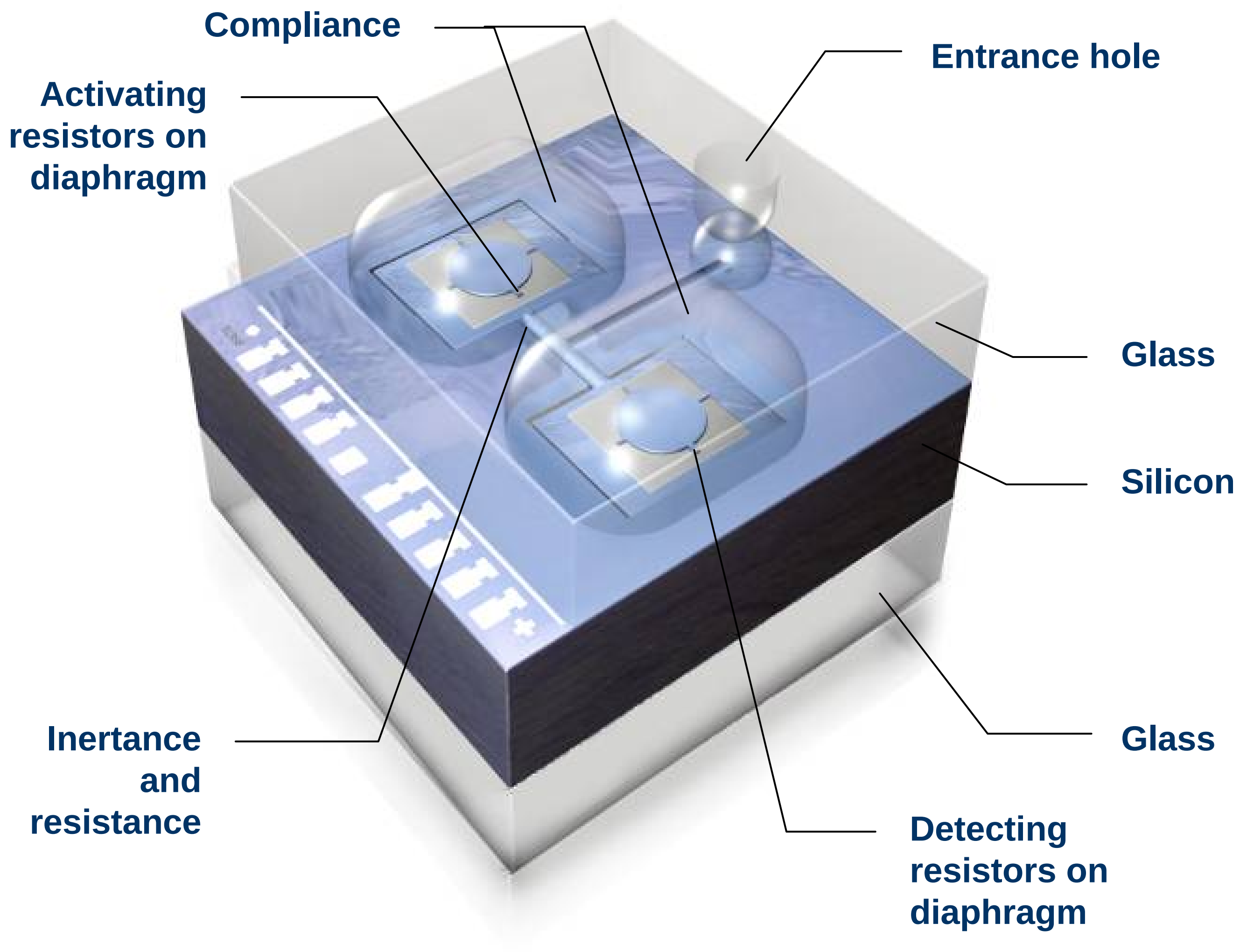
Compliant gas volume V

$$f_r = \frac{c}{2\pi}\sqrt{\frac{A}{\ell \cdot V}}$$

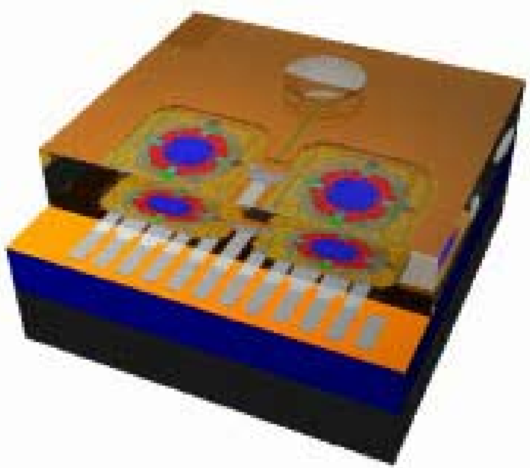
$$Q \approx a \cdot \sqrt{\frac{\omega_r}{2\mu}}$$

$\mu$: kinematic viscosity of gas

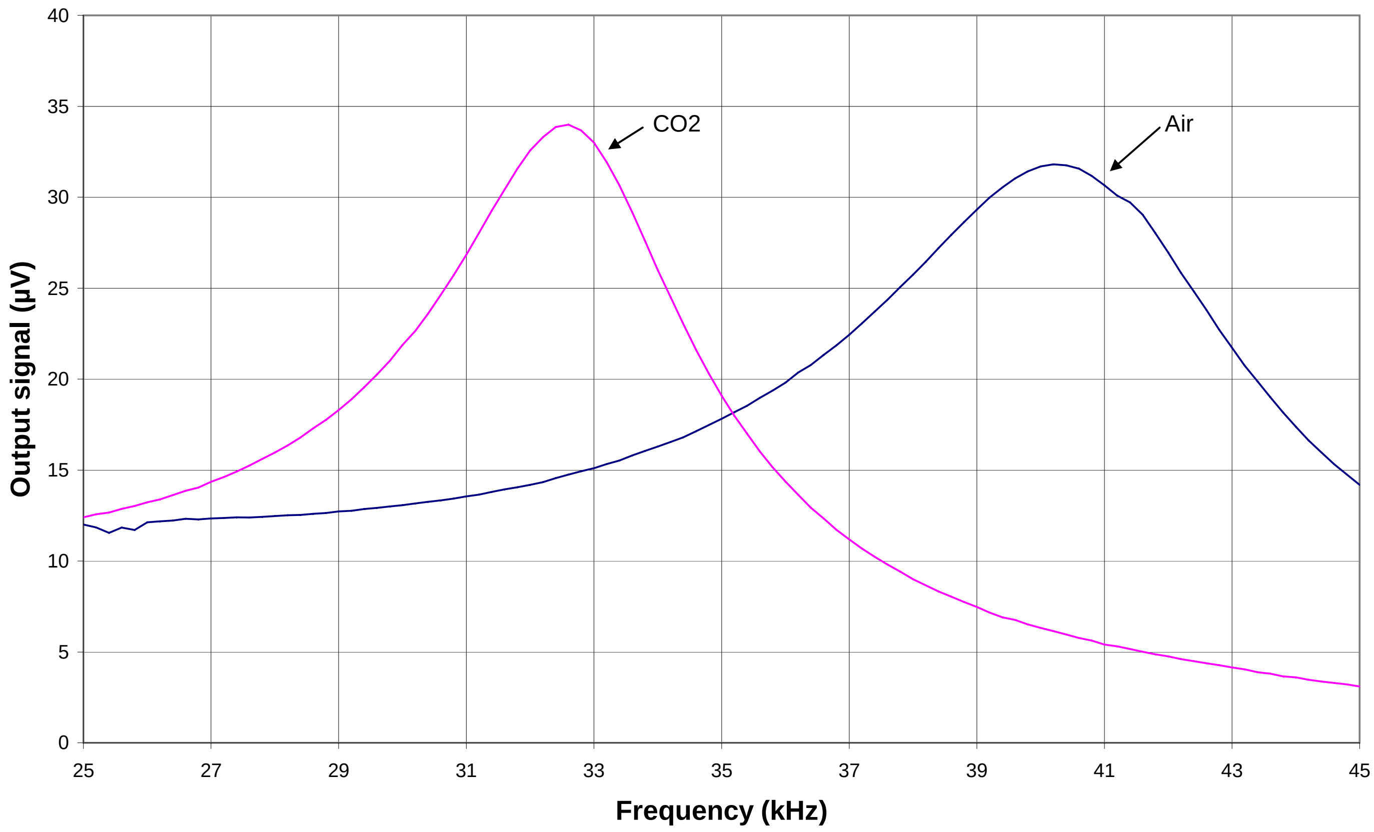
# Schematic drawing of sensor chip



# MASCOT in operation



# Sensor output signal in air and $CO_2$




The resonance frequency shifts from 40 to 32 kHz and the Q factor increases from 6.5 to 8.1

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# Sensor characteristics

| | $f_r$ | Q |
|---|---|---|
| Typical value | 40250 Hz | 6.60 |
| $CO_2$ | -11 Hz/1000ppm | +0.009/1000ppm |
| RH | +4 Hz/%RH | -0.001/%RH |
| Temp | 63 Hz/°C | -0.015/°C |
| Pressure | 0 | +0.04/kPa |
| Resolution | ±2 Hz (±200 ppm $CO_2$ or ±0.5% RH) | ±0.01 |

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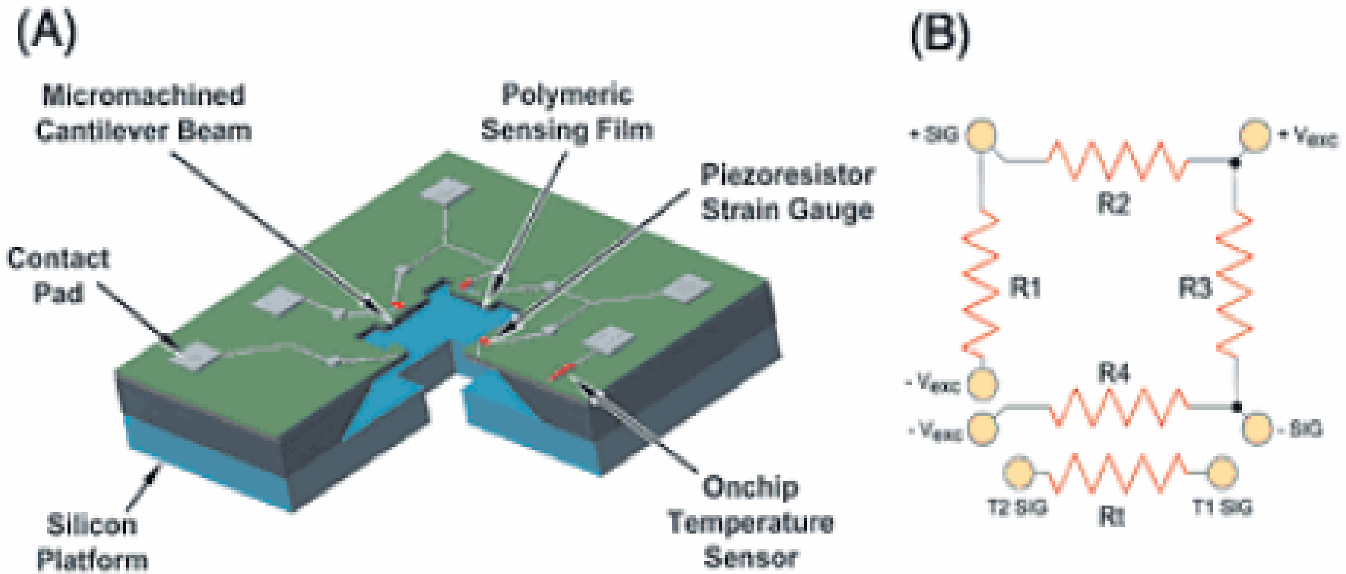
# MEMS based humidity sensors




Die Size: 2 mm x 2 mm

Figure 3. The HMX2000, a silicon-based RH sensor, contains a full Wheatstone bridge circuit and a temperature sensor on a single chip (A). The circuitry is shown for the devices on the sensor chip (B).

# Some aspects of multi sensors

- The challenge is often NOT to be sensitive to humidity and temperature
- Temperature sensors are easily implemented as an integral part of standard electronics.
- Multi sensors are often based on integration of several sensors at the same electronic boards.
- MEMS devices have good potential for integration since they are small and often based on the same principles (piezoresistive, capacitive and optical)
- MEMS also opens for a higher degree of monolithic integration
  - Today:Temperature sensors as part of the gas sensor chip

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# Conclusion

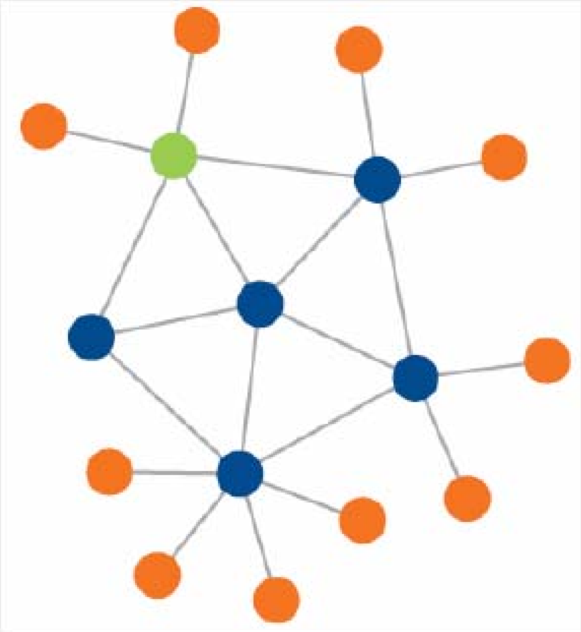
- IR technology offers highly sensitive, selective and reliable gas sensors.
- MEMS based IR sources, IR detectors, tuneable optical filters, and complete gas and humidity sensors are available.
- IR gas sensors are, however, still expensive due to large size, expensive components, packaging, and drift compensation. Higher level of integration is required.
- A **DOE** based $CO_2$ under industrialization by Optosense AS
- A MEMS based **photo-acoustic** gas sensor for $CO_2$ is demonstrated offering high selectivity, sensitivity, and is compatible with MEMS technology.
- A new class of **electro-acoustic** MEMS-implemented $CO_2$ sensors has been demonstrated:
  - Simple and uncritical geometry
  - Strong potential for mass-production at low cost
- A CO sensor based on a thermally tuned **F-P filter** is demonstrated. The detection limit for CO was 20 ppm•m, and 50 ppm•m for methane.
- MEMS based sensors are by their small size and fabrication and packaging technology potentially suitable for multi-sensor integration

# Autonomous Sensors
# ”the multi-CEPOC vision”

- Low power multi-sensor (MASCOT development)
- Low power, efficient nodes (EYES, e-CUBES)
  - Infineon, Thomas Lentsch et al. (*montie)
  - Chipcon/Texas Instr., Tunheim et al. (*montie)
- Integrated System of Systems
  - IAQ/IEQ
  - Energy and Asset Management
  - Continuous Commisioning
  - Safety and Security
  - Built-in ”Smart Components”

# ZigBee Protocol:

IEEE 802.15.4 PHY and MAC



- Standard for low data rate wireless Personal Area Networks (PANs)
- Focus on low power, low cost and robustness
- Defines the physical (PHY) and medium access control (MAC) communication layers
- 250 kbps at 2.4 GHz, available world-wide

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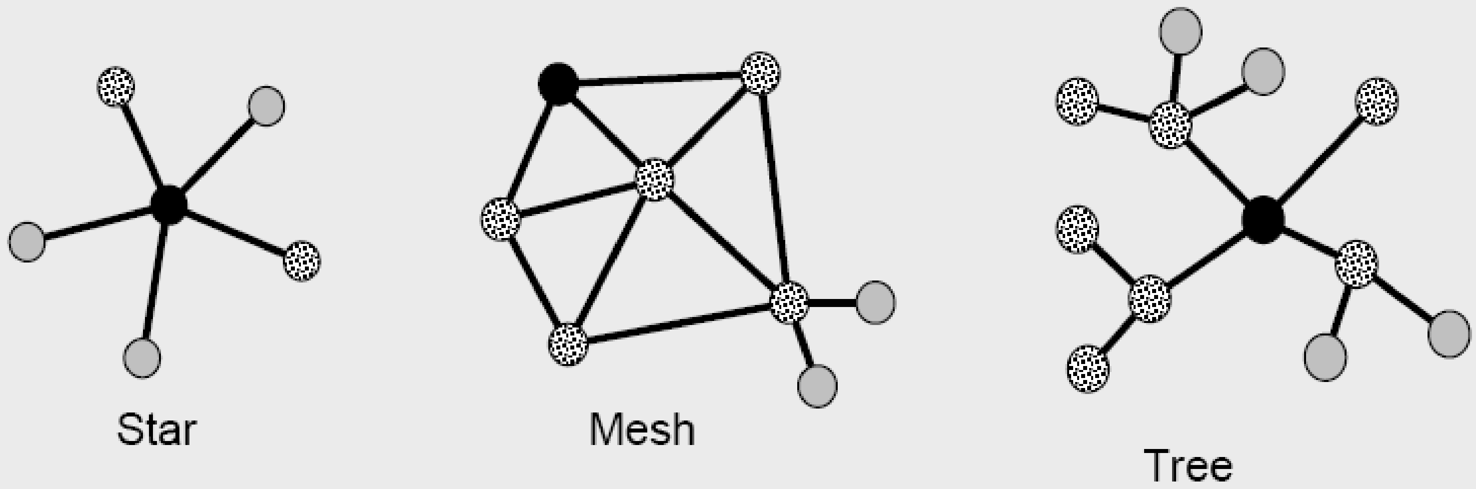
# ZigBee Protocol:

## Types of networks

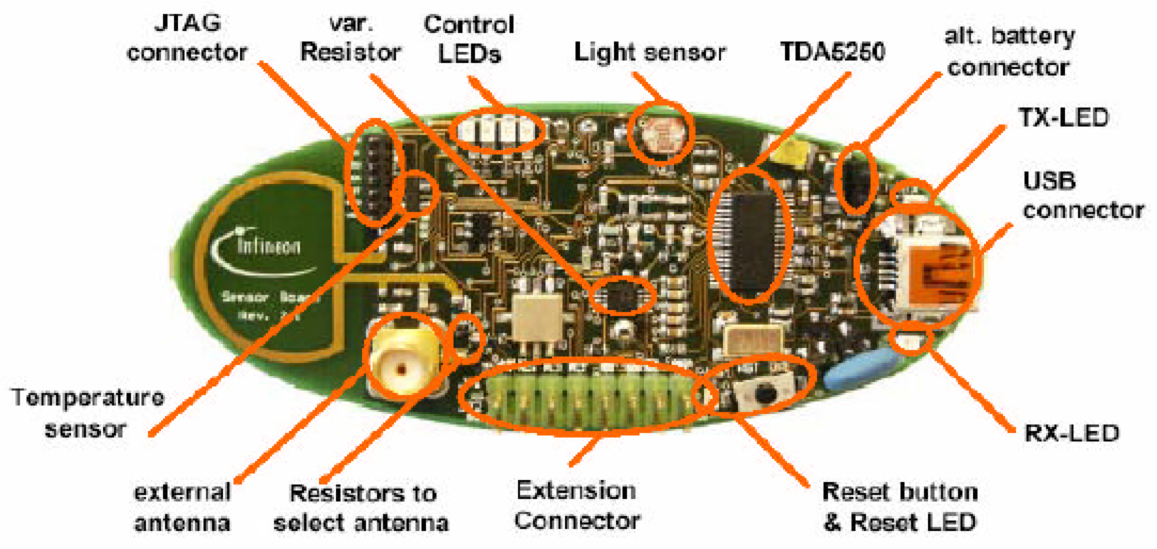
- ZigBee defines three network topologies:

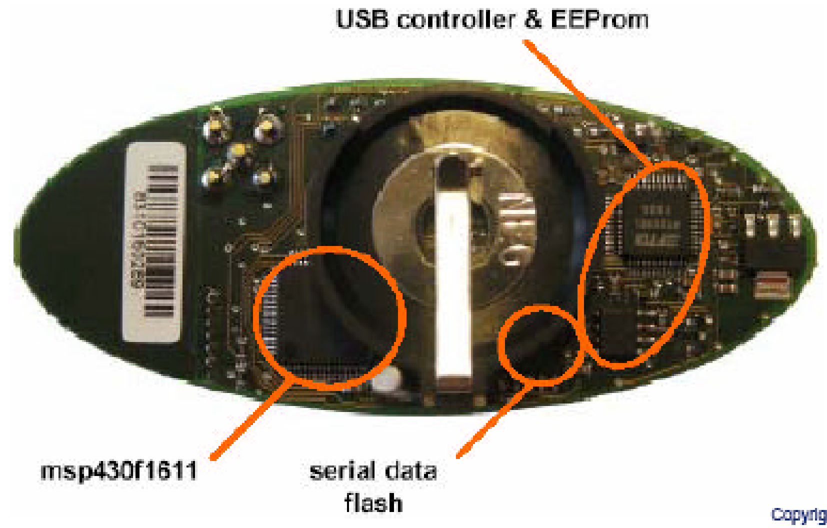



- PAN Coordinator - “Coordinator”
- Full Function Device - “Router”
- Reduced Function Device - “End Device”

Chipcon

# The *eyesIFX* WSAN node



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# *eyesIFX* node specification

- Supply Voltage: 3V, Li-coin cell
- Current consumption:
  - Sleep mode 8.95 µA
  - Transmit mode 11,95mA @ 4dBm
  - Receive mode: 9.42mA
- Modulation: FSK
- Transmit frequency: 868,3 MHz
- Data rate: 19,2 kBps
- Adjustable transmit power (-35 to +4dBm)

TinyOS

- RAM size 10 kByte
- ROM size 48 kByte
- Serial data flash size: 4MBit

- Sensors on board: Light, Temperature, RSSI
- Multi-I/O port extender, USB-interface, JTAG-interface

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# ”The future is up to YOU!”

Thanks for your attention!