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

COST Action TD1105

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*Innovations and Challenges for Air Quality Control Sensors*

FFG - Austrian Research Promotion Agency - Austrian COST Association

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# CMOS INFRARED EMITTERS AND DETECTORS FOR ENVIRONMENTAL MONITORING


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**Function in the Action:** WG Member

**United Kingdom**

CAMBRIDGE CMOS SENSORS



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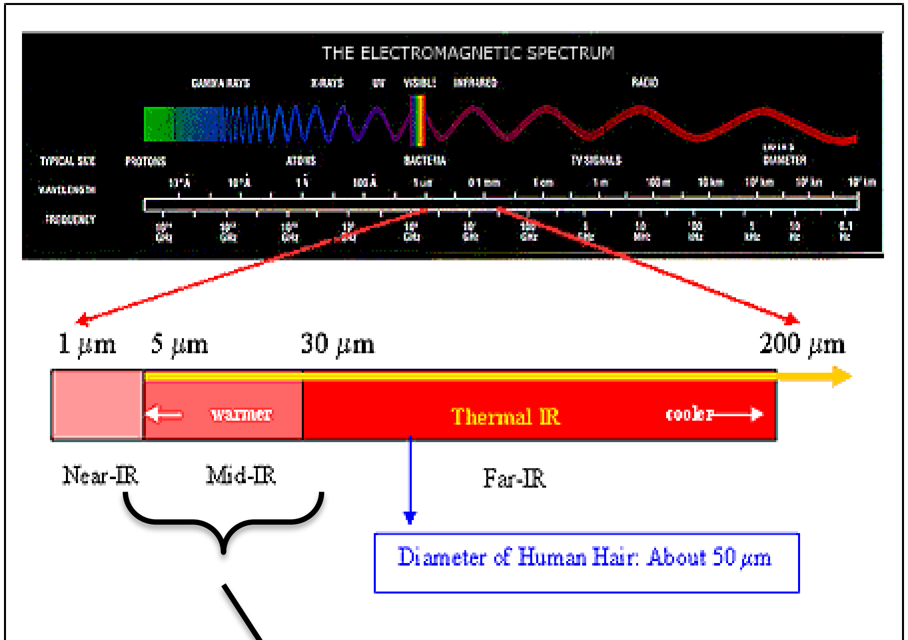
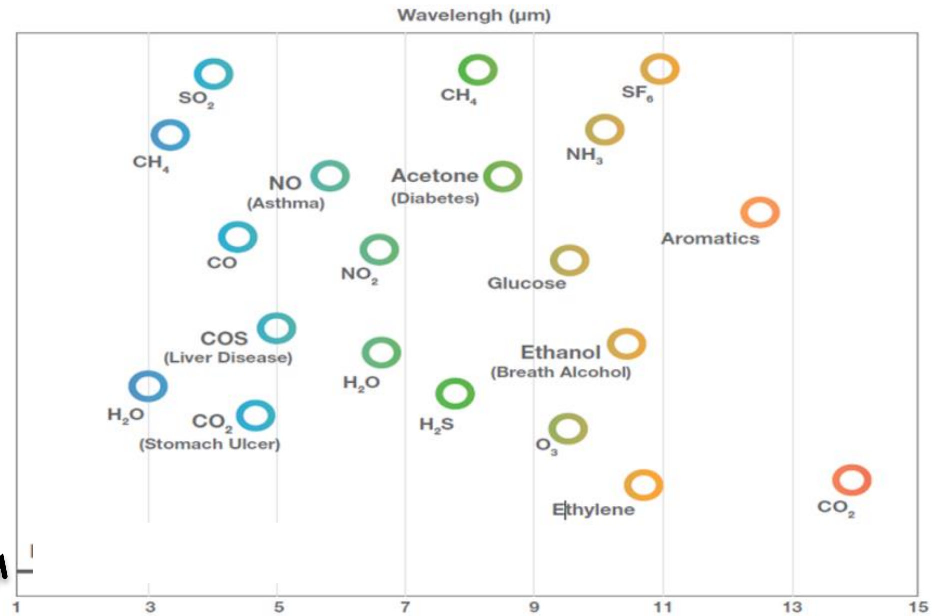
# Environmental pollution is a BIG concern!

**More than 3 million people a year die prematurely from outdoor air pollution, more than Malaria and HIV/Aids – and this will double by 2050**

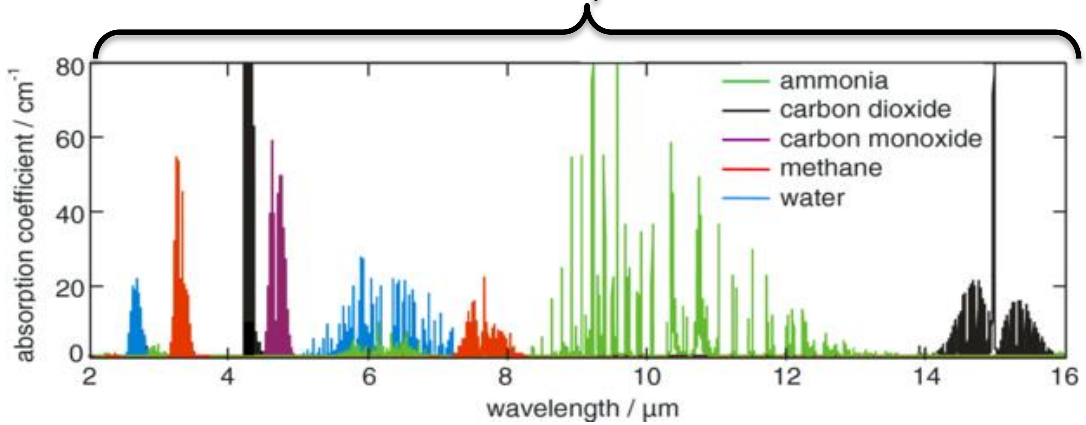
*Source: Nature, September 2015*

# Mid-Infrared Spectrum



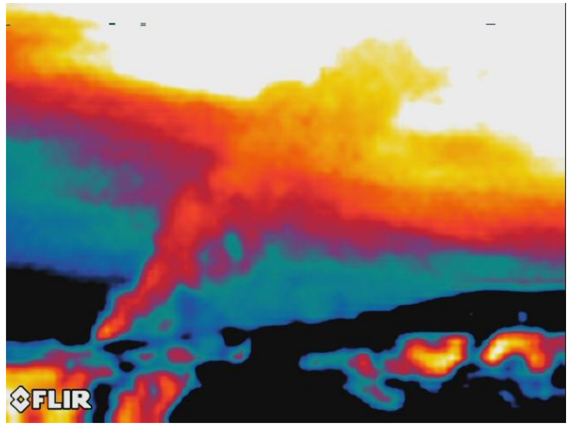



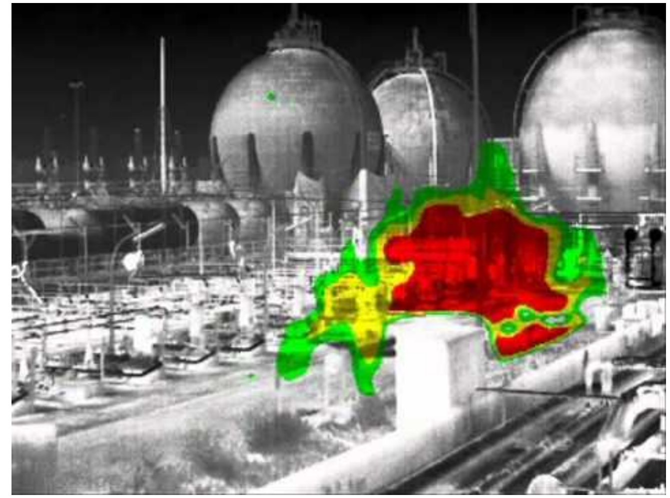

Other Mid-IR gases




Key environmental gases

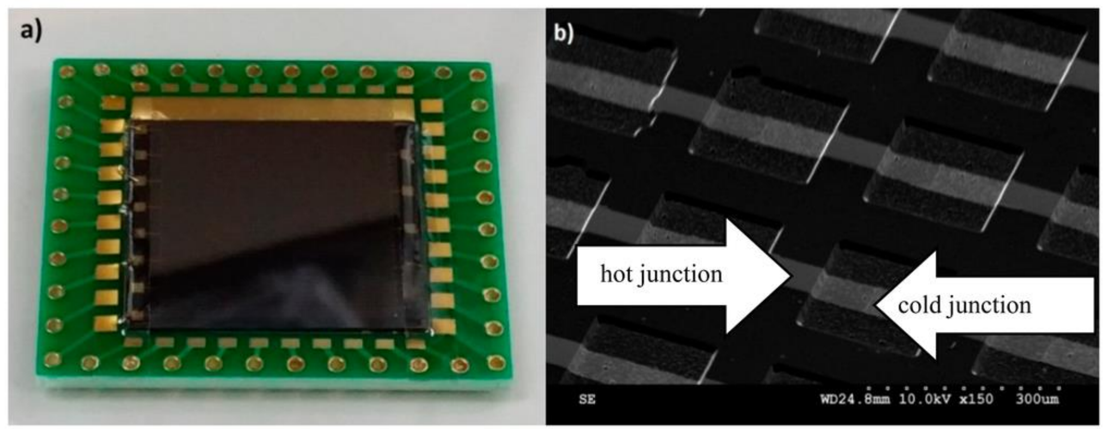
# Mid-Infrared Instrumentation



IR imaging to detect gas leaks, types of gas emission etc

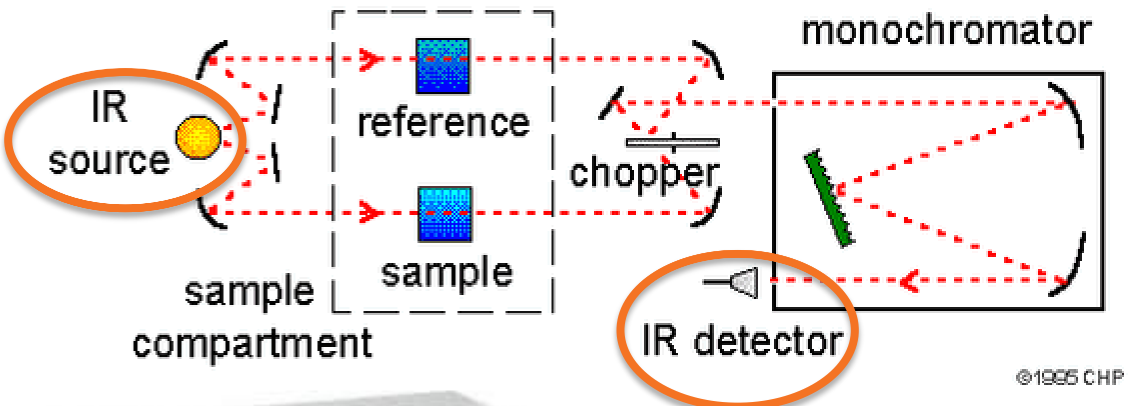
Smartphone with IR imaging




Low-cost thermopile IR image sensor

# Mid-Infrared Instrumentation

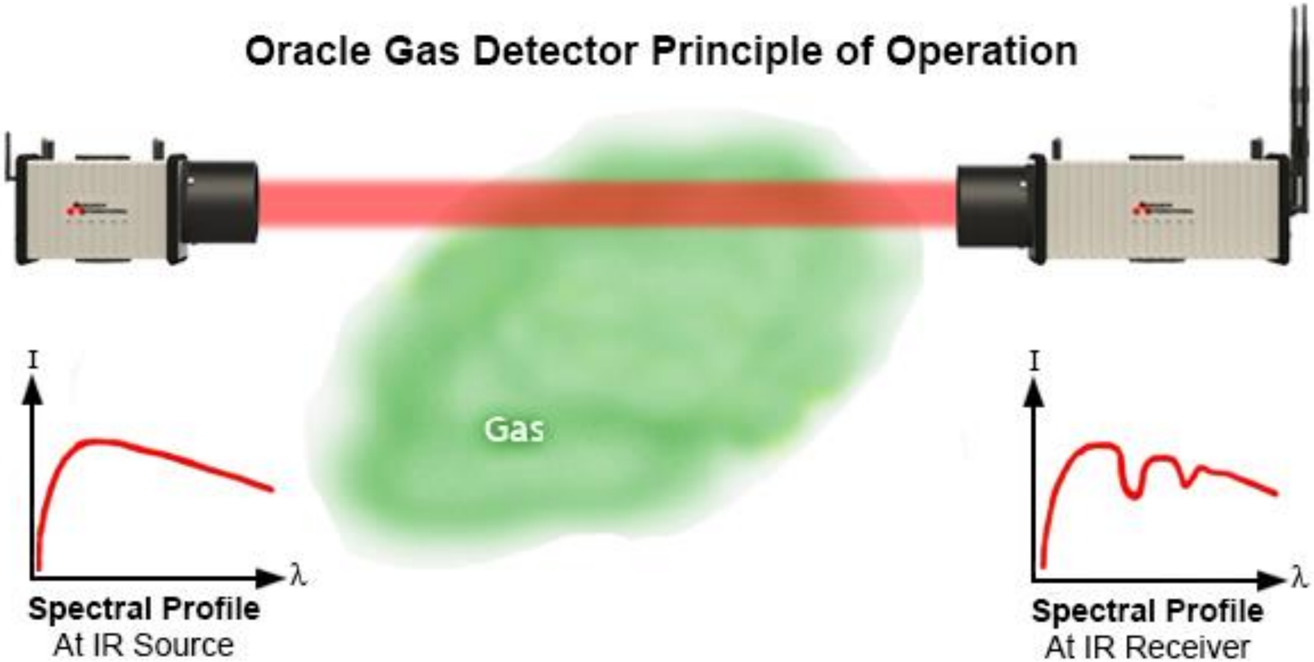
- IR spectrometry works similar principles as spectrometry.
- IR light is absorbed at a specific wavelength and this is detected to identify the molecule.
- IR radiation causes the molecules to vibrate.
- The vibration of the bonds in a molecule depend on the energy absorbed.
- The IR spectrometer detects how the absorption varies with each bond and produces an IR spectrum.




- The IR lamp emits broadband radiation.
- The light passes through the sample and the reference sample.
- The light is then passed through a chopper and passed to monochromator.
- This allows the correct light through to the detector.
- The computer translates the information and outputs and IR spectrum.


Low-cost ATR spectrometer for liquid

# Mid-Infrared Instrumentation




- Remote IR source
- Analysis of transmitted beam at receiver in the 3-5μ and 8-12μ spectral ranges
- Absorption "fingerprint" provides gas identification and concentration estimate
- Ideal for subways, airports, chemical facility perimeter

http://www.resrchintl.com/Gas_Detection.html

Portable

"Wearable"

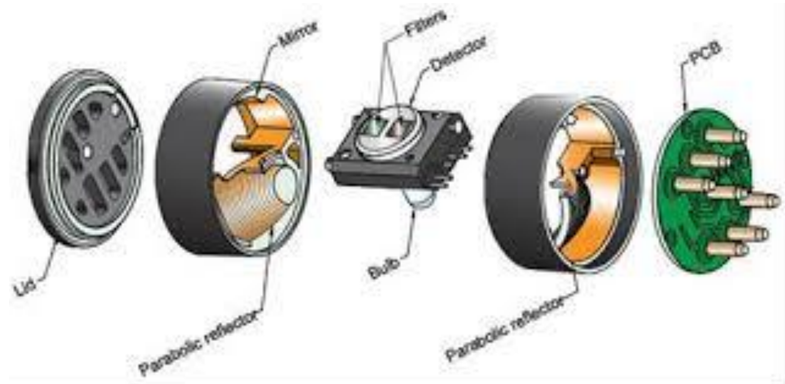
**Industrial and scientific equipment**

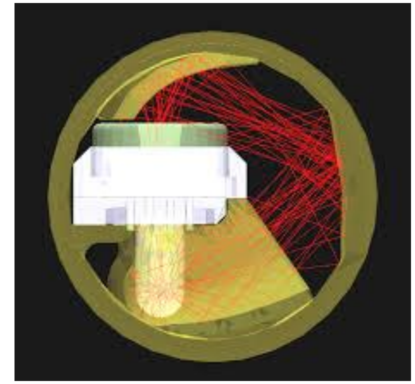
# Mid-Infrared Sensor



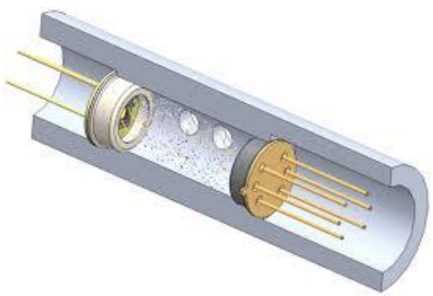

**IR Sensors are getting more compact**

# Construction of typical NDIR Sensors

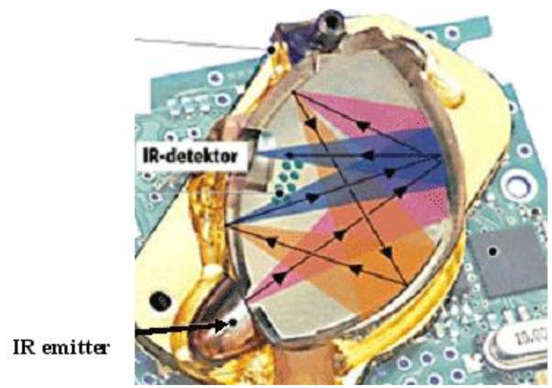



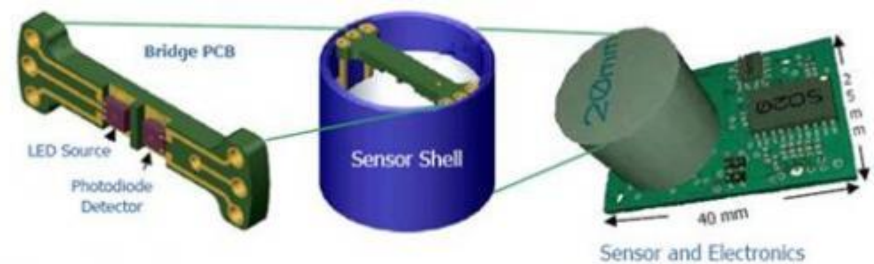
Compact “electrochemical” type



Simple face-to-face tube type




Complex longer path



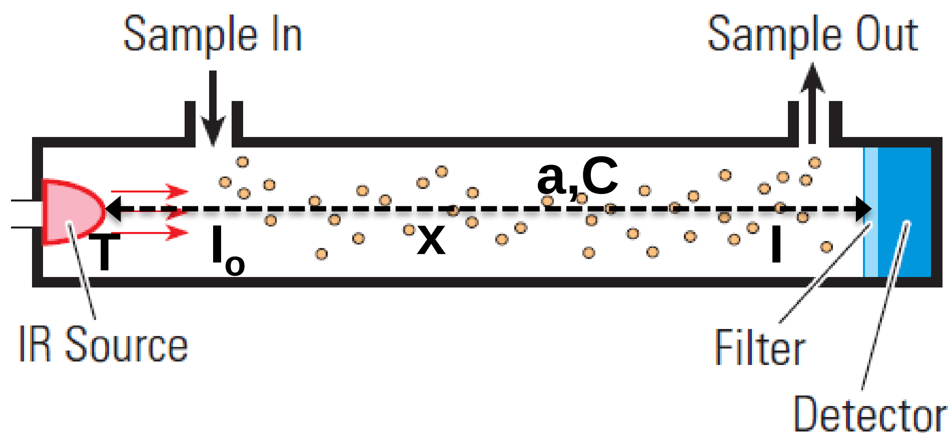

LED and Photodiode

***Key components: Emitter -> Optical Path -> Filter -> Detector -> Electronics***

# Non-Dispersive Infrared (NDIR) Fundamental

## Beers Law

$$T = I/Io = e^{(-axC)}$$




where:

| | |
|---|---|
| T | = Transmittance of light through the gas to the detector |
| I | = light intensity after absorption by gas |
| Io | = light intensity at zero $CO_2$ concentration |
| a | = specific gas molar absorption coefficient |
| x | = path length |
| C | = gas concentration |

# How compact NDIR sensor be made?

**Concentration (C) = (ln(I/Io)) / (a*x) or**

**Path length (x) = (ln(I/Io)) / (a*C)**

**I and Io -** are measured by detector (SNR of the instruments readout)

**a -** is a constant (e.g $CO_2$ molar absorption coefficient at a wavelength of 4.6 µm)
***(Typically, a ~ 1.73 x $10^6$ $cm^2$ $mol^{-1}$ at 27°C and 170bar)***

***Typical path length needed:***

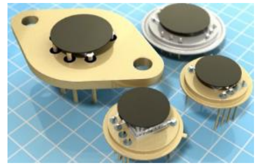
- ***5000ppm >>> at lease 30mm (Environment)***
- ***50000ppm <<< less than 10mm (Breath analysis)***

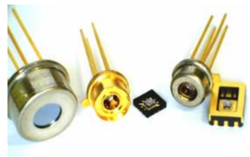
***Essentially higher the C shorter the path length***

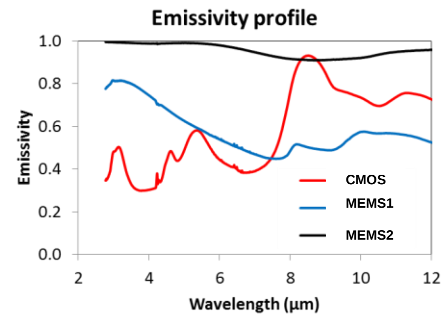
# Types of infrared sources

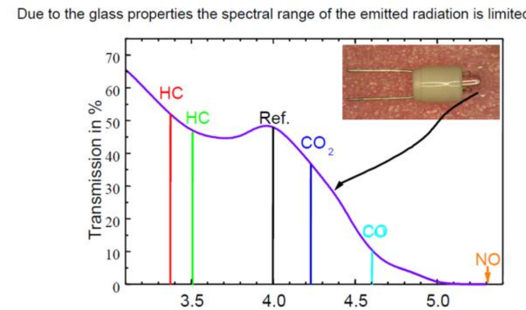
## Thermal

- Micro-bulb
- Black-body
- MEMS



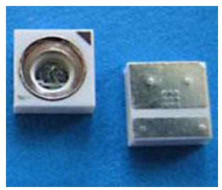


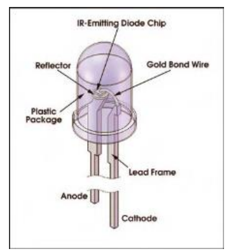


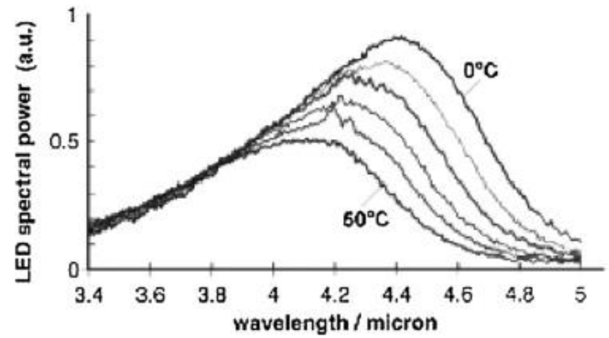




## Light Emitting Diode

- Band-gap
- Quantum-Well

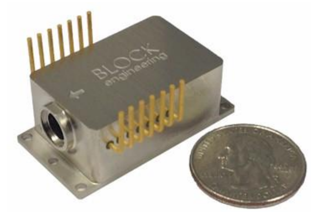


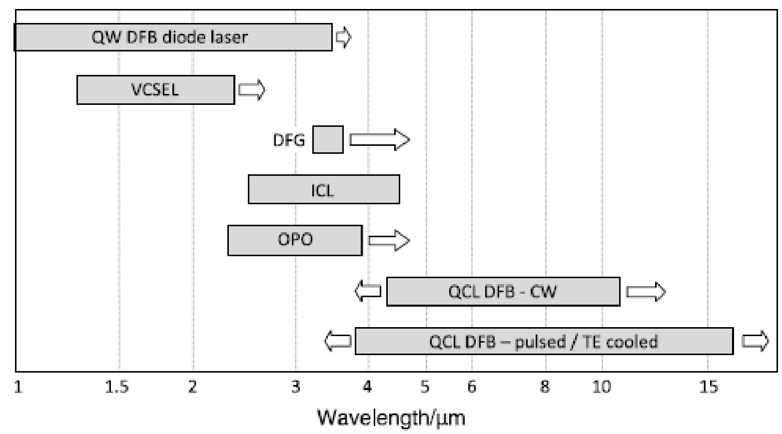



## Laser

- TLDS
- QCL



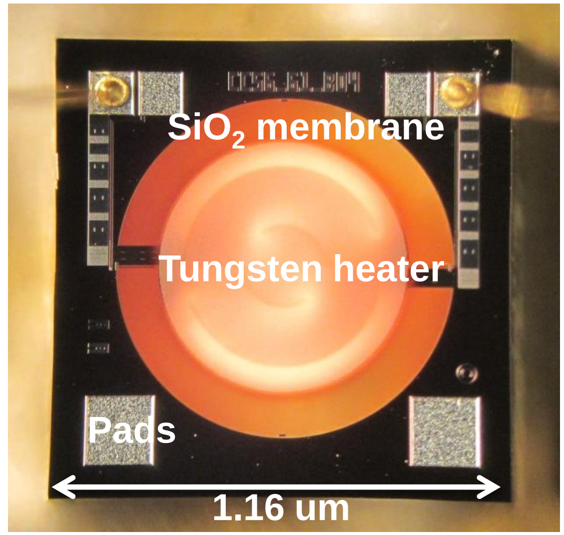


# CMOS infrared sources

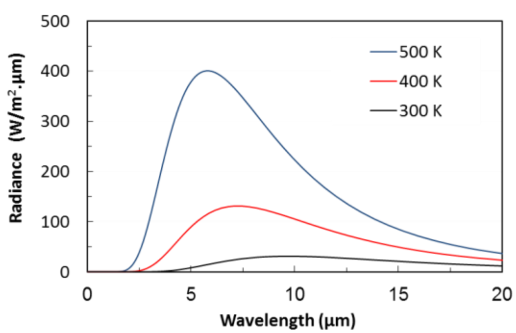
- Radiated power (*W*) from a source:

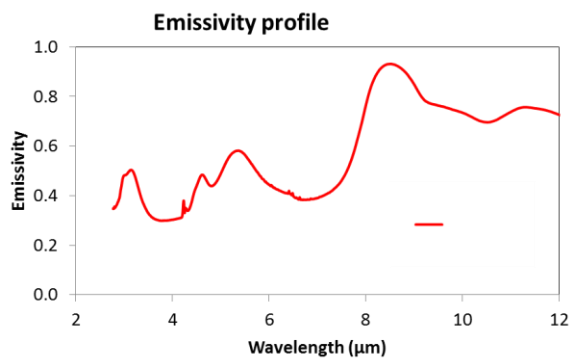
$$W = Ae\sigma T^4$$ ← Stefan–Boltzmann law

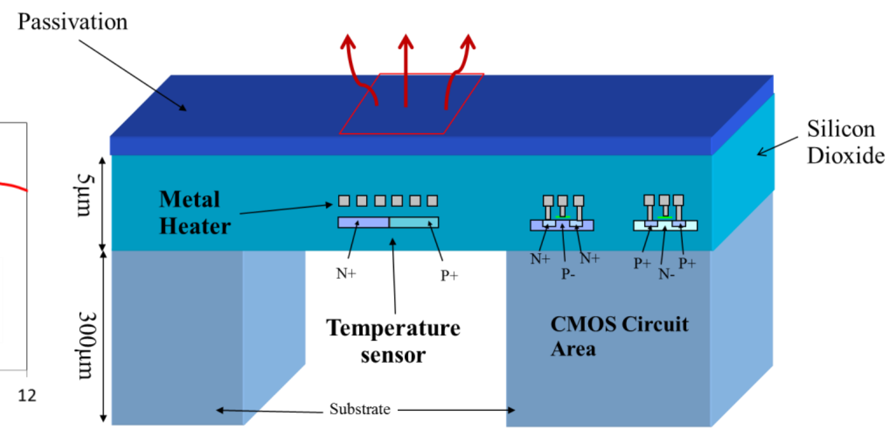
- Radiated power (*W*) from a source can be maximised by increasing the heater area (*A*), emissivity (*e*) and temperature (*T*)
- Emissivity (e) is the efficiency of a material to emit infrared radiation relative to a blackbody (perfect emitter) at a given wavelength
- A blackbody has an emissivity of 1




IR source




Typical CMOS Process

# Summary of Mid-IR source

| Type | Power | Spectrum | Directivity | Cost | Freq | Filter |
|---|---|---|---|---|---|---|
| Thermal | Medium | Wide | Low | Low | Low | Yes |
| Mid-IR LED | Medium | Narrow | Med | Med | Medium | No |
| IR Laser | High | Very Narrow | High | High | High | No |

# Comparison of Mid-IR Sources

| Parameter | CMOS MEMS | Other MEMS | Filament Bulb | LED | QCL | TDL |
|---|---|---|---|---|---|---|
| Full Broad wavelength (2-14um) | ✓ | ✓ | x | x | x | x |
| DC Power Consumption < 50mW + | ✓ | x | x | ✓ | x | x |
| High Optical Output Power Option - | ~ | ✓ | ✓ | x | ✓ | ✓ |
| 50% Modulation > 50Hz | ✓ | ✓ | x | ✓ | ✓ | ✓ |
| Lifetime > 10000 hours * | ✓ | ~ | ~ | ✓ | x | ~ |
| Thermal Stability < 5% over lifetime | ✓ | ~ | x | ~ | x | ~ |
| High Selectivity | ~ | ~ | ~ | ~ | ✓ | ✓ |
| High Volume/Mass Market Capability | ✓ | ~ | ✓ | ~ | x | x |
| High Reproducibility | ✓ | x | x | ~ | ~ | ~ |
| Low Cost High Volume | ✓ | x | ✓ | x | x | x |
| Calibration free | ✓ | ~ | x | x | x | ~ |
| CMOS Compatible | ✓ | ~ | x | x | x | x |
| On-chip temperature sensing/driver | ✓ | ~ | x | x | x | x |
| Compact | ✓ | ✓ | ~ | x | x | x |
| Harsh Environment (>125 ºC) | ✓ | ~ | x | x | x | x |

**✓ Yes; ~ Possibly; x No**
*** Depends on operating mode**
**+ smallest low power option**
**- Output power can be increased, but much lower than QCL and TDL**

# Basic IR Detection Principle

The radiation absorption induces a temperature change in the sample

$$\nabla \cdot \left(\underline{k} \nabla T\right) = G_A - G_R$$

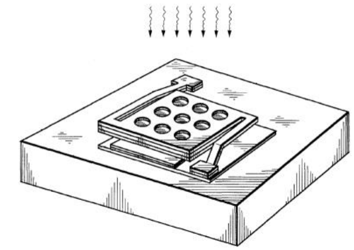
where

| | |
|---|---|
| $\underline{k}$ | sample thermal conductivity matrix |
| $G_A = \frac{A \cdot P}{d}$ | heat generation due to the IR radiation |
| $G_R \sim 8 \varepsilon \sigma_S T_0^3 \Delta T$ | heat dissipated by radiation. |

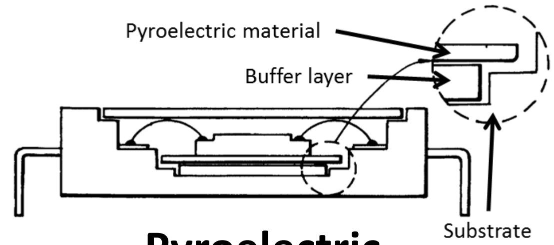
with

| | |
|---|---|
| $A, d, \varepsilon$ | layer absorptivity, thickness and emissivity |
| $\sigma_S$ | Stephan-Boltzmann constant |

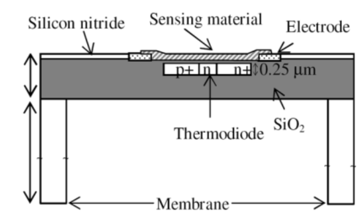
*They all use this relation to sense the IR signal power*



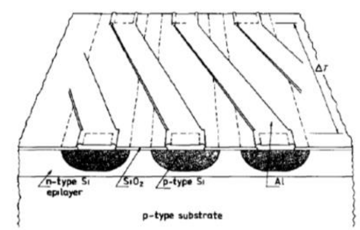
**Microbolometer**




**Pyroelectric**




**Thermodiode**



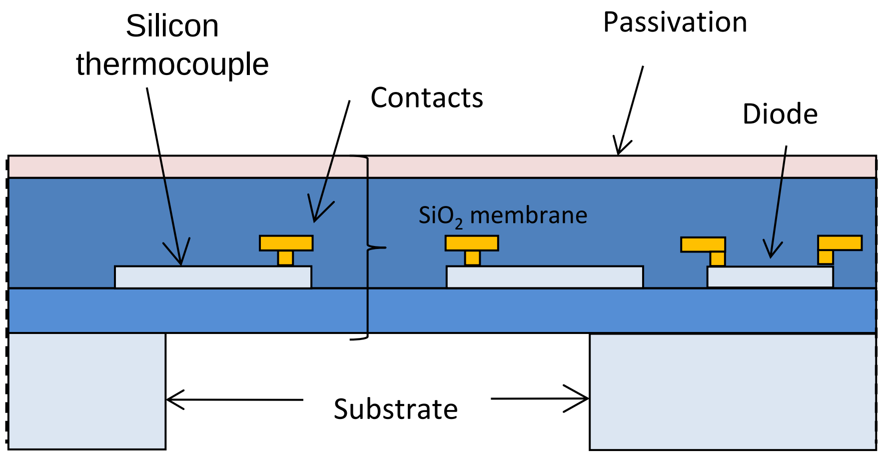
**Thermopile**

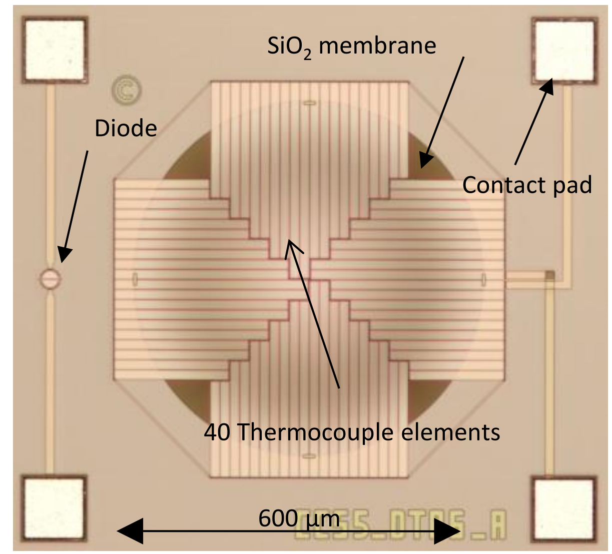
# Comparison of Mid-IR Detectors

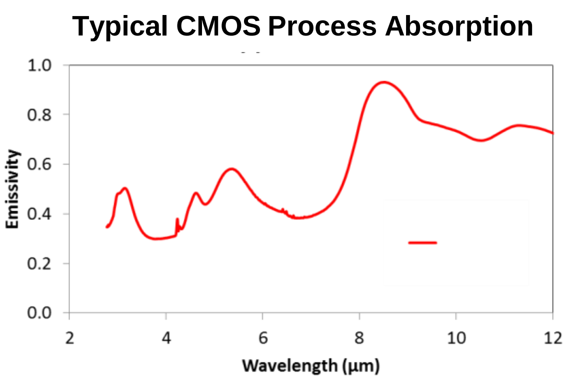
| Device | Pros | Cons |
|---|---|---|
| Microbolometer | • low **cost**<br>• low **weight**<br>• low **power dissipation**<br>• wide **spectral response**<br>• high **thermal insulation** | • require **additional steps and materials** not included in the standard CMOS technology. |
| Pyroelectric detector | • **competitive** in 8–12 $\mu$m range<br>• Do not need **cooling**.<br>• **good speed**.<br>• output **unrelated to the wavelength** | • requires **materials non compatible** with CMOS standard technology.<br>• **high performance readout amplifier** |
| Thermopile | • no **offset error** and **offset drift**<br>• **interferences** only with light.<br>• **readout** very easy<br>• **compatible** with CMOS techology | • **limited thermal resistance**<br>• high **electrical resistance** |
| Thermodiode | • **high** electrical and thermal **insulation.**<br>• absence of **heat flux**<br>• absence of **cross-talk**<br>• higher **maximum temperature** | • **sensitivity** lower than other solution.<br>• High sensitivity configurations increase **noise** and **self-heating.** |
| Photoelectric detectors | • order of magnitude **faster** than other presented sensors. | • **high input power** |

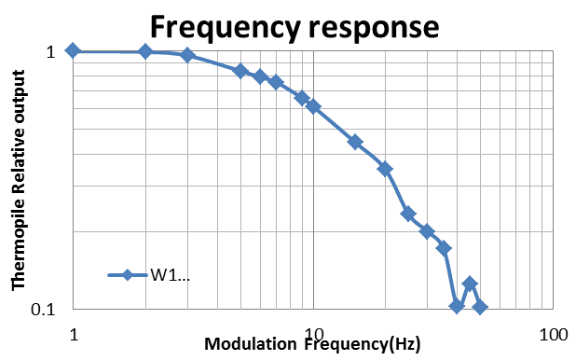
# CMOS infrared detector

Design: CMOS thermopile with Tungsten interconnects. $SiO_2$ membrane of high thermal resistance to enhance the IR heating of the thermopile



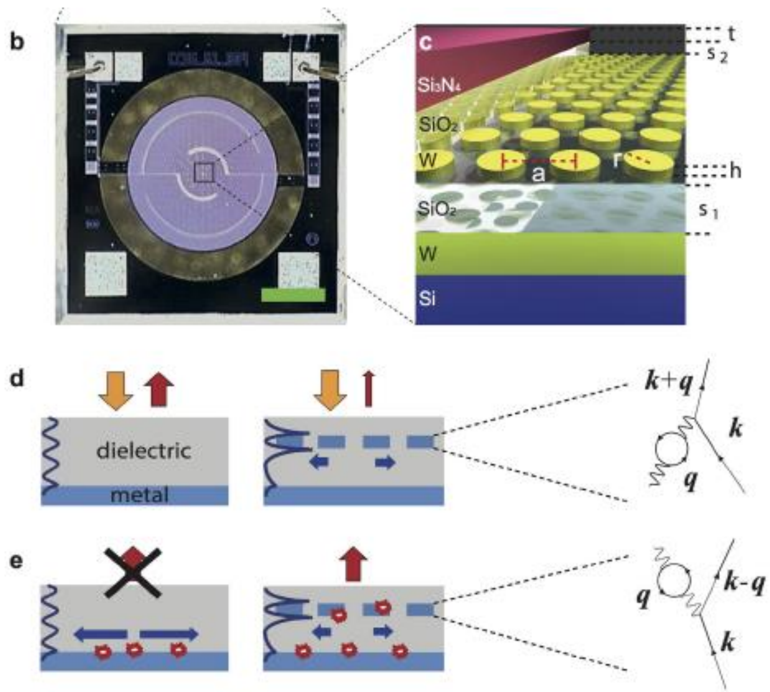



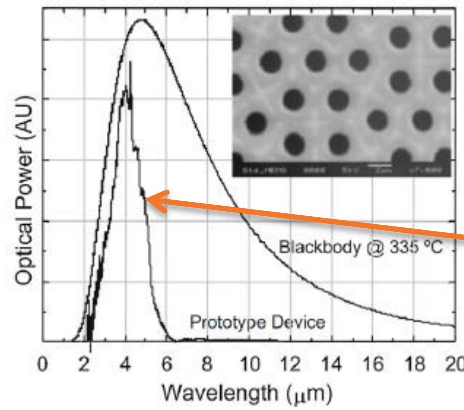




1.16mm x 1.06mm chip, Sensing area $0.3mm^2$

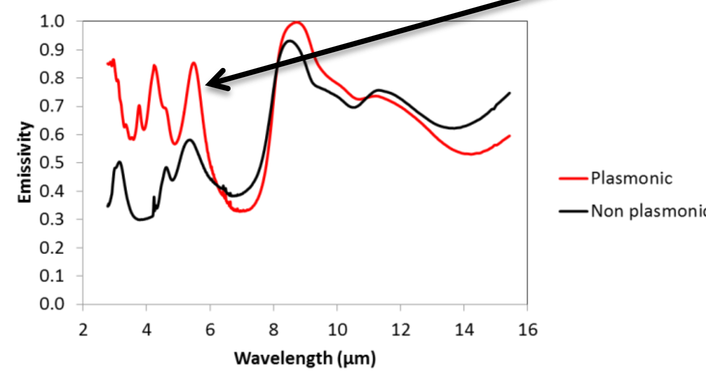
# CMOS IR emission and absorption enhancements

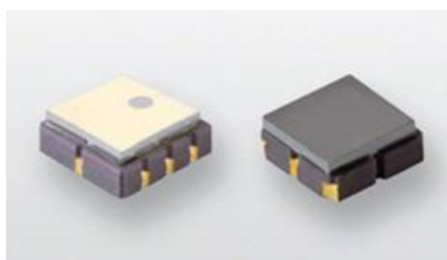


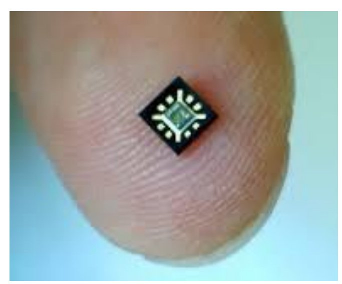



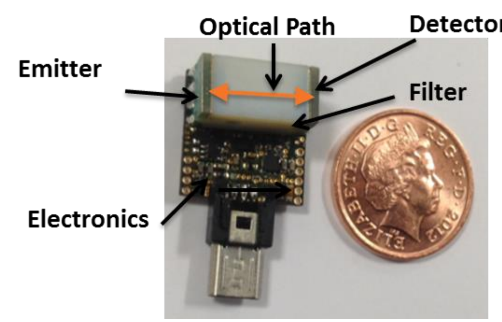

Now much Compact NDIR sensors are possible

Enhanced emissivity







# Possible applications CMOS IR devices for environmental gas sensing

| Gas | Wavelength | Path length | Det Limit | Technique | With CMOS |
|---|---|---|---|---|---|
| NH3 | 10.34um | 76m | 0.2ppb | Direct TDLS | No |
| | 9.7um | 1.5m | 80ppm | NDIR | May be |
| | 1.532um | 4cm | 50ppb | TDLS PAS | Yes |
| CO2 | 1.603um | 12km | 0.1ppm | CRDS | No |
| | 4.26um | 40cm | 25ppm | NDIR | Yes |
| | 4.24um | 1m | 16ppb | FTIR | May be |
| CO | 1.564um | 4.2km | 12ppb | OA-ICOS | No |
| | 4.43um | 30cm | 1.1ppm | Direct TDLS | Yes |
| | 4.6024um | 400m | 0.2ppb | ICOS | No |
| H2S | 1.5745um | 10cm | 0.17ppm | Direct PAS | Yes |

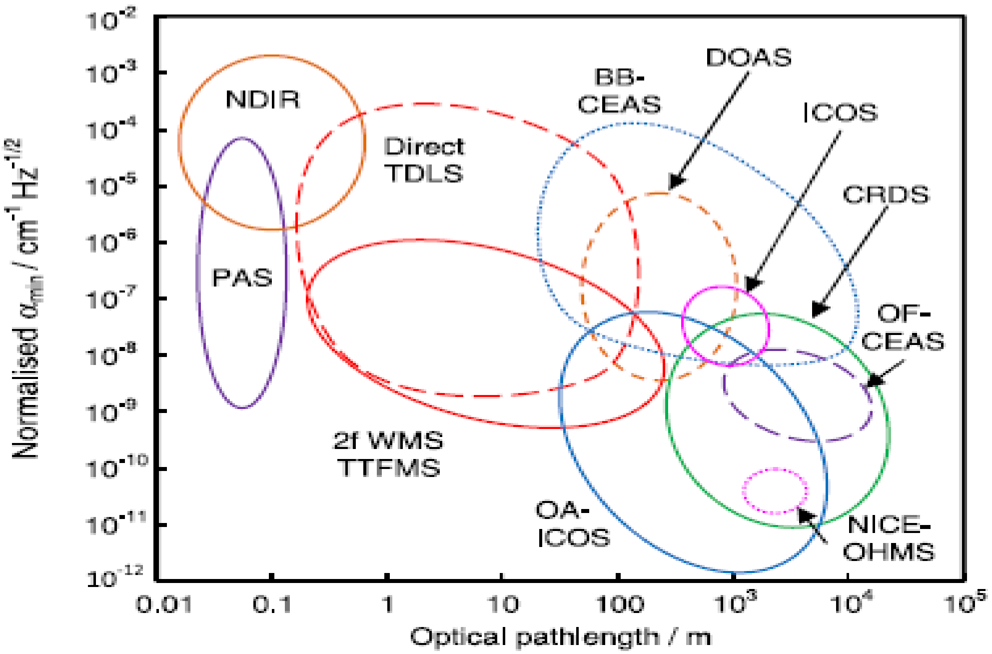
# Possible applications CMOS IR devices for environmental gas sensing

| Gas | Wavelength | Path length | Det Limit | Technique | With CMOS |
|---|---|---|---|---|---|
| CH4 | 1.654um | 2.1km | 0.3ppb | OA-ICOS | No |
| | 3.3um | 4cm | 170ppm | NDIR | Yes |
| | 3.3um | 1.4mm | 5ppm | Correlation | Yes |
| NO | 5.263um | 1.5km | 0.7ppb | ICOS | No |
| | 5.263um | 21cm | 2.7ppm | Direct TDLS | Yes |
| | 5.405um | 76m | 0.2ppb | 2f WMS | No |
| N2O | 7.84um | 1km | 2ppb | OF-CEAS | No |
| | 6.2um | 4m | 2ppm | NDIR | May be |
| | 5.4um | 50cm | 10ppm | Direct TDLS | Yes |
| | 7.87um | 76m | 0.16ppb | Direct TDLS | No |

# Possible applications CMOS IR devices for environmental gas sensing

| Gas | Wavelength | Path length | Det Limit | Technique | With CMOS |
|---|---|---|---|---|---|
| NO2 | 6.09um | 2km | 1.2ppb | CRDS | No |
| | 6.25um | 9.2cm | 0.5ppb | PAS 300mW | Yes |
| | 6.23um | 40m | 75ppt | 2f WMS | No |
| SO2 | 7.505um | 1.44m | 2ppm | Direct TDLS | No |
| H2O | 1.651um | 12km | 50ppm | CRDS | No |
| | 1.396um | 5.3mm | 9ppm | QEPAS 8mW | Yes |
| | 1.3925 | 46.7m | 70ppt | 2f WMS | No |
| Benzene | 5.1um | 107m | 1ppm | 2f WMS | No |
| | 14.8um | 10cm | 11.5ppm | Direct TDLS | May be |
| Formaldehyde | 3.5um | 1.2km | 2ppb | CW CRDS | No |
| | 3.5um | 5.3mm | 0.6ppb | QEPAS 3mW | Yes |
| | 3.53um | 100m | 5ppt | WMS | No |

# IR gas sensing methods and path length

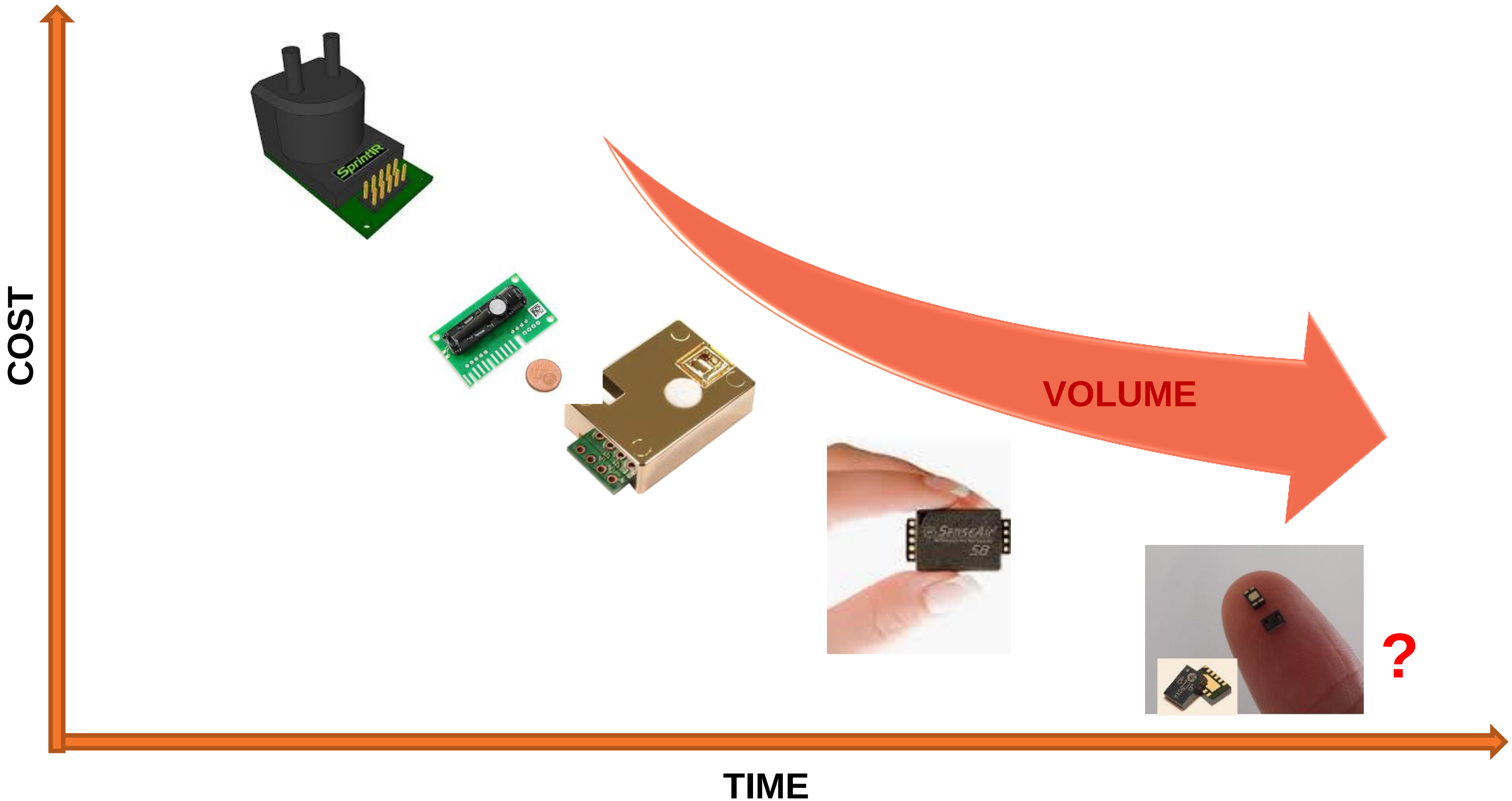



BB-CEAS—broadband cavity-enhanced spectroscopy,
OF-CEAS—optical feedback CEAS
CRDS—cavity ringdown spectroscopy, direct
TDLS—directly scanned tunable diode laser spectroscopy,
DOAS—differential optical absorption spectroscopy, 2 *f*
WMS—second harmonic wavelength modulation spectroscopy,
ICOS—integrated cavity output spectroscopy, OA-ICOS—off-axis ICOS,
NDIR—non-dispersive infrared,
NICE-OHMS—noise-immune cavity-enhanced optical heterodyne spectroscopy,
PAS—photoacoustic spectroscopy,
TTFMS—two-tone frequency modulation spectroscopy.

| Gas | With CMOS |
|---|---|
| NH3 | Yes |
| CO2 | Yes |
| CO | Yes |
| H2S | Yes |
| CH4 | Yes |
| NO | Yes |
| N2O | Yes |
| NO2 | Yes |
| SO2 | No |
| H2O | Yes |
| Benzene | May be |
| Formaldehyde | Yes |

***Yes – either IR emitter or detector or both (depends on the method used)***

# Future of NDIR gas sensors with CMOS solutions



# CONCLUSIONS

- CMOS IR emitters and detectors offers great potentials for NDIR environmental gas sensors miniaturisation.
- It will help to enable low cost, high volume capabilities.
- Potential integration of NDIR sensors in smartphones, wearables etc.
- Not all gases can be detected, but most can be!
- Very low concentration level of detection using compact design on NDIR may not be possible.
- Using PAS method it looks promising.
- IR components can be used for other purposes.

# Acknowledgements

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