Sensores Integrados

Graça Minas
gminas@dei.uminho.pt

Departamento de Eletrónica Industrial

Universidade do Minho
Escola de Engenharia
Departamento de Electrónica Industrial

UMINHO CMEMS
CENTER FOR MICROELECTROMECHANICAL SYSTEMS

Review previous classes

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- Piezoresistivity
- Capacitive techniques
- Seebeck effect
- Peltier effect
- Hall effect
- Magnetoresistive
- PT100
- P-N Junction temperature sensors
- Radiação
- Reflexão interna total
- Absorvência
- Fluorescência
- Lminescência
- SPR

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Resumo

1. Sensores de pressão
2. Sensores de fluxo
3. Sensores óticos

1. Pressure Sensors

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Pressure Sensors

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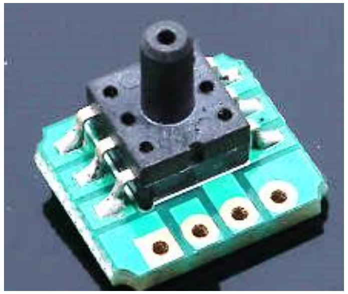
- Introduction
  - The application of MEMS to the measurement of pressure is a mature application of micromachined silicon sensors, and devices have been around for more than 40 years.
  - The suitability of MEMS to mass-produced miniature high-performance sensors at low-cost has opened up a wide range of applications:
    - *Automotive*
    - *Industrial process control*
    - *Hydraulic systems*
    - *Microphones*
  - Pressure is defined as a force per unit area, and the standard SI unit of pressure is N/m^2 or Pascal (Pa). $1\ Pa = 1\ N/m^2$

Units of Pressure and Conversion Factor to Pa (to Two Decimal Places)

Unit	Symbol	No. of Pascals
Bar	bar	1×10^5
Atmosphere	atm	1.01325×10^5

Pressure Sensors

- Pressure sensor types
  - Absolute pressure sensors
    - Devices that measure ***relative to a vacuum*** *and therefore must have a reference vacuum encapsulated within the sensor. Atmospheric pressure is measured using absolute sensors.*



  - Gauge pressure sensors
    - *Devices that measure* ***relative to atmospheric pressure****, and therefore, part of the sensor must be vented to the ambient atmosphere.*

  - Differential pressure sensors
    - *Devices that measure the* ***difference between two pressure*** *measurands. The design of differential pressure sensors often represents the greatest challenge since two pressures must be applied to the mechanical structure.*

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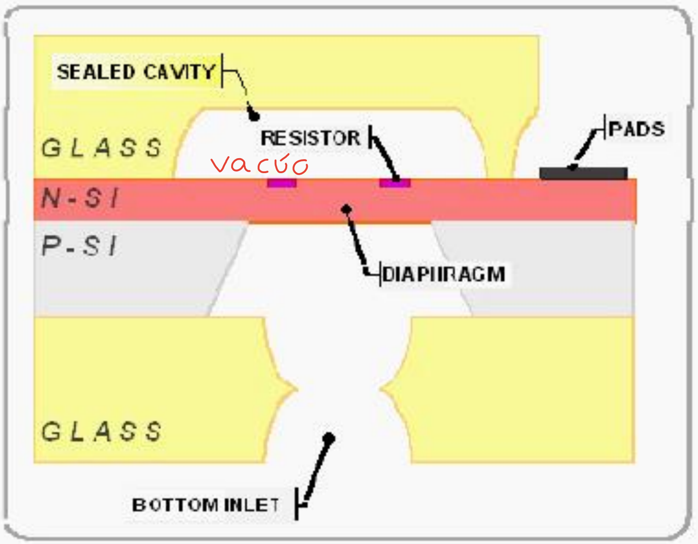
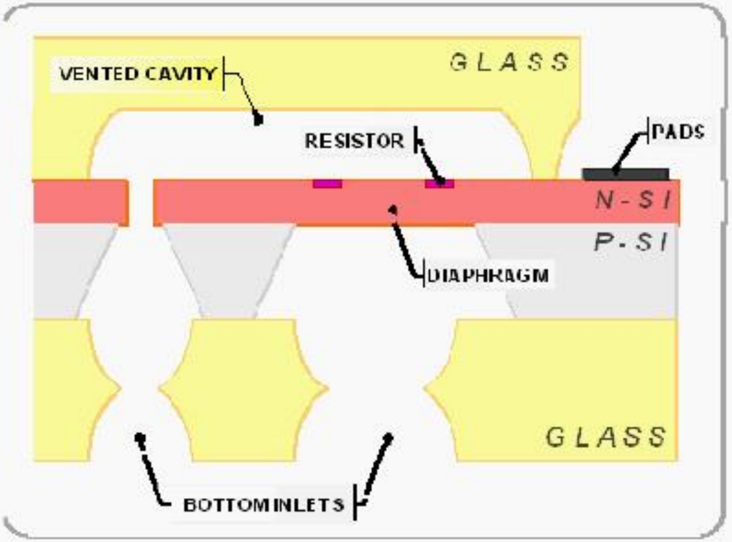


Absolute Pressure Sensor

Relative Pressure Sensor



Pressure sensors

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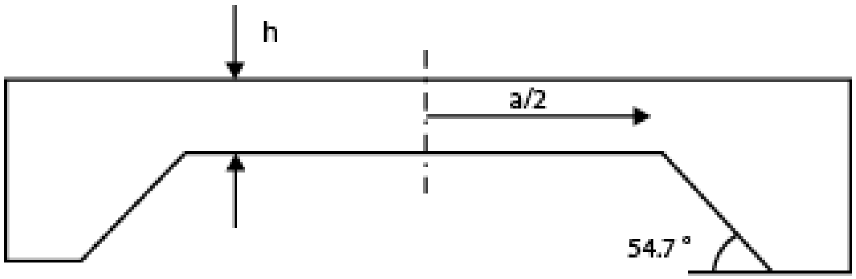
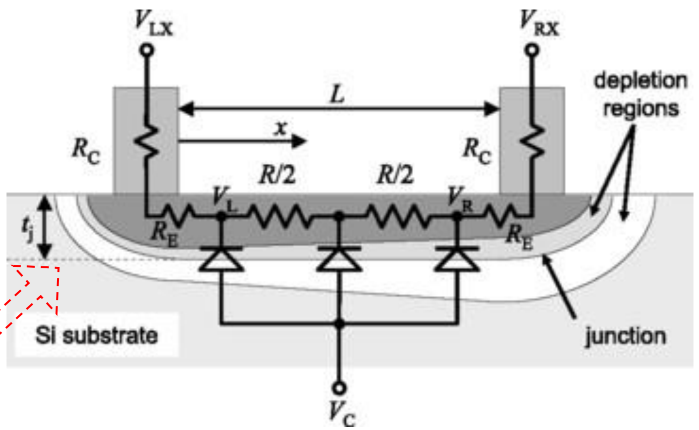
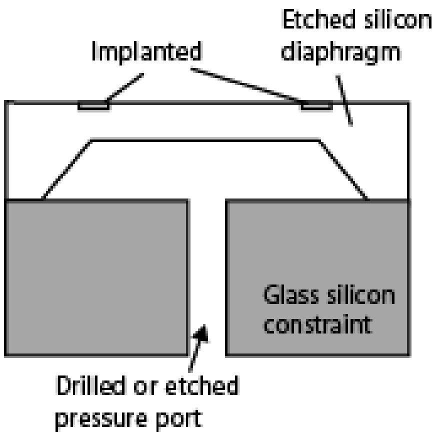
- Micromachined Silicon Diaphragms

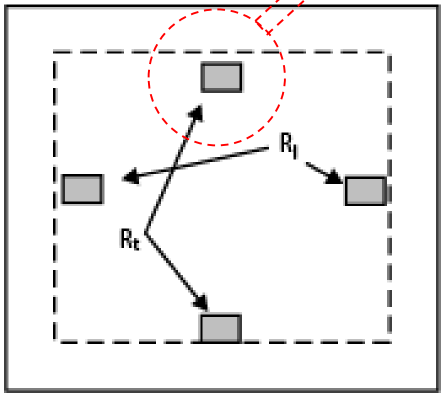


  - Fabricated using anisotropic wet etching.



Diffused resistor, in the piezoresistive sensing element





The piezoresistive nature of silicon makes the use of diffused or implanted resistors an obvious and straightforward technique for measuring the strain in micromachined silicon diaphragm.

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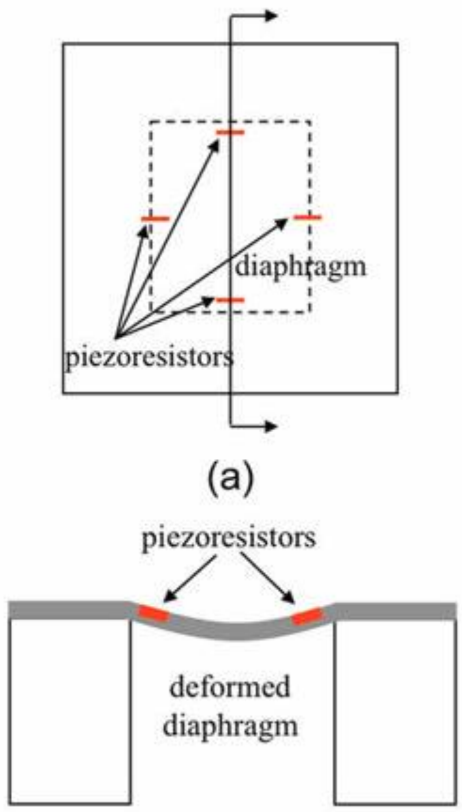
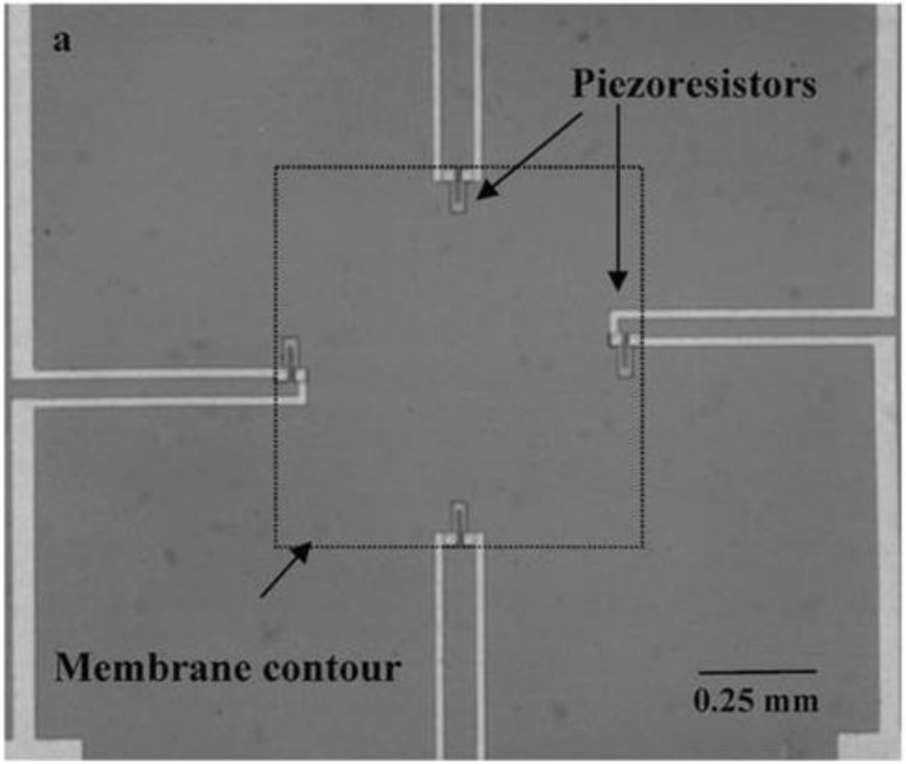
- Piezoresistive Pressure Sensors



(a)

(b)



(c)

Other example: Aluminium strain Gauges (SG) in a flexible Kapton substrate

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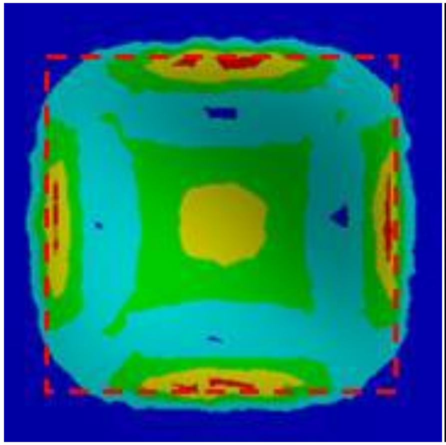

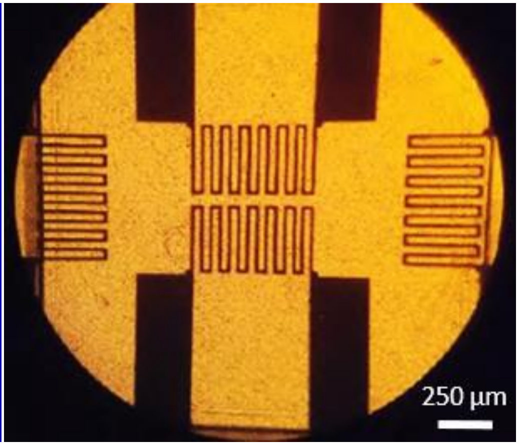

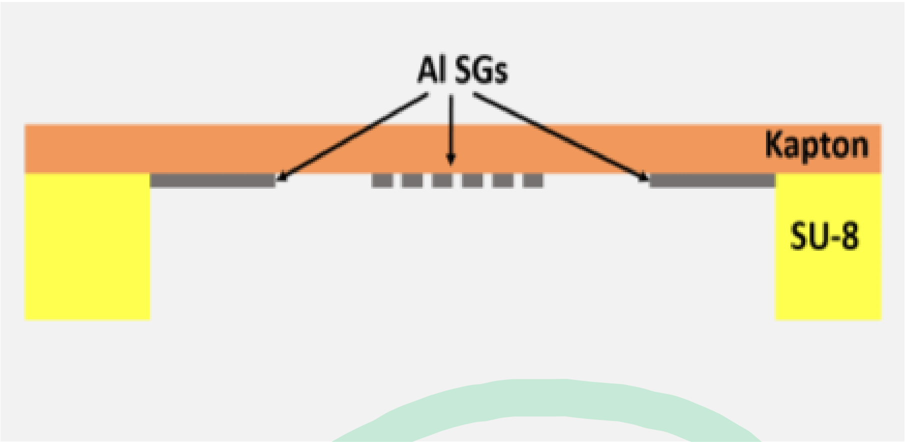

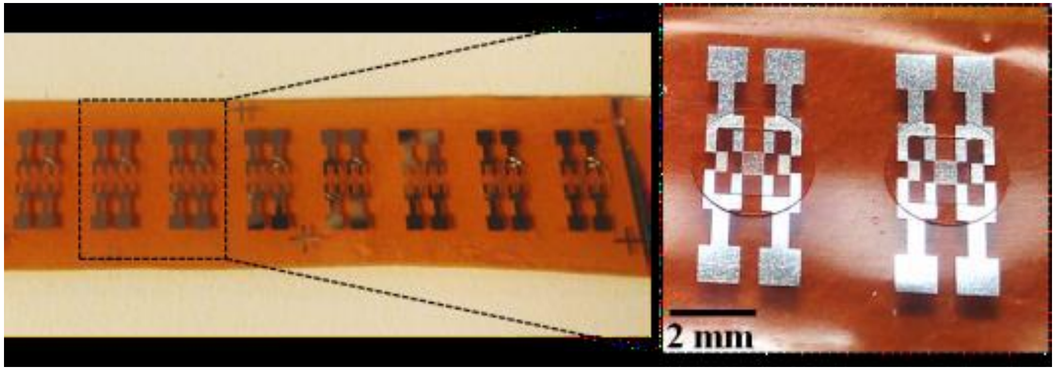

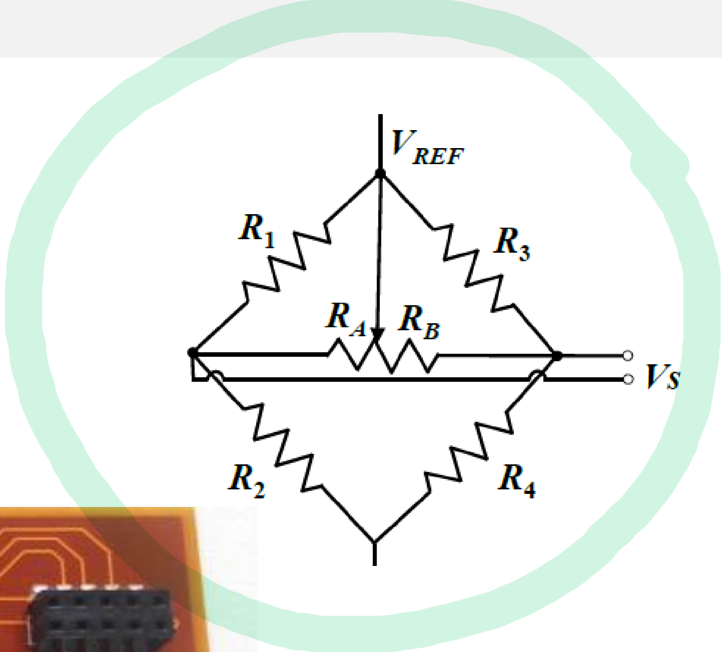

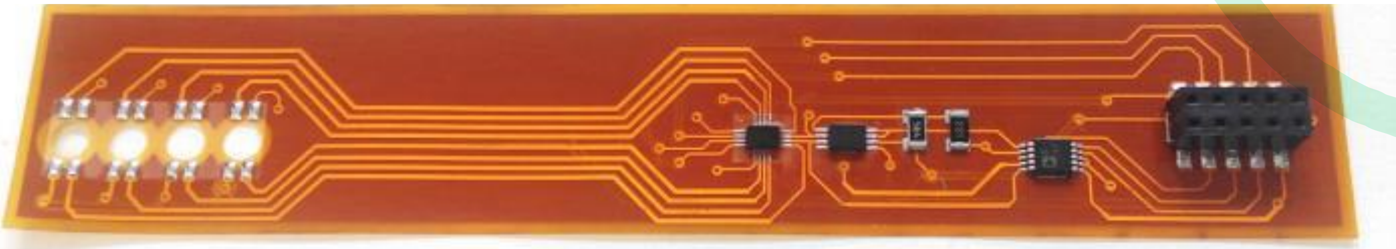

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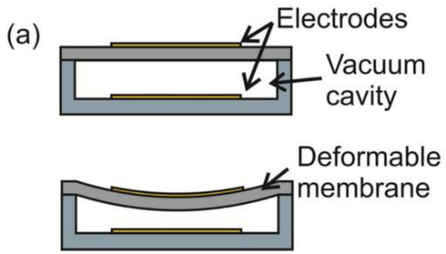
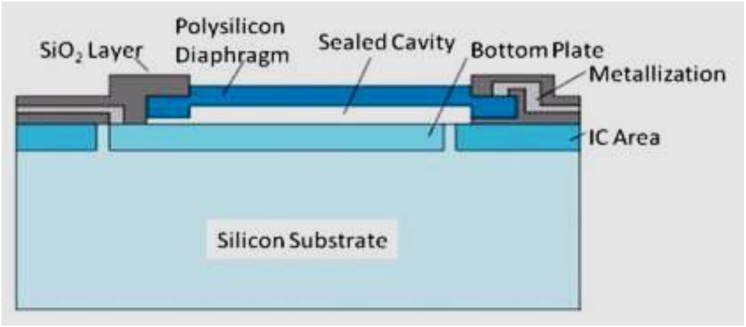
▪ Capacitive Pressure Sensors

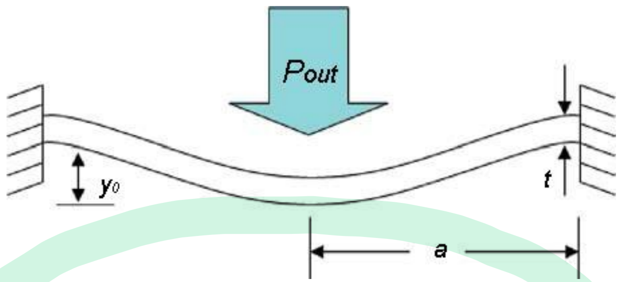
- Capacitive pressure sensors are typically based upon a parallel plate arrangement, with a fixed electrode and the other one movable. As the flexible electrode deflects under applied pressure, the gap between electrodes decreases and the capacitance increases.
  - *Advantages:*
    - High sensitivity to pressure.
    - Low power consumption.
    - Low temperature cross-sensitivity.
  - *Drawbacks:*
    - Nonlinear output of the sensor
    - Electronics complexity (compared with the resistive bridge)



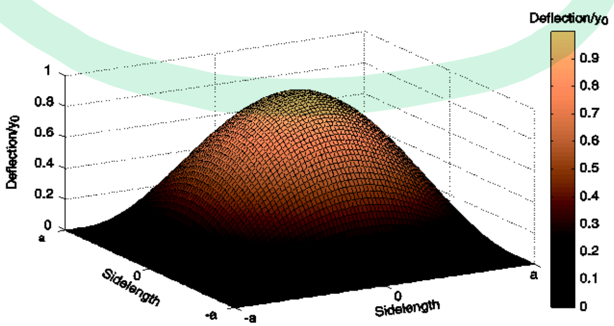


Pressure Sensors - Capacitive

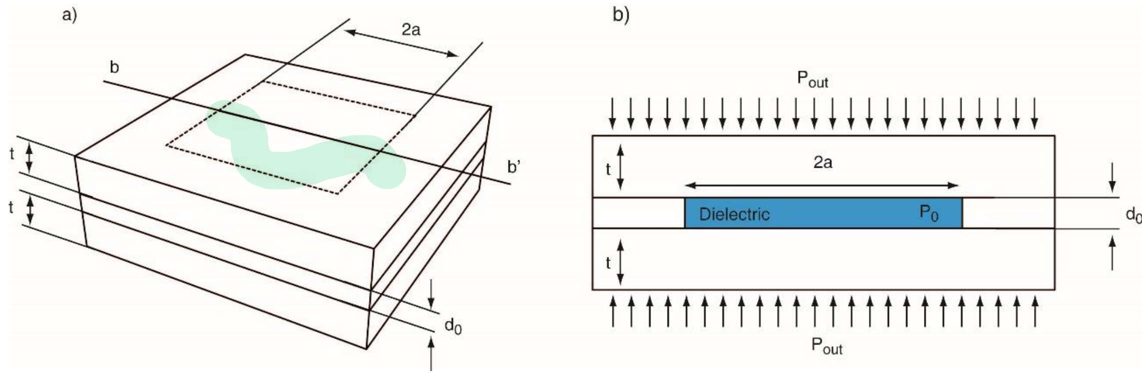
- Analytical model
  - Mechanical domain
    - Bending of diaphragm



$$P_{out} = \frac{Et^4}{(1-\upsilon^2)a^4}\left[4.20\frac{y_0}{t} + 1.58\frac{y_0^{\;3}}{t^3}\right]$$



$$y(x,y) = y_0\left[\left(\cos\left(\frac{\pi x}{2a}\right)\right)\left(\cos\left(\frac{\pi y}{2a}\right)\right)\right]$$



- Electrostatic domain
  - Capacitor

$$C = \varepsilon_0 \varepsilon_r \frac{wl}{d_0}$$

$$C = \int_0^{2a}\int_0^{2a} \frac{\varepsilon_0 \varepsilon_r}{d_0 + 2y(x,y)}\,dydx$$

Pressure Sensors – BMP280

Piezo-resistive
Fully CMOS compatible MEMS manufacturing
Hermetic sealing of the cavity

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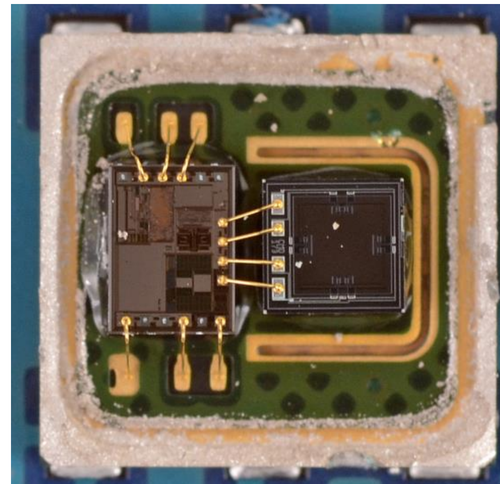
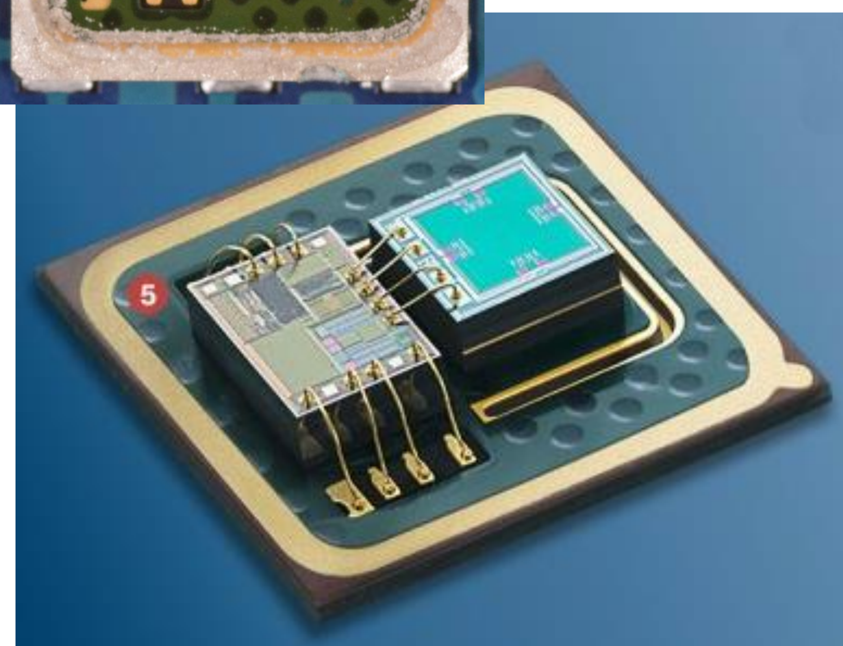
Parameter	Technical data
Package dimensions	8-Pin LGA with metal 2.0 x 2.5 x 0.95 mm³
Operation range (full accuracy)	Pressure: 300...1100 hPa Temperature: -40...85°C
Supply voltage VDDIO Supply voltage VDD	1.2 ... 3.6 V 1.71 ... 3.6 V
Interface	I²C and SPI
Average current consumption (1Hz data refresh rate)	2.74 µA, typical (ultra-low power mode)
Average current consumption in sleep mode	0.1 µA
Average measurement time	5.5 msec (ultra-low power preset)
Resolution of data	Pressure: 0.01 hPa (< 10 cm) Temperature: 0.1°C
Absolute accuracy p=950 ... 1050hPa (T=0 ... +40°C)	~ ±1 hPa
Relative accuracy pressure p=950 ... 1050hP (+25°C)	± 0.12 hPa (typical) equivalent to ±1 m
Temperature coefficient offset (+25°...+40°C @900hPa)	1.5 Pa/K equiv. to 12.6 cm/K

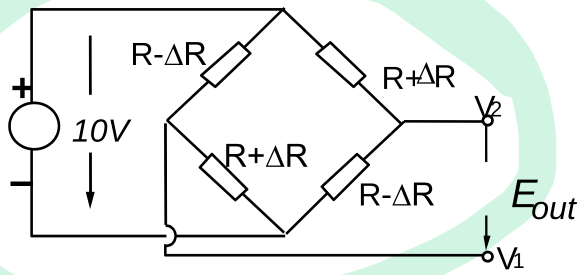


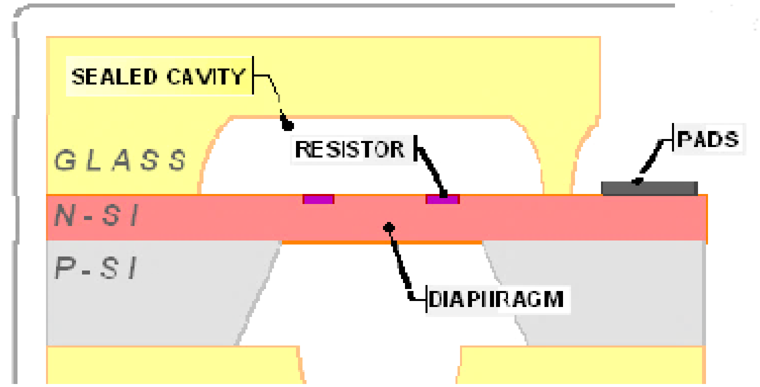


1 hectopascal = 1 millibar   1 bar = 100 kilopascal

Quatro extensómetros são utilizados numa membrana (módulo de elasticidade (Young) de 1 x 10^7 N/m2) para implementar um sensor de pressão. O extensómetro tem uma resistência nominal (não deformado) de 240Ω, um fator de Gauge de 2.0 e um coeficiente de variação com a temperatura de 0.003Ω/Ω/ºC. A ponte de Wheatstone tem 4 extensómetros ativos (R+ΔR e R-ΔR).

EXERCÍCIO





$$E = \frac{\text{tensão}}{\text{deformação}} = \frac{F/A}{\Delta l/l}$$

$$G_f = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} \Rightarrow \Delta L$$

a) Qual a alteração na resistência do extensómetro para uma pressão de 1 atm? (4.8Ω)

b) Qual a tensão na saída da ponte de Wheatstone para uma pressão de 1 atm? (200mV)

c) Qual a sensibilidade do sensor de pressão, quando alimentado a 10V? (200mV/atm)

d) Qual a tensão na saída da ponte de Wheatstone para uma carga de 1 atm, se a temperatura aumentar 10ºC em todos os extensómetros? (200mV)

e) Qual o maior erro na tensão de saída da ponte de Wheatstone, se um dos extensómetros estiver 1ºC acima dos restantes? (7mV?)

2. Flow Sensors

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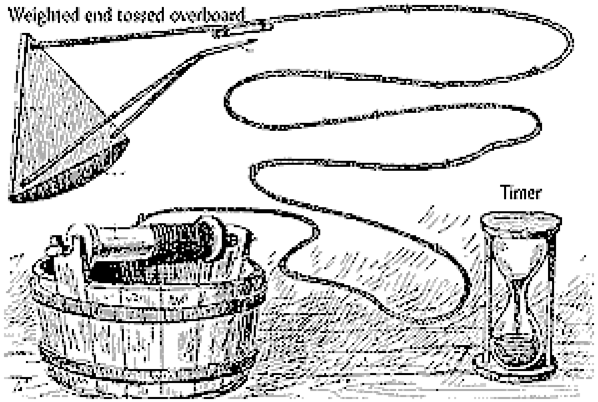
Sensores de
Fluídos



Flow Sensors

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- Introduction
  - First micromachined flow sensors date back to the seventies.
  - A fluid flow can be either a gas flow or a liquid flow and the measurands can be either mass moved (weight per second), distance moved (meters per second) or the volume moved (volume per second).
  - Microfabrication offers:
    - *High resolution.*
    - *Fast time response.*
    - *Integrated signal processing.*
    - *Low-cost.*
  - Applications
    - *Automotive – Fuel injection systems (MAF), climate control.*
    - *Civil engineering – Wind forces on buildings.*
    - *Medicine.*
    - *Process Industry.*
    - *Water metering*

Flow Sensors

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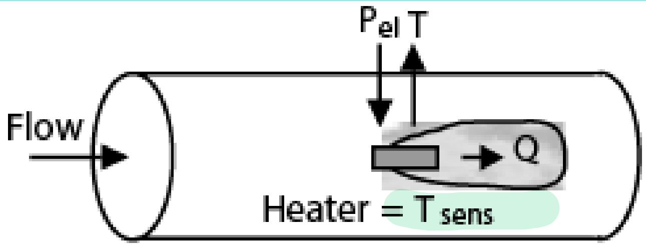
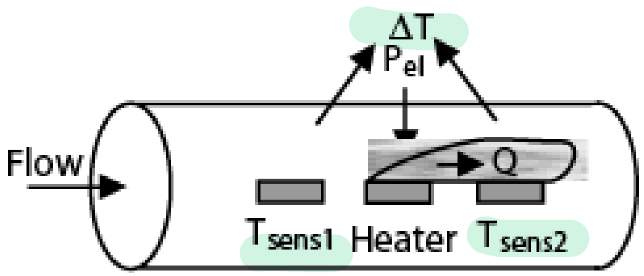
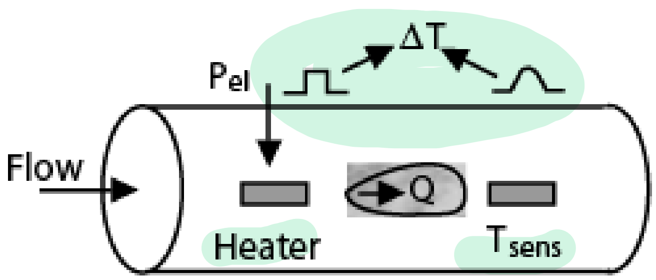
- Thermal flow sensors
  - Many micro-flow sensors work in the thermal domain.
  - Thermal flow sensors have been classified into three basic categories:
    - *Anemometers*.



    - *Calorimetric flow sensors*.



    - *Time of flight sensors.*



Flow Sensors

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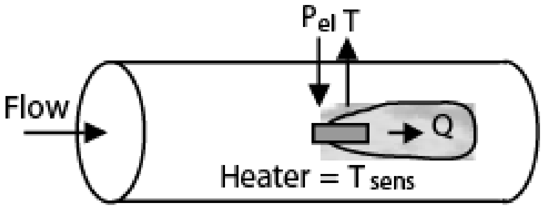
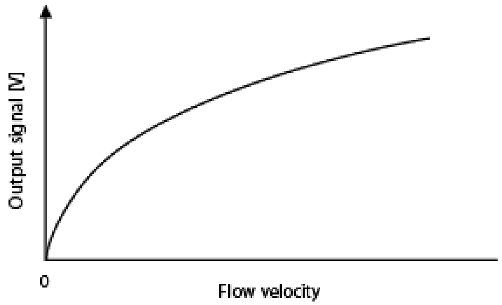
- Anemometers (Heat Loss)
  - Consist of a element that is heated, and the influence of the fluid flow on the element is measured.
  - They are operated in:
    - *Constant power mode – Heat is dissipated from the resistor into the fluid flow, and the resulting temperature of the resistor is a measure of that flow.*
    - *Constant temperature mode – The temperature of the heater is directly measured and kept constant above ambient temperature. The electrical power needed to maintain a constant temperature is a measure of the flow.*

- Fast responses.
- Not bidirectional.
- Limited power range.
- Sensitive to contamination.
- Made very thin to have a fast response.





Curve of an anemometer flow sensor operated in constant power mode

Flow Sensors

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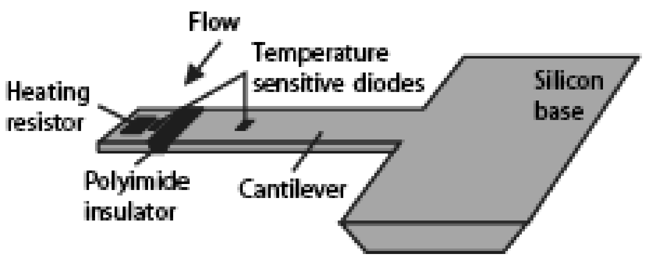
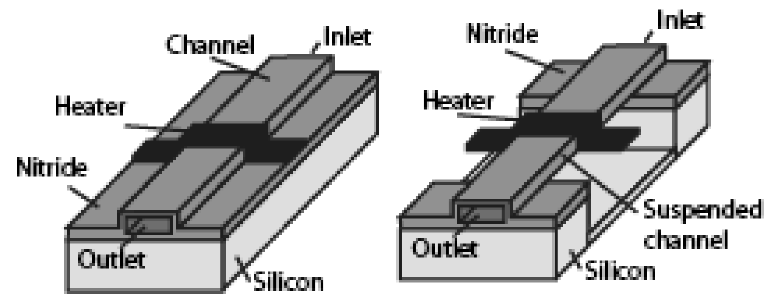
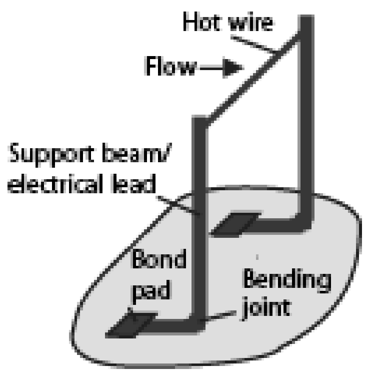
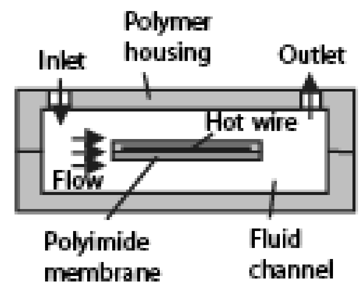
- Anemometers (Heat Loss)
  - Examples









Source: *MEMS Mechanical Sensors*

Flow Sensors

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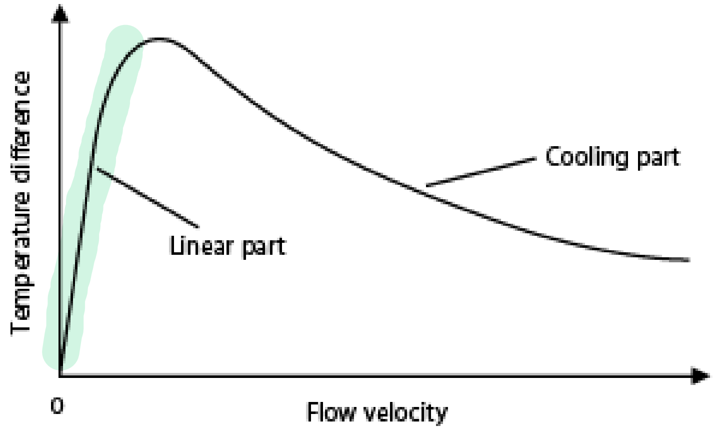
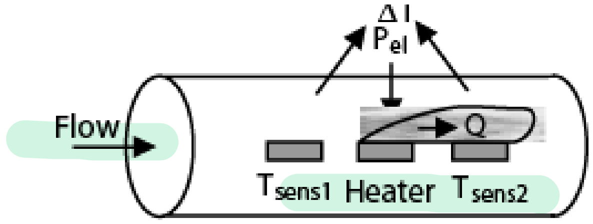
- Calorimetric flow sensors
  - This type of sensors use a heating element with temperature sensing elements up- and downstream:
    - *The upstream sensor is cooled by the flow and the downstream sensor is heated due to the heat transport from the heater in the flow direction.*
    - *The amount of heat measured is proportional to the flow rate.*
    - *The output signal is the difference in temperature between the up- and downstream sensors.*
  - Needs calibration for each fluid.





Curve of an calorimetric flow sensor operated in constant power mode

Measurements can be taken at linear part

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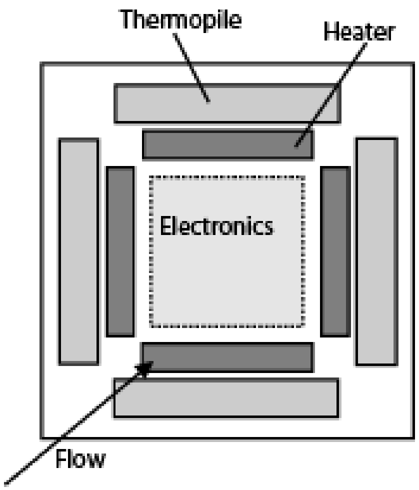
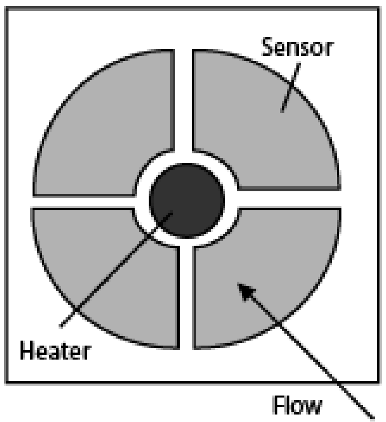
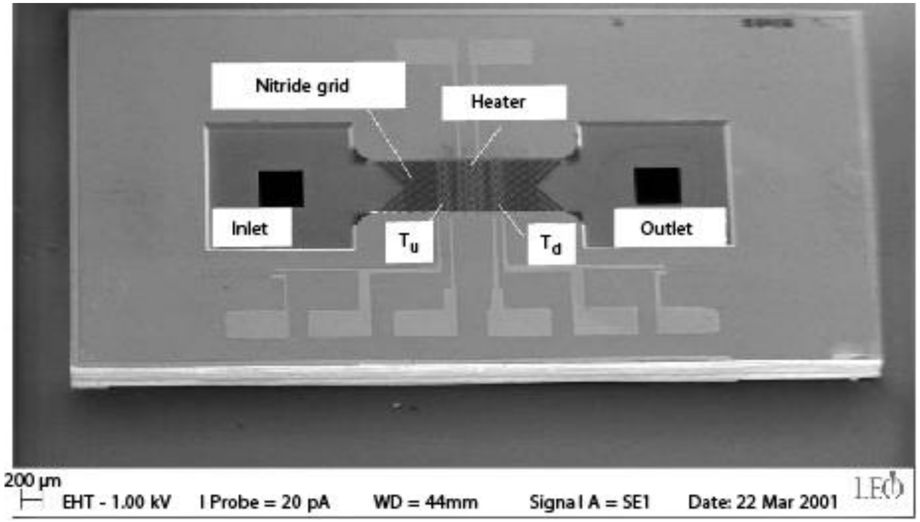
- Calorimetric flow sensors
  - Examples







Flow Sensors

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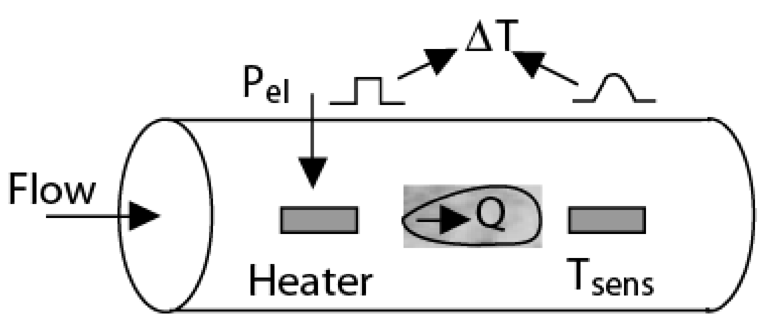
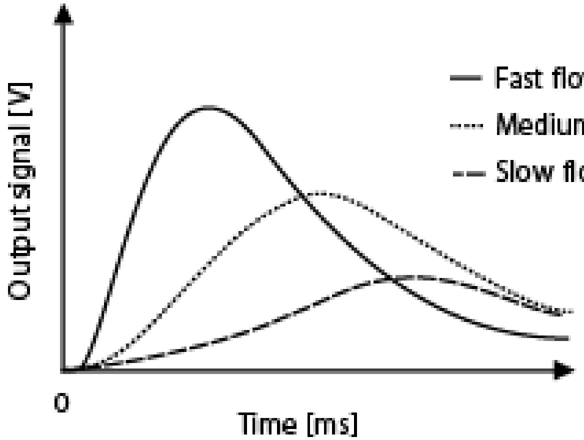
- Time of flight sensors
  - The heater is continually pulsed with a certain amount of electrical energy. The heat pulse is carried away from the heater by the flowing fuid, and the temperature sensor is used to measure the time delay between heat source and heat detection.
  - Tolerant to changes in ambient temperature.
  - Measurement range set by the distance between heat source and heat detection.





Typical measurement curve of a thermal of flight flow sensor

Ultrasonic time of flight flow sensor

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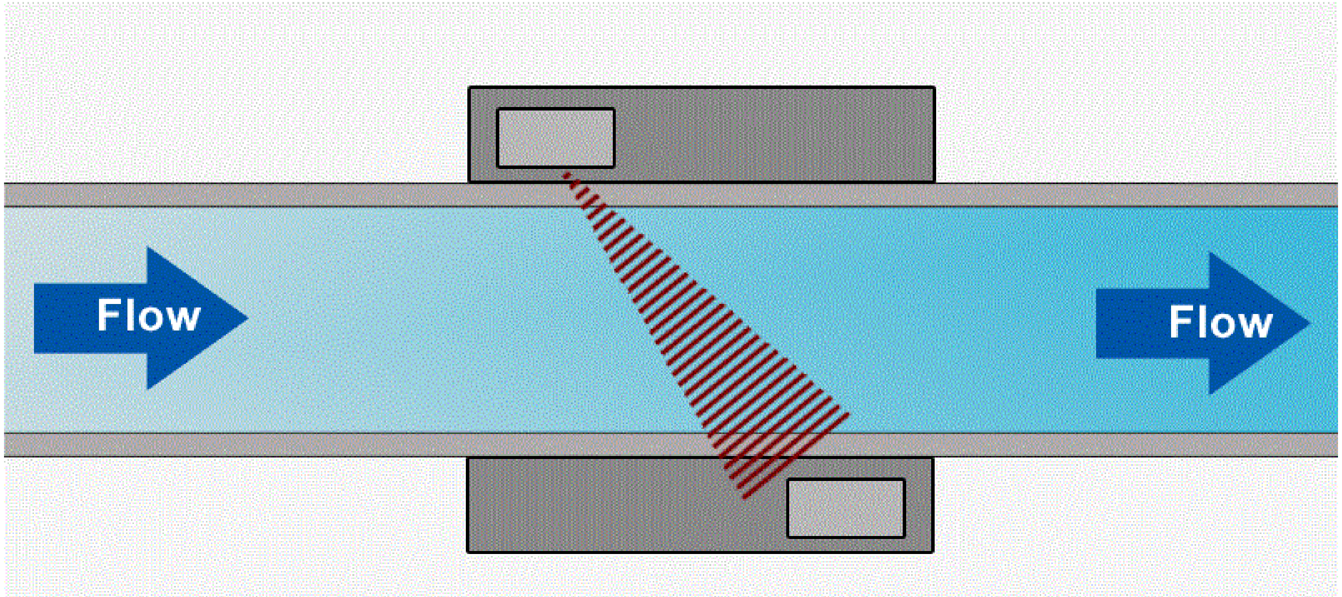

Ultrasonic time of flight flow sensor

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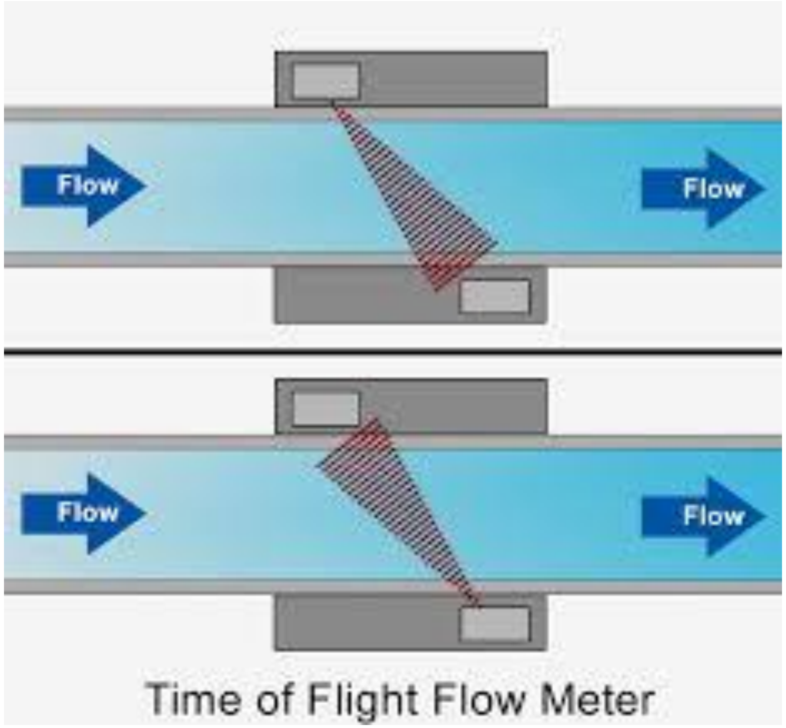

Ultrasonic Doppler flow sensor

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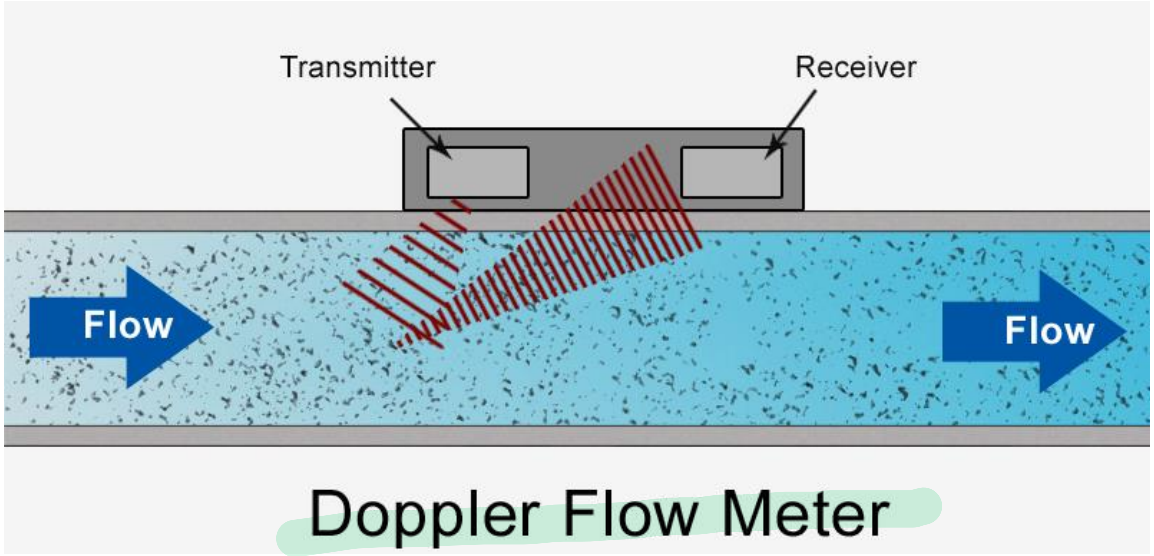
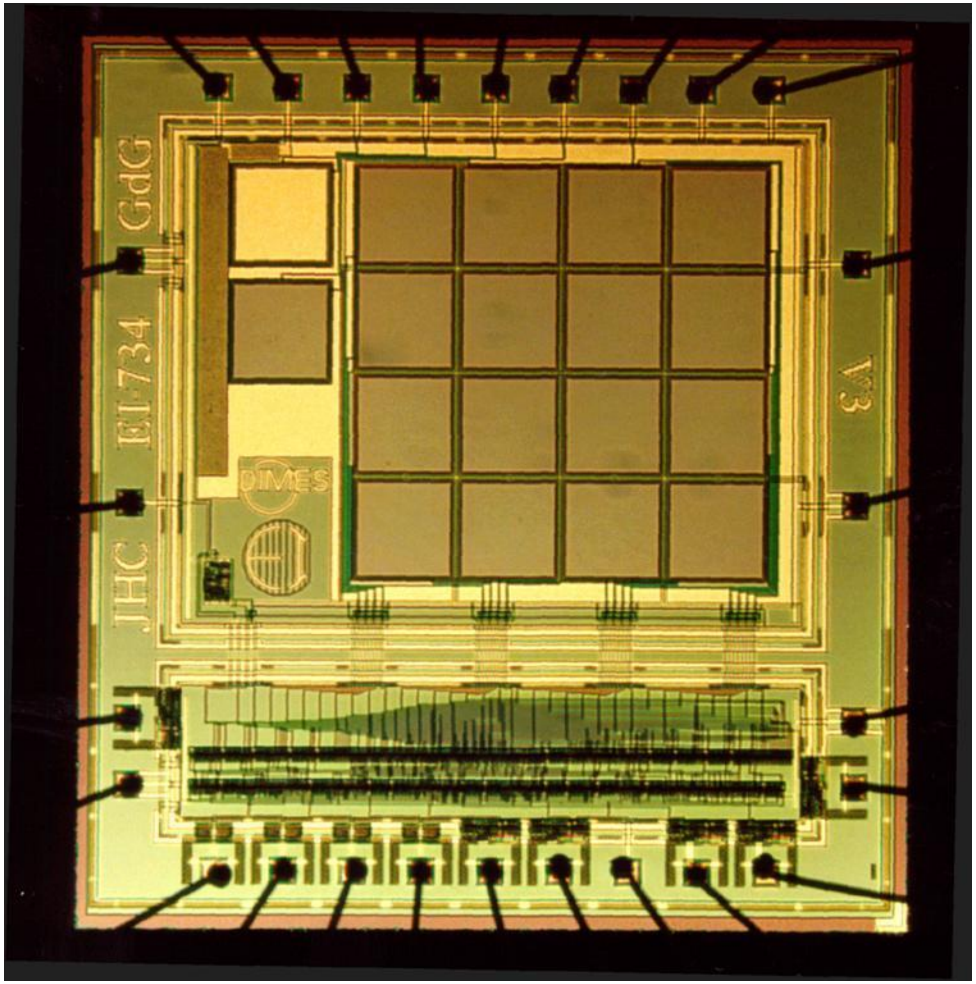


3. Sensores Óticos



Sensor - Photodetector

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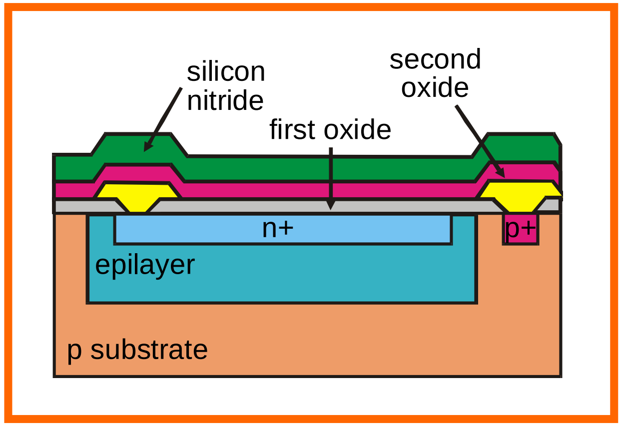
Fotodetector



- Photodiode n+ / p-epilayer
- CMOS standard process
- Provides the best possible quantum efficiency in the desired spectral range

Photodetector

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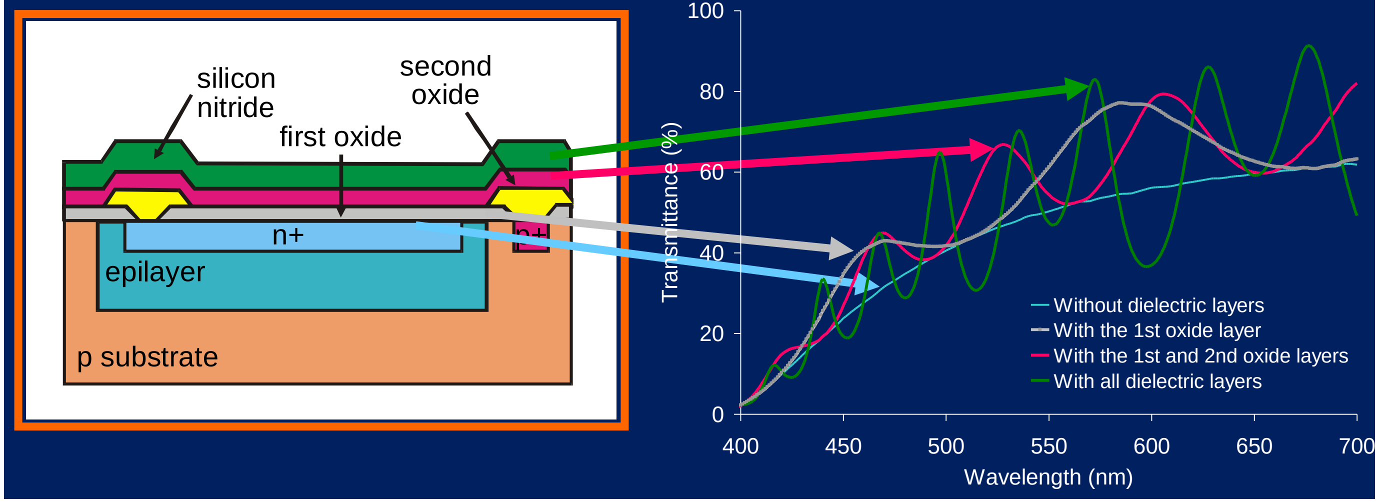
Photodiode



Photodetector

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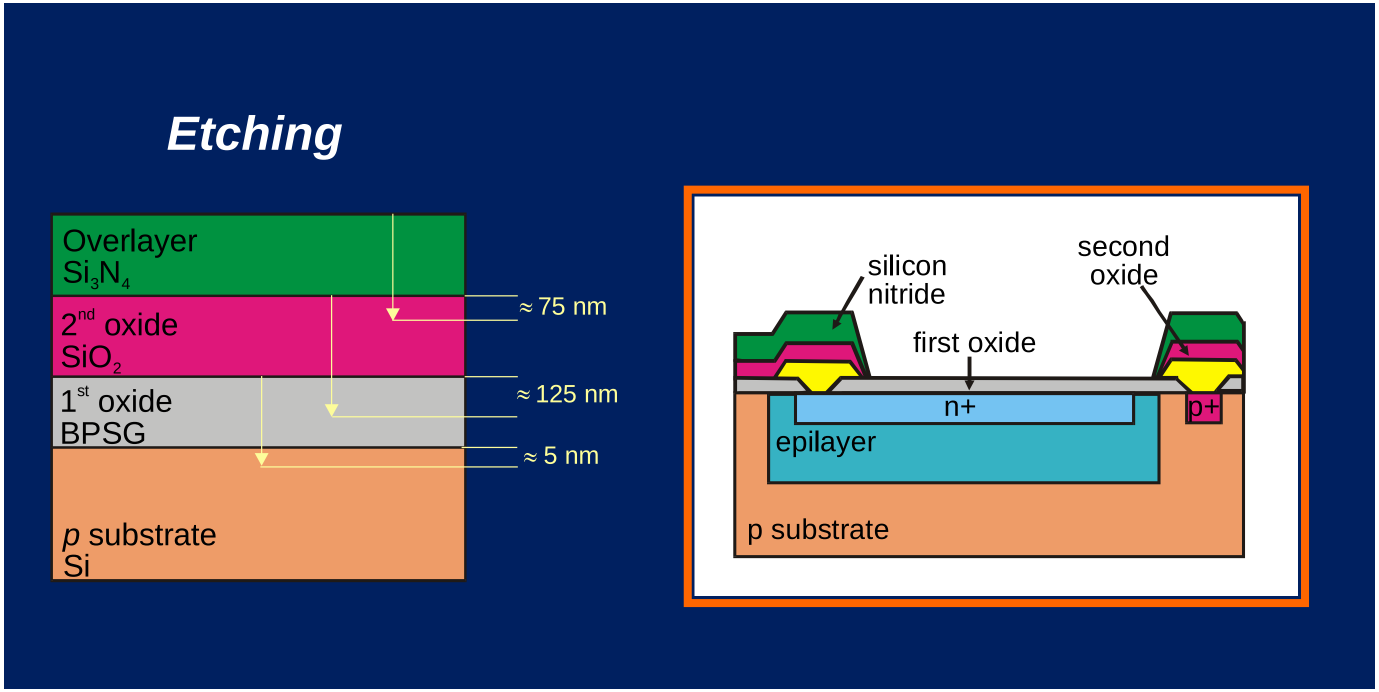
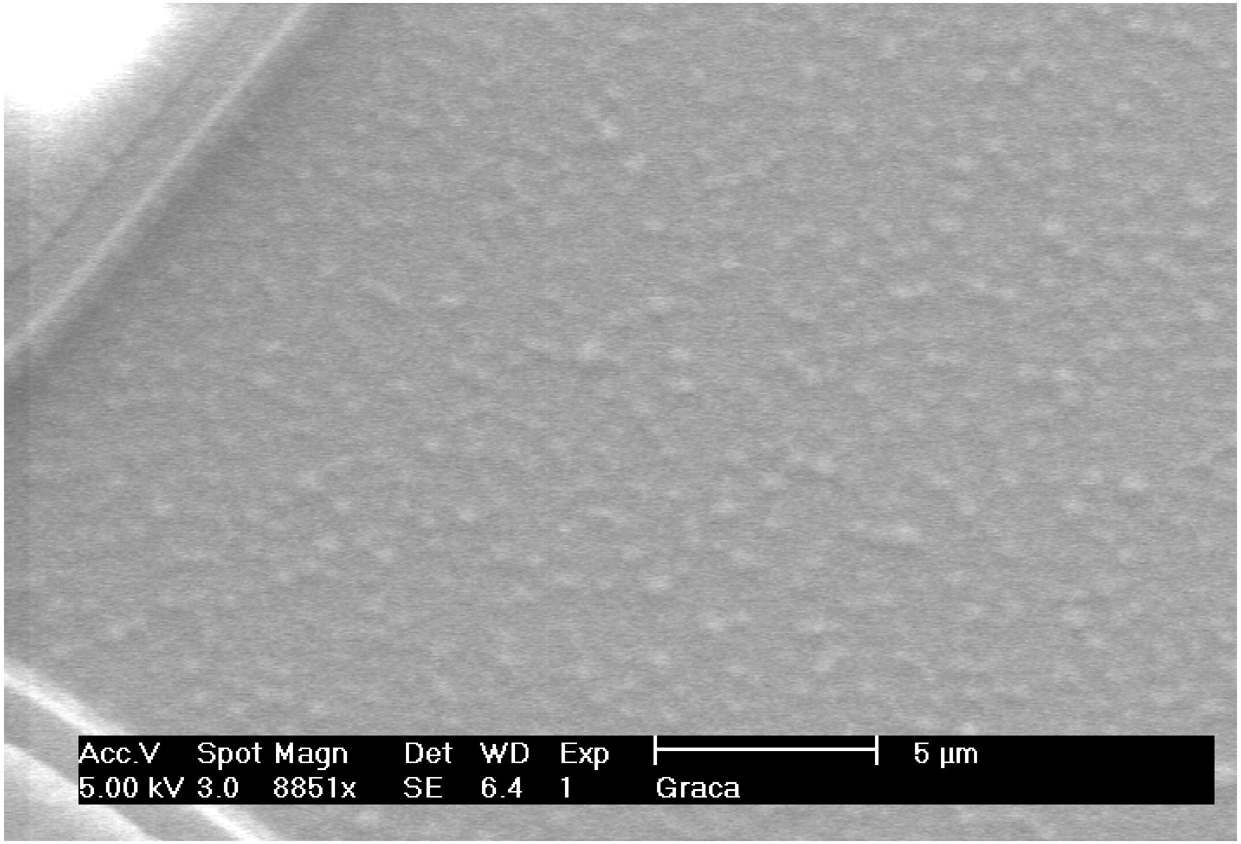


Photodetector



Photodetector

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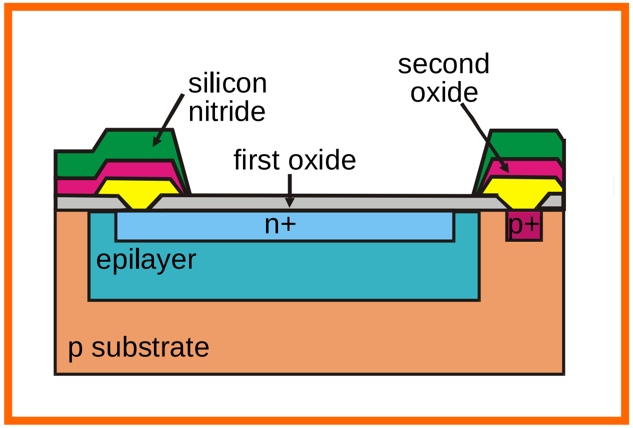
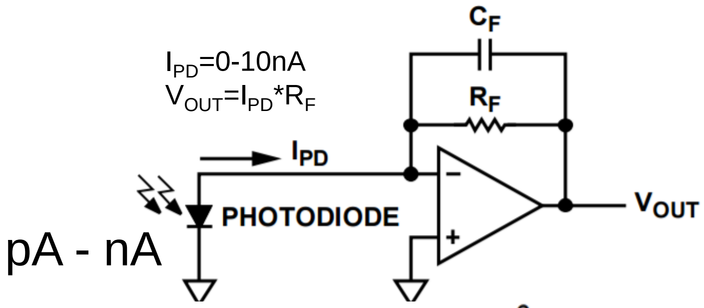
Photodiode

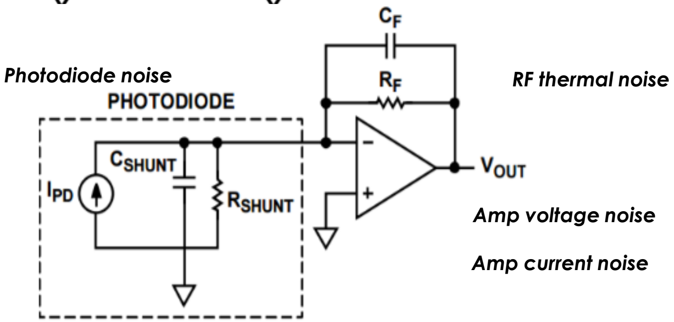


A light-to-frequency converter is integrated with the photodiodes to convert the photocurrent into a digital signal

Electronics - Detection



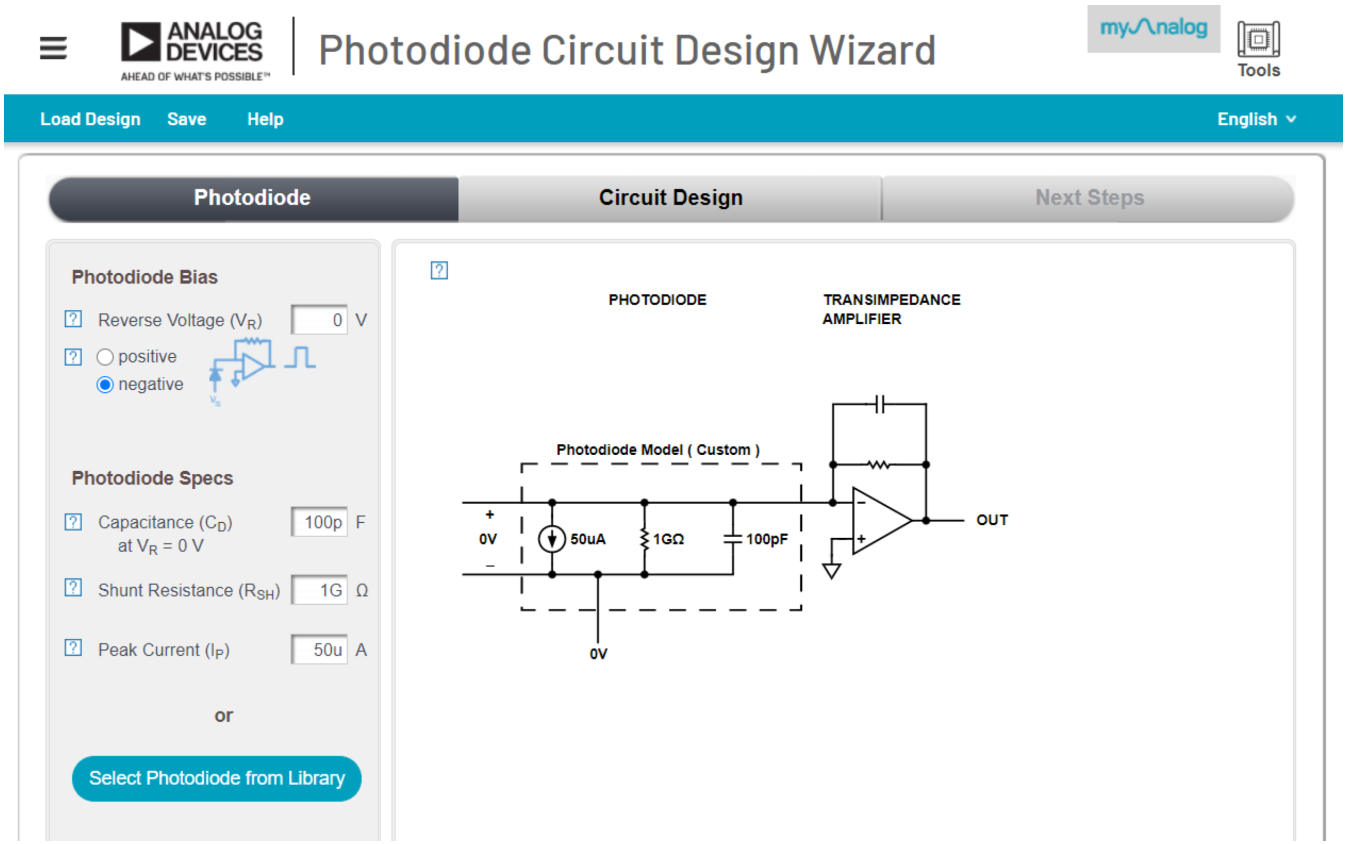
Light Detection is based in a typical transimpedance amplifier optimized for low noise operation



Noise Source	RTO Noise Equation
R_F	$\sqrt{4\,k\,TR_F}$
R_{SHUNT} (Photodiode)	$\frac{R_F}{R_{SHUNT}}\sqrt{4\,k\,TR_{SHUNT}}$
Amp Current Noise	$I_N\,R_F$
Amp Voltage Noise	$V_N \times (1 + \frac{C_{SHUNT}}{C_F})$

Photodiode Circuit Design Wizard

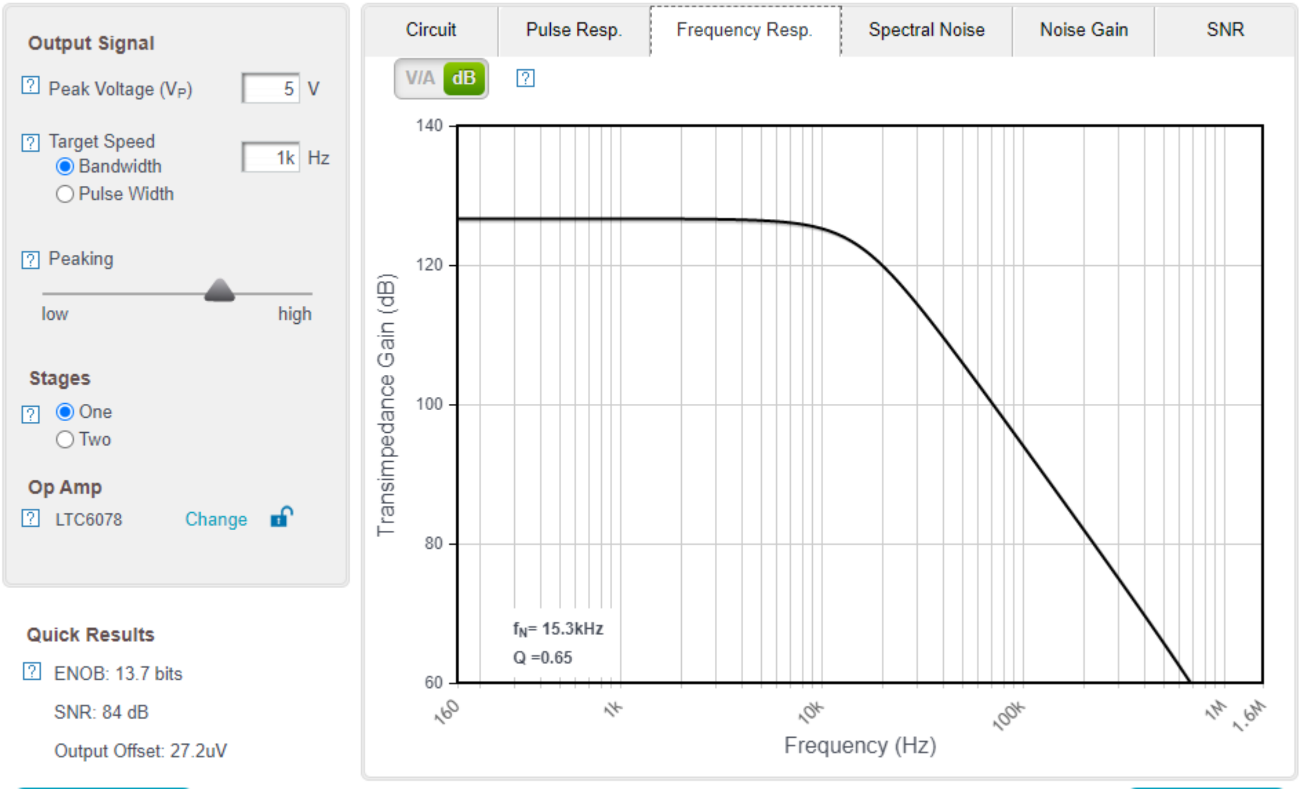
https://tools.analog.com/en/photodiode/



Seleção das características do fotodiodo e da saída do circuito

Photodiode Circuit Design Wizard

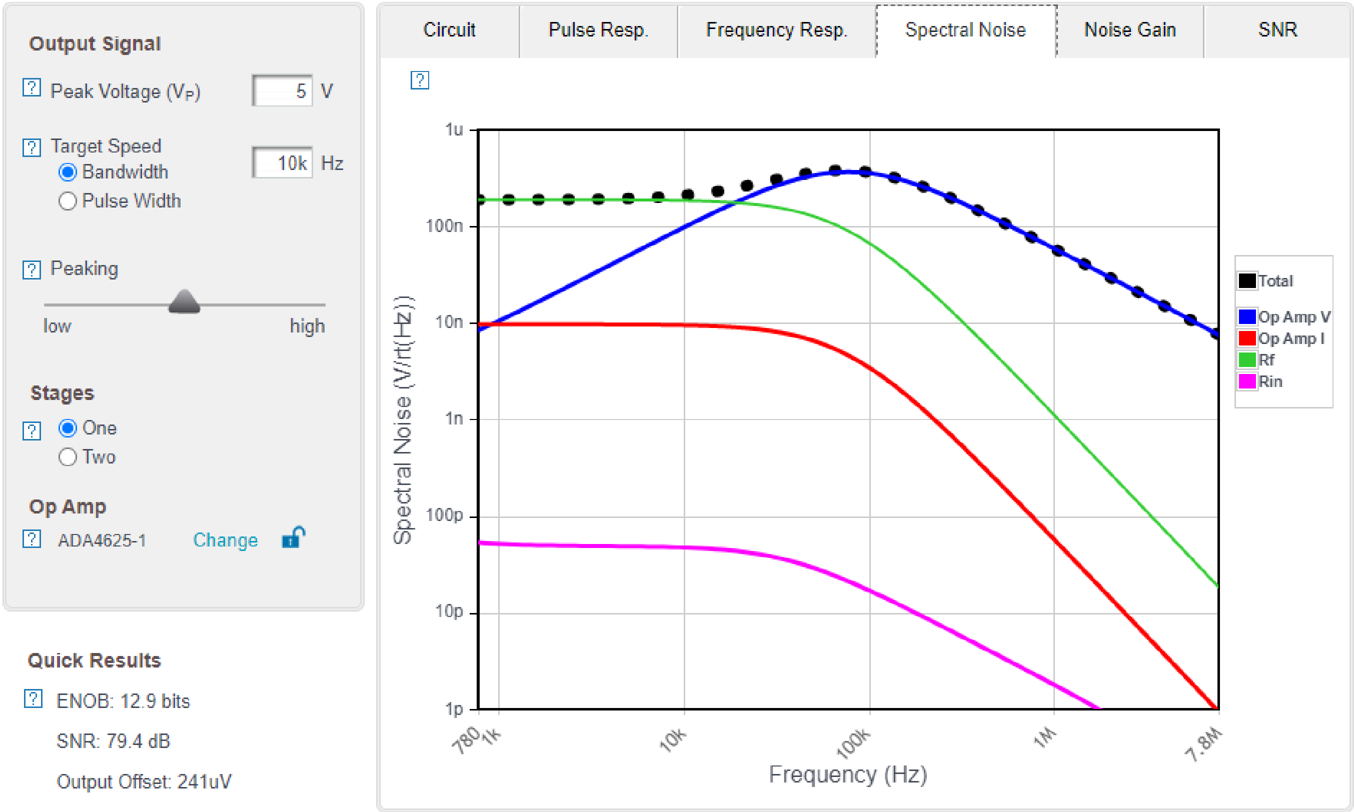
https://tools.analog.com/en/photodiode/



Resposta em frequência (ganho é V/A)
O peaking permite a justar o Q (fator qualidade)

Photodiode Circuit Design Wizard

https://tools.analog.com/en/photodiode/



Ruido em função da frequência.
ENOB; SNR; Offset

ELECTRÓNICA de LEITURA

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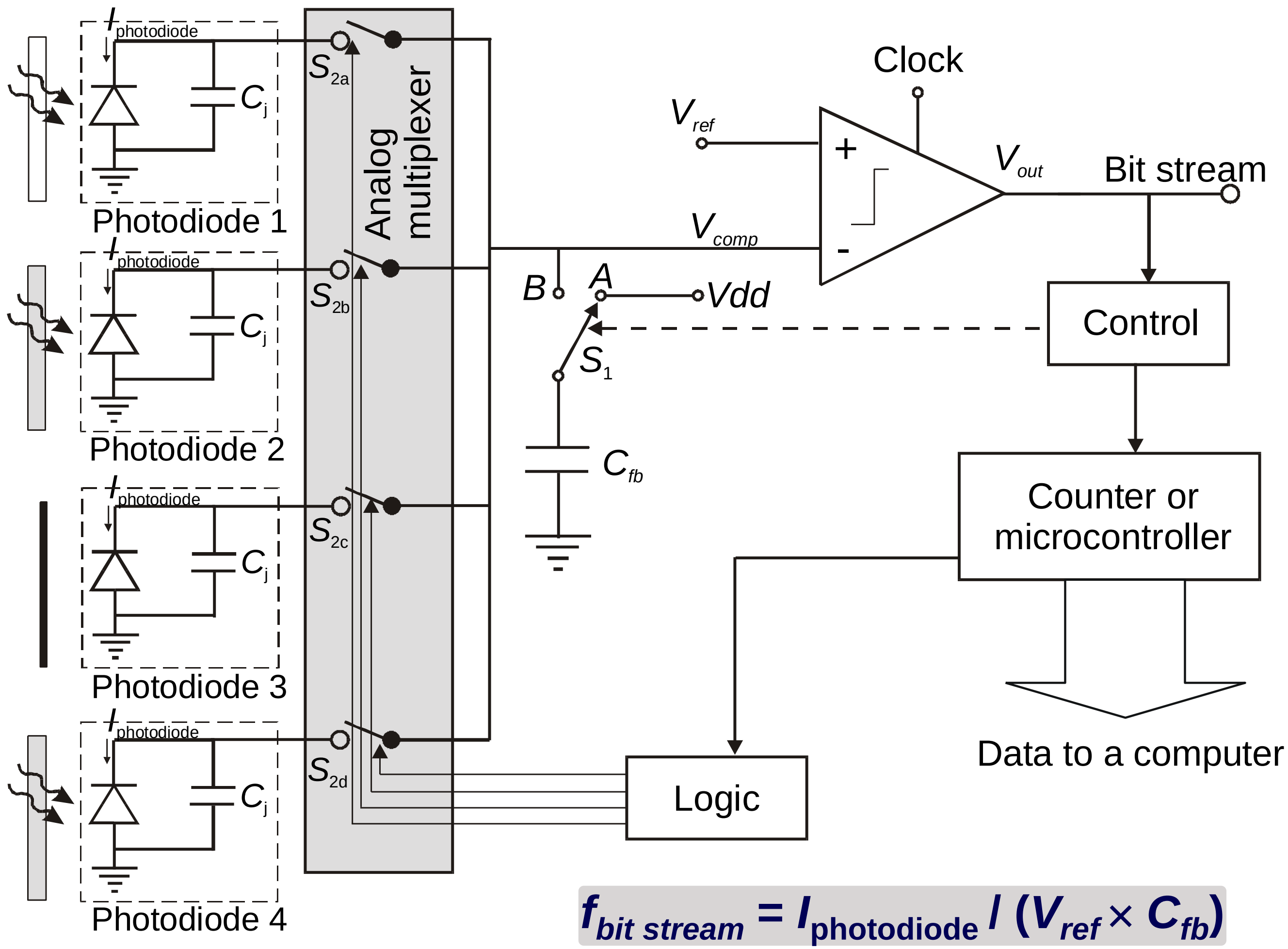

$$f_{bit\ stream} = I_{photodiode} / (V_{ref} \times C_{fb})$$

O SISTEMA de DETECÇÃO e LEITURA

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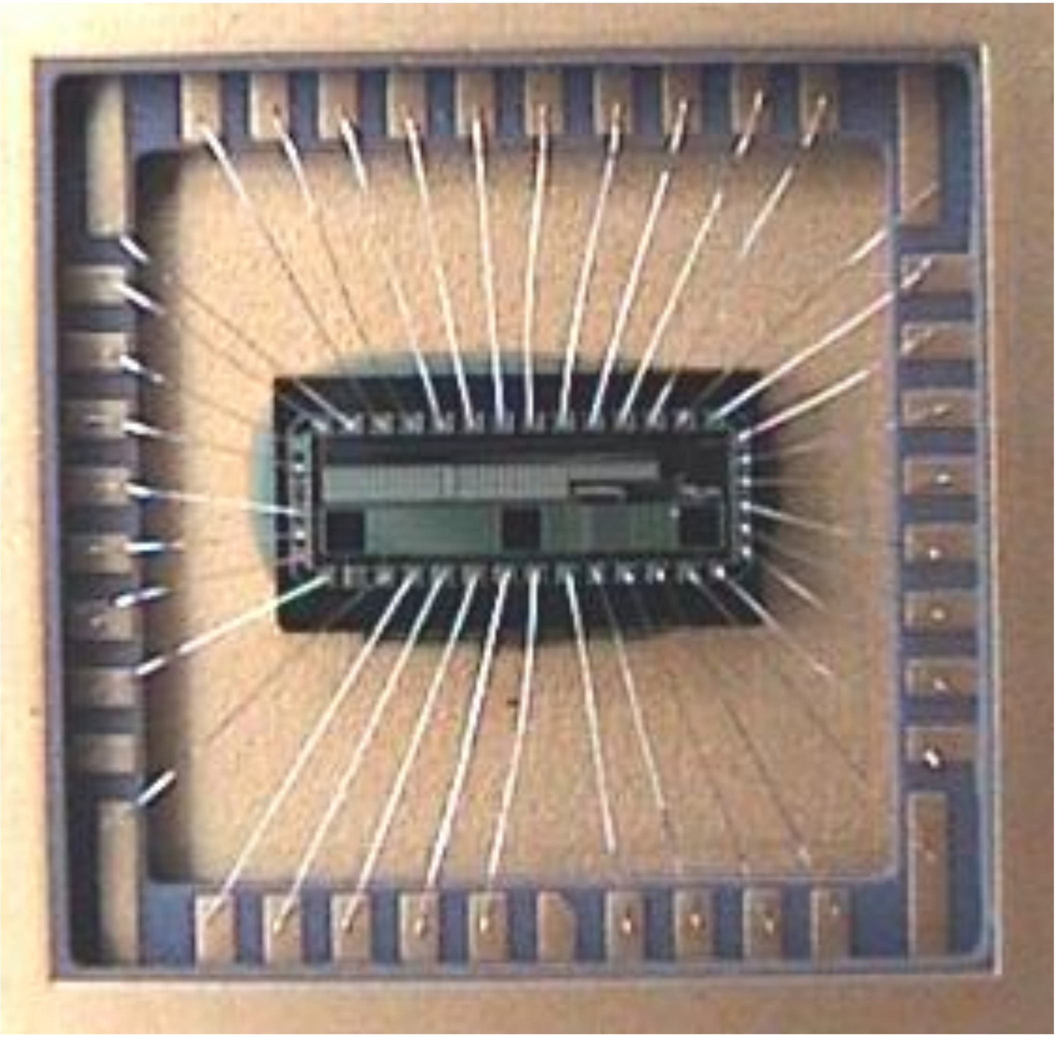

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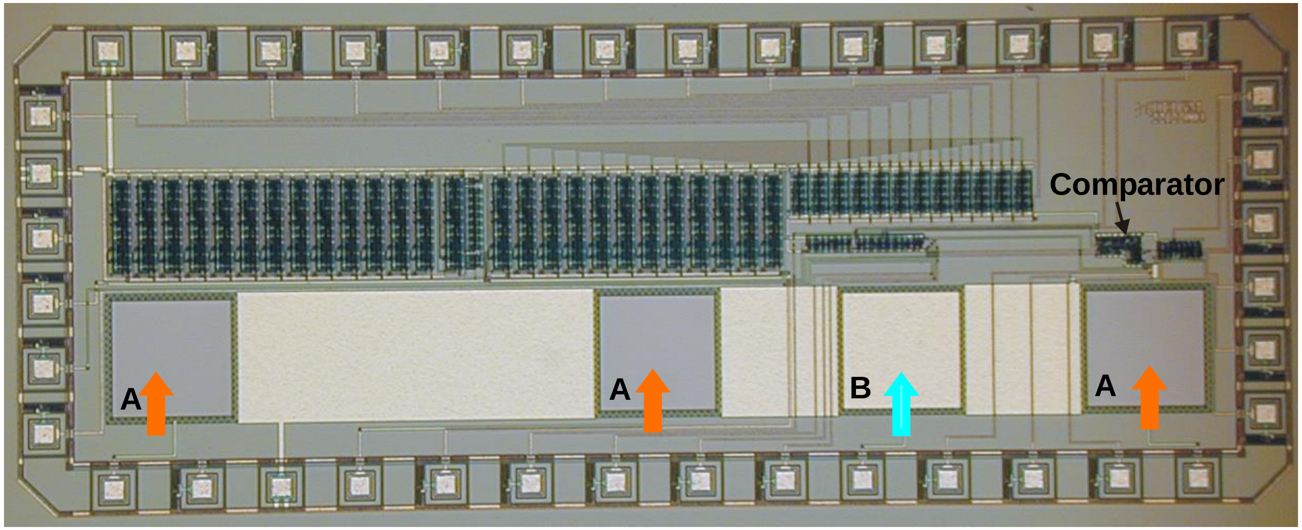

- 1.6 μm n-well CMOS standard process, with double-metal and single-polysilicon
- Each optical channel area is 500 μm × 500 μm

O SISTEMA de DETECÇÃO e LEITURA

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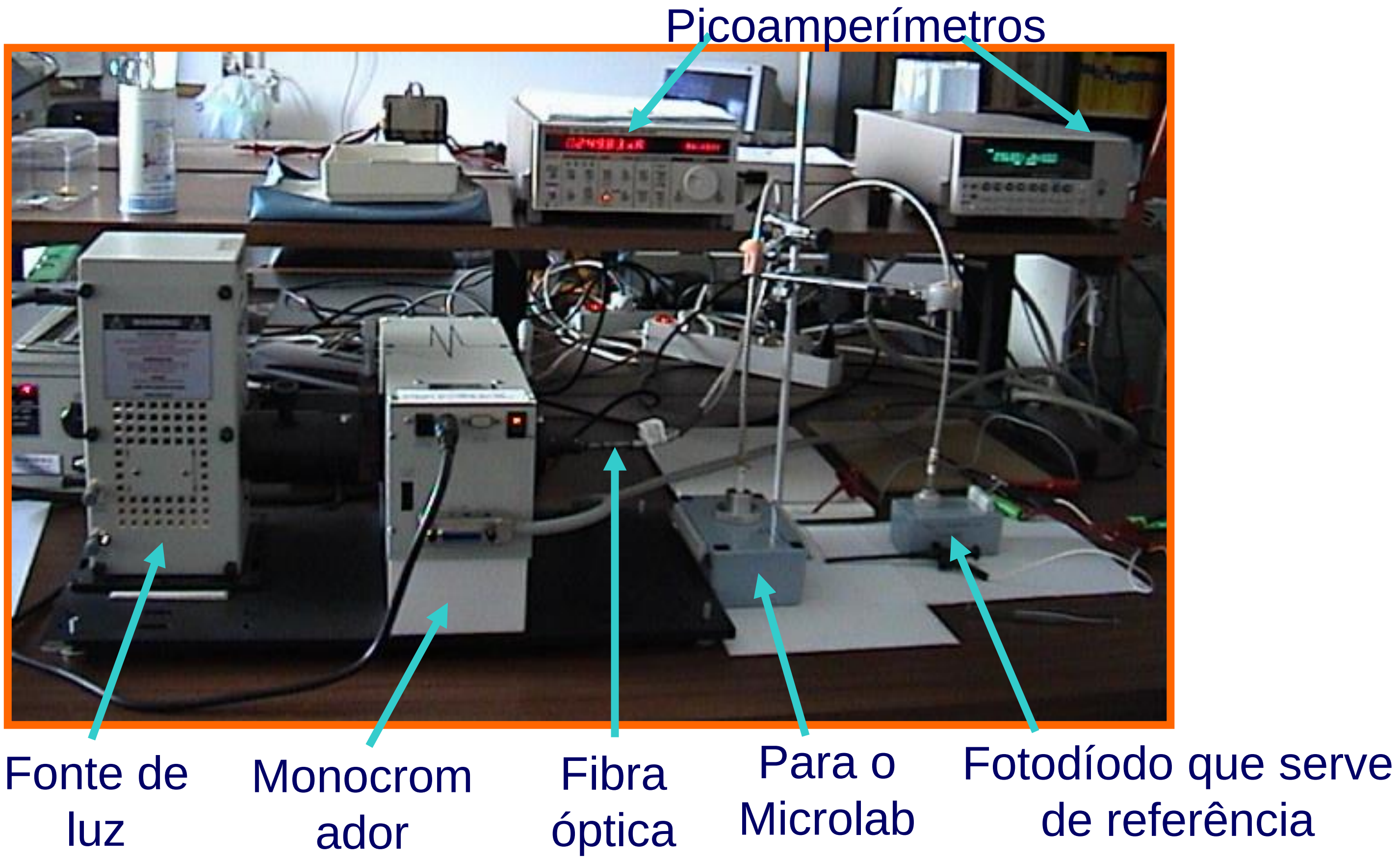
Conversor luz - frequência

Aumento Diminuição da intensidade da luz

- A frequência da saída do conversor é diretamente proporcional à intensidade da luz

INSTALAÇÃO EXPERIMENTAL



INSTALAÇÃO EXPERIMENTAL

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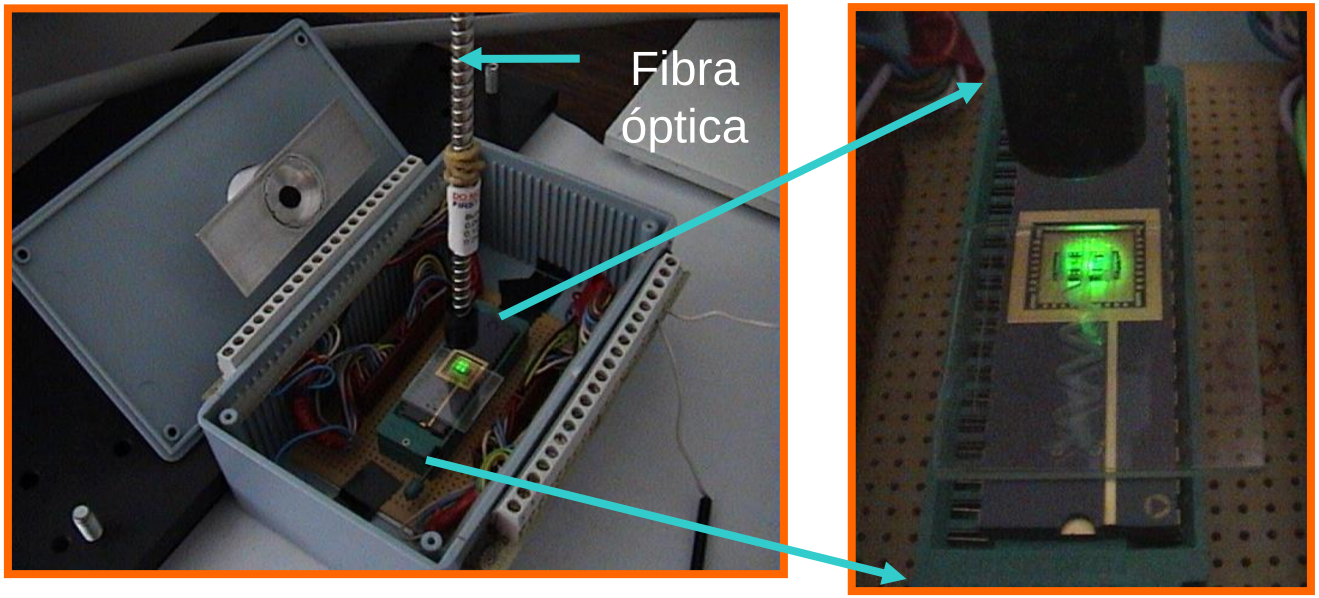

Optical detection system

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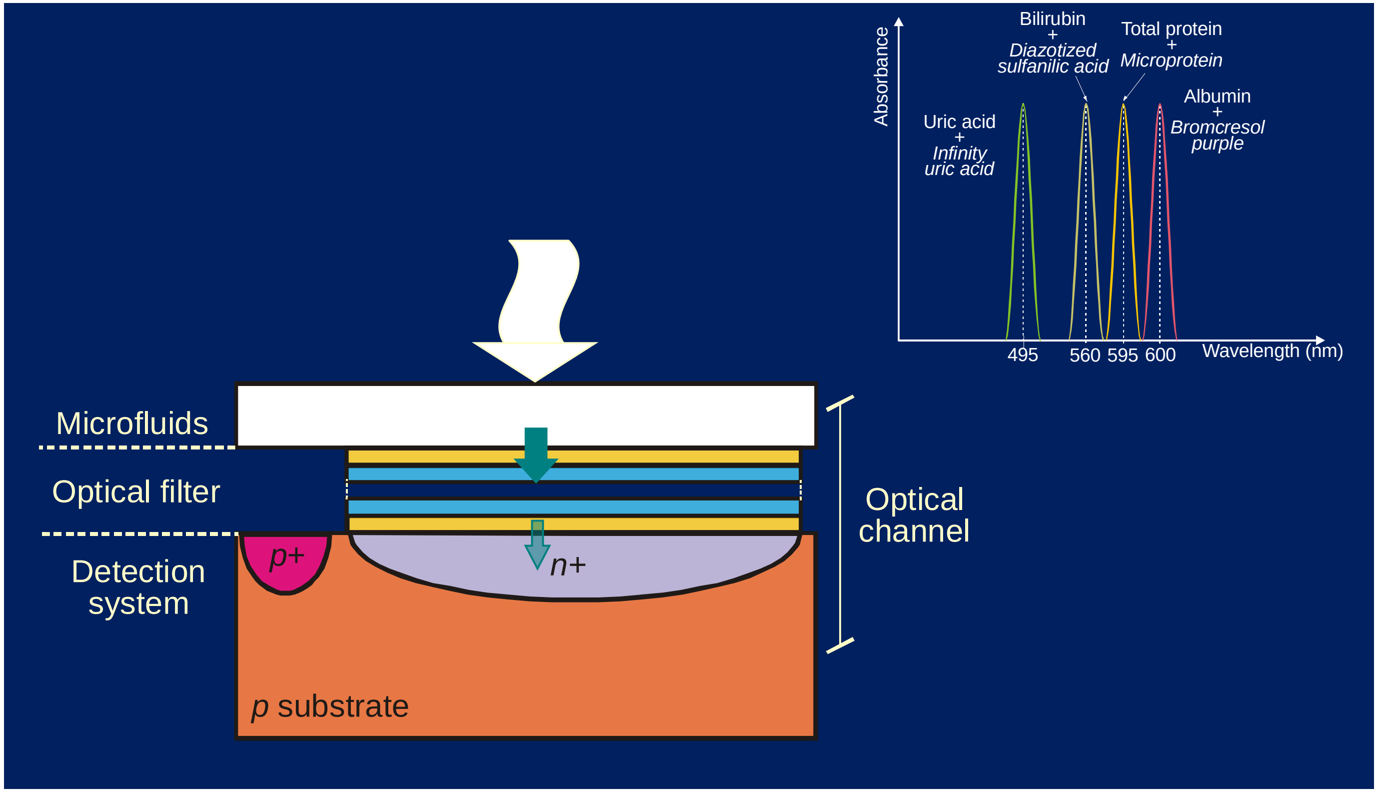
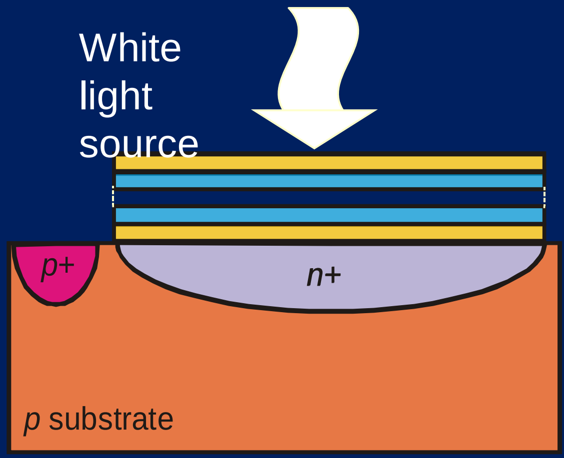


Optical detection system

Portability



- Structurally optimized for:
  - high transmittance
  - high selectivity (low FWHM)
- FP thin-films optical resonators with dielectric mirrors (TiO_2 and SiO_2)
- High reflectivity with low absorption losses

Layers post-processed on top of the photodiodes by Ion Beam Deposition (IBD)

Optical detection system

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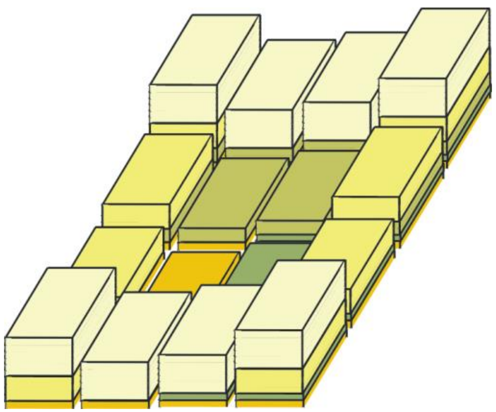

- Each of the Fabry-Perot cavities is tuned to transmit in different spectral band