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Active Heat-Loss Compensated Micro-Pirani Gauge for Vacuum Packages

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Content:

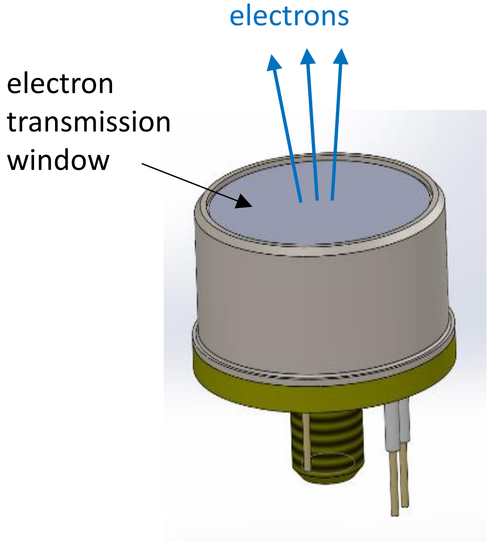
Pressure determination in vacuum package

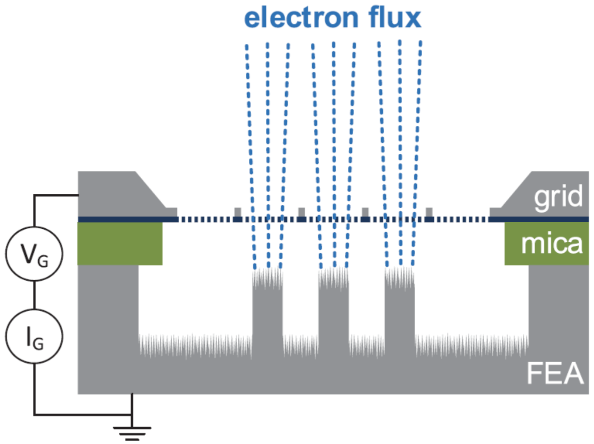
Several MEMS components or miniaturized MEMS applications require vacuum packaging:

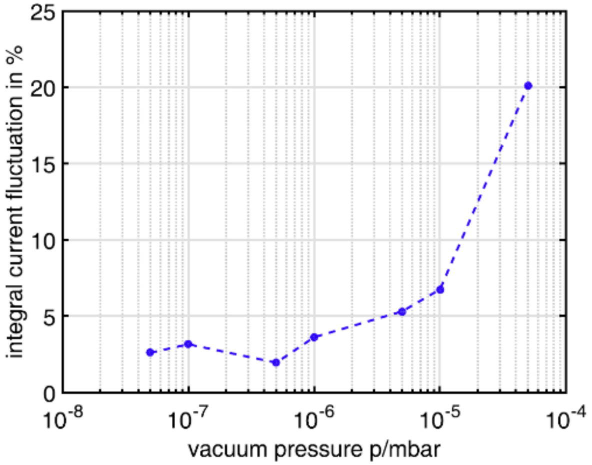
- acceleration sensors
- gyroscope sensors
- micro bolometer
- …

High vacuum packaging is required for field emission based electron sources or x-ray sources [4]

Vacuum range: < 10^{-5} mbar







[4] M. Bachmann et al. In: J. Vac. Sci. Techn. B 38, 023203 (2020)

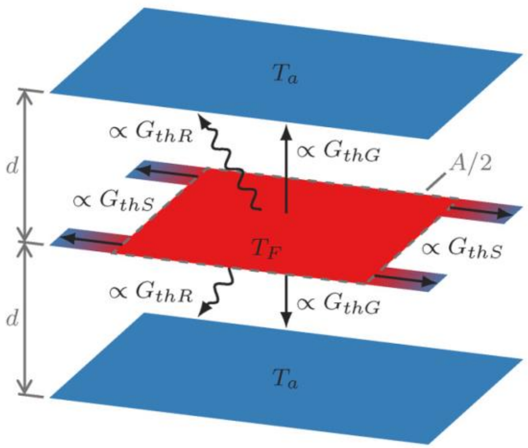
Background: Miniaturized Pirani vacuum gauges

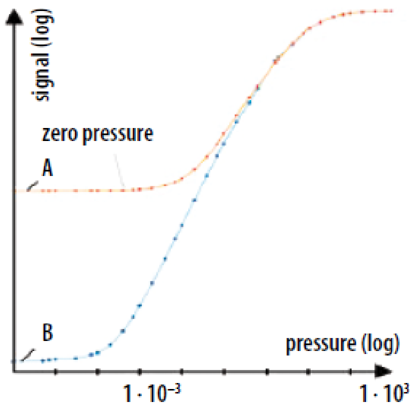
Measuring range: 10^{-5} to 10^{3} mbar

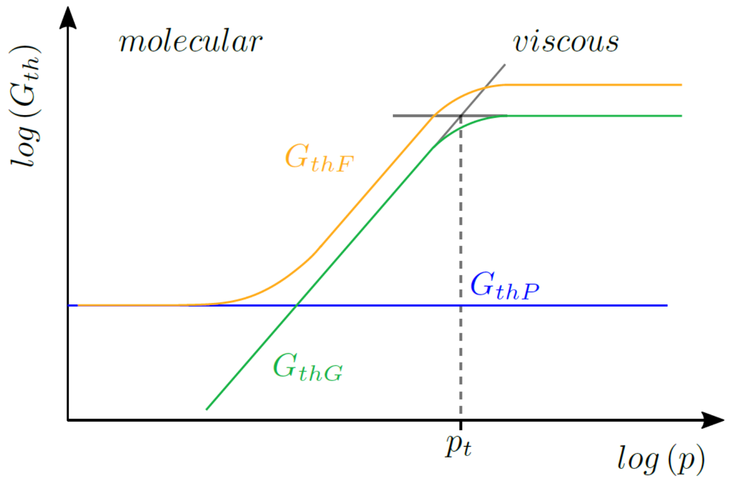
$$G_{thF} = G_{thG} + \underbrace{G_{thR} + G_{thS}}_{G_{thP}}$$

At low pressures: G_{thF} dominated by G_{thP}

Reduction of G_{thP} leads to a higher dynamic range and can extend the measuring range to lower pressures







Motivation: Reduction of G_{thP}

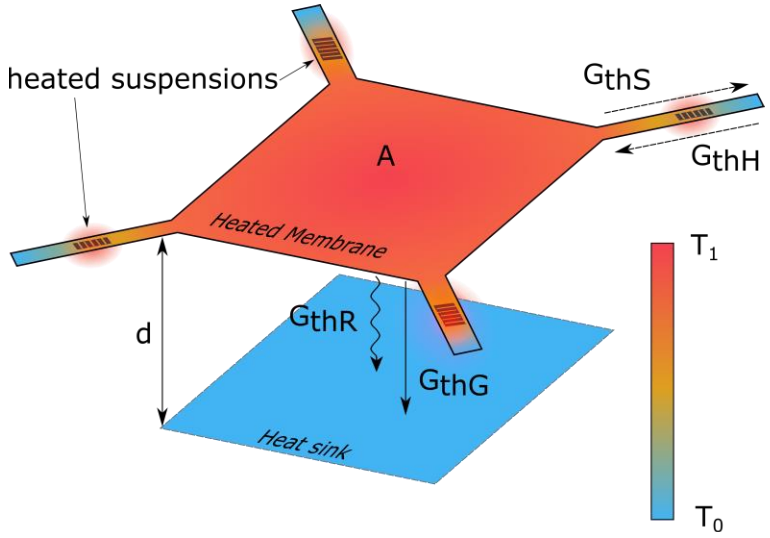
Approaches so far: Passive reduction of G_{thP}

Reduction of G_{thR}: Coating with material of low emissivity (e.g. Au) [1]

Reduction of G_{thS}: Small suspensions, using materials of low thermal conductivity [2,3]

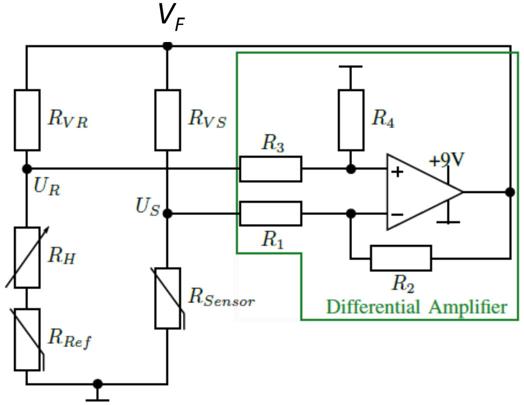
Our approach:

Active heat-loss compensation by additional heating elements located at the suspensions of the sensor membrane



[1] F. Völklein et al. In: J. Vac. Sci. Techn. A 31, 061604 (2013)
[2] H. Miyashita et al. In: Patent US8230746B2 (2011)
[3] L. Gu et al. In: Patent US9335231B2 (2016)

Theory: Influencing factors of Pirani Sensitivity

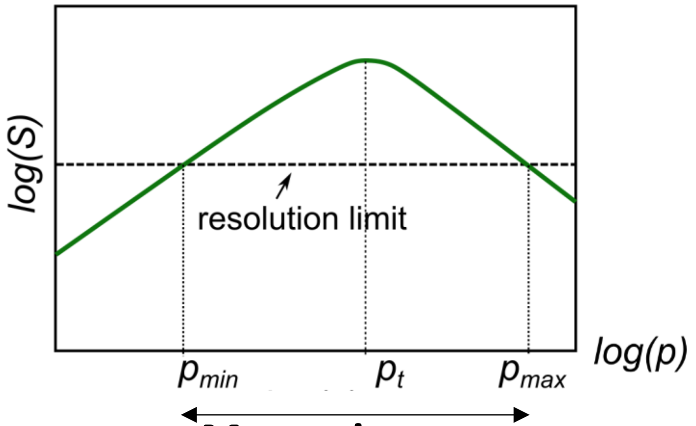


Constant temperature (CT) control circuit

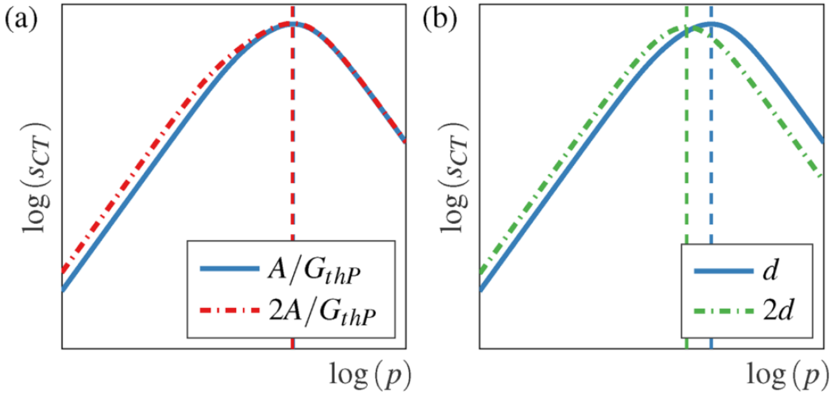
$$G_{th} = \frac{P_F}{\Delta T} = \frac{V_F^2}{R_0(1 + \alpha(T_0 + \Delta T)) \cdot \Delta T}$$

The sensitivity of an instrument is the change of output divided by the change of the measurand

$$S = \frac{\partial V_F}{\partial(\log_{10} p)}$$



$$S_{norm} = \frac{\ln(10)\,\frac{\varepsilon A}{G_{thP}}\,p}{2(\gamma d p + 1)^2 \sqrt{\left(\frac{\varepsilon A}{G_{thP}}\frac{p}{1+\gamma d p} + 1\right)\left(\frac{\varepsilon A}{G_{thP}}\frac{1}{\gamma d} + 1\right)}}$$

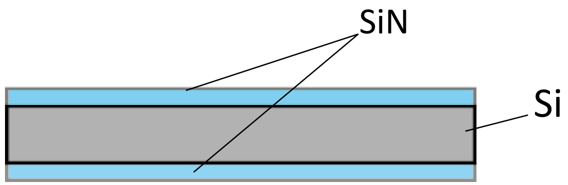


A reduction of G_{thP} leads to a higher sensitivity in the high vacuum regime

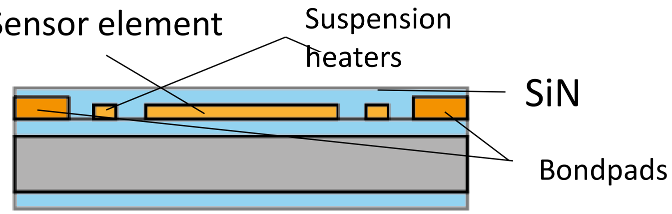
C. Langer, D. Berndt, R. Schreiner „ Sensitivity of thermal conductivity vacuum gauges for constant current and constant temperature operation“ In: J. Vac. Sci. Techn. B 40, 054203 (2022)

Sensor Design and Fabrication

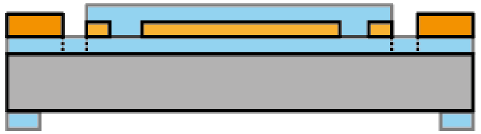
1. **Front- and backside SiN deposition** (PECVD)



2. **Deposition of heater structures and protection layer** (photo, PVD, PECVD)

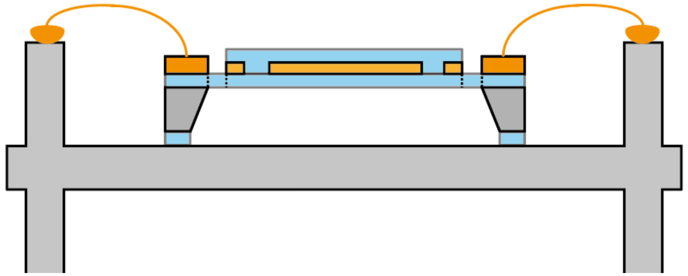


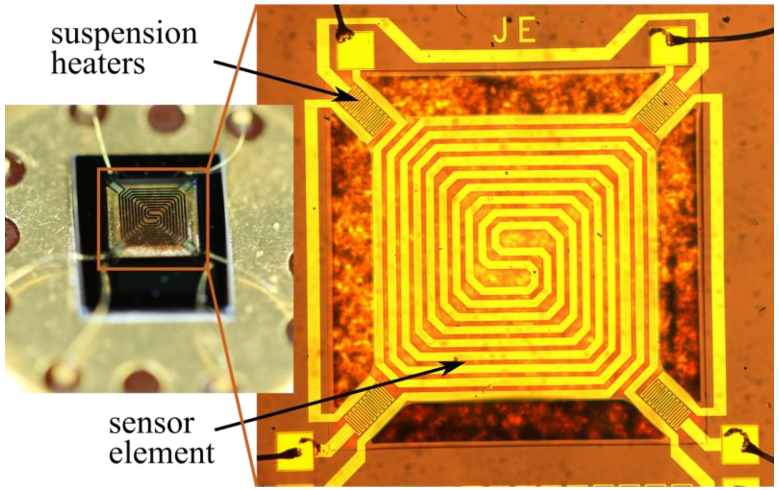
3. **Bondpad and backside opening** (dry etch)



4. **Membrane release** (wet etch)

5. **Mounting on TO-platform** and **wire bonding**





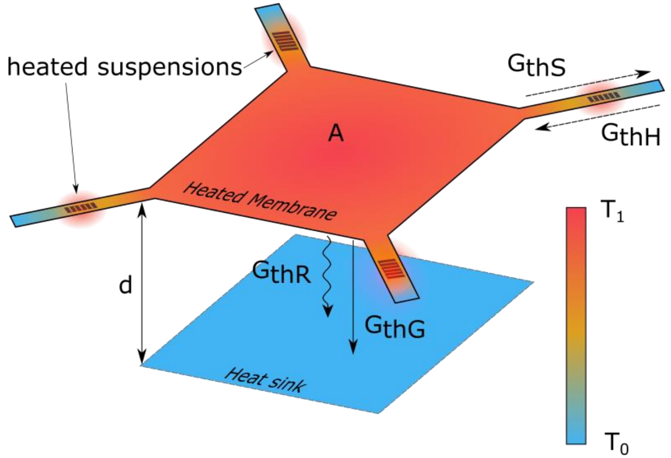
Experimental Setup : Sensor Operation

Sensor Element:

Constant Temperature (CT) Circuit

- constant temperature difference ΔT_{sensor} = **30°C** to the ambient
- Heating power is adapted when pressure changes in order to keep T_{sensor} constant

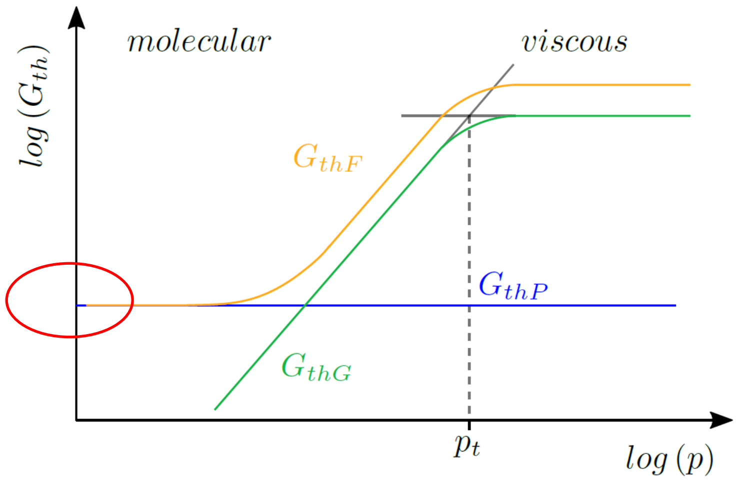
- **V_F as measured quantity of sensor**



Heated Suspensions: G_{thS} is not pressure dependent

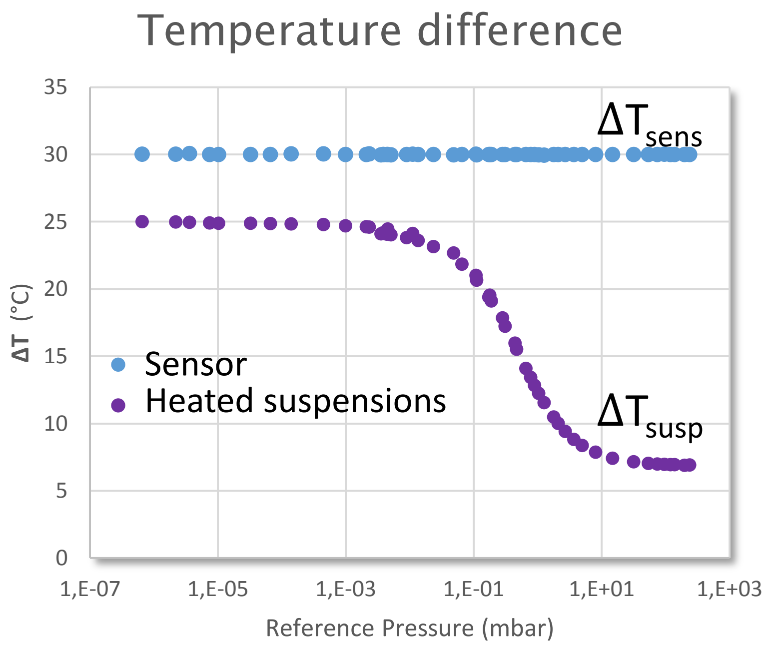
-> Constant Power (CP) Circuit

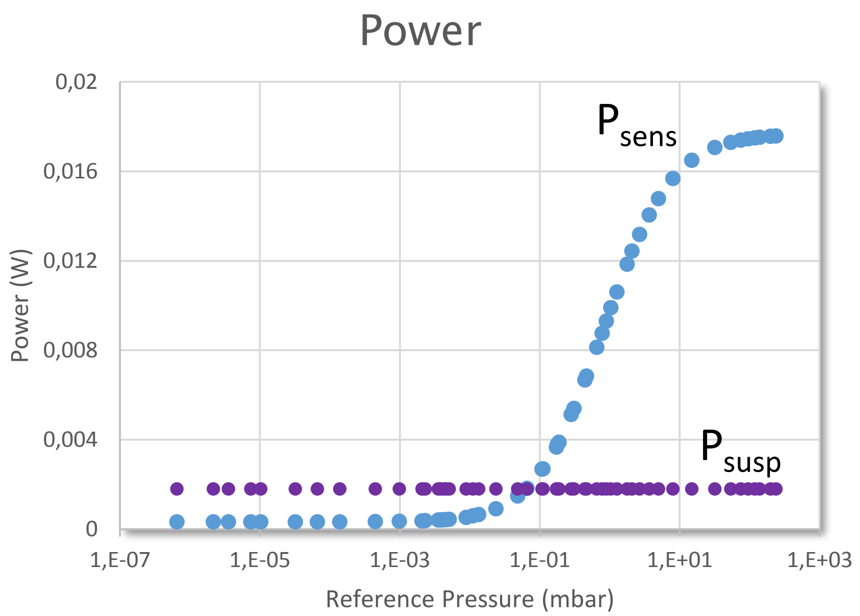
- at „zero" pressure $T_{susp} \approx T_{sensor}$
- determination of P_{susp} and maintaining throughout measurement to reduce the influence of G_{thS}



Constant Temperature and **Constant Power** operations are performed using a **digital PID control.**

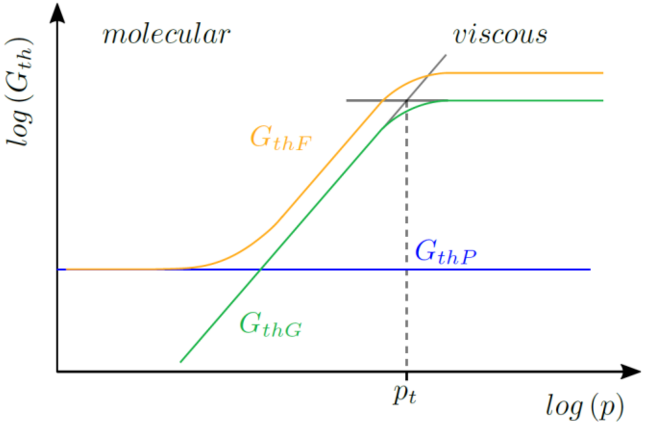
Temperature difference and power during active heat-loss compensation





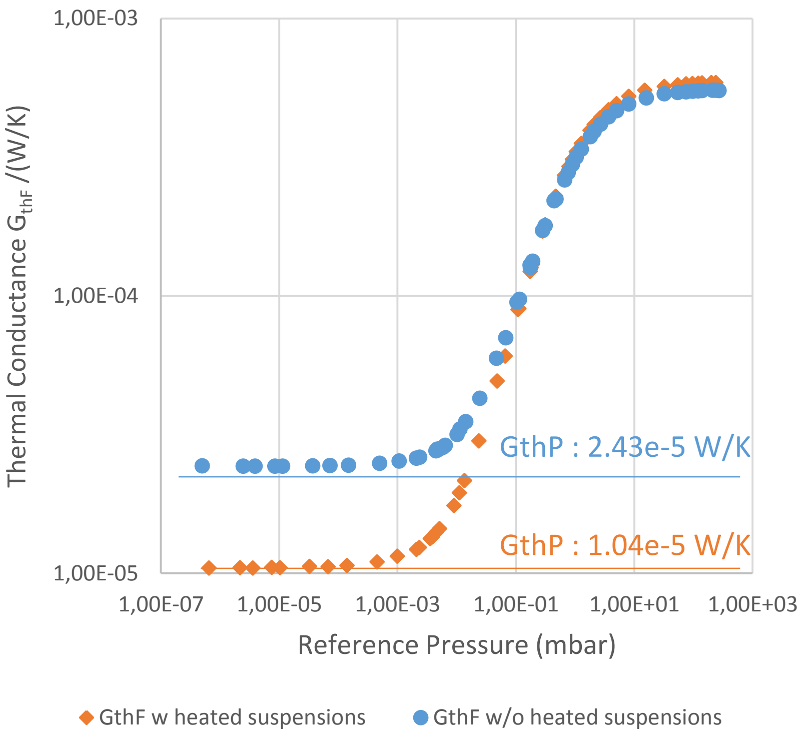
- Sensor temperature T_{sens} is constant (30°C) while power P_{sens} is varied with pressure
- P_{susp} = 1.8 mW is necessary to heat the suspensions to 25°C at “zero“ pressure. This power is then maintained throughout the whole pressure region

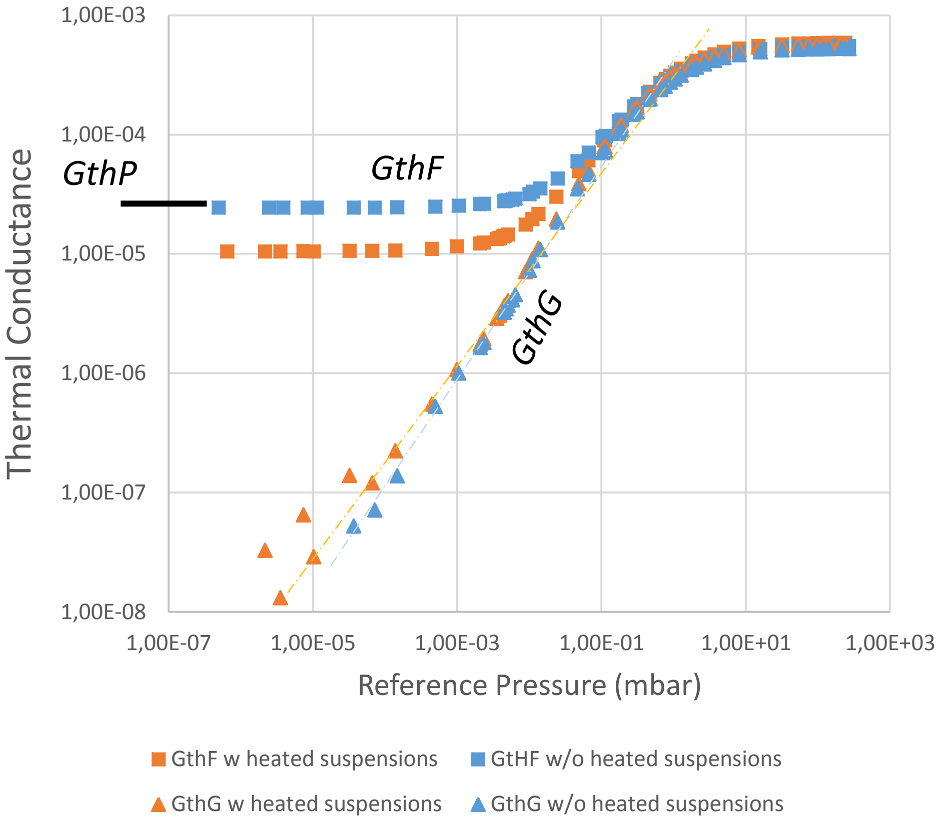
Thermal conductance



$$G_{thF} = \frac{P_F}{\Delta T}$$

$$G_{thF} = G_{thG} + \underbrace{G_{thR} + G_{thS}}_{G_{thP}}$$





- Parasitic heat loss (G_{thP}) is **reduced by over 50%** by implementing heated suspension

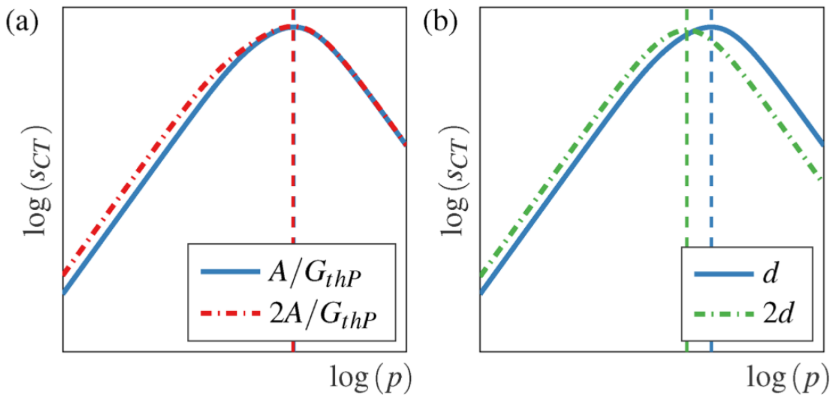
Sensor Sensitivity

Definition of sensitivity based on measured quantity V_F:

$$S = \frac{\partial V_F}{\partial(\log_{10} p)} \qquad S_N = \frac{S}{V_{FMAX}}$$

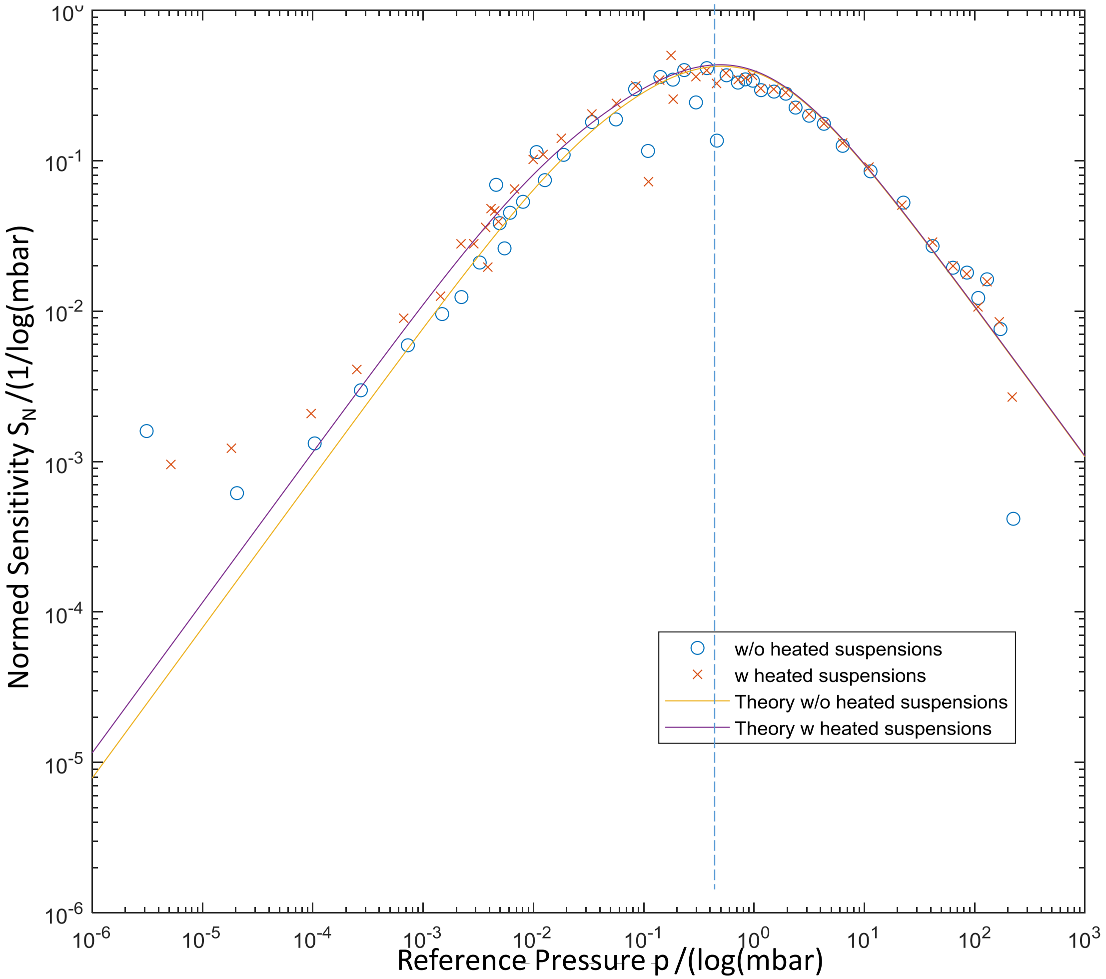
Sensitivity comparison with and without heated suspensions:

- High pressure region (>10^0 mbar): Sensitivity is unchanged
- Low pressure region (<10^0 mbar): Sensitivity higher with heated suspensions



Theory

Experiment



Conclusion

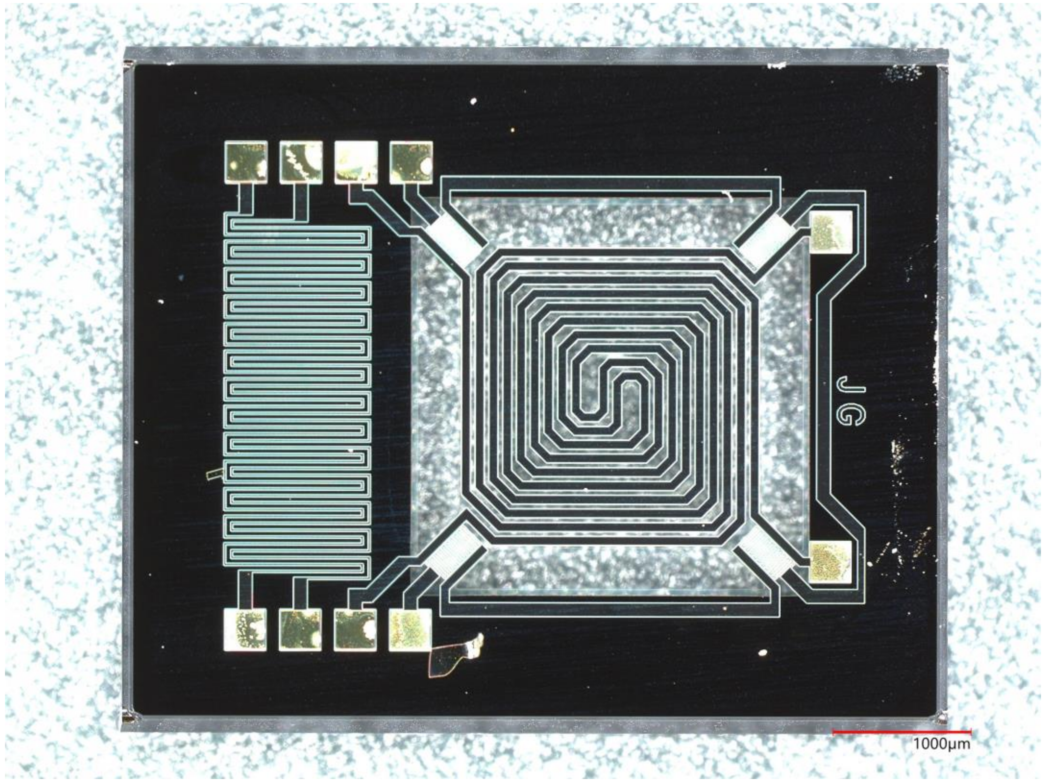
- Heat-loss compensation of Pirani sensors can reduce the parasitic contributions by more than 50%
- Higher dynamic range and improvement of the sensitivity in the low pressure region

Outlook

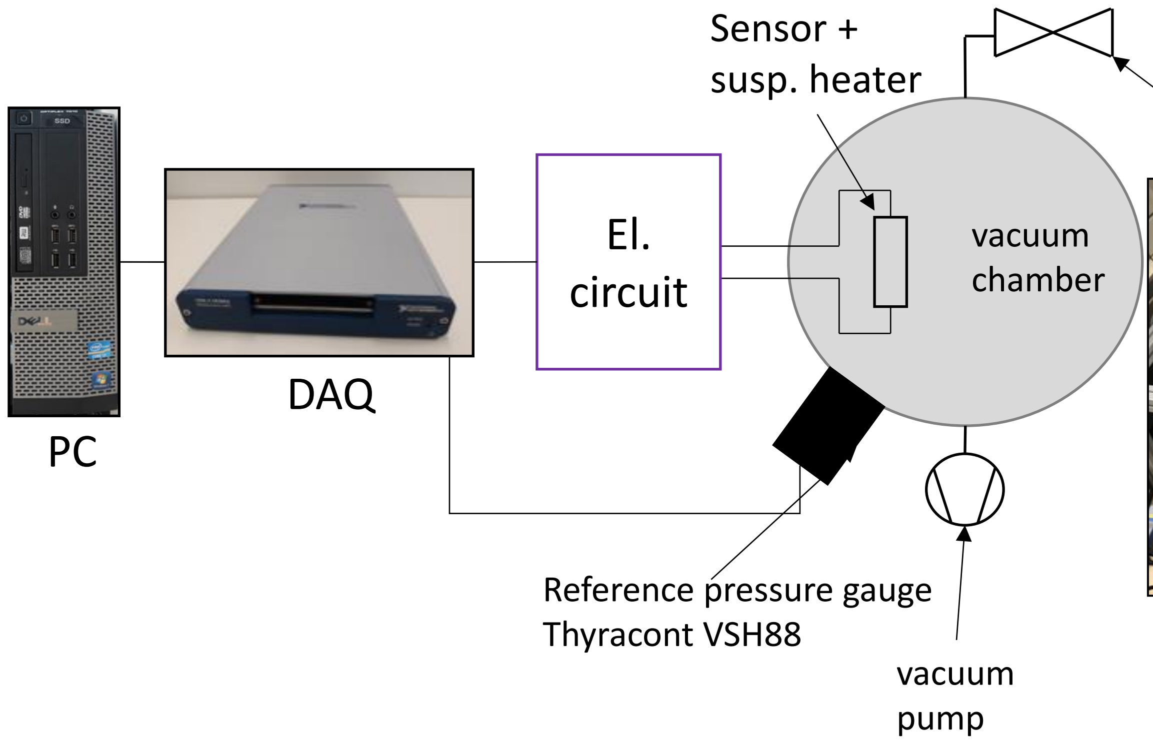
- Implement better electronic circuit to enhance resolution limit
- Further improving sensitivity in low pressure regions by adjusting gap distance to heat sink

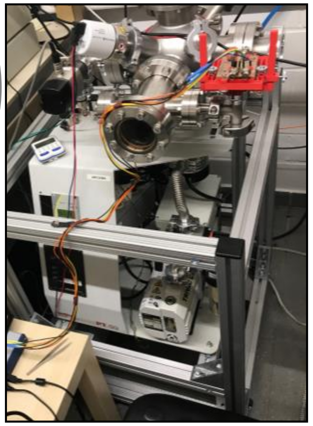
Thanks for your attention!

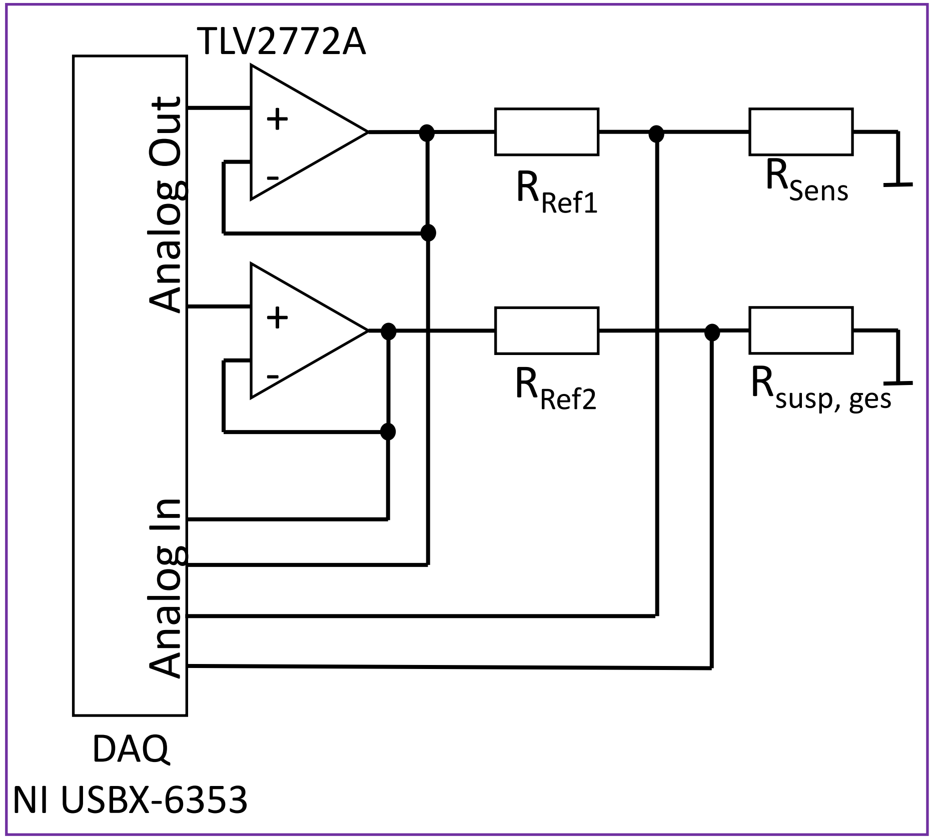
Any questions?



Experimental Setup : Vacuum Chamber and El. Circuit







Theory of thermal conductivity vacuum gauges

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

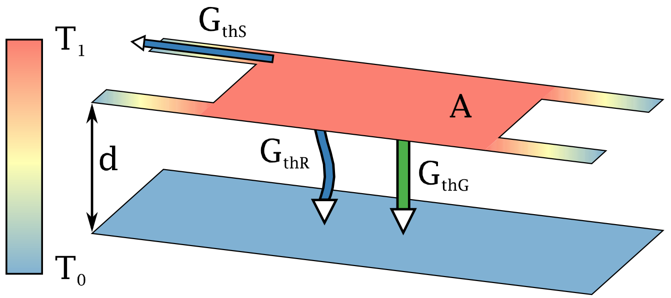
$$G_{thF} = G_{thG} + G_{thP}$$

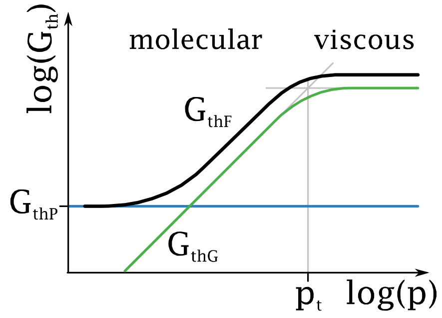
$$G_{thG} = \lambda_G \frac{A}{d} = \frac{\varepsilon\, d\, p}{1 + \gamma\, d\, p} \frac{A}{d}$$

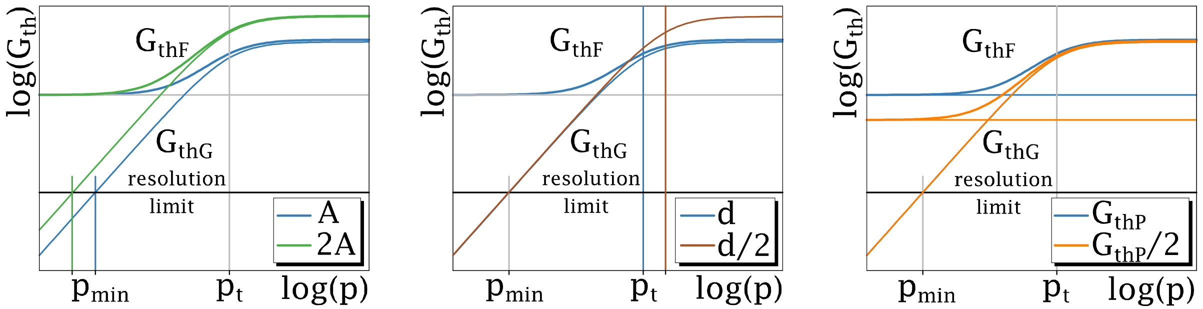
$$p < p_t \colon G_{thG} = \varepsilon\, A\, p$$

$$G_{thF} = \frac{P}{\Delta T} = \varepsilon\, A\, p + G_{thP}$$

$$p = \frac{1}{\varepsilon\, A}\left(\frac{P}{\Delta T} - G_{thP}\right)$$







Related Equations

Temperature dependent resistance

$R = R_0 (1 + \alpha \Delta T)$

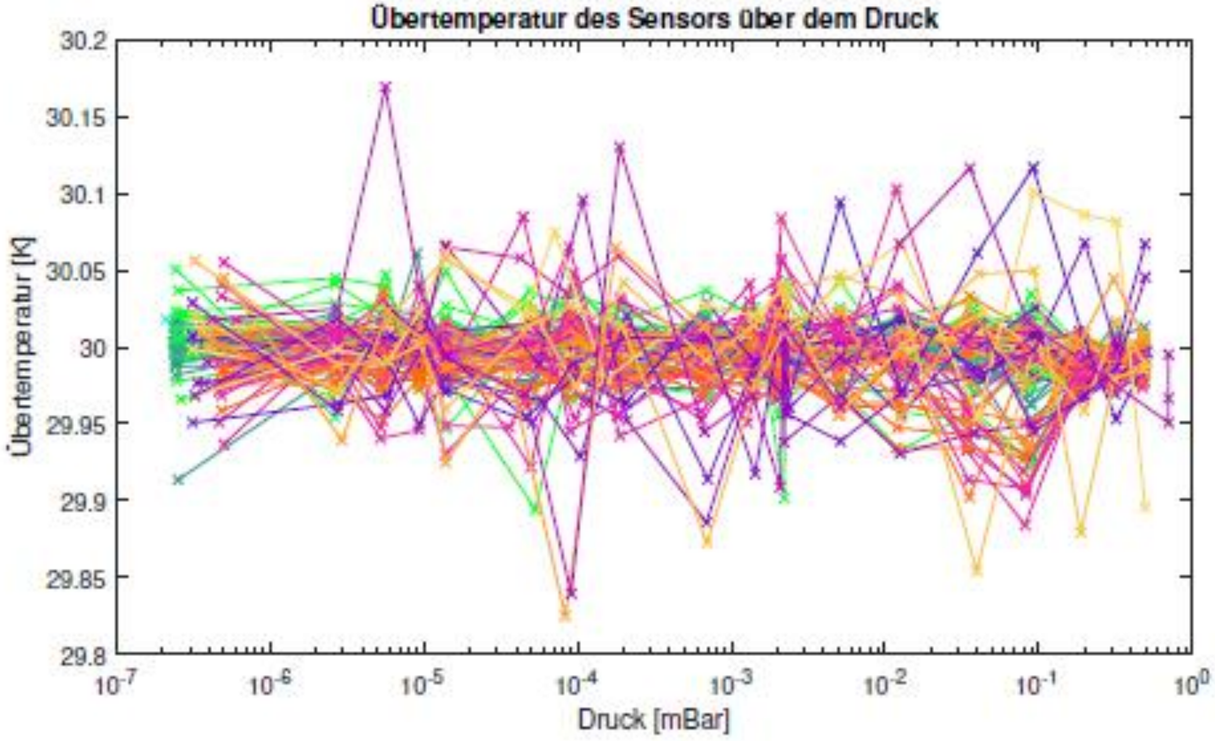
Temperature coeffiecient of resistance α

$\alpha = (R2 - R1) / R1 (T2 - T1)$

Heat conductance

$$P_S = G_{TH} \cdot (T_S - T_{amb})$$

$P_s = (G_g(p) + G_s + G_r) \cdot (T_s - T_{amb})$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Sensitivity definition by change of **thermal conductance ΔGtHF / Δlog(P)**