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ALLGEMEINWISSENSCHAFTEN UND MIKROSYSTEMTECHNIK

Combined vacuum gauge based on MEMS pressure Sensors

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1. Classification of pressure ranges (rough-, medium-, high-vacuum)
2. Direct and indirect measurement methods
3. MEMS sensors for rough and medium vacuum measurement
4. Auto-Calibration Sensor System

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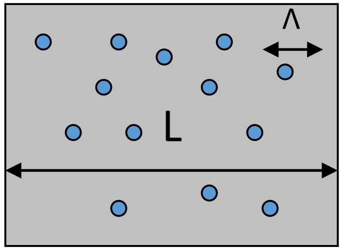
allocation of the pressure domains:

(based on the pressure dependency of the mean free path)



At high pressures (rough vacuum): L >> Λ („viscous”)

Gas particles collide much more often with other gas particles than with the side walls of the recipient
Elastic collisions between the particles determine the properties of the residual gas

At low pressures (high vacuum): L << Λ („molecular“)

Gas is highly thinned out, that gas particles can travel towards the opposite sidewall without collisions with each other
Adsorption of the gas particles on the sidewall surface determines the properties of the residual gas

In the intermediate range (medium vacuum, „Knudsen-gas“): L ≈ Λ

Mean free path of the gas particles and recipient size have similar order of magnitude

What does it mean in numbers?

Pressure range	pressure p pressure in hPa (mbar)	particle density n particles per cm³	mean free path Λ
ambient pressure	1013,25	$2,7 \cdot 10^{19}$	68 nm
rough vacuum	**1013…1**	**$2,7 \cdot 10^{19} \ldots 10^{16}$**	**0,07…100 µm**
medium vacuum	**$1 \ldots 10^{-3}$**	**$10^{16} \ldots 10^{13}$**	**0,1…100 mm**
high vacuum (HV)	**$10^{-3} \ldots 10^{-7}$**	**$10^{13} \ldots 10^{9}$**	**100 mm…1 km**
ultra-high vakuum (UHV)	$10^{-7} \ldots 10^{-12}$	$10^{9} \ldots 10^{4}$	$1 \ldots 10^{5}$ km
extreme high Vakuum (XHV)	$<10^{-12}$	$<10^{4}$	$>10^{5}$ km

for comparison: vacuum in space contains in average only one particle per cm³

Microsystems: $L \approx \Lambda$ is already for rough vacuum valid („Knudsen-gas“)

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How to measure low pressures?

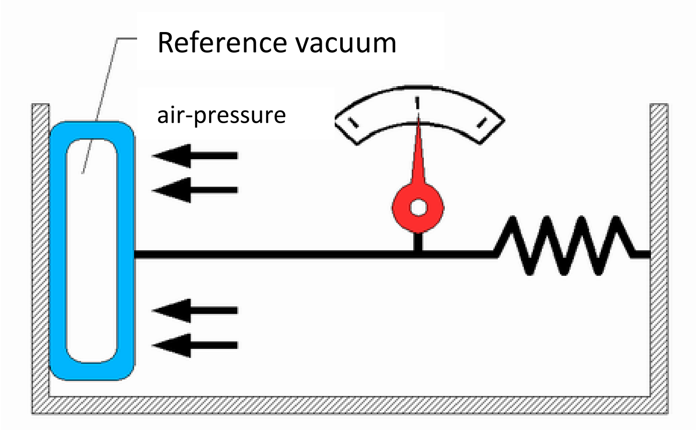
Direct measurement methods:

measurement result does not depend on gas species (by definition of pressure)

e.g. Diaphragm manometer

measurement of pressure as force on area

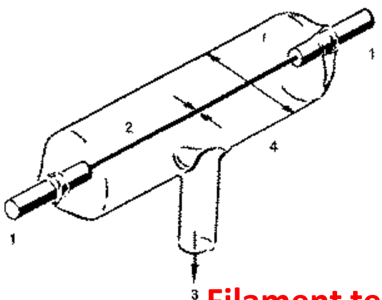
$$p = \frac{F}{A} = n \cdot k_B \cdot T$$



Indirect methods: depends on gas species

e.g. Heat conduction manometer (Pirani)

thermal conductance G_{thG} of gas is a function of pressure p:

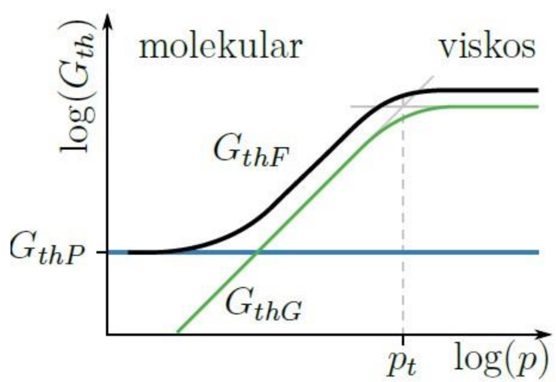


$$G_{th} = \frac{P}{\Delta T}$$

$$G_{thF} = G_{thG} + G_{thP}$$

(Filament) (gas) (parasitics)

Filament temperature T_1 is kept constant and heating power P is measured as a function of pressure p



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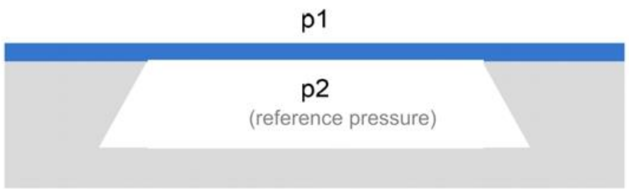
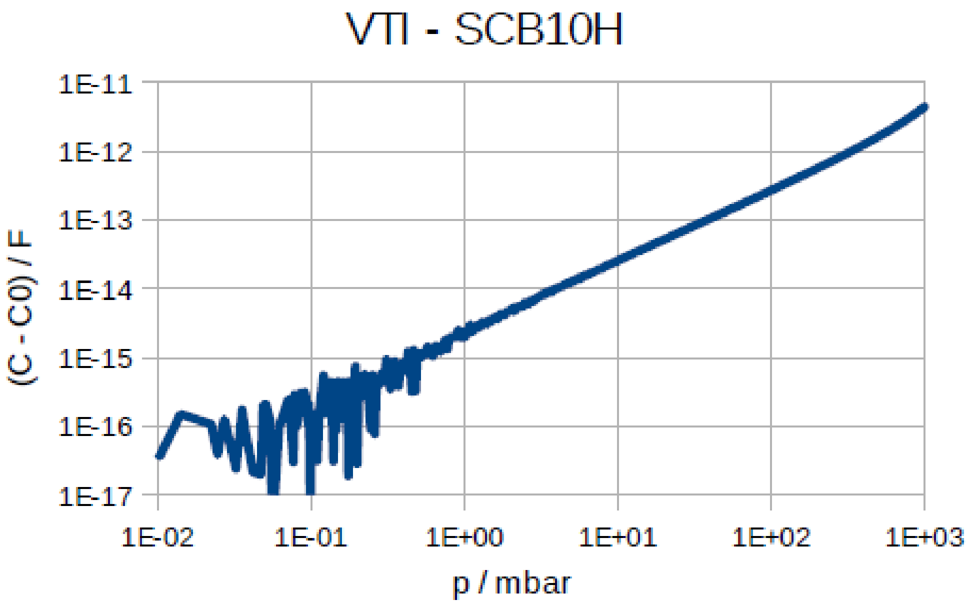
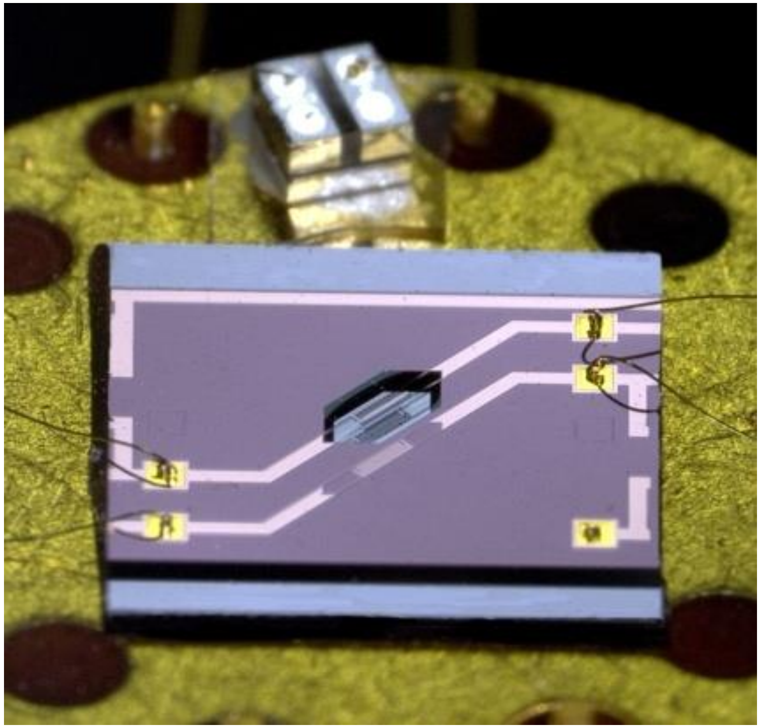
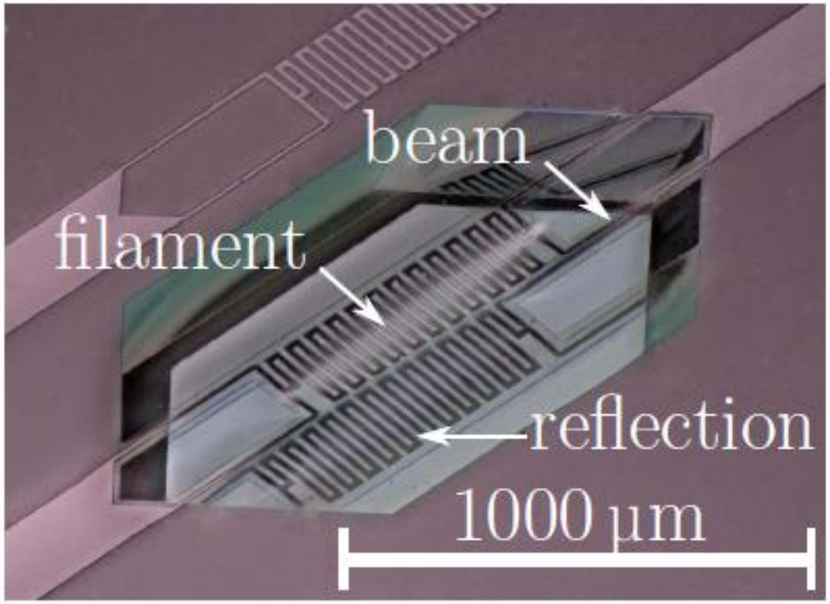
MEMS membrane pressure sensors





MEMS Pirani Sensors

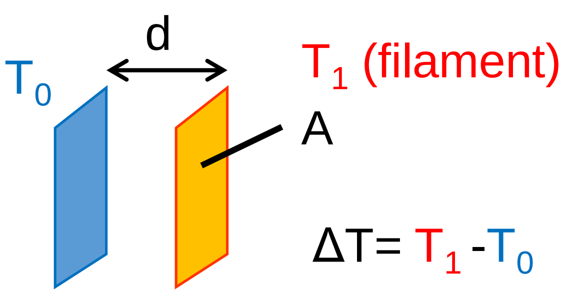




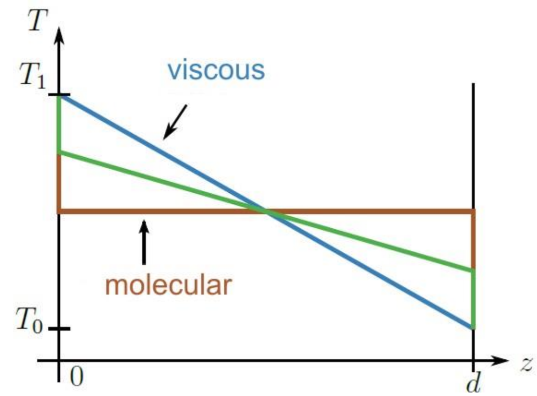
F. Dams and R. Schreiner, "A high thermal resistance MEMS-based pirani vacuum sensor chip," in *Proc. of SPIE 8763, Smart Sensors, Actuators, and MEMS VI*, Grenoble, France, Apr. 2013, p. 87630P.

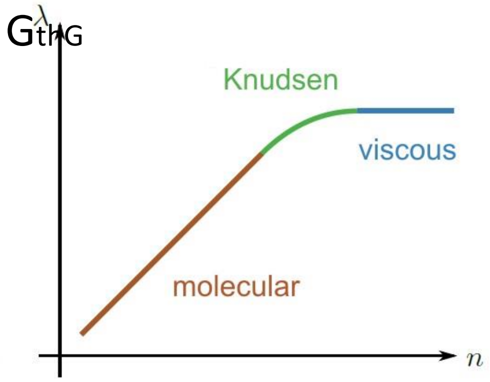
Sensor system consisting of a capacitive membrane sensor VTI SCB10 (top) and a customized MEMS Pirani sensor (bottom) in a TO-package.

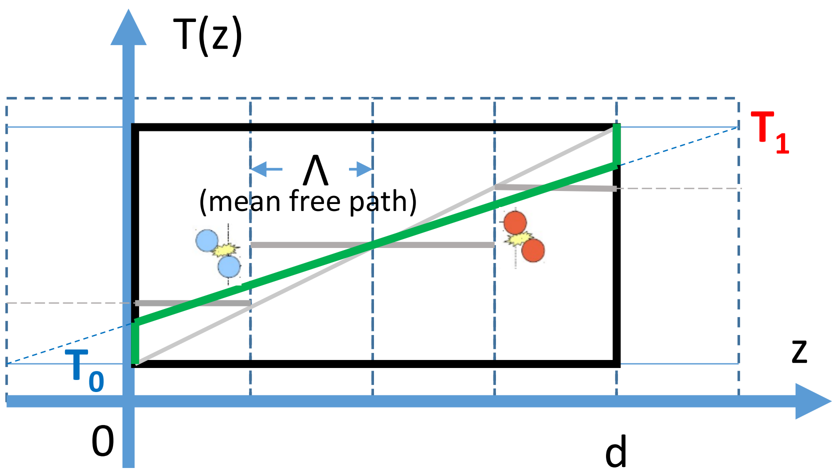
How does the thermal conductance of a gas depend on the pressure?



temperature profile between the 2 surfaces (inside the gas)







Temperature discontinuities at both surfaces

thermal conductance G_{thG} of the gas

$$G_{thG} = \frac{\epsilon\ A \cdot p}{1 + \gamma\ d \cdot p}$$

ϵ and γ combine gas species dependent constants

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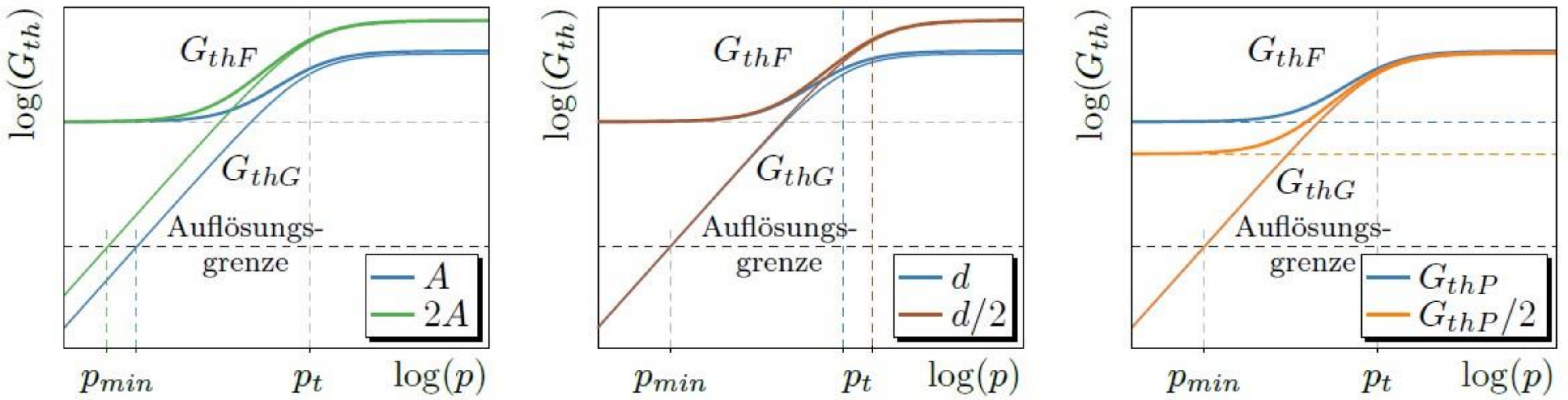
How does the geometry influence the resolution and the sensitivity?

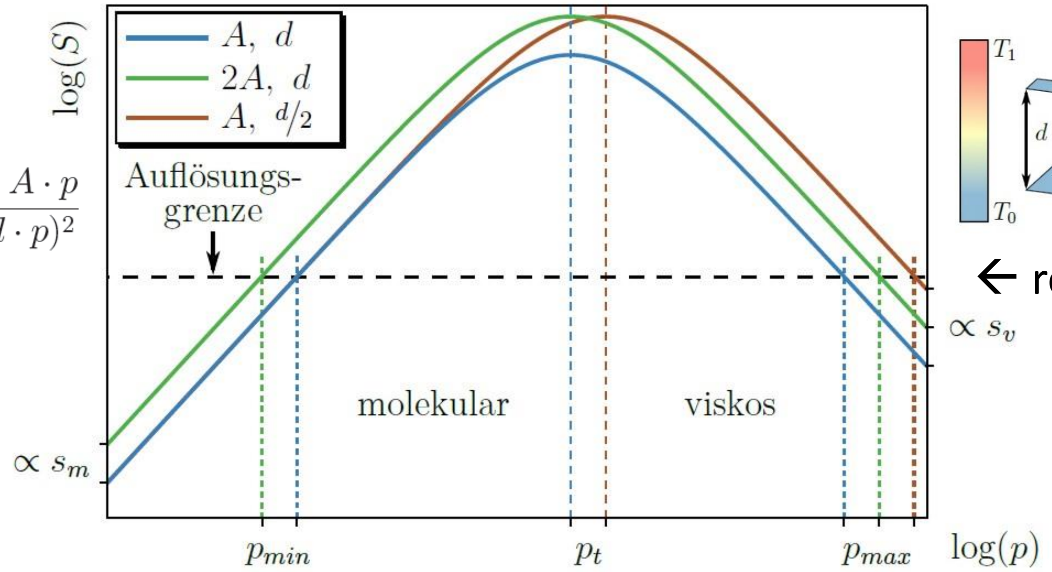


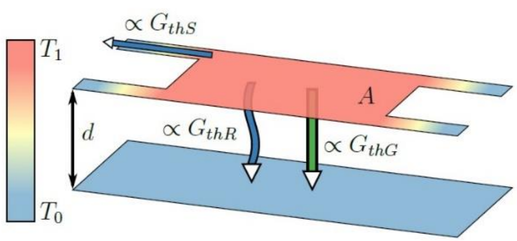
Sensitivity:

$$S = \frac{\partial G_{thF}}{\partial(\log_{10} p)} = \frac{\ln(10)\ \epsilon\ A \cdot p}{(1+\gamma\ d \cdot p)^2}$$

$$s_m = \ln(10)\ \epsilon \cdot A$$

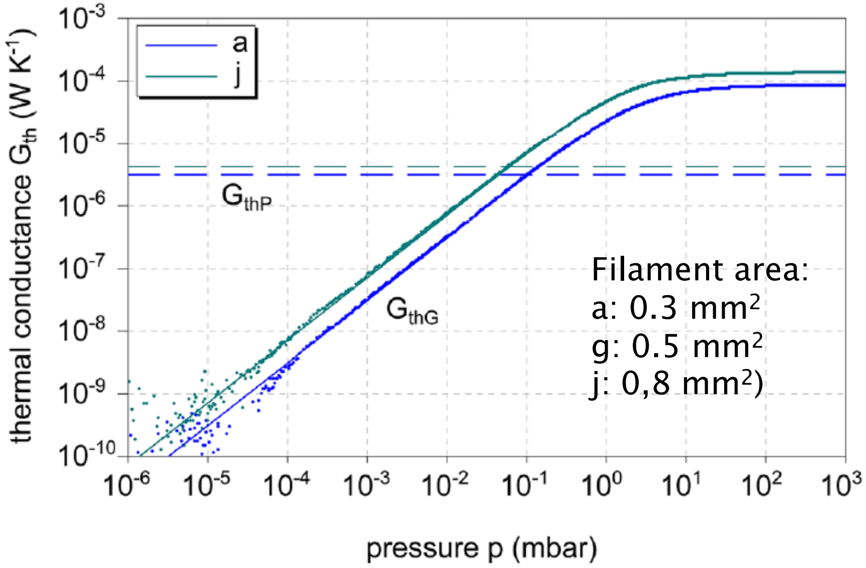
$$s_v = \frac{\ln(10)\ \epsilon \cdot A}{(\gamma \cdot d)^2}$$

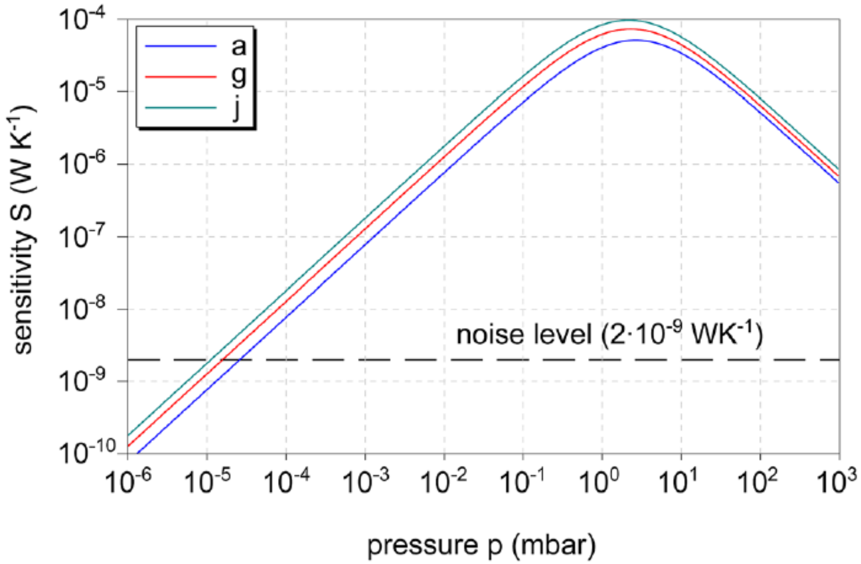


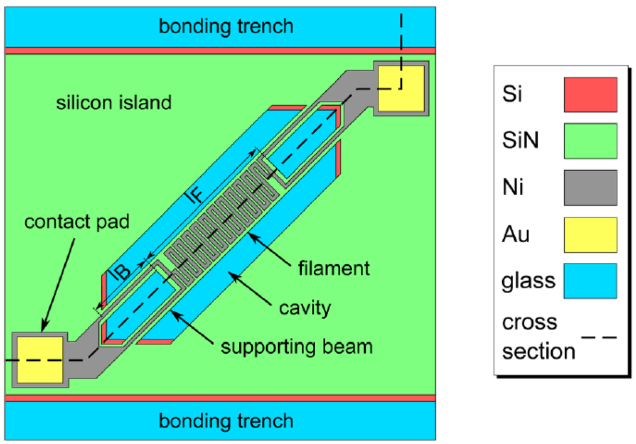


← resolution limit

Experimental results:







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gas species dependency:

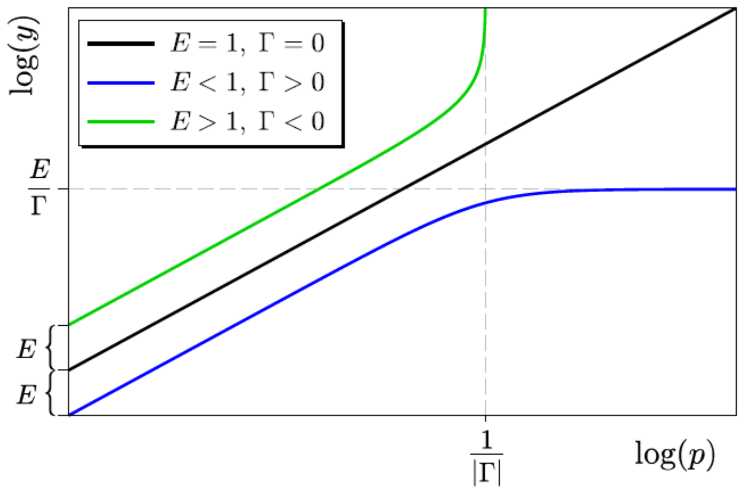

Fig. 3: Mathematical description of the output signal y of a Pirani vacuum gauge for different parameter combinations. The black line ($y = p$) is the curve of an optimally calibrated gauge.

$$E = \epsilon\ A\ \Delta T \qquad \Gamma = \gamma\ d$$

$$y = G_{thG} \cdot \Delta T = \frac{E \cdot p}{1 + \Gamma \cdot p}$$

The output signal y is extracted from the heating power to achieve a constant temperature rise ΔT

Low pressure region ($\Gamma\ p \ll 1$):

- signal rises linearly with pressure p
- proportionality constant: E (gas species dependent)

High pressure region ($\Gamma\ p \gg 1$):

- signal tends to saturation value E/Γ (blue line, Fig. 3)
- light gases (H_2, He, Ne): heating power rises to extremely high values
- negative value for Γ describes singularity at $1/|\Gamma|$ (green line, Fig. 3)

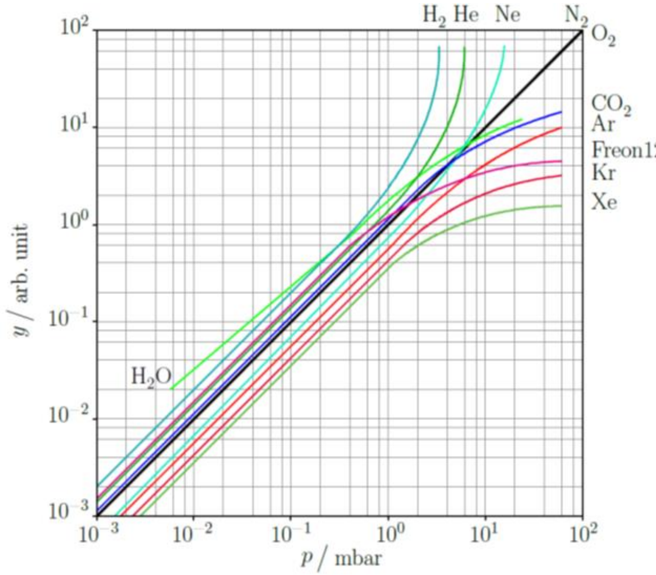

Fig. 1: Typical nomogram of a thermal conductivity vacuum gauge (Pfeiffer TPR280) of the sensor output signal y as function of gas pressure p for different gases.

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How to get rid off this gas dependency?

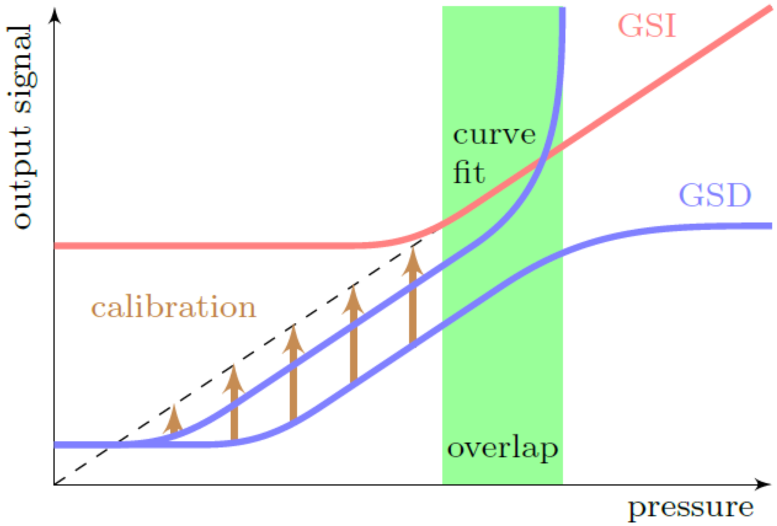

Fig. 2: Principle of automated calibration procedure in a system containing a gas species dependent (GSD) and a gas species independent (GSI) gauge.

- Overlap region during evacuation: recording of output signal y of the GSD gauge and the pressure p from the GSI gauge.
- Leaving overlap region: parameters E and Γ are calculated by curve fitting of Eq. (2) to the recorded values y and p.
- Implementation curve fitting: linear regression algorithm. Therefore modification of Eq. (2) to give a linear relation between the inverses of p and y.

$$\frac{1}{y} = \frac{1}{E} \cdot \frac{1}{p} + \frac{\Gamma}{E} \tag{3}$$

$$y = G_{thG} \cdot \Delta T = \frac{E \cdot p}{1 + \Gamma \cdot p} \tag{2}$$

In the measurement region of the GSD gauge, E and Γ are used to calculate a corrected pressure value p_c from its output signal y. This calibration of the GSD signal is done by solving Eq. (2) for p:

$$p_c = \frac{y}{E - \Gamma \cdot y} \tag{4}$$

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experimental result:

- GSI gauge: membrane sensor (MKS Baratron), 1 mbar to 1000 mbar
- GSD gauge: MEMS-based thermal conductivity vacuum gauge

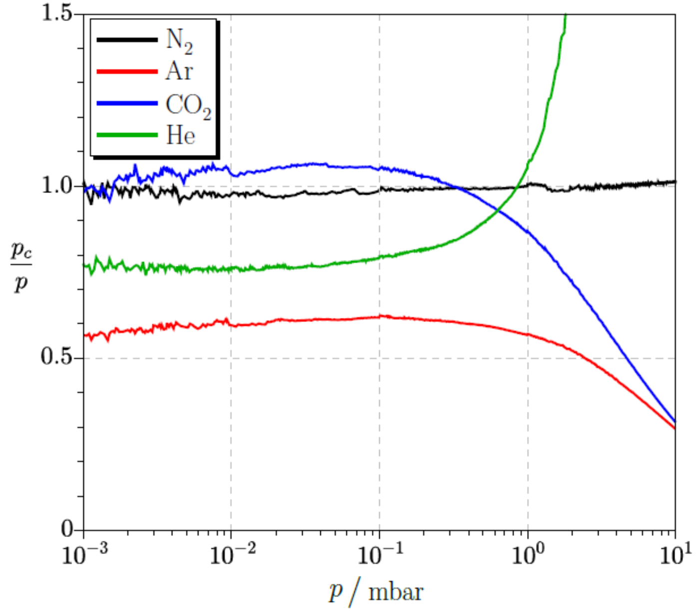

Fig. 7: Pressure p_c measured by the Pirani gauge divided by reference pressure manual calibration on N_2.

significant reduction of the gas species dependency

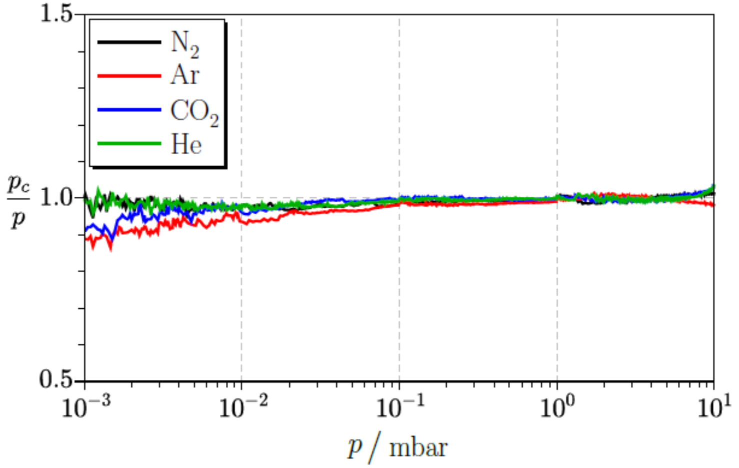

Fig. 8: Pressure p_c measured by the Pirani gauge divided by reference pressure p after automatic calibration.

Reference-Sensors (for absolute pressure measurement):

- MKS Baratron: 10^{-3} mbar … 1 mbar
- MKS Baratron: 1 mbar … 1000 mbar

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