Temperature sensors

14.11.2022

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T. Seebeck

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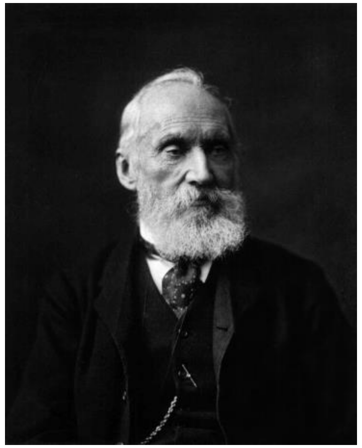


Lord Kelvin

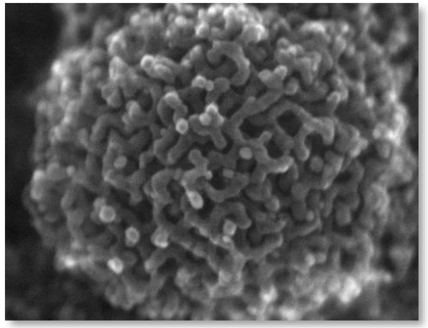
E. Altenkirch

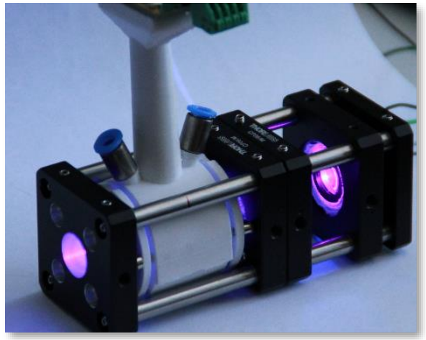
Chair for Gas Sensors – in brief

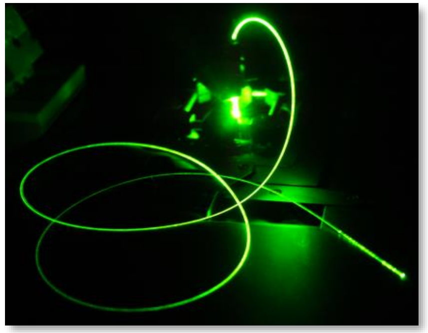
Who? Prof. Jürgen Wöllenstein

Where? Building 102, Labs 00-026 and 040

What? MEMS gas sensors, optical sensors, spectroscopy



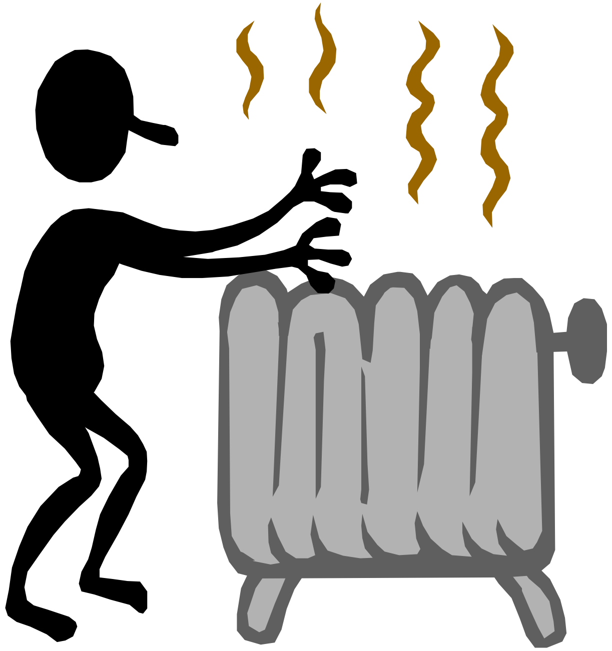




Before we start

Temperature vs. heat

How do you measure temperature?



Outline

- Introduction
- Expansion thermometers
- Thermocouples
- Thermopiles
- Resistance thermometer
- Thermistors
- Pyrodetector

Introduction

Temperature is the most important parameter to measure

- Measurement of temperature directly or indirectly
- Compensation of temperature dependent sensor readings
- Worldwide market: several billion $

Important to know:

- What do I measure?
- What is my measurand physically?

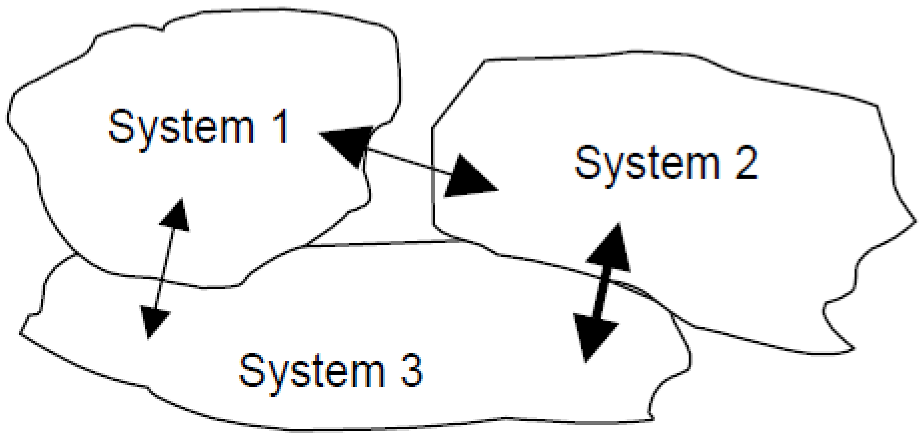
Introduction

Physiology:

- Warm receptors (Ruffini bodies)
- Cold receptors (Krausch bodies)

Thermodynamics:

- “Zeroth law of Thermodynamics” = Temperature as equilibrium term (empirical law)



Statistical definition

Average kinetic energy $\overline{E_{\text{kin}}} = \left\langle \frac{mv^2}{2} \right\rangle = \frac{3}{2} k_{\text{B}} T$

- $k_{\text{B}} = 1.3 \times 10^{-23}\ \text{J K}^{-1}$ Boltzmann constant

Temperature is the average kinetic energy and thus, a statistical value.

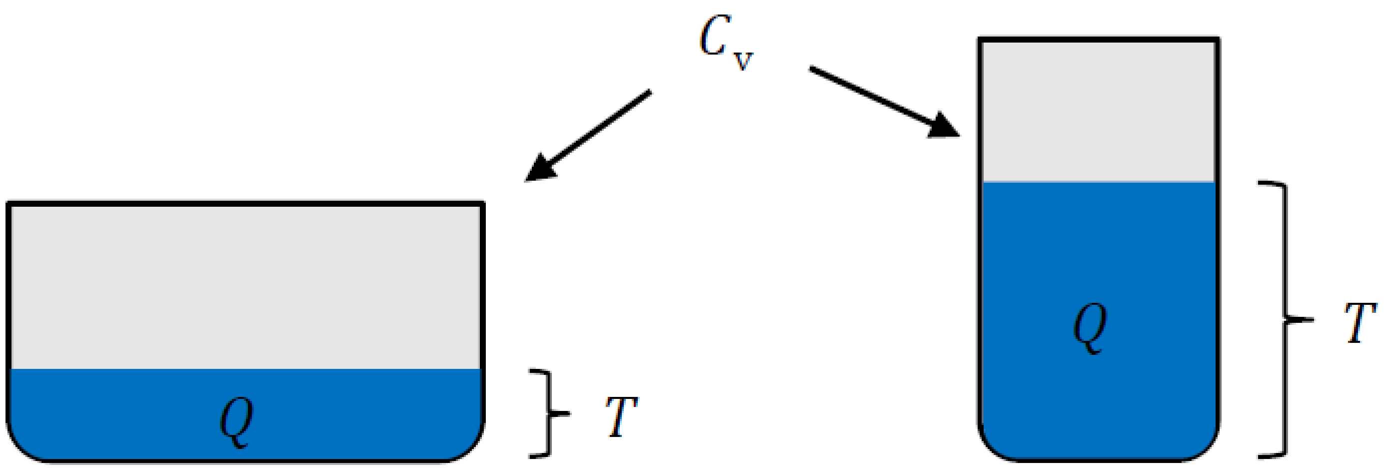
- Consequence: **Fluctuations!**

$$\frac{\Delta T^2}{T^2} = \frac{k_{\text{B}}}{C_{\text{v}}} \qquad C_v = c_v \cdot m = \frac{\mathrm{d}Q}{\mathrm{d}T}$$ **Thermal capacity**

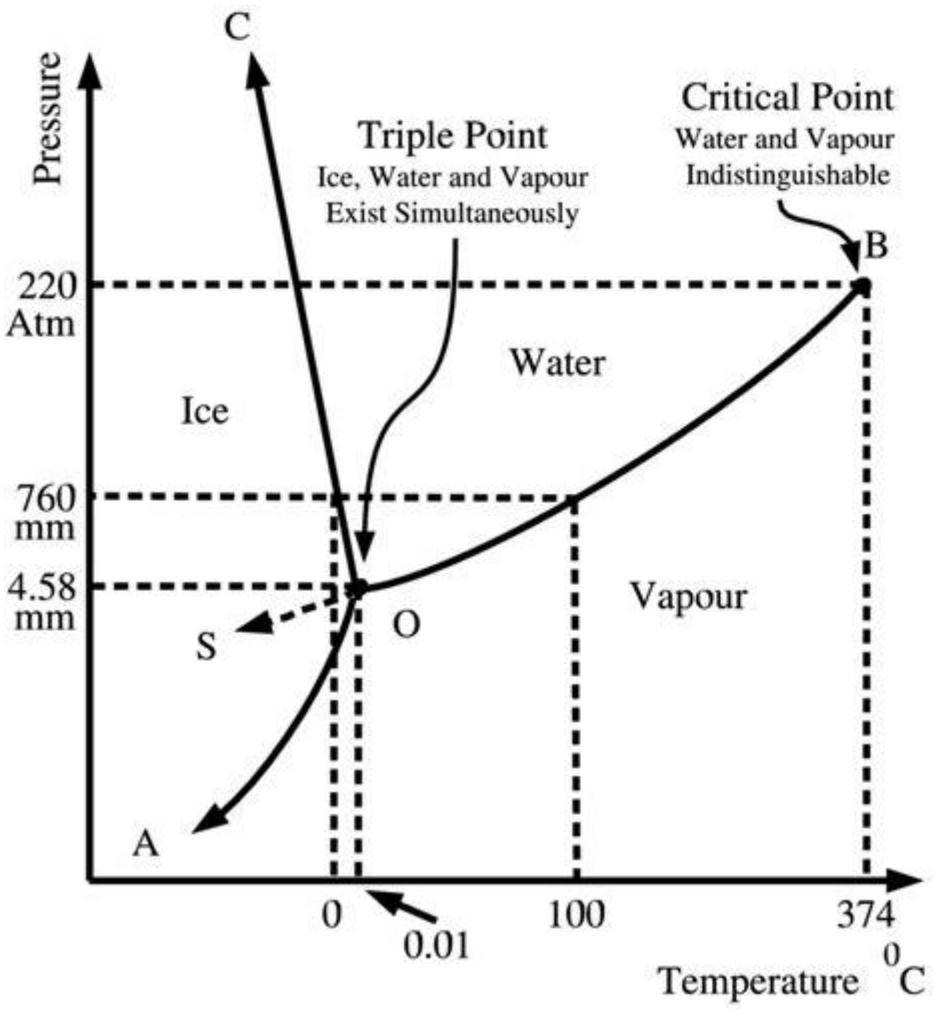
- Example: Ge-cubus of 50 nm side length ➔ Fluctuation of σ = 0.6 mK

Descriptive definition

Property	Analogy
Heat Q = non directed energy	Liquid quantity
Temperature T ~ average kinetic energy	Liquid height
Thermal capacity C_v	Container shape



Temperature scale



In thermodynamics, the **triple point** of a substance is the unique combination of temperature and pressure at which solid phase, liquid phase, and gaseous phase can all coexist in thermodynamic equilibrium.

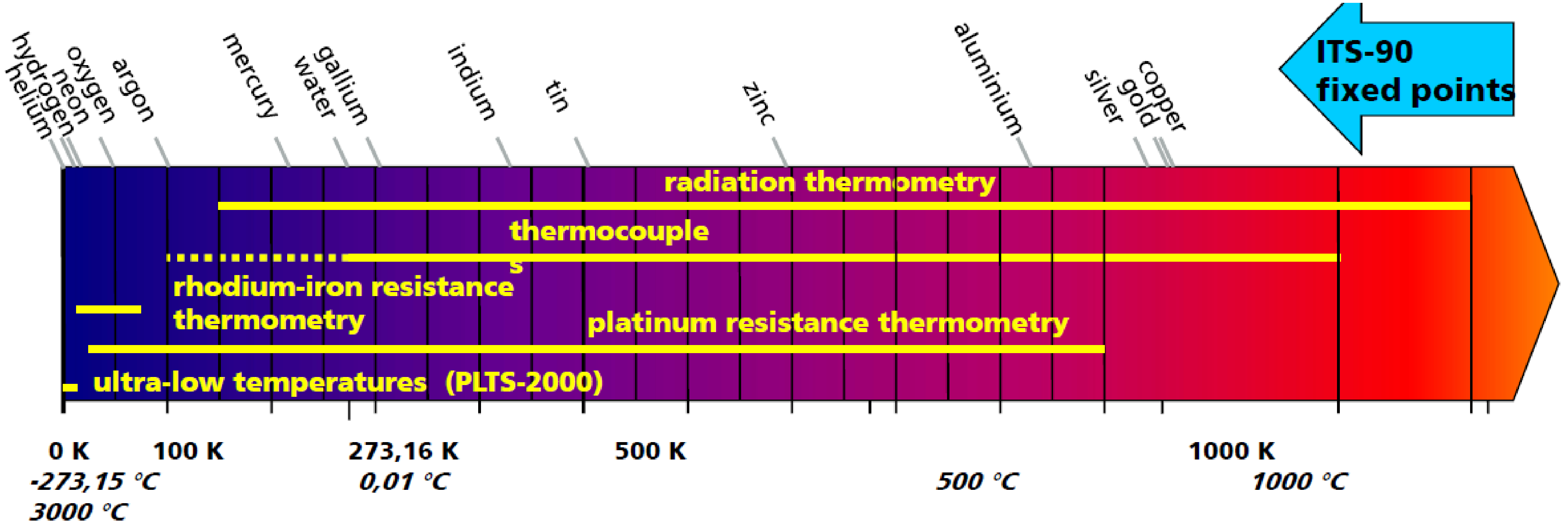
By international agreement, the **triple point of water** has been assigned a value of 273.16 K (0.01 °C; 32.02 °F) and a partial vapor pressure of 6.1166 mbar.

The **triple point of water** is the standard fixed-point temperature for the calibration of thermometers. This agreement also sets the size of the Kelvin as 1/273.16 of the difference between the triple-point temperature of water and absolute zero. It was named after William Thomson, later Lord Kelvin (1824 – 1907), who introduced the thermodynamic temperature scale at the age of 24.

Temperature scales and their fixed points

	Kelvin	Celsius	Fahrenheit
nuclear fusion (Deuterium-Tritium)	$100 \cdot 10^6$	$100 \cdot 10^6$ °C	$180 \cdot 10^6$ °F
average surface temperature of the sun	6050 K	5777 °C	10430 °F
melting point of iron	1808 K	1535 °C	2795 °F
boiling point of water	373,15 K	100 °C	212 °F
highest outside air temperature	330,95 K	57,80 °C	136,04 °F
human body temperature after Fahrenheit	310,93 K	37,78 °C	100 °F
freezing point of water	273,15 K	0 °C	32 °F
lowest temperature in Danzig, winter 1708/1709	255,37 K	-17,78 °C	0 °F
lowest temperature in Germany, 12.2.1929, Wolnzach	235,35 K	-37,8 °C	-36,04 °F
freezing point of alcohol	158,75 K	-114,40 °C	-173,92 °F
boiling point of nitrogen	77,35 K	-195,80 °C	-320,44 °F
boiling point of helium	4,2 K	-269 °C	-452 °F
laser cooling of Cs atoms	$2 \cdot 10^{-6}$ K	-273,15 °C	-459,67 °F
absolute zero	0 K	-273,15 °C	-459,67 °F

Temperature as a measurand



superconductivity environmental petrochemical power coking

paper rubber combustion

liquid natural gas energy management plastics glass steel

ceramics

cryogenic storage healthcare semiconductor heat treatment

refractories

frozen foods food processing aerospace

cryoengineering pharmaceutical electrical defence

Expansion thermometers

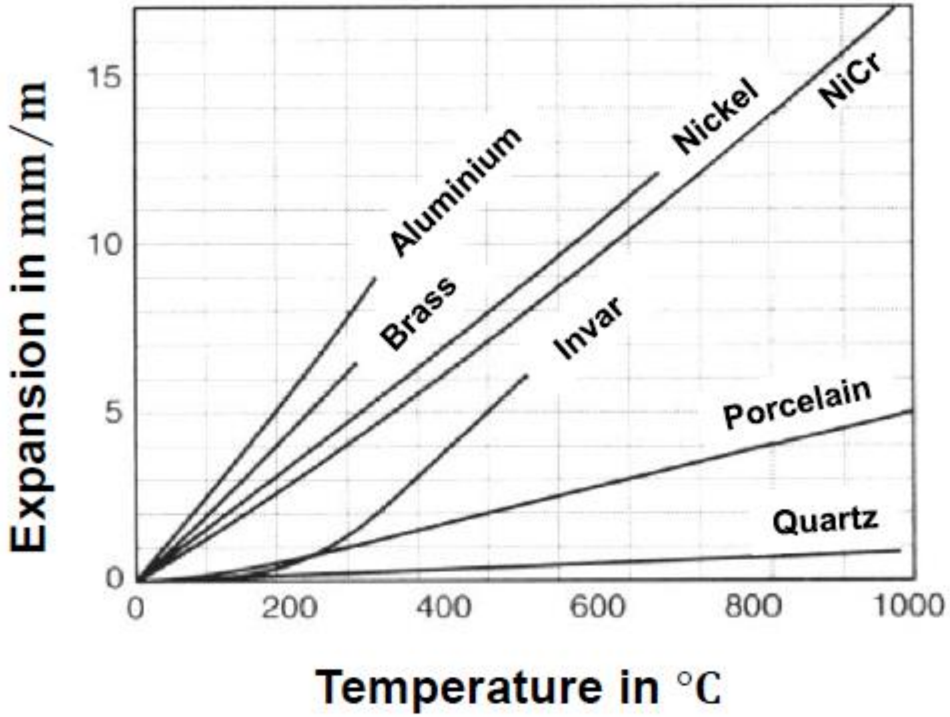
Measuring instrument / measuring procedure	Operating range (°C)
Liquid glass thermometer	
▪ non moistening (metallic) liquid	–58 … 630 (1,000)
▪ moistening (organic) liquid	–200 … 210
Liquid spring thermometer	
▪ non moistening liquid	
▪ with moistening liquid	–35 … 350
▪ vapour pressure thermometer	–200 … 700
Expansion thermometer	0 … 1,000
Bimetal thermometer	–50 … 600

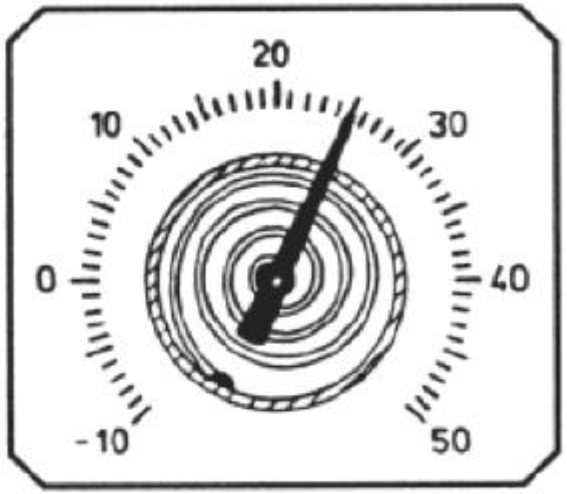
Solid expansion thermometer

Expansion of a solid body :

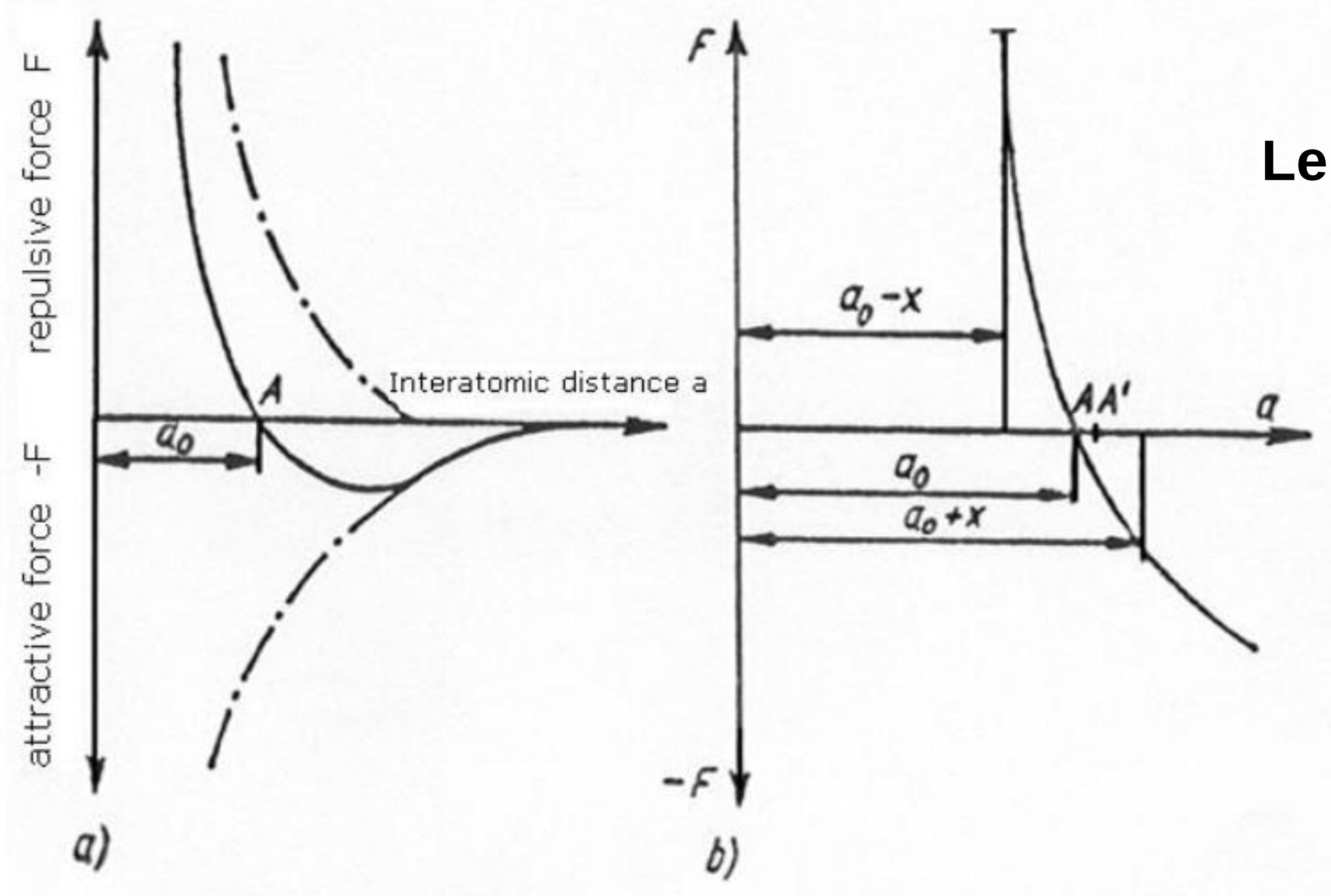
$$\Delta L = \alpha \cdot L \cdot \Delta T$$

α ... Expansion coefficient (1/K)





Why does matter expand?

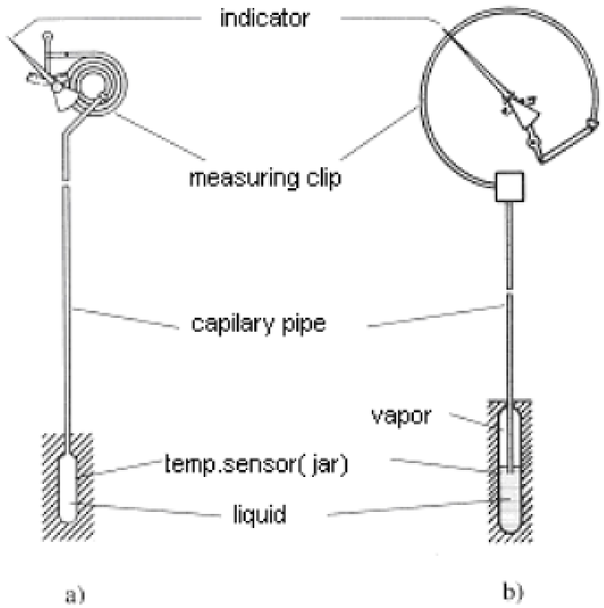


Lennard-Jones potential

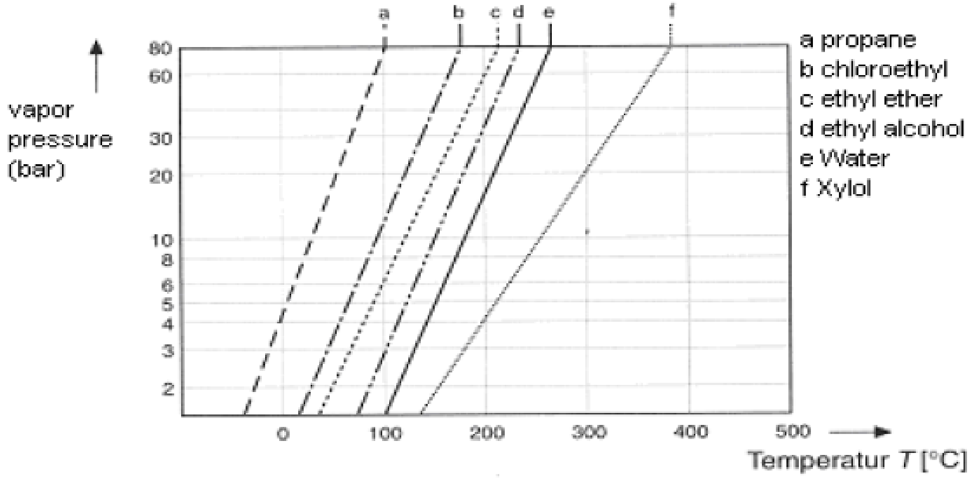
a) impact force between atoms as a function of the distance (schematically)
b) resulting power function near the equilibrium position of the atoms

Expansion thermometer

Expansion of a solid body and a liquid: $\Delta L = \alpha \cdot L \cdot \Delta T$



Volume expansion $\gamma = 1/V_0 \left(\frac{\partial V}{\partial T}\right)$



Expansion thermometer with tubes and mechanical readout:

- Liquid - spring thermometer
- Vapor pressure thermometer

Vapor pressure of liquids

Expansion thermometer

Expansion thermometer
Model 70, stainless steel version

WIKA data sheet TM 81.01

for further approvals
see page 8

Applications

- General-purpose temperature measuring instruments for gaseous, liquid and highly-viscous process media in harsh working environments
- Refrigeration industry
- Machine building

Special features

- Case and stem made of stainless steel
- Design per EN 13190
- Different designs of connection and mounting
- With capillary
- With various fixed connections

WIKA
Part of your business

Fig. left: expansion thermometer model M70.50.100
Fig. right: expansion thermometer model B70.50.063

Description

This series of thermometers is universally suitable for machine building, refrigeration and air-conditioning industry. Expansion thermometers can be installed in or mounted at nearly all locations. Versions with capillaries are used in locations which are not easily accessible and where long distances have to be bridged.

Case, capillary, stem and process connection are made from stainless steel. Various insertion lengths and process connections are available to match the requirements of each measuring location optimally.

Scale ranges, measuring ranges 1)

Scale range in °C	Measuring range in °C	Limit error ±°C	Scale division in °C
-60 ... +40	-50 ... +30	2	1
-40 ... +60	-30 ... +50	2	1
-30 ... +50	-20 ... +40	2	1
-20 ... +60	-10 ... +50	2	1
-20 ... +80	-10 ... +70	2	1
0 ... 60	10 ... 50	2	1
0 ... 80	10 ... 70	2	1
0 ... 100	10 ... 90	2	1
0 ... 120	10 ... 110	4	2
0 ... 160	20 ... 140	4	2
0 ... 200	20 ... 180	4	2
0 ... 250	30 ... 220	5	5
0 ... 300	30 ... 270	10	10
0 ... 400	50 ... 350	10	10

Other scale ranges on request.

1) The measuring range is indicated on the dial by two triangular marks.
The stated limit of error per EN 13190 is only valid within this range.

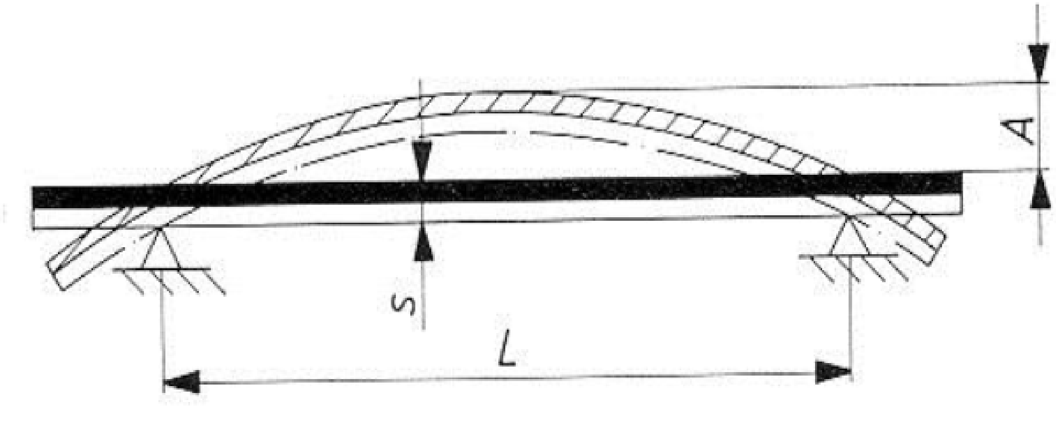
Bimetallic thermometer

Laminated composite materials from at least two components with different coefficients of expansion α.

Example:

- Material 1: $\alpha > 1.5 \times 10^{-5}\,\mathrm{K}^{-1}$ and material 2: $\alpha > 5 \times 10^{-6}\,\mathrm{K}^{-1}$

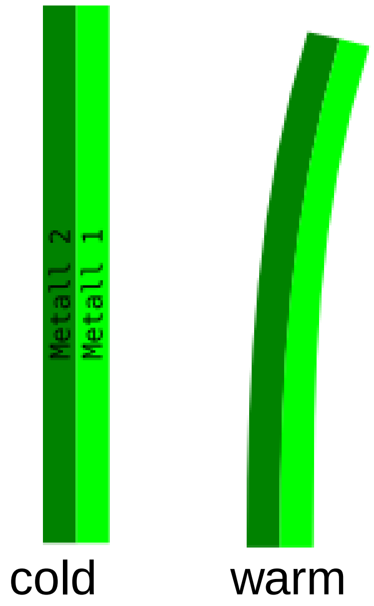
- Specific thermal bending k (material constant) $k = \dfrac{A \cdot s}{(L^2 + A^2 - A \cdot s)\Delta T}$

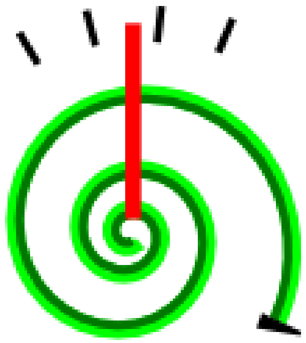


with $A < 0.05L$

$$k = \frac{8A \cdot s}{L^2 \cdot \Delta T}$$

Free bending $A \sim (kL^2\Delta T)/s$





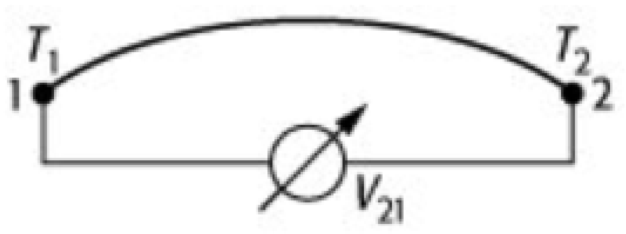
Bimetallic thermometer

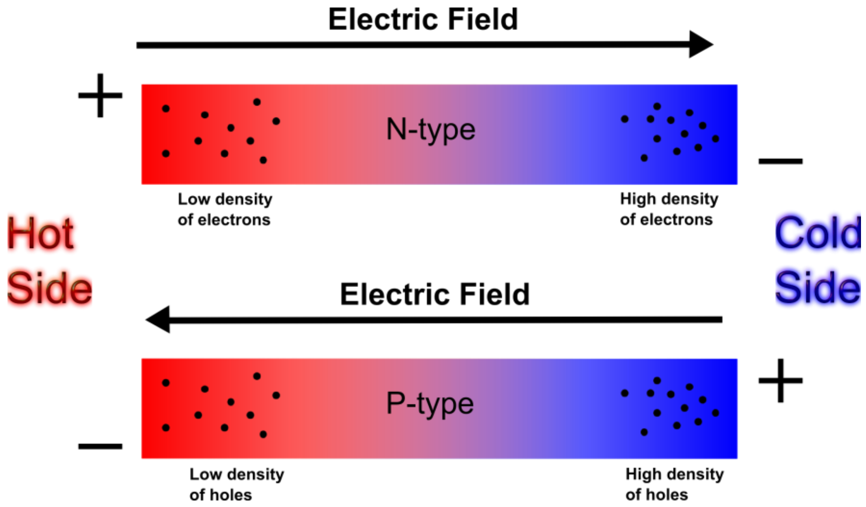
20 metal combinations commercially available

- **Production volume:** ~ 10,000 T per annum
- **Design:** bars, helix, coils, …
- **Applications:** domestic appliances, toaster, …
- **Advantages:** easily available, cheap, configurable, linear, temperature range up to 650 °C
  > 20 mio. cycles
- **Disadvantages:** only one type of deformation

Thermocouples

Principle: Seebeck effect (1821)

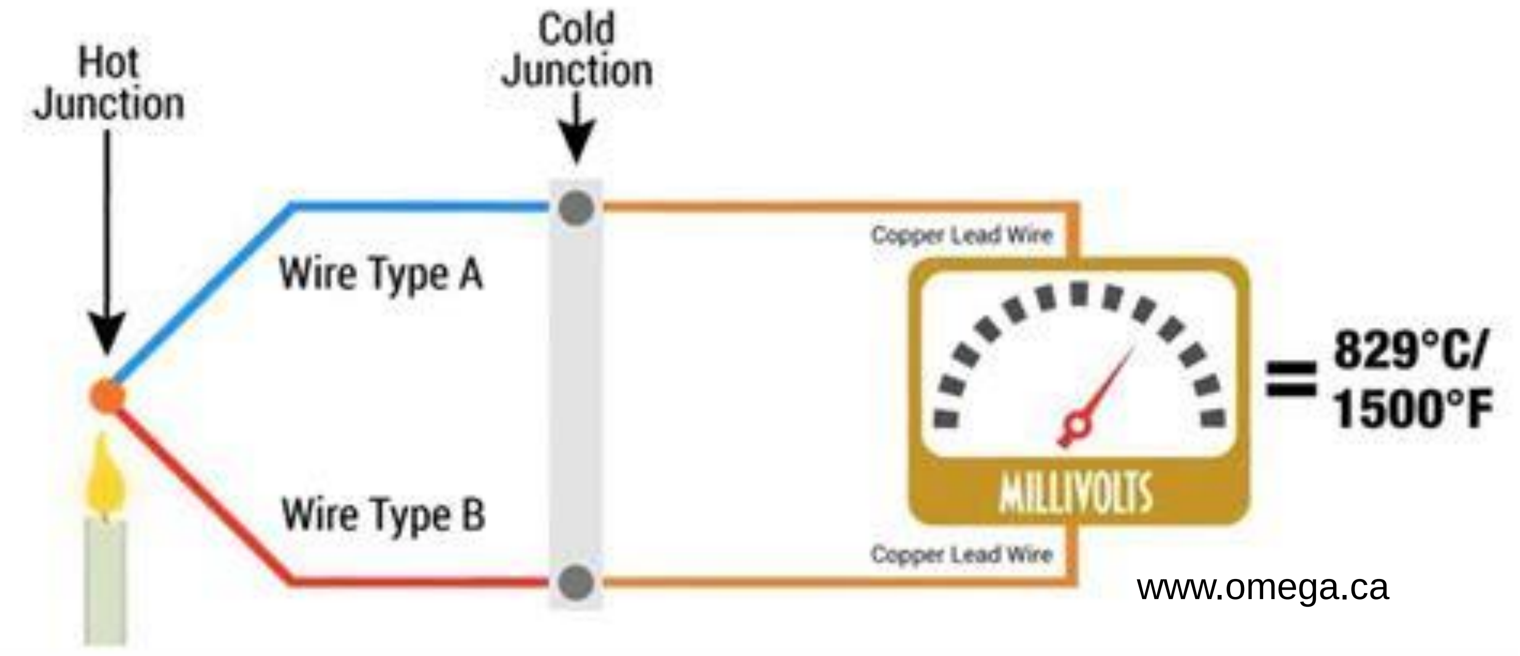




The **Seebeck effect** is the electromotive force (emf) that develops across two points of an electrically conducting material with a temperature difference between them. The ratio between the emf and temperature difference is the Seebeck coefficient *S*.

$$\mathbf{E}_{\mathrm{emf}} = -S\nabla T$$

Thermocouples



$$U_{Th} = (\alpha_A - \alpha_B)\ \Delta T \qquad \Delta T = T_{\text{warm}} - T_{\text{cold}}$$

Thermocouples

Seebeck coefficients of metals

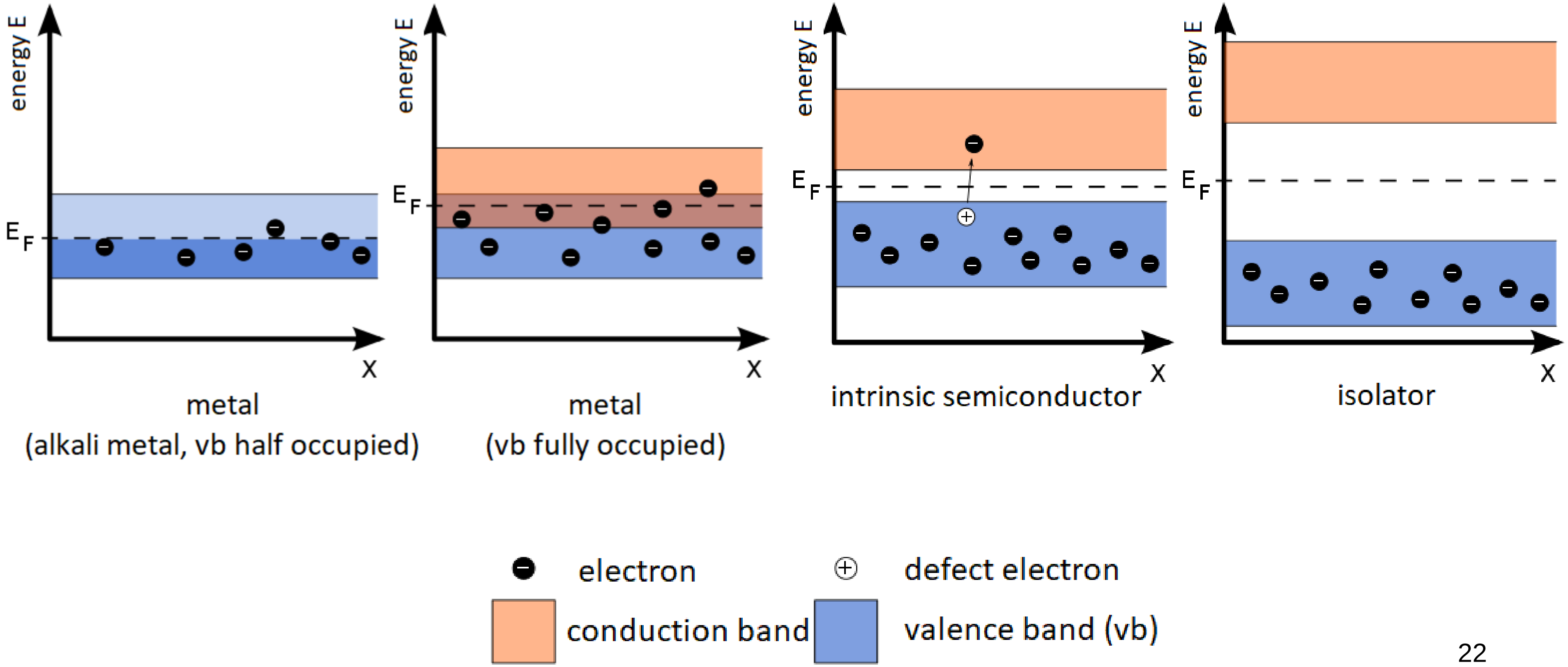
Metal	S at 0 °C (μV K^{-1})	S at 27 °C (μV K^{-1})
Na		−5
K		-12.5
Al	−1.6	−1.8
Mg	−1.3	
Pb	−1.15	−1.3
Pd	−9.00	−9.99
Pt	−4.45	−5.28
Mo	+4.71	+5.57
Li	+14	
Cu	+1.70	+1.84
Ag	+1.38	+1.51
Au	+1.79	+1.94

Metals	Seebeck Coefficient
	µV/K
Antimony	47
Nichrome	25
Molybdenum	10
Cadmium	7.5
Tungsten	7.5
Gold	6.5
Silver	6.5
Copper	6.5
Rhodium	6.0
Tantalum	4.5
Lead	4.0
Aluminum	3.5
Carbon	3.0
Mercury	0.6
Platinum	0
Sodium	-2.0
Potassium	-9.0
Nickel	-15
Constantan	-35
Bismuth	-72

Normalized to Pt!

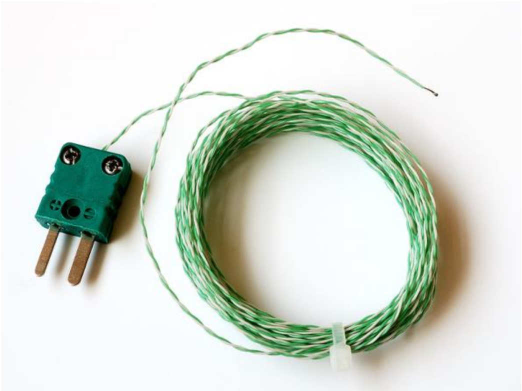
Thermocouples

But why are there n- and p-metals?
In metals, the electrons conduct, don‘t they?
-> Band model of solids (metals, semiconductors)



Thermocouples

In the application:



Thermocouple Type K

Thermocouple Type J

In the case of thermal cables, the conductor material consists of thermocouple alloys (e.g. Cu-CuNi, Fe-CuNi), the compensating cables of substitute materials (e.g. Cu).

The thermal voltages of the thermocouples are specified in basic value series

• PtRh30%-PtRh6%	Type B
• Fe-CuNi	Type J
• NiCr-NiAl	Type K
• PtRh87/13%-Pt	Type R
• PtRh90/10%-Pt	Type S

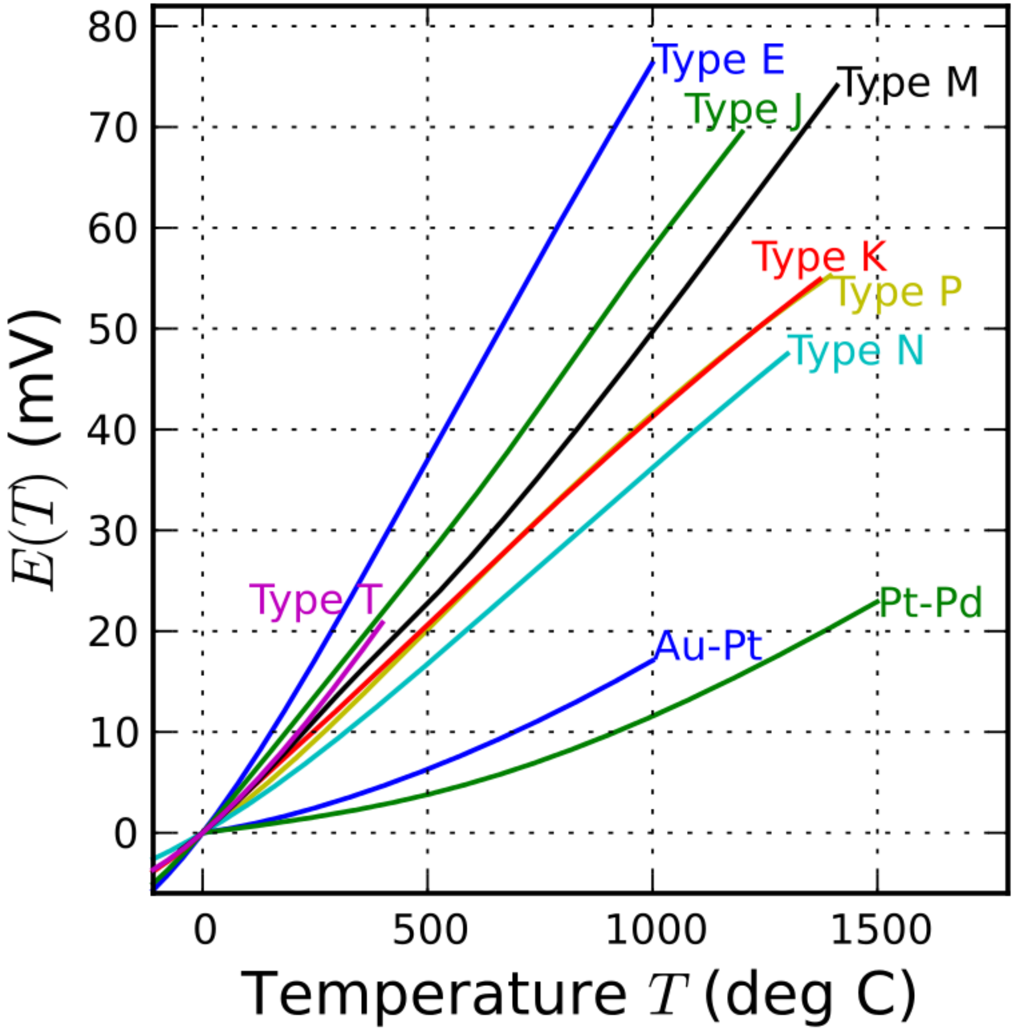
The various types differ primarily in the temperature range to be measured

Thermocouples

Type	Temperature range [° C]
K	-200…..+1300
N	-200…..+1300
J	-250…..+800
T	-250…..+400
E	-273…..+800
R	0…..+1600
S	0…..+1600

Thermo pairs, types, materials, colour codes			
Element	Norm	Materials	Colour code
Type T	EN 60584	Cu-CuNi	+ −
Type E	EN 60584	NiCr-CuNi	+ −
Type J	EN 60584	Fe-CuNi	+ −
Type K	EN 60584	NiCr-Ni	+ −
Type S	EN 60584	Pt10%Rh-Pt	+ −
Type R	EN 60584	Pt13%Rh-Pt	+ −
Type B	EN 60584	Pt30%Rh-Pt	+ −
Type L	EN 43710	Fe-CuNi	+ −
Type U	EN 43710	Cu-CuNi	+ −

Thermocouples



Characteristic functions for thermocouples that reach intermediate temperatures, as covered by nickel-alloy thermocouple types E, J, K, M, N, T. Also shown are the noble-metal alloy type P and the pure noble-metal combinations gold–platinum and platinum–palladium.

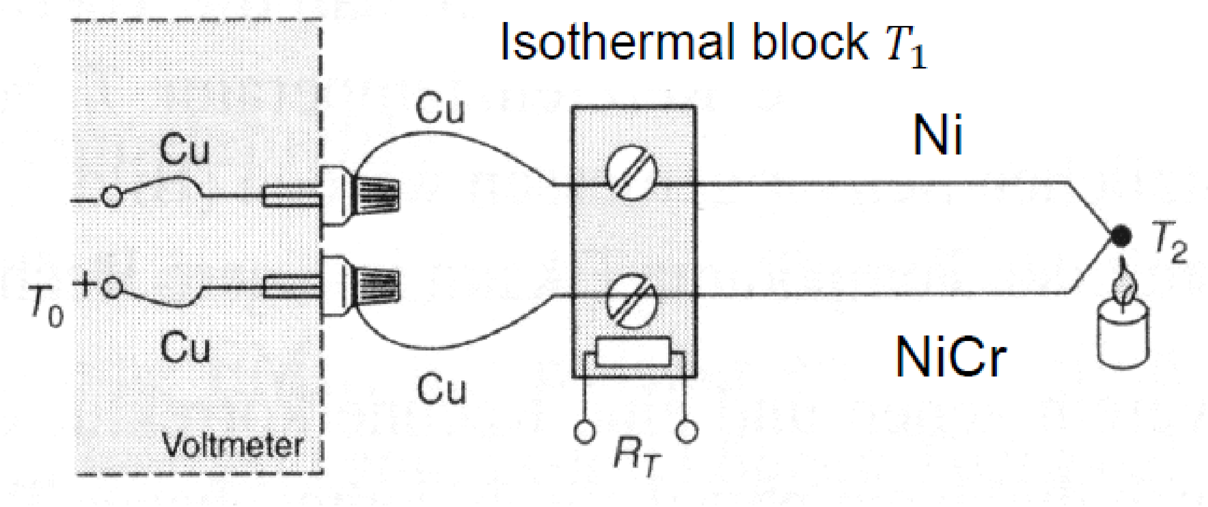
Source: wikipedia

Thermocouples

Thermocouple measurements need a reference temperature.

SETUP

- Establishing a reference temperature with an isothermal block

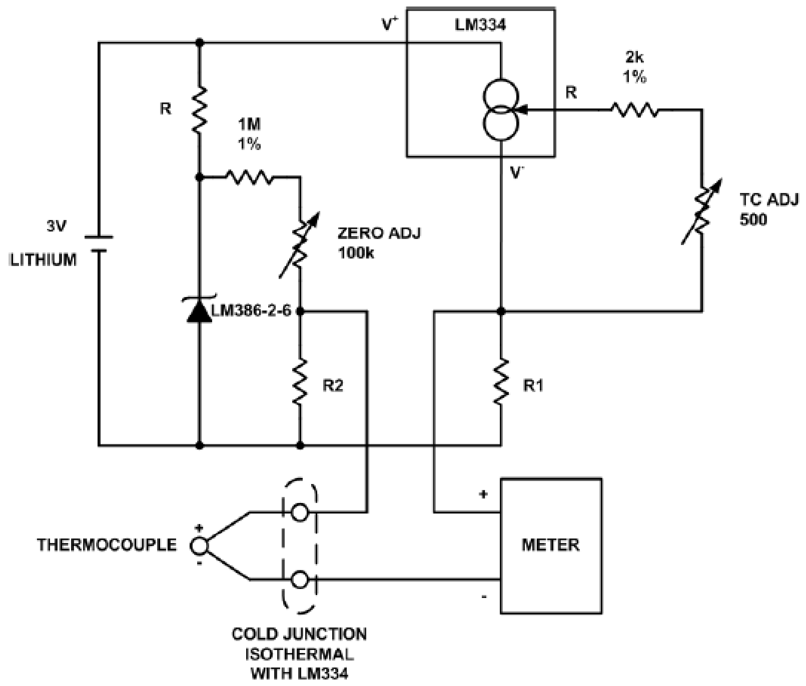


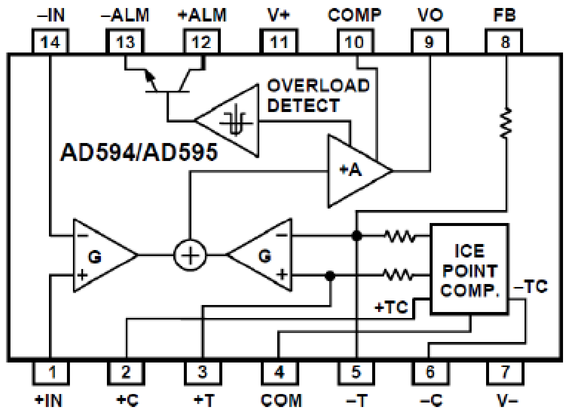
Reference temperature of isothermal block T_1 is measured with resistance thermometer R_T.

In former times:
ICE BATH!

Thermocouples

Electronic reference temperature compensation



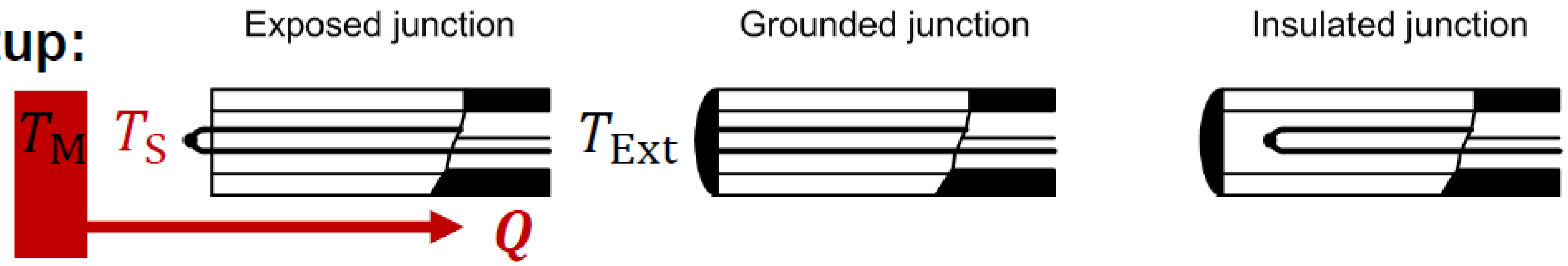


Scheme of the monolithic integrated circuitry of AD 594/AD 595 for reference compensation, amplification and linearization of Fe-Cu-Ni or NiCr-NiAl- thermocouples

Thermocouple types

In reality fine wires cannot be used because of mechanical instabilities ➔ Sheath thermocouples or thermocoax!

Setup:



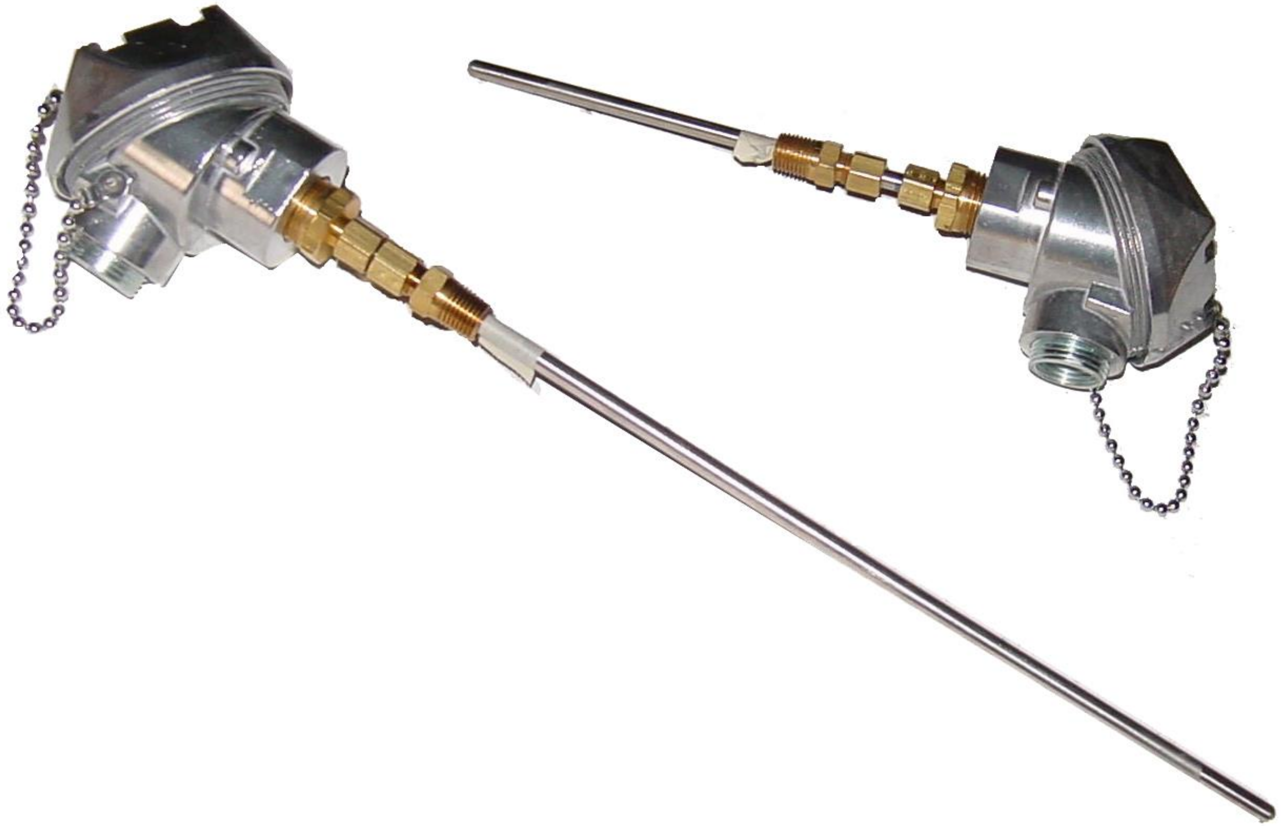
Measurement error due to: $\boldsymbol{Q \cdot R_{Th} = \Delta T}$

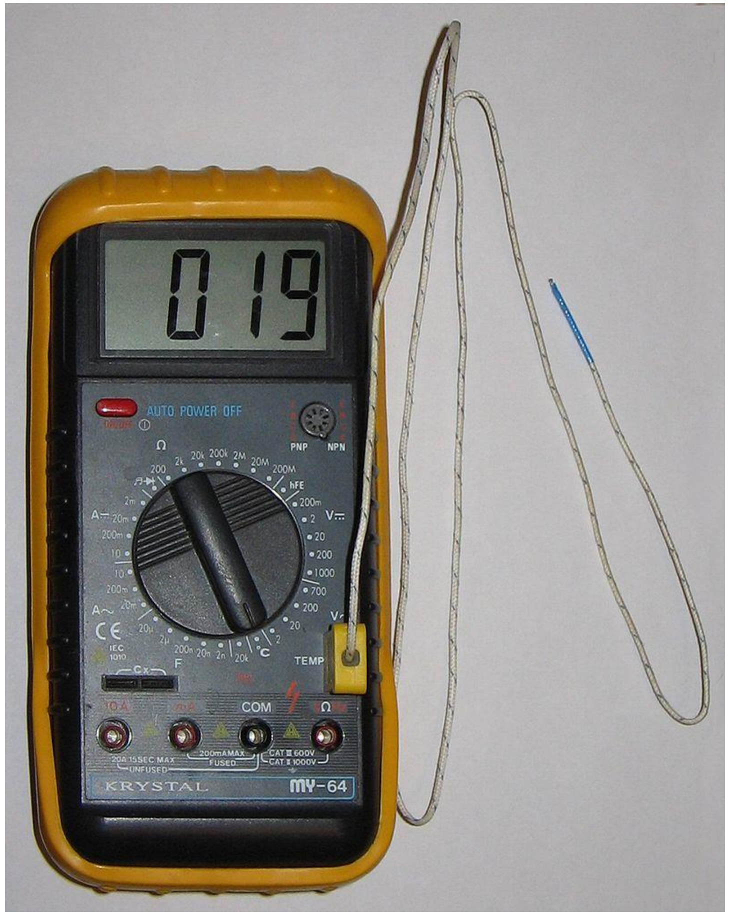
Time resolution ➔ time constant: $\boldsymbol{\tau_{Th} = R_{Th} \cdot C_{Th}}$

Aging

- Aging at 1000 °C $\approx \mathbf{3} \times \mathbf{10^{-3}}$ per annum with NiCr/Ni thermocoax

Thermocouples





Thermocouple characteristics

Advantages:

- Reliable - if purity of material is high (class 1)
- Good long term stability and reproducibility - if encapsulated (Thermocoax)
- High temperature application

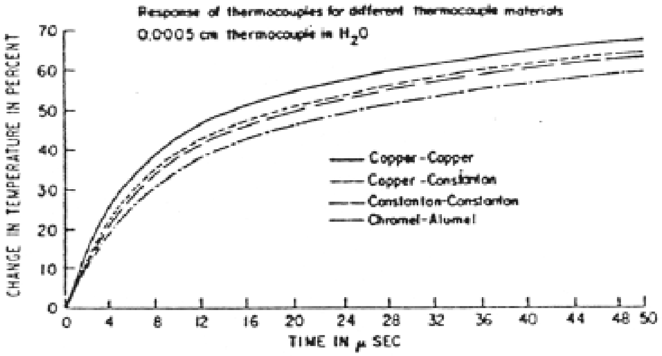
Disadvantages:

- Low signal level
- Noise from contacts
- Reference temperature necessary
- In reality purity and encapsulation weak
- **In principle: Low accuracy and precision (1.5 K max.)**

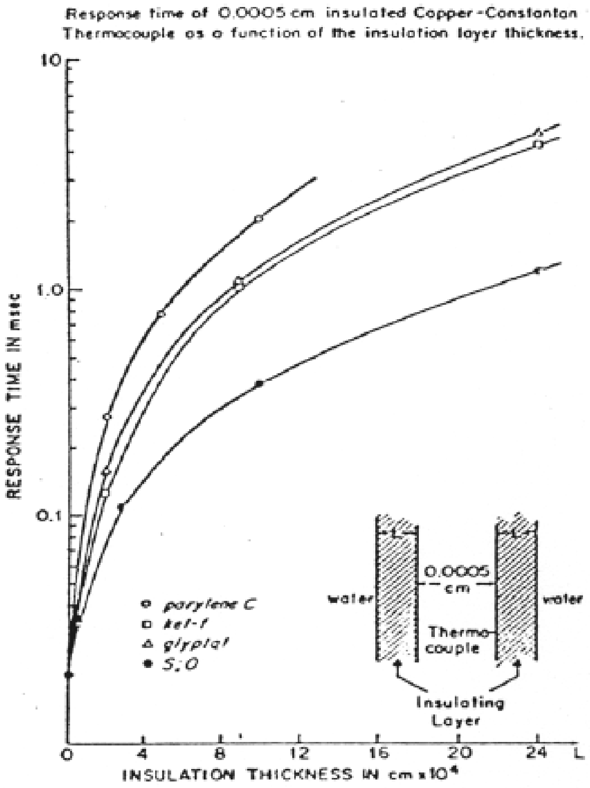
Micro thermocouples

Time constant (heat capacity, heat transfer) depends on diameter of wire! Thermocouple wires can be produced down to diameters of 5 µm.

Computer simulations of time constants of different fine-wire thermocouples

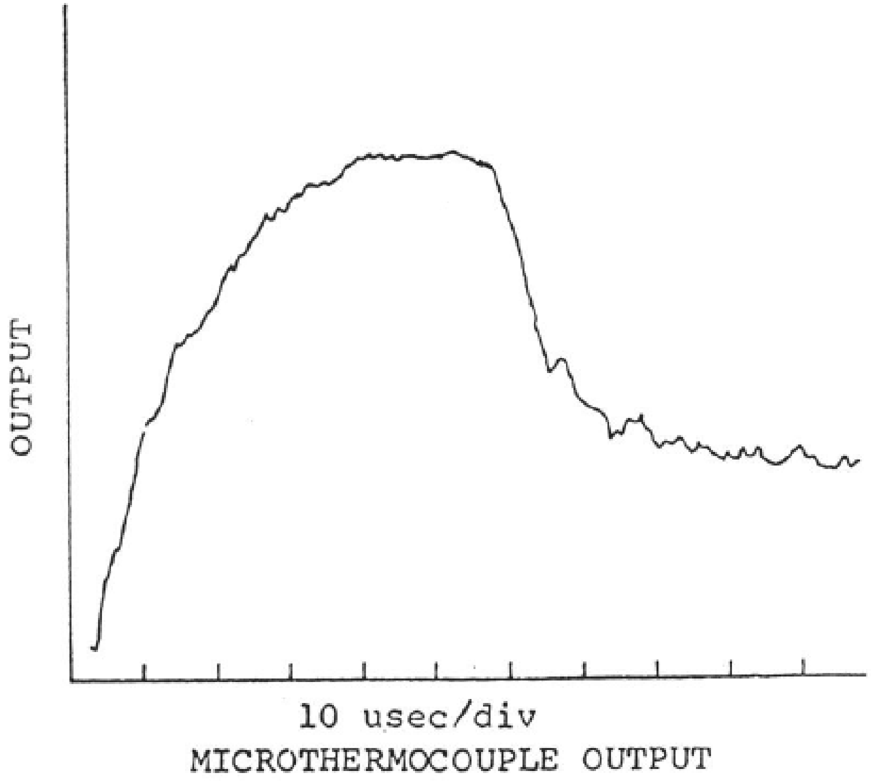


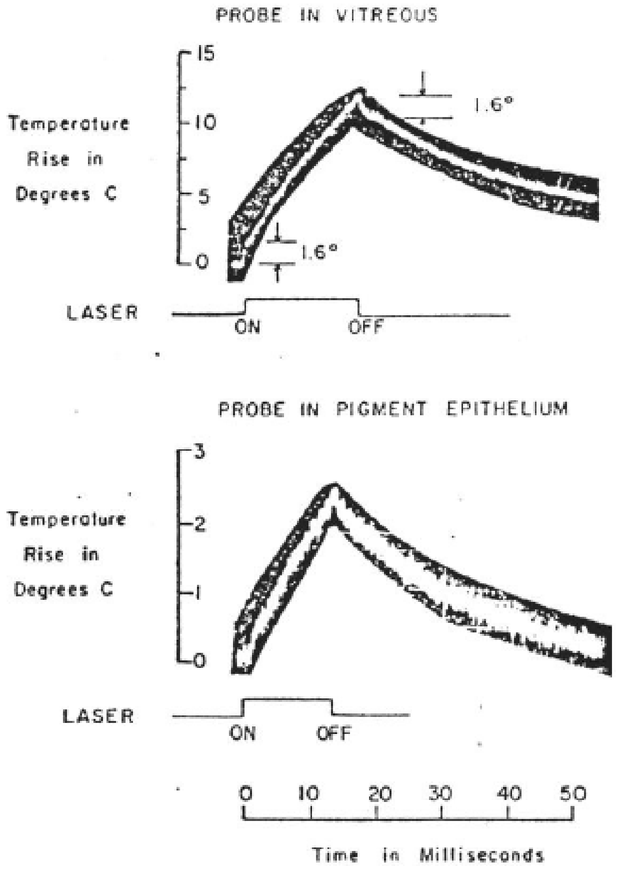
. Computed temperature changes at the center of 0.0005 cm thick slabs of different materials after subjection to a step function temperature change in the surrounding water. The copper/constantan and Chromel/Alumel slabs represent actual thermocouple junction and the copper/copper with constantan/constantan slabs are also included for comparison.



Computer study of the effect of insulating layers of different thickness on the response of the thermocouple.

Application of thermocouples in biology



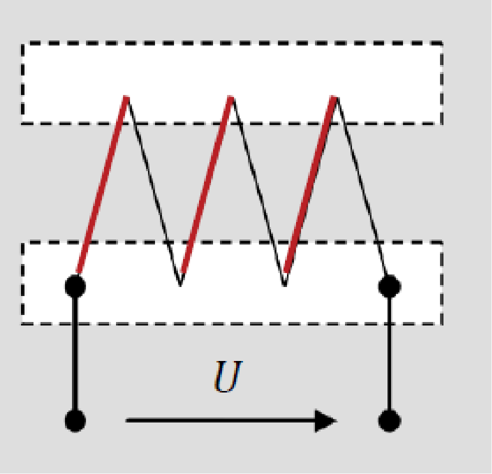


Temperature rise in a rabbit's eye during light radiation with Argon-laser.

Thermopiles

Sensitivity of thermocouples is low ➔ **Thermopiles**

Basic circuit



Warm contact T_W

Cold contact T_C

$$U = N \cdot \alpha_s \cdot \Delta T$$

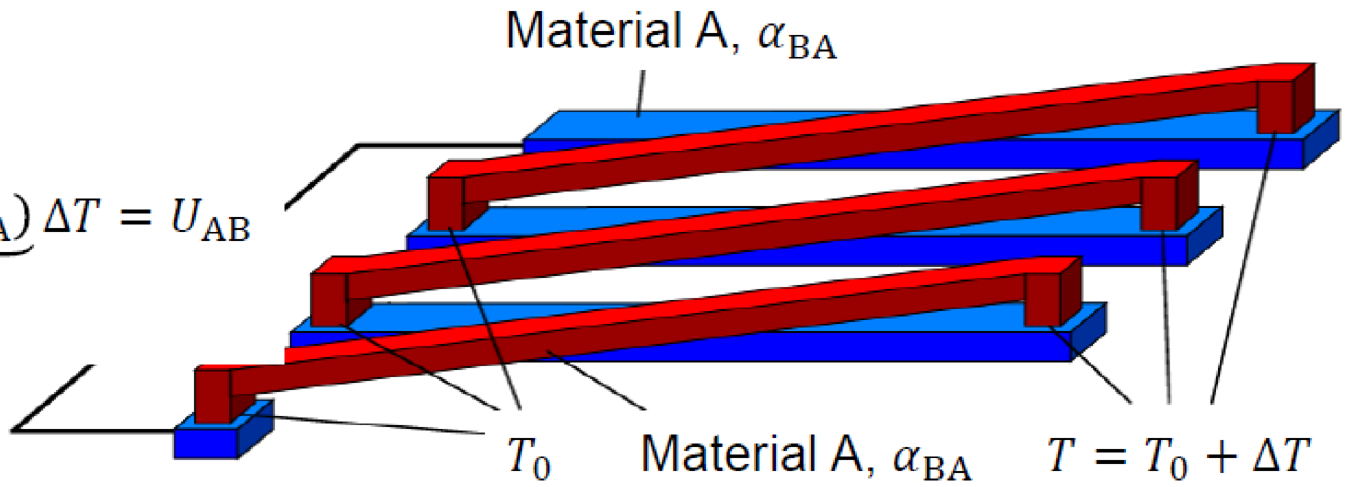
N…Number of thermocouples

α_s…Seebeck coefficient

$$\Delta T = T_W - T_C$$

Thermopiles

$$\underbrace{N\,(\alpha_B - \alpha_A)}_{\alpha_{BA}}\,\Delta T = U_{AB}$$



poly-Si / Aluminum, 300 K

$\boldsymbol{n^+}$ $\quad \alpha_{BA} = -90 \text{ up to } -120\ \mu V/K$

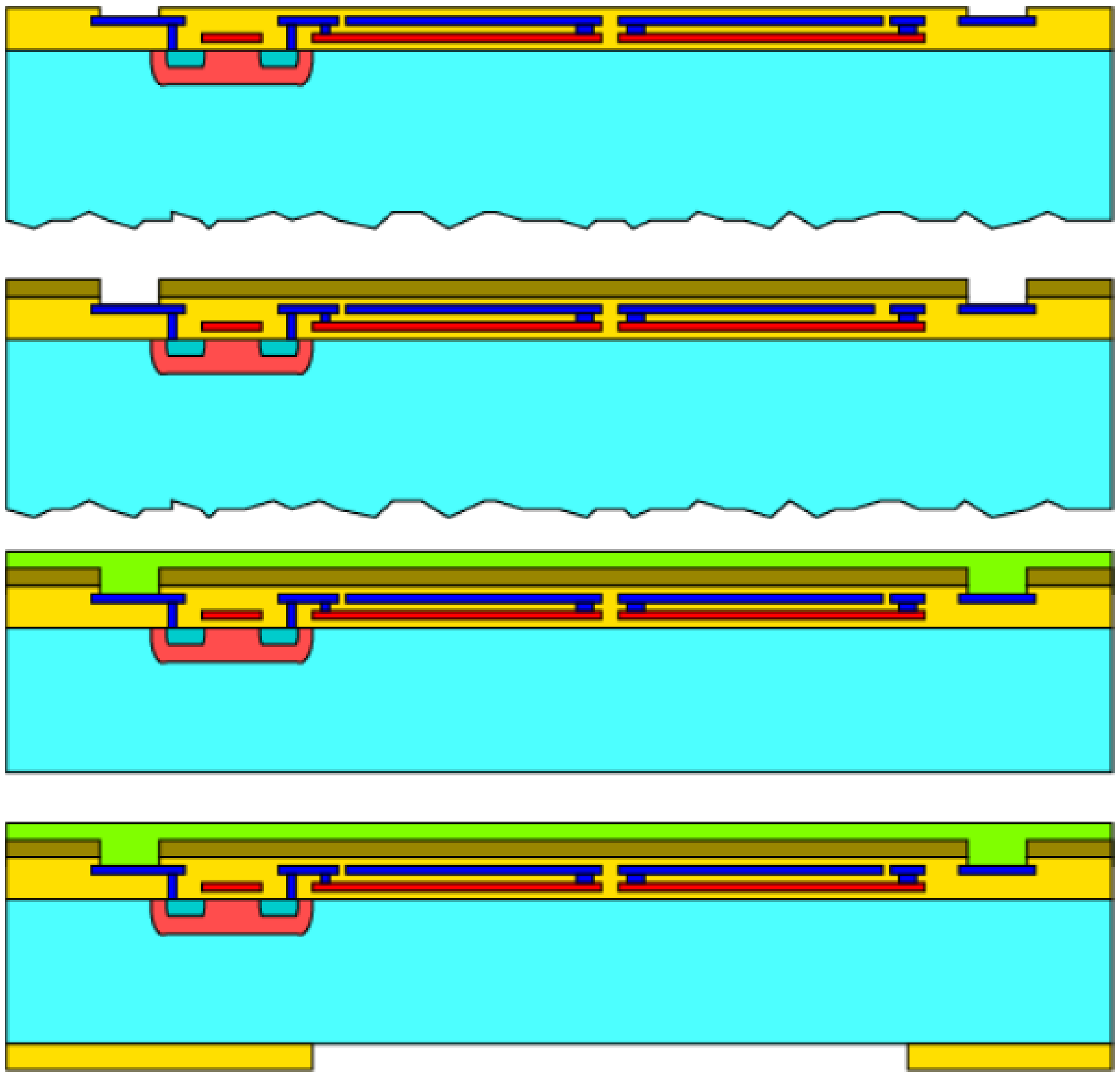
$\boldsymbol{n}$ $\quad \alpha_{BA} \sim -200\ \mu V/K$

$\boldsymbol{p}$ $\quad \alpha_{BA} \sim +400\ \mu V/K$

mono–Si/Al: α_{BA} up to $1200\ \mu V/K$

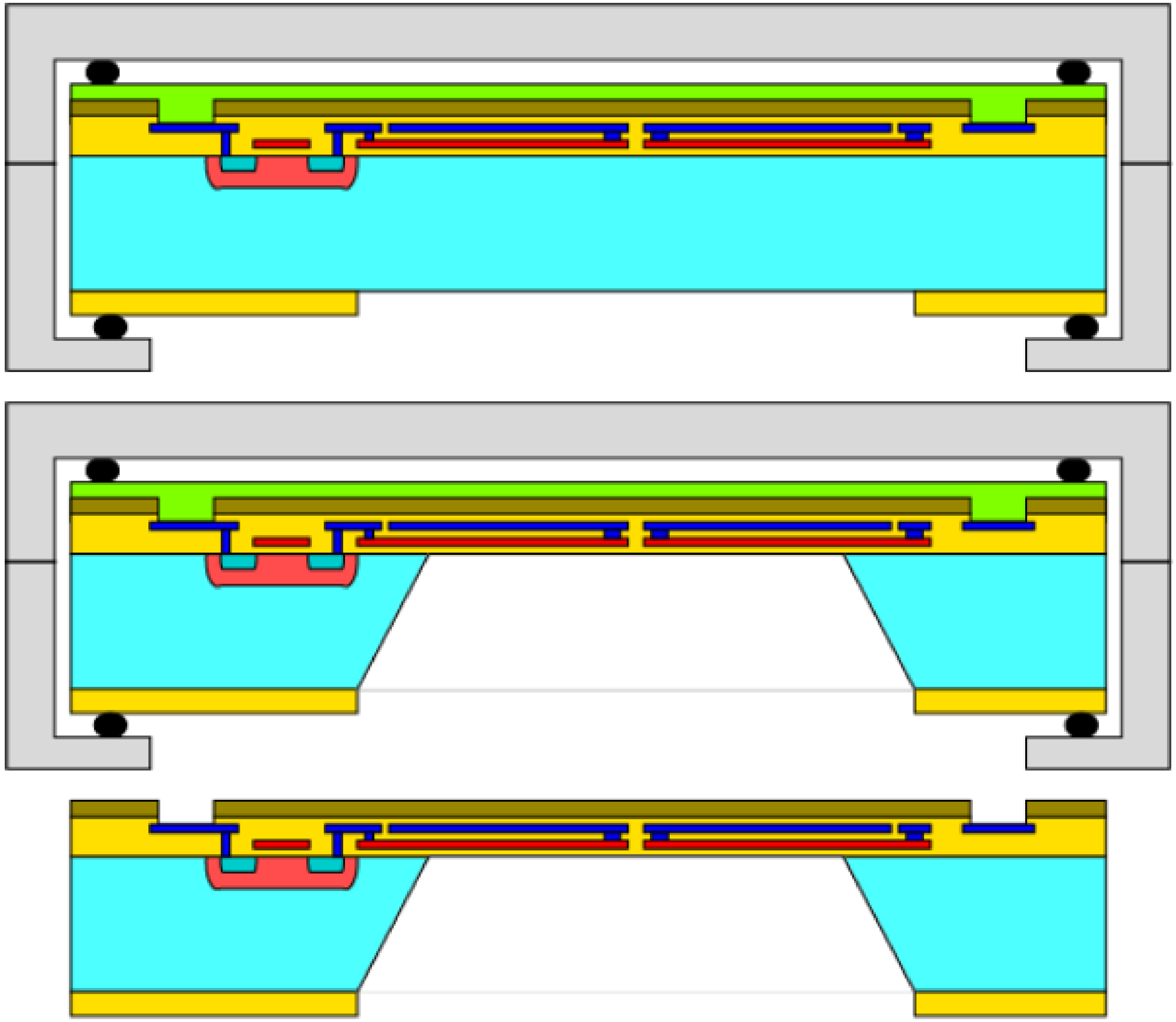
Thermopiles – silicon microstructuring

- CMOS process
- Sensor passivation and protective layer
- Chemical back polish
- Back mask and structuring

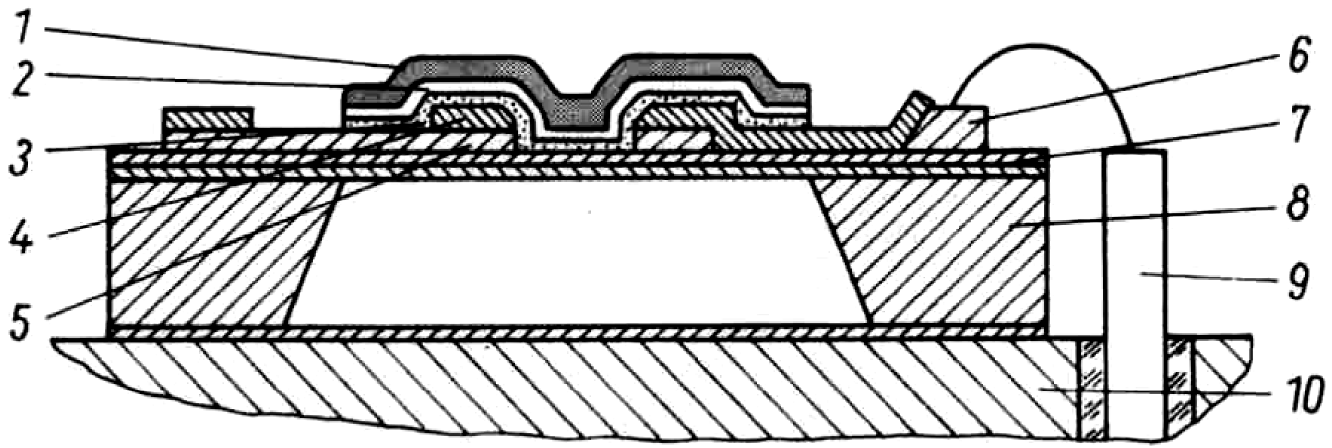


Thermopiles – silicon microstructuring

- Etching protection box: anisotropic etching in **6 M KOH @ 95 °C**
- Protective layer removal
- Result: diaphragms



Thermopile based on Bi/Sb



1 absorption layer

2 thermal compensation layer

3 insulator layer

4 Sb layer

5 Bi layer

6 bondpads

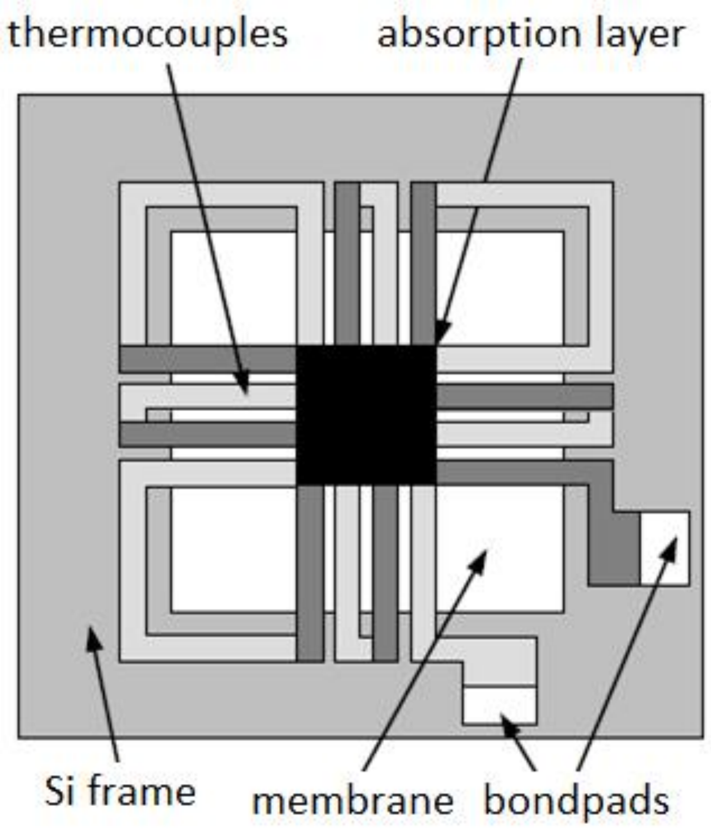
7 SiO_2/Si_3N_4 membrane

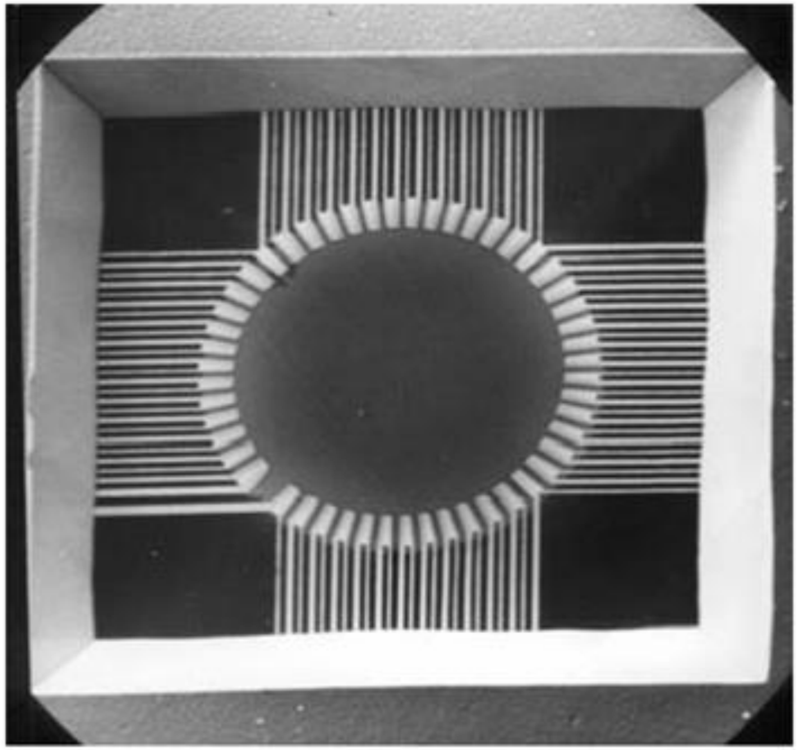
8 Si wafer

9 wiring

10 TO socket

Thermopile detectors





Thermopile detectors

Important parameters

Gas filling:

Gas filling	Sensitivity	Modulation velocity
Ar	100%	100%
Xe	200%	75%
Ne	35%	> 100%

highest sensitivity in vacuum!

Ambient temperatures: Bi/Sb: max. 85°C (in some cases up to 125 °C)

Poly-Si/metal: higher temperatures

Packaging: standard TO5

Field of view: 80°

Linearity range: 5 decades (10^{-6} – 10^{-1} W/cm²)

Frequency range: sensitive to almost all frequencies from UV to FIR

(dependent on absorbing layer)

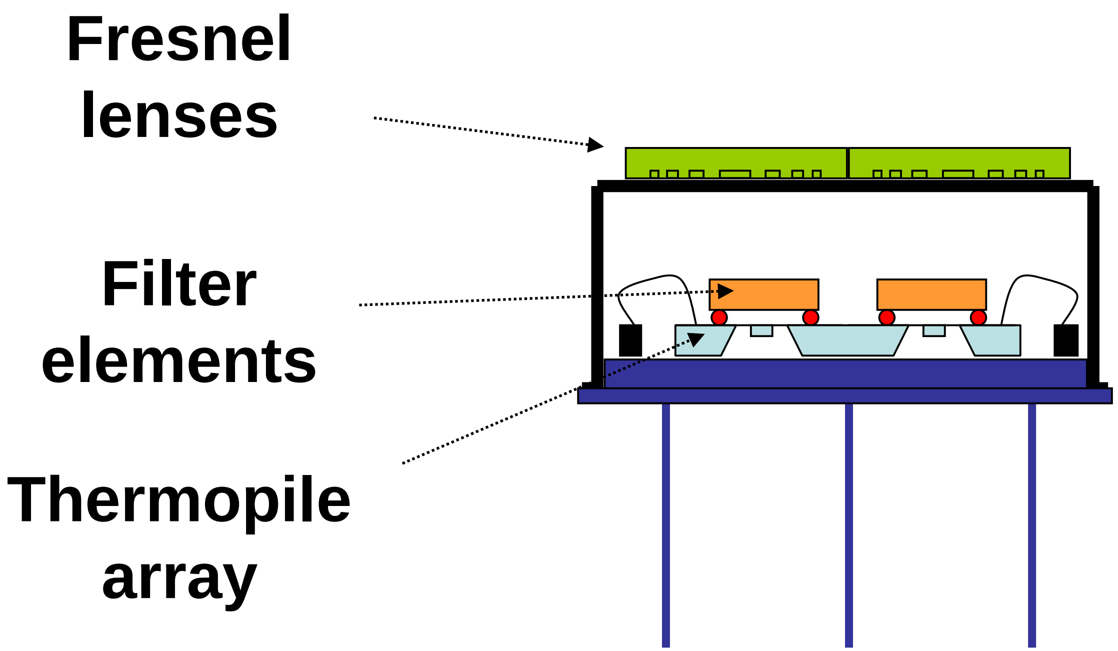
Window: KBr, sapphire, BaF_2, CaF_2, Irtran-2, KRS-5, UV quarz, Ge

source: Dexter

Thermopiles - applications

Thermopile detectors for gas measurements

Detector module for multi-spectral measurement



TO5-TO8 packaging

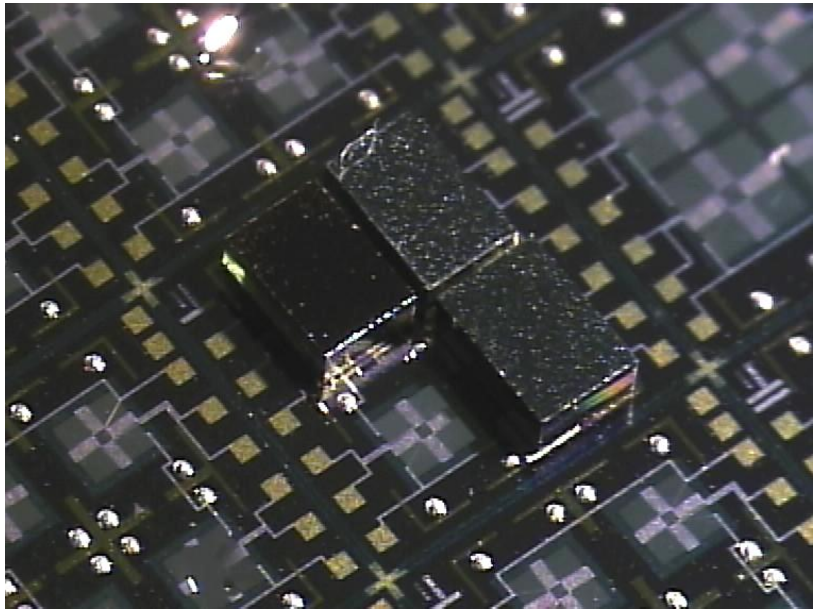
Broadband filter selection

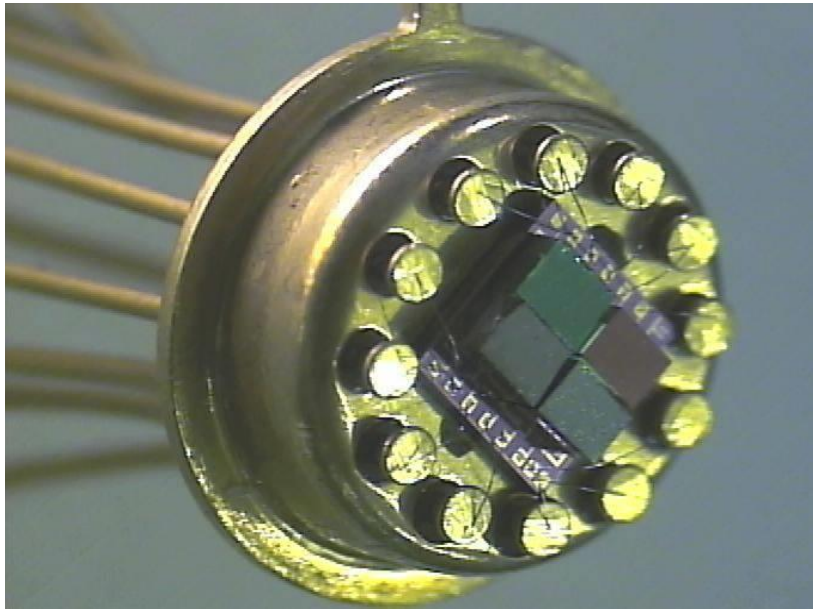
Filter	Central wavelength / µm	Transmission range/ µm
Reference	**3.95**	4.0 – 3.9
Ethene	**10.6**	11.0 – 10.2
Ammonia	**9.7**	10.1 – 9.3
Ethanol	**3.46**	3.6 – 3.3

Thermopile detectors for gas measurements

2x2 thermopile array

Flip-chip & Dicing & Bonding & Mounting

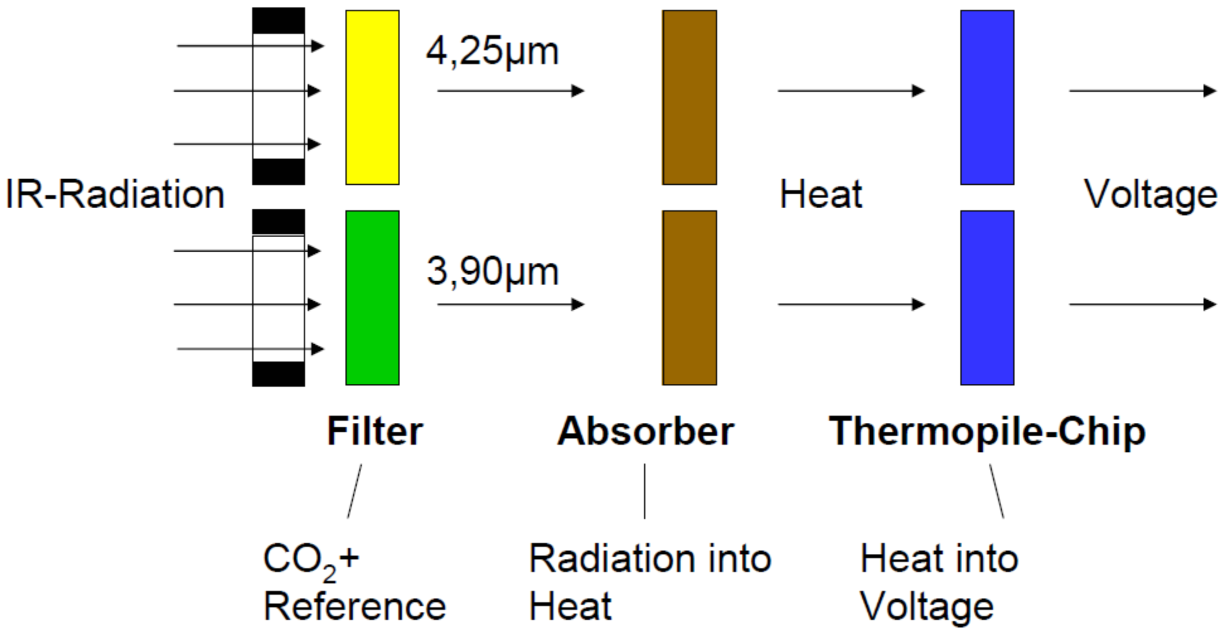




Thermopile detectors for gas measurements

Infrared Carbon Dioxide Sensor for Automotive Applications

Bosch Infrared Gasdetector

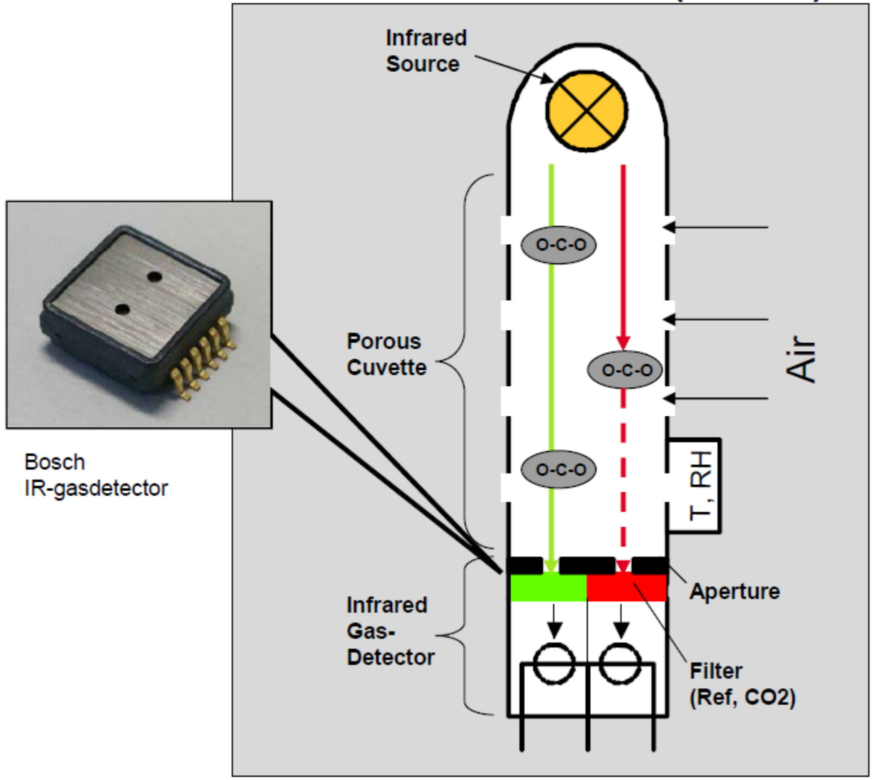


BOSCH

Thermopile detectors for gas measurements

Infrared Carbon Dioxide Sensor for Automotive Applications

Climate Control Sensor (CCS)



Range: 0..3 vol.%
Resolution: <0.02 vol.%
Interface: digital or analog

Resistance thermometers

For resistive temperature sensors, the field part of current density equation applies:

➔ **Isotropic, macroscopic homogenous materials**

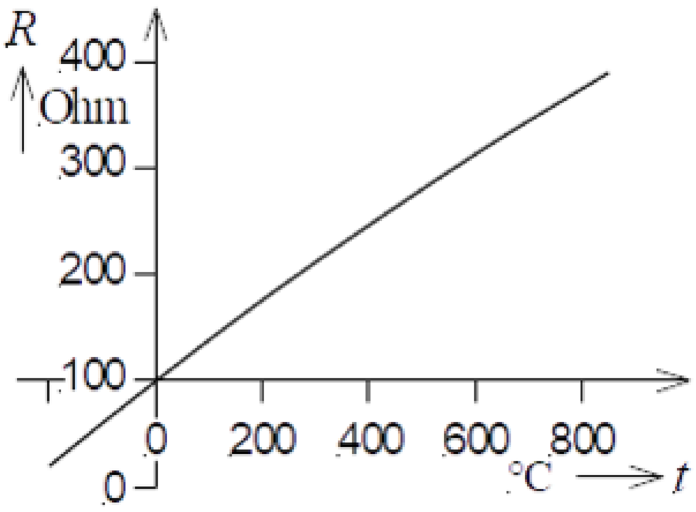
$$R = \frac{1}{e n_{\mathrm{n}} \mu_{\mathrm{n}}} \frac{L}{A} = \rho_{\mathrm{sp}} \frac{L}{A} = \frac{1}{\sigma_{\mathrm{sp}}} \frac{L}{A}$$

Temperature coefficient of resistance α (TCR)

$$\alpha = \frac{1}{R} \frac{\partial R}{\partial T}$$

Resistance thermometers

- Used metals: **Pt, Ni, TaNi, Ir**
  - For high temperature applications: **Mo, W**
- Platinum thermometers are very accurate and precise (calibration standard) – noble metal, linear sensitivity:
  - 1 mK, linearity: 0.2%,
  - Used since 1870!



Characteristic curve of the Pt100 resistance thermometer

Resistance vs. temperature

$$R_T = R_0\left(1 + \alpha(T_1 - T_0)\right)$$

- R_T…Resistance at temperature T_1,
- R_0…Resistance at 0 °C usual 100 Ohm (**PT100**), 1000 Ohm **(PT1000)**
- α… Temperature coefficient

Resistance thermometers

Platinum: $\alpha = 0.00385\,\mathrm{K}^{-1}$, **Nickel**: $\alpha = 0.00618\,\mathrm{K}^{-1}$

Non-linearity $R_\mathrm{T} = R_0(1 + AT + \mathrm{B}T^2 + ..)$ **A, B...Constants**

For Pt: $R_\mathrm{T} = R_0(1 + AT - \mathrm{B}T^2 + CT^3)$ **(negative B!)**

Pt-resistance thermometers are available in two quality standards class A and class B, there are also 1/10 DIN standards available with 10-times better specifications, for Ni-thermometers exists only one standard.

Resistance thermometers – DIN 43760

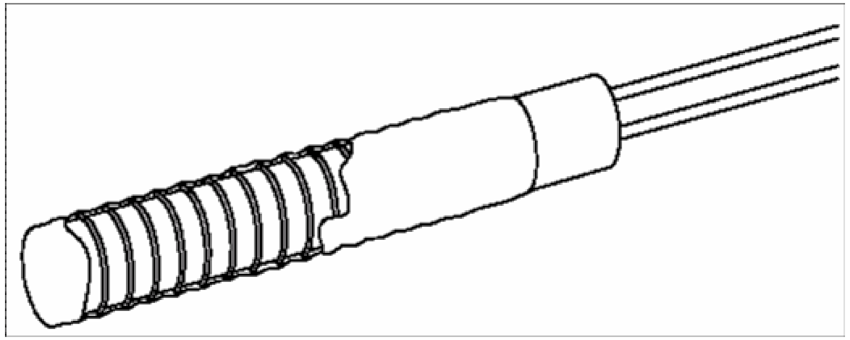
T in °C	Nickel			Platinum				
	Basic value	Deviation		Basic value	Deviation Class A		Deviation Class B	
	Ω	Ω	°C	Ω	Ω	°C	Ω	°C
-200	-	-	-	18.49	± 0.24	± 0.55	± 0.56	± 1.3
-100	-	-	-	60.25	± 0.14	± 0.35	± 0.32	± 0.8
-60	69.5	± 1.0	± 2.1	-	-	-	-	-
0	100.0	± 0.2	± 0.4	100.0	± 0.06	± 0.15	± 0.12	± 0.3
100	161.8	± 0.8	± 1.1		± 0.13	± 0.35	± 0.30	± 0.8
200	223.2	± 1.3	± 1.7	-	-	-	-	-
300	-	-	-		± 0.20	± 0.55	± 0.48	± 1.3
400	-	-	-		± 0.27	± 0.75	± 0.64	± 1.8
500	-	-	-		± 0.33	± 0.95	± 0.79	± 2.3
600	-	-	-		± 0.38	± 1.15	± 0.93	± 2.8
650	-	-	-		± 0.43	± 1.35	± 1.06	± 3.3
700	-	-	-		± 0.46	± 1.45	± 1.13	± 3.6
750	-	-	-		-	-	± 1.17	± 3.8
800	-	-	-		-	-	± 1.28	± 4.3
850	-	-	-		-	-	± 1.34	± 4.6

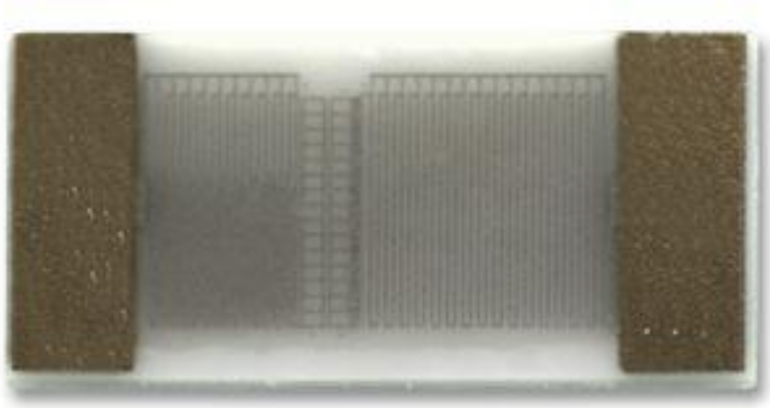
Resistance thermometers

PT 100 temperature sensors are available in countless versions

PT 100 made of a platinum wire on a glass body

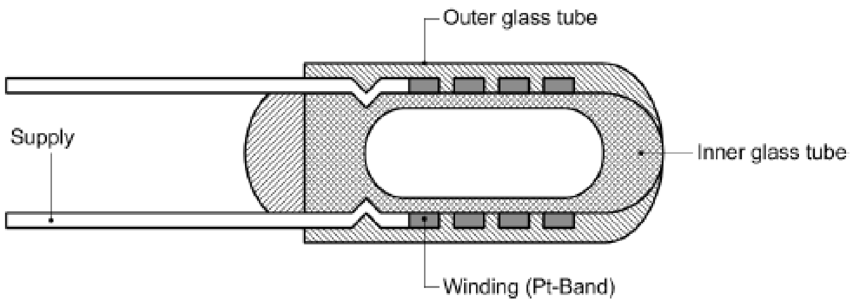
PT 10000 realized on a ceramic substrate with a vapor-deposited platinum film.





Resistance thermometers

a)



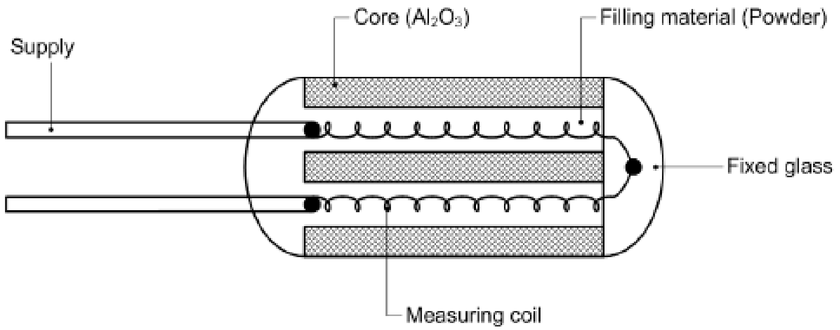
Advantages:

- Mechanically stable

Disadvantages:

- Hysteresis
- Parasitic conductance due to high temperatures

b)



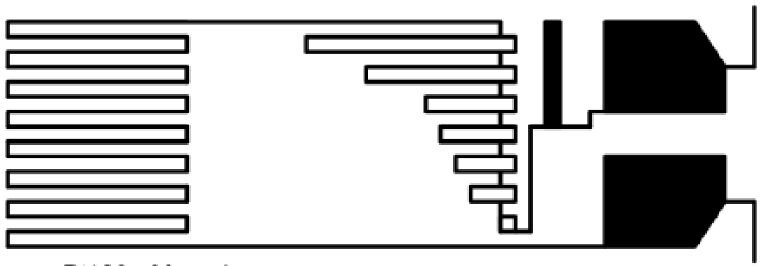
Advantages:

- No hysteresis

Disadvantages:

- Lower vibrational stability
- Risk of fracture

c)



Pt100 - Meander

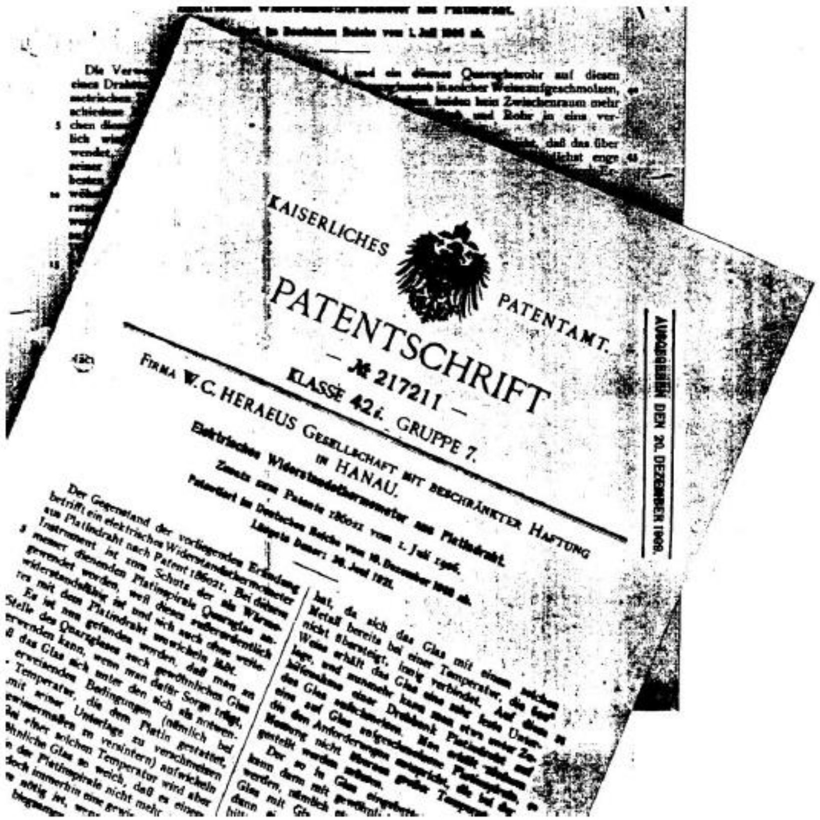
Advantages:

- Low cost

Disadvantages:

- Hysteresis due to thermal expansion
- Temperature increase can damage the substrate.

Resistance thermometers


KAISERLICHES PATENTAMT.

PATENTSCHRIFT

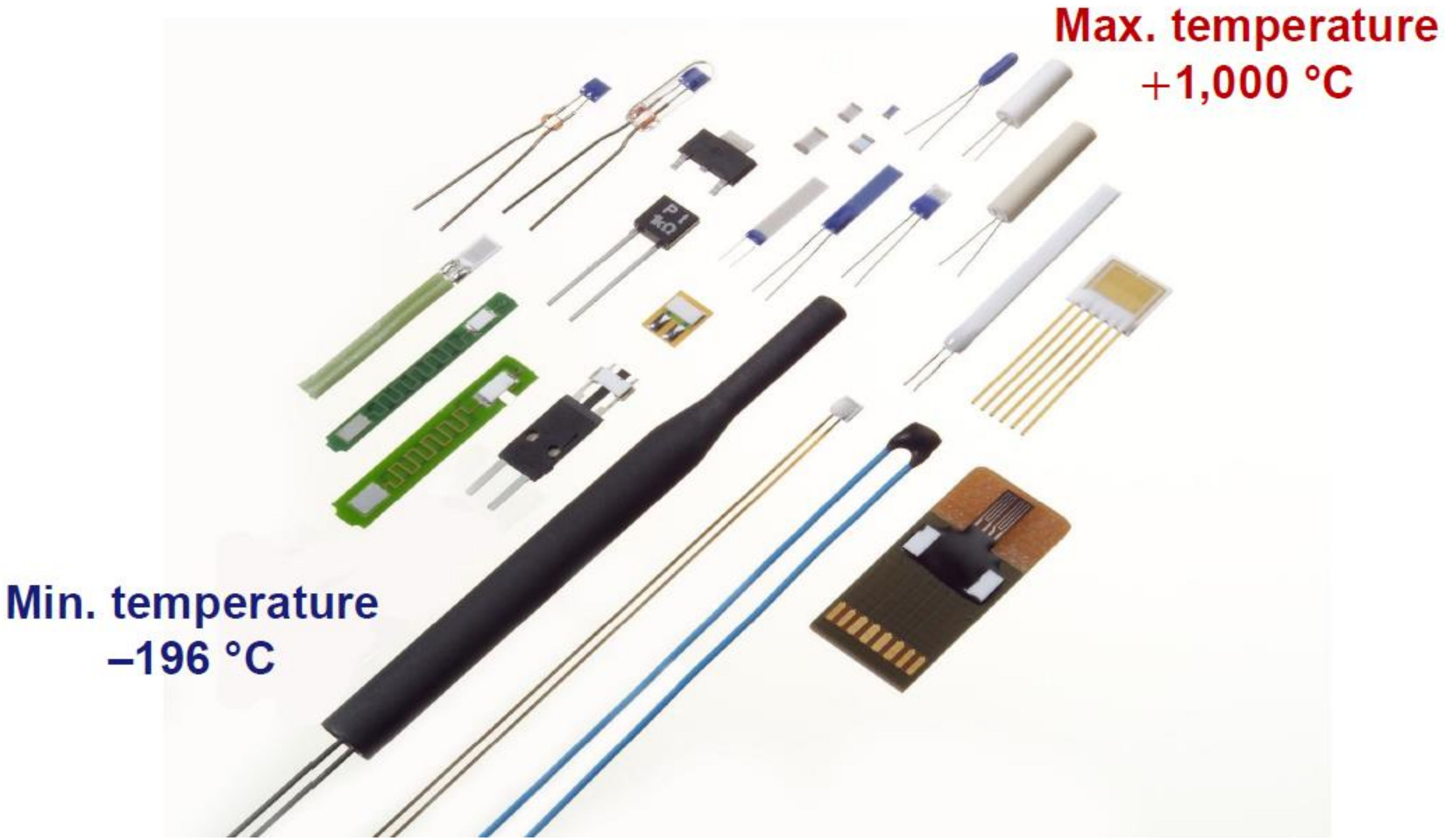
— № 217211 —

KLASSE 42i. GRUPPE 7.

FIRMA W. C. HERAEUS GESELLSCHAFT MIT BESCHRÄNKTER HAFTUNG IN HANAU.

Patent of the 1st platinum resistance thermometer by Richard Küch (1906)

Resistance thermometers

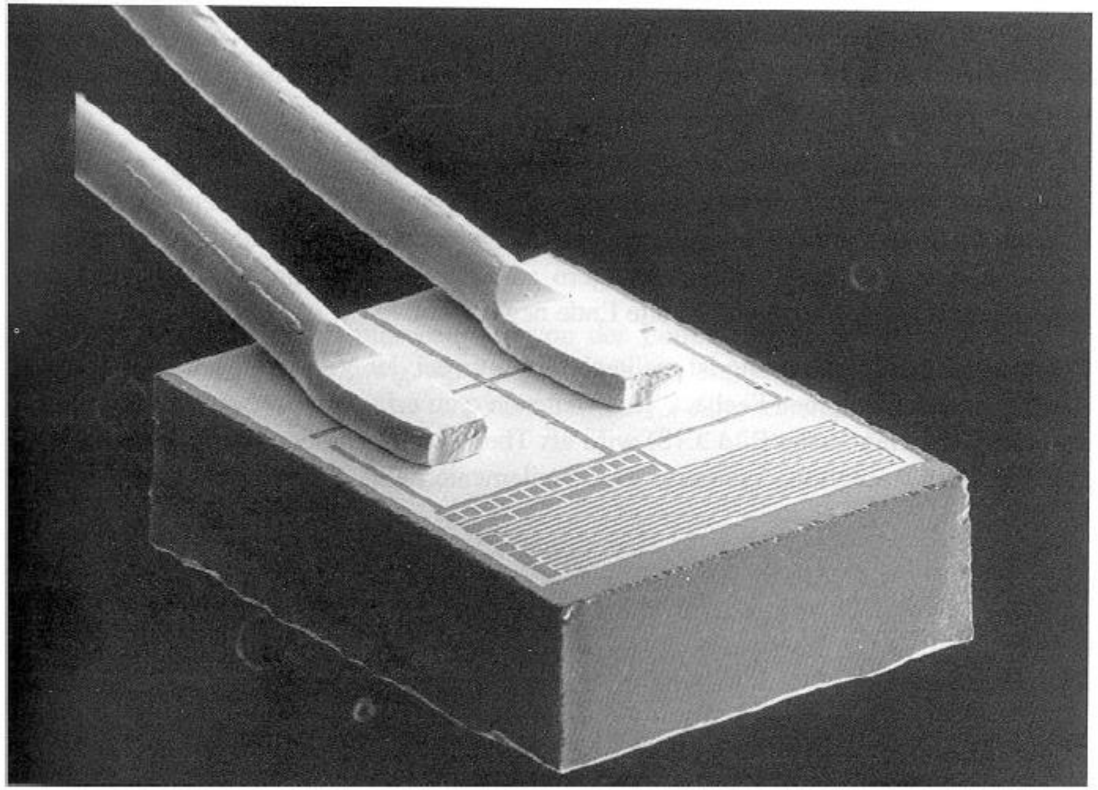


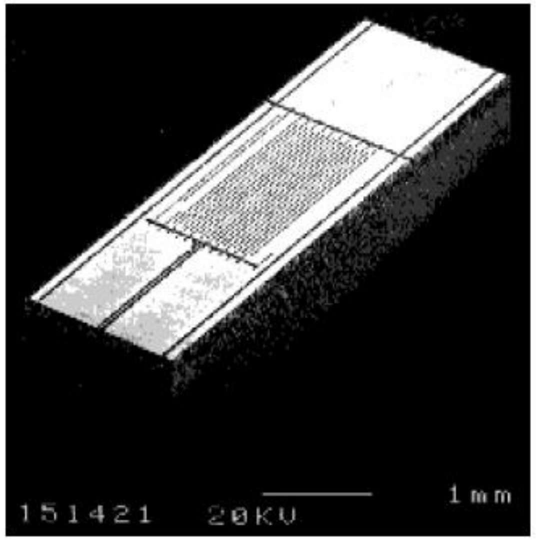
Resistance thermometers

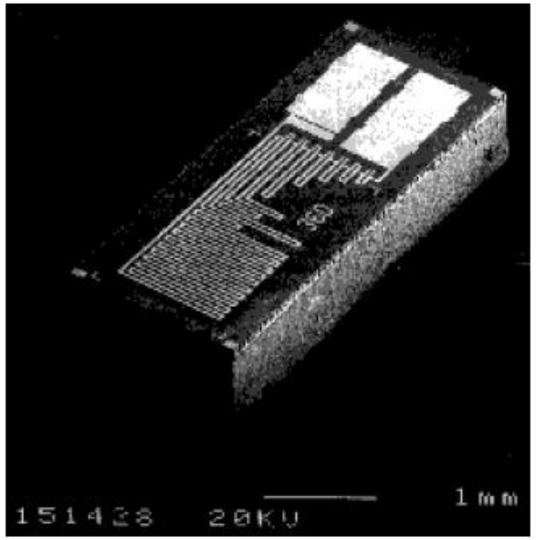
In reality harsh environments → protection by housing

Resistance thermometers

Production of thin film thermometers

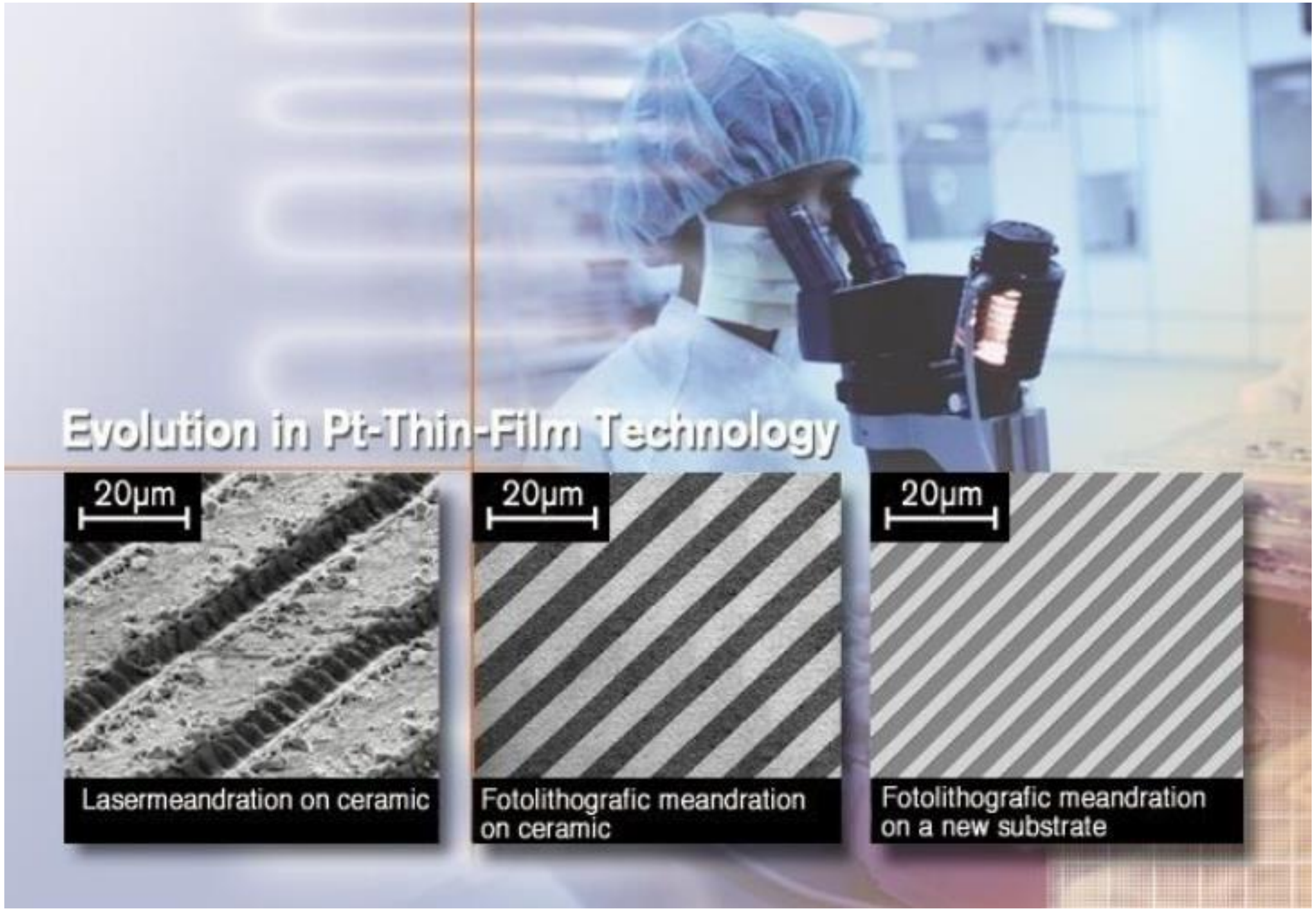






Pt layers evaporated onto ceramic substrates and structured by RIE (reactive ion etching)

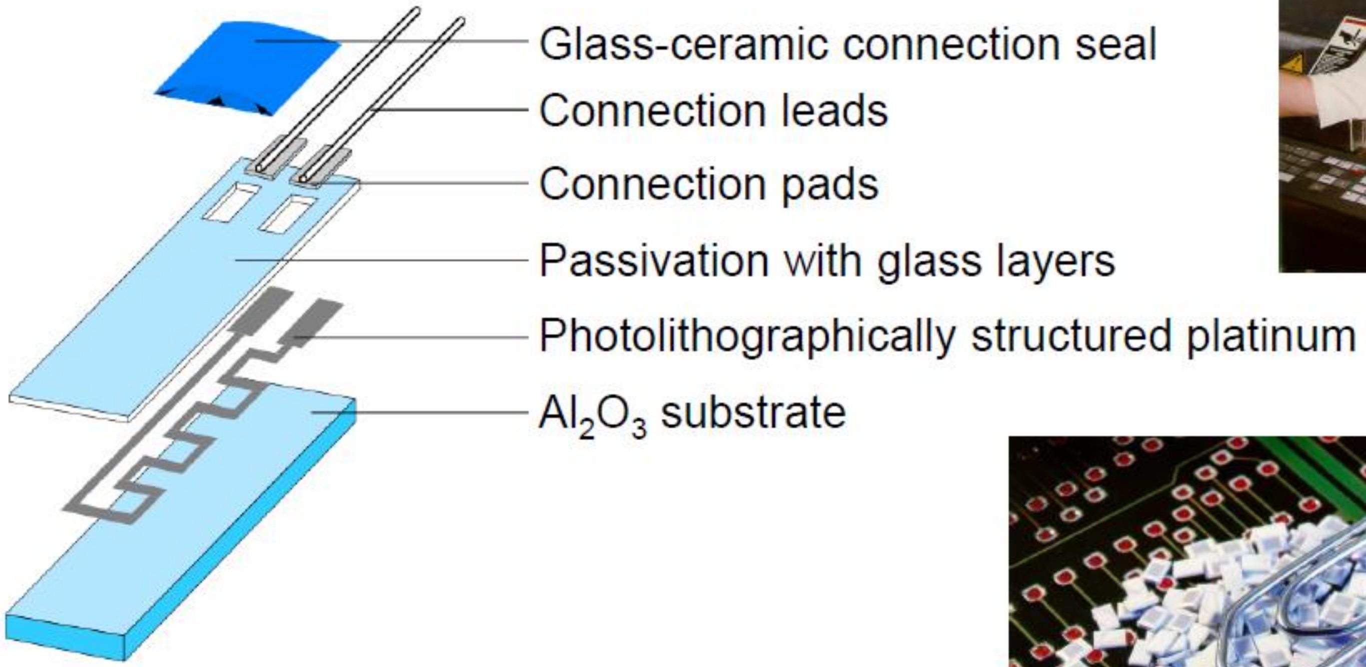
Thin-film resistance thermometers

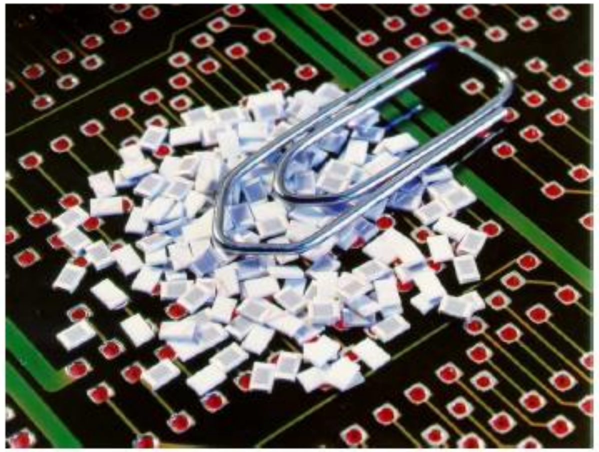


Example: Heraeus

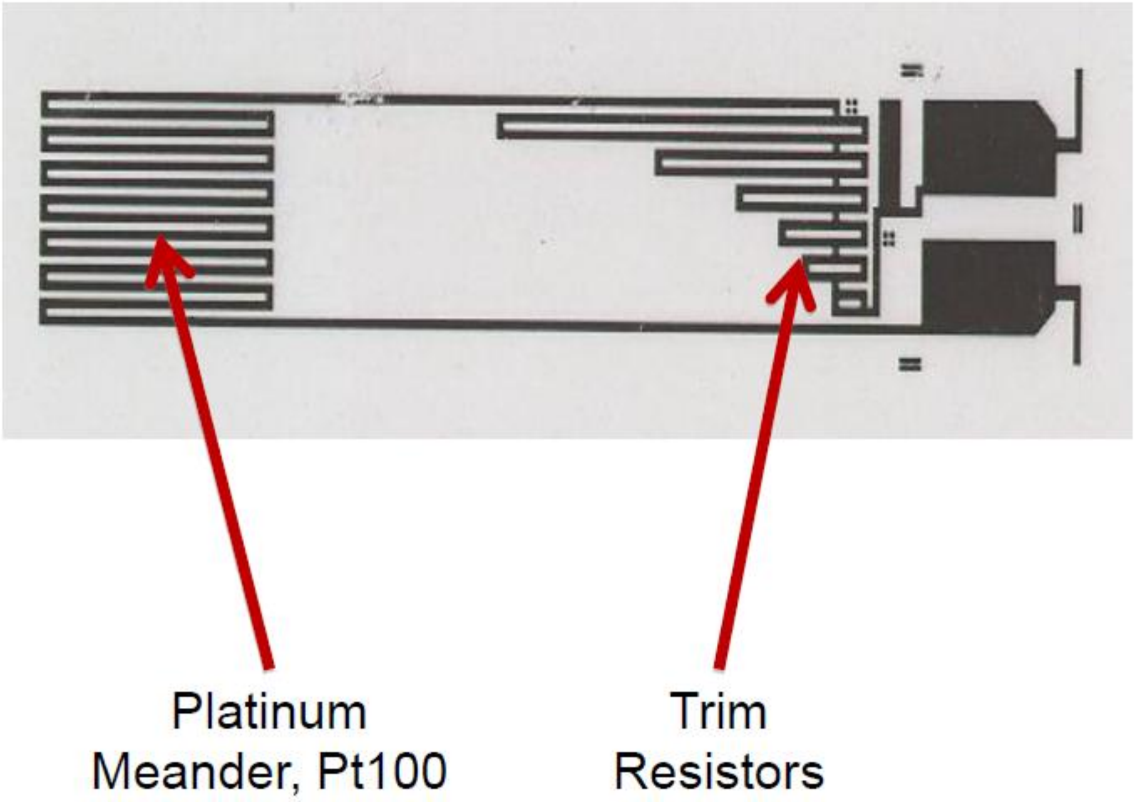
Thin-film resistance thermometers

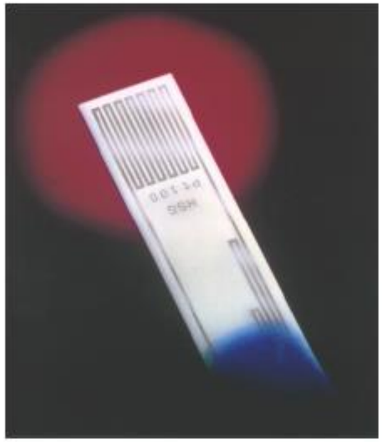
Design of platinum thin-film sensors



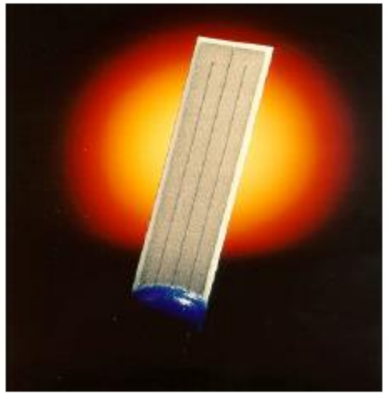


Thin-film resistance thermometers





Pt100



Pt 6, 8

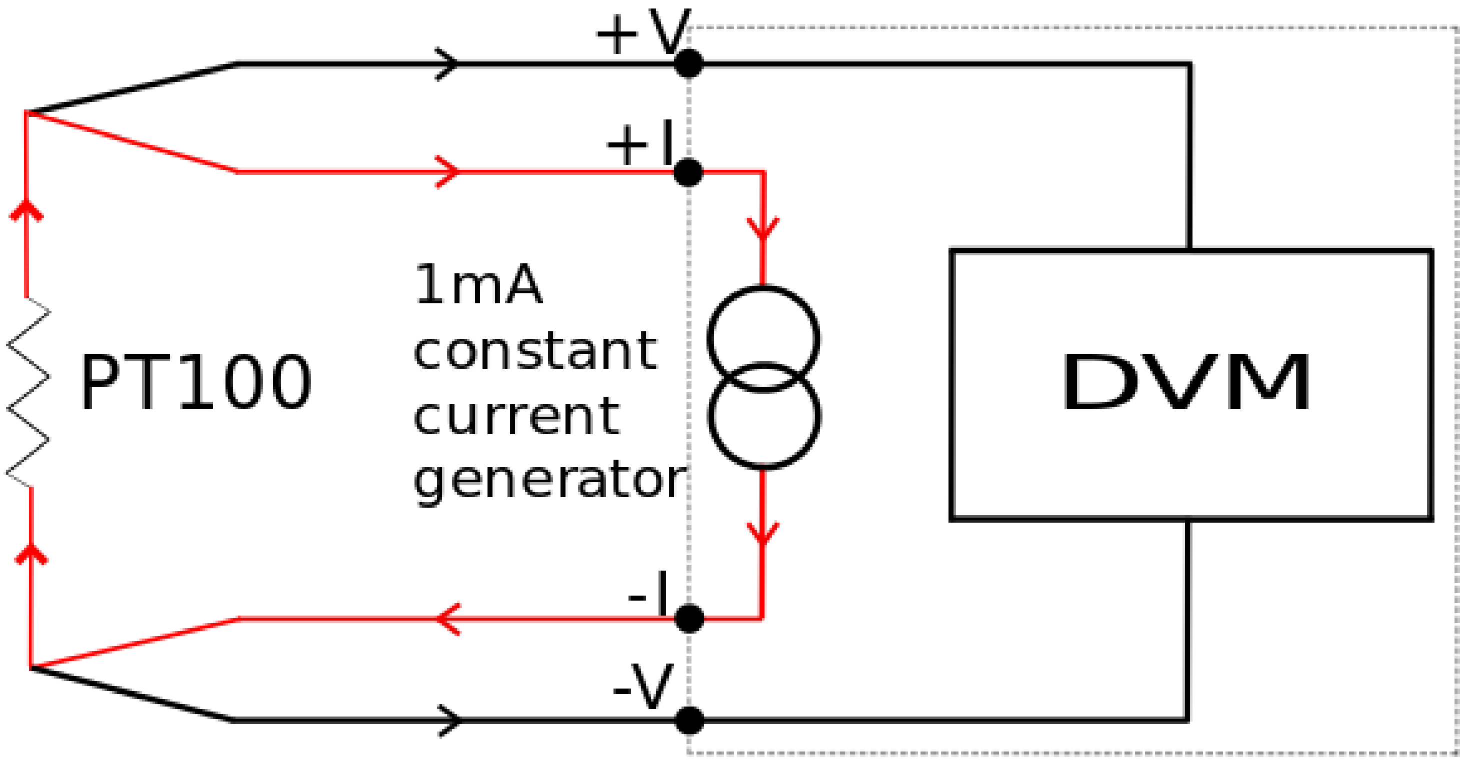
Thin-film resistance thermometers

Pt resistance sensor: requirements for the measurement circuit

- Generation of a precise, constant measuring current through the sensor
- The self-heating in the sensor due to the measuring current should not falsify the measurement!
- Like any resistance through which a current flows, temperature sensors are also slightly heated by the measuring current
- The so-called heating error depends on:
  - the electrical power supplied ($P = I^2R$)
  - the amount of heat removed
  - the equipment constant E (self-heating coefficient)

Thin-film resistance thermometers

Metal resistance thermometers are low resistance devices and therefore, a **4-wire method should be applied to compensate the resistance of conducting lines.**

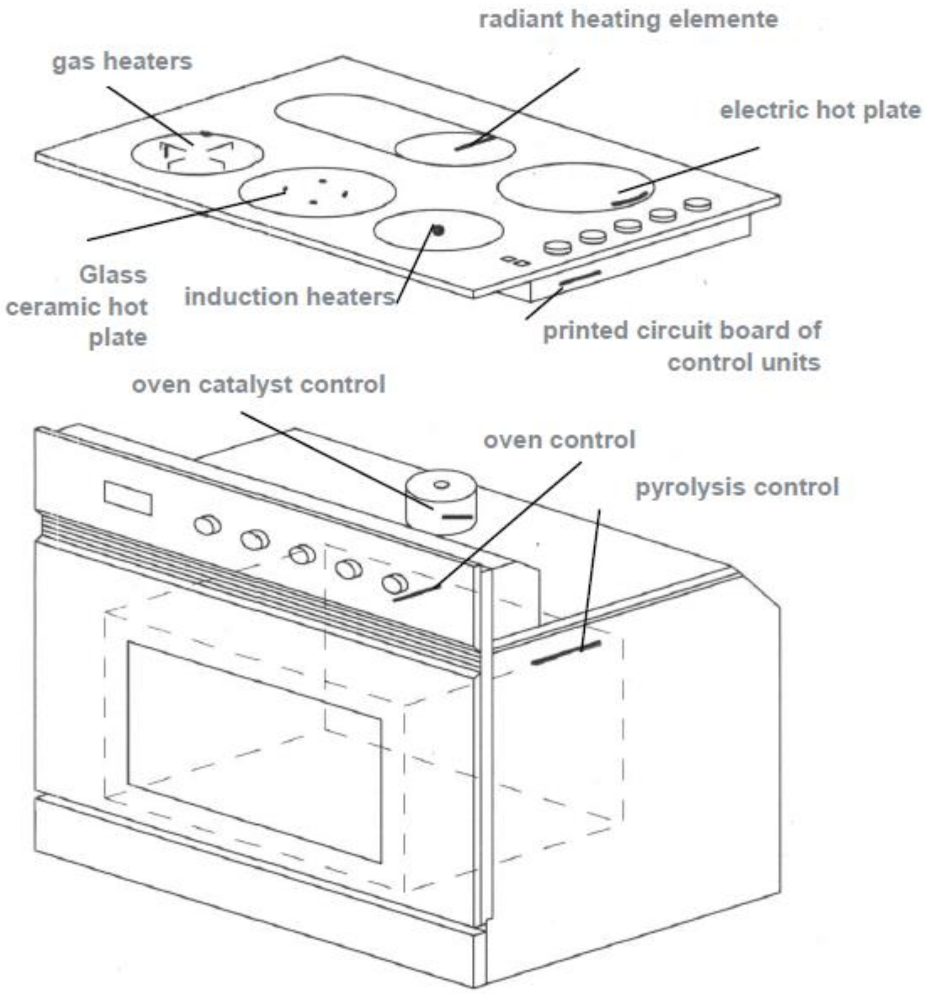


Source: wikipedia

Resistance thermometer: Pt100 applications

- Process technology with protection
- Air conditioning: standard – heat metering, chimney temperature, boiler temperature
- Automotive: thermal flow sensor, catalyst temperature
- Refrigeration engineering
- Temperature control for cooking plate, hot plate

Pt100 application example



Different temperature sensors in/for

- Hot plates
- Gas heaters
- Glass ceramic hot plate
- Electronic control units
- Ovens
- Pyrolysis control

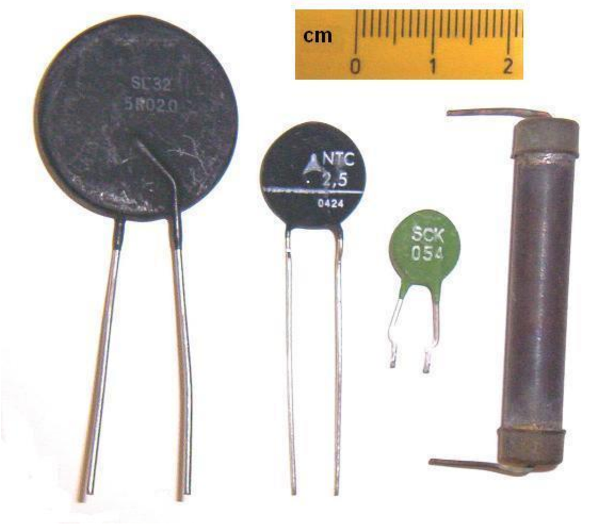
Comparison: resistance thermometer *vs.* thermocouple

Factors	Resistance thermometer	Thermocouple
Location	Metal wire	0-dimensional
Range	–270 … +850 °C (+1,000 °C)	–270 … +2,400 °C
Accuracy	0.3 ... 0.25% of measured temperature, min. ±0.1 °C	0.3 … 0.75% of temperature, ±1 °C
Long term stability (1 year)	Better than ±0.5 °C	Better than ±1.5 °C
Errors	Constant voltage source, self heating	Reference temperature
Isolation error	Important!	Low influence
Sensitivity	~ 5 mV / °C	~ 50 µV / °C

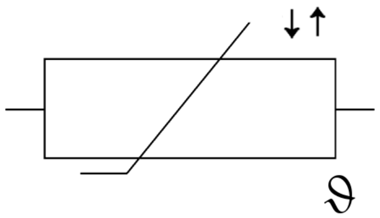
Thermistors

- **Thermistor**: made up from **therm**al and res**istor**
- Resistance is strongly dependent on temperature (even more than in standard resistors)
- Typical operational temperature: between −100 °C and 300 °C
- Two types of thermistors, based on their conduction model:
  - Negative Temperature Coefficient (NTC): less resistance at higher temperatures; inrush current limiters, temperature sensors
  - Positive Temperature Coefficient (PTC): higher resistance at higher temperatures; self-resetting overcurrent protectors, and self-regulating heating elements

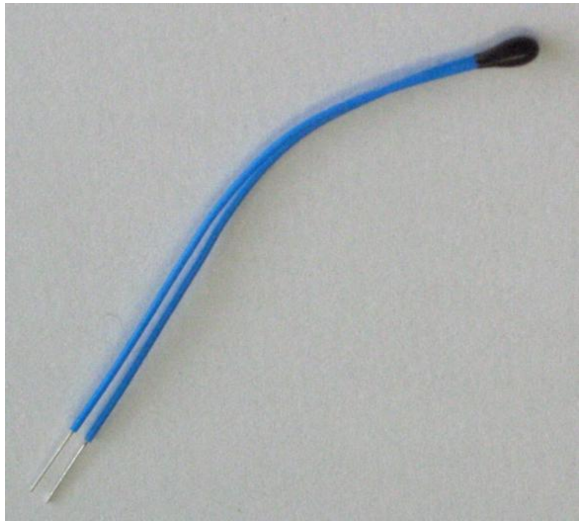
Thermistors - NTC



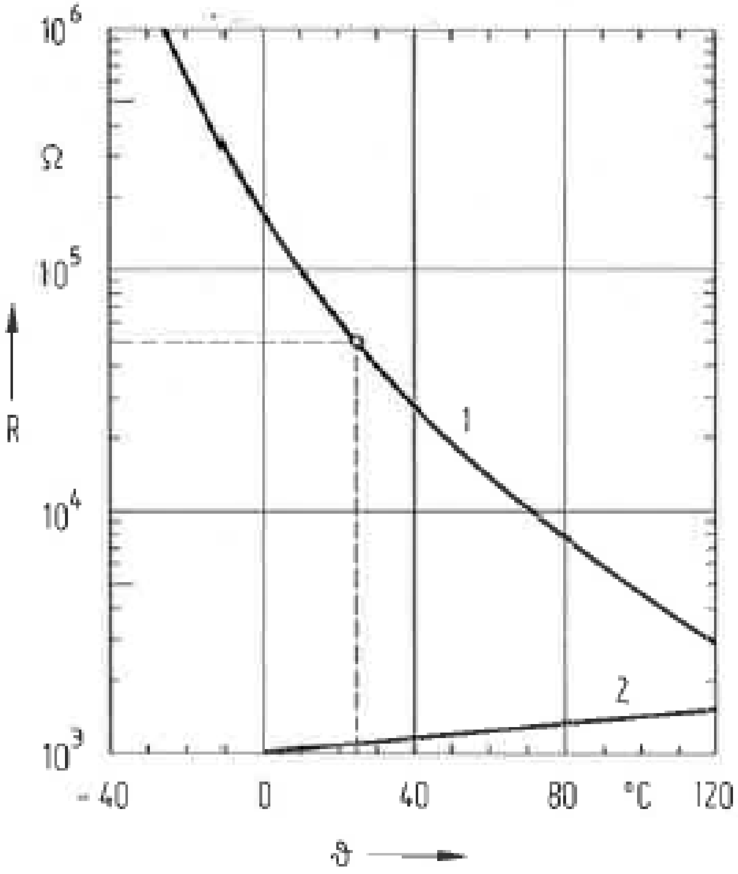
Different thermistor types and sizes



Thermistor symbol



Negative temperature coefficient (NTC) thermistor, bead type, insulated wires (Wikipedia)



Resistance of an NTC resistor (1) R0 = 50 kOhm compared to a Pt 1000 (2) depending on the temperature

Thermistors – what‘s the difference?

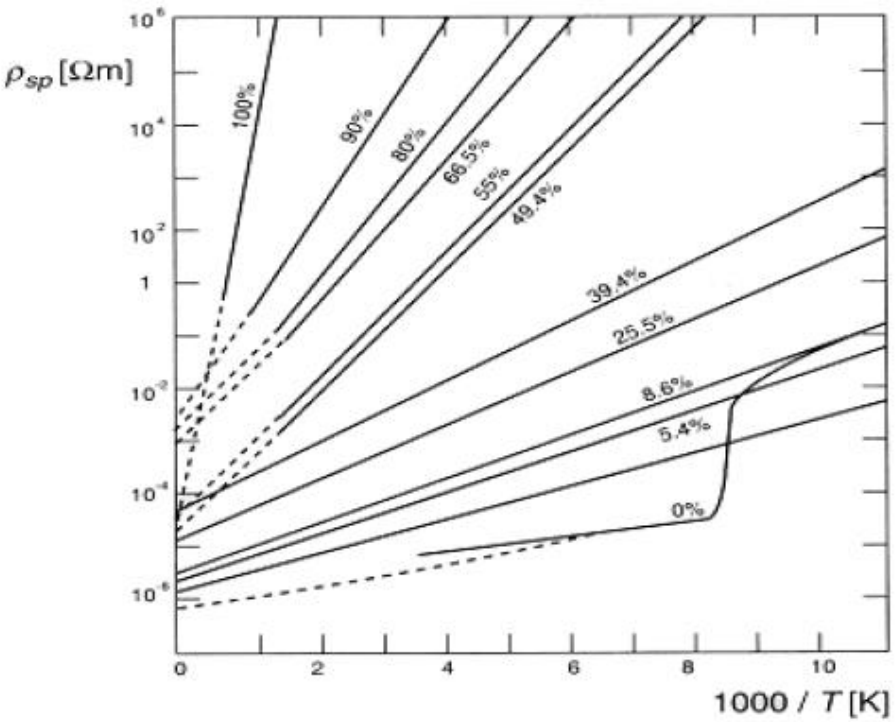
- **NTC**: less resistance at higher temperatures – due to an increase in conduction electrons bumped up by thermal agitation from the valence band
- **PTC**: higher resistance at higher temperatures – due to increased thermal lattice agitations, particularly those of impurities and imperfections
- NTCs have generally higher sensitivity (~ 10x at room temperature), but can only be used up to several hundred degrees

Materials:

NTC: oxides of the iron group of metals: e.g. CrO, Cr_2O_3, MnO, CoO, Fe oxides, Ni oxides

PTC: Ba-, Sr or Pb titanates (e.g. $PbTiO_3$

NTC materials



Adjustable temperature coefficient of the resistivity of magnetite (Fe_3O_4) with different mixtures of the spinel ($MgCr_2O_4$).

Thermistors – basic operation

Assuming, as a first-order approximation, that the relationship between resistance and temperature is linear, then

$$\Delta R = k\,\Delta T,$$

where

ΔR, change in resistance,

ΔT, change in temperature,

k, first-order temperature coefficient of resistance.

Depending on type of the thermistor in question the k may be either positive or negative.

k positive for PTCs, negative for NTCs

Thermistors – basic operation

But closer to reality: Steinhart-Hart equation

NTC thermistors can be characterized with a (idealized) form of the Steinhart-Hart equation: the **B parameter equation**

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B}\ln\frac{R}{R_0},$$ R_0 is the resistance at temperature T_0 (25 °C = 298.15 K)

solving for R yields

$$R = R_0 e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

or alternatively

$$R = r_\infty e^{B/T},$$

where $r_\infty = R_0 e^{-B/T_0}$.

This can be solved for the temperature:

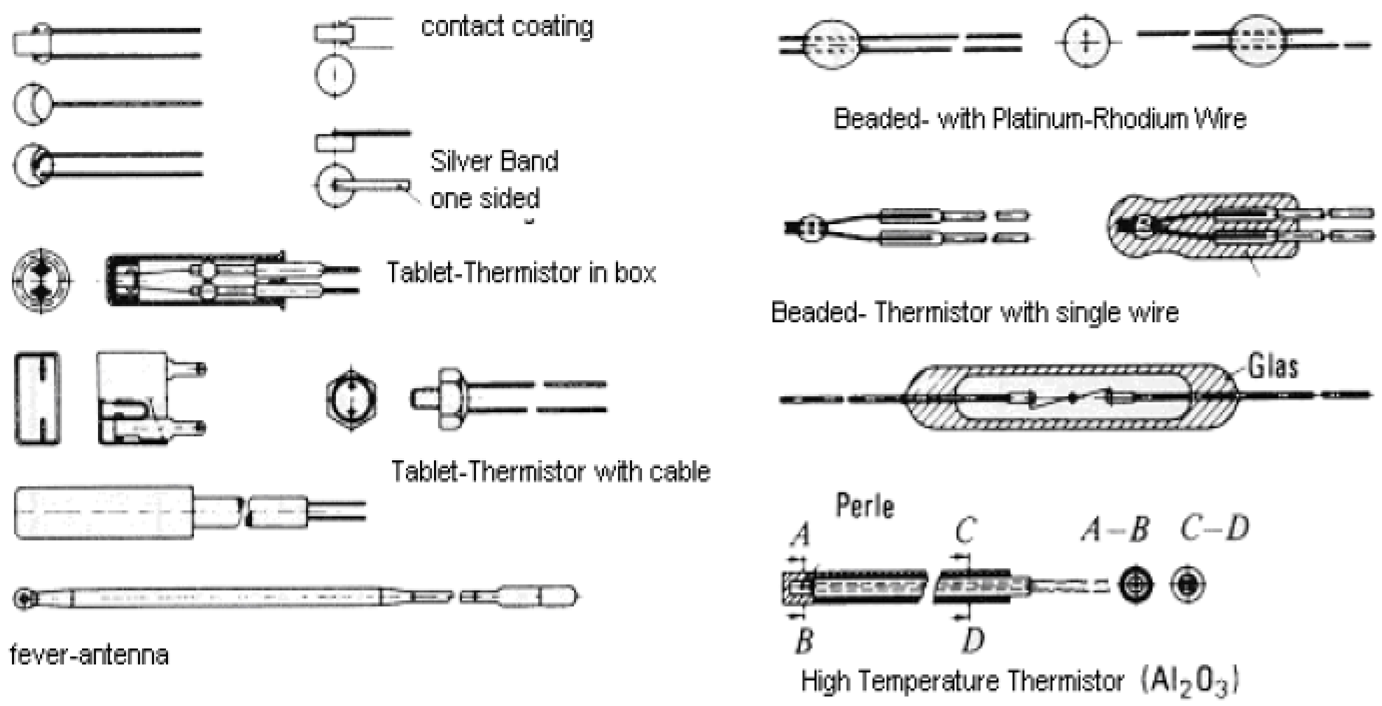
$$T = \frac{B}{\ln(R/r_\infty)}.$$

The B parameter equation can also be written as $\ln R = B/T + \ln r_\infty$.

This can be used to convert the function of R vs. T of a thermistor into a linear function of ln R vs. 1/T. The average slope of this function is then the estimate for B.

Thermistor designs

- Disk and rod shaped designs
- For medical applications: miniaturized thermistors with Ø ~ 100 µm

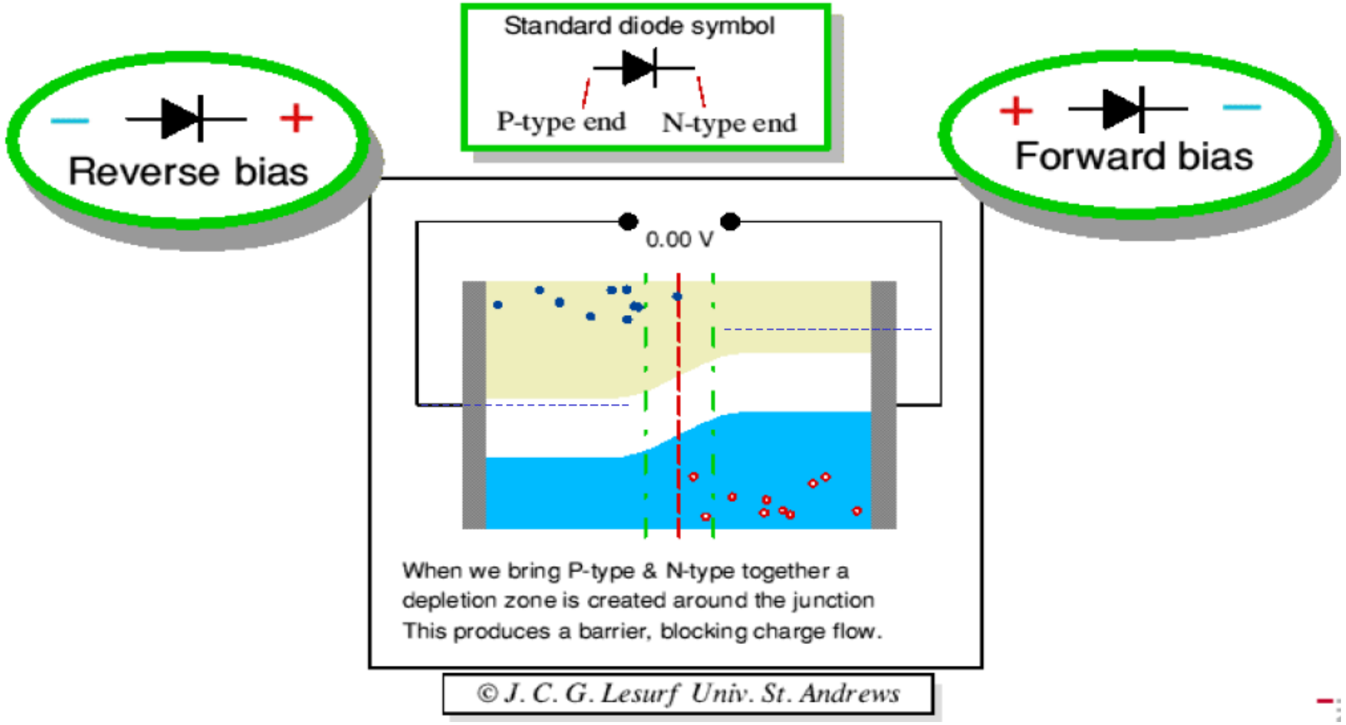


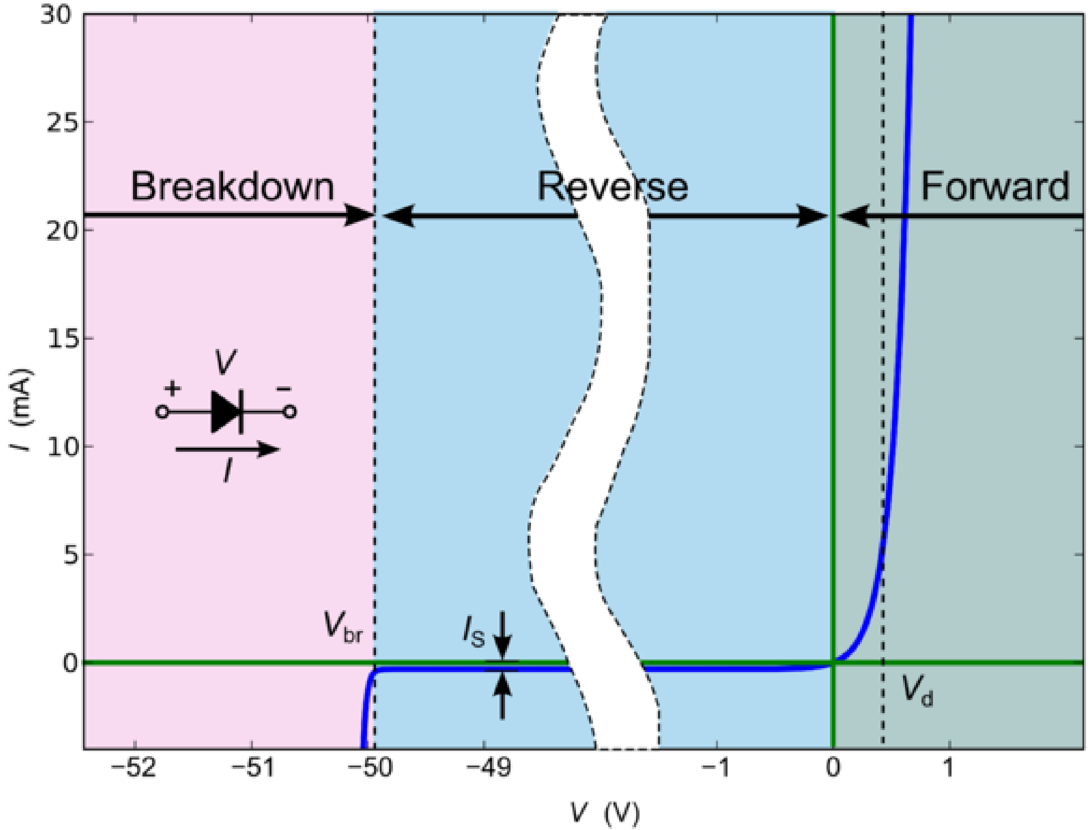
Thermistor designs

Housing – soft glass (application temperatures to 300 °C) or hard glass (application temperatures to 600 °C).

- Tablet, bead or pill form

Diodes





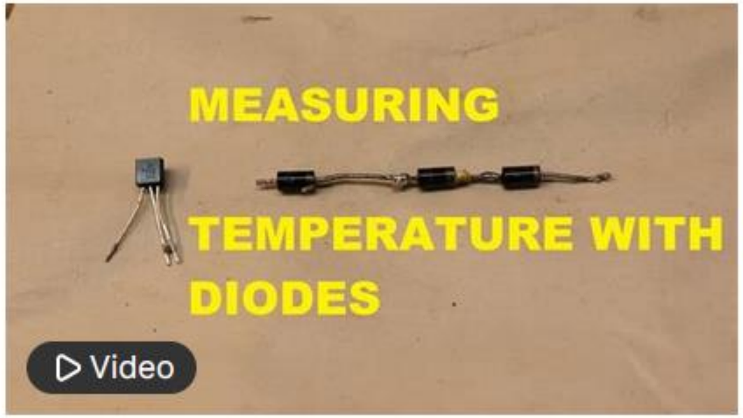
I–V (current vs. voltage) characteristics of a p–n junction diode (Wiki)

Diodes as temperature sensors

- forward voltage drop across the diode depends on temperature
- I-V characteristic is given by the Shockley ideal diode equation

$$I = I_S \left(e^{V_D/(nV_T)} - 1 \right)$$

I diode current,
I_S reverse bias saturation current,
V_D voltage across the diode,
V_T thermal voltage
n ideality factor (*quality factor, emission coefficient*).
n typically varies from 1 to 2

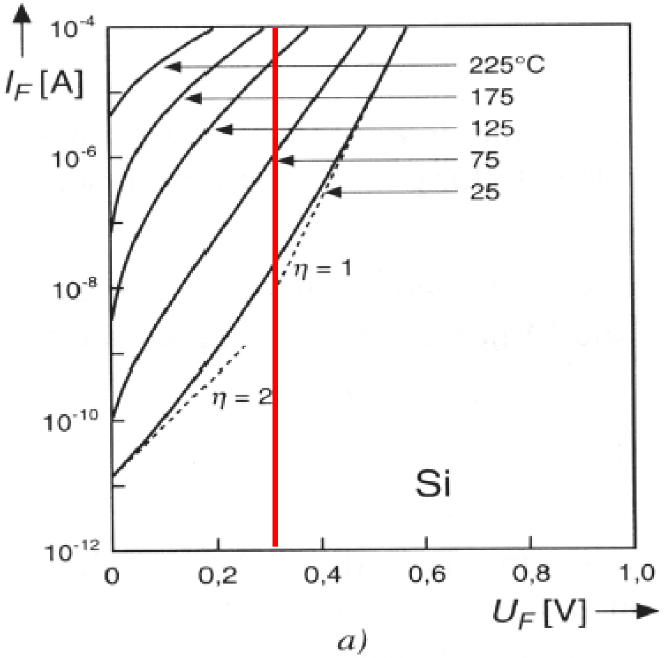


https://youtu.be/W3PaCzOe7FQ

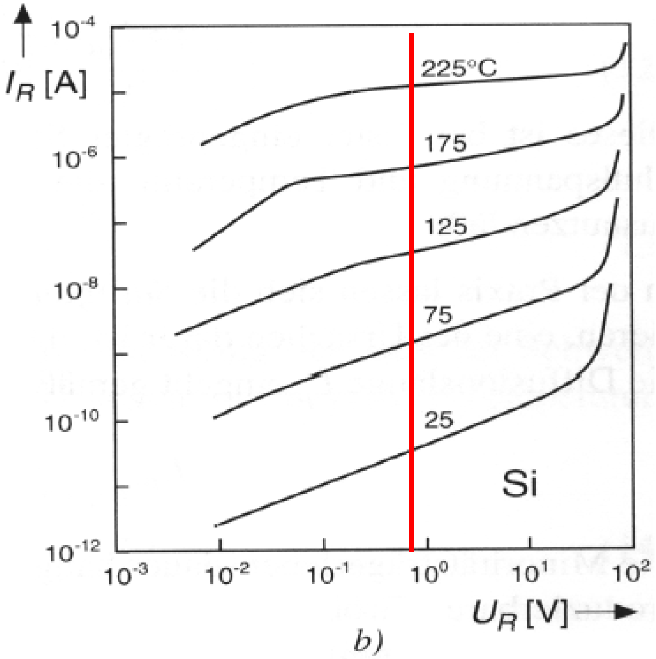
- Usually the variation of the reverse saturation current term is more significant than the variation in the thermal voltage term.
- Most diodes therefore have a *negative* temperature coefficient, typically −2 mV/°C for Si diodes.
- The temperature coefficient is approximately constant for temperatures above about 20 K.

Diodes as temperature sensors

➔ In practice, the saturation current is depended on the concentration of deep impurities and lattice defects, which makes it not reproducible.



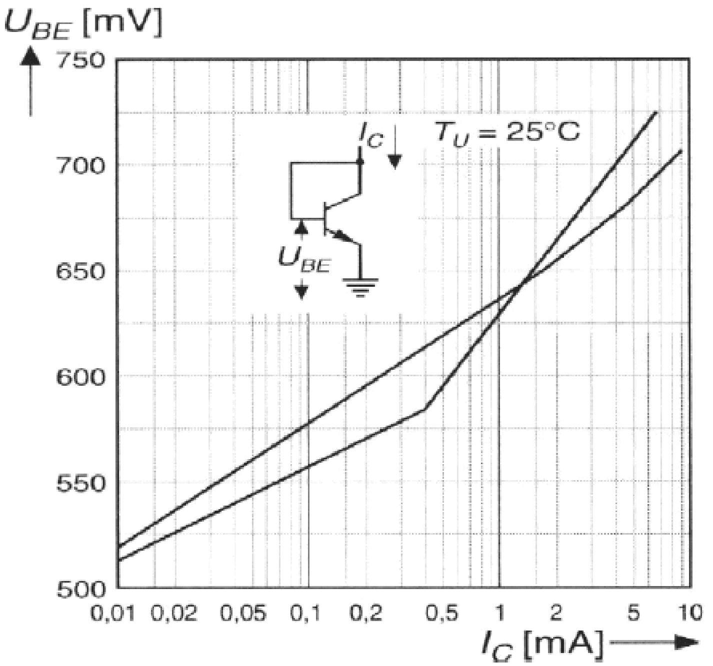
Forward biased



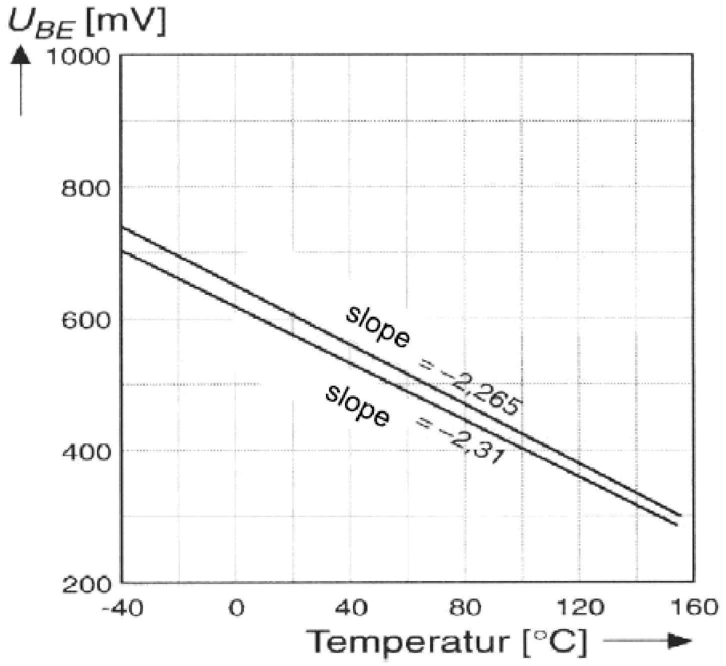
Reversed biased

Bipolar transistors

Emitter - basis length with short circuit basis collector connection increases reproducibility – it depends now only on the base width d - can be reproduced easily!

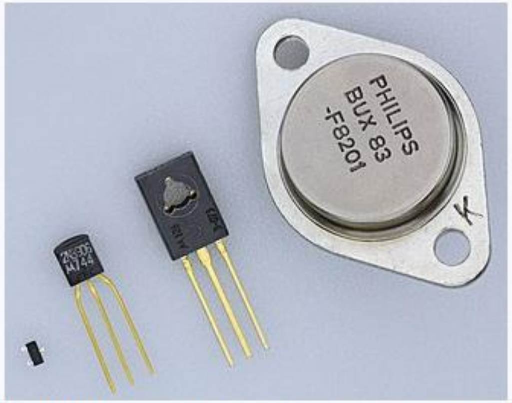


Source Schaumburg: Sensor Band 3



AD TMP36 (-40 to 150°C) or LM35/TMP35

Bipolar junction transistor (BJT)



Typical individual BJT packages. From top to bottom: TO-3, TO-126, TO-92, SOT-23

Working principle	Semiconductor
Invented	December 1947
Pin configuration	Collector, base, emitter

Electronic symbol

BJTs PNP and NPN schematic symbols

Transistors as temperature sensors

Advantages:

- very linear
- large, normalized output signal due to amplification
- low-cost

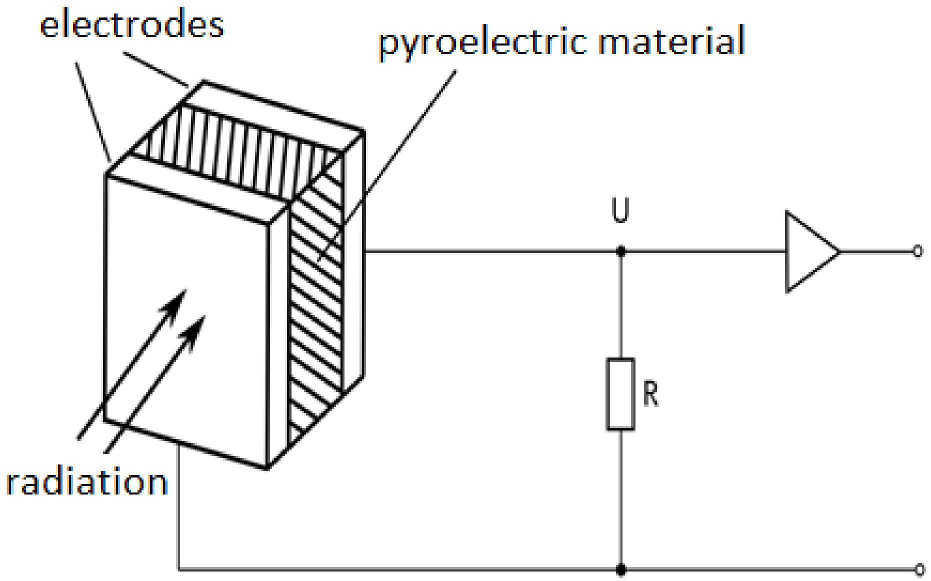
Disadvantages:

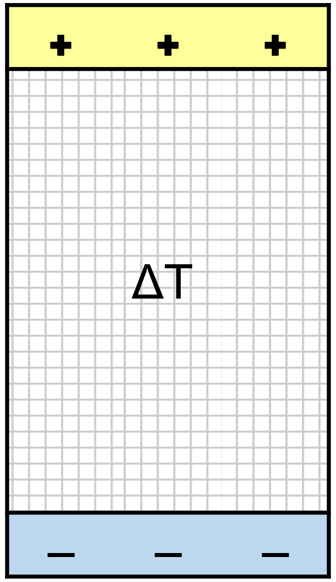
- can only be used up to 200 °C
- power supply required
- slow, since integrated circuits have to be installed in a housing with a large heat capacity
- self-heating of the integrated circuit

Pyrodetectors

Pyroelectric effect – is the property of piezoelectric crystals to react to a temporal temperature change ΔT with charge separation. Piezoelectric crystals consist of electrically polar unit cells.

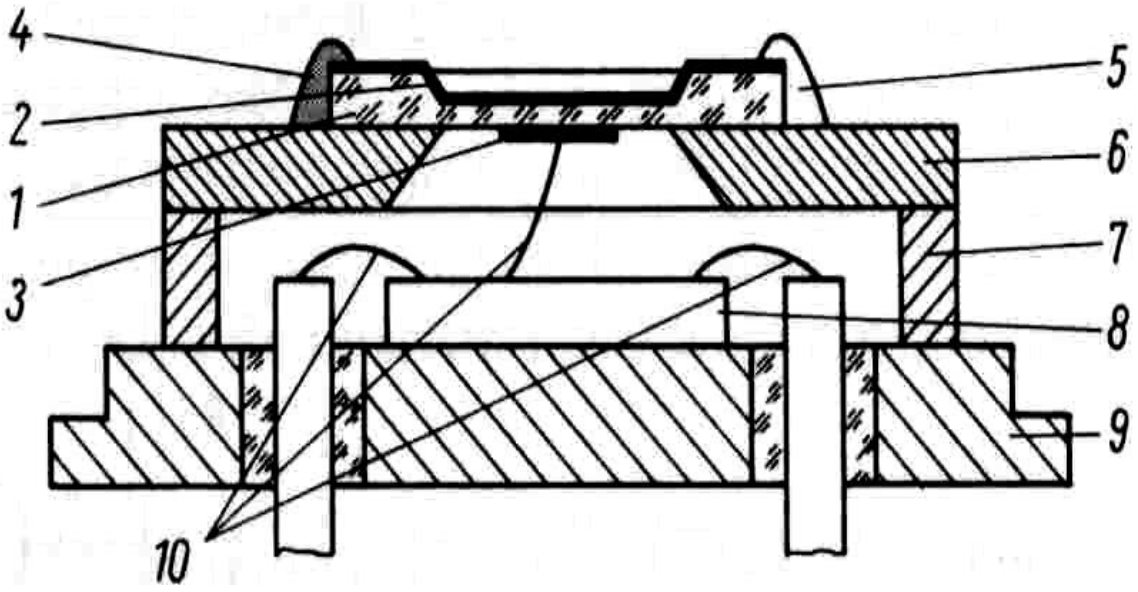
Material: lithium niobate, lithium tantalate





Pyrodetectors

Basic setup



1 pyroelectric wafer (made by ion beam etching), 2 front electrode, 3 back electrode, 4 conductive adhesive (elastic), 5 wafer fixation (elastic), 6 carrier, 7 intermediate ring, 8 preamp, 9 TO5 socket, 10 bond wires

Pyrodetectors

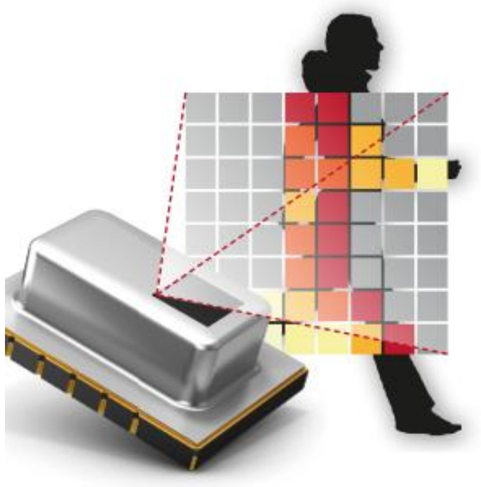
Pyrometer basics

Any object with a temperature greater than 0 Kelvin emits thermal radiation, the intensity and position of the emission maximum of which depends on its temperature.

If the measurement object is colder than the pyrometer, the radiant flux is negative, i.e. the pyrometer emits thermal radiation to the measurement object (2nd law), which can also be evaluated.

Stefan-Boltzmann law, Wien's displacement law, Planck's radiation law

Pyrodetectors - applications



Comparison of uncooled thermal IR detectors

	Thermopile	Bolometer	Pyrodetector
Principle	Seebeck effect	charge carrier density/mobility	Dielectric polarization
measurand	Temperature gradient	Temperature	Temperature change
Signal	Voltage Δ V	Resistance Δ R	Polarization Δ Q
Temperature control	Not necessary	necessary	Not necessary/necessary
Modulation of light source	Not necessary/necessary	Not necessary	necessary

What else is out there?

- Temperature sensor with oscillating crystal as measuring element: The resonant frequency of the oscillating quartz changes depending on the temperature and can be measured very precisely.
- Fiber optic temperature sensors measure the temperature profile along a glass fiber. They are based on the Raman effect or the temperature-dependent change in the refractive index in fiber Bragg grating sensors
- Color changing labels

Sensor principle characteristics

	Measuring range (°C)	Local resolution (mm)	Temperature resolution (mK)	Accuracy
Expansion thermometer	−270…+1,000	~ 1	> 10	10 mK
Thermocouple	200…+1,600	> 0.01	~ 50	0.6 K (1%)
Resistance metal	−270…+850	~ 1	~ 1	1 mK abs. ~ 0.3% rel.
Resistance thermistor	−50…+150	> 0.02	~ 1	200 mK abs. ~ 0.3% rel.
Thin film thermistor	−200…+160	0.1	0.1	
PTC	−50…+350	~ 1	1	small
PTAT	−50…+150	~ 1	>1	(1%) 0.5 K
Capacitive		> 0.04		1 K abs.
Inductive		~ 1	~ 10	0.1 K abs.
Pyroelectric sensor	0…+4,000	~ 1	> 0.006	0.1 K abs.
Quartz resonator	−40…+300	~ 1	> 0.1	5 mK abs.
Noise thermometer	100…+1,600	> 0.1	theor. ~10	0.1% rel.
Optical sensor	0…+4,000	~ 1	100	2 K
Pyrometer		~ 1	500	0.5% rel.
Color temperature		~ 1	~ 1,000	5% rel.

Thank you!

Questions?