FONDAZIONE BRUNO KESSLER | CENTER FOR SENSORS & DEVICES

INFN LNF
Istituto Nazionale di Fisica Nucleare

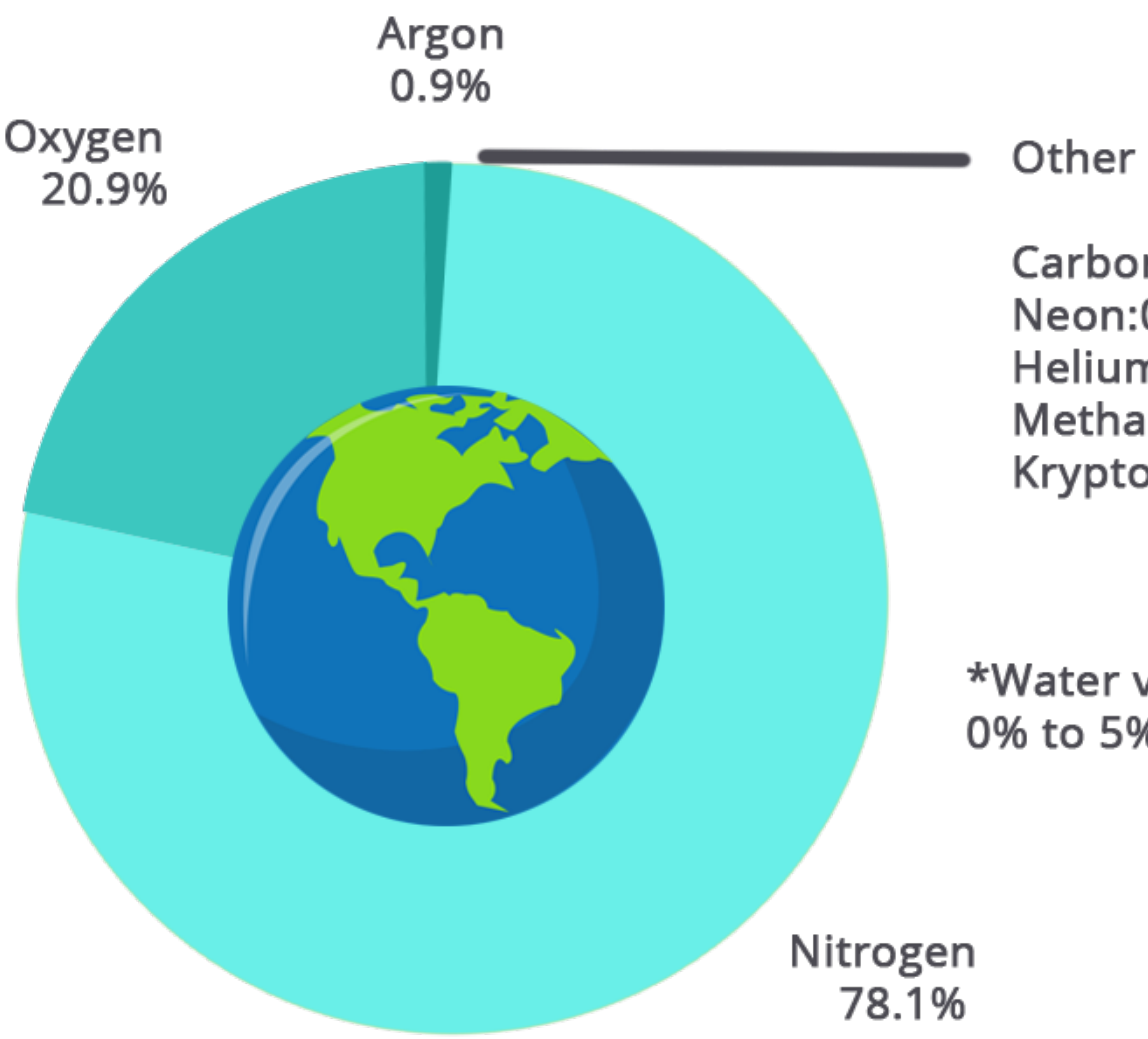
Nanotechnology for environmental monitoring

A. Gaiardo, P. Tosato, M. Valt
Center for Sensors & Devices
Fondazione Bruno Kessler

INSPYRE
INternational School on modern PhYsics and REsearch

mvalt@fbk.eu
www.fbk.eu

Air Composition



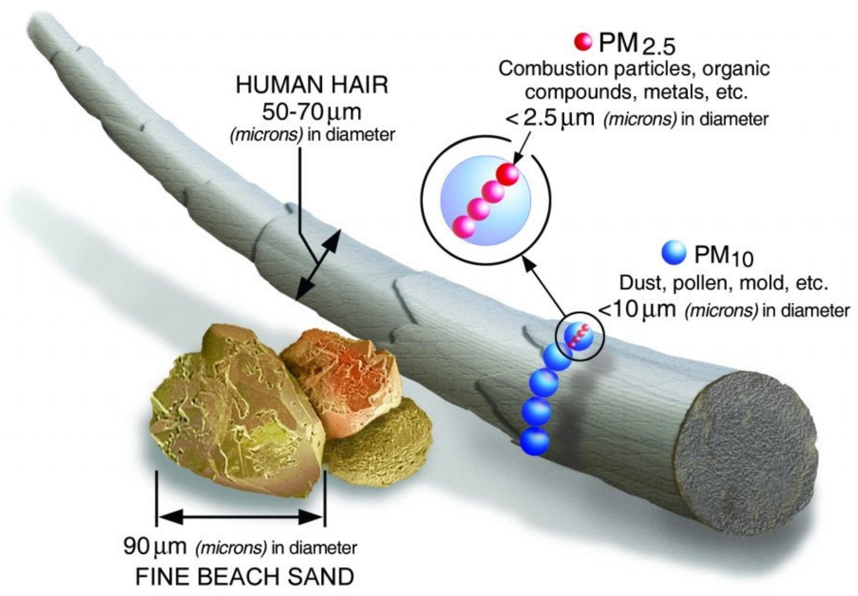
Carbon Dioxide; 0.4150%
Neon:0.0018%
Helium: 0.00052%
Methane: 0.00019%
Krypton;0.00011%

*Water vapour accounts for 0% to 5%, averaging around 0.4%.

Air quality monitoring: pollutants and GHG

Particle pollution: Particulate matter (PM)

Mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye.



PM 10: diameter lower than 10 um
PM 2.5: diameter lower than 2.5 um

Effect on body: group 1 carcinogen

Gaseous pollutants

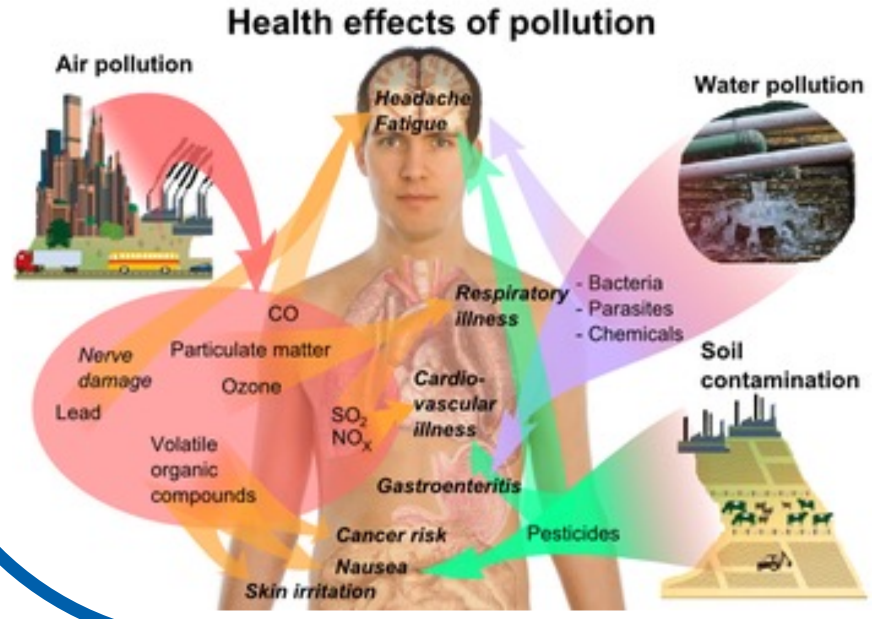
Gas molecules (chemical species) that may lead to adverse health effects for humans.

NO_2, NO, NH_3, CO, BTX, SO_2, O_3, VOCs

Toxic concentration: ppm, ppb

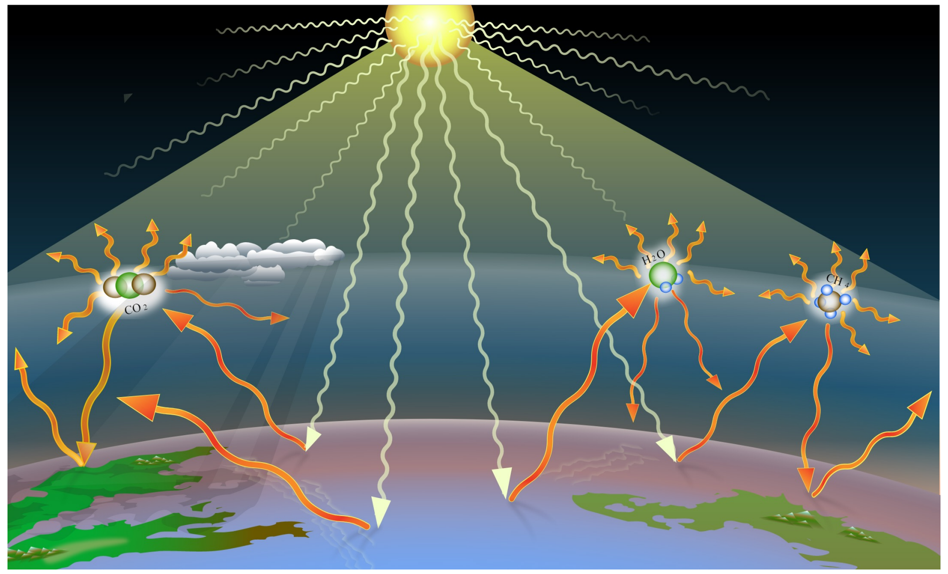
Sources: human activities or natural phenomena

Effect on body: cardiovascular disease, stroke, lung disease



Greenhouse gases

Gases that trap heat in the atmosphere and warm the planet!



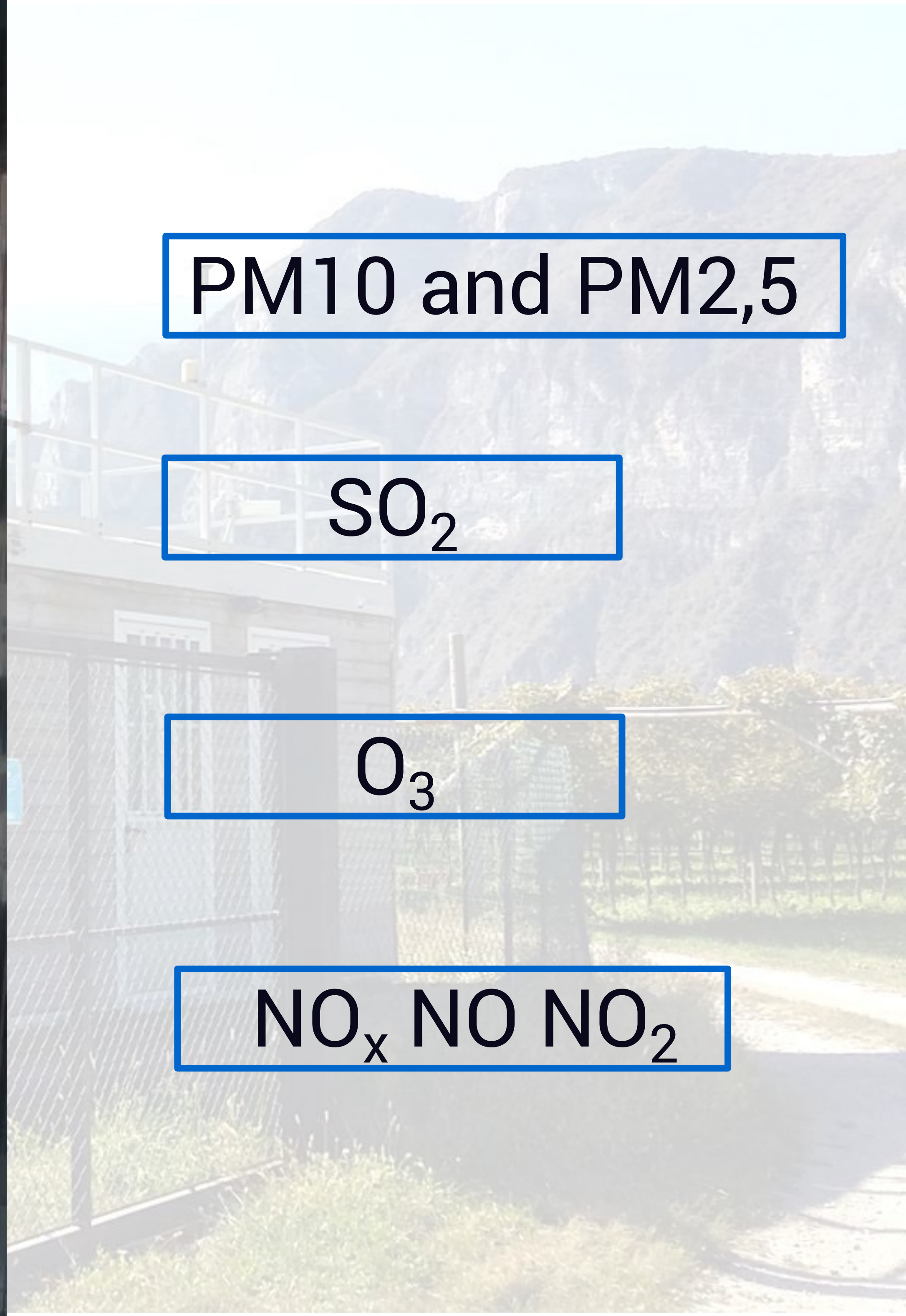
How much any one greenhouse gas influences global warming depends on:

- Concentration (ppm, ppb or ppt)
- Lifetime
- Global Warming Potential (GWP)

CO_2, CH_4, N_2O, halocarbons

Enviromental protection agency
Monitoring Network

https://www.appa.provincia.tn.it/



PM10 and PM2,5

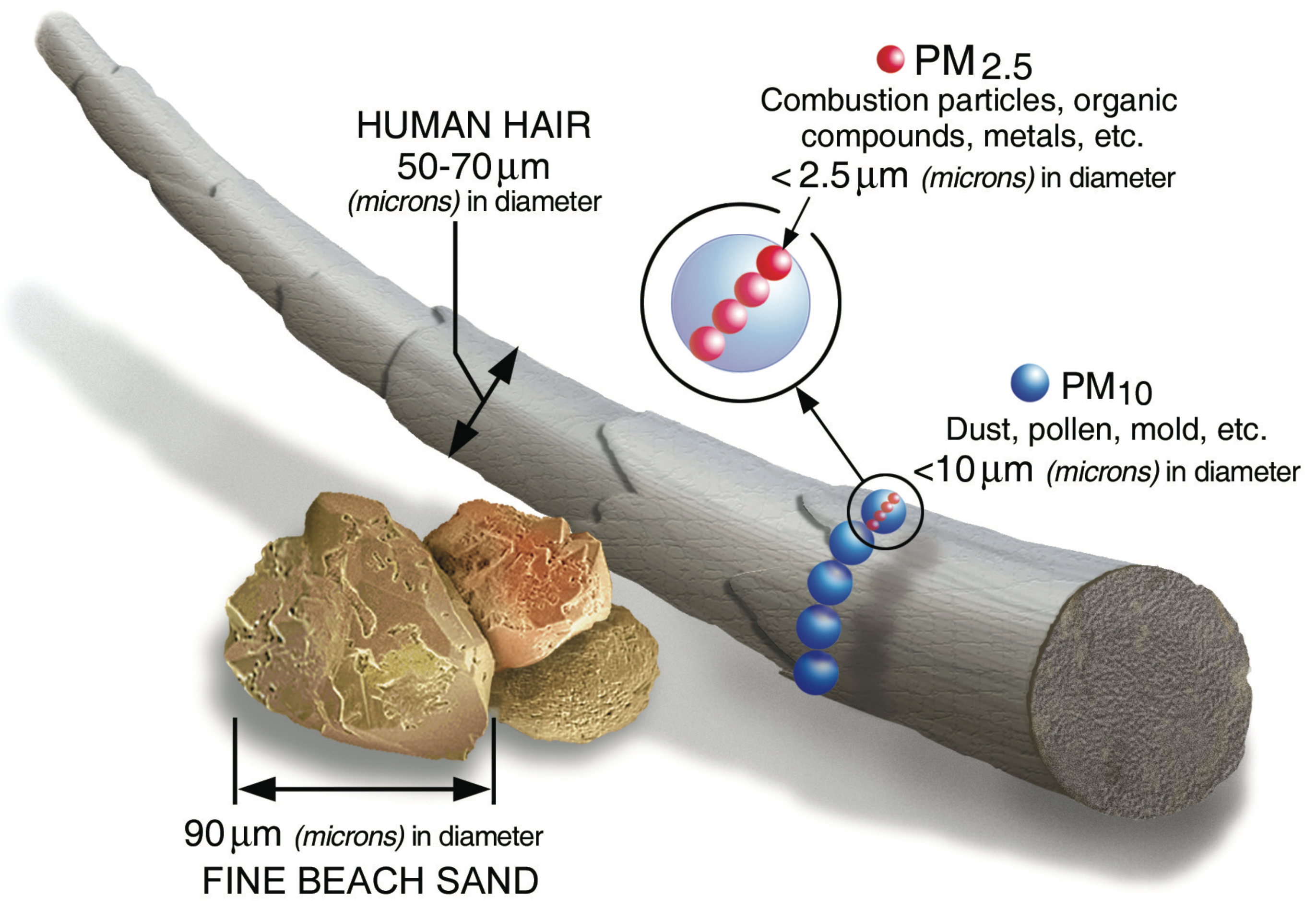
SO_2

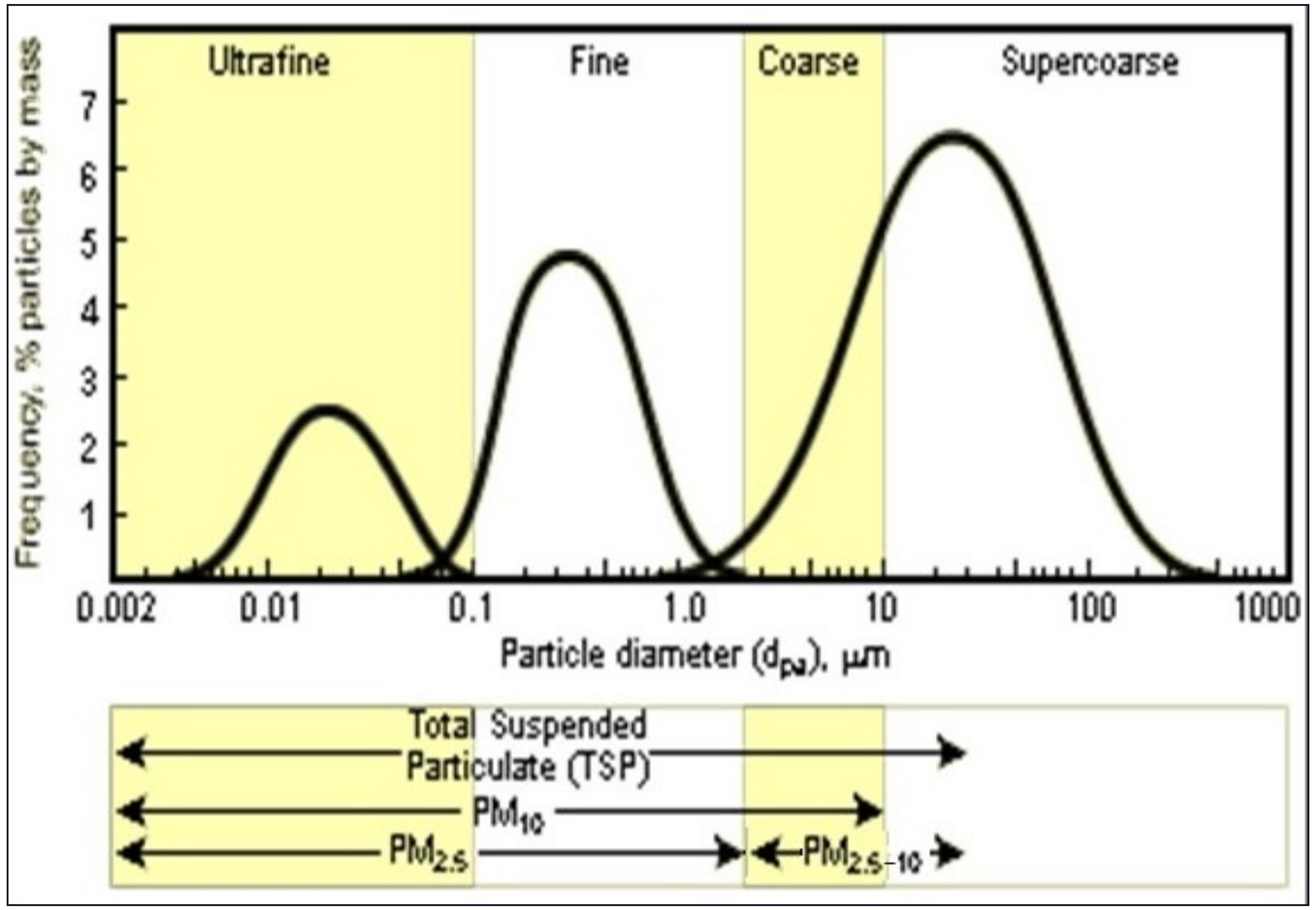
O_3

NO_x NO NO_2

Particulate Matter:
Aerodynamic Diameter

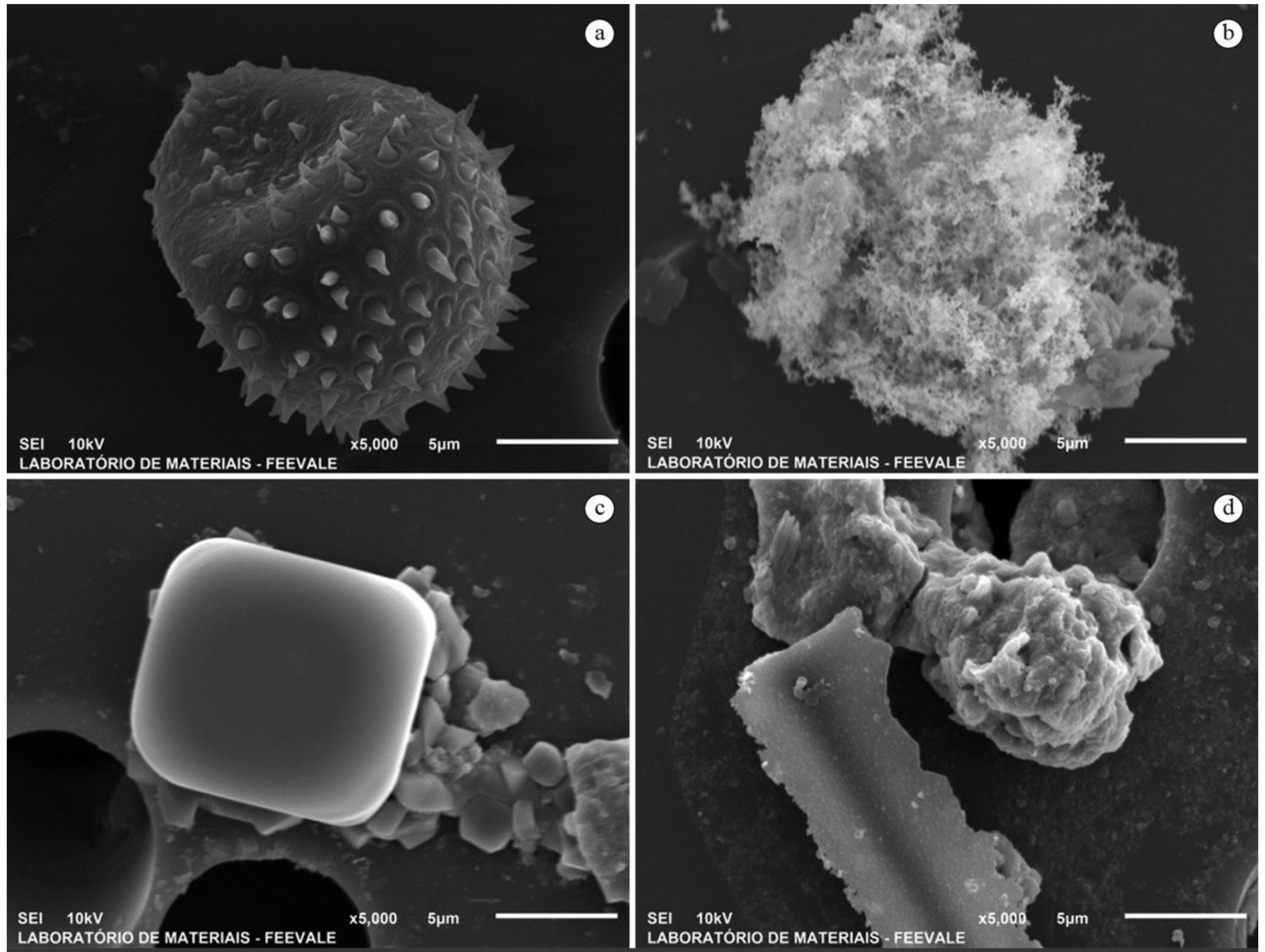
Establishing a particle size definition for irregularly shaped particles necessitates the use of a standardized measure referred to as the aerodynamic diameter, measured in microns or micrometers (µm), a unit equal to one millionth of a meter. The graph at the right shows the distribution of the 4 main particle size categories, with the categories historically and currently regulated by EPA indicated below. By comparison, a human hair is approximately 70 microns in diameter.





What is Particulate Matter?

Particulate matter (PM) describes a wide variety of airborne material. PM pollution consists of materials (including dust, smoke, and soot), that are directly emitted into the air or result from the transformation of gaseous pollutants. Particles come from natural sources (e.g., volcanic eruptions) and human activities such as burning fossil fuels, incinerating wastes, and smelting metals.



(a) Particle of biological origin, identified in the PM2.5-10
(b) Soot particle, identified in the PM2.5-10 (b)
(c) Cubic-shaped particle, identified in the PM2.5-10
(d) Particle characteristic of soil resuspension and particle possibly originated from anthropic sources, both identified in the PM2.5-10

Where does PM originate?

Sources may emit PM directly into the environment or emit **precursors** such as **sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs),** which are transformed through atmospheric chemistry to form PM.

Mobile Sources
(vehicles)
VOCs, NO_2, PM

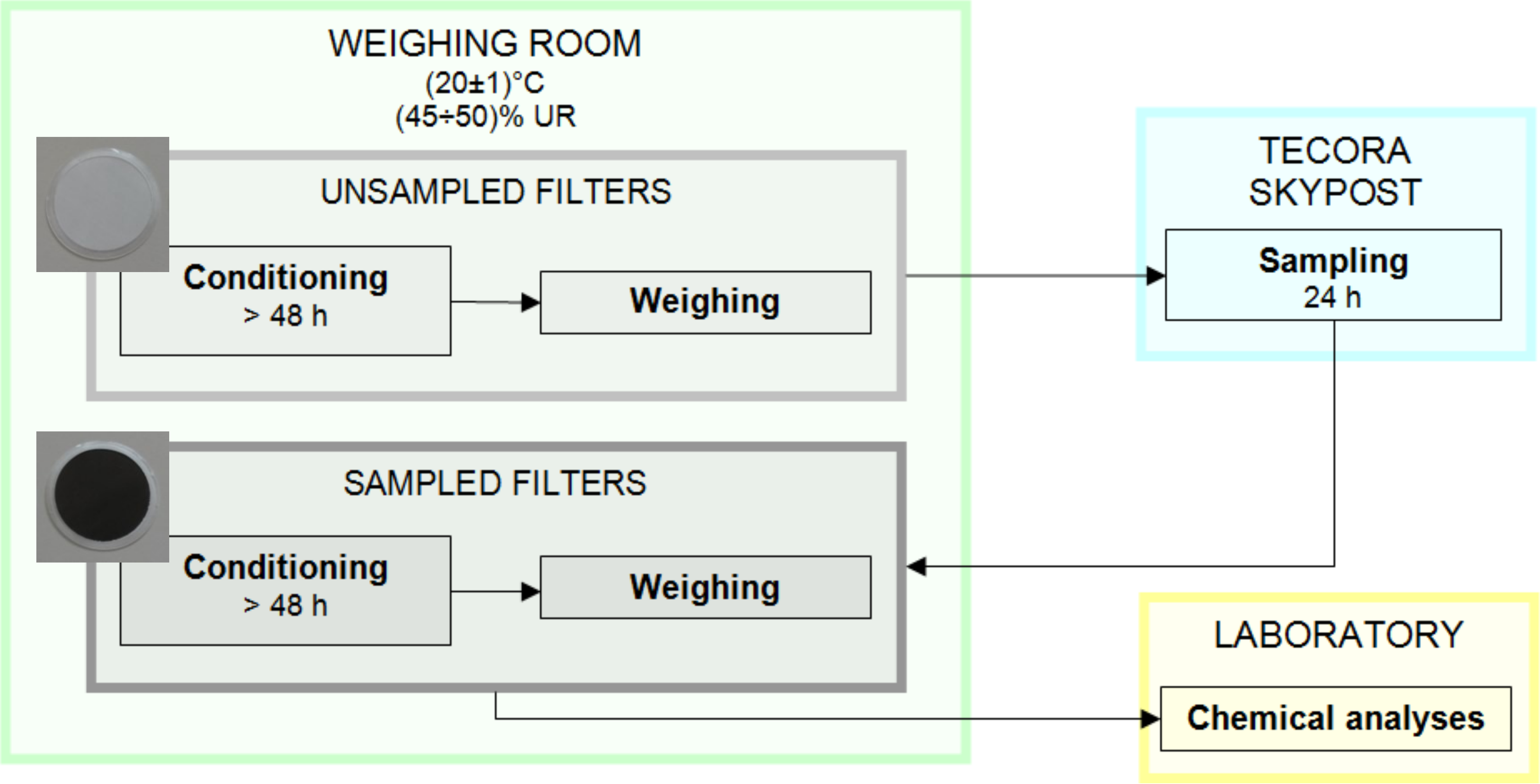
Area Sources
(drycleaners, gas stations)
VOCs

Natural Sources
(forest fires, volcanoes)
PM

Stationary Sources
(factories)
NO_2, SO_2, PM

Particulate:

UNI EN 12341:2014 “Ambient air - Standard gravimetric measurement method for the determination of the PM10 or PM2,5 mass concentration of suspended particulate matter”

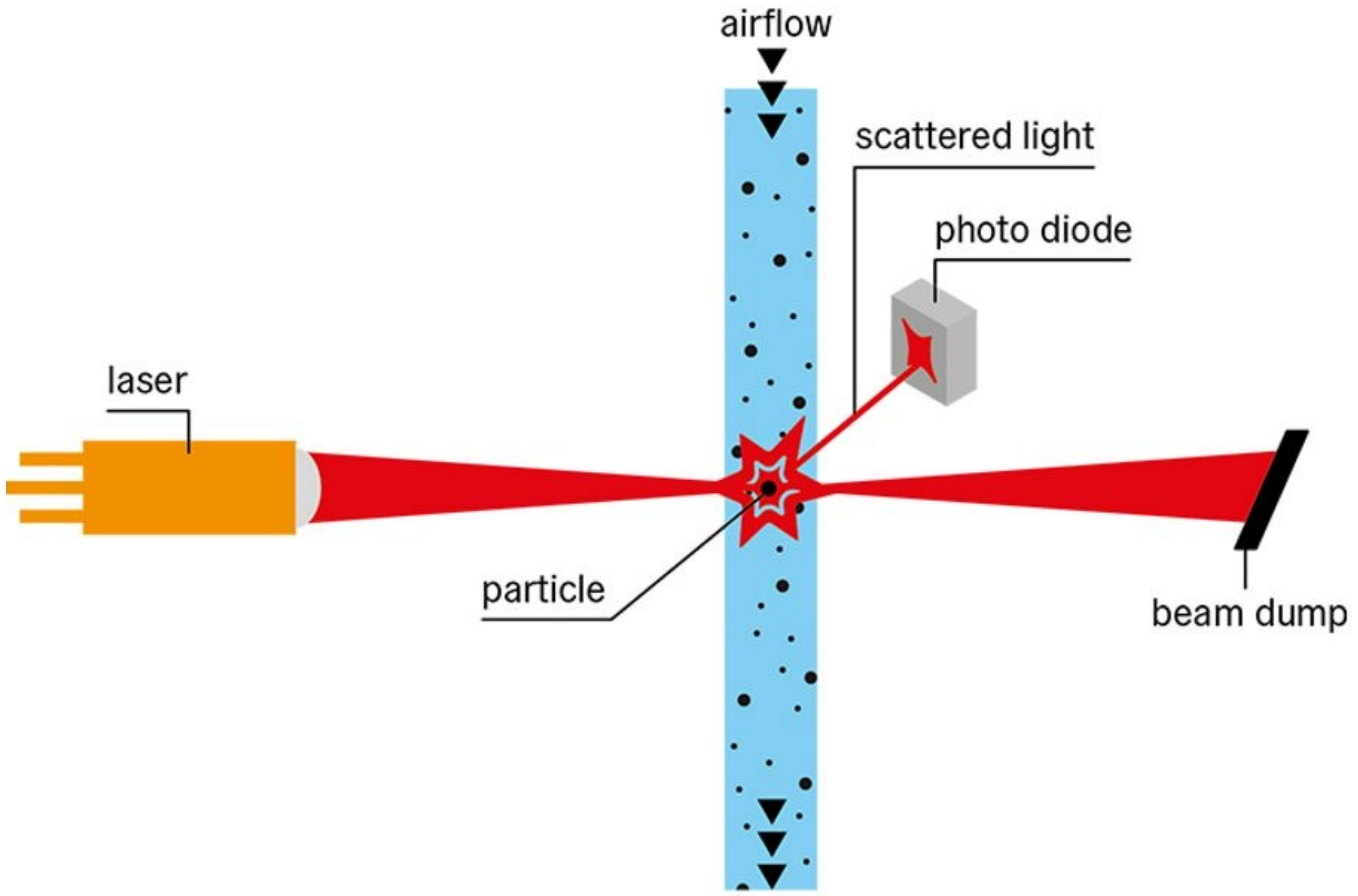


Laser-based optical particulate sensor
Measurement principle

This measurement principle is based on laser light scattering. Airflow is generated inside the sensor with the aid of a fan. This airflow carries particulate matter in the ambient air from the inlet of the sensor to the outlet. Near the photodiode, the particles in the airflow pass through a focused laser beam, scattering the laser's light. A photodiode converts this scattered light into an electrical signal, which is then converted on the internal microcontroller into an output value for the matter's mass and concentration using algorithms.

John William Strutt, 3rd Baron Rayleigh

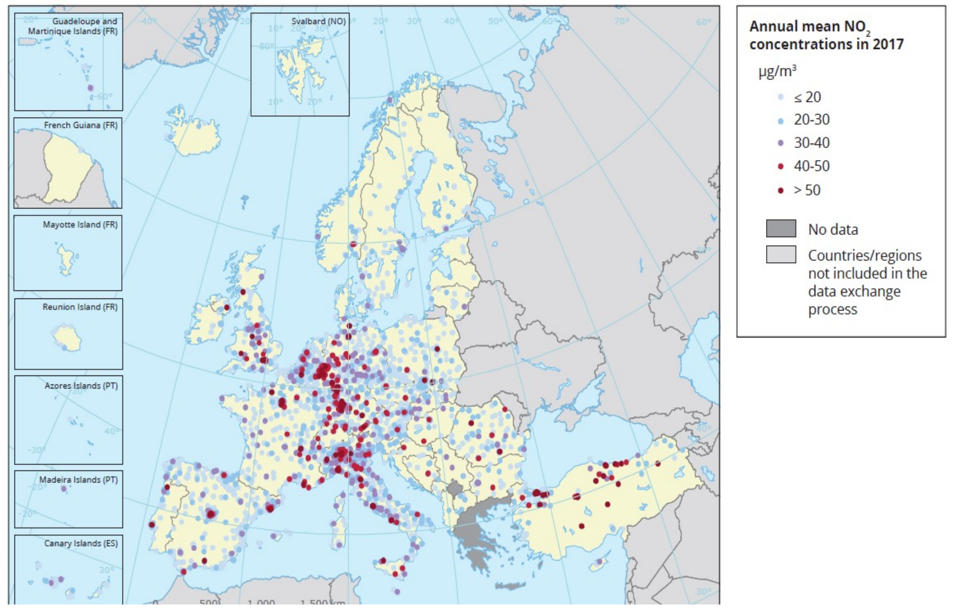
- British physicist
- known especially for the Rayleight scattering in 1871.



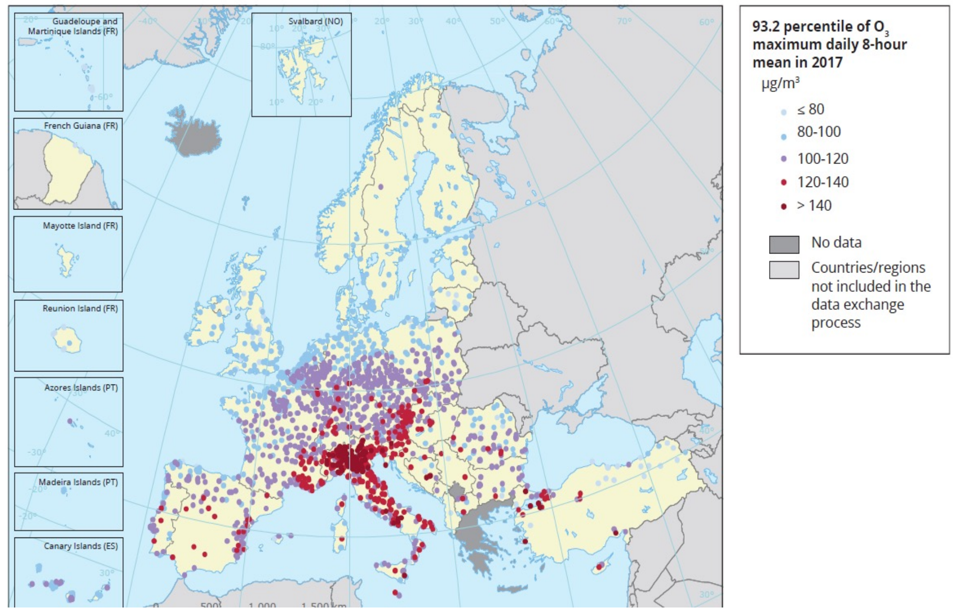
Gases

In the last decades, pollutant gases have been strongly decreased in the atmosphere. However, some of them still exceed the limitations recommended by policy makers, including in EU.

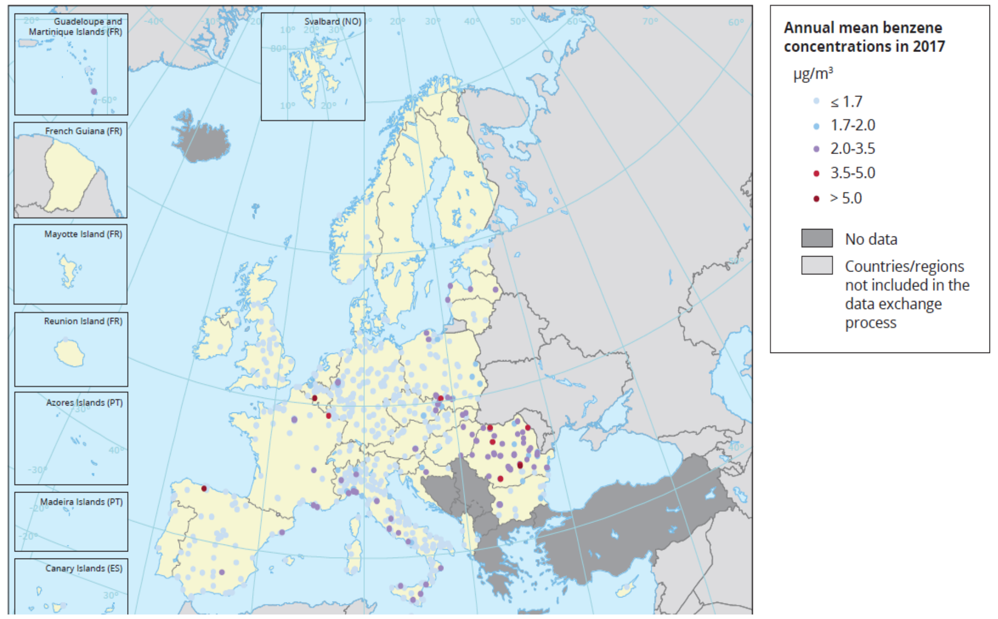
NO_2



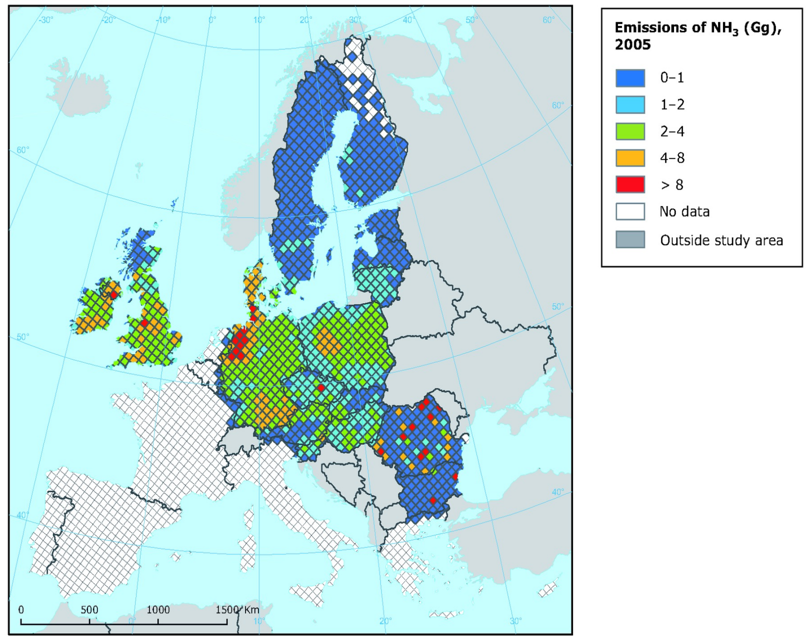
O_3



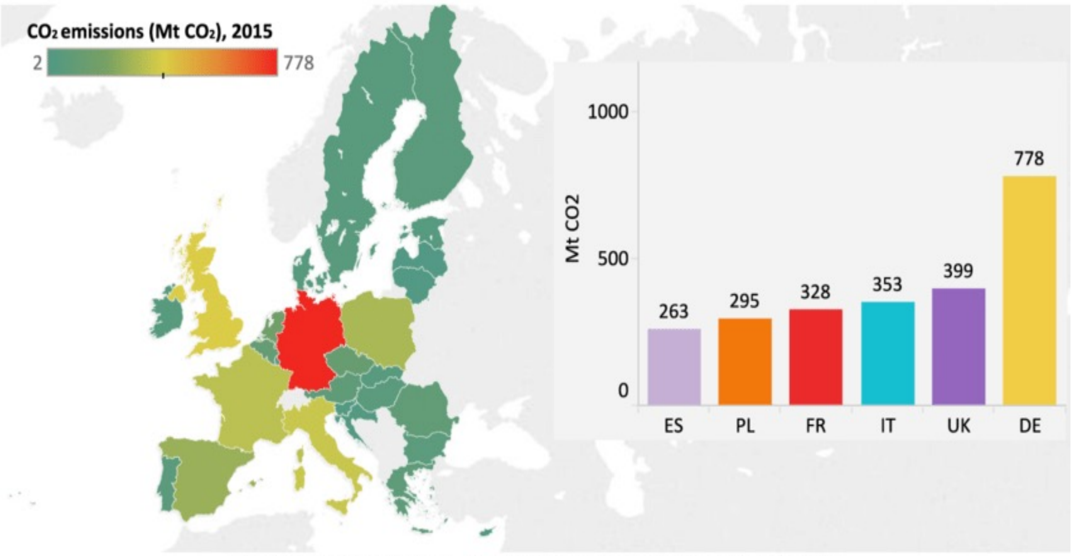
BTX (benzene, toluene, ethylbenzene and xylene)



NH_3



Greenhouse gases: CO_2

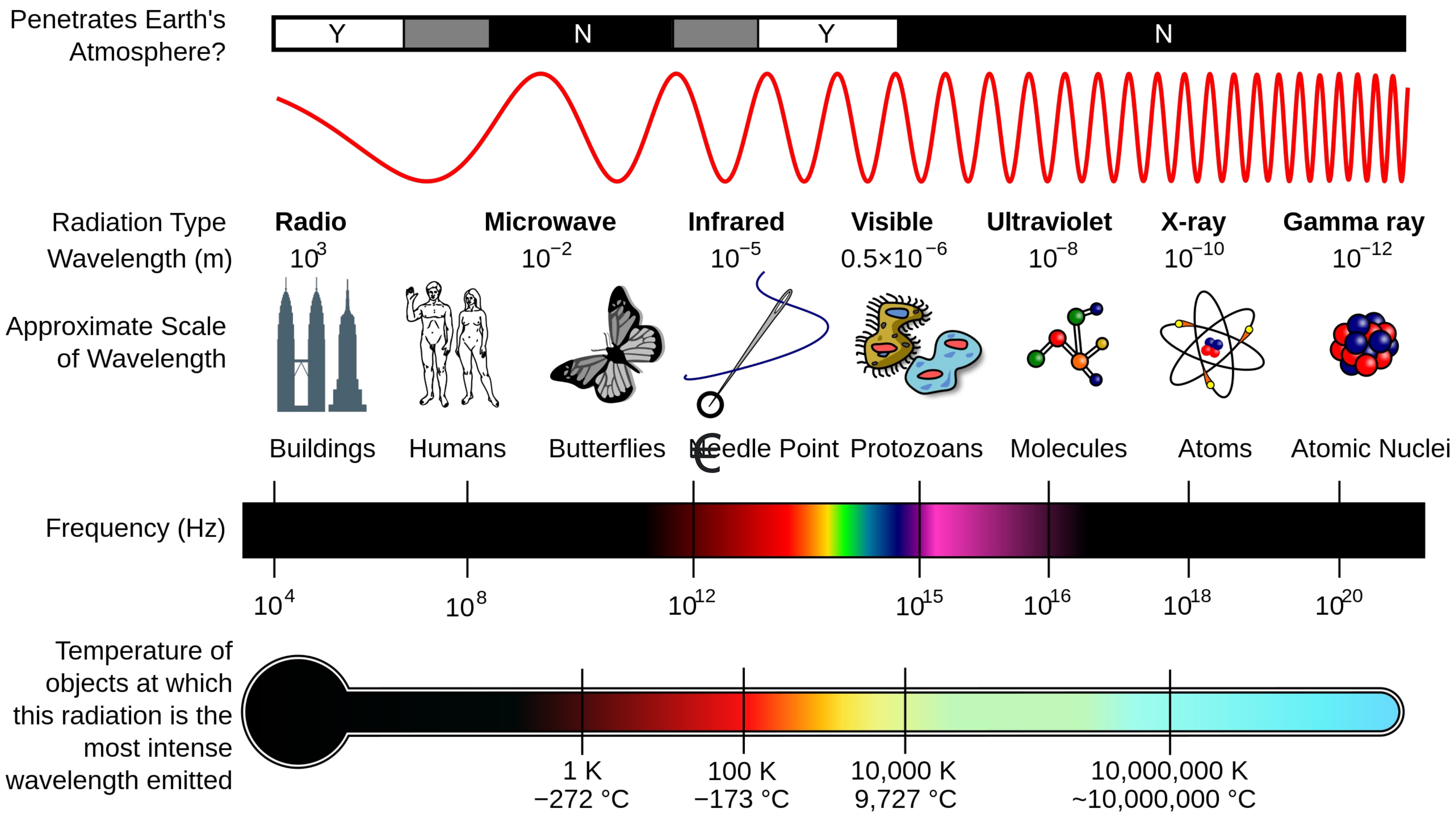


Source: JRC Emission Database for Global Atmospheric Research (EDGAR)

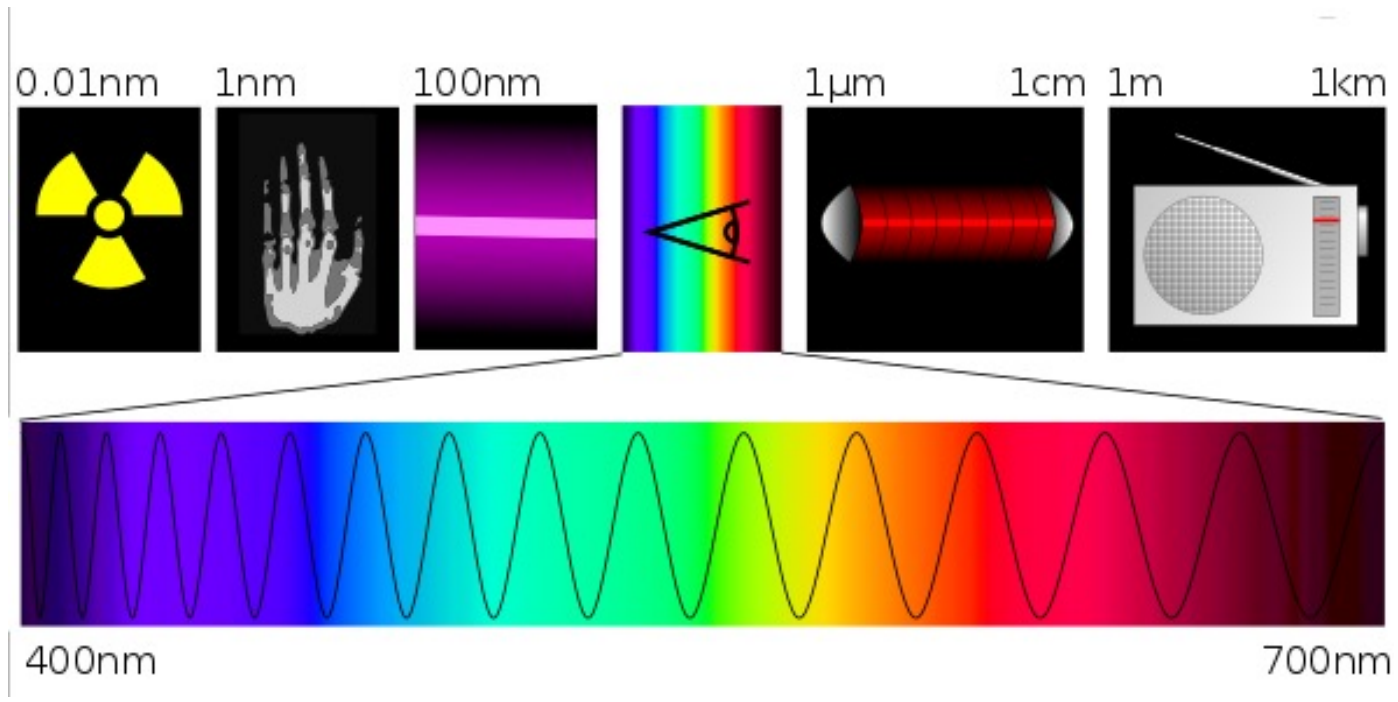
EU air quality map

https://airindex.eea.europa.eu/Map/AQI/Viewer/

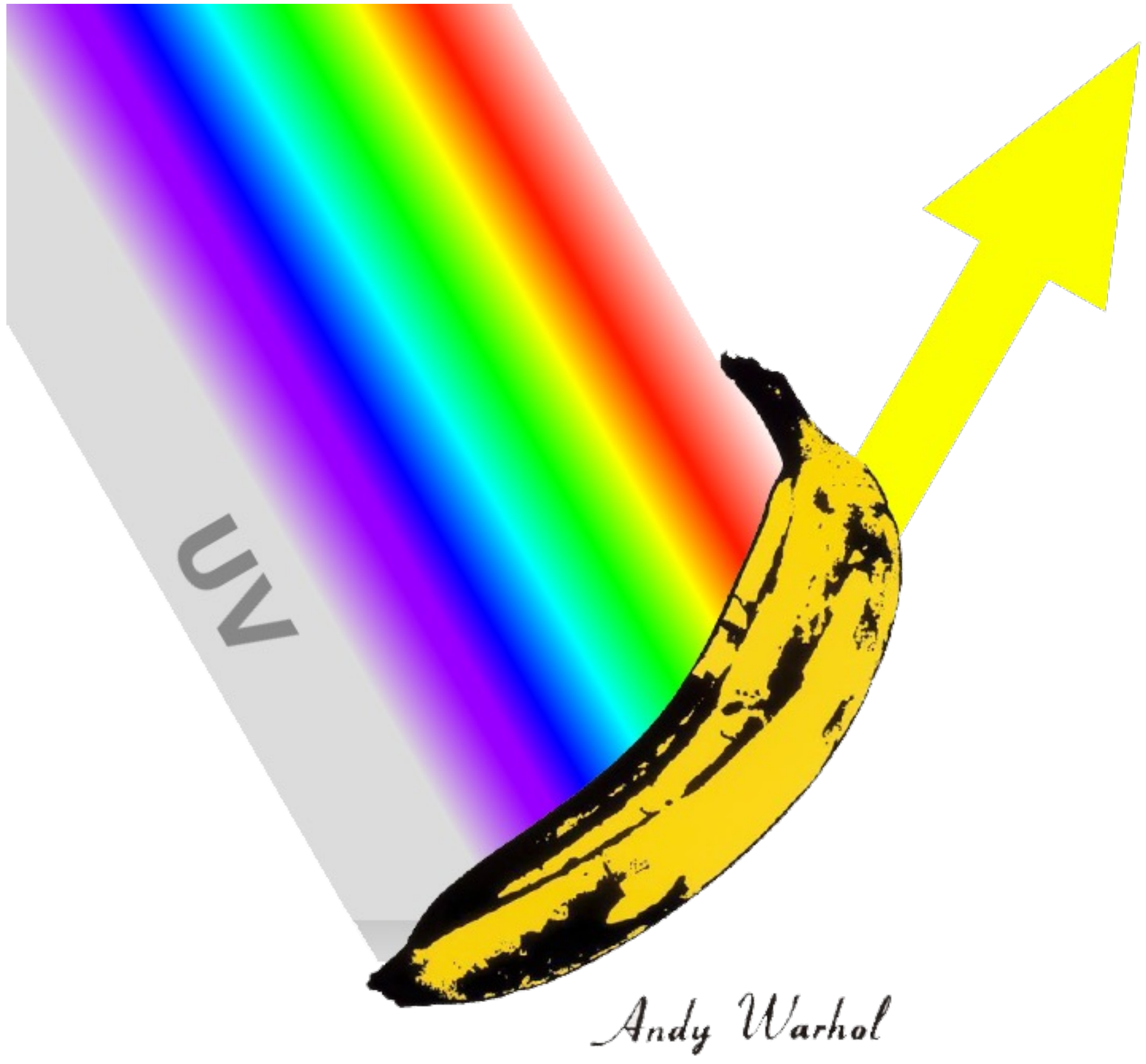
Electromagnetic spectrum



The electromagnetic (EM) spectrum is the range of all types of EM radiation. Radiation is energy that travels and spreads out as it goes – the visible light that comes from a lamp in your house and the radio waves that come from a radio station are two types of electromagnetic radiation. The other types of EM radiation that make up the electromagnetic spectrum are microwaves, infrared light, ultraviolet light, X-rays and gamma-rays.



Light – Matter interaction



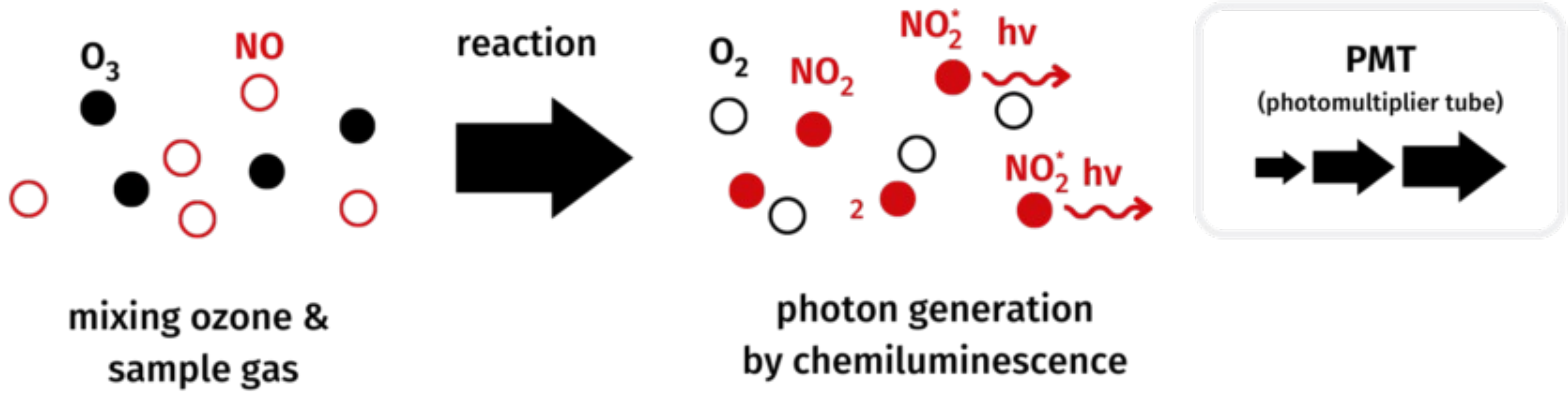
What may happen when light strikes an object?

1. All wavelengths of the light may be entirely reflected from the surface, which would result in what we perceive as the “color” white.
2. All wavelengths may be entirely absorbed by the object, which would result in what we perceive as the “color” black.
3. The light may be completely transmitted through the object, with little interaction, resulting in what we call a colorless object. Glass is an example of this.
4. Some wavelengths can be reflected and others absorbed, resulting in the appearance of the different colors.

Chemilumiscence

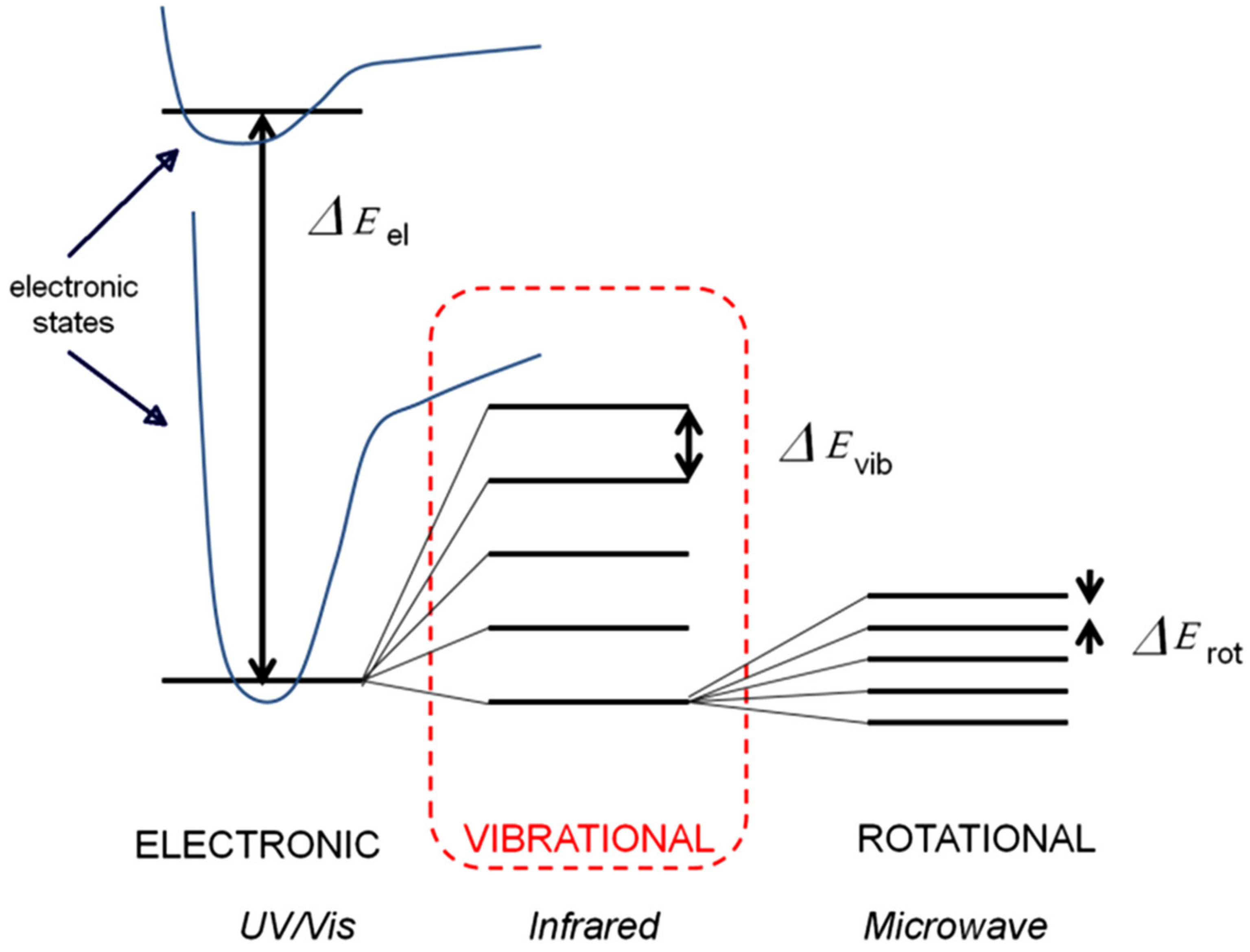
Chemiluminescence refers to light which is emitted after excitation of a molecule during a chemical reaction. It is being used in the analysis of nitrogen gases.
Nitrogen monoxide reacts with ozone to excited nitrogen dioxide.

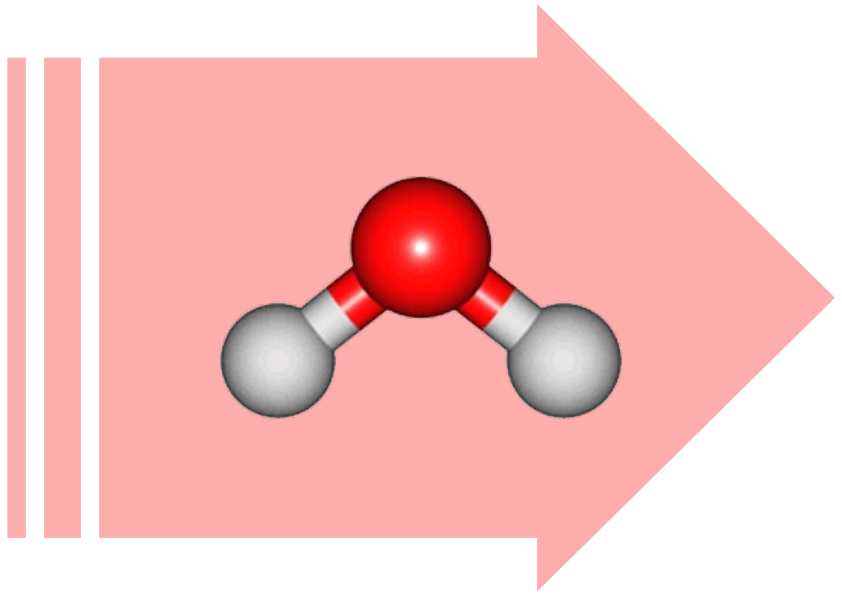
$$NO + O_3 \rightarrow NO_2^* + O_2$$
$$NO_2^* \rightarrow NO_2 + h\nu \text{ (luminescence)}$$

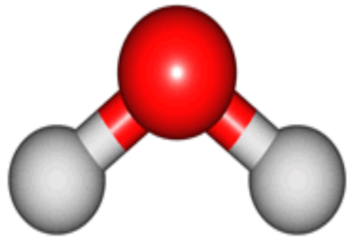


Light – Matter interaction

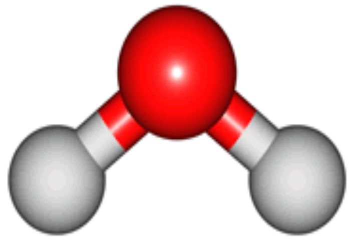
- IR light interacts with the sample molecules (e.g. water).
- Depending on its energy, IR radiation can trigger the vibration of specific molecular bonds (absorbtion).



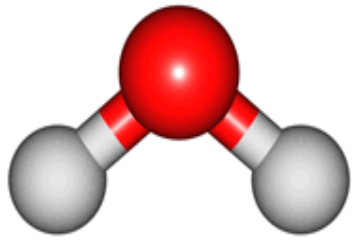




Symmetric
Stretch Vibration



Anti-symmetric
Stretch Vibration



Deformation
Vibration

NDIR
Working principle

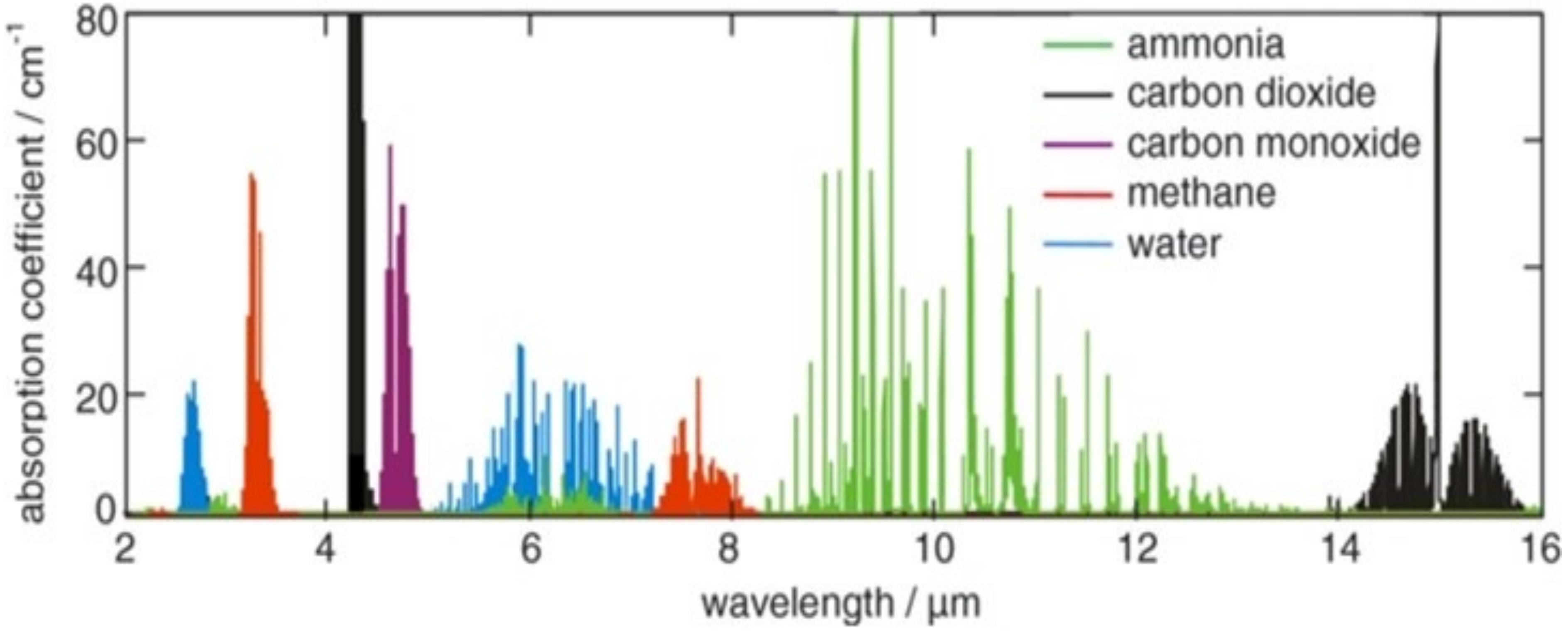
Requirements for IR Absorption

- *Lower quantum levels must be "populated"*
- *Dipole moment (degree of charge imbalance) must change with the vibrational "motion"*
  - *CO_2 and CH_4 absorb IR*
  - *Homonuclear diatomics such as H_2 DO NOT absorb IR*
  - *Also IR-transparent:*
    - *N_2*
    - *O_2*
    - *F_2*
    - *Cl_2*
    - *Hg_2*
    - *Ar*

GfG Instrumentation

November 2009 Principles of gas detection Slide 133

- IR fingerprint of gas molecules



Absorption spectra for five gases in the mid IR region of the spectrum (all at 100% vol), taken from the PNNL database, from Optical gas sensing: a review; Jane Hodgkinson and Ralph P Tatam 2013 Meas. Sci. Technol. 24 012004 doi:10.1088/0957-0233/24/1/012004

Monitoring Pollutants from the space
Copernicus EU programme

Sentinel-5P provides timely data on a multitude of trace gases that can affect our health such as nitrogen dioxide and carbon monoxide. It will also measure sulphur dioxide, which mainly comes from industrial processes and motor vehicle emissions, but can also be in volcanic plumes.

What sets Tropomi apart is that it measures in the ultraviolet and visible (270–500 nm), near-infrared (675–775 nm) and shortwave infrared (2305–2385 nm) spectral bands. This means that a wide range of pollutants such as nitrogen dioxide, ozone, formaldehyde, sulphur dioxide, methane and carbon monoxide can be imaged more accurately than ever before. With a resolution as high as 7 km × 3.5 km, it has the potential to detect air pollution over individual cities.

Only Stratospheric Ozone

https://maps.s5p-pal.com/no2/

Pros and Cons

1. **Accuracy:** Extreme precision and repeatability of the measure

2. **Calibration**: Periodic calibration must be done on all sensor types. However, on laboratory units, as long as the zero is maintained, the unit is assured a good response and good span accuracy. Because of this characteristic, abnormal functioning of a unit can be easily determined.

3. **Life Expectancy**: A well-designed unit has a life expectancy of more than 10 years.

4. **Continuous Exposure to Gas**: The functional components are protected by the optical parts, which are basically inert to most chemicals.

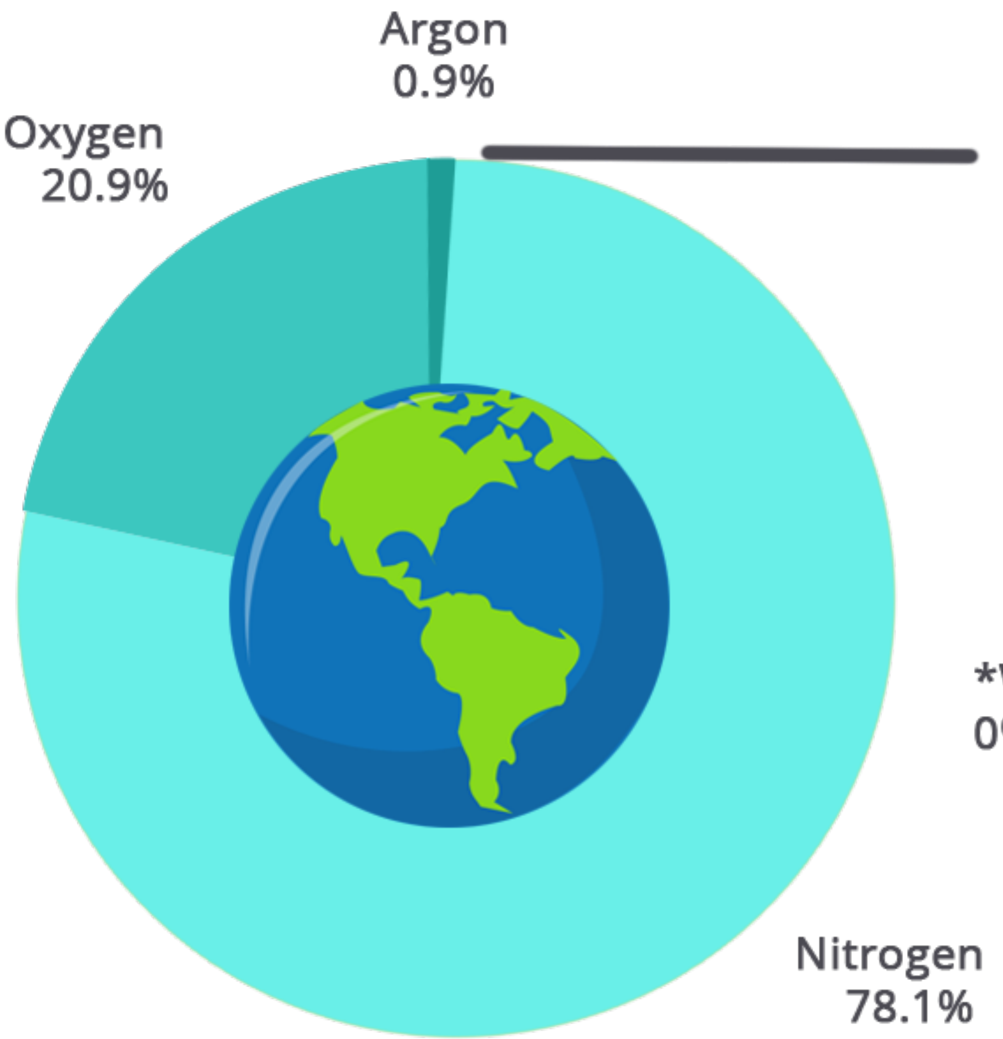
BUT EXPENSIVE

(10-20k€)

OUTLINE

- FBK sensor group & problem statement
- Low cost gas sensors
- Chemoresistive gas sensors: working principle
- Sensing materials
- Substrates
- Working principle and influencing parameters

Composition of air



Carbon Dioxide; 0.4150%
Neon:0.0018%
Helium: 0.00052%
Methane: 0.00019%
Krypton;0.00011%

*Water vapour accounts for 0% to 5%, averaging around 0.4%.

Air quality monitoring: physical dimensions

Typical <u>concentrations</u> at which a pollutant begins to <u>be harmful to humans</u>: **part per million by volume (ppmv) – part per billion by volume (ppbv)**

Standard units of measurement used by EPA = **mg/m³ and µg/m³**

Conversion

$$\mathrm{mg/m^3} = \mathrm{ppmv} \cdot \frac{M}{(0.082057338 \cdot T)}$$

M = molecular mass
T = air temperature (K)

Example

Carbon monoxide (CO)
$M_{(CO)}$ = 28.01 g/mol
T = 298 K

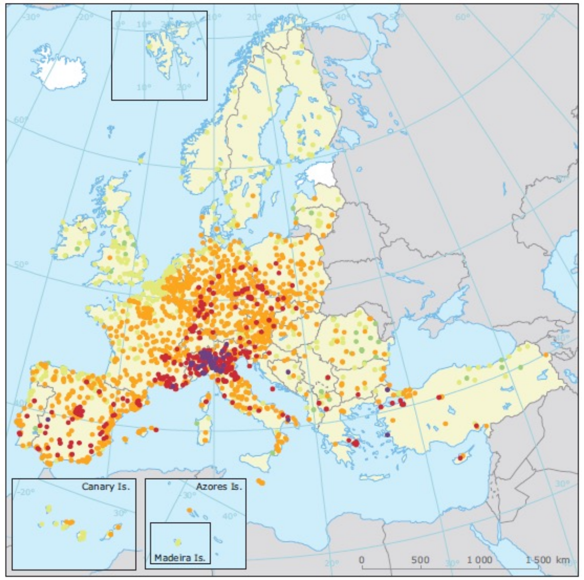
1 ppmv $_{(CO)}$ = 1.15 mg/m³

EU policy

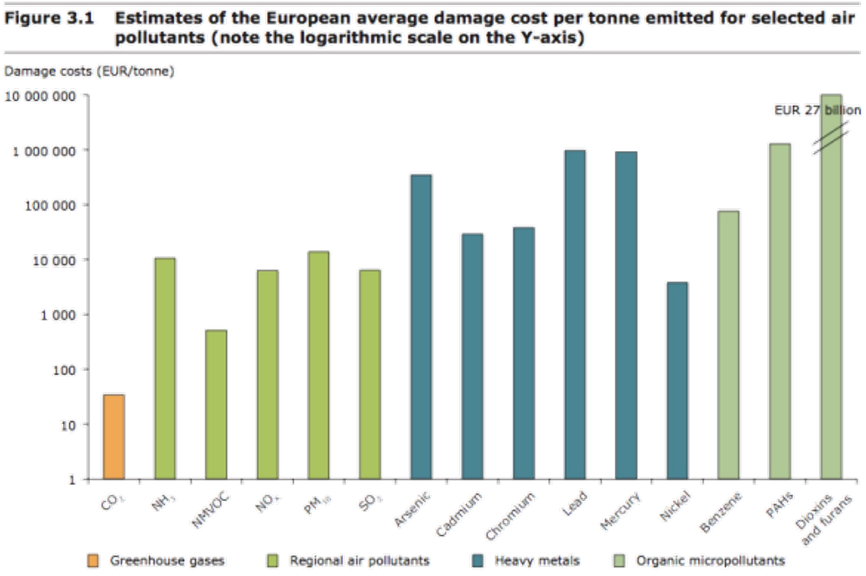
Pollutant	Averaging period	Objective	Concentration	Comments
		EU Air Quality Directives		
$PM_{2.5}$	24-hour	Target value		
$PM_{2.5}$	Annual	Limit value	25 µg/m³	
$PM_{2.5}$	Annual	Indicative limit value	20 µg/m³	
PM_{10}	24-hour	Limit value	50 µg/m³	Not to be exceeded on more than 35 days/year
PM_{10}	Annual	Limit value	40 µg/m³	
O_3	Max. daily 8-hour mean	Target value	120 µg/m³	Not to be exceeded on more than 25 days/year (averaged over 3 years)
O_3	Max. daily 8-hour mean	Long-term objective	120 µg/m3	
O_3	8-hour	Target value		
O_3	Peak season [3]	Target value		
NO_2	Hourly	Limit value	200 µg/m³	Not to be exceeded on more than 18 hours/year
NO_2	Annual	Limit value	40 µg/m³	
NO_2	24-hour	Target value		
SO_2	Hourly	Limit value	350 µg/m³	Not to be exceeded on more than 24 hours/year
SO_2	24-hour	Limit value	125 µg/m³	Not to be exceeded on more than 3 days/year
CO	Max. daily 8-hour mean	Limit value	10 mg/m³	
CO	24-hour	Target value		
C_6H_6	Annual	Limit value	5 µg/m³	
BaP	Annual	Target value	1 ng/m³	Measured as content in PM_{10}
Pb	Annual	Limit value	0,5 µg/m³	Measured as content in PM_{10}
As	Annual	Target value	6 ng/m³	Measured as content in PM_{10}
Cd	Annual	Target value	5 ng/m³	Measured as content in PM_{10}
Ni	Annual	Target value	20 ng/m³	Measured as content in PM_{10}

Perchè investigare sensori di gas innovativi?

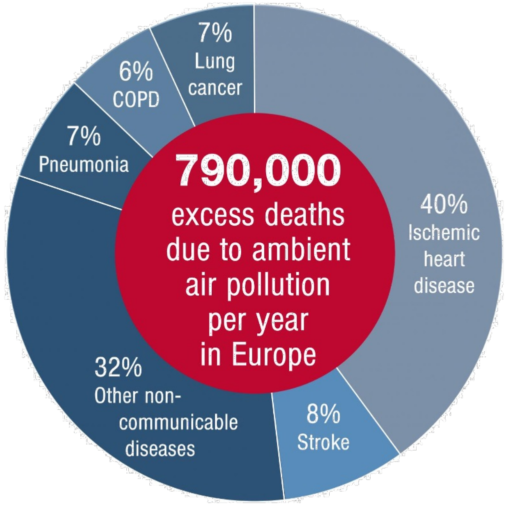
Pollutant gases:
NO_2, NO, NH_3, CO, SO_2, BTX, SO_2



Greenhouse gases:
CO_2, O_3, CH_4, N_2O, fluorocarburi



High costs



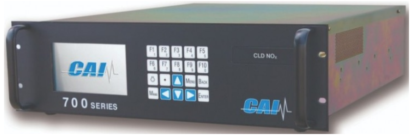
Premature deaths

Perchè investigare sensori di gas innovativi?

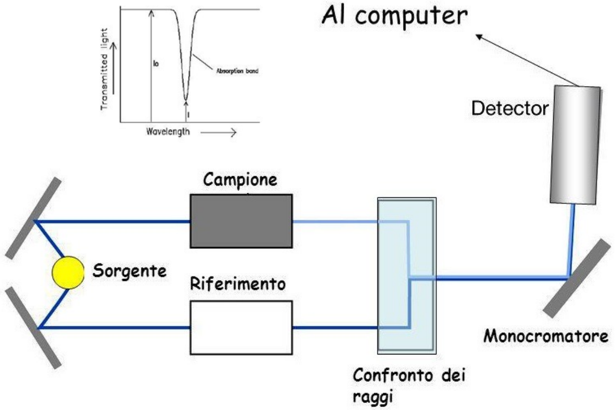
Certified monitoring tools

FT-IR

Chemiluminescenza



Based on radiation-matter interaction



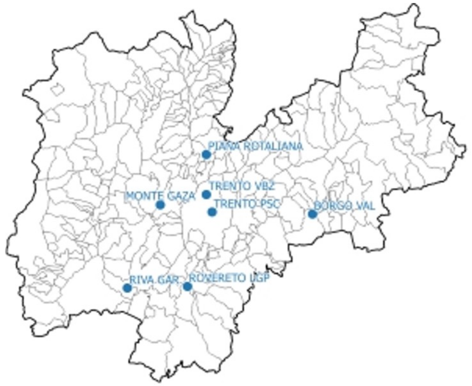
Vantaggi

- Alta sensibilità
- Alta selettività

Svantaggi

- Ingombranti
- Alto costo (10-30 K€)
- Lavorano a T e umidità specifiche

Only few monitoring stations can be deployed
=
Low spatial-time resolution on the data collected



7 monitoring stations

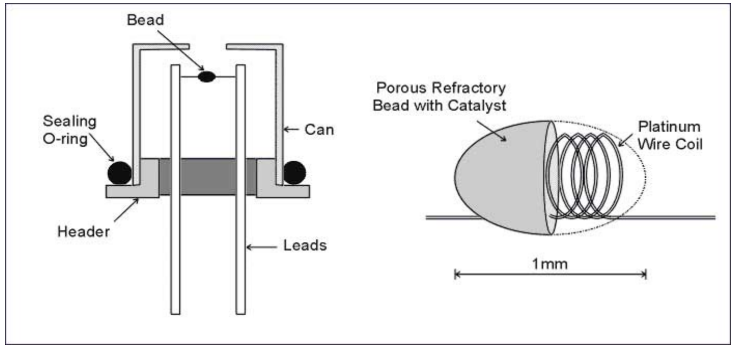
Why gas sensors?

Lack of high-performing, low cost and portable sensing platform

<u>Resolution 13/3/2019</u>: EU calls on **the Commission** and the **Member States to support research**, **development and certification at EU level for innovative smart multi-sensor systems** for **air quality monitoring**. Smart air quality monitoring systems can be a viable tool for citizen science, and also of special benefit for people suffering from asthma and cardiovascular diseases

<u>Solid state gas sensors</u>

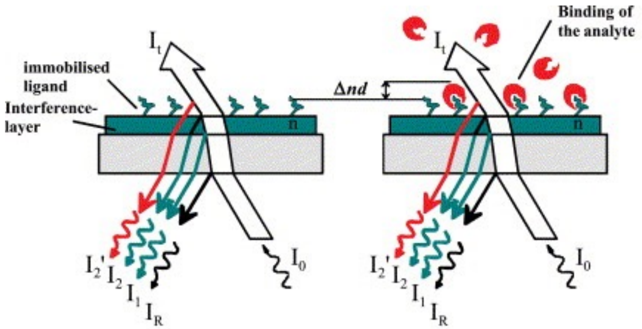
Thermometric



- High stability
- Low cost
- High durability

- Low selectivity
- Low sensitivity
- High power consumption

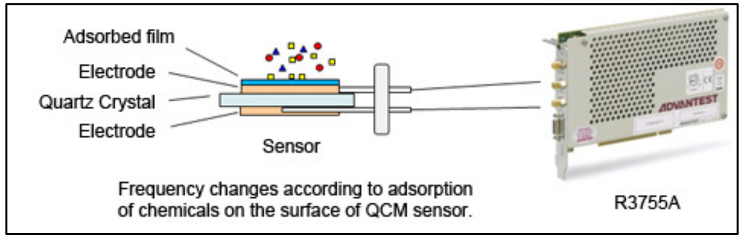
Optical gas sensors



- High selectivity
- High sensitivity

- Expensive
- Bulky

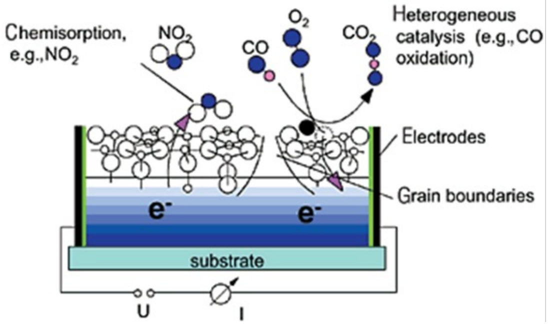
Quartz microbalance

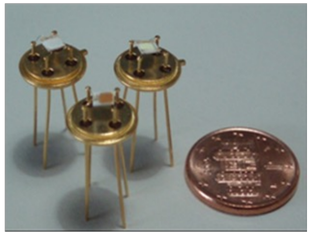


- High sensitivity
- Low cost
- Low power consumption

- Low selectivity
- Low durability
- Low stability

Electrochemical





- High stability
- High sensitivity
- Suitable for MF
- Low cost

- Low selectivity
- High power consumption

OUTLINE

- FBK sensor group & problem statement
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- Chemoresistive gas sensors: working principle
- Sensing materials
- Substrates
- Working principle and influencing parameters

Receptor-Transducer mechanism in a chemical sensor

- Receptor:

  “The chemical information is transformed, by the sensor into a form of energy, which may be measured by the transducer”

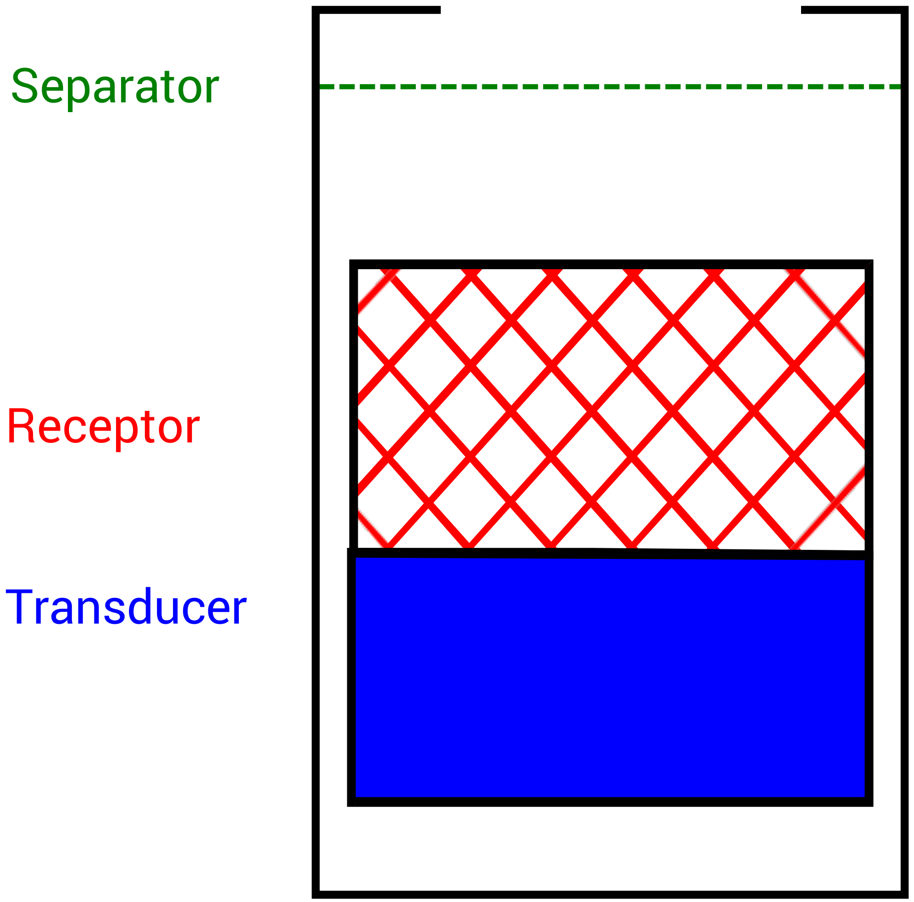
- Transducer:

  “Transforms the energy carrying the chemical information about the sample into a useful analytical signal.”

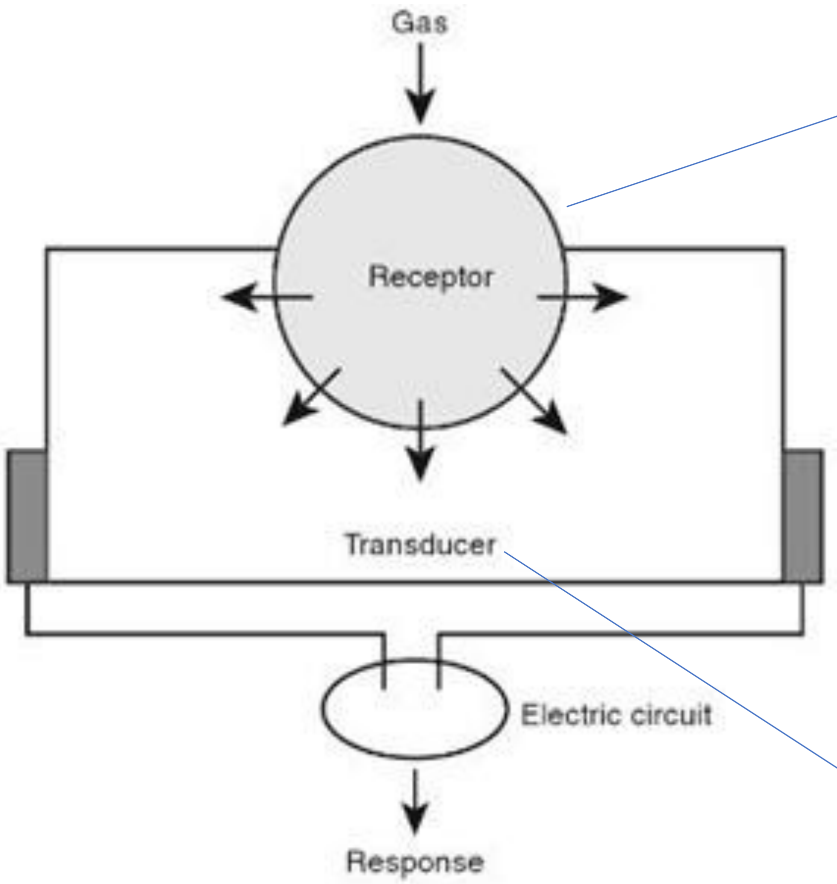
  “The transducer as such does not work as a sensor”

- Separator: can be included in a sensor,

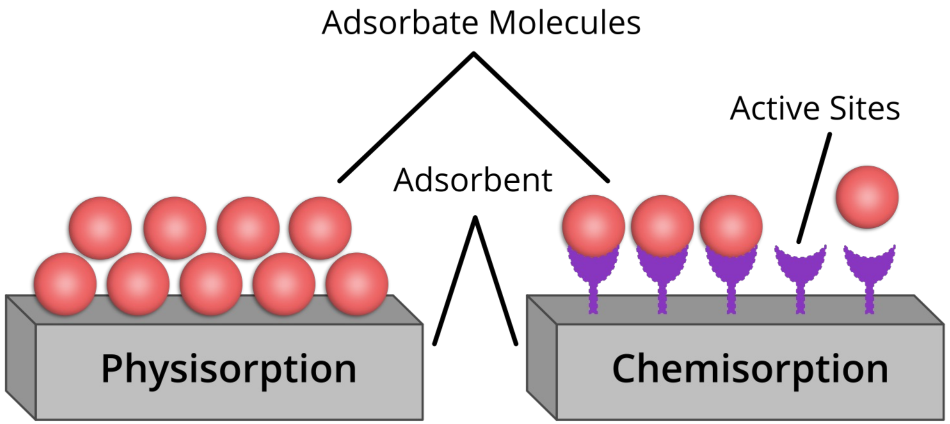
  e.g. a membrane



Receptor-Transducer mechanism in a chemical sensor



The receptor is usually a reactive material



Physisorption = only involves physical interactions between analyte and sensing layer)
Chemisorption = involves a chemical reaction between the surface and the analyte

The reaction occurring between sensing material and analyte (gas) is transform into a readable electrical signal

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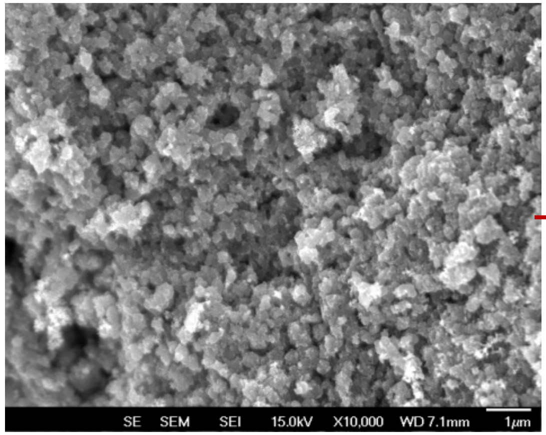
Chemoresistive Gas Sensors

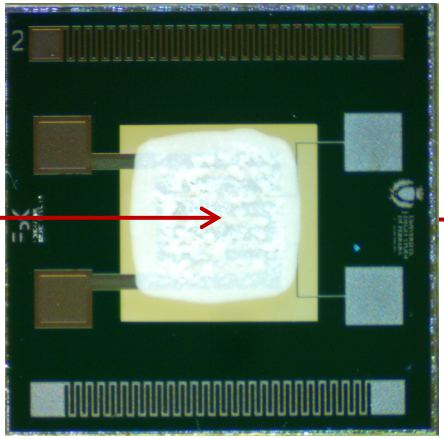
Detection of **low gas concentrations** through a **change of resistance in nanostructured semiconducting** materials in thermal- or photo-activation mode**.**

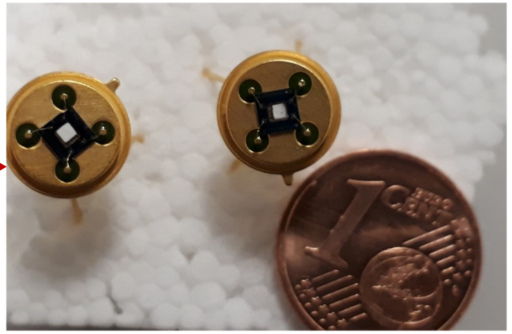
The materials most *widely used* so far are the ***MOX semiconductors***

Advantages

- High thermal stability
- Easy to synthesize in nanometric scale
- Reversible surface reaction in temperature
- Excellent sensitivity
- Fast response and recovery
- Small dimensions and simple integration in IoT platforms
- Low costs of manufacturing





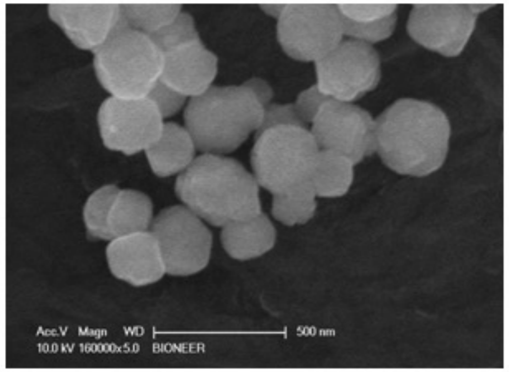


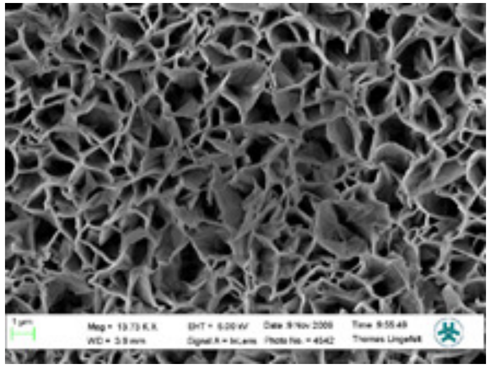
Receptor → **Transducer**

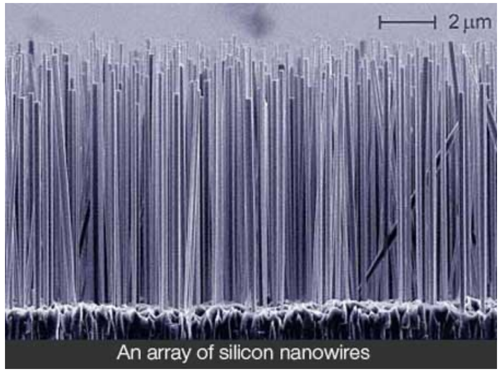
- The chemoresistive gas sensors are used in different **applications**:
  - ➢ *control units for the* ***indoor/outdoor air quality monitoring****;*
  - ➢ *analysis and* ***diagnosis of clinical disease*** *with non-invasive methods.*

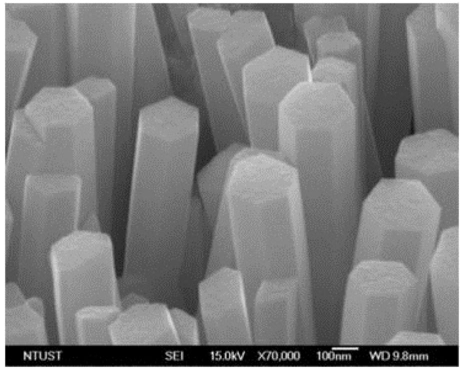
Chemoresistive Gas Sensors: Main Components

Sensing Material => Receptor and **Transducer** of the Surface Chemical Reaction

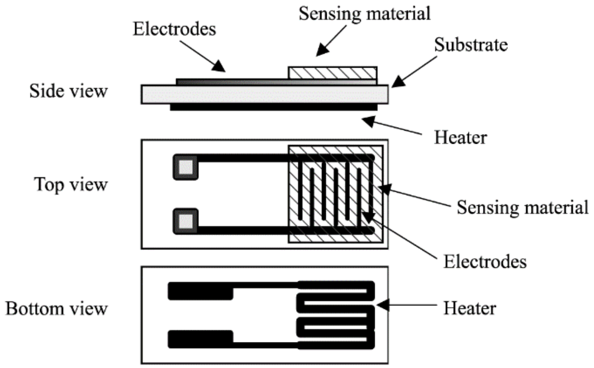


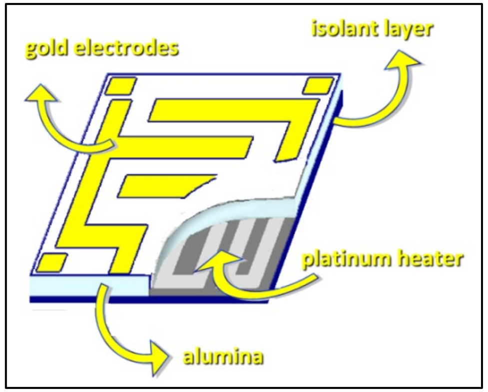


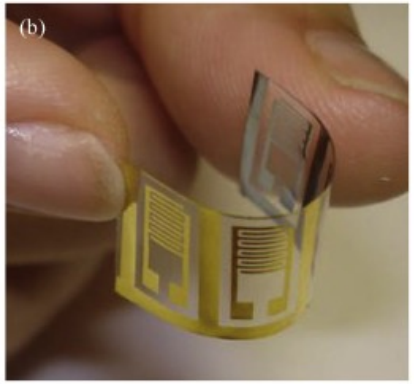


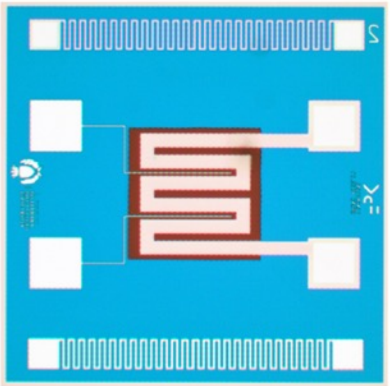


Substrate => Triple Role: **Mechanical Support**, hosts **Heater** and **Electrodes** for the sensing material **signal read-out**





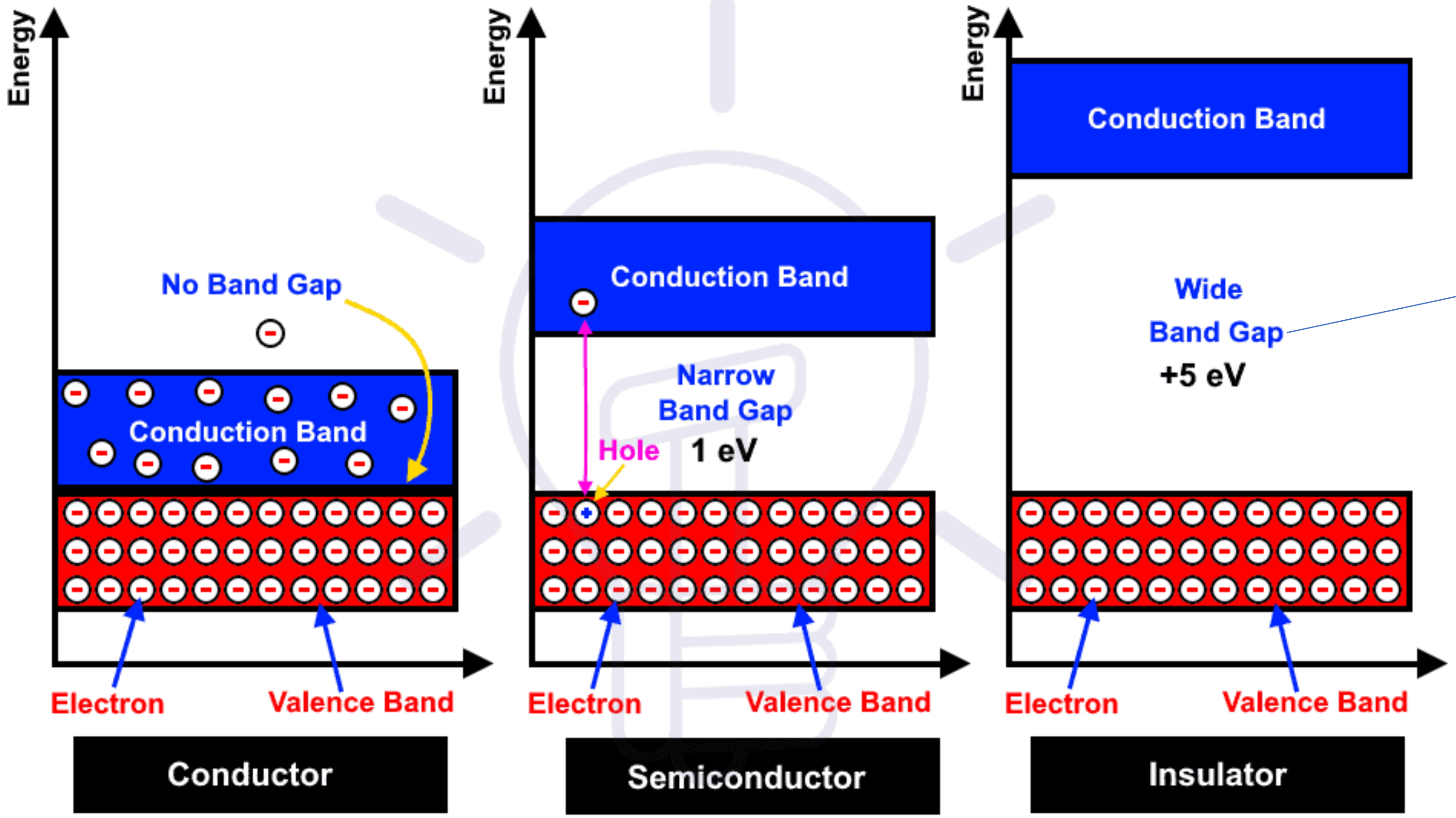




OUTLINE

- FBK sensor group & problem statement
- Low cost gas sensors
- Chemoresistive gas sensors: working principle
- Sensing materials
- Substrates
- Working principle and influencing parameters

What is a semiconductor?



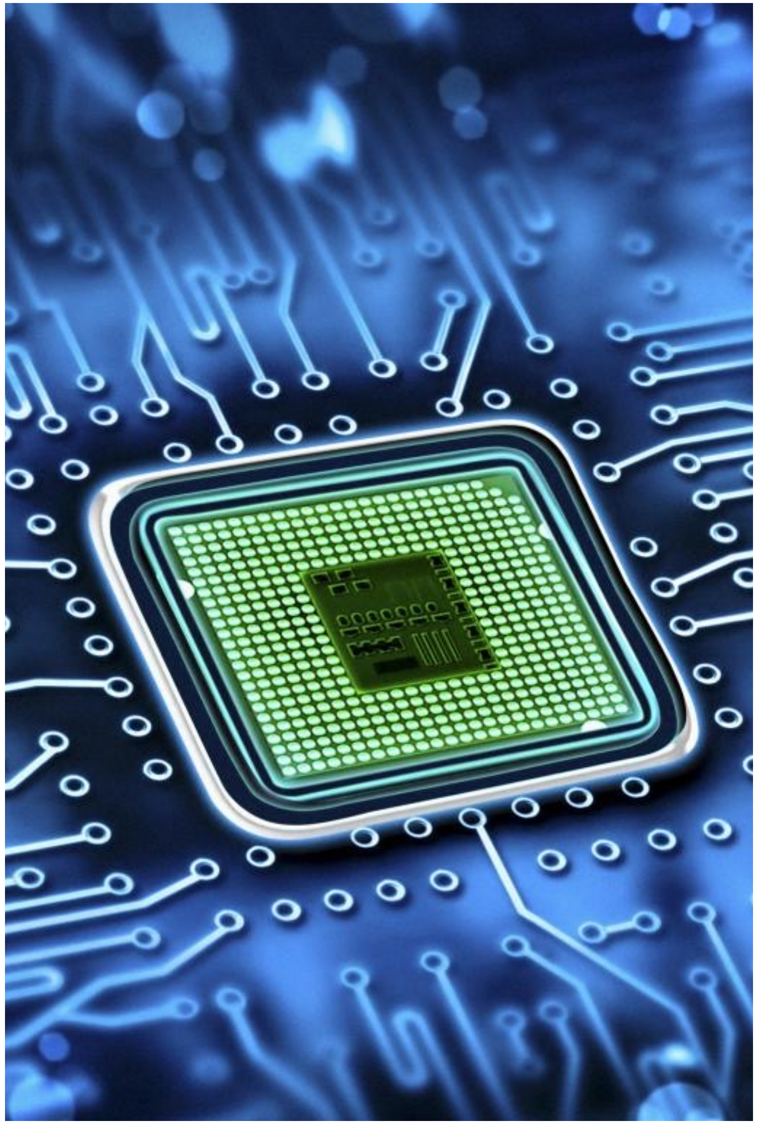
<u>Band gap</u>: *distance between the valence band of electrons and the conduction band.*
Essentially, the **band gap represents the minimum energy** that is required **to excite an electron up to a state in the conduction band <u>where it can participate in conduction</u>**

Conductors: allow the current flow due to the presence of free electron or ions which starts moving when voltage is applied.

Semiconductor: a material whose conductivity lies between conductor and insulator. Energy must be apply in order to push electrons from the valence to the conduction band, increasing the material conductivity

Insulator: a material that does not allow the flow of current.

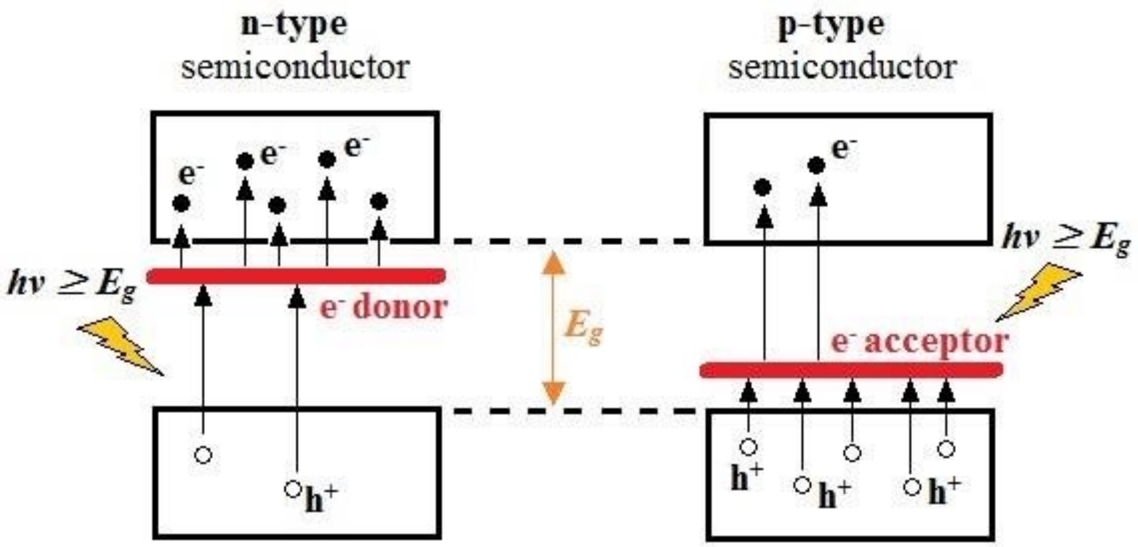
What is a semiconductor?



Basic materials for the development of modern-day technologies!
Silicon = basic material for microchips

The electrical conduction inside semiconductors is due to the movement of electrons and holes

n-type semiconductors: charge carriers = electrons
p-type semicoductors: charge carriers = holes

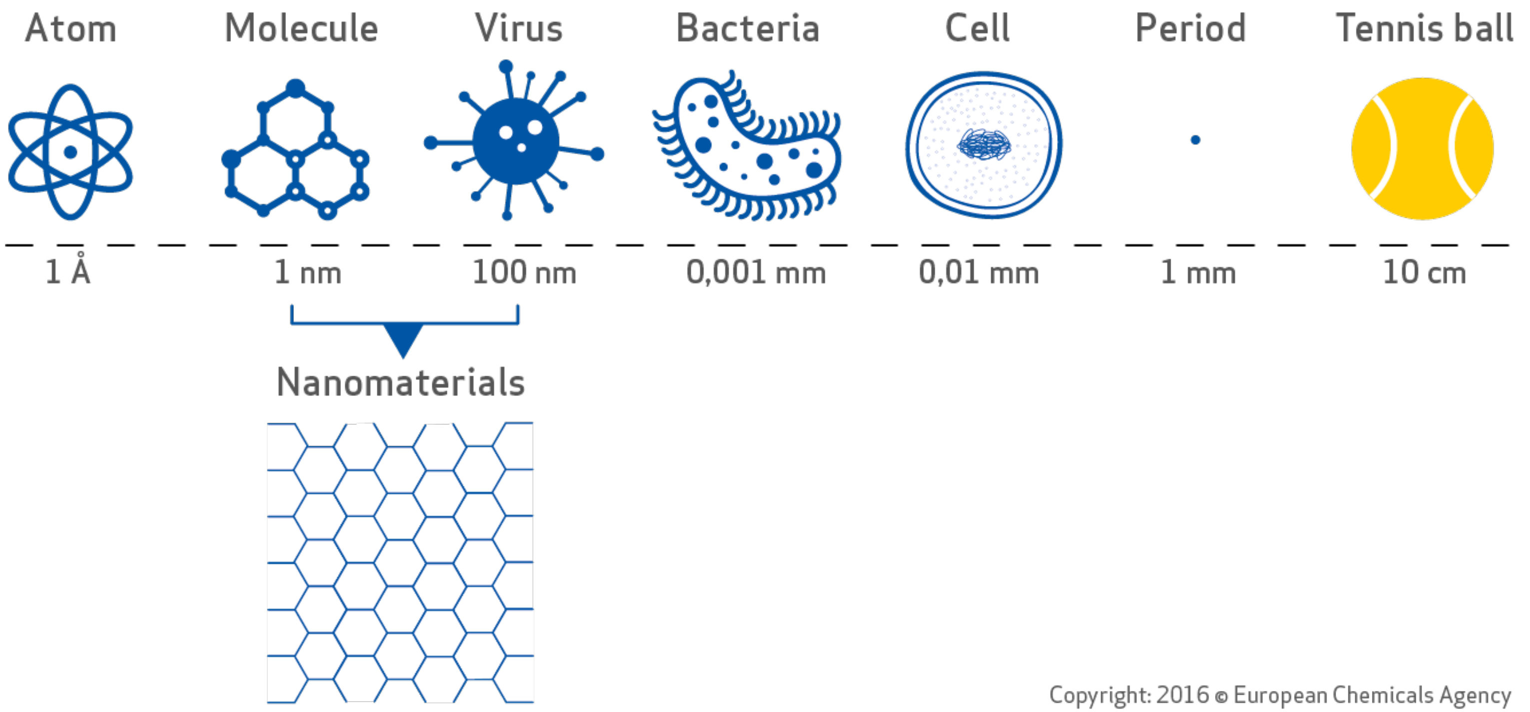


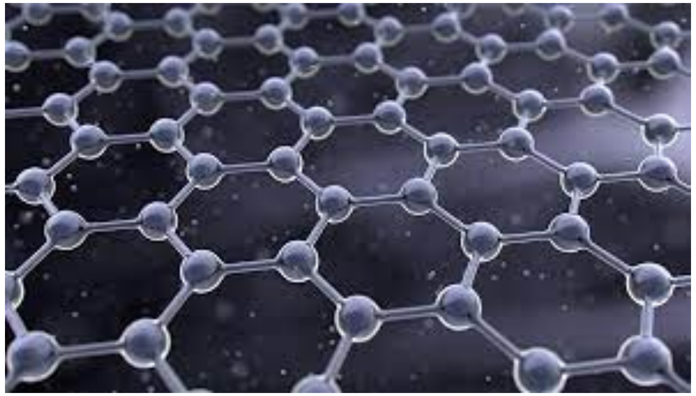
The **sensing material** is a **nanostructured semiconductor**, so it needs **<u>to be ACTIVATED to work properly</u>**

What is a nanostructured material?

Nanomaterial: material composed of particles consisting of atomic or molecular aggregates with a diameter of approximately 1 to 100 nm

→ Produced and used for nanotechnology development





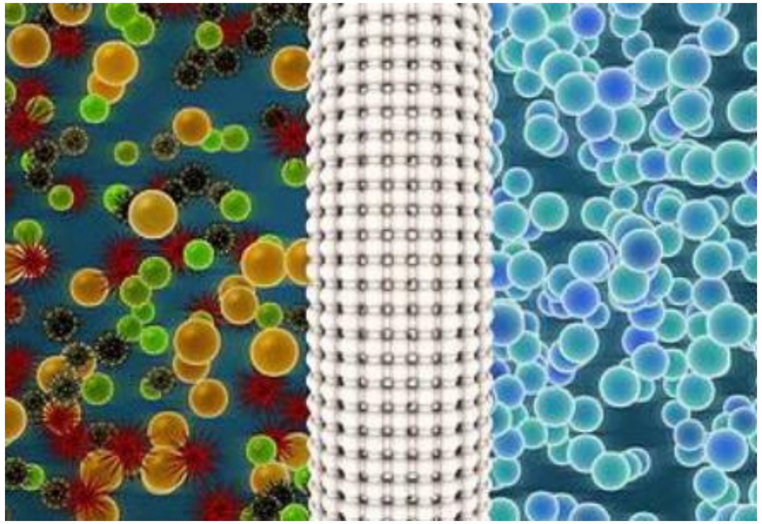
Advantages:

1) **Very high surface area-to-volume ratio**
2) **Different chemical and physical properties compared with macro-material**

Sensing materials

The most widely used **semiconductors** as sensing materials **are METAL OXIDES (MOX) = metal + oxygen**

- Wide range of choices (SnO_2, WO_3, ZnO, TiO_2, etc.).
- Simple and low-cost syntheses

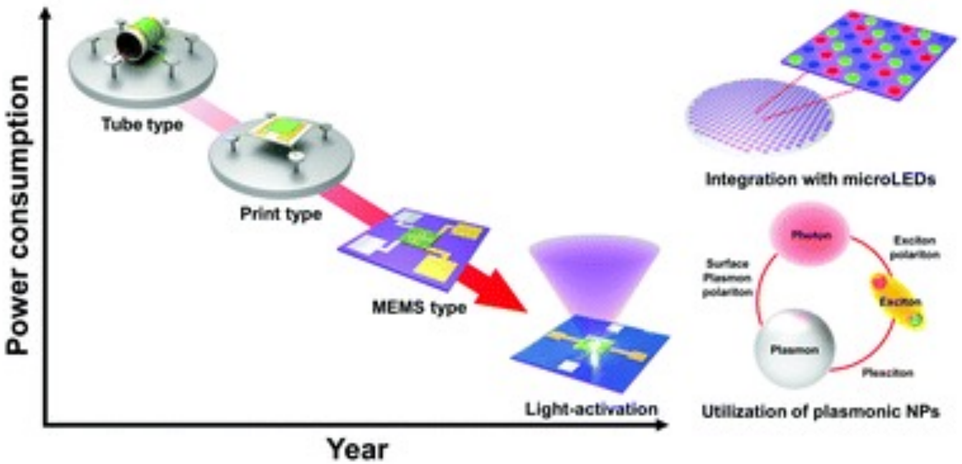


Advantages in using as a sensitive material:

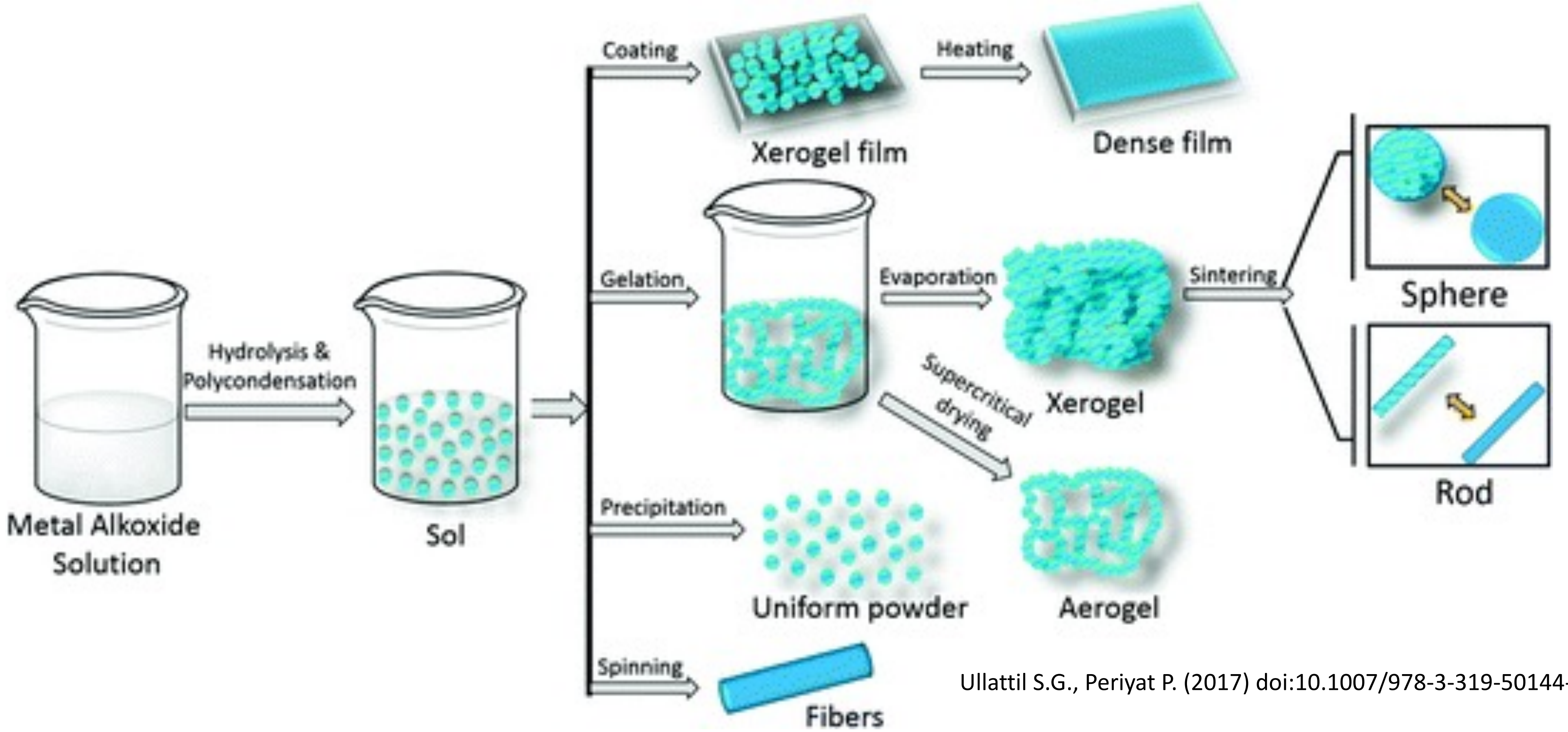
- High sensitivity
- High thermal stability
- Reversible surface reactions in activation
- Fast responses to the presence of gases

Chemoresistive properties can be activated by:

- Heating = thermo- activation
- Electromagnetic radiation (light) = photo-activation



Nanostructured MOX: Synthesis



Ullattil S.G., Periyat P. (2017) doi:10.1007/978-3-319-50144-4_9

Synthesis process
- Solvent effect (PEG, alfa-terpineol)
- Reagents (metal-organics)
- pH control
- Complexing agent

Heat treatments
- Temperature
- Timing
- Atmosphere

High control of morphology and crystal structure

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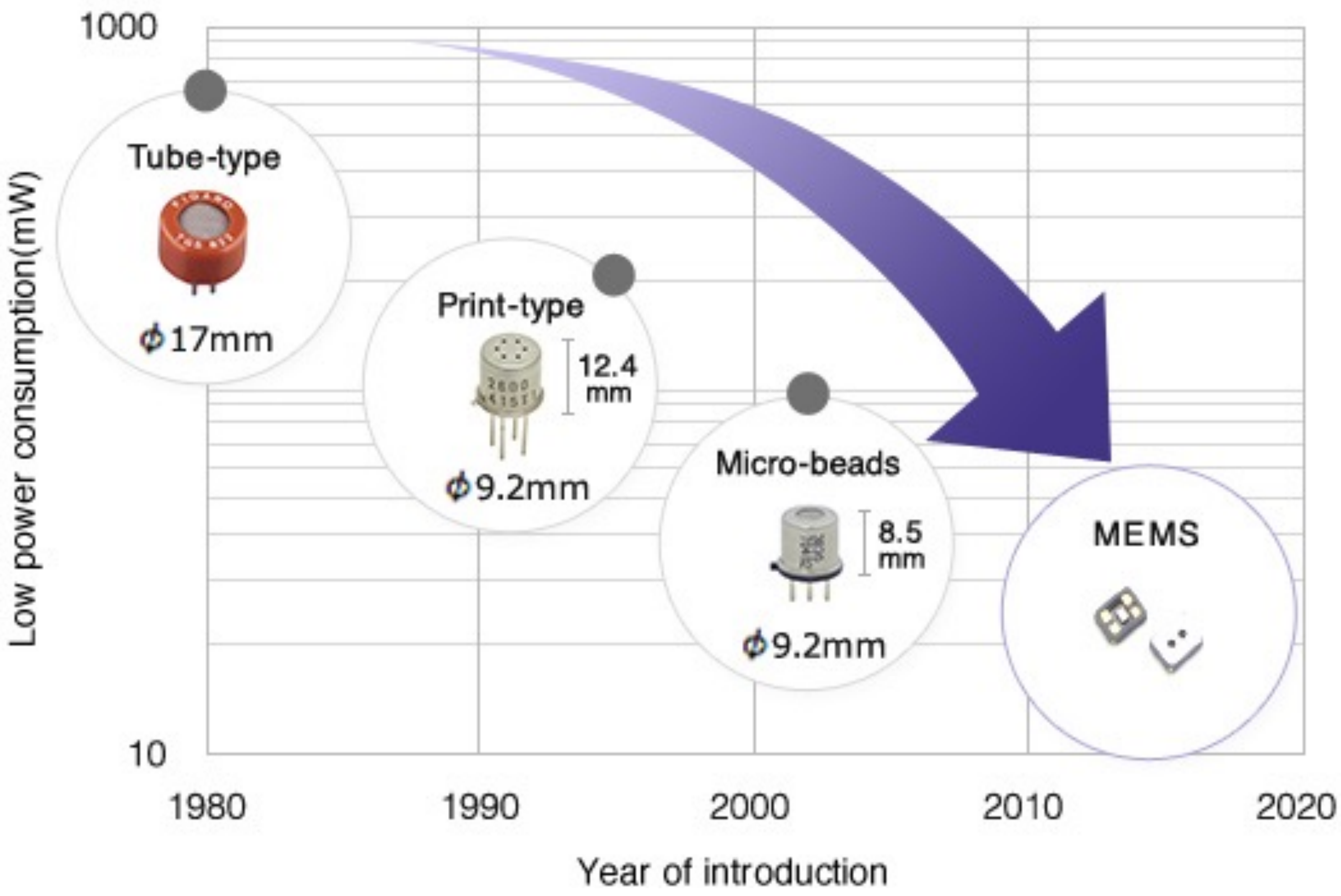
Substrate

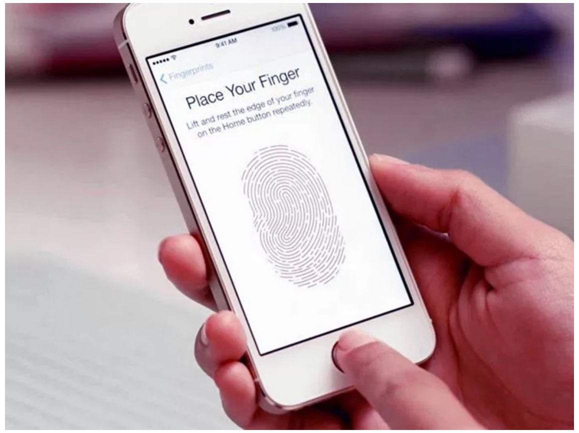
Triple Role: **Mechanical Support**, hosts **Heater** and **Electrodes** for the sensing material **signal read-out**



Optimization of the substrate over the time:

1) *Decrease of power consumption*
2) *Size decrease*

Integration into portable devices

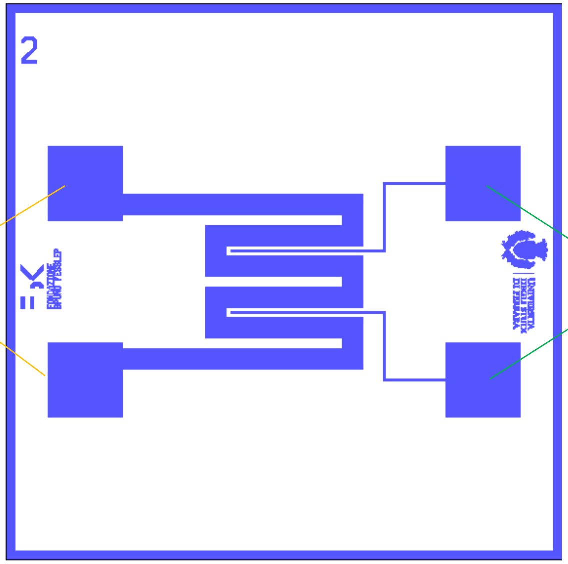


Substrate: silicon microheater

Process used: Silicon microfabrication

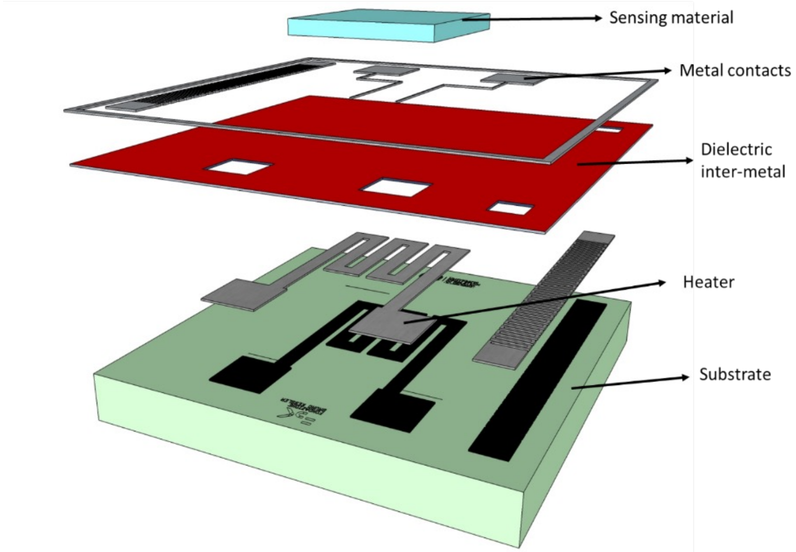
Microheater: top view (3x3 mm²)

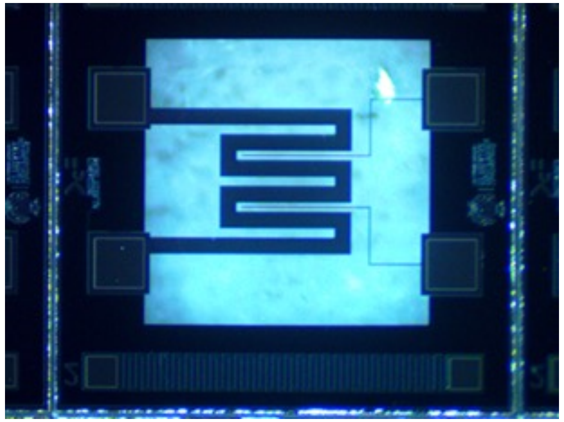
Heater: Pt, heating through Joule heating effect

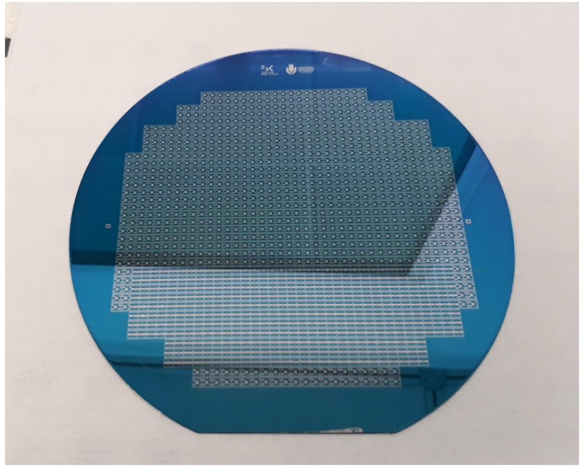


Elettrodes: read-out of the sensing material resistance

Microheater: Cross section







6“ silicon wafer: 1350 microheaters

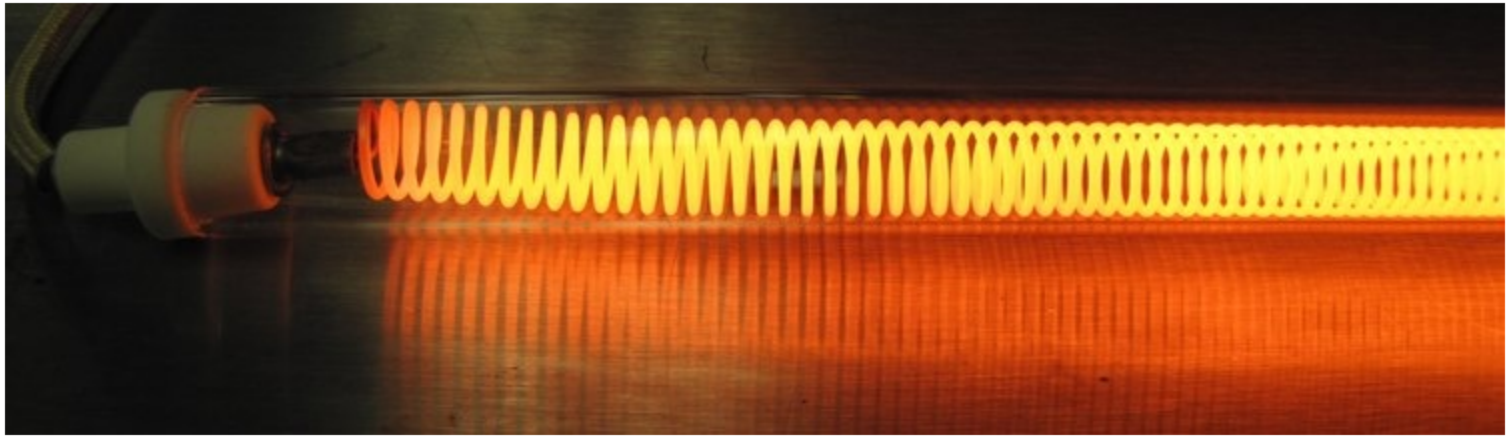
Joule heating

Joule heating, also known as resistive, resistance, or Ohmic heating, **is the process by which the passage of an electric current through a conductor produces heat.**

Joule's first law states that the power of heating generated by an electrical conductor equals the product of its resistance and the square of the current:

$P = I^2 * R$

Why?: A potential difference (V) between two points of a conductor creates an electric field that **accelerates charge carriers (e.g. e^-)** in the direction of the electric field, giving them kinetic energy. When the charged particles collide with the conductor lattice, **energy is being transferred from them to the material**!



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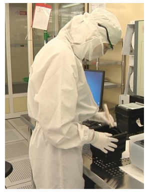
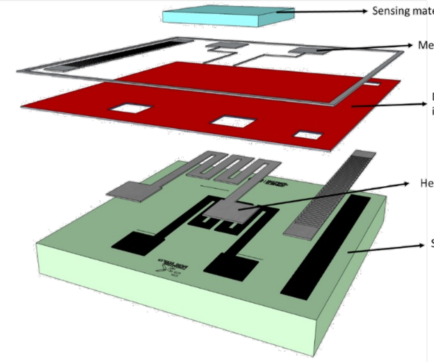
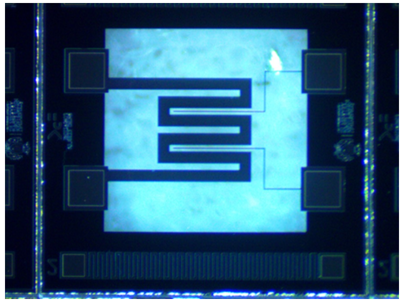
Sensor production @ FBK

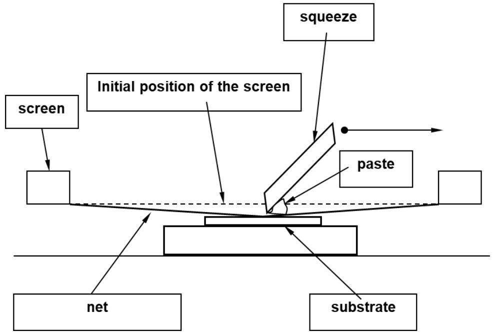


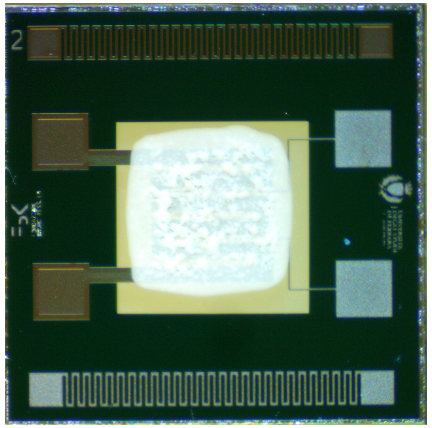
Microfabrication process of silicon MH



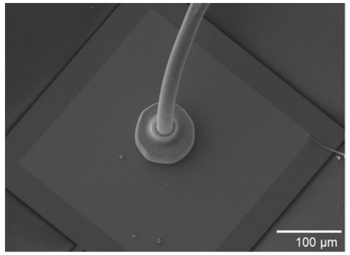


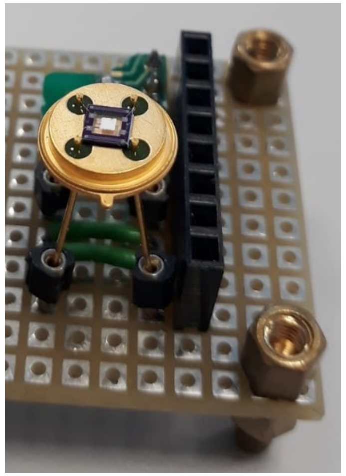
Sensing material deposition



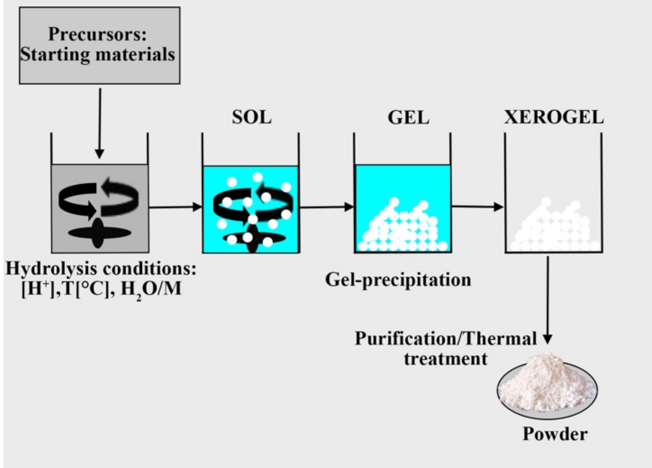


Ball bonding and Packaging





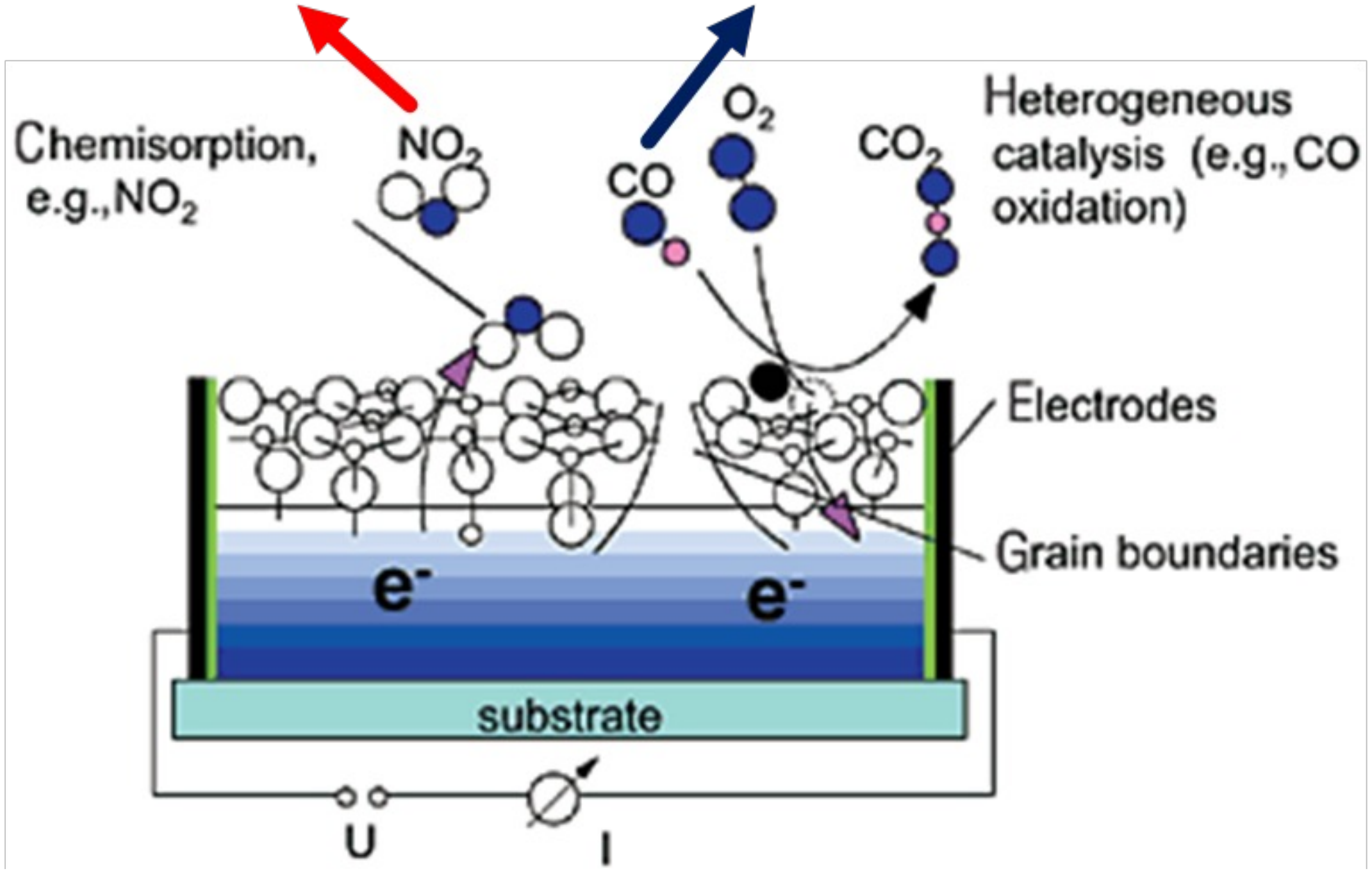
Sol gel synthesis of nanostructured MOX, MOX decoration, preparation of other semiconductors



MOX Chemoresistive gas sensors: Gas – Surface Interaction

Oxidizing gas: removes electrons from another species. Then, an oxidizer transfers electronegative atoms (oxygen) to a substrate.

Reducing gas: loses or donates electrons to another chemical species, then the reducer has been oxidized.



CENTER FOR SENSORS & DEVICES
FONDAZIONE BRUNO KESSLER

Nanotechnology for environmental monitoring Hands-on

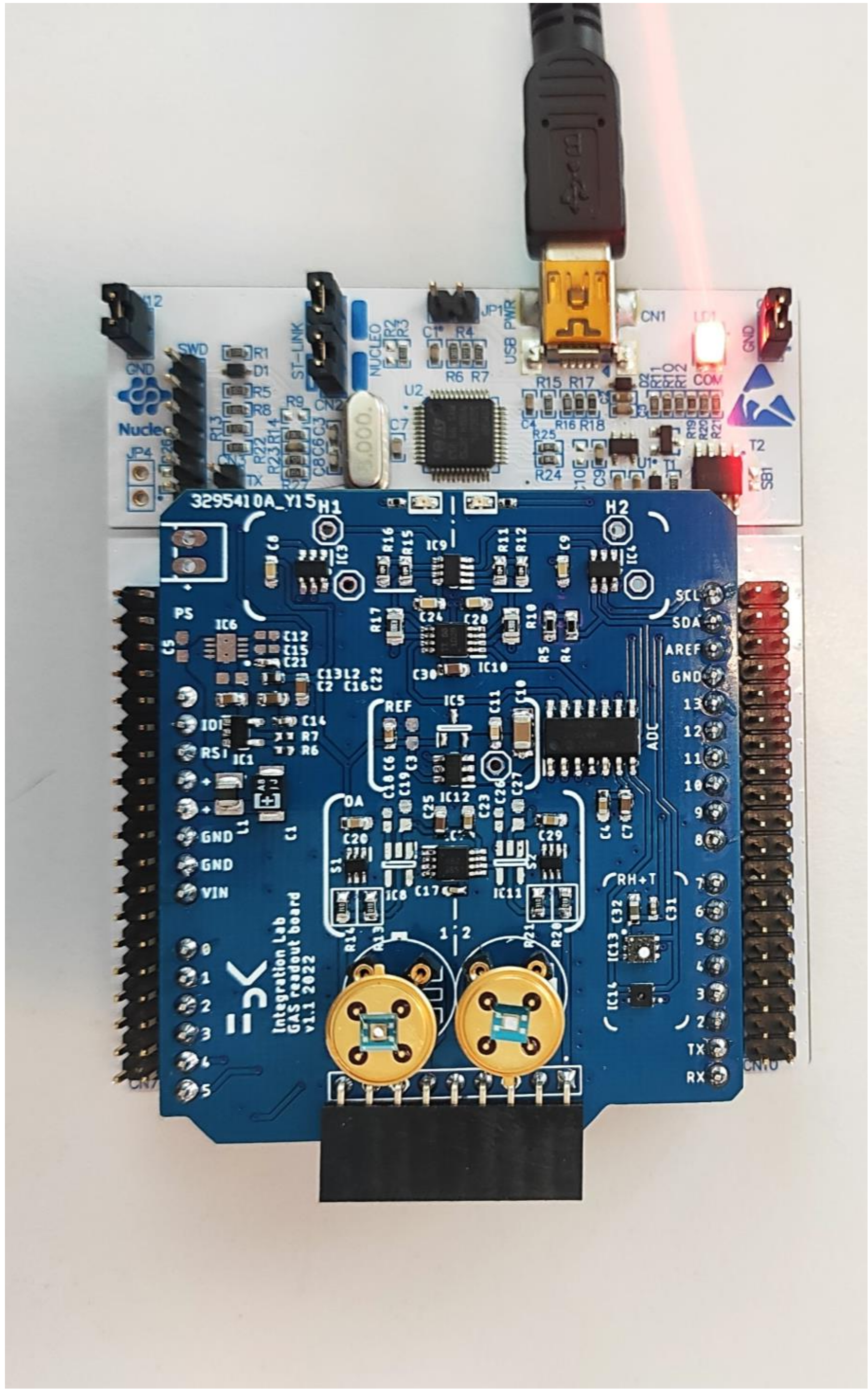
Pietro Tosato, Matteo Valt, Andrea Gaiardo
Center for Sensors & Devices
Fondazione Bruno Kessler

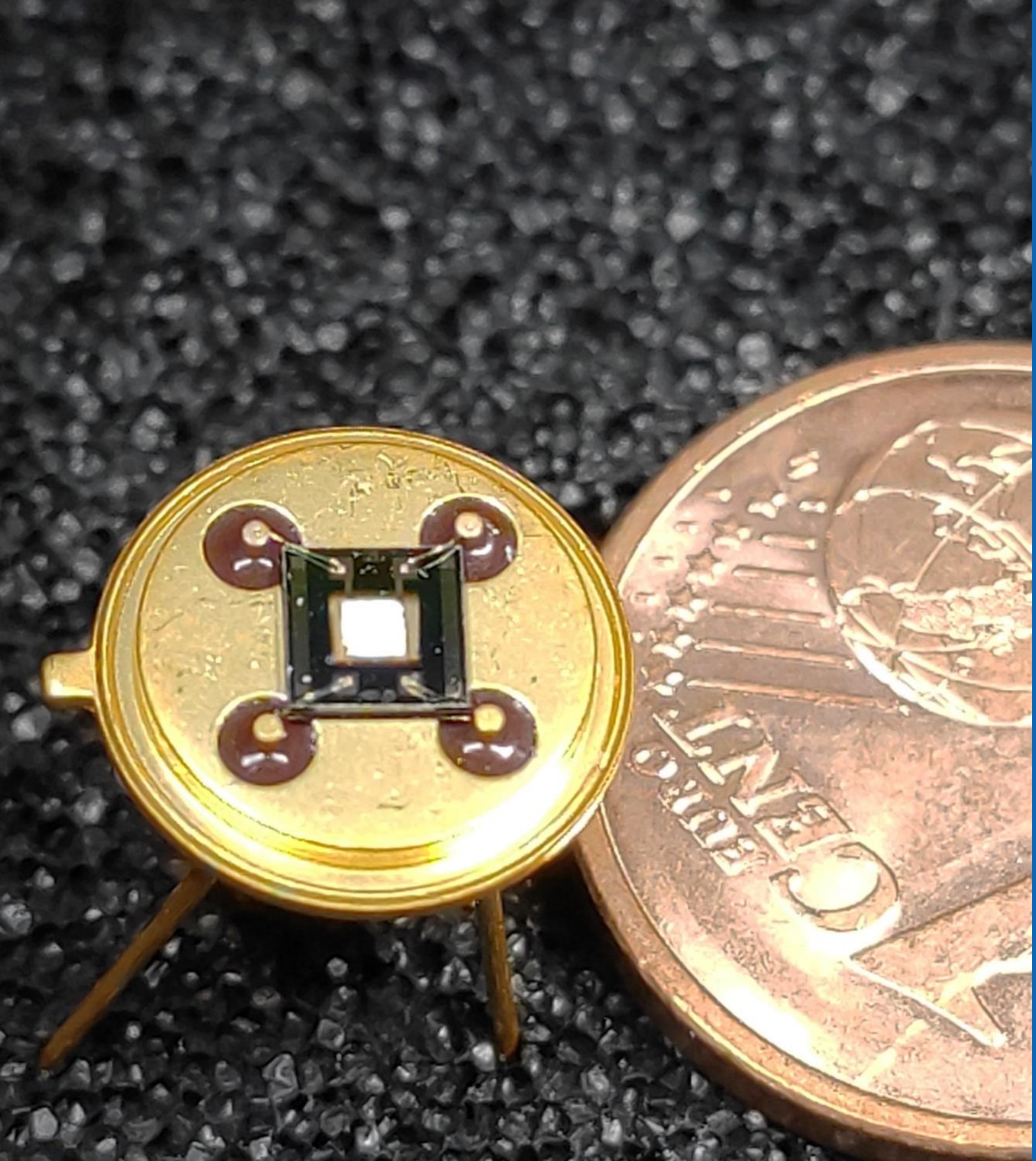
Inspyre, March 29-30 2023

ptosato@fbk.eu
www.fbk.eu

Agenda

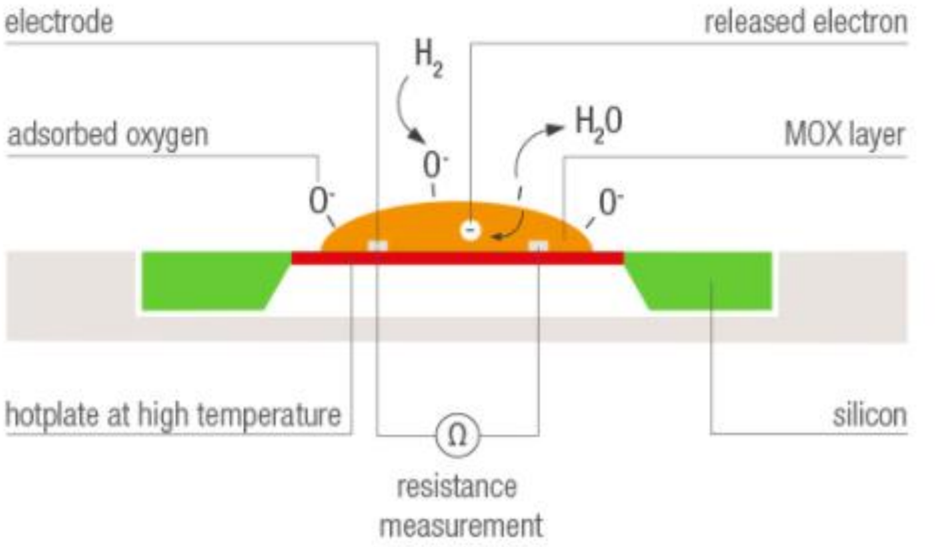
- Chemoresistive sensors
- Electronics for sensors readout
- Hands-on with ST Nucleo

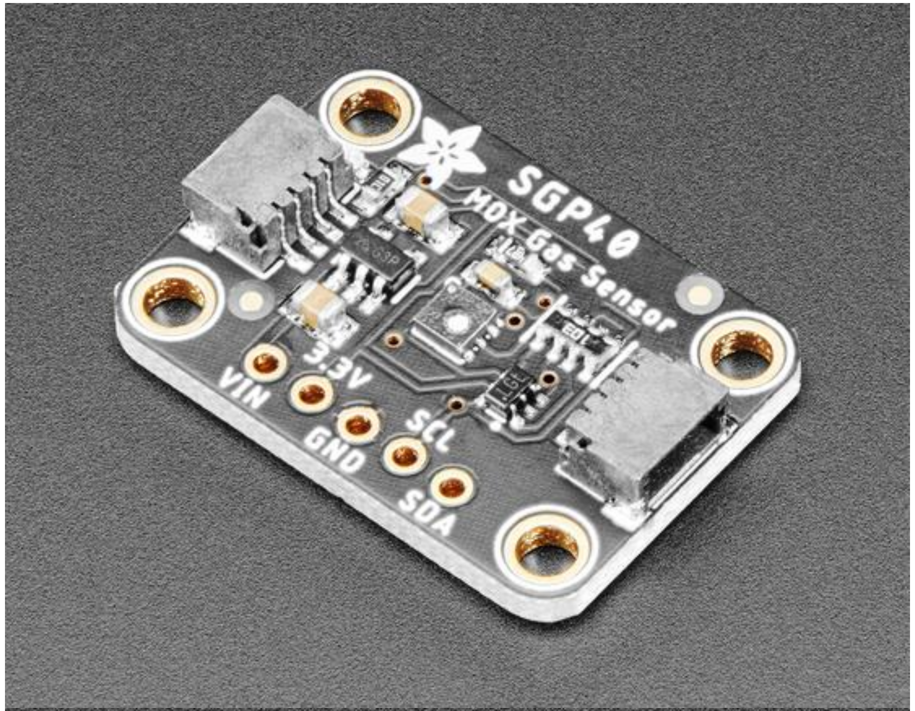




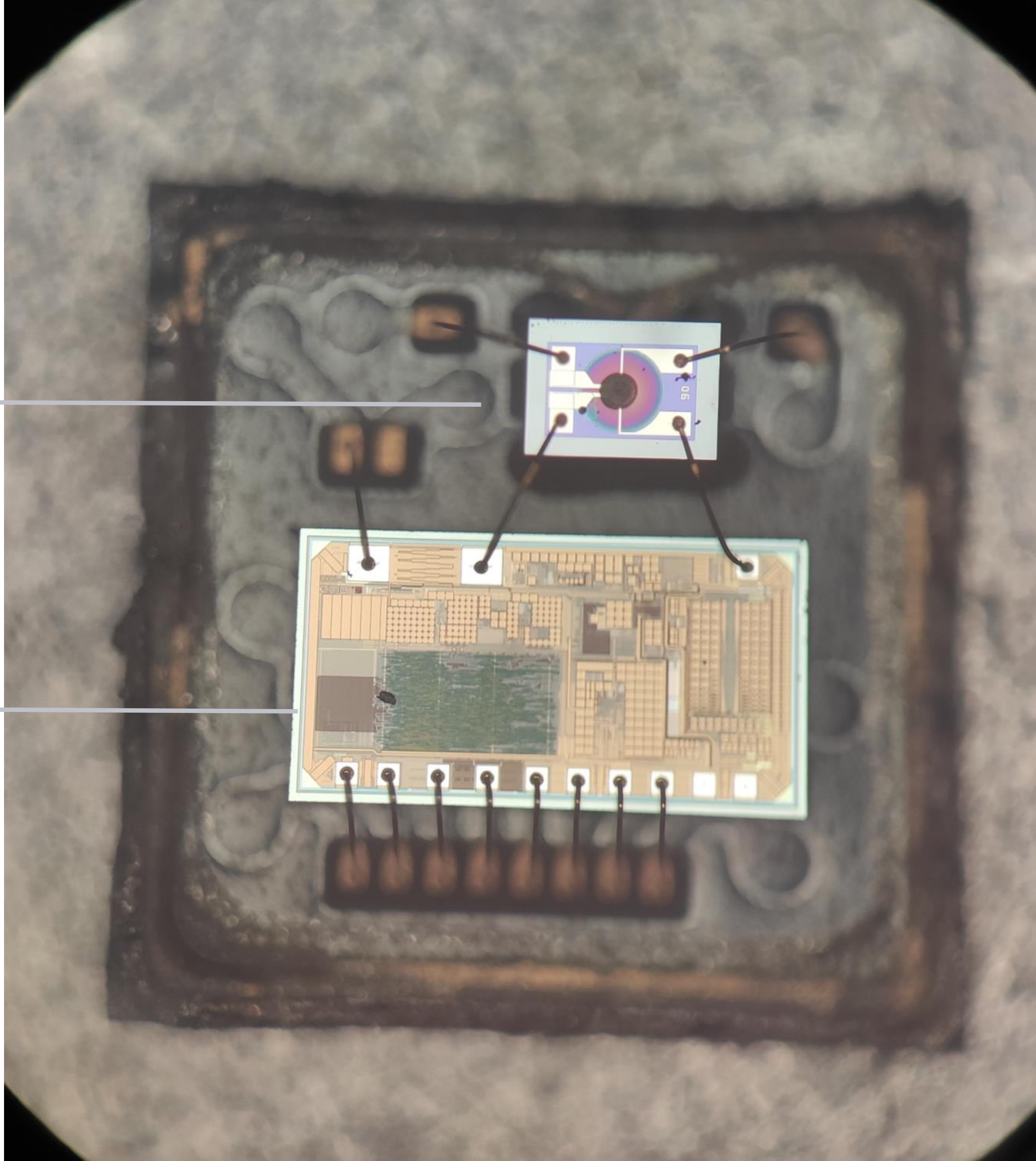
Chemoresistive sensor, mounted on a TO package

That’s like a commercial sensor





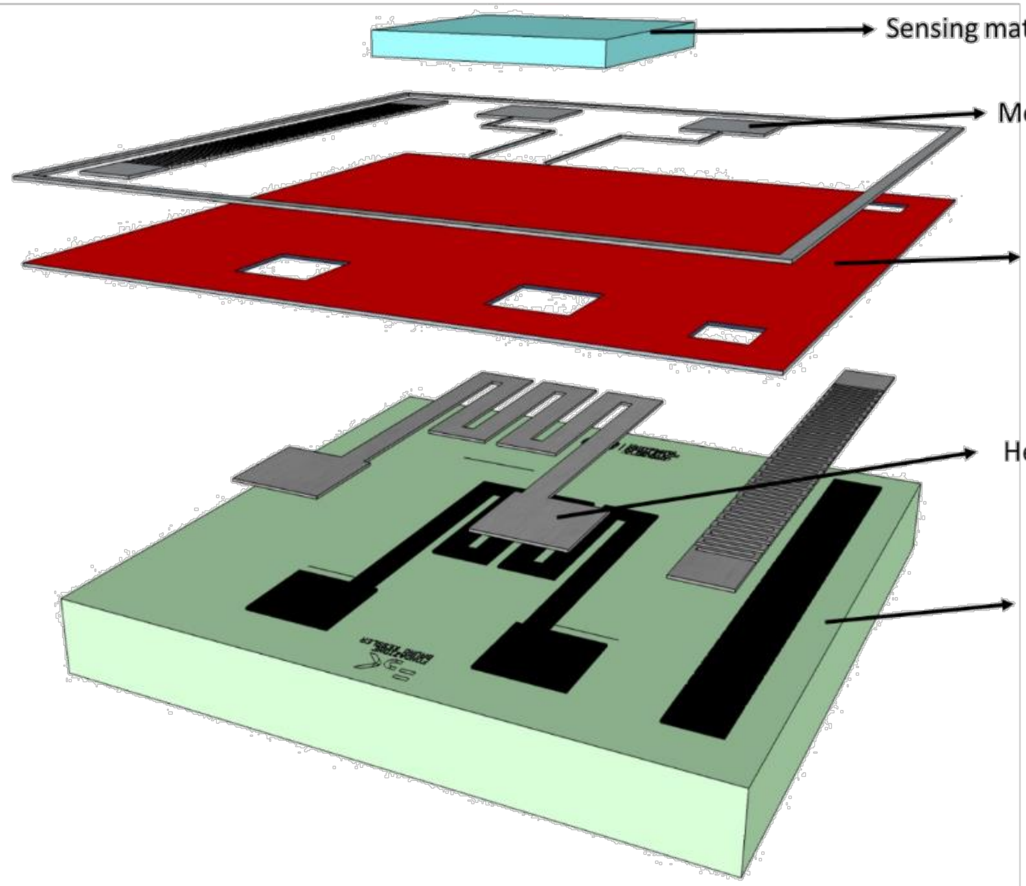
What’s inside:



Sensor element

Electronics to power, read and interface

Technology



1 Sensing material

It's a MOX nano-structured paste, interact with specific types of gas

2 Substrate

Mechanical support, heater and electrical circuit

Sensor – pysical characteristics

We built a lot of different sensors, **every one** has different characteristics

- LaFeO3 → **<100 kOhm**
- STN → **>100 MOhm**
- WO3 → **~10 Mohm**

It varies with temperature!
And gas concentration, clearly.

We are going to measure its resistance

Heater – pysical characteristics

Again, we have different layout of the silicon, that are designed for different temperature setpoints, usually characterized at the wafer level

Electronics must find a sweet spot where the sensor should operate:
The membrane is fragile, can break with thermal shock or overtemperature

Usually **80-120 Ohm at 3.5-4.5 V** → max 200mW

Sensor

Heater

It is powered by a dedicated circuit, heat up the sensor at the right temperature. On the board is available a DAC that can be used to this purpose.

MOx sensible layer

Thanks to a 1.024 V reference, it is possible to measure the resistance of the sensor. The current flowing in the sensor is amplified and read by an ADC.

Electronics

What electronics do

1. Measure a low current (or high resistance)
2. Supply variable voltage at the heater
3. Measure resistance at the heater side
4. Multiply it for different channels (2 in our case)
5. Processing and communication…

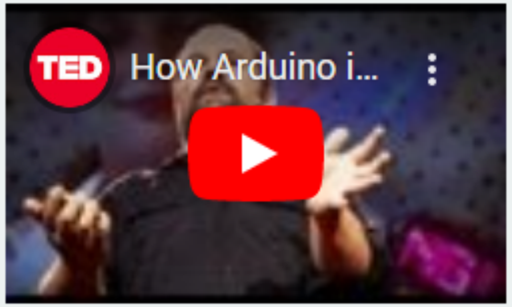
ADC and DAC

In electronics, an **analog-to-digital converter** (**ADC**, **A/D**, or **A-to-D**) is a system that converts an analog signal, such as a sound picked up by a microphone or light entering a digital camera, into a digital signal.

In electronics, a **digital-to-analog converter** (**DAC**, **D/A**, **D2A**, or **D-to-A**) is a system that converts a digital signal into an analog signal. An analog-to-digital converter (ADC) performs the reverse function.

https://en.wikipedia.org/wiki/Analog-to-digital_converter

Arduino



WHAT IS ARDUINO?

Arduino is an open-source electronics platform based on easy-to-use hardware and software. It's intended for anyone making interactive projects.

Learn more about Arduino

ARDUINO BOARD

Arduino senses the environment by receiving inputs from many sensors, and affects its surroundings by controlling lights, motors, and other actuators.

Discover the official Arduino boards

ARDUINO SOFTWARE

You can tell your Arduino what to do by writing code in the Arduino programming language and using the Arduino development environment.

Download the Arduino Software

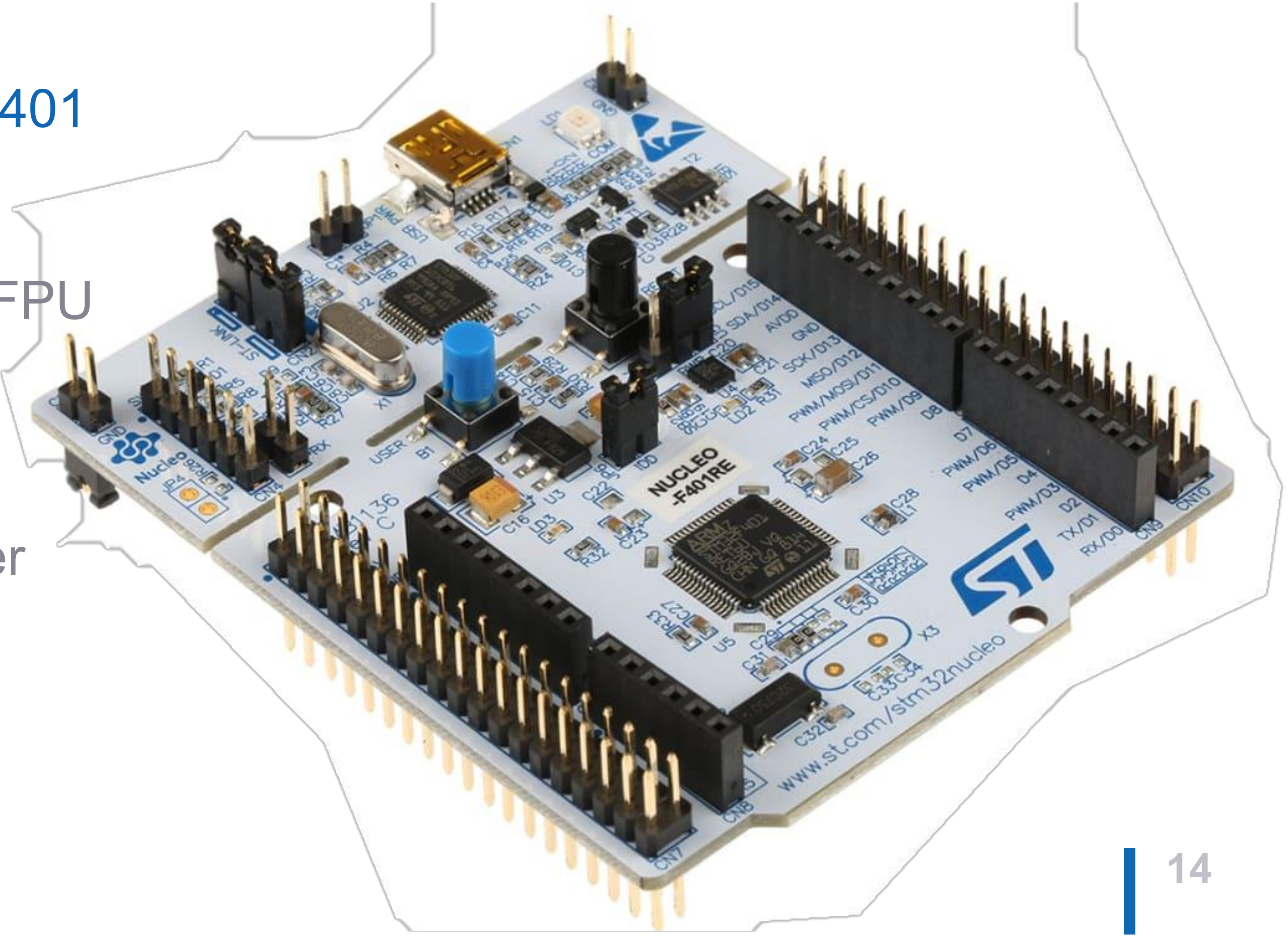
Development board

STMicroelectronics Nucleo-F401

STM32F401RE
32-bit Cortex®-M4 CPU with FPU
frequency up to 84 MHz
512 Kbytes of Flash memory

USB connection and debugger on-board

Arduino friendly!



Readout Electronics

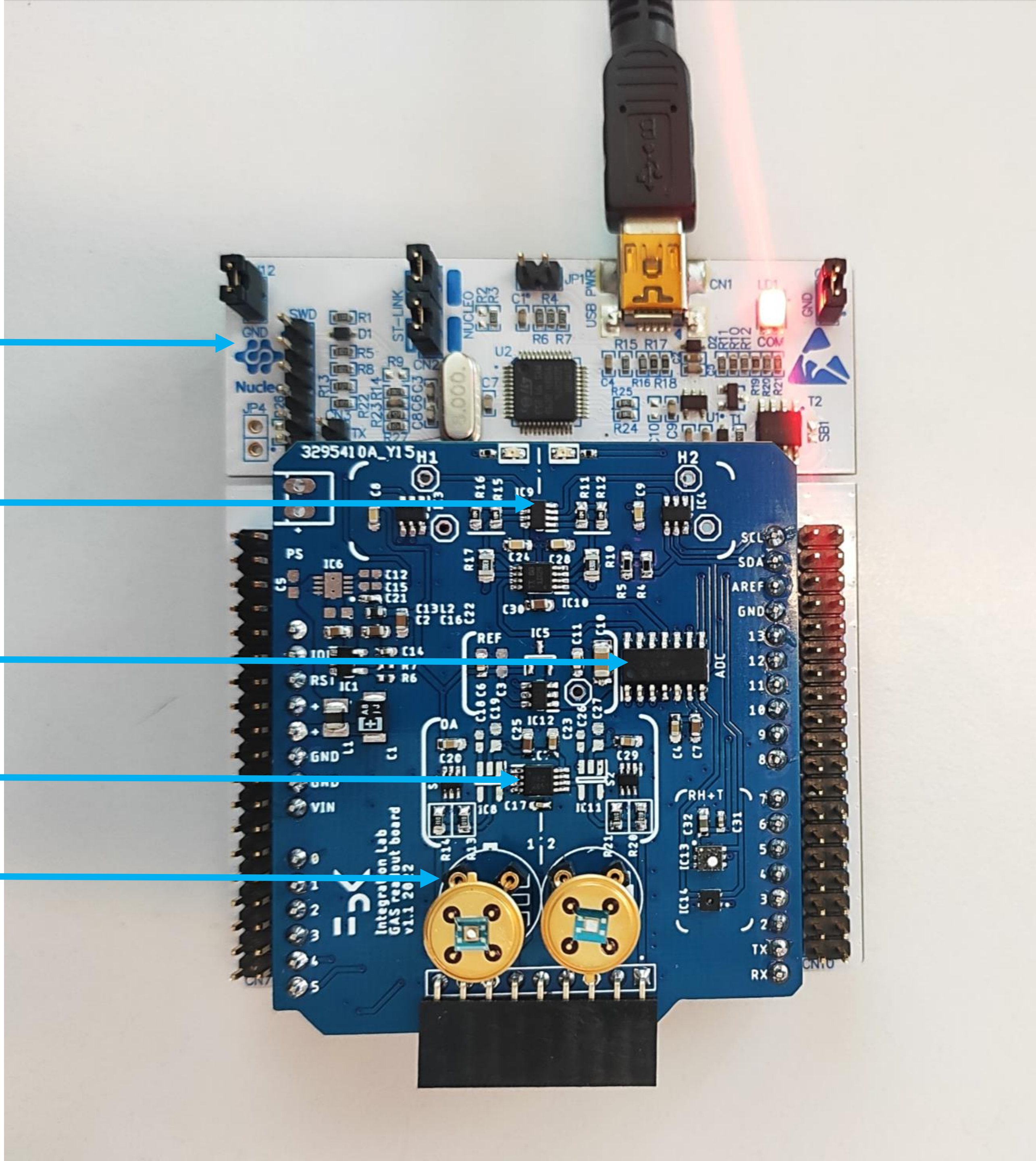
STM32 nucleo

DAC and driving circuit

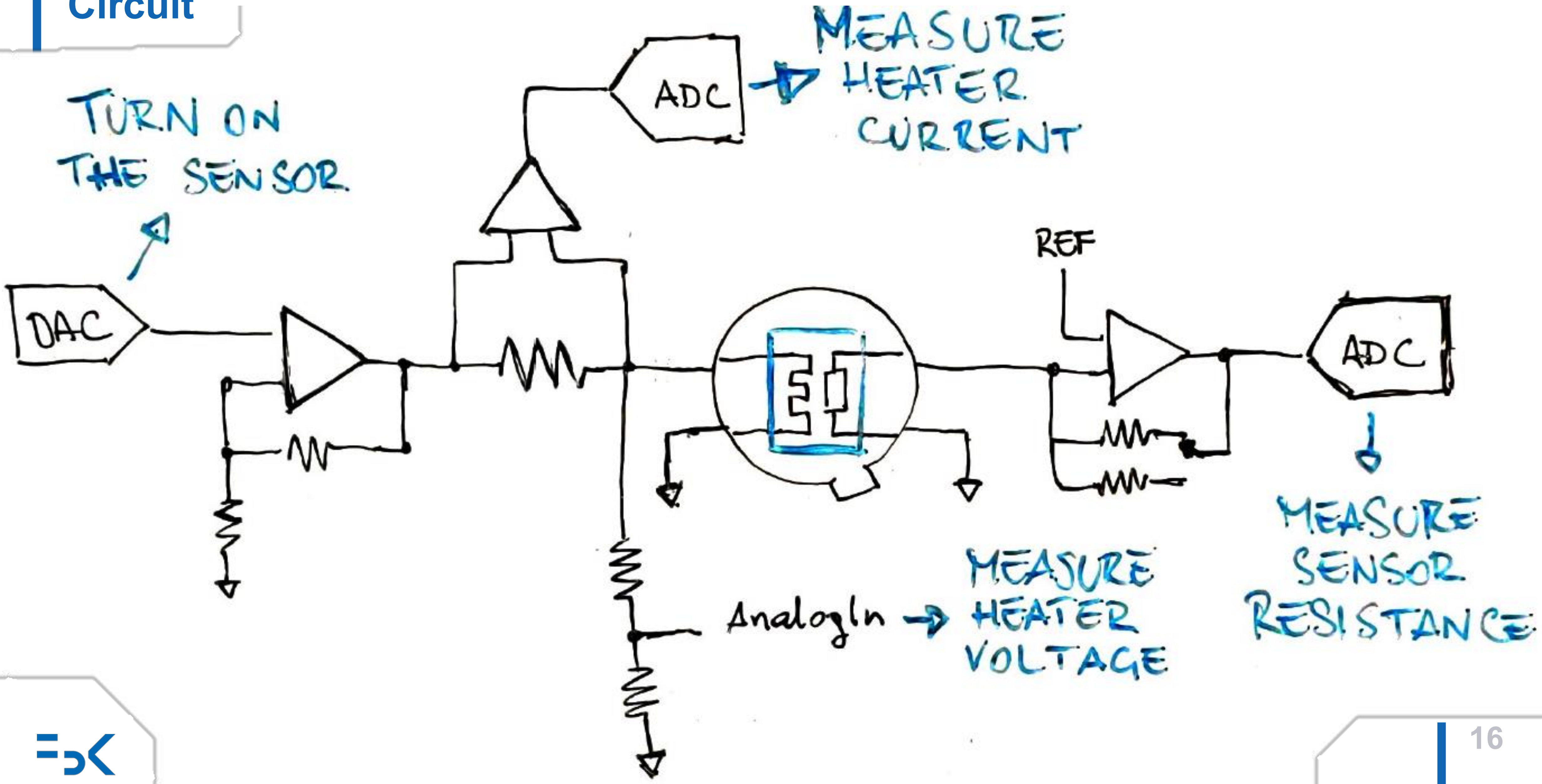
ADC

Amplifier

Sensors



Circuit


TURN ON THE SENSOR
DAC
ADC
MEASURE HEATER CURRENT
REF
ADC
MEASURE SENSOR RESISTANCE
AnalogIn
MEASURE HEATER VOLTAGE

Arduino setup

Install Arduino

Legacy IDE (1.8.X)

Arduino IDE 1.8.19

The open-source Arduino Software (IDE) makes it easy to write code and upload it to the board. This software can be used with any Arduino board.

Refer to the **Getting Started** page for Installation instructions.

SOURCE CODE

Active development of the Arduino software is **hosted by GitHub**. See the instructions for **building the code**. Latest release source code archives are available **here**. The archives are PGP-signed so they can be verified using **this** gpg key.

DOWNLOAD OPTIONS

Windows Win 7 and newer
Windows ZIP file

Windows app Win 8.1 or 10 Get

Linux 32 bits
Linux 64 bits
Linux ARM 32 bits
Linux ARM 64 bits

Mac OS X 10.10 or newer

Release Notes

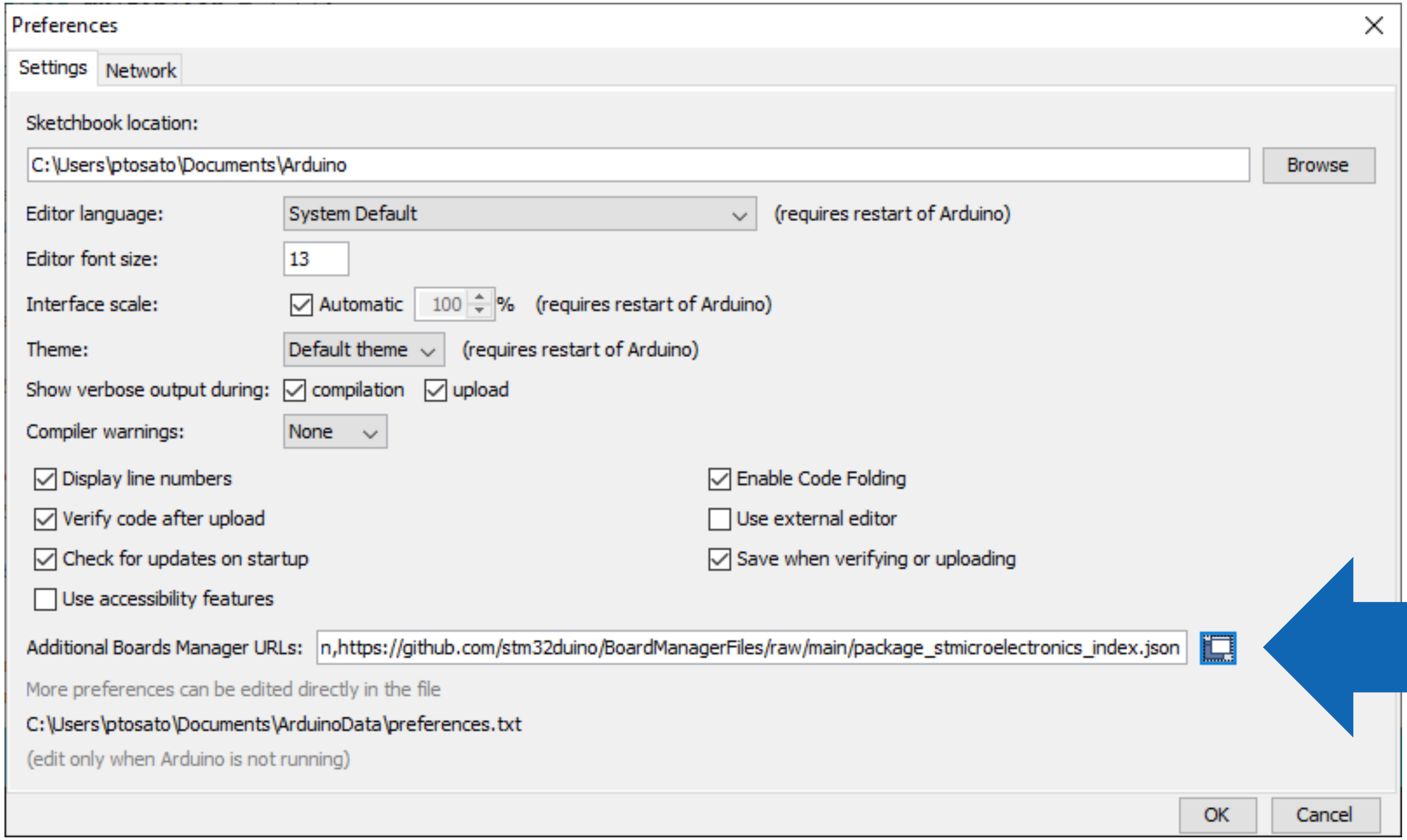
Checksums (sha512)

https://www.arduino.cc/en/software

Arduino for ST Nucleo: add source URL

Add source for STMicroelectronics boards, so that you will be able to install the tools

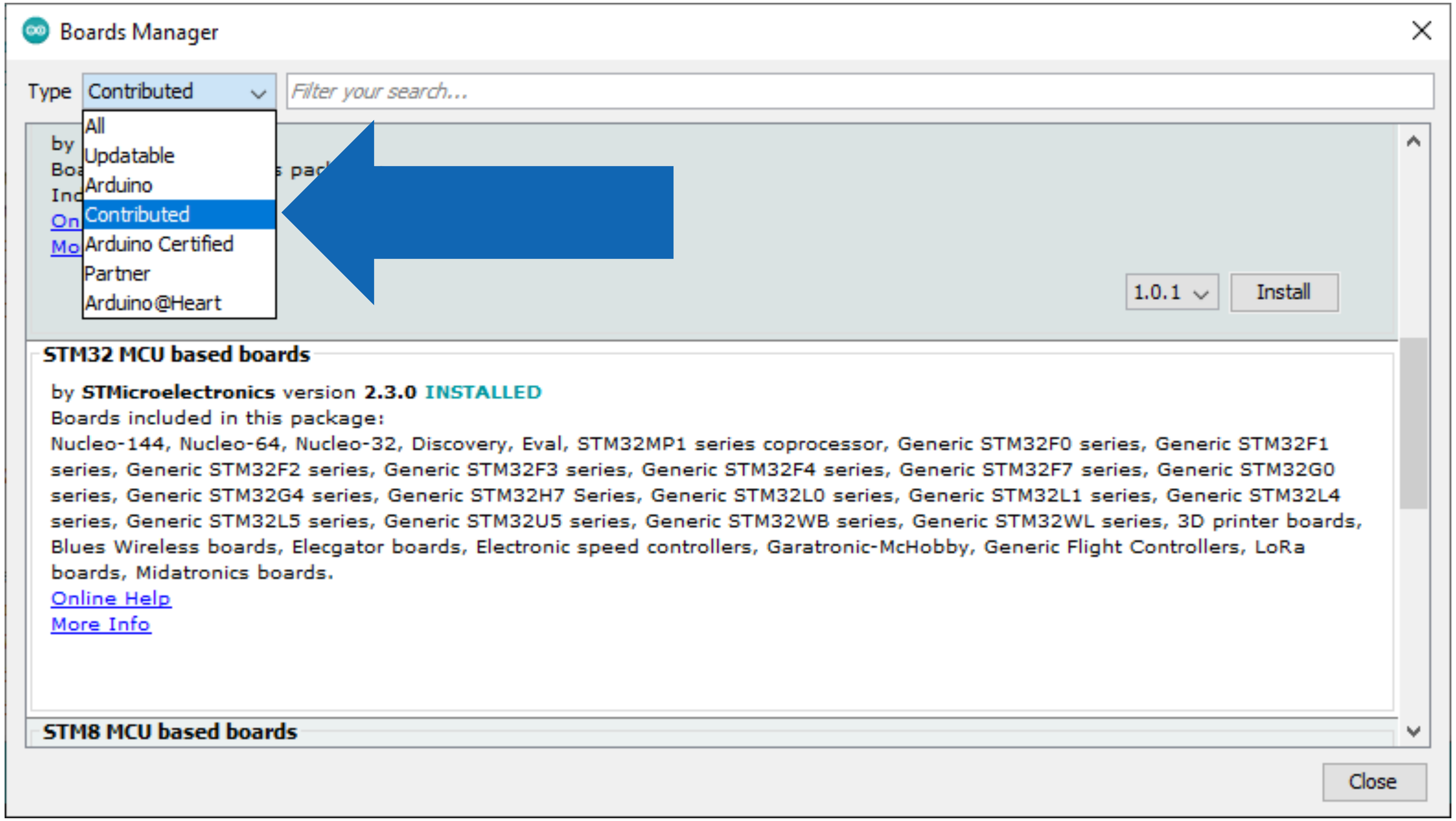
- File → Preferences
- Add stm32duino URL



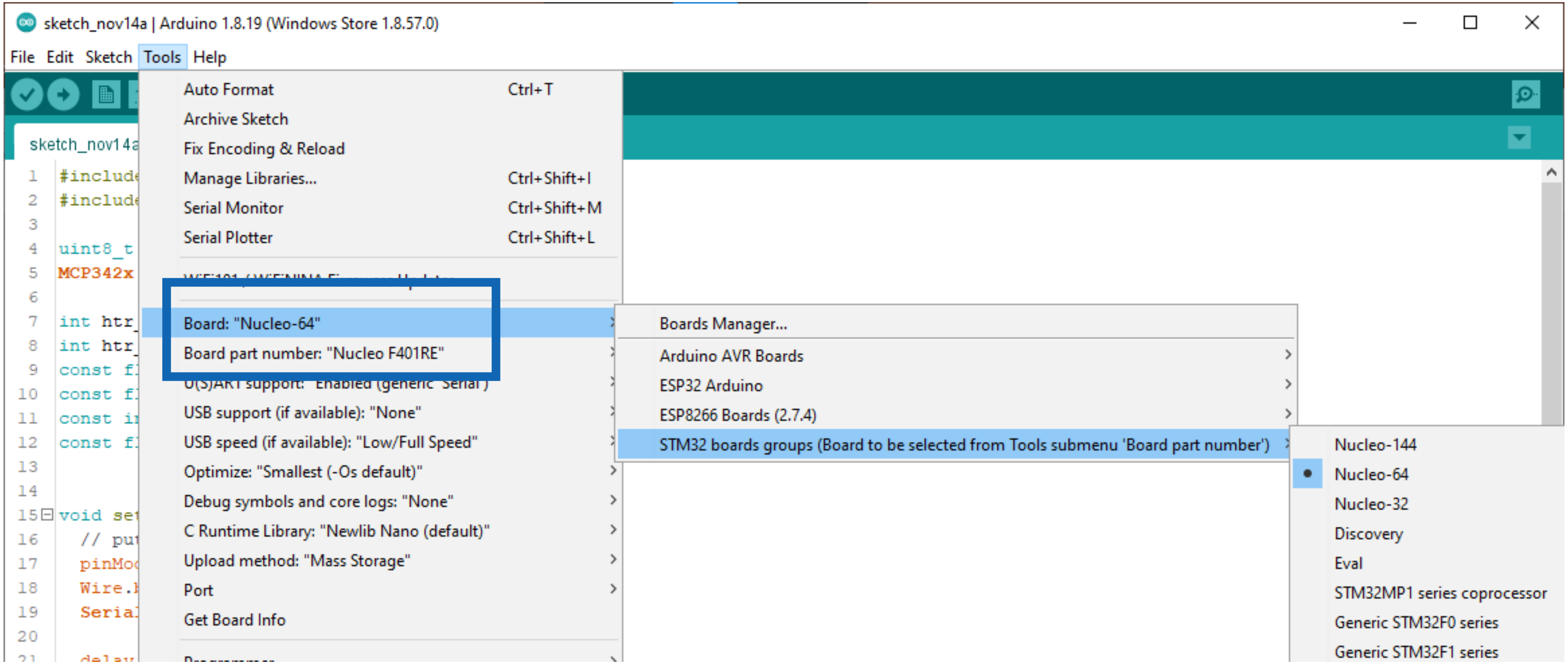
Arduino for ST Nucleo: install the toolchain

Add the boards needed, i.e. STM32 based boards

- Tools → Board → Board Manager
- Select Contributed
- Install STM32 MCU based boards
- Arduino will install the tools needed to work with such boards.
  It might take a while…



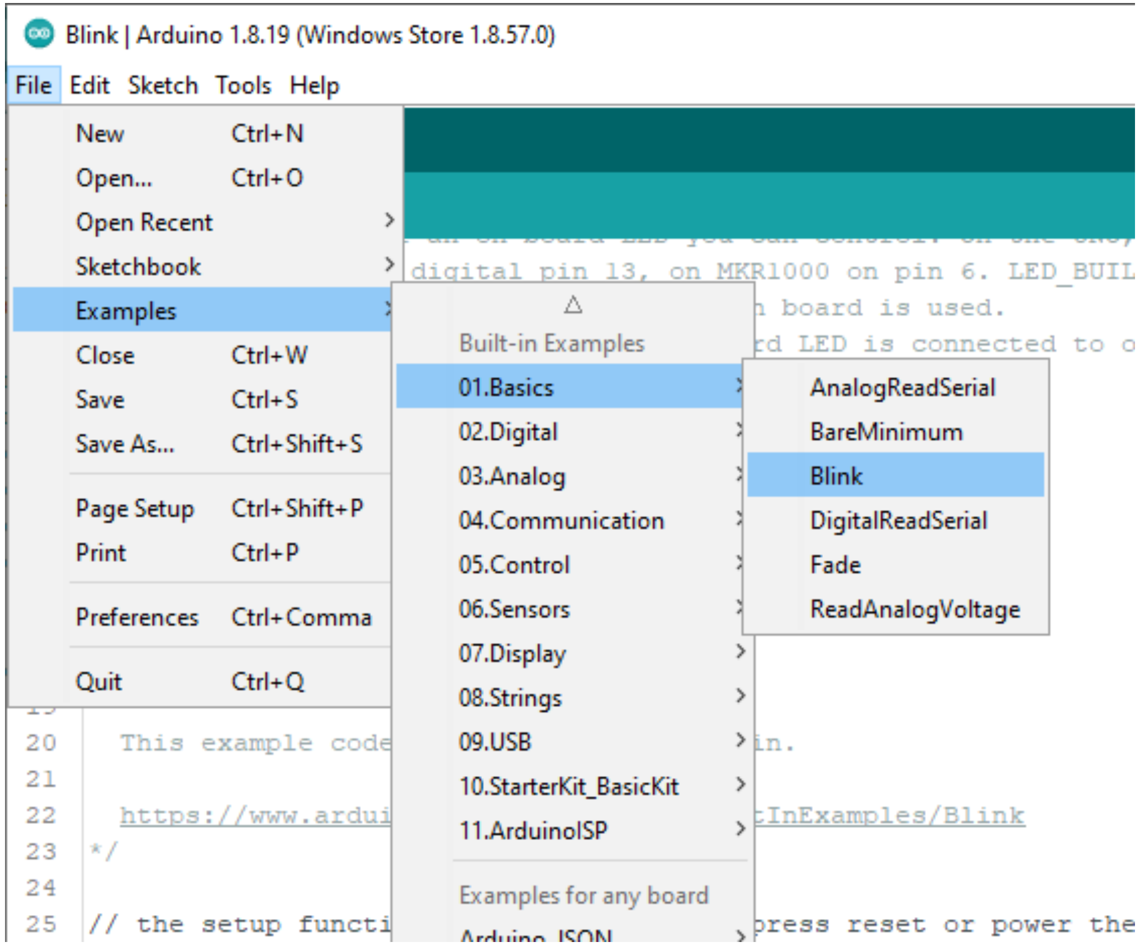
Arduino for ST Nucleo: select the right board



Hello World!

```
void setup() {
  // initialize digital pin LED_BUILTIN as an output.
  pinMode(LED_BUILTIN, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {
  digitalWrite(LED_BUILTIN, HIGH);
  delay(1000);                       // wait for a second
  digitalWrite(LED_BUILTIN, LOW);
  delay(1000);                       // wait for a second
}
```

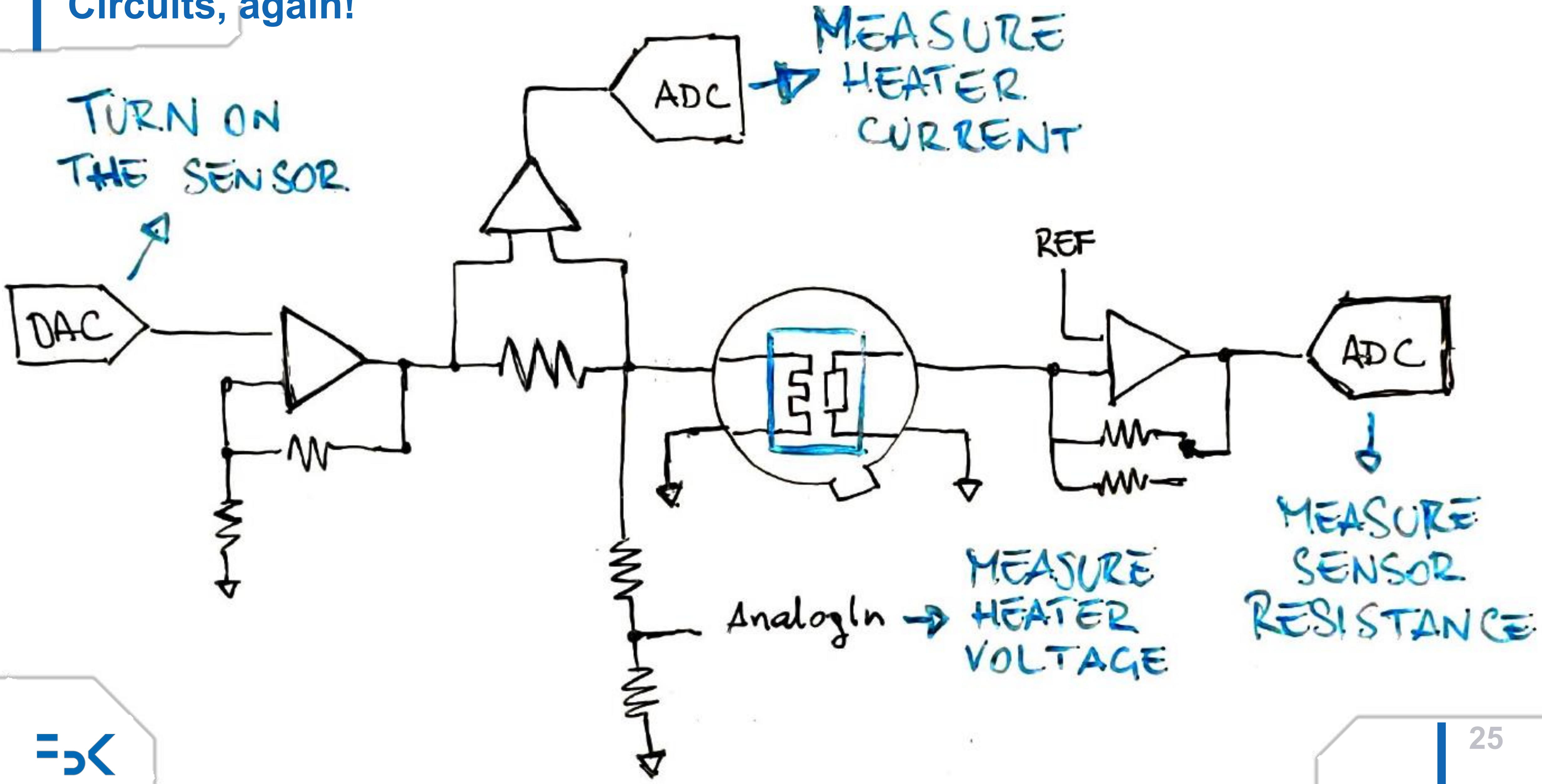


Codebase

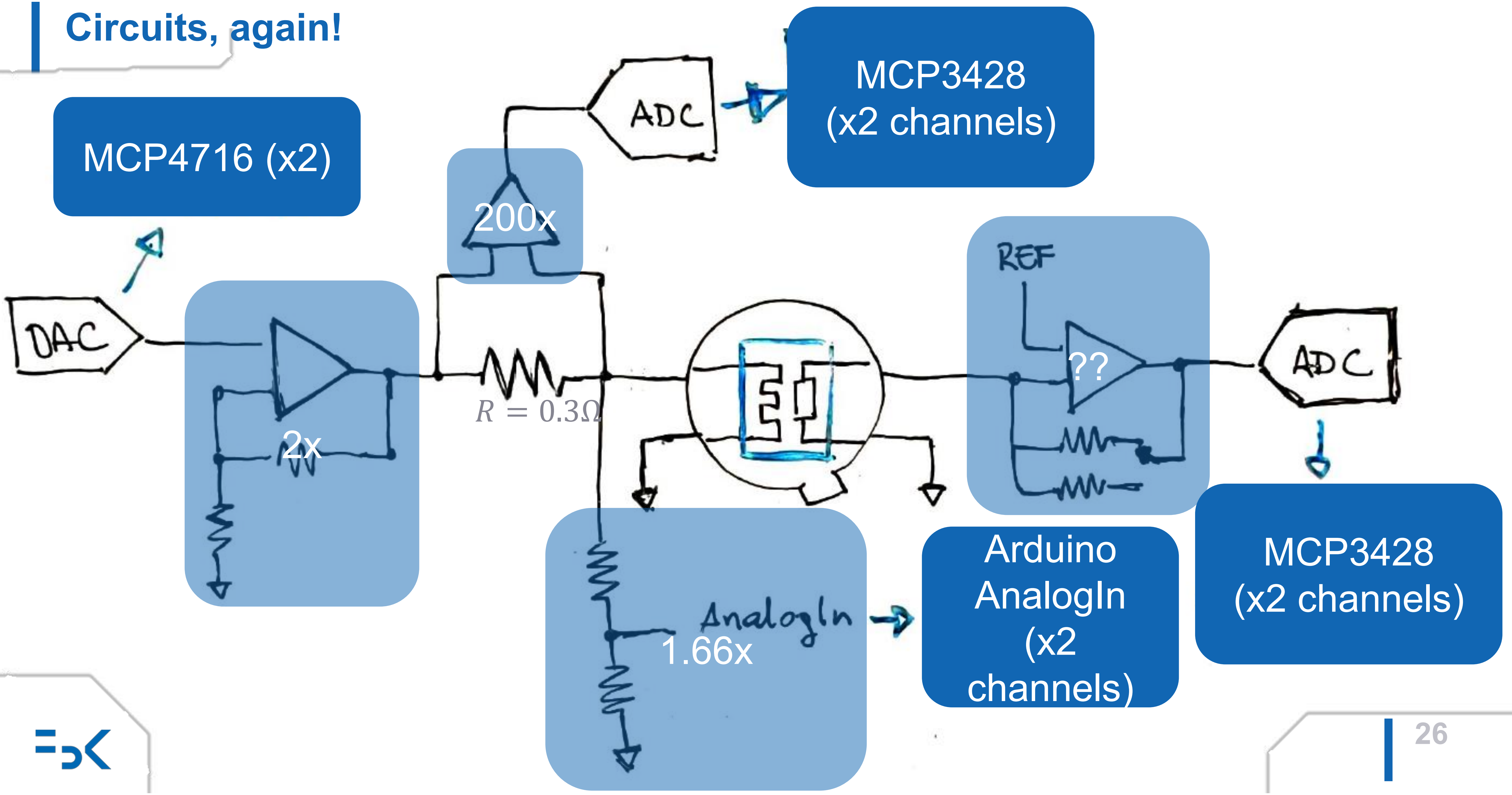
https://gitlab.fbk.eu/ptosato/inspyre23

Back to the HW

Circuits, again!



Circuits, again!



Measure the resistance

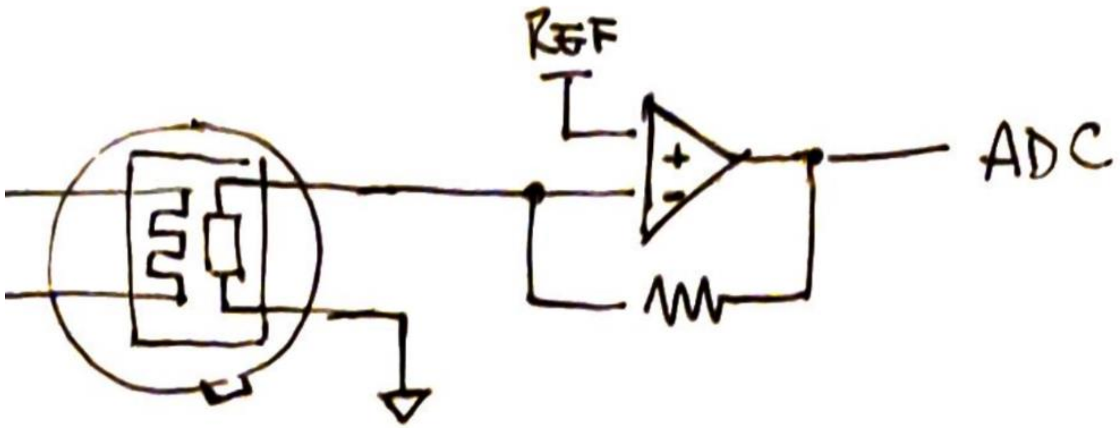
$$V = IR$$

$$V_{ADC} = I_{sensor} R_{FB}$$

$$R_{sensor} = \frac{R_{FB} V_{ref}}{V_{ADC}}$$

$V_{ref} = 1.024\ V$

$R_{FB} = 1\ k\Omega$, 1 MΩ



Code setup

MCP3428 (ADC)

Datasheet: https://bit.ly/3a6C7ob

MCP4716 (DAC)

Datasheet: https://bit.ly/3LVJZ9m

MCP3428

Channel

This chip has 4 channels

Resolution

Number of bits used by the digitizer, should use 16 bits

Gain

An internal amplifier can further amplify the signal (1 to 8x)

4.9 Digital Output Codes and Conversion to Real Values

4.9.1 DIGITAL OUTPUT CODE FROM DEVICE

The digital output code is proportional to the input voltage and PGA settings. The output data format is a binary two's complement. With this code scheme, the MSB can be considered a sign indicator. When the MSB is a logic '0', the input is positive. When the MSB is a logic '1', the input is negative. The following is an example of the output code:

(a) for a negative full scale input voltage: 100...000

Example: (CHn+ - CHn-) •PGA = -2.048V

(b) for a zero differential input voltage: 000...000

Example: (CHn+ - CHn-) = 0

(c) for a positive full scale input voltage: 011...111

Example: (CHn+ - CHn-) • PGA = 2.048V

The MSB (sign bit) is always transmitted first through the I^2C serial data line. The resolution for each conversion is 16, 14, or 12 bits depending on the conversion rate selection bit settings by the user.

The output codes will not roll-over even if the input voltage exceeds the maximum input range. In this case, the code will be locked at 0111...11 for all voltages greater than (V_{REF} - 1 LSB)/PGA and 1000...00 for voltages less than -V_{REF}/PGA. Table 4-2 shows an example of output codes of various input levels for 16-bit conversion mode. Table 4-3 shows an example of minimum and maximum output codes for each conversion rate option.

The number of output code is given by:

EQUATION 4-2:

$$\text{Number of Output Code} = (\text{Maximum Code} + 1) \times PGA \times \frac{(CHn+ - CHn-)}{2.048V}$$

Where:

See Table 4-3 for Maximum Code

The LSB of the data conversion is given by:

EQUATION 4-3:

$$LSB = \frac{2 \times V_{REF}}{2^N} = \frac{2 \times 2.048V}{2^N}$$

Where:

N = Resolution, which is programmed in the Configuration Register: 12, 14,

Table 4-1 shows the LSB size of each conversion rate setting. The measured unknown input voltage is obtained by multiplying the output codes with LSB. See the following section for the input voltage calculation using the output codes.

TABLE 4-1: RESOLUTION SETTINGS VS. LSB

Resolution Setting	LSB
12 bits	1 mV
14 bits	250 µV
16 bits	62.5 µV

TABLE 4-2: EXAMPLE OF OUTPUT CODE FOR 16 BITS (NOTE 1, NOTE 2)

Input Voltage: [CHn+ - CHn-] • PGA	Digital Output Code
≥ V_{REF}	0111111111111111
V_{REF} - 1 LSB	0111111111111111
2 LSB	0000000000000010
1 LSB	0000000000000001
0	0000000000000000
-1 LSB	1111111111111111
-2 LSB	1111111111111110
- V_{REF}	1000000000000000
< -V_{REF}	1000000000000000

Note 1: MSB is a sign indicator:
0: Positive input (CHn+ > CHn-)
1: Negative input (CHn+ < CHn-)

2: Output data format is binary two's complement.

TABLE 4-3: MINIMUM AND MAXIMUM OUTPUT CODES (NOTE)

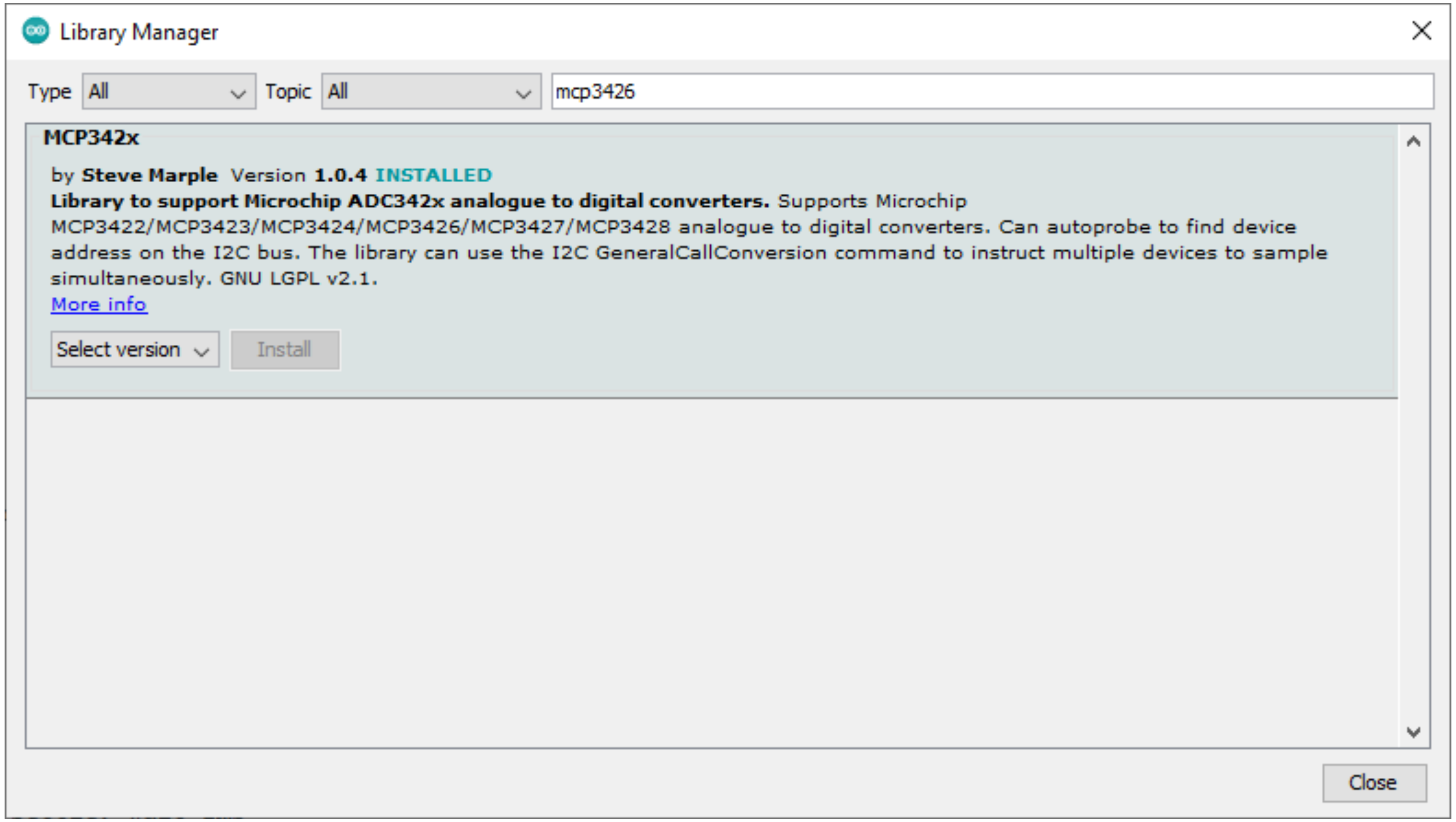
Resolution Setting	Data Rate	Minimum Code	Maximum Code
12	240 SPS	-2048	2047
14	60 SPS	-8192	8191
16	15 SPS	-32768	32767

Note: Maximum n-bit code = 2^{N-1} - 1
Minimum n-bit code = -1 x 2^{N-1}

Code for MCP3428

Select Tools → Library Manager to search for additional libraries.

After installation you can find some examples ready to be used.



Code for MCP3428

```
const float adc_res = 62.5E-6;
long value = 0;
MCP342x::Config status;
MCP342x::Gain gain = MCP342x::gain1;

// read heater current - channel 1
uint8_t err = adc.convertAndRead(MCP342x::channel4, MCP342x::oneShot,
        MCP342x::resolution16, gain, 1000000, value, status);

lsb = adc_res / 1;
float htr1_i = value * lsb / 0.3 / 200;

// read sensor - channel 1
gain = MCP342x::gain8;
err = adc.convertAndRead(MCP342x::channel1, MCP342x::oneShot,
        MCP342x::resolution16, gain, 1000000, value, status);

lsb = adc_res / 8;
sensor_raw = value*lsb;
float sen1_r = ...
```

MCP4716

Channel

This chip has only one channel, but there are two on the board.

Resolution

Only 10 bits, but more than enough

Gain

There is an internal amplifier, but we use the external one that is more capable

MCP4706/4716/4726

8-/10-/12-Bit Voltage Output Digital-to-Analog Converter with EEPROM and I²C™ Interface

Features:

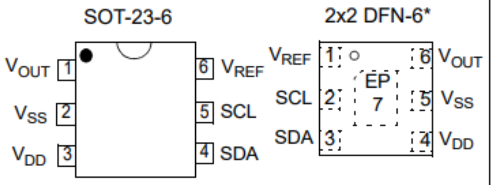
- Output Voltage Resolutions:
  - 12-bit: **MCP4726**
  - 10-bit: **MCP4716**
  - 8-bit: **MCP4706**
- Rail-to-Rail Output
- Fast Settling Time of 6 µs (typical)
- DAC Voltage Reference Options:
  - V_{DD}
  - V_{REF} Pin
- Output Gain Options:
  - Unity (1x)
  - 2x, only when V_{REF} pin is used as voltage source
- Nonvolatile Memory (EEPROM):
  - Auto Recall of Saved DAC register setting
  - Auto Recall of Saved Device Configuration (Voltage Reference, Gain, Power-Down)
- Power-Down modes:
  - Disconnects output buffer
  - Selection of V_{OUT} pull-down resistors (640 kΩ, 125 kΩ, or 1 kΩ)
- Low-Power Consumption:
  - Normal Operation: 210 µA typical
  - Power-Down Operation: 60 nA typical (PD1:PD0 = 11)
- Single-Supply Operation: 2.7V to 5.5V
- I²C™ Interface:
  - Eight Available Addresses
  - Standard (100 kbps), Fast (400 kbps), and High-Speed (3.4 Mbps) modes
- Small 6-lead SOT-23 and DFN (2x2) Packages
- Extended Temperature Range: -40°C to +125°C

Applications:

- Set Point or Offset Trimming
- Sensor Calibration
- Low-Power Portable Instrumentation
- PC Peripherals

Package Types

MCP4706/16/26



* Includes Exposed Thermal Pad (EP); see Table 3-1.

Description:

The MCP4706/4716/4726 are single channel 8-bit, 10-bit, and 12-bit buffered voltage output Digital-to-Analog Converters (DAC) with nonvolatile memory and an I²C serial interface. This family will also be referred to as MCP47X6.

The V_{REF} pin or the device V_{DD} can be selected as the DAC's reference voltage. When V_{DD} is selected, V_{DD} is connected internally to the DAC reference circuit. When the V_{REF} pin is used, the user can select the output buffer's gain to 1 or 2. When the gain is 2, the V_{REF} pin voltage should be limited to a maximum of $V_{DD}/2$.

The DAC register value and Configuration bits can be programmed to nonvolatile memory (EEPROM). The nonvolatile memory holds the DAC register and Configuration bit values when the device is powered off. A device Reset (such as a Power-on Reset) latches these stored values into the volatile memory.

Power-Down modes enable system current reduction when the DAC output voltage is not required. The V_{OUT} pin can be configured to present a low, medium, or high resistance load.

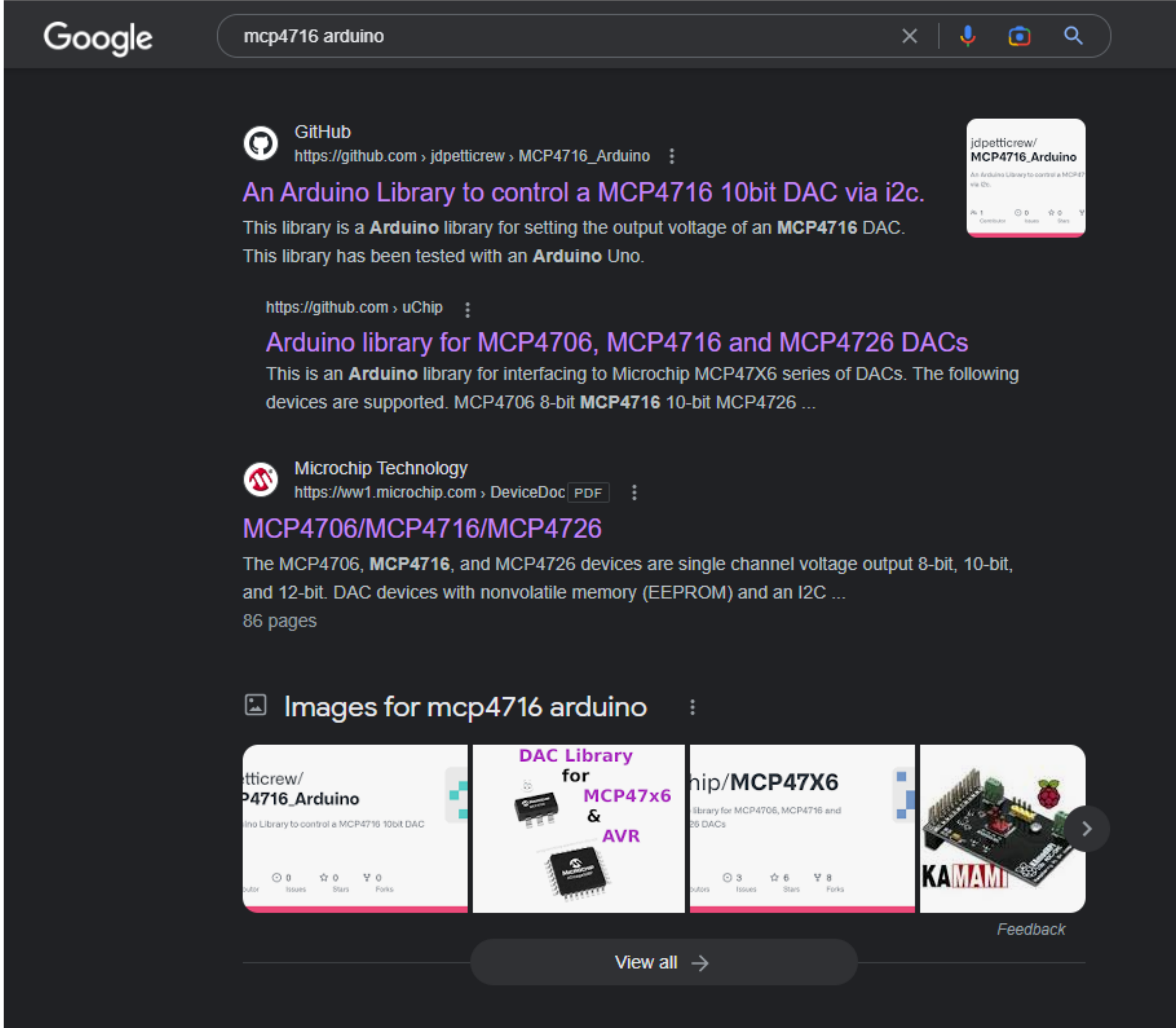
These devices have a two-wire I²C™ compatible serial interface for standard (100 kHz), fast (400 kHz), or High-Speed (3.4 MHz) mode.

These devices are available in small 6-pin SOT-23 and DFN 2x2 mm packages.

Code for MCP4716

There is no library in the Library Manager, so we may ask Google for that.

In this case you can download the code from GitHub and paste it in the folder where you have your Arduino code.



Code for MCP4716

```
uint8_t address_DAC1 = 0x63;
uint8_t address_DAC2 = 0x61;


MCP4716 dac1 = MCP4716(address_DAC1);
MCP4716 dac2 = MCP4716(address_DAC2);

uint16_t dacOut1 = 50;  // 160mV -> around 320mV on the heater
uint16_t dacOut2 = 100; // 320mV -> 650mV

dac1.setVout(dacOut1);
dac2.setVout(dacOut2);
```

$$LSB = \frac{3.3}{1023} = 0.0032\ V$$

Other constants and connections

Signal	Arduino Port
LED1	D11
LED2	D12
EN	D9
Heater voltage (channel 1)	A4
Heater voltage (channel 2)	A5
SW (channel 1)	D10
SW (channel 2)	D8

Signal	MCP3428 channel
Heater current (channel 1)	4
Heater current (channel 2)	3
Sensor resistance (channel 1)	1
Sensor resistance (channel 2)	2
Resistance	**SW value**
1 kOhm	HIGH
1MOhm	LOW