ELECTRONICS Design Division

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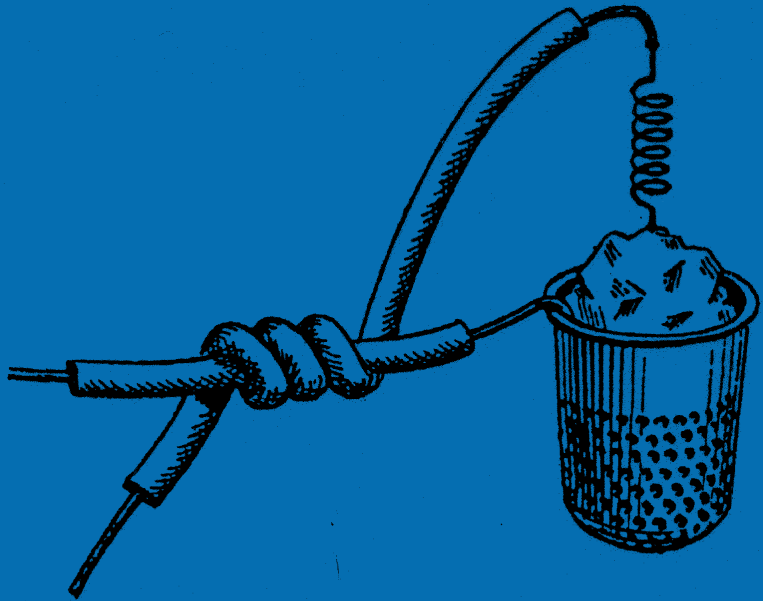
Sensor devices

Thermal sensors



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Outline

- 7 Thermal sensors
  - Introduction
  - Heat transfer
  - Thermal structures
  - Thermal-sensing elements
  - Thermal and Temperature sensors

Introduction

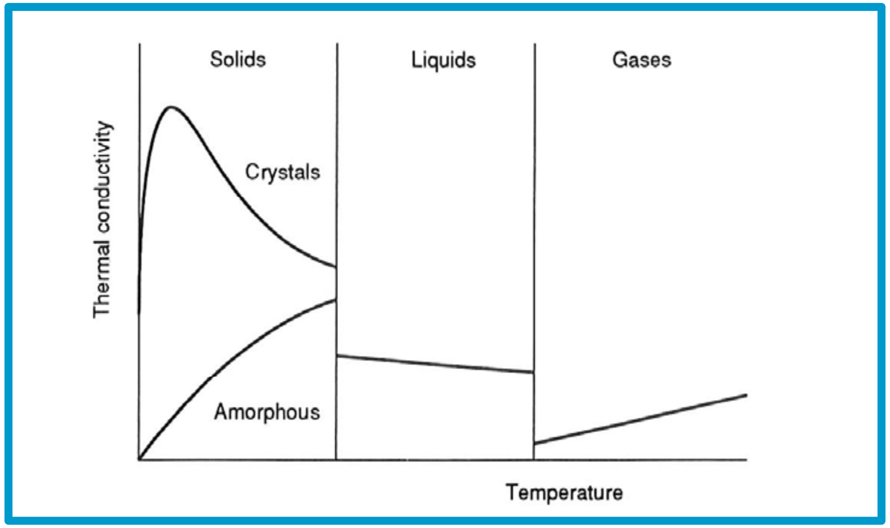
- Physical quantitaties is converted into heat
- The heat is converted into electrical quantities
- The process is done into three steps
  - Electromagnetic radiation is transduced into a heat flow
  - The heat flow is converted into a temperature difference
  - The temperature difference is transduced into a electric signal using a temperature (difference) sensor

Heat transfer

- Heat
  - Gas and Liquid “average velocity of the molecules”
  - Solids “Phonons, vibrations of atoms in lattice and transportations of heat by free electrons”
- Specific heat and thermal capacitance
  - Heat required to increase the temperature with 1 K at constant pressure

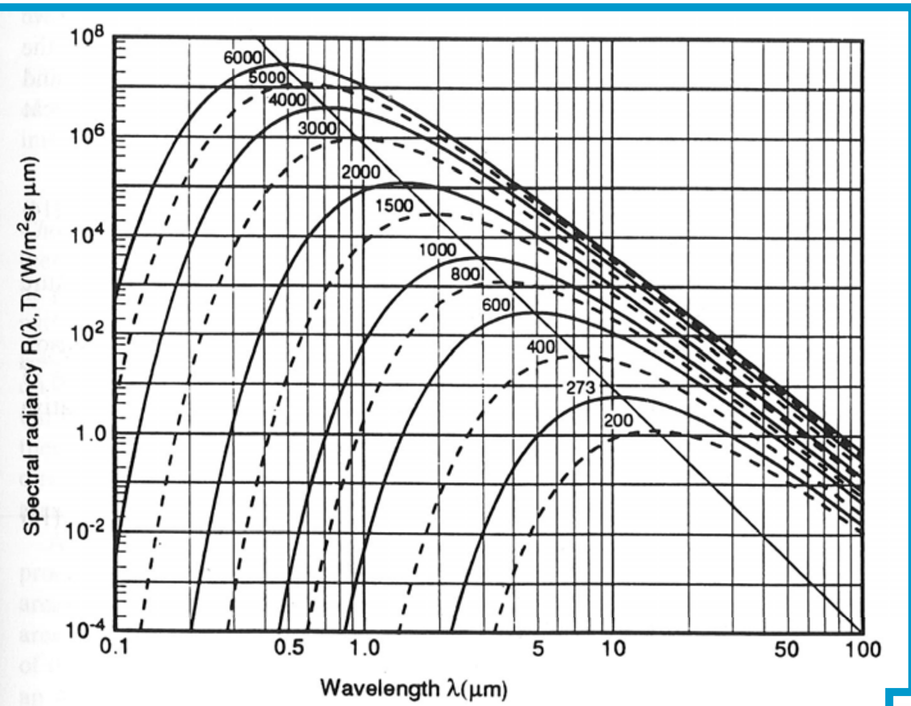
$$\boxed{c_p = \left(\frac{dH}{dT}\right)_p}$$

Heat transfer



- Conduction
  - Conductivity
    - Heat will flow from hotter to colder region
  - Convection
    - Heat transfer to flowing fluids (Liquid or gas)
    - Laminar flow
    - Turbulent flow

Heat transfer

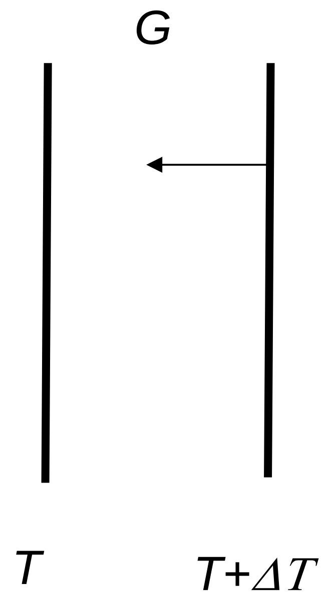


- Radiation
  - Black-body Radiation
    - A body which absorb all of the radiation " absorptivity=1" is called a black body
    - A black-body with absorptivity=1 also have an emissivity=1
    - Stefan-Boltzmann law

$$P''_{\mathrm{rad}}(T) = \epsilon \sigma T^4$$

$$\sigma = 56.7 \times 10^{-9}\ \mathrm{W/m^2\text{-}K^4}.$$

Heat transfer



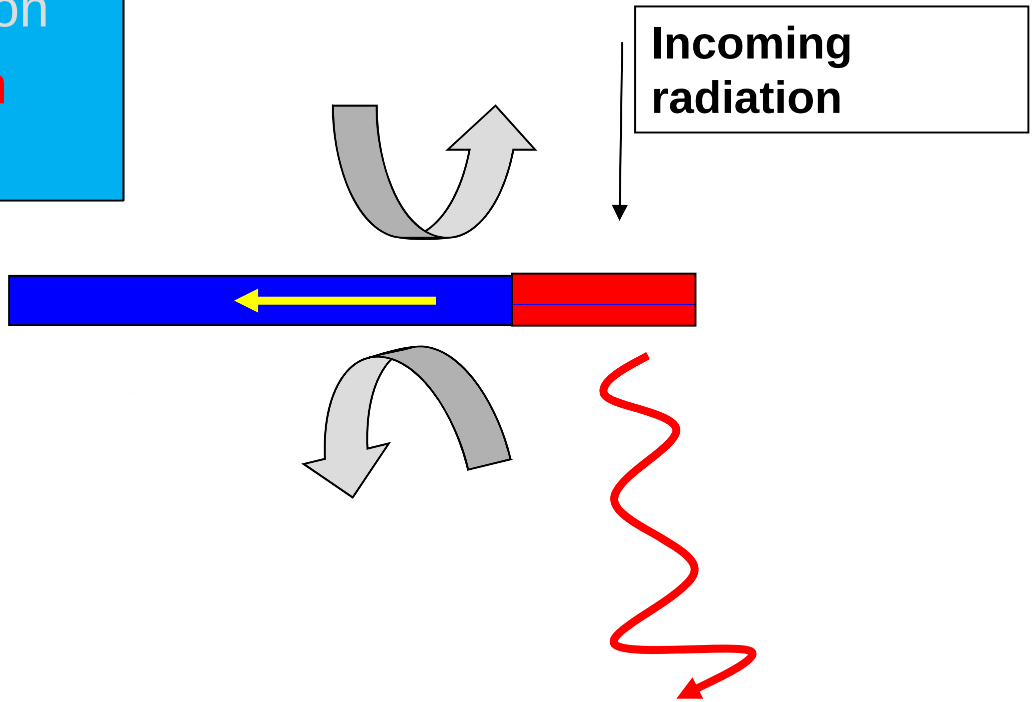
- Heat transfer by infrared radiation
  - Two parallel plates

$$\boxed{G''_{\mathrm{rad}} = 4\epsilon\sigma T^3 = \epsilon \times 6\ \mathrm{W/K\text{-}m^2}.}$$

- Silicon is almost transparent above 1.1 um. At room temperature the radiation have its maximum at 10 um wavelength and the absorptivity, emissivity is as low as 0.1-0.3

Heat transfer Summary

Conduction
Convection
Radiation



Thermal structures

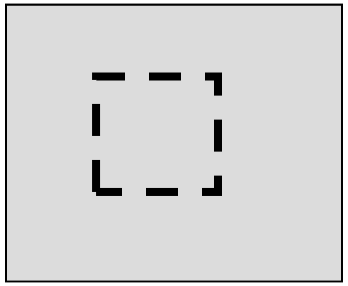
- Purpose
  - Reduce “self heating”
  - Reduce “heat leakage”

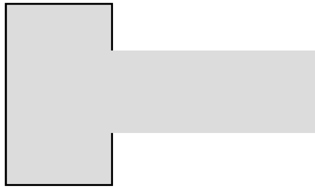
In case of temperature difference like sensor structure, make R_{th} large

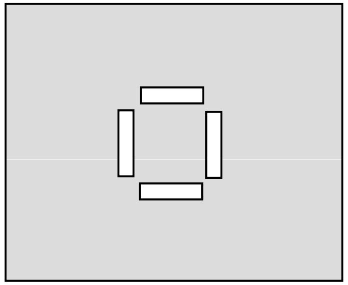
$R_{th}=\Delta T/P$

Often solved by using thin membranes

- The membrane can be of type







Thermal structures

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TABLE 1 Electrical Equivalents of Thermal Parameters

Thermal Parameter	Electrical Parameter
Temperature: T (K)	Voltage: V (V)
Heat flow, Power: P (W)	Current: I (A)
Heat: Q (J = W s)	Charge: Q (C = A-s)
Resistance: R (K/W)	Resistance: R ($\Omega = V/A$)
Conductance: G (W/K)	Conductance: G ($S = \Omega^{-1}$)
Capacity: C (J/K)	Capacitance: C (F = A-s/V)
Thermal resistivity: ρ_{th} (K-m/W)	Electrical resistivity: ρ_{el} (Ω-m)
Thermal conductivity: κ (W/K-m)	Electrical conductivity: σ (S/m)
Specific heat: c_p (J/kg-K)	Permittivity: ε (F/m)

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Thermal structures

One dimensional heat flow

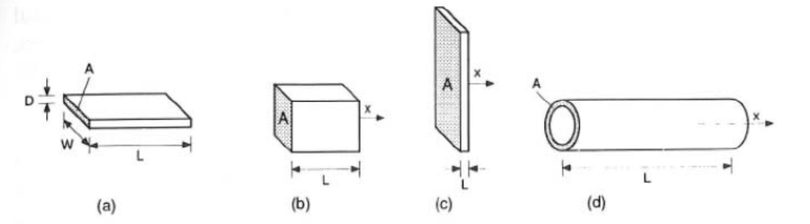


Fig. 5 One-dimensional heat flow along the axis of rods, wires, rectangular plates and tubes. The symbol L denotes the linear dimension in the direction of the heat flow. (After Ref. 1)

Thermal resistance 1 dimension

$$R_{th} = \frac{L}{\kappa A}$$

K= thermal conductivity

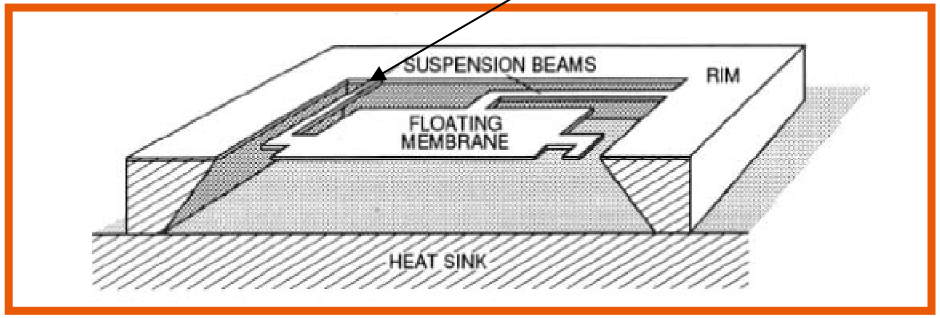
Thermal resistance of object in fig 5a

$$R_{th} = \frac{L}{W}\frac{1}{\kappa D}.$$

Thermal structures

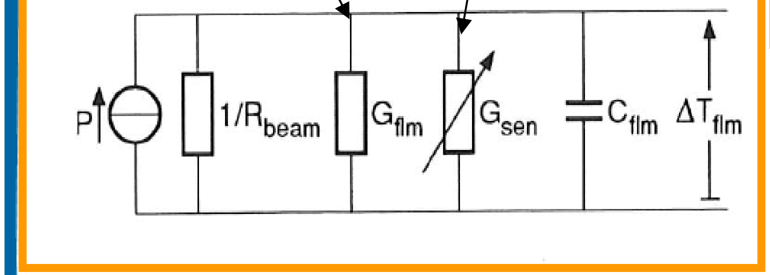
- Floating Membranes
- Thermal model

R_{beam}



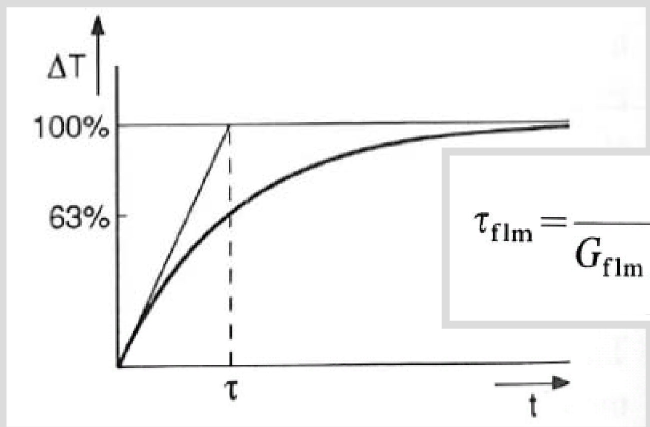
Parasitic conductance by convection, radiation etc

Depended of frequency of incoming signal



$$\Delta T_{flm} = T - T_{amb} = P/(1/R_{beam} + G_{flm} + G_{sen})$$

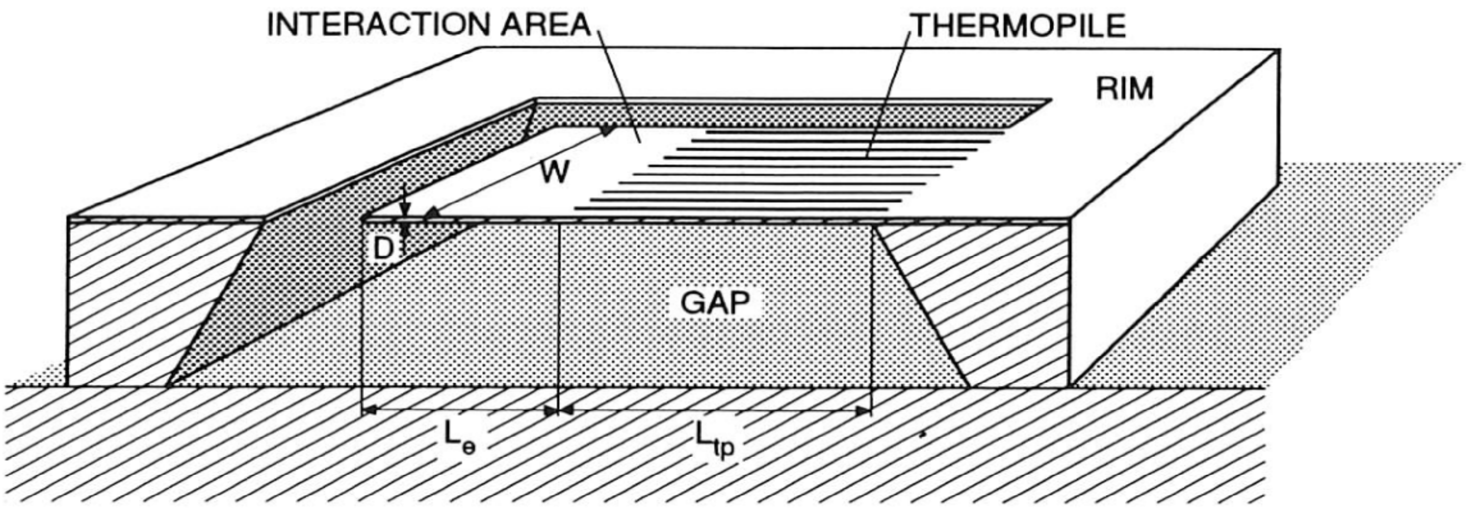
$$\Delta T_{flm}(t) = \frac{P}{1/R_{beam} + G_{flm} + G_{sen}}(1 - \exp(-t/\tau_{flm}))$$



$$\tau_{flm} = \frac{C_{flm}}{G_{flm} + G_{sen} + 1/R_{beam}}.$$

Thermal structures

Cantilever beam and bridges



No convection and infrared radiation

$$R_{th} = R_{st} \frac{L_{tp}}{W}.$$

$$R_{st} \ (= 1/(\kappa D))$$

Thermal structures

Cantilever beam and bridges

In case of heat convection and infrared radiation

$$R_{\mathrm{th}} = R_{\mathrm{st}} \frac{L}{W} \frac{\tanh(\gamma L)}{\gamma L}$$

heat convection and infrared radiation

$$R_{\mathrm{th}} = R_{\mathrm{st}} \frac{L}{W} \left(1 - \frac{R_{\mathrm{st}}(G_p'' + j\omega C_{\mathrm{th}}) L^2}{3} \right)$$

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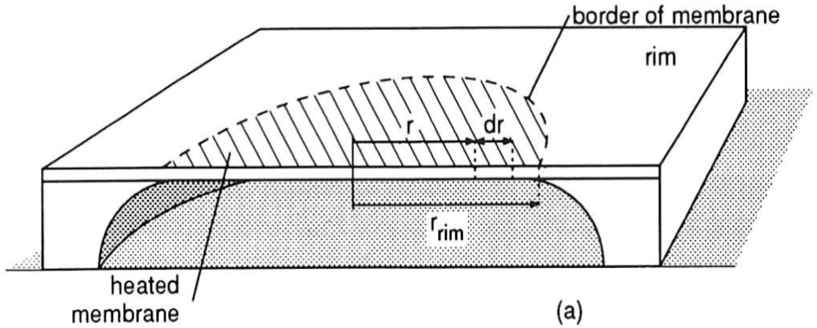
Thermal structures

Closed membranes



$$T(r) = P'' R_{st}(r_{rim}^2 - r^2)/4.$$

P'' (in W/m^2),

Uniform heating of membrane with power density *P´´*

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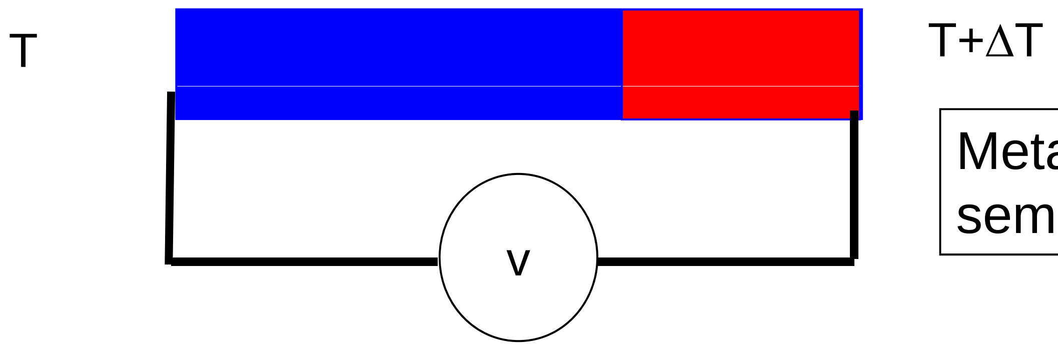
Thermal-sensing elements

- Resistors
  - **Bridge coupled mono or poly silicon resistors**
  - **Platinum resistors Pt100, 100ohm at 0ºC, 0.38%/K**
- Thermopile
- Acoustic sensing elements

Thermal-sensing elements

$$\Delta V = \alpha_S \Delta T$$

α_S is the Seebeck coefficient expressed in V/K.



Metal or semiconductor

Thermal-sensing elements

Seebeck Coefficients

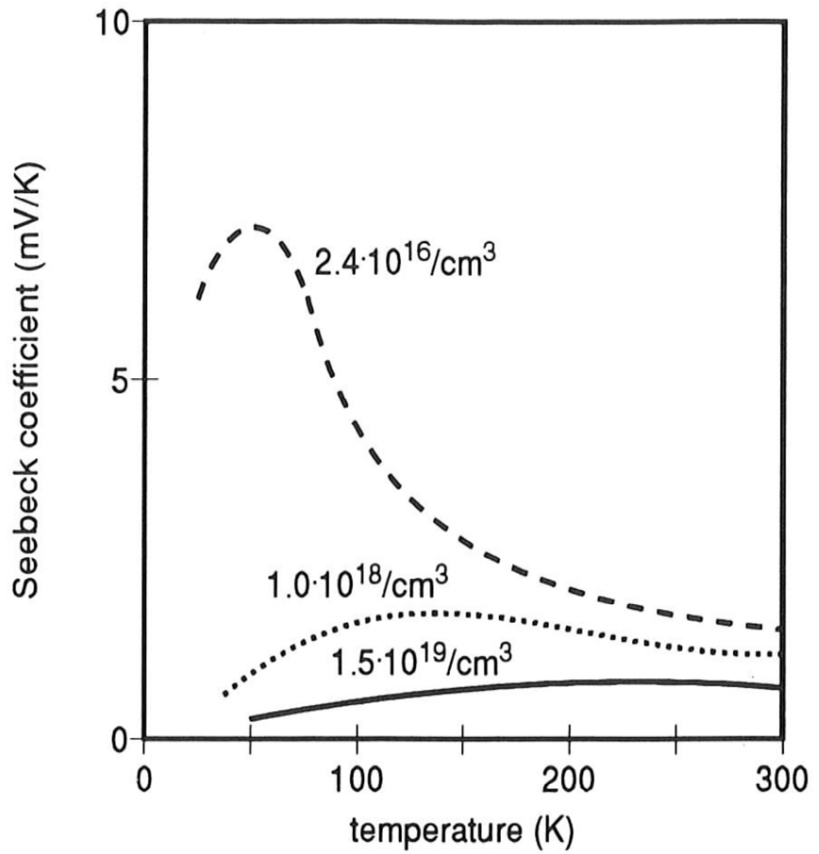
TABLE 2 Seebeck Coefficient for Some Metals and Mono- and Poly-Silicon (in $\mu V/K$)

Material	273 K		300 K
p-type mono silicon (Si)			300 to 1000
Antimony (Sb)		43[a]	
Chrome (Cr)	18.8		17.3
Gold (Au)	1.79		1.94
Copper (Cu)	1.70		1.83
Aluminum (Al)			−1.7
Platinum (Pt)	−4.45		−5.28
Nickel (Ni)	−18.0		
Bismuth (Bi)		−79[a]	
n-type polysilicon (Si)			−200 to −500

[a]Averaged over 0 to 100°C.

Thermal-sensing elements

Seebeck Coefficients, dependencies of temperature and doping in p-type silicon



Thermal-sensing elements

Thermopile

$\Delta V=(S_a-S_b)\Delta T$

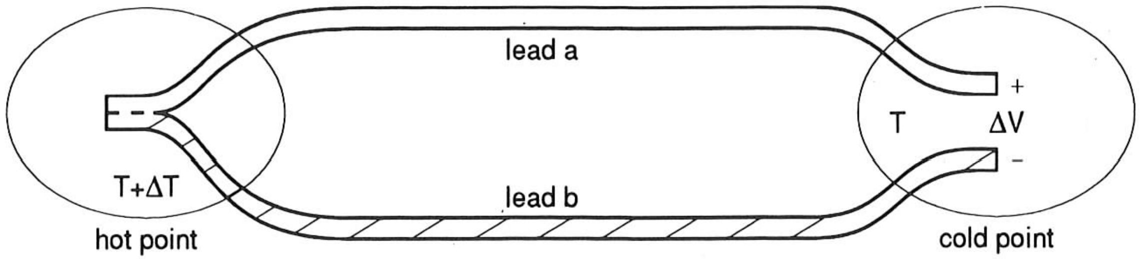


Fig. 11 The Seebeck effect: an electrical voltage ΔV is generated due to a temperature difference ΔT. (After Ref. 1)

Design rule number of thermopile

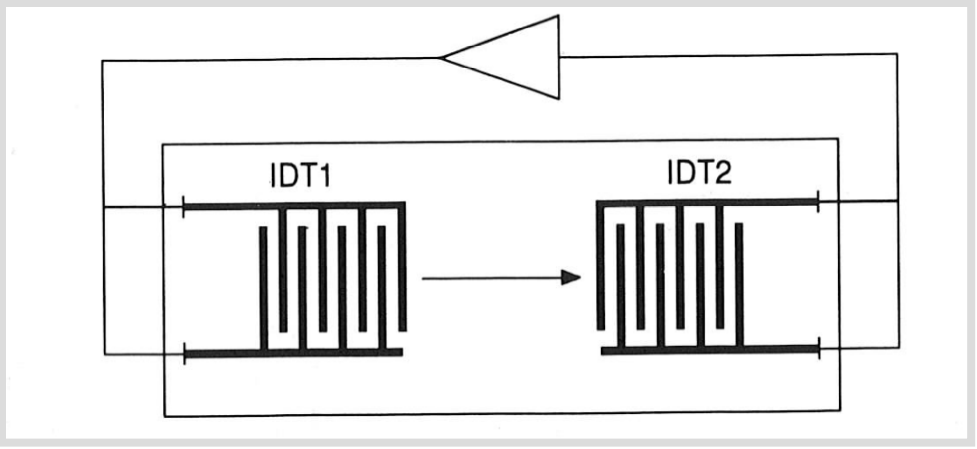
R_{st}=thermal sheet resistance

R_{se}= electrical sheet resistance

$$N \simeq \sqrt{\frac{R_{st}W}{R_{se}L_x}}$$

Thermal-sensing elements

- Acoustic wave sensors
- feedback loop, oscillators
- sensitivity ~2.8kHz/ºC



Thermal and Temperature sensors

Thermopile, SU8 with Ni and Ti as thermopile element

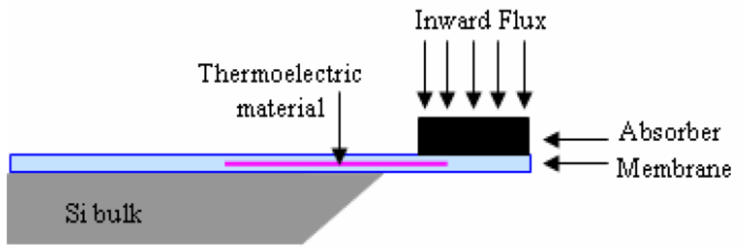
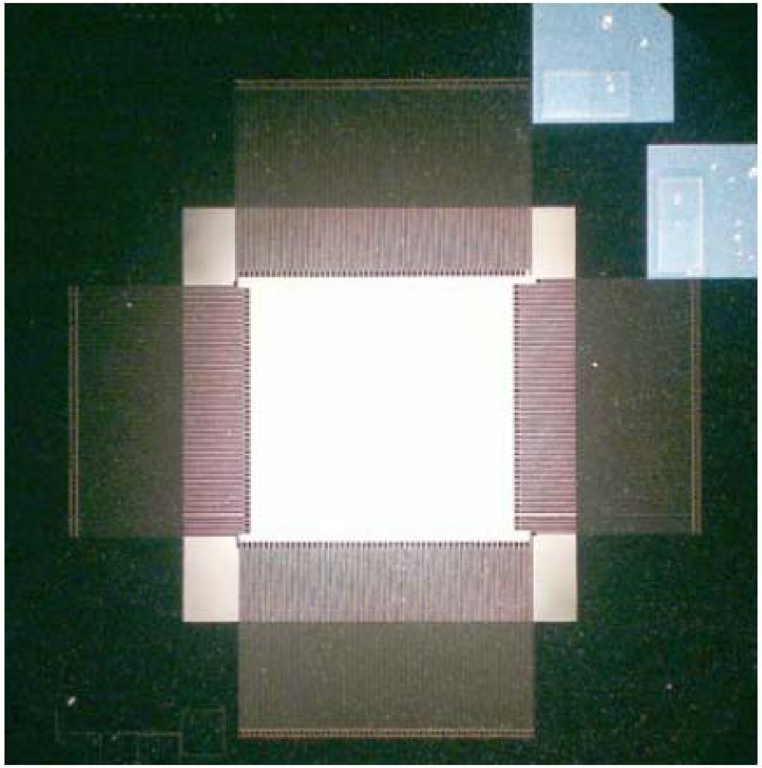


Figure 1. Cross-sectional view of simulated thermopile structure



Thermal and Temperature sensors

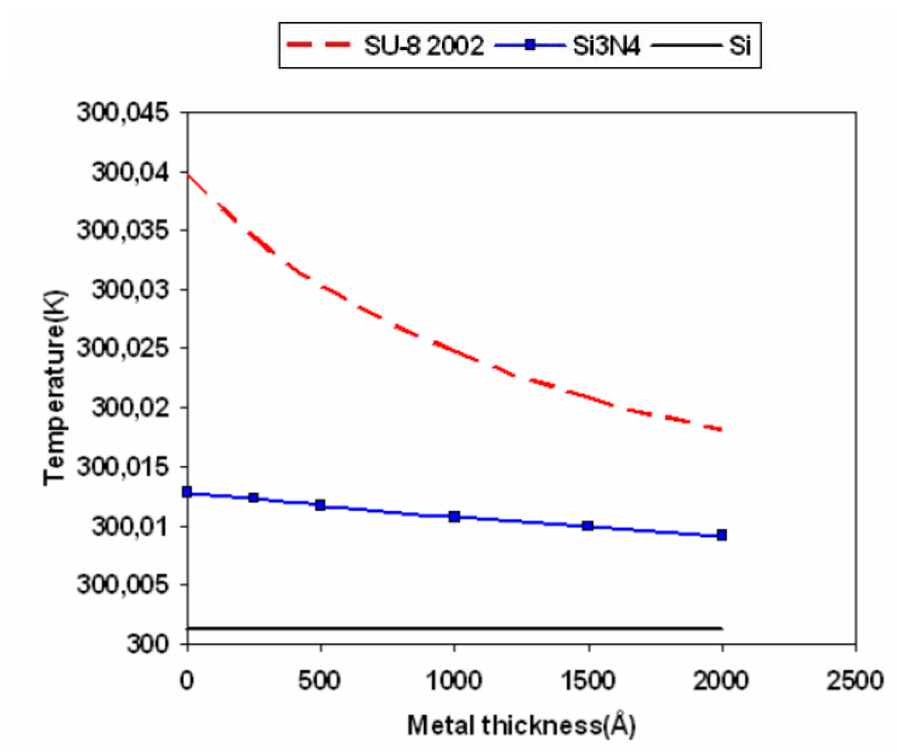
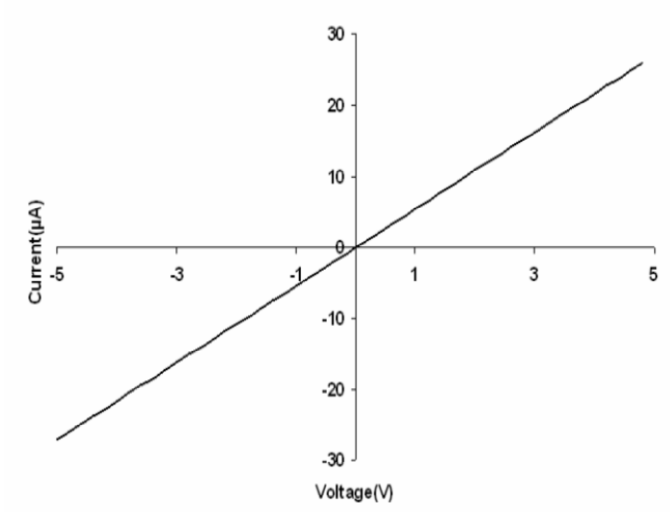


Figure 4. Thermal response as function of metal thickness for different membrane materials



Thermal and Temperature sensors

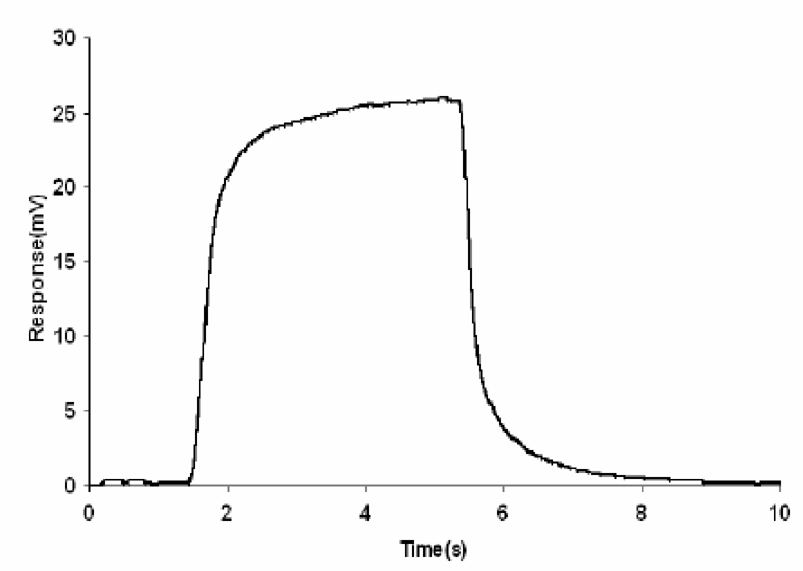


Figure 7. Measured detector response from a 1.56µm laser with a power of 4.5mW

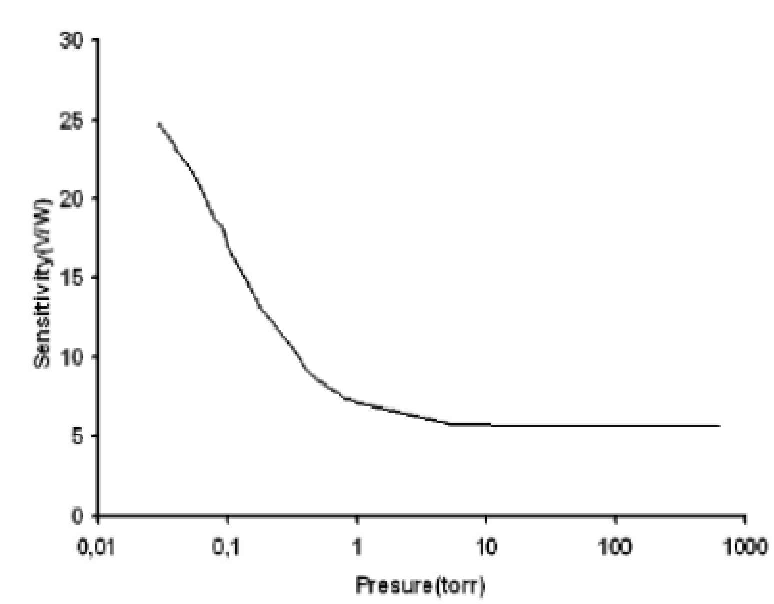
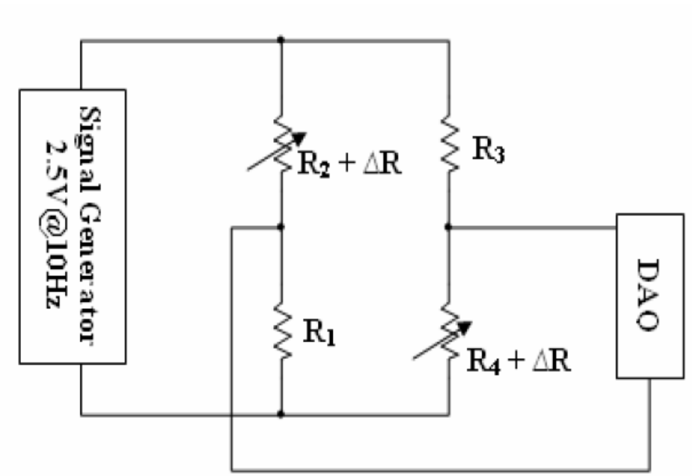


Figure 8. Sensitivity of thermopile detector as function of air pressure

Thermal and Temperature sensors

Bolometer



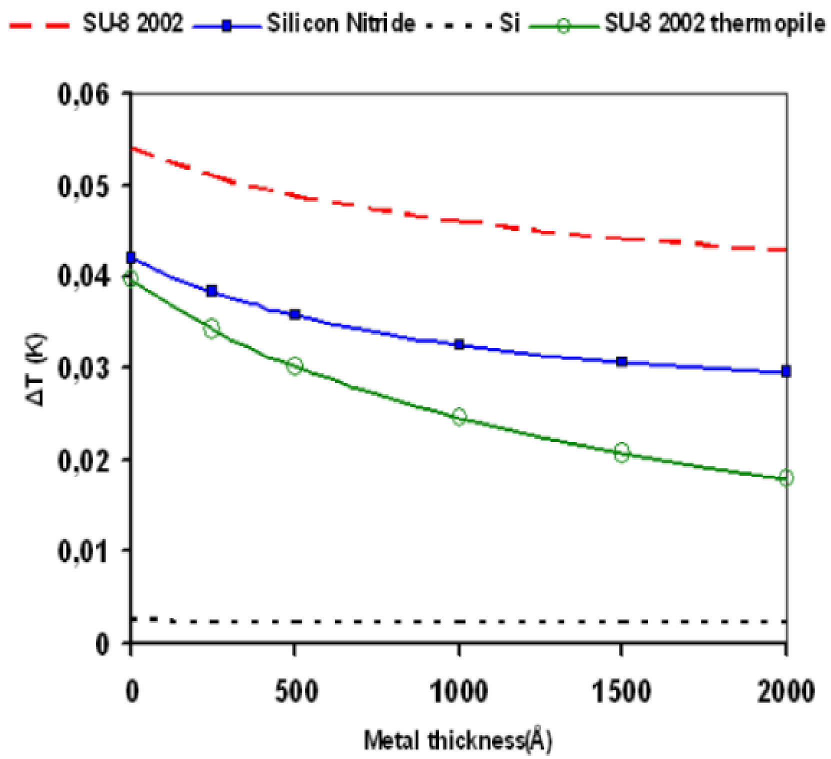


Figure 3. Thermal response as function of metal thickness.

Thermal and Temperature sensors

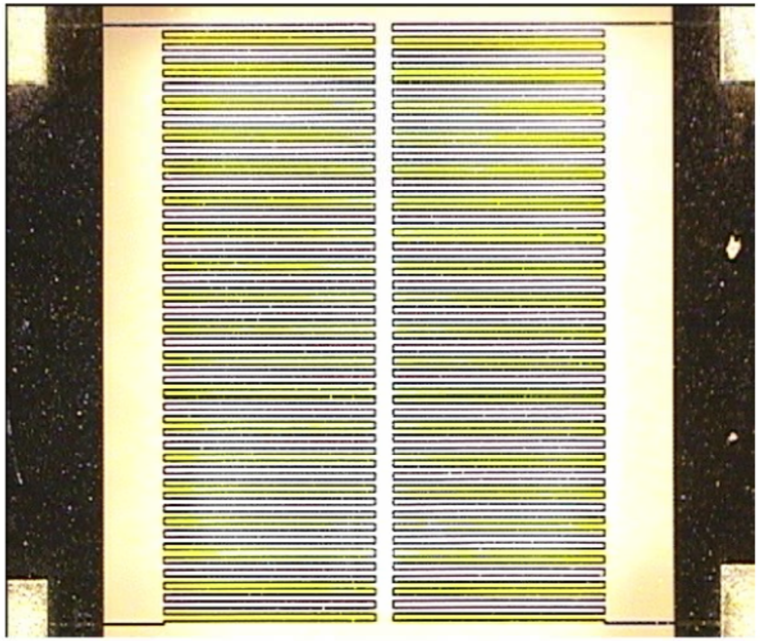


Figure 5. Top view image of IR sensitive resistances (R_2 and R_4) on fabricated bolometer.

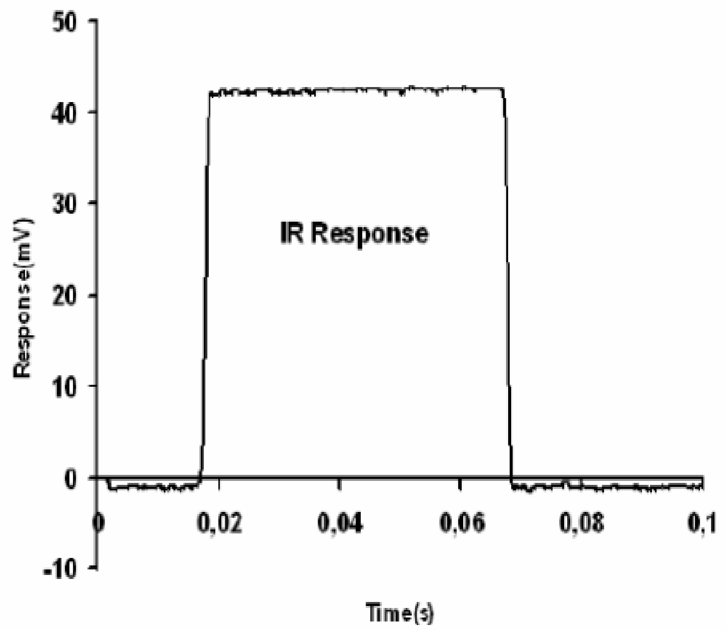


Figure 6. Measured detector response from a 1.56 μm laser with a power of 4.5 mW.

Thermal and Temperature sensors

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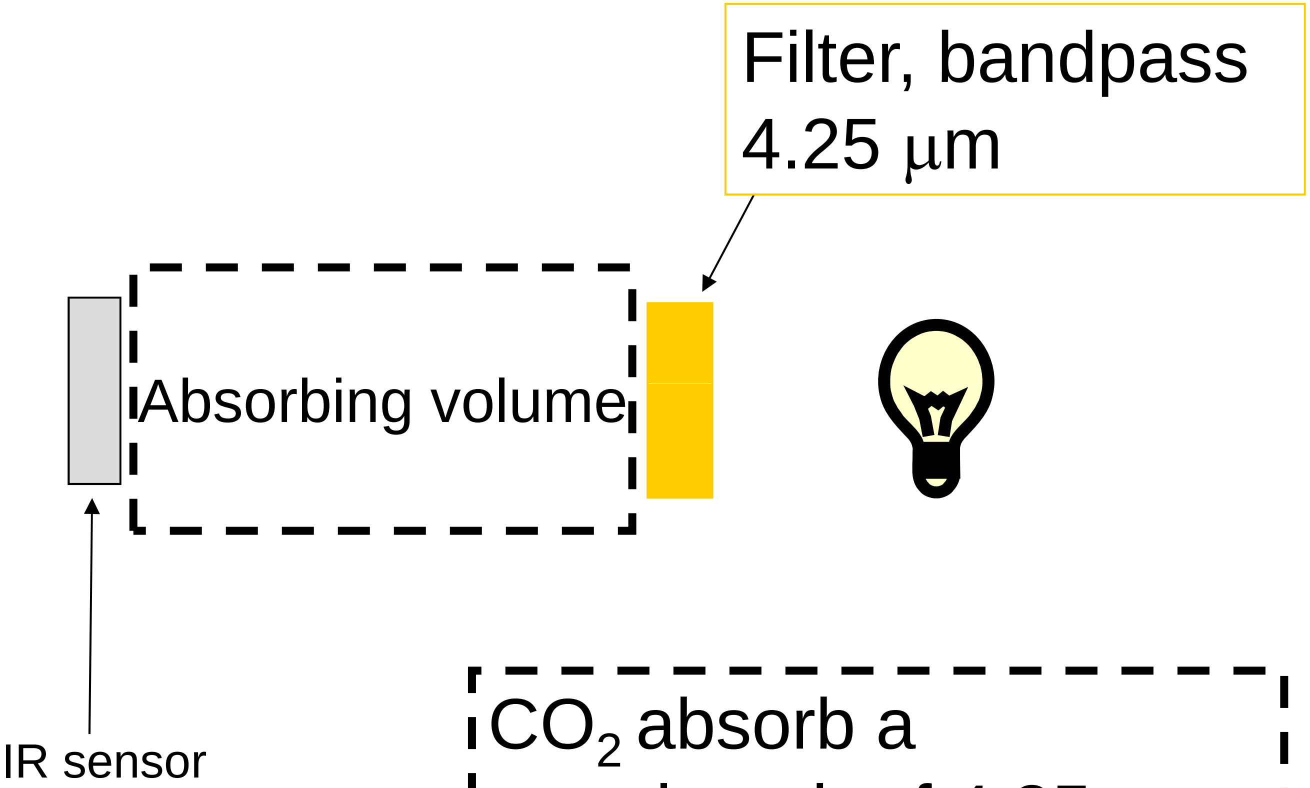
Carbon-dioxide sensor schematic



CO_2 absorb a wavelength of 4.25 µm

Exercises

Processing part (chapter 2)

3.1 How long does it take to grow 100 nm of oxide in wet oxygen at 1000 °C (assume 100 silicon)? In dry oxygen? Which process would be preferred?

3.2 A 1.2-μm silicon dioxide film is grown on a <100> silicon wafer in wet oxygen at 1100 °C. How long does it take to grow the first 0.4 μm? The second 0.4μm? The final 0.4 μm?

4.1 A phosphorus diffusion has a surface concentration of $5 \times 10^{18}/\text{cm}^3$, and the background concentration of the *p*-type wafer is $1 \times 10^{15}/\text{cm}^3$. The Dt product for the diffusion is 10^{-8} cm^2.

(a) Find the junction depth for a Gaussian distribution.

(b) Find the junction depth for an erfc profile.

(c) What is the sheet resistance of the two diffusions?

(d) Draw a graph of the two profiles.

3.1 9 min, 2.3h 4:1 5.8 um, 5.3 um, 47ohm/Square, 60 ohm/square

Exercise

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6. Thermal Model of Floating-Membrane Sensor. A floating-membrane sensor has a suspension beam 2 mm in length, 200 μm in width and 5 μm in thickness ($\kappa_{Si} = 150$ W/K-m). At its end a floating membrane is suspended with an area of 2 mm^2, between heat sinks at 0.5 mm distance under and above the membrane. The sensor is encapsulated in argon ($\kappa_{Ar} = 18$ mW/K-m).

a) What is the beam's thermal resistance compared to that of the floating membrane?

b) How do the thermal time constants of the beam and the overall system (using a simple model) compare? Note, that the specific heat of silicon is $c_p = 1.6$ MJ/m^3-K.