MEMS based sensors for indoor environment applications

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MiNaLab (Micro Nano Lab)

- Clean room area:
  - SINTEF: 800 m²
  - University of Oslo: 600 m²
- 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
- Other available foundry processes
- In-house MEMS processes
Key parameters for IAQ control

- Temperature
- $\text{CO}_2$
- Humidity
- Other gases (e.g. CO)

There is a strong demand for (networks of) low cost multi sensors
Infrared (IR) gas sensing

**Advantages:**
- Selective
- Sensitive
- Non contact
- Reliable

**Disadvantages:**
- Inherently expensive (at least two components)
- Large size
- Requires drift compensation
- Complex packaging
MEMS devices for infrared gas sensing
Micro ElectroMechanical Systems (MEMS)

Miniaturized systems that carry out several operations. Typically: sensing, signal 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

Two ultra-miniature medical pressure sensors in the eye of a needle.

Piezo resistors

Pressure sensor
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
IR sources

- Thermal sources
  - Conventional “light bulbs”
  - MEMS based IR sources
- IR LEDs
- IR LASERS
The SINTEF infrared emitter

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

- Single gas selectivity
- Compensation
- Multi gas detection (CO, humidity)
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
  \[ \Delta T \sim 25^\circ C \]
- Designed to synthesize a characteristic gas spectrum
- Electrically modulated 10 nm
- Wavelengths from 1.2 \( \mu \text{m} \) ->
- Modulation frequency: 1 Hz
- Simple design, low cost

Rogne, Bernstein, Avset, Ferber, and Johansen
MOEMS ’99, Heidelberg
CO absorption pattern

Absorption pattern synthesized by multi-line filter
CO measurements with the slab sensor
Diffractive optics for gas sensors
MEMS based IR detectors

Thermopile detector

Wolfgang Schmidt and Jörg Schieferdecker
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
The photoacoustic signal
CO₂ Measurement with the PA sensor:

- **Time [s]**
- **PA-Signal [PA]**
- **Gasconcentration [ppm]**

**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 an packaging technology required
- Long term drift compensation has to be implemented
MASCOT:
Micro-Acoustic Sensors
for CO$_2$ Tracking

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Electro-acoustic IAQ sensor
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 ($=8.314 \text{ J/mol K}$),
- $T$: 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

Activating resistors on diaphragm

Compliance

Entrance hole

Glass

Silicon

Glass

Detecting resistors on diaphragm

Inertance and resistance
Sensor output signal in air and CO₂

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

<table>
<thead>
<tr>
<th></th>
<th>$f_r$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical value</td>
<td>40250 Hz</td>
<td>6.60</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>-11 Hz/1000ppm</td>
<td>+0.009/1000ppm</td>
</tr>
<tr>
<td>$RH$</td>
<td>+4 Hz/%RH</td>
<td>-0.001/%RH</td>
</tr>
<tr>
<td>Temp</td>
<td>63 Hz/\degree C</td>
<td>-0.015/\degree C</td>
</tr>
<tr>
<td>Pressure</td>
<td>0</td>
<td>+0.04/kPa</td>
</tr>
<tr>
<td>Resolution</td>
<td>±2 Hz (±200 ppm $CO_2$ or ±0.5% RH)</td>
<td>±0.01</td>
</tr>
</tbody>
</table>
MEMS based humidity sensors

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 MCM integration.
- MEMS devices is potential easy to integrate since the are small and often based on the same principles (piezoresistive, capacitive and optical)
- MEMS also opens for a higher degree monolithic integration
  - Temperature sensors as part of the gas sensor chip
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 Optosene 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$\cdot$m, and 50 ppm$\cdot$m for methane.
- MEMS based sensors are by their small size and fabrication and packaging technology potentially suitable for multi-sensor integration