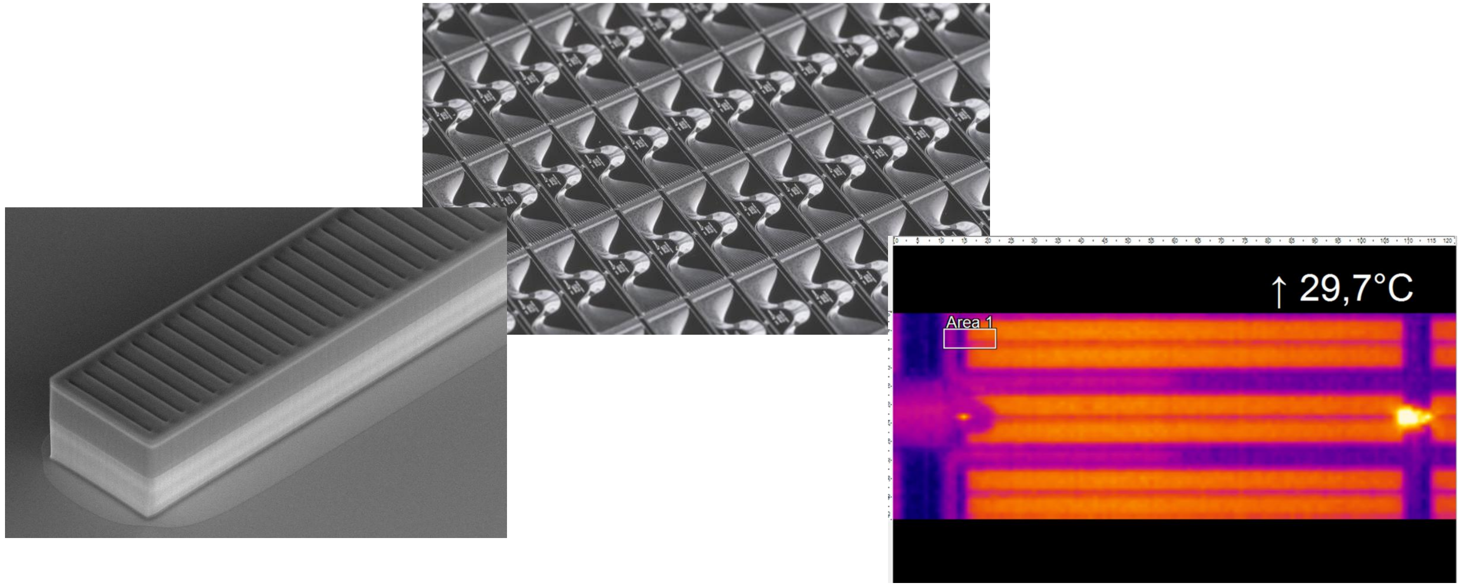
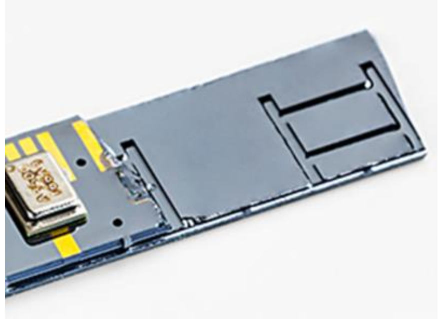
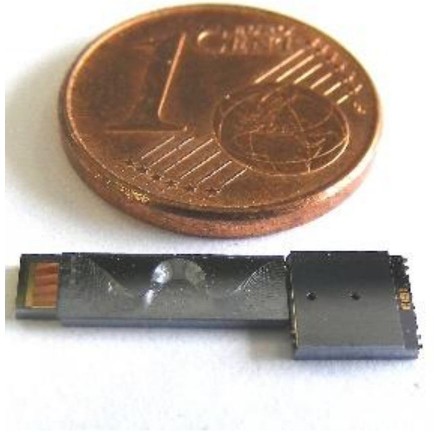


III/V Silicon QC-Lasers and Photonic Integrated Circuits: Towards Ultimate Miniaturization of Mid-IR Sensors





Dr. Badhise Ben Bakir

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Optics and Photonics Department

EPIC Online Technology Meeting on Photonics for Wearables | 10 July 2023

Chemical Sensing Requirements

- The same principle of operation (BB source+ PA cell)
- We have two opposites:
  1) A testing lab solution with ultra-low detection limit
  2) A low cost/footprint solution with moderate performances
- Our developments on Si: 1+2 thanks to finely tuned devices / integration

Air Quality

Measure

Limit of Detecti

Size

Multispecies

CO

Leakage

Humidity

Safety

Ownership

erformances

CO_2

Green House Gasses

Low-cost PA-CO2 sensor:

- Indoor air quality monitoring
  → Application: Smart IoT devices
- LoD: 400 ppm
- Footprint: ½ cm², typically

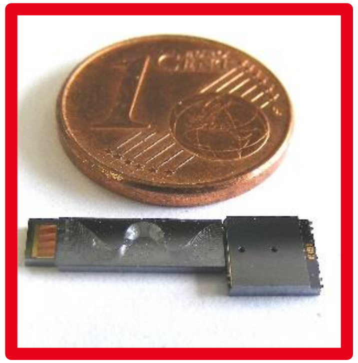
Courtesy from Infineon

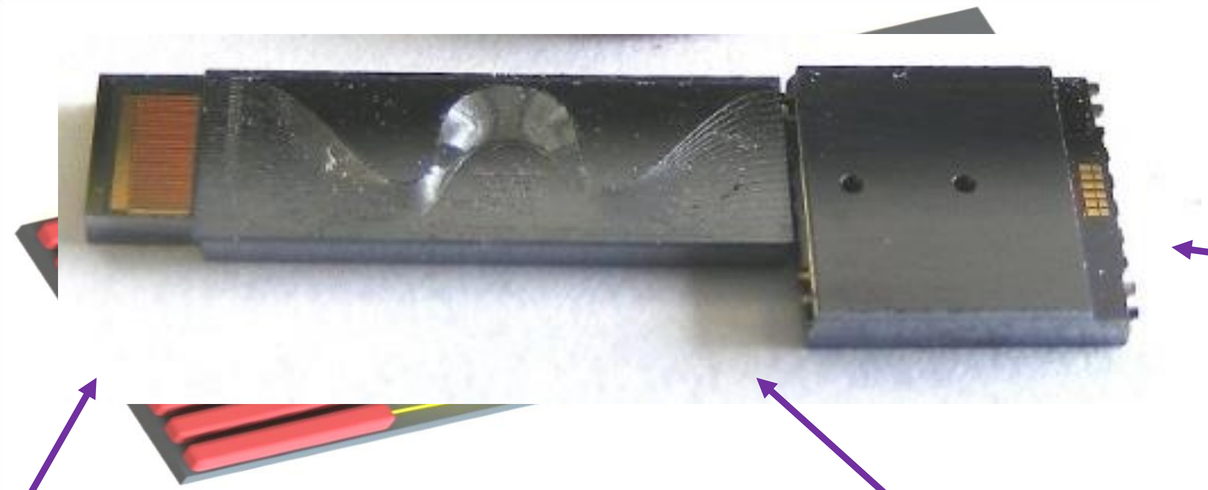
Courtesy from ThermoFisher Scientific

FTIR equipment:

- Part of a testing lab solution
  → detecting gases and chemicals < <ppm
  → In a laboratory w/ well-controlled ambient conditions

Concept of Integrated Multigas Sensor on Si





Array Quantum Cascade Lasers on Si

Multigas detection enabler

Photonics Integrated Circuit Beam Combiner

Replace costly and fragile discrete optics

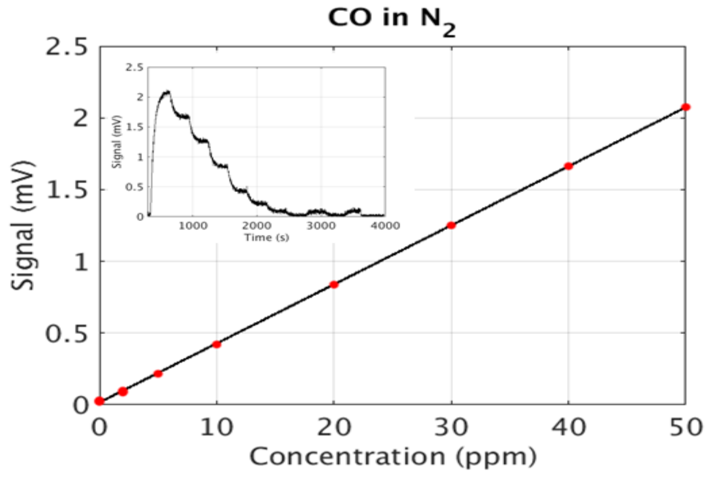
Gas sensing cell – PA detector with MEMS µPhone

Replace bulky multipass cells

Laboratory Gas measurement: Limit of Detection

Linear sensor's response : CO_2 ; CO ; H-CHO ; NO ; CH_4 ; NH_3 ; NO_2 …

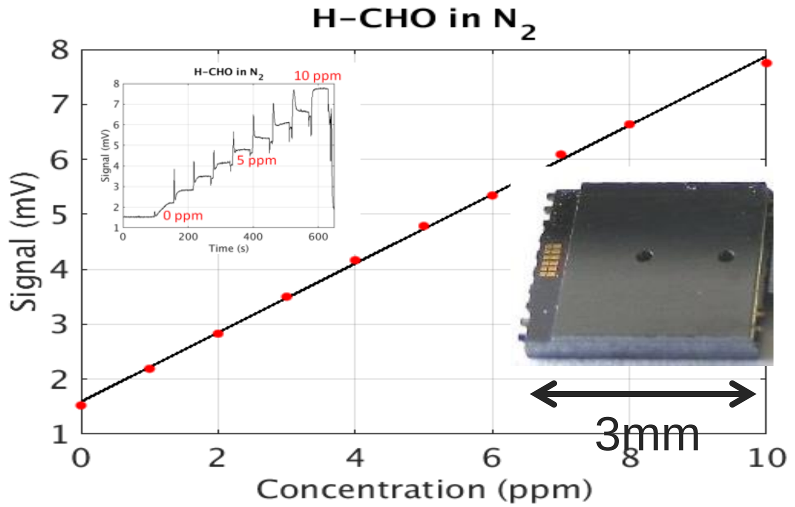
$$S_{PA} \propto \frac{\alpha(C_{gas})}{\sqrt{V_C}} P_0$$

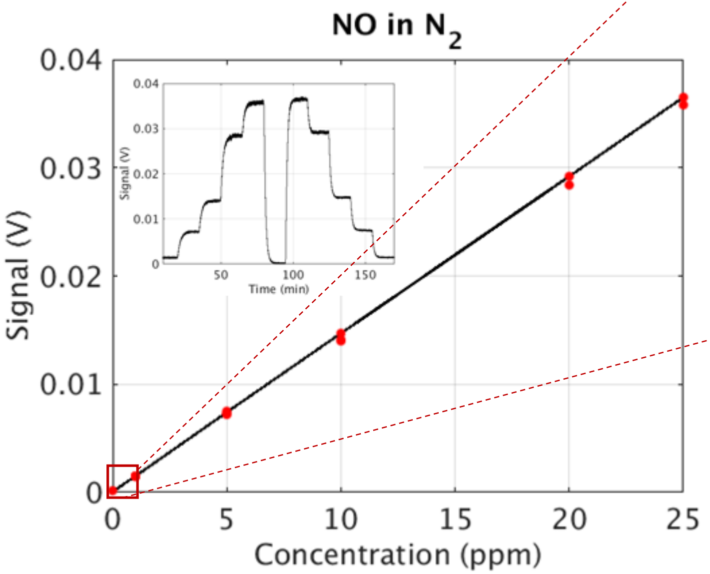


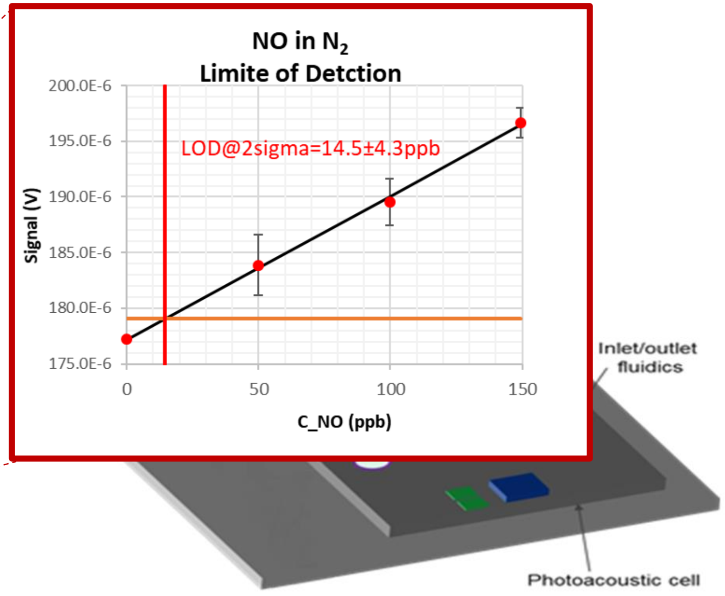
Typical values /results

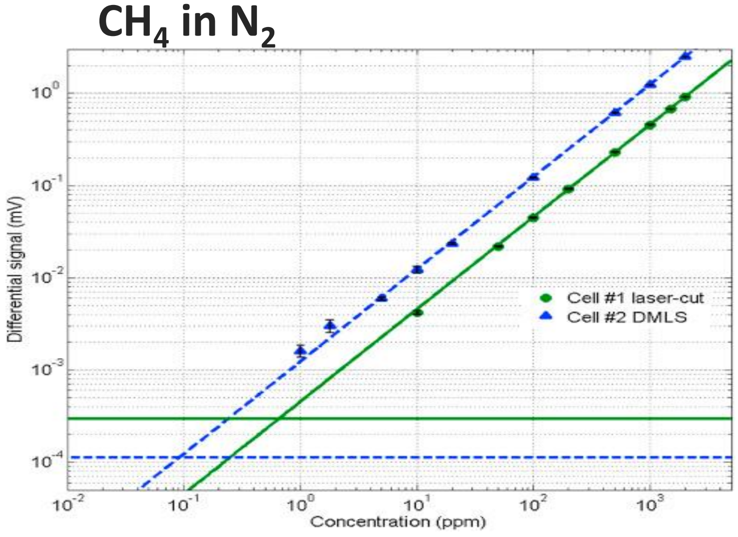
LOD < 1ppm, 1s

QCL ~ 1mW



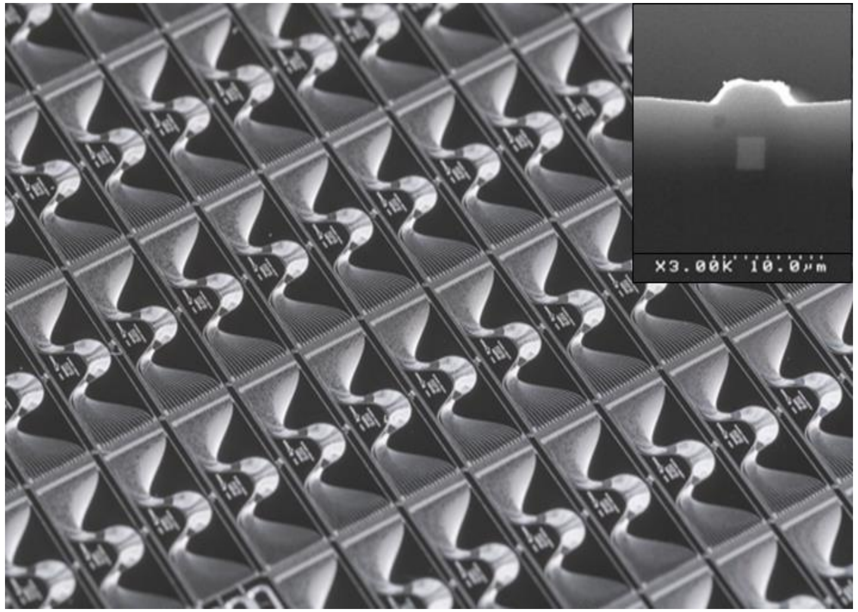


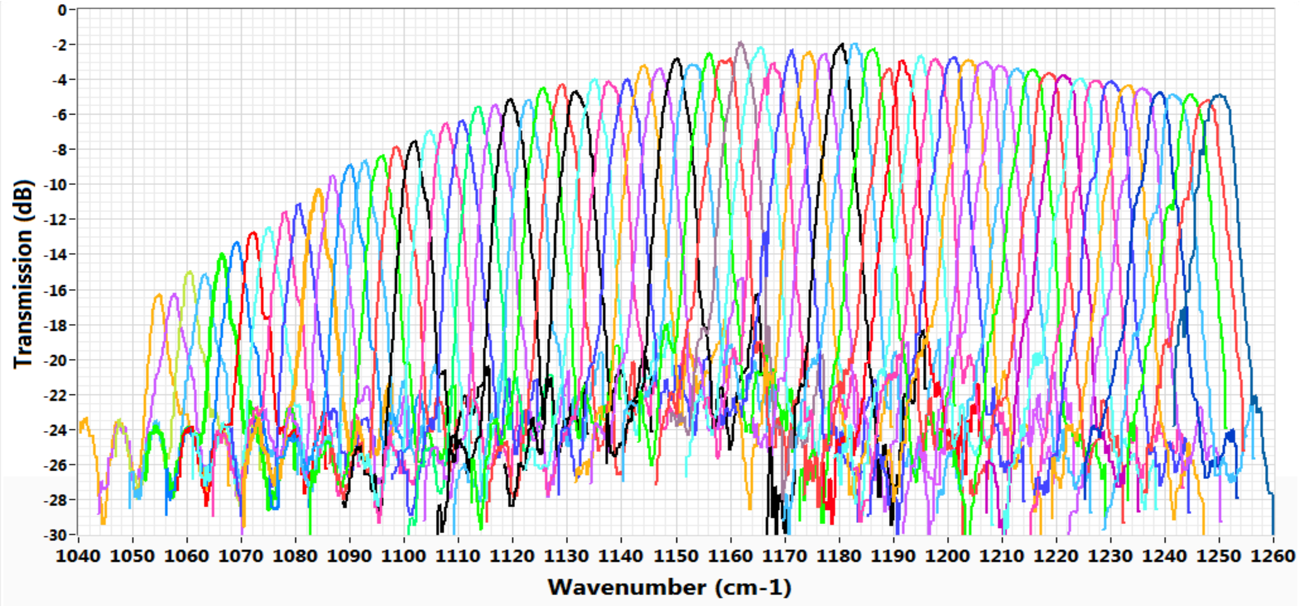




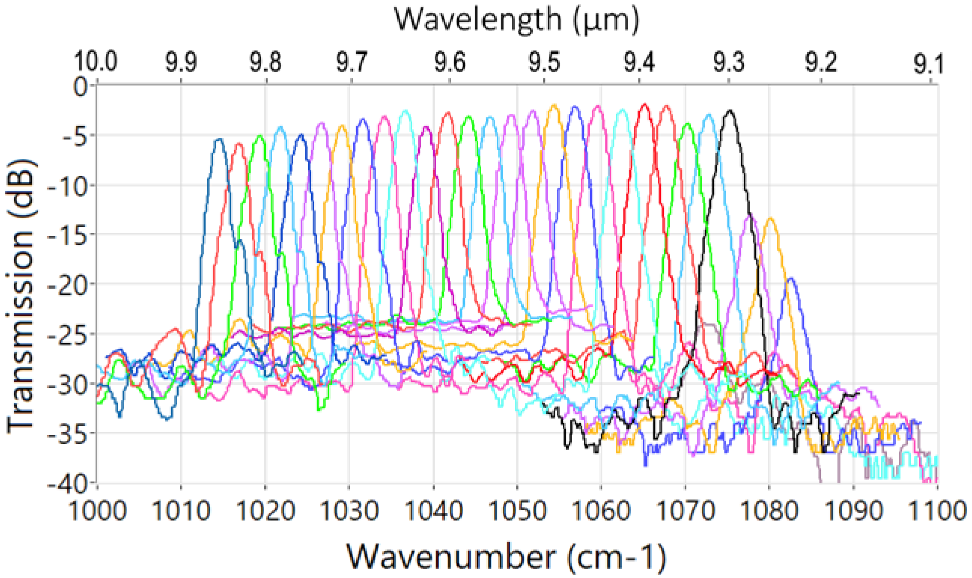
Mid-IR PICs – Results on MUX/DEMUX

SiGe/ Ge MIR-PICs



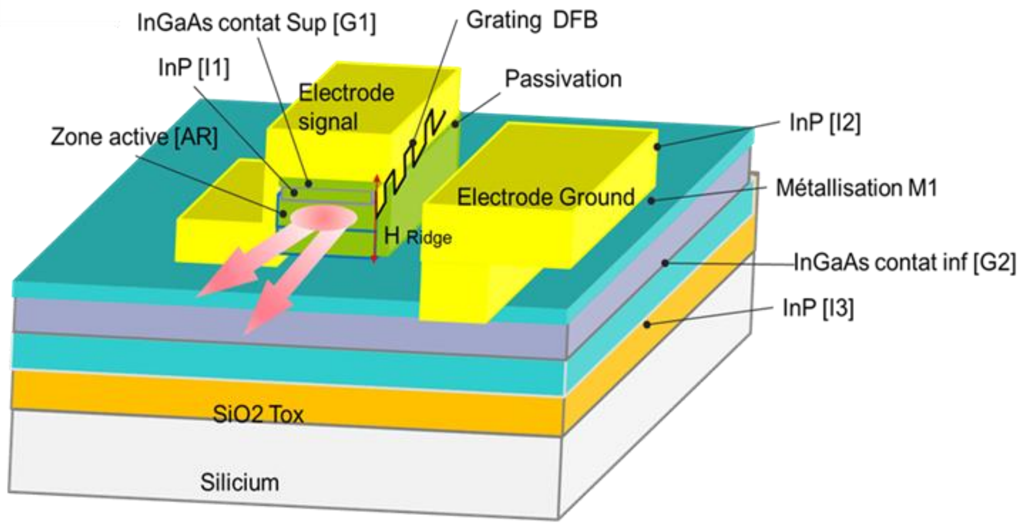


- Mid-IR photonics circuit based on $Si_{60}Ge_{40}/Si$
  - Wavelength range: 3µm – 8µm
  - Propagation loss: 0.3dB/cm (@4.5µm)
  - Combiner 35 inputs with low insertion loss (-1.6 dB)
  - cross talk < -12 dB
- Mid-IR photonics circuit based on Ge/SiGe
  - Wavelength range: → 12µm
  - Propagation loss: 5dB/cm (@9.5µm)

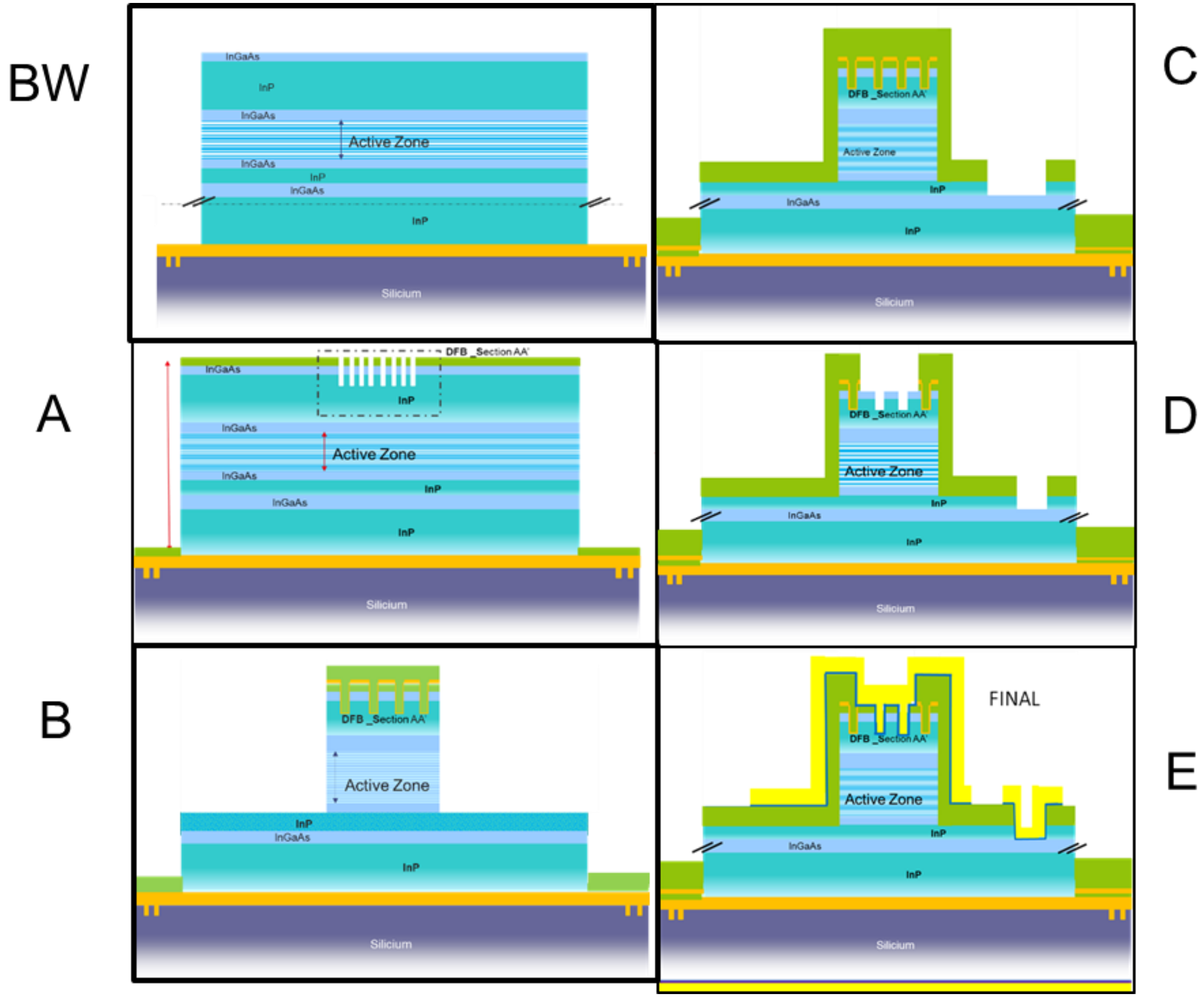


Heterogeneous integration on Silicon: a 200mm platform for large-scale and high-yield production

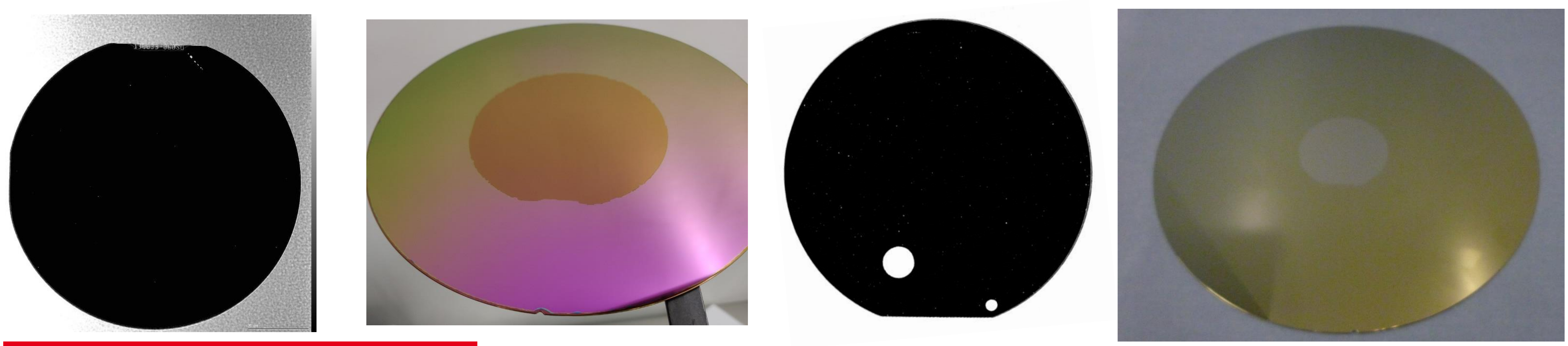
Integration scheme developed @ Leti



- Process Flow
  - WB: wafer bonding & substrate removal
  - A: DFB definition
  - B: DFB encapsulation and ride waveguide definition
  - C/D: passivation and contact opening
  - E: Metallization / contact definition

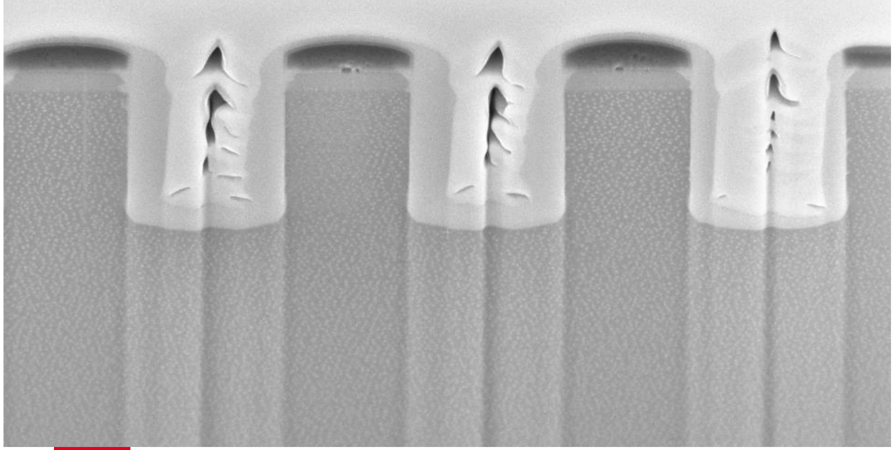


2” & 4” wafer bonding and InP substrate removal

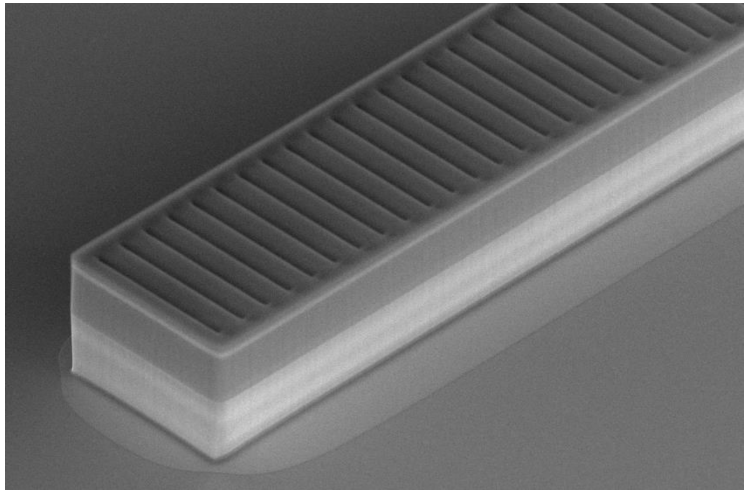


DFB etching / definition

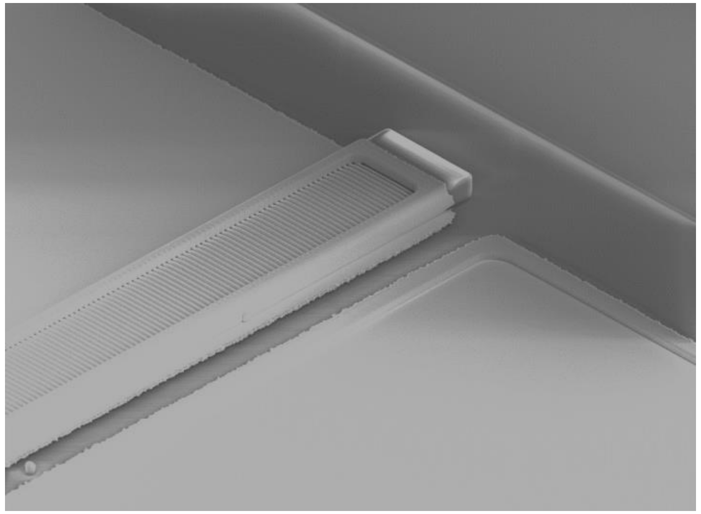
(with specific EP-detection)



Deep ridge QCL waveguide



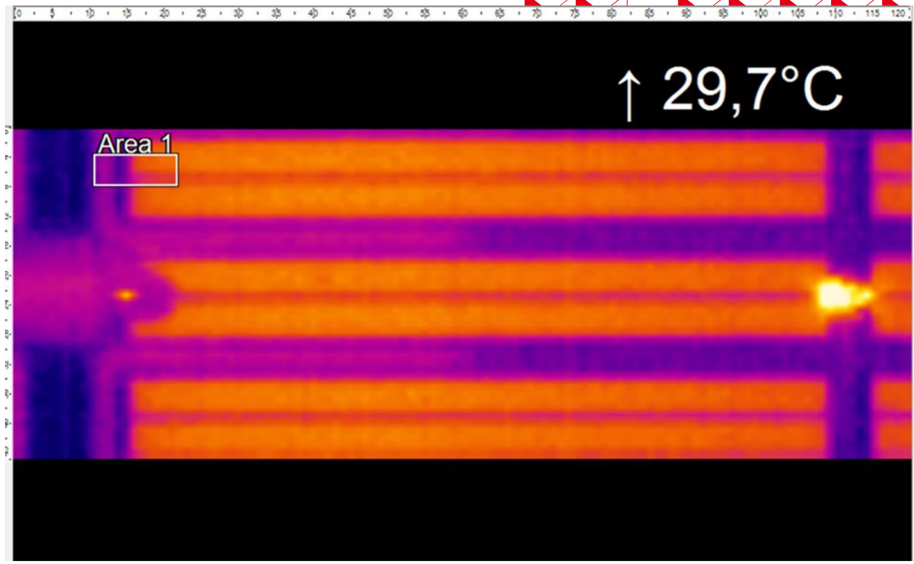
Metallization

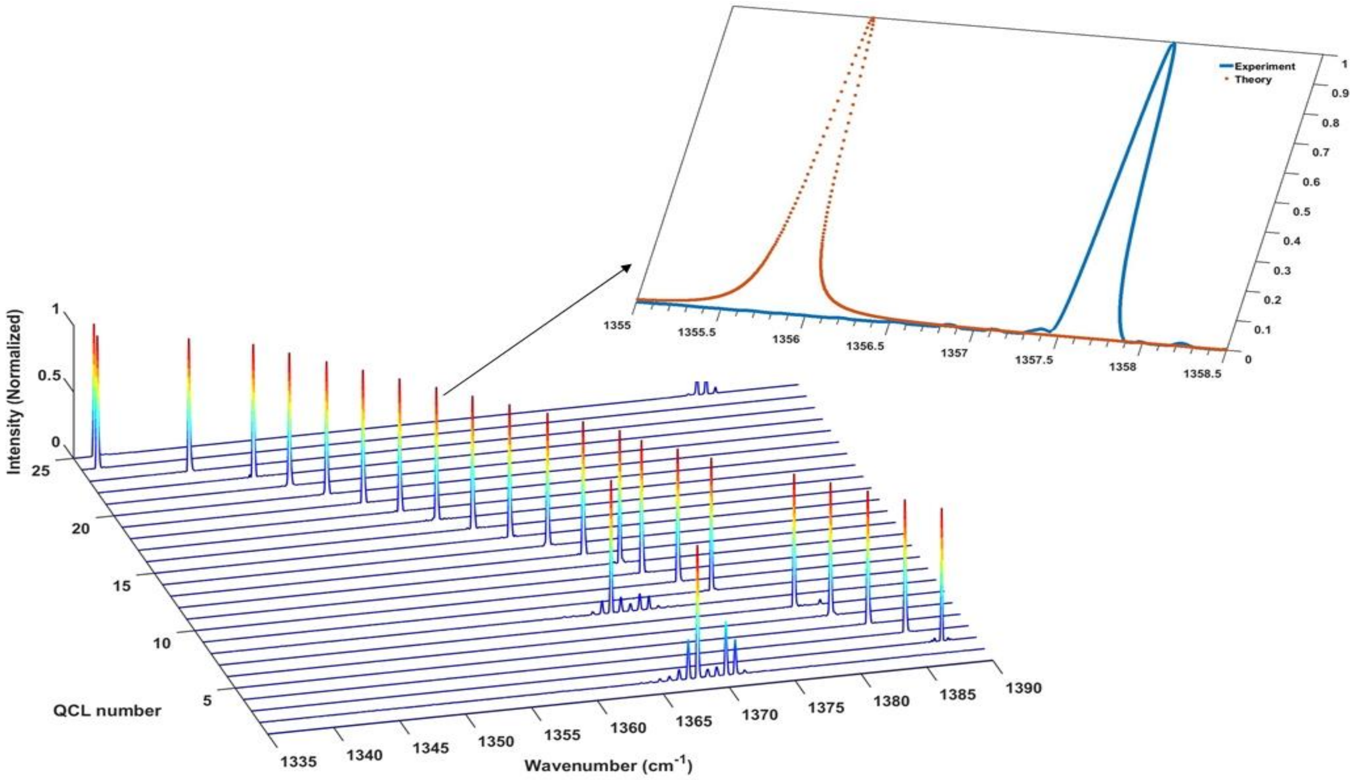


III/V Silicon QC-Lasers

Results

- High yield
- C-MOS/MEMS compatible process
- Performances to be improved (issues on cladding absorption, heating, metallization…)



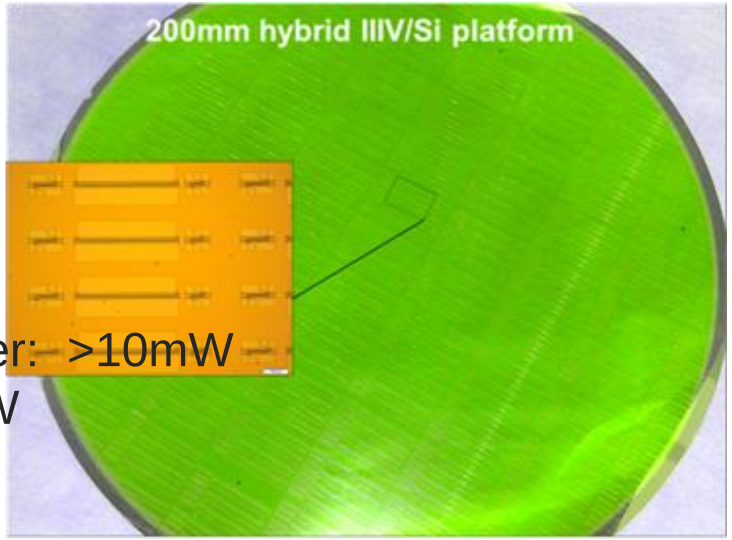


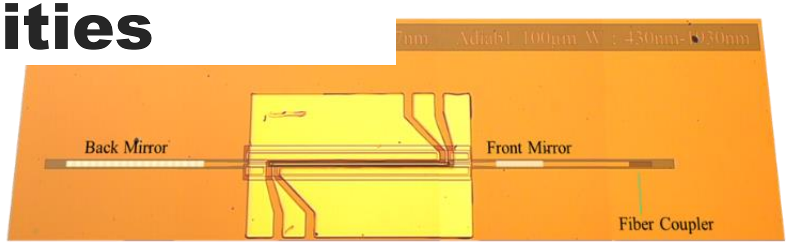
Further integration on Silicon: Hybridization of III-V and Si waveguides for a wealth of new functionalities

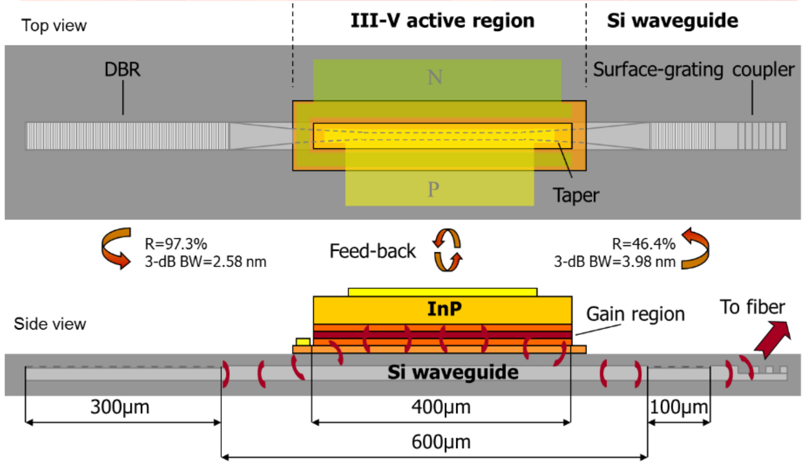
Example: DBR-laser in the NIR

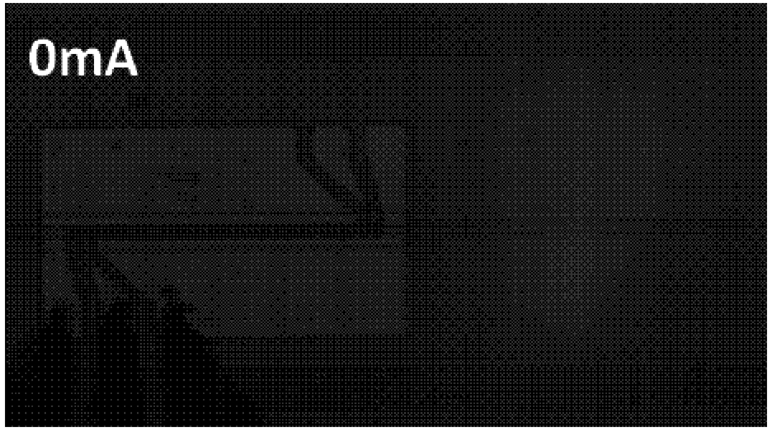
400µm-long gain section:

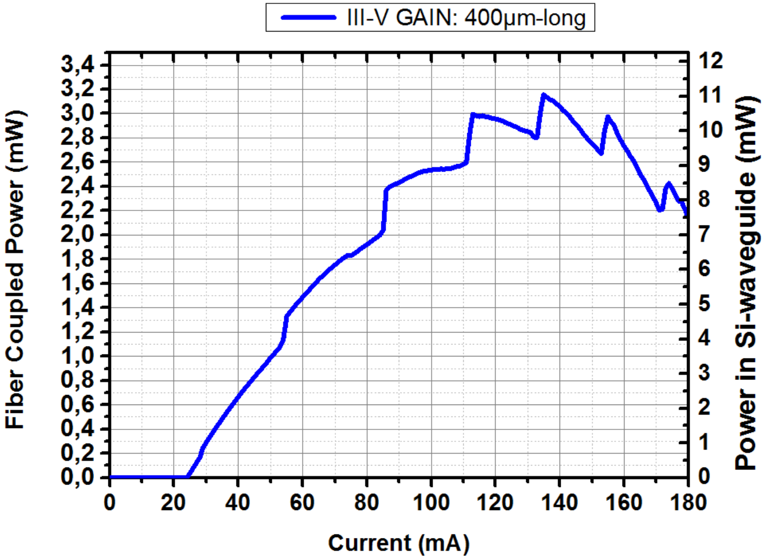
- Laser threshold @ RT: 25mA
- Max. Si-Waveguide coupled power: >10mW
- Max. Fiber coupled power: > 3mW
- SMSR: 55dB

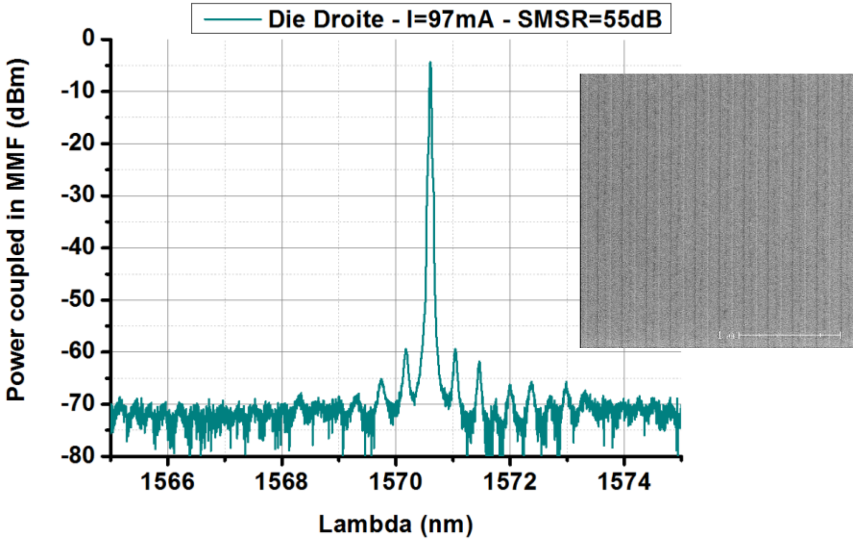






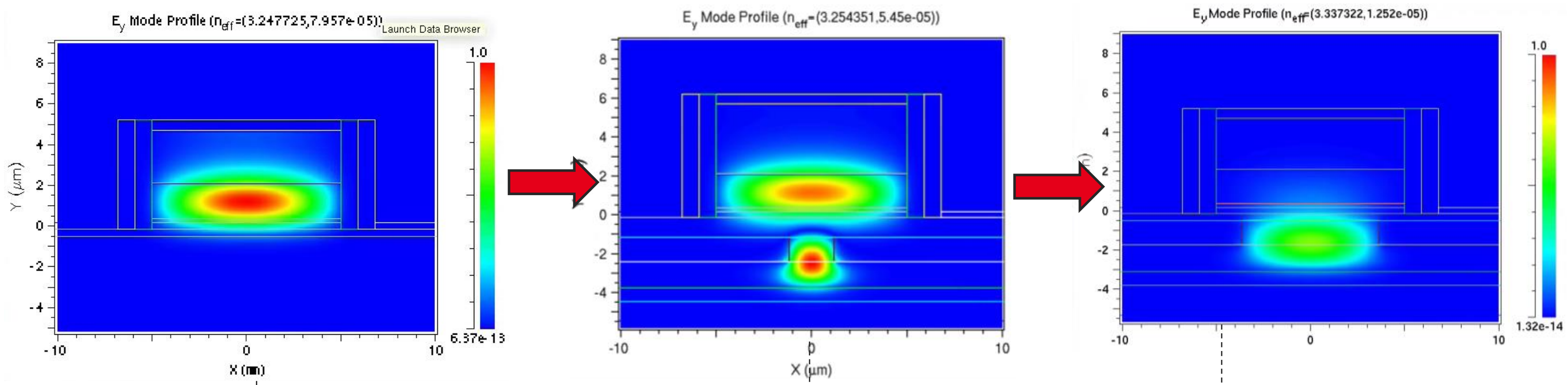






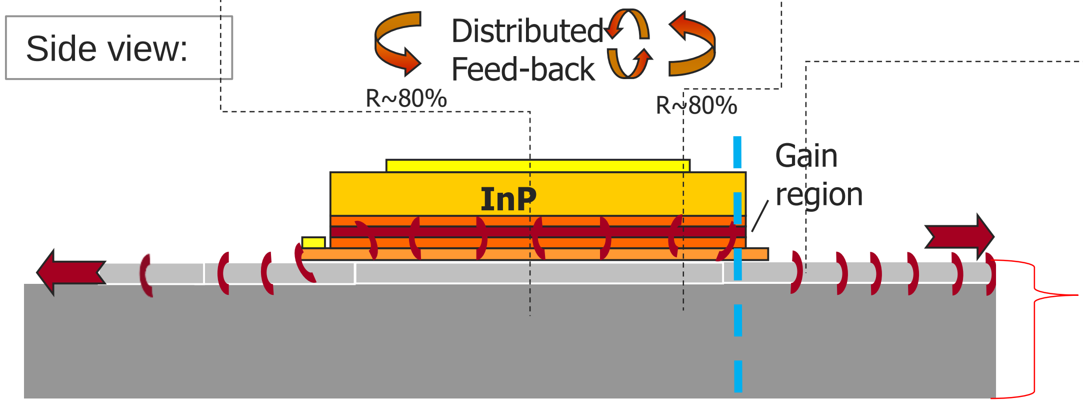
Design & fabrication of a hybrid Si-III/V QCL @ 4.5µm

Efficient power transfer of theTM00 laser mode



- Coupling scheme based on a high index contrast platform

Side view:


Distributed Feed-back

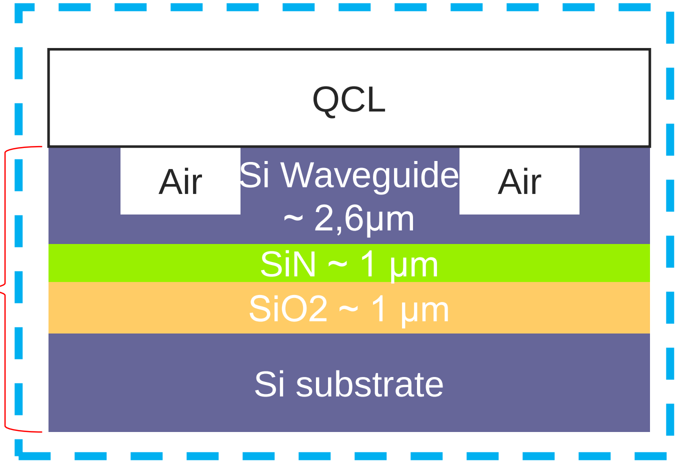
R~80%

R~80%

InP

Gain region

Cross section:


QCL

Air

Si Waveguide ~ 2,6µm

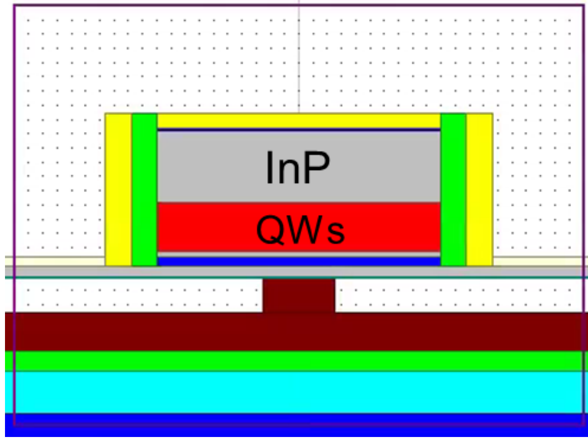
Air

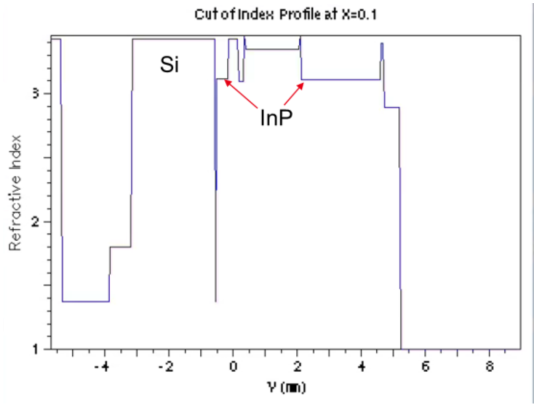
SiN ~ 1 µm

SiO2 ~ 1 µm

Si substrate

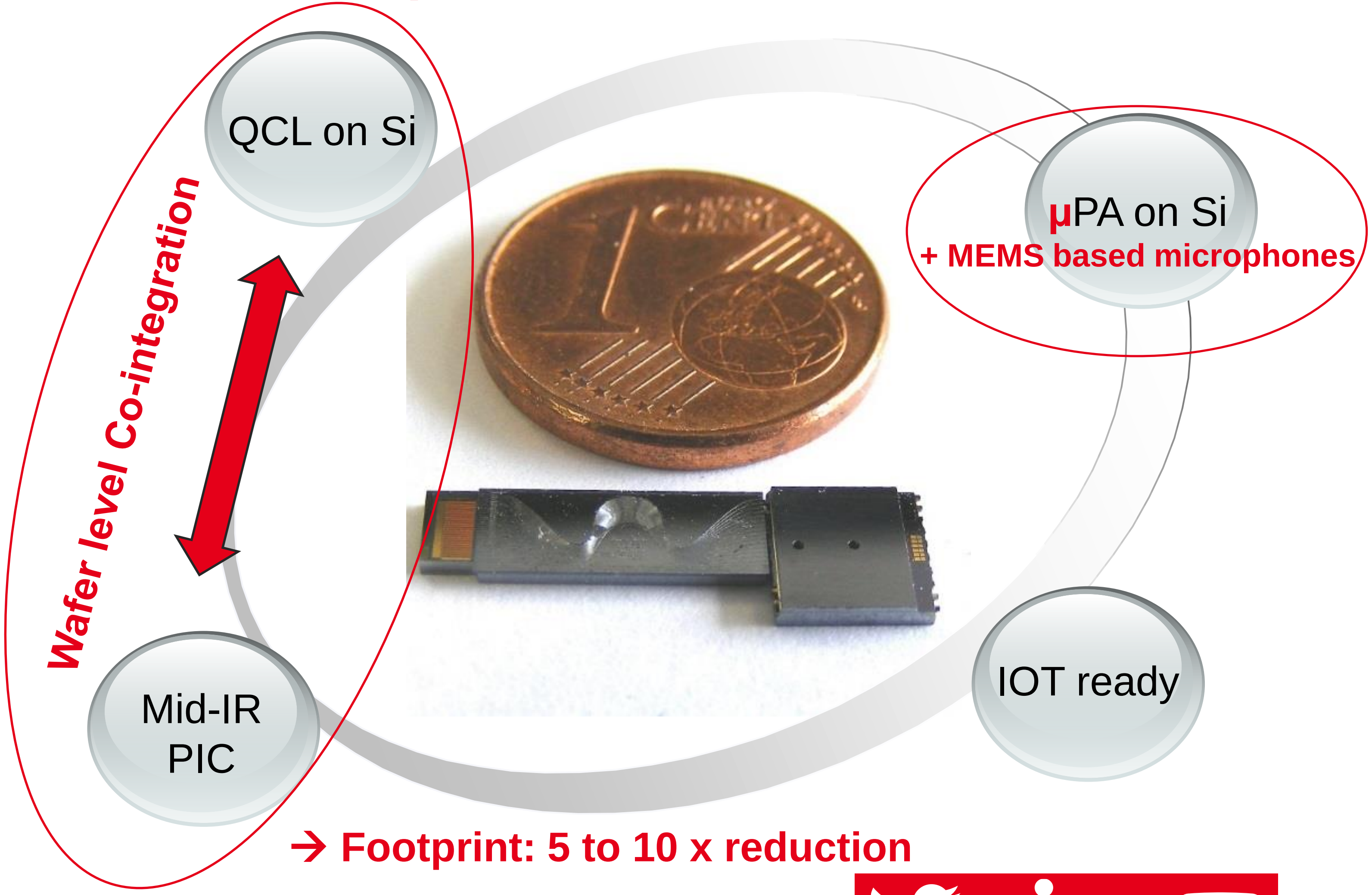
New Si (or SiGe) / SiN Platform
Under construction





On-Chip PA Sensors – Takeaway

Integration on Silicon for portable and wearable devices



QCL on Si

Wafer level Co-integration

Mid-IR PIC

µPA on Si

+ MEMS based microphones

IOT ready

→ Footprint: 5 to 10 x reduction

Industry
Process control
Emission monitoring

Defense
Hazardous chemical detection

Healthcare
Breath analyses
Early diseases detection

Environment
Air quality monitoring

Research for industrial innovation

Thanks for your attention!

Feel free to contact us for further discussions and/or future collaborations

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Business Developer

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Dr. Badhise Ben Bakir

Senior Scientist

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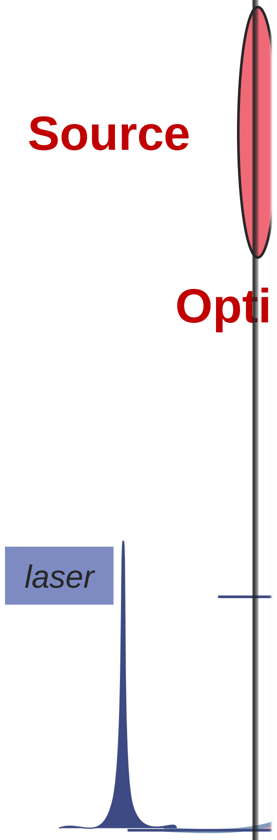
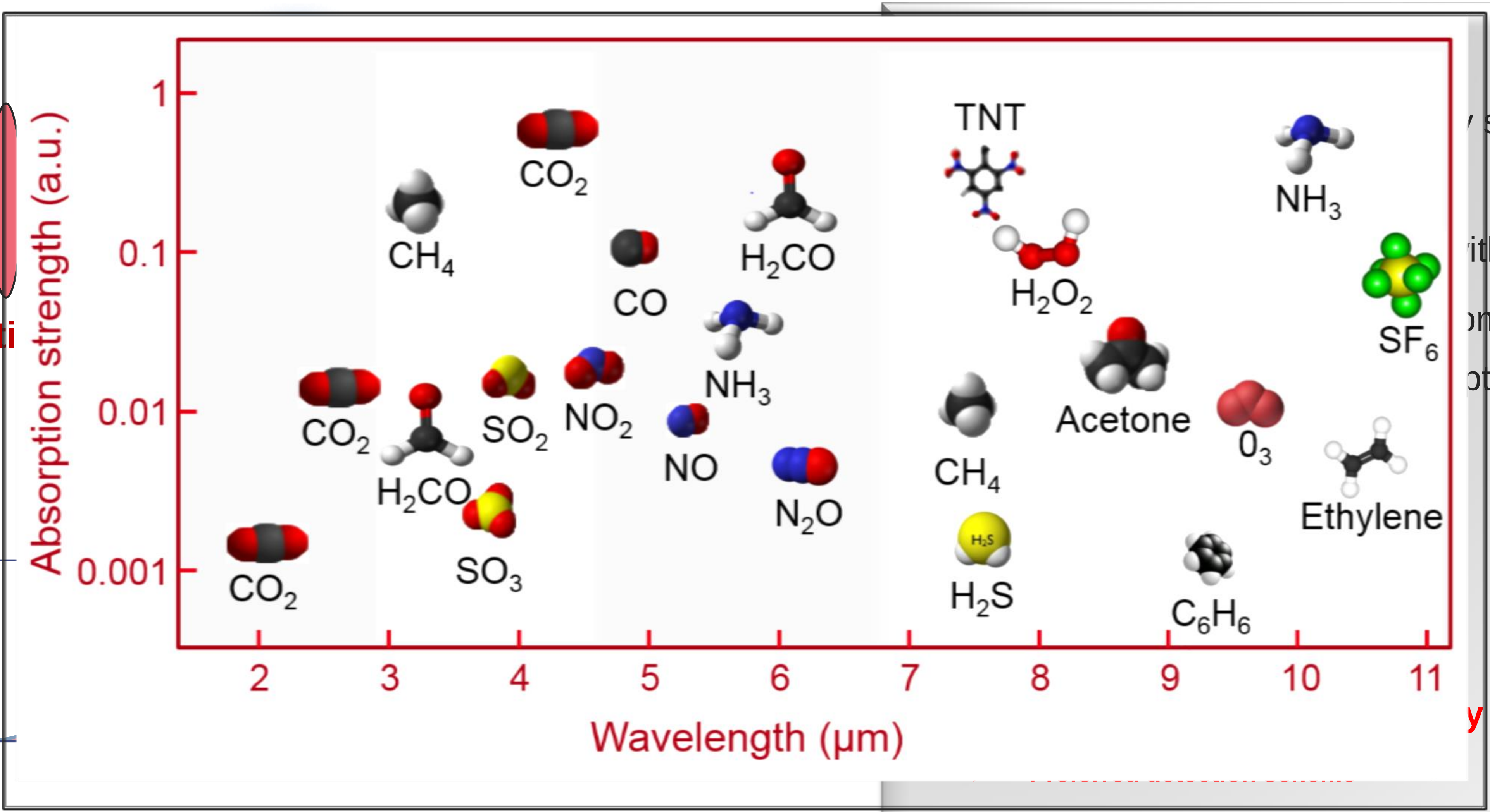
Optics and Photonics Department

CARNOT Research for industrial innovation

The Principle of Optical Detection





source and

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omatic laser

tion lines

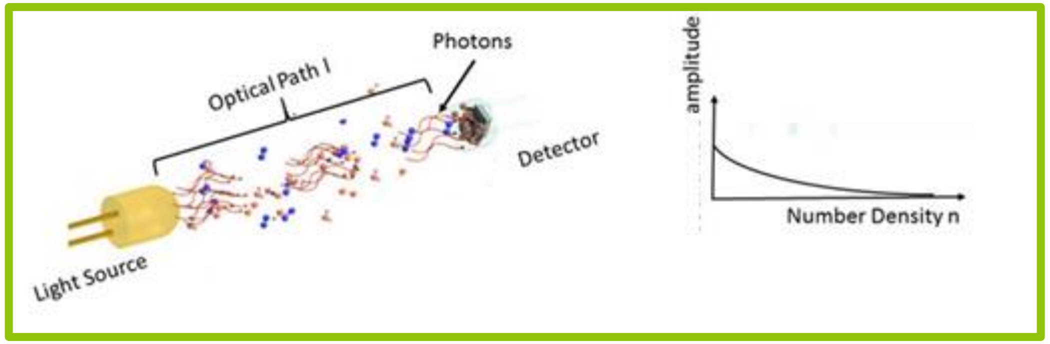
y

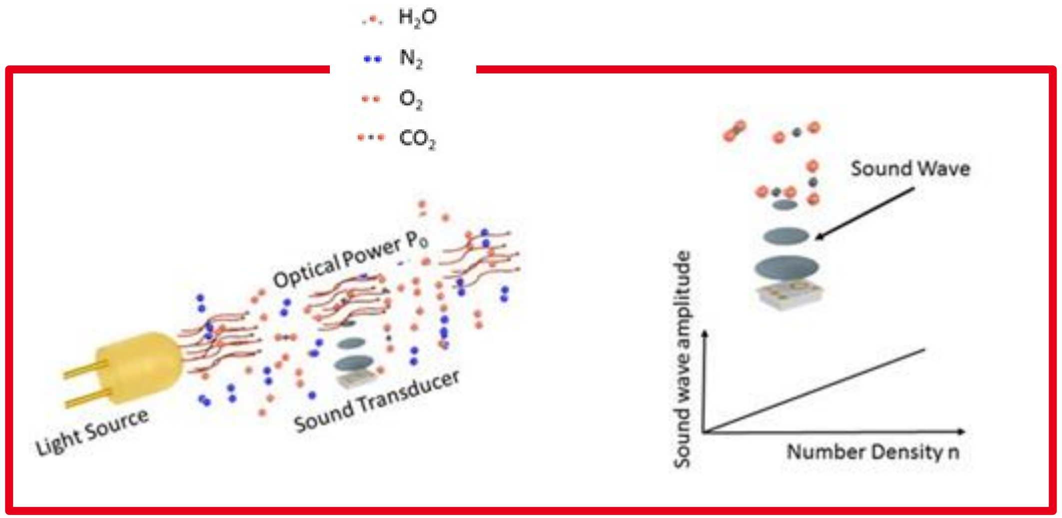
- ➢ **Responds to size, cost & performances criteria**

(TD)LAS – (Tunable Diode) Laser Adsorption Spectroscopy
or QCL/ICL + PA Cell

The Principle of Optical Detection

Direct absorption versus Photoacoustic





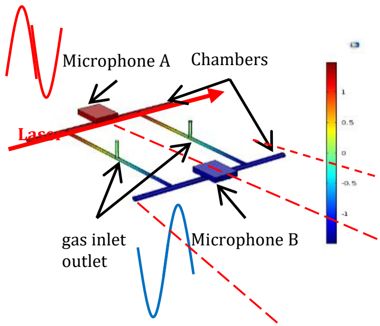
Direct Absorption

$$S_{direct} \propto P_0 . e^{-\alpha.(C_{gas}).L}$$

Beer- Lambert

Photoacoustic

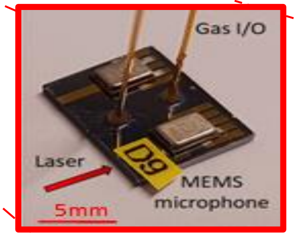
Differential Helmholtz resonant photoacoustic cell

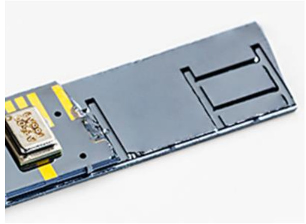


Size reduction

→ *Easy integration*

$$S_{PA} \propto \frac{\alpha(C_{gas})}{\sqrt{V_C}} P_0$$





Sensors **2020**, 20, 2745; doi:10.3390/s20092745