Fast Pressure Prediction with a MEMS Pirani Sensor for Protection of MOMA-MS

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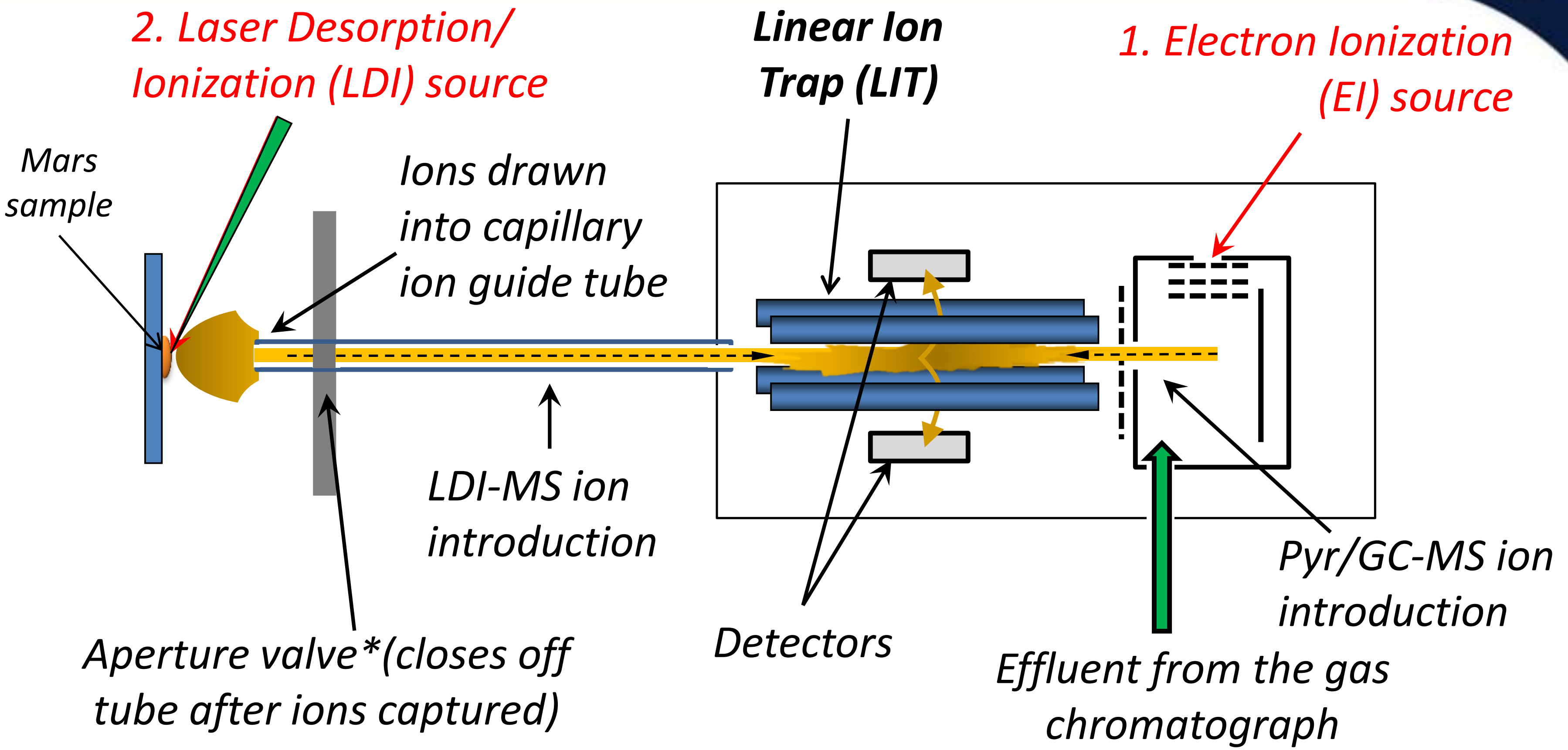
MOMA MS has two ion sources, an (1) EI source and (2) an LDI source.

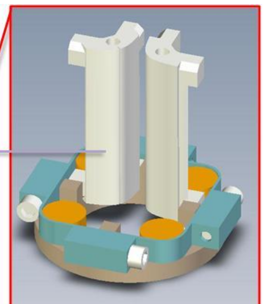


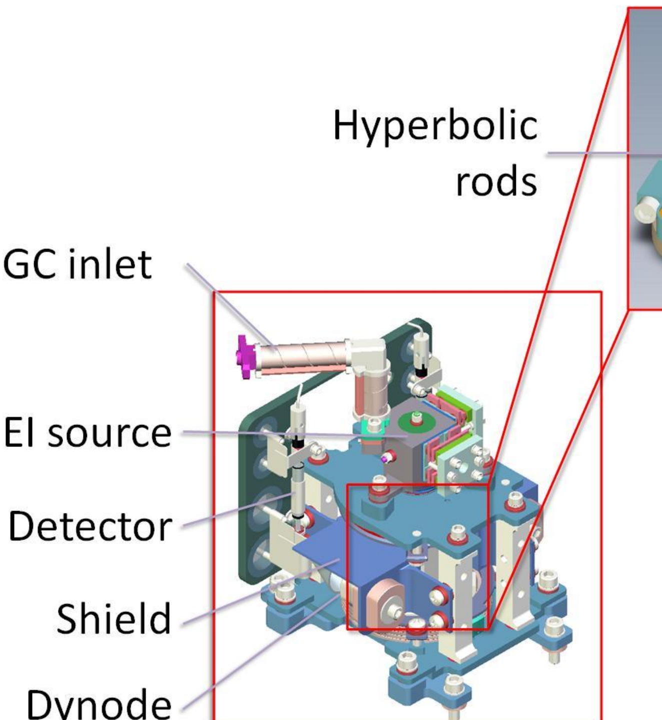
Definition:
Static mode: EI source (1) is used and gas composition is helium at 3 mtorr.
Dynamic mode: LDI source (2) is used and gas composition is mostly mars mix at pressures between 60 mtorr and <0.1 mtorr

*Anal Chem. 2008 Jun 1;80(11):4026-32. doi: 10.1021/ac800014v. Epub 2008 May 8

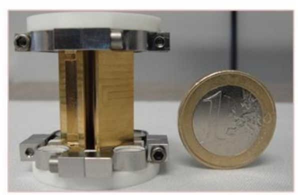
The pressure must be kept low to protect the filament (static mode) and high voltage supplies (dynamic mode)

MOMA-MS includes several elements requiring high voltges that are sensitive to overpressure





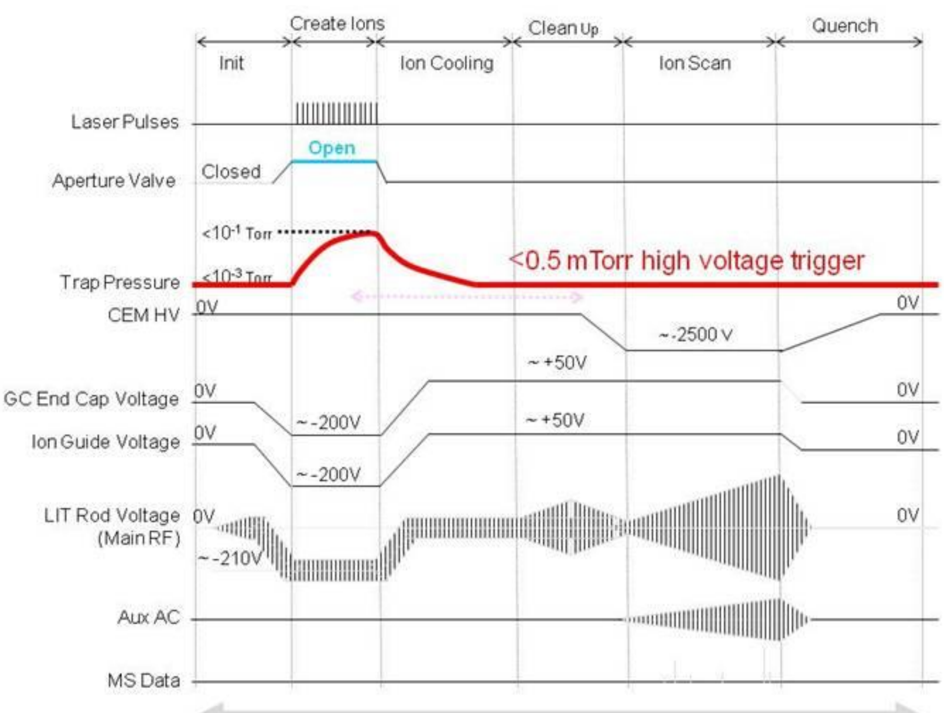
__Linear Ion Trap__



Components:	Problem with overpressure
Filament	Reduced lifetime
High voltage supplies: • Dynode • Channeltron multiplier • Rods of the LIT	Arc discharge followed by failure of the power supply
Pump	Reduced lifetime

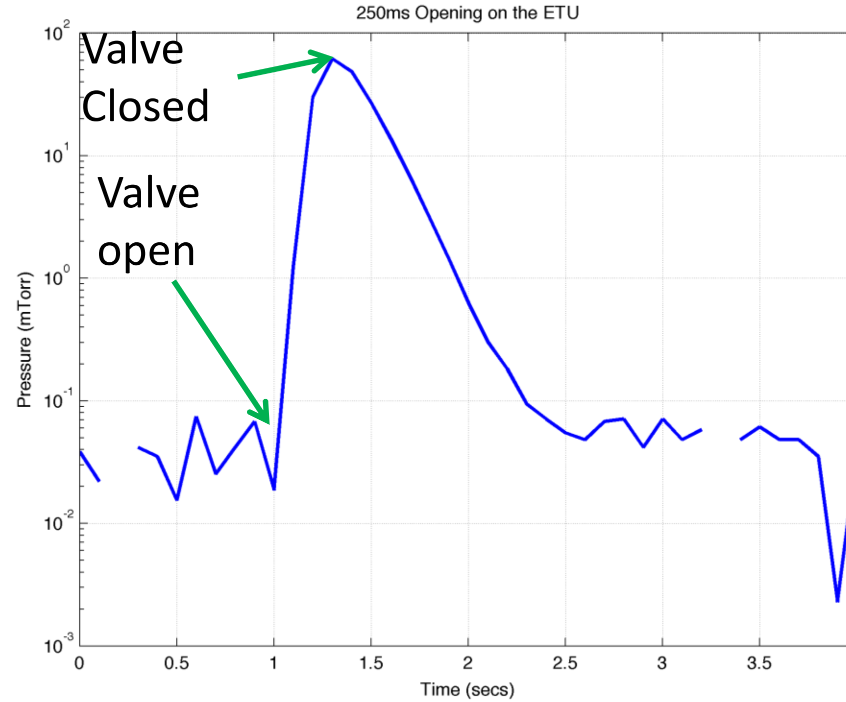
The pressure sensor must respond within less than a second

Timing diagram during dynamic mode: After the aperture valve closes, the pressure must get below 0.5 mtorr before the RF voltage can ramp (during the resonant ejection process). When SWIFT is used response time must be even shorter (not shown below).



1 – 3 seconds per cycle

Actual pressure variation during dynamic mode (using reference gauge)



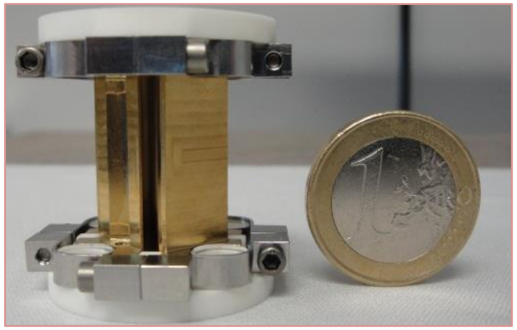
Valve Opening Time	Max Pressure	Pump down Time to 0.5mTorr
80ms	30mTorr	0.65secs
250ms	60mTorr	0.75secs
500ms	90mTorr	0.85secs
1000ms	95mTorr	0.9secs

Pump down time as low as 0.65 s

A MEMS pressure sensor is smaller than the MOMA ion trap unlike other common sensors

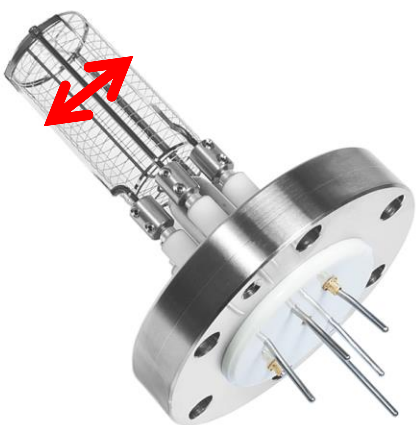
MOMA linear ion trap

Approx. 28 mm



It would be problematic if MOMA-MS should have a pressure sensor larger than its ion trap

BA gauge



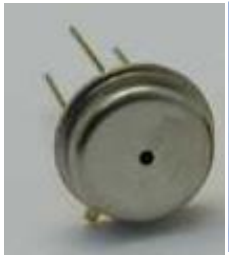
>33 mm

Capacitance Manometer or diaphragm gauge

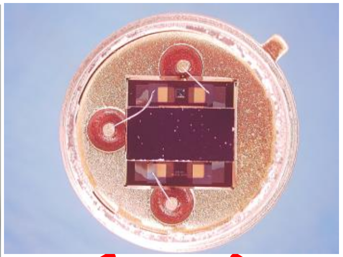
>50 mm

(Heimann) MEMS pirani sensor

Package (TO39) with lid



Package without lid

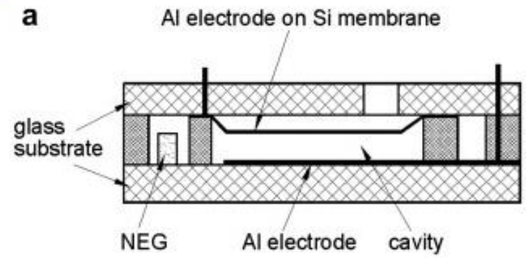


9.2 mm

Miniature thermal conductivity gauges are the ones best suited for fine to high vacuum pressure measurements

Miniature diaphragm gauges use the change of capacitance (or field emission from below) due to diaphragm deformation

Example

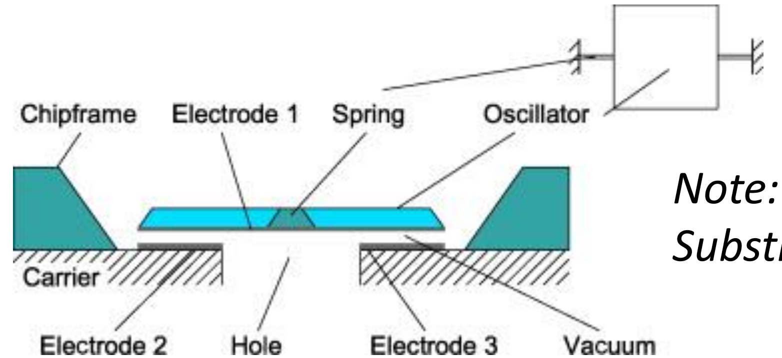


Hemni H, Shooji S, Yosimi K, Esashi M. Transducers'93, In: Seventh international conference on solid-state sensors and actuators, Denki-Gakkai Proc; 1993. p. 584.

Note:
Pressure range:
3E-3 to 3E-2 torr

Micromechanical torsion resonator gauges use the influence of gas pressure on the resonant frequency of an oscillating system

Example

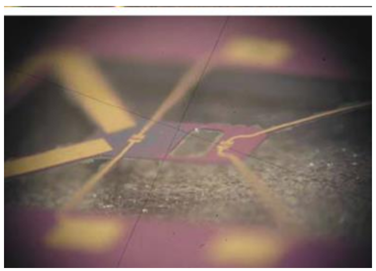


D. Tenholte, S. Kurth, T. Geßner, W. Dötzel,http://dx.doi.org/10.1016/j.sna.2007.05.031.

Note:
Substrates are 4”

Miniature thermal conductivity gauges use the change of gas thermal conductivity and convection with pressure (commercially available from MKS,Heimann,Xensor)

Unusual Example



M. Kimura, F. Sakurai, H. Ohta, T. Terada. Microelectronics Journal, 38 (2) (2007), pp. 171–176

Note:
Great pressure range
7.5 E-6 to 760 torr.

Volklein's carefully optimized MEMS pressure sensors can detect pressure variations from 1E-6 to 10 torr

Researcher	Type of gauge		Pressure range (Torr)
Van Herwaarden, Sarro, 1988[1]	Heated cantilever combined with thermopile		10^{-3}–100
Völklein and Schnelle, 1991[2]	Heated resistor combined with thermopile (Bi resistor, Bi/Sb thermopile)		10^{-3}–$7.5\cdot10^{+2}$
Mastrangelo and Muller, 1991[3]	Microbridge (poly-Si beam)		$7.5\cdot10^{-2}$–75
Robinson *et al.*, 1992[4]	Resistor on dielectric membrane (poly-Si)		10^{-2}–100
Swart *et al.*, 1994[5]	Microbridge (poly-Si)		10^{-1}–10^{+3}
Paul *et al.*, 1994[6]	Resistor on dielectric membrane (poly-Si)		$7.5\cdot10^{-1}$–$7.5\cdot10^{+2}$
Shie *et al.*, 1995[7]	Resistor on dielectric membrane (platinum)	1 →	10^{-7}–1 [a]
Chuo *et al.*, 1997[8]	Resistor on dielectric membrane (platinum)		10^{-1}–10^{+5}
Stark *et al.*, 2003[9]	Resistor on dielectric membrane (platinum)		10^{-2}–10^{+3}
De Jong *et al.*, 2003[10]	Resistor on dielectric membrane (platinum)		$7.5\cdot10^{-2}$–150
Chae *et al.*, 2004[11]	Microbridge (p++ silicon coil)		$2\cdot10^{-2}$–2
Moelders *et al.*, 2004[12]	Microbridge		10^{-2}–1
Doms *et al.*, 2005[13]	Microbridge (platinum beam)		$7.5\cdot10^{-1}$–$7.5\cdot10^{+2}$
Stark *et al.*, 2005[14]	Microbridge (poly-Si beam)		10^{-2}–$7.5\cdot10^{+3}$
Zhang *et al.*, 2006[15]	Resistor on dielectric membrane		$7.5\cdot10^{-2}$–$7.5\cdot10^{+2}$
Mitchell *et al.*, 2008[16]	Microbridge (poly-Si beam)		10^{-2}–$7.5\cdot10^{+2}$
Khosraviani and Leung, 2009[17]	Microbridge (nichrome film)		10^{-1}–$7.5\cdot10^{+3}$
Qui *et al.*, 2009[18]	Metallic wire		$7.5\cdot10^{-3}$–$7.5\cdot10^{-1}$
Li *et al.*, 2010[19]	Microbridge		$8\cdot10^{-2}$–$2\cdot10^{+2}$
Jiang *et al.*, 2010[20]	Microbridge		$7.5\cdot10^{-4}$–7.5
Schlecher *et al.*, 2011[21]	Ni-microbeam		$2.25\cdot10^{-2}$–$7.5\cdot10^{+2}$
Wang *et al.*, 2011[22]	W-microplate		$7.5\cdot10^{-4}$–$7.5\cdot10^{+2}$
Santagata *et al.*, 2011[23]	Tube-shaped		10^{-3}–10^{+3}
Mercier *et al.*, 2012[24]	Cr/Au-resistor on $LiNbO_3$-substrate (SAW-device)	2 →	$7.5\cdot10^{-6}$–$7.5\cdot10^{+2}$
Chen, 2012[25]	Microbridge		1–10^{+3}
Present paper		3 →	$1\cdot10^{-6}$–10

Note: The lower limit of pressure range depends on noise reduction. Given a signal of 100 µV, Shie's actual lower limit (1) is 4E-5 torr . The lowest lower limit, 1E-6 torr is provided by Heimann (3)

Volklein J. Vac. Sci. Technol. A 31, 061604 (2013)

How to determine pressure using a pirani sensor by determining two temperatures

Concept:

The loss of heat through gas conduction is proportional to pressure.

Monitoring the temperature of an electrically heated membrane enables the determination of the pressure.

Non-equilibrium heat equation (equilibrium version provided by Volklein et al. (2013)): Note: Heimann optimized membrane geometry and materials to reduce P_r and P_{sc}

$$C\frac{dT}{dt} = N - P_{sc} - P_r - P_{gc}$$

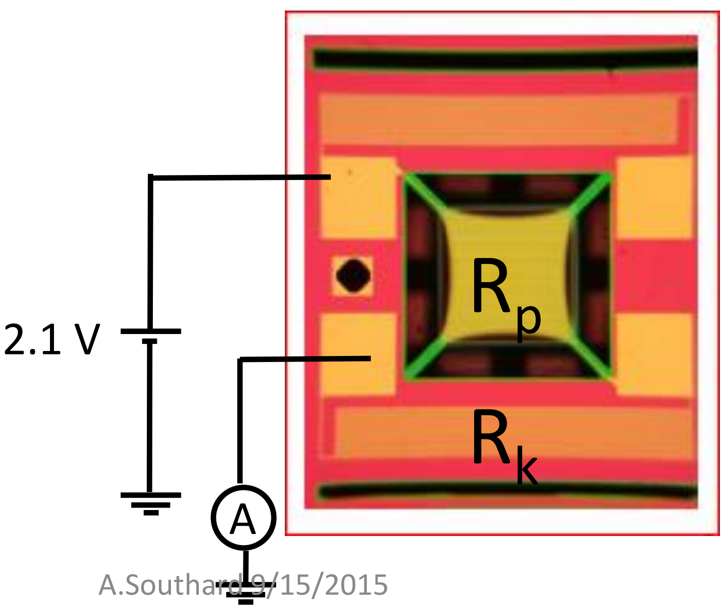
$$p = \frac{1}{\gamma T_0^{(-0.5)} * A * (T - T_0)}\left(N - C\frac{dT}{dt} - G_c(T - T_0) - 2\sigma A \varepsilon_{eff}\left(T^4 - T_0^4\right)\right)$$

The two temperatures are found by measuring the resistance of two resistors

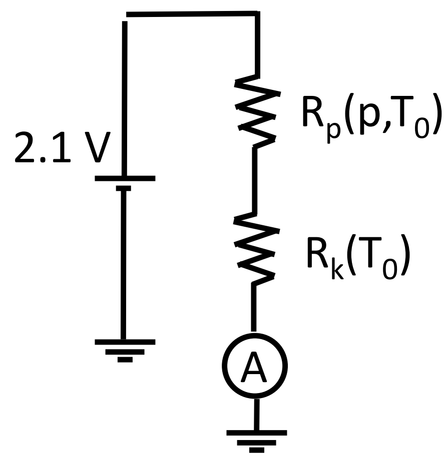
Determining temperatures with the Heimann mems pirani sensor:

The membrane temperature and ambient temperature are found by measuring the resistance of the membrane heater, $R_p(p, T)$, and a second resistor thermally sunk to the heat sink, $R_k(T_0)$.

Picture of membrane with electrical



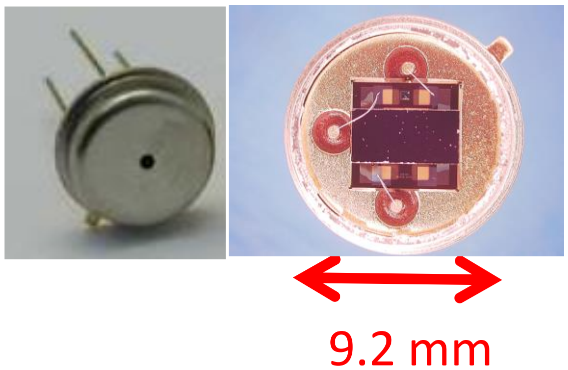
Equivalent circuit:
Measuring voltage V_k and current A give resistances



(Heimann) MEMS pirani sensor

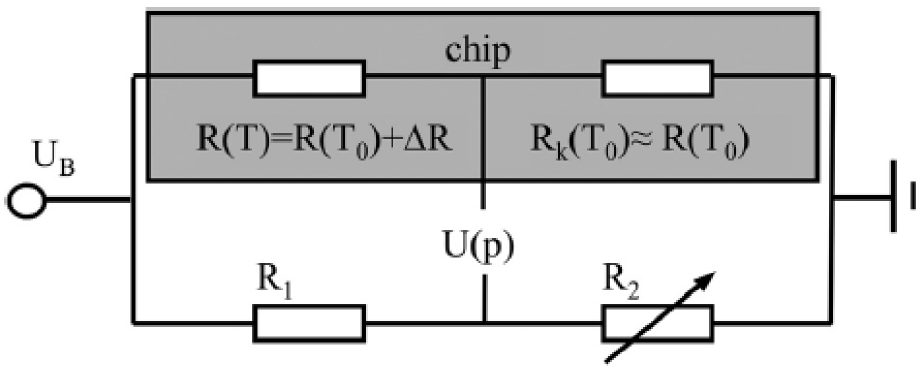
Package (TO39) with lid

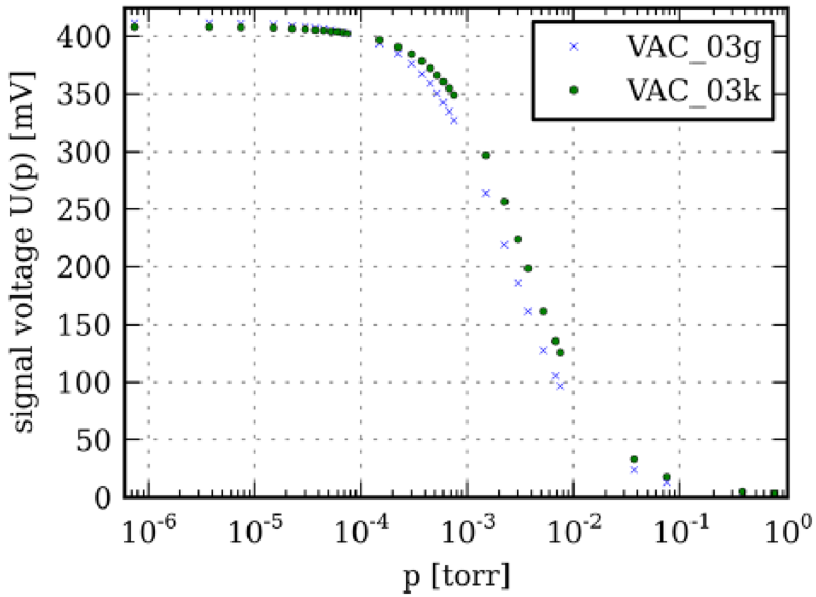
Package without lid



Note: Power use < 200 μWatts. Using matched temperature coefficients helps to control for ambient temperature variation

Heimann's suggested use

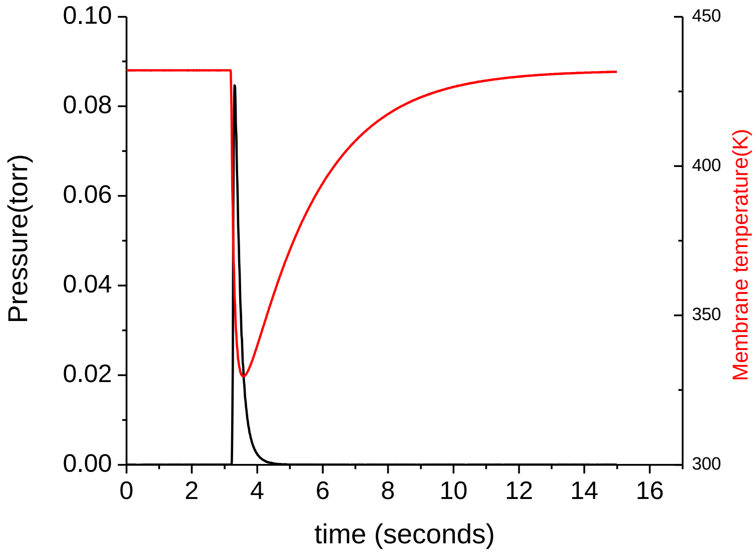




How to deal with slow response of the Heimann mems pirani sensor (model HVS-03k)

Obstacle:

Response is slow due to heat capacity of membrane



Solutions:

The full, non-equilibrium heat equation must be solved. Sensor to sensor variability even among the same batch requires calibration of G_c, ε_{eff}, C, and γ to achieve the target pressure accuracy over ambient temperature and for the two important gases used with MOMA helium and mars mix

$$p = \frac{1}{\gamma T_0^{(-0.5)} * A * (T - T_0)} \left(N - C\frac{dT}{dt} - G_c(T - T_0) - 2\sigma A \varepsilon_{eff}\left(T^4 - T_0^4\right)\right)$$

Since the lower limit of pressure detection strongly dependent on electrical noise (thermal, EMI), digital and analog filtering required to deal with derivative term.

Calibrations process starts with (1) 2^{nd} order dependence of resistance on temperature for both resistors in an oven.

Oven setup for Resistance-temperature correlation

Note: Source small 10 µA current to avoid self-heating and measure voltage drops.

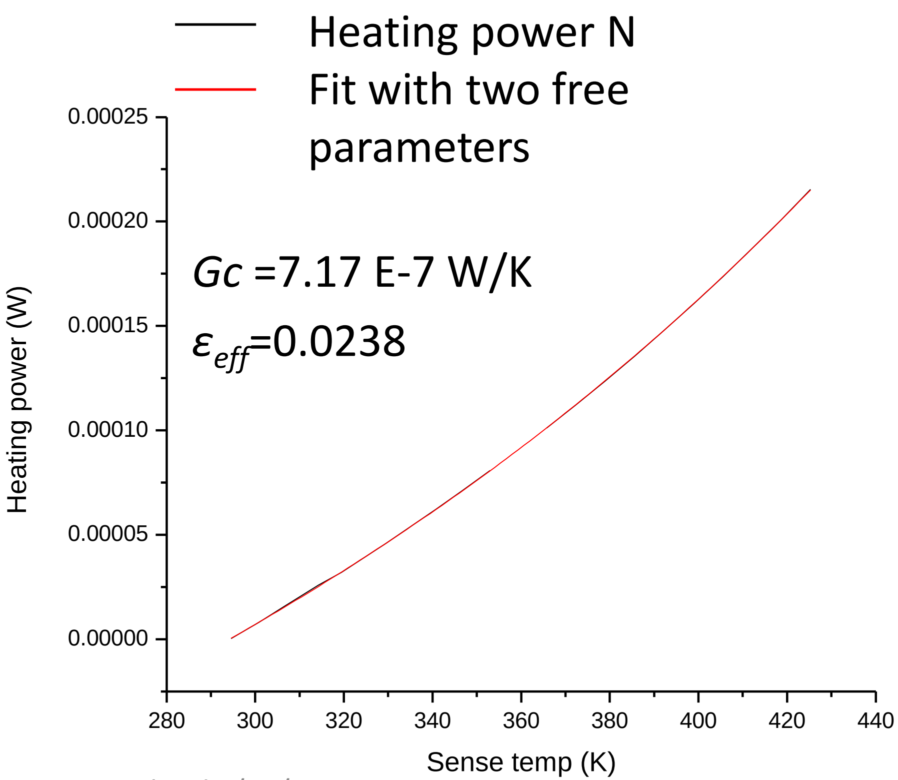
Determining Gc & ε_{eff} using a two parameter fit

At low pressure (~1e^{-6} Torr), thermal equilbrium

$$N = G_c(T - T_0) + 2\varepsilon_{eff} A^* \sigma\left(T^4 - T_0^{\ 4}\right)$$

N is the heating power, A is the membrane area, and σ is the Stefan-Boltzmann constant.

At T_0=293 K, we can vary *T* and *N* by changing the applied voltage. We can then fit the right side of the equation to the calculated heating power by treating Gc & ε_{eff} as free parameters



Fits routinely achieve R^2 of 0.99999

Note:

The graph to the right was obtained with a voltage sweep up to 2.7 V. Experiments done by us and Heimann would later suggest that device failure was occurring due to thermal stress and lower bias voltages must be used.

The scaling factor γ is found by sweeping pressure and scaling results

Concept:

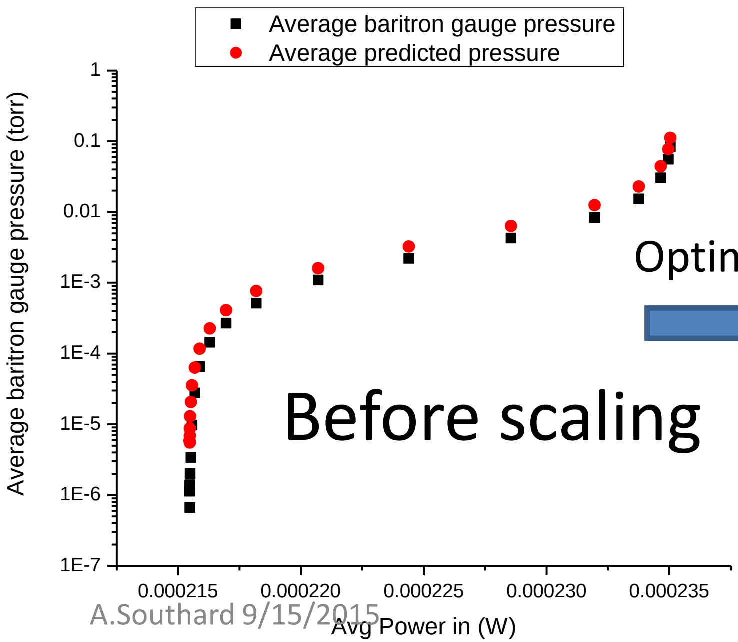
The scaling factor γ depends on the mass of the gas molecule and the accommodation coefficient, a measure of how effective energy transfer is at the surface of the membrane

Procedure to determine γ :

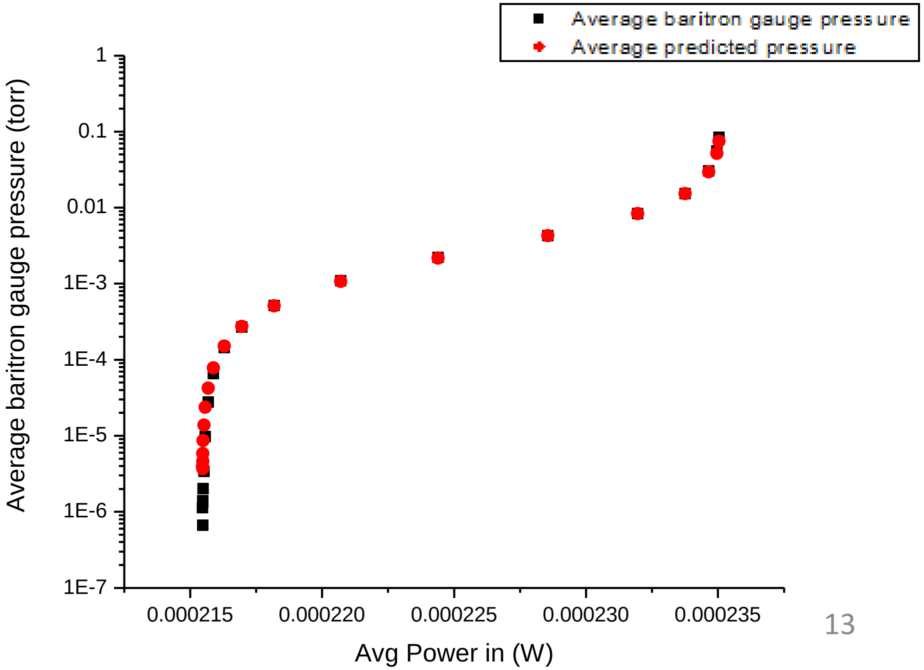
Use a baratron reference gauge to vary pressure from ~1e^{-6} Torr to 0.1Torr and choose γ to match the reference pressure at reference pressure of 0.01 torr (under equilibrium conditions).

Note: This is done for both helium and mars mix. These methods provide information about surface physics.

$$p = \frac{1}{\zeta * A * T_0^{(-0.5)} * (T - T_0)} \left(N - P_r - P_{sc}\right)$$



Optimizing γ



Using smoothing and averaging to determine heat capacity

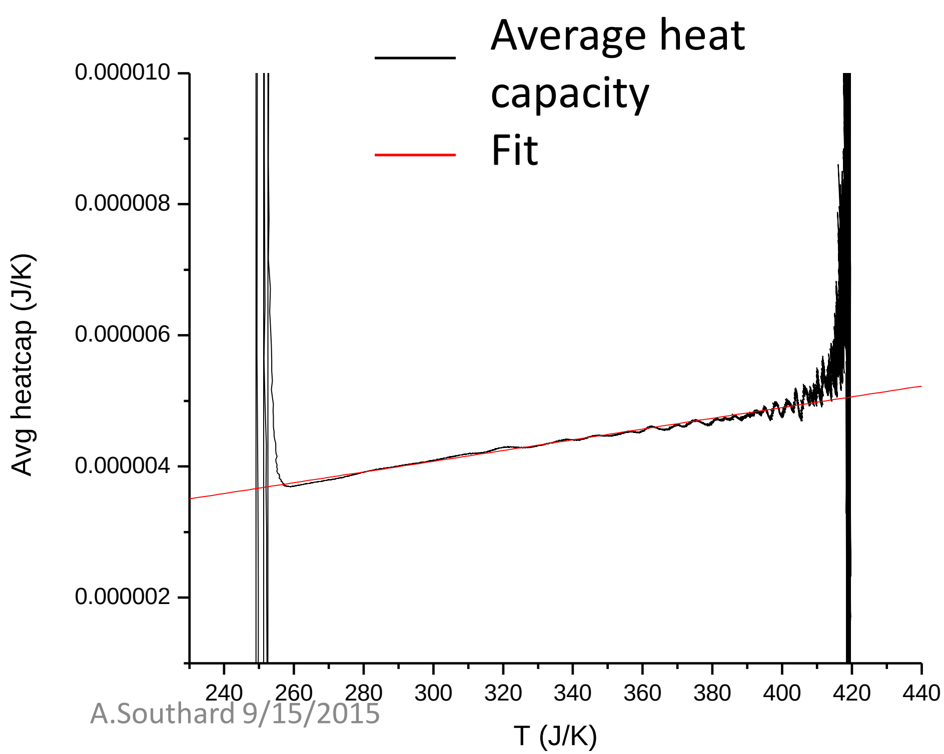
Method:

The heat capacity is determined by pulsed calorimetry: Under high vacuum, the sensor is powered on abruptly at an ambient temperature of 293 K and voltage & current measurements are taken as the sensor heats up

Signal processing steps:

1) All power terms are smoothed with a centered moving average
2) Five experiments are synced and averaged to improve S/N
3) The resulting average heat capacity vs. *T* is twice smoothed with a centered moving average and fit with a first order equation in T

$$C = \frac{N - P_r - P_{SC}}{\left(\frac{dT_p}{dt}\right)}$$



Coefficients determined from linear fit

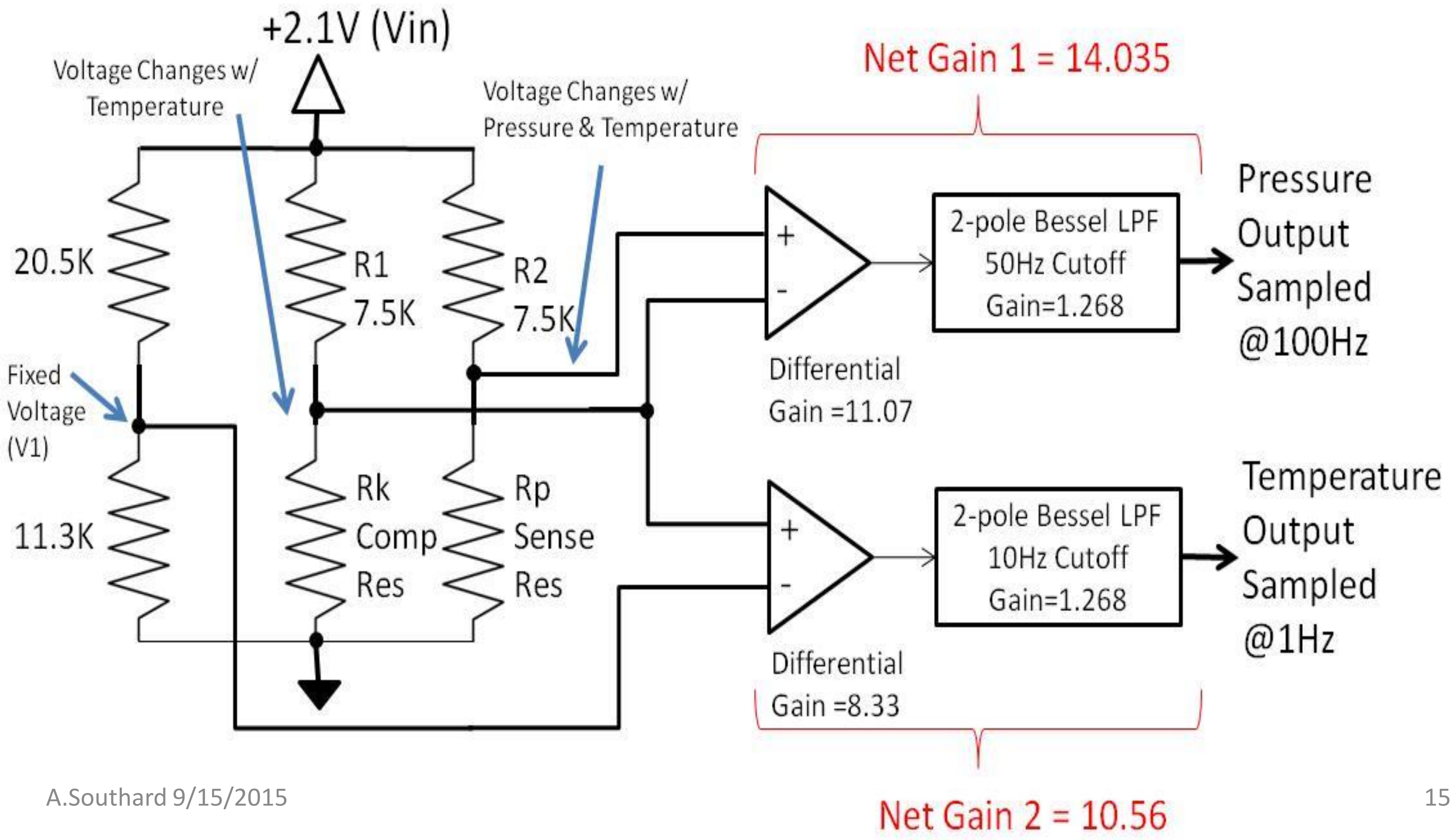
C=C1+C2*T

Typical values:

C1=2E-6 J/K, C2=5E-9 J/K^2

The sensor control circuit provides filtering, gain, and removes offset

Simplified circuit diagram for the sensor control circuit
Note: Control circuit uses milliWatts of power (signficantly more than sensor but still not much)



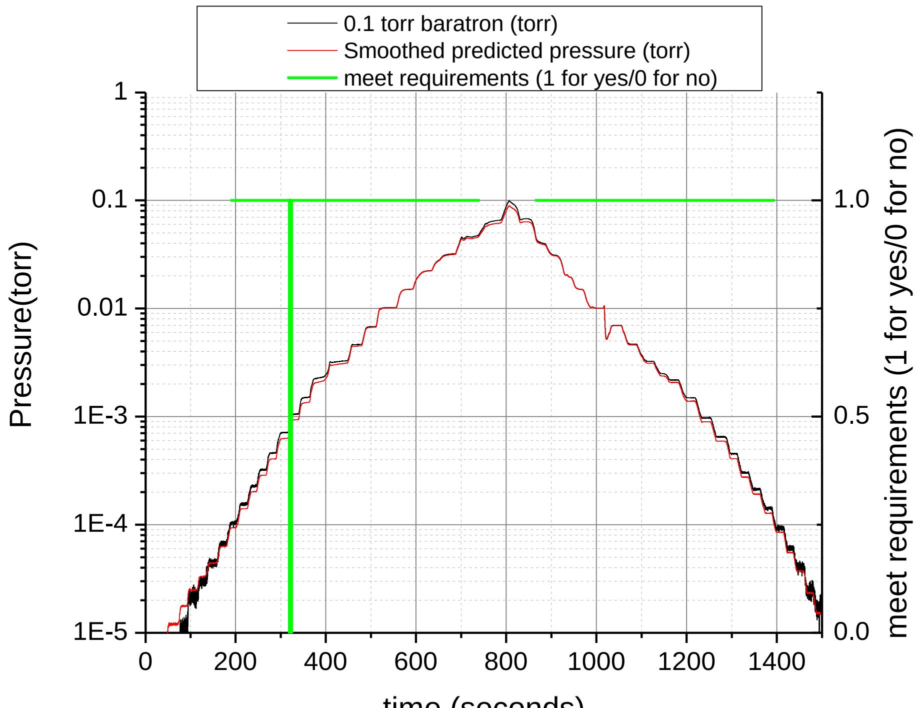
Predicting helium pressure at -30 and 80 °C

Ambient temperatures on MOMA can vary from -30 to 80 °C

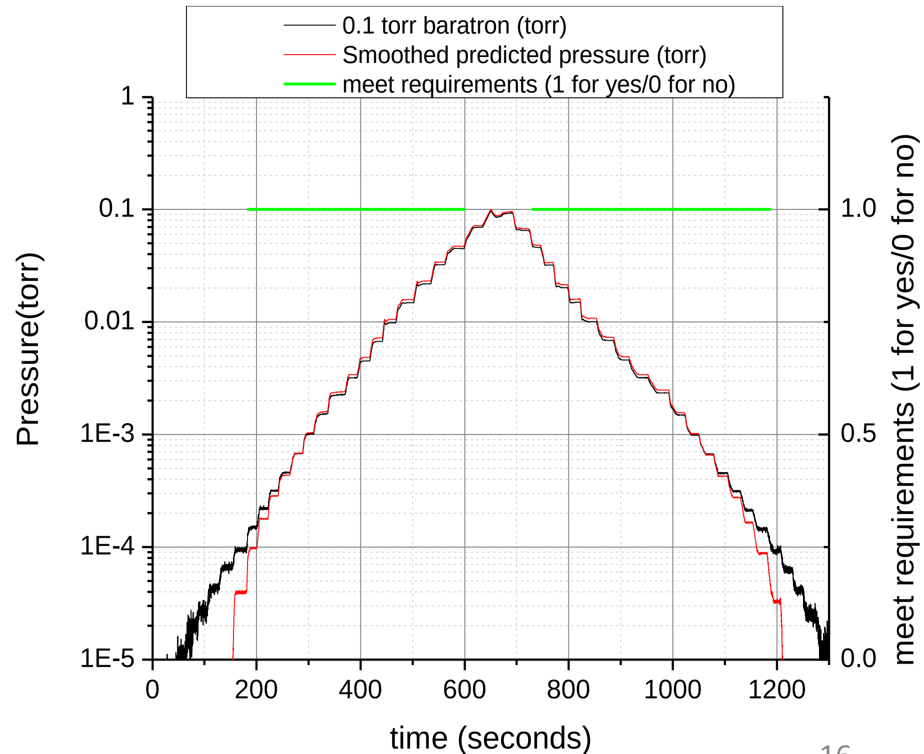
Requirements:

- 0.1 mtorr accuracy in the 0.1 to 1 mtorr regime
- 20% accuracy in the 1 to 50 mtorr regime

T_0=-30 °C



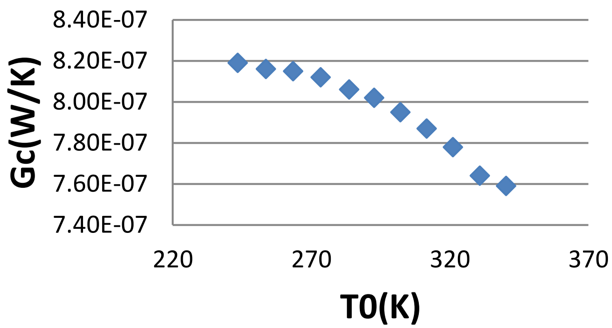
T_0=80 °C



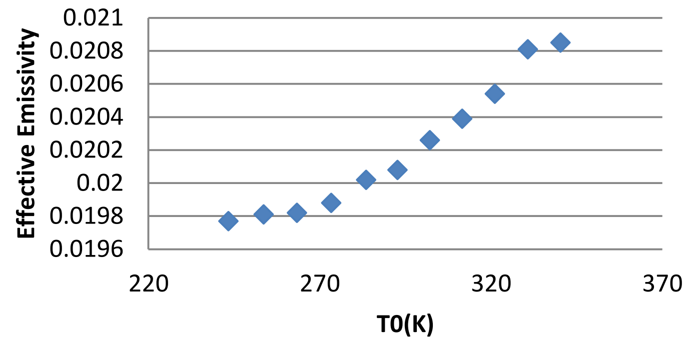
Improving low pressure prediction by accounting for ambient temperature dependence of Gc & ε_{eff}

A second order polynomial can be fit to the dependence of Gc and ε_{eff} on T0

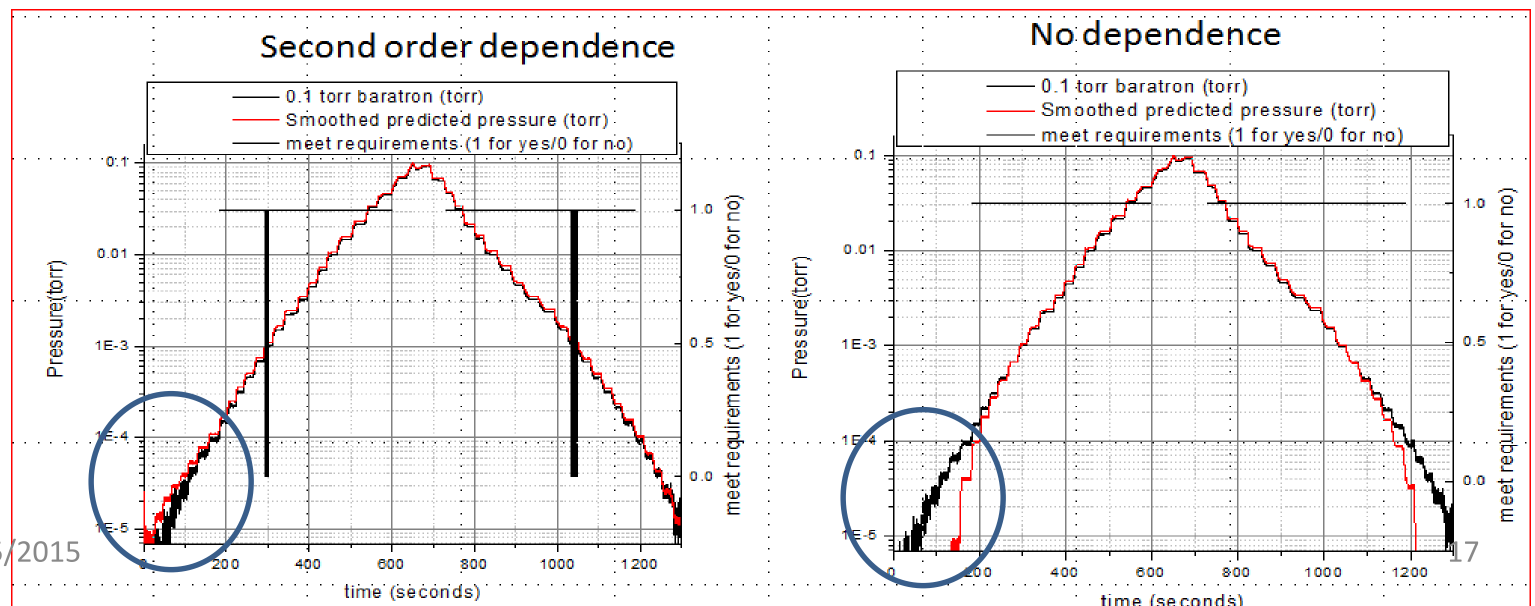
Dependence of Gc on ambient temperature T0



Dependence of ε_{eff} on ambient temperature T0

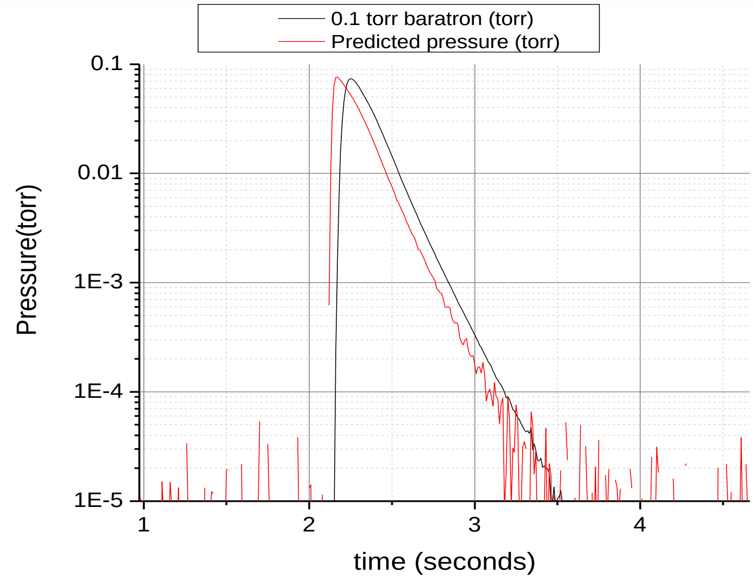


Low pressure prediction can be improved by using the second order fit to predict pressure

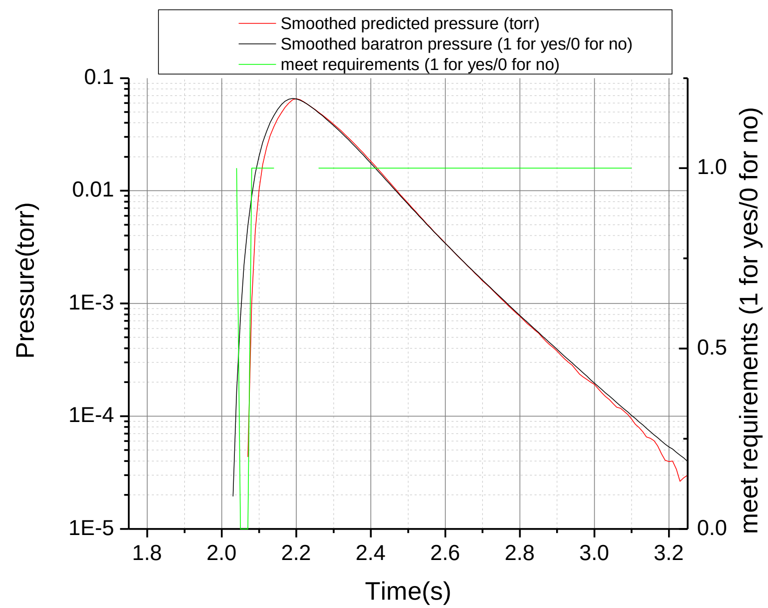


Predicting dynamic changes in mars mix pressure at 20 °C

Initial use of the dynamic algorithm without any post-processing applied demonstrated that the reference gauge response was less noisy but lagging behind by 0.09 s.



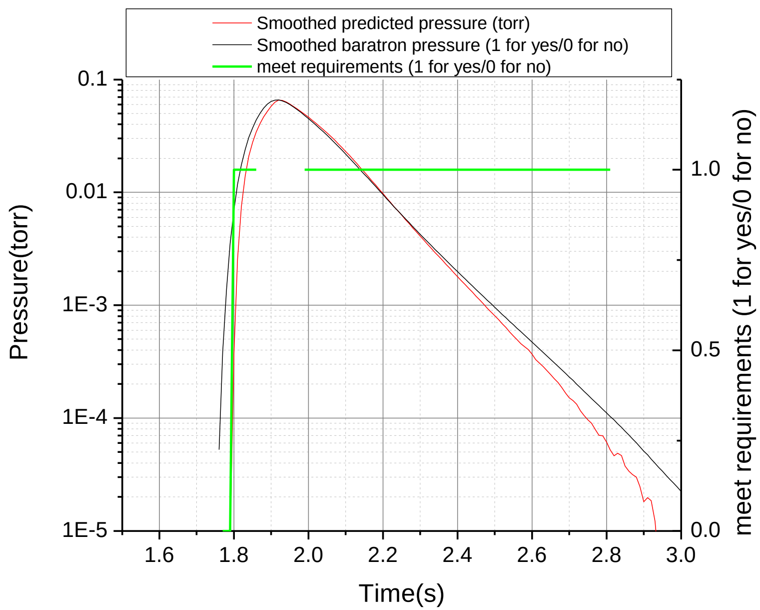
Using a 0.1 s centered moving average to smooth both pressures and delaying the predicting pressure by 0.09 s provided a must stronger match.
Note:
Here the green line indicates we are meeting our accuracy requirements: 0.2 mtorr accuracy in the 0.1 to 1 mtorr regime, and 20% from 1-50 mtorr



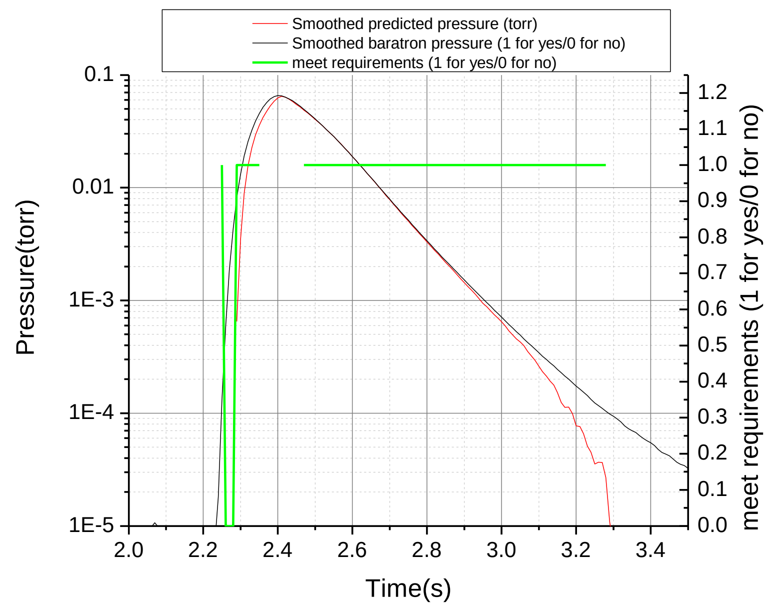
Predicting dynamic changes in mars mix pressure at -30 and 80 °C

Again, while pressure predictions meet requirements, predicted pressure is lower than true below 0.1 mtorr

T_0=-30 °C

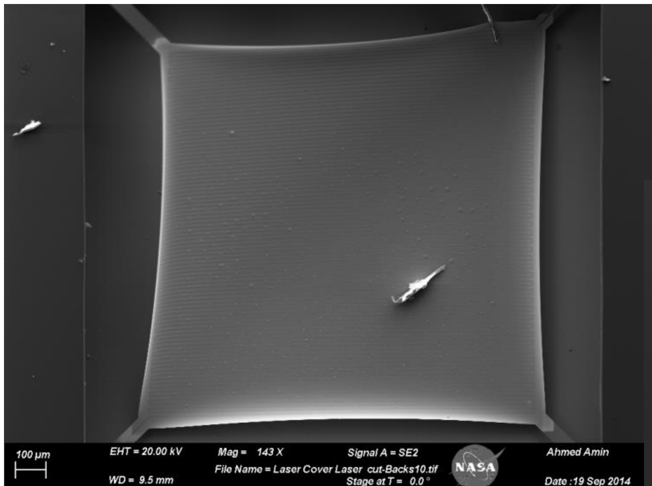


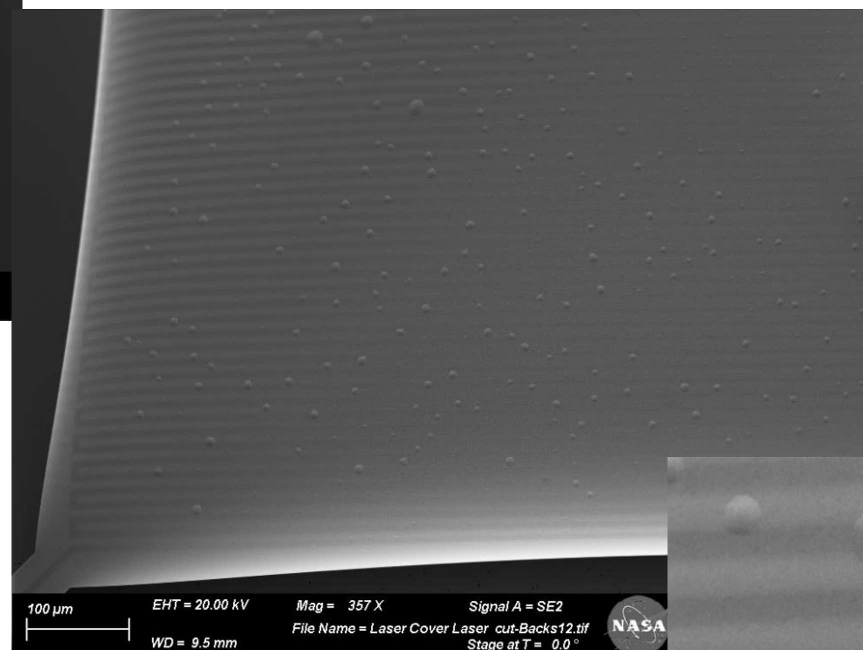
T_0=80 °C

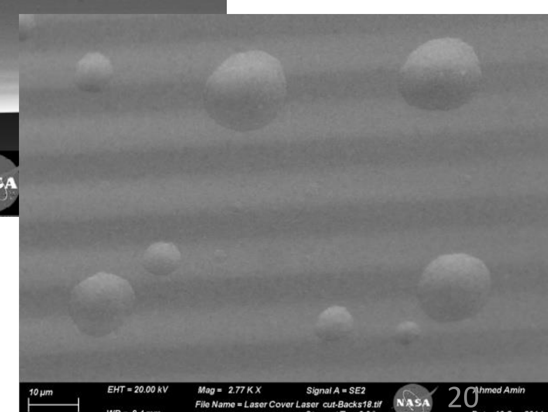


Increasing voltage increases sensitivity but can lead to device failure

"Blisters" formed on membrane due to overpowering at bias of 2.7 V







Life tests revealed that prolonged biasing at 2.7 V could impact usable lifetime

Number of gauges	Bias voltage
15	1.5
10	2.1
5	2.6

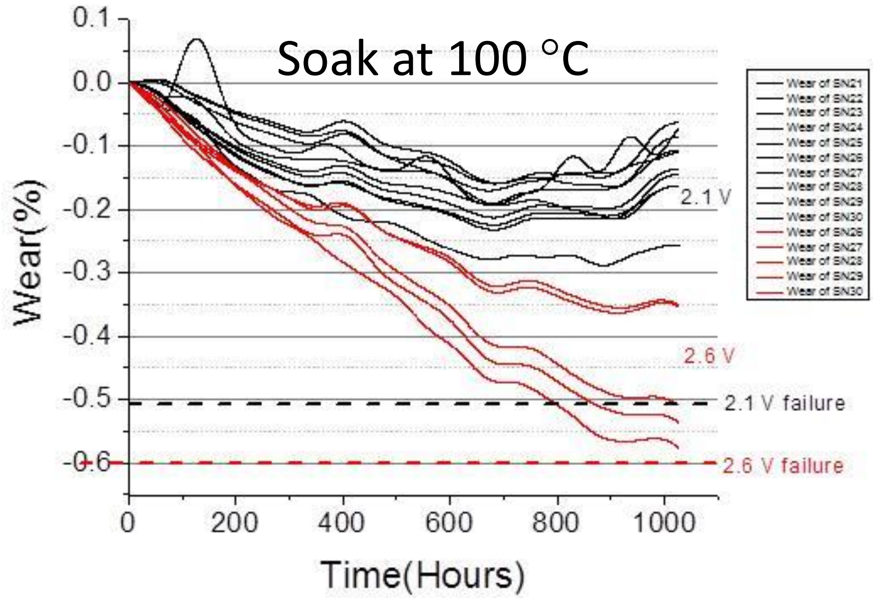
A lifetest was conducted to determine whether overpowering could be an issue:

Definition: Wear = Resistance drift normalized by initial resistance and compensated for ambient temperature swings

Drift in the 2.6 V batch was a greater fraction of the tolerated allowance and too great to reach 2x life

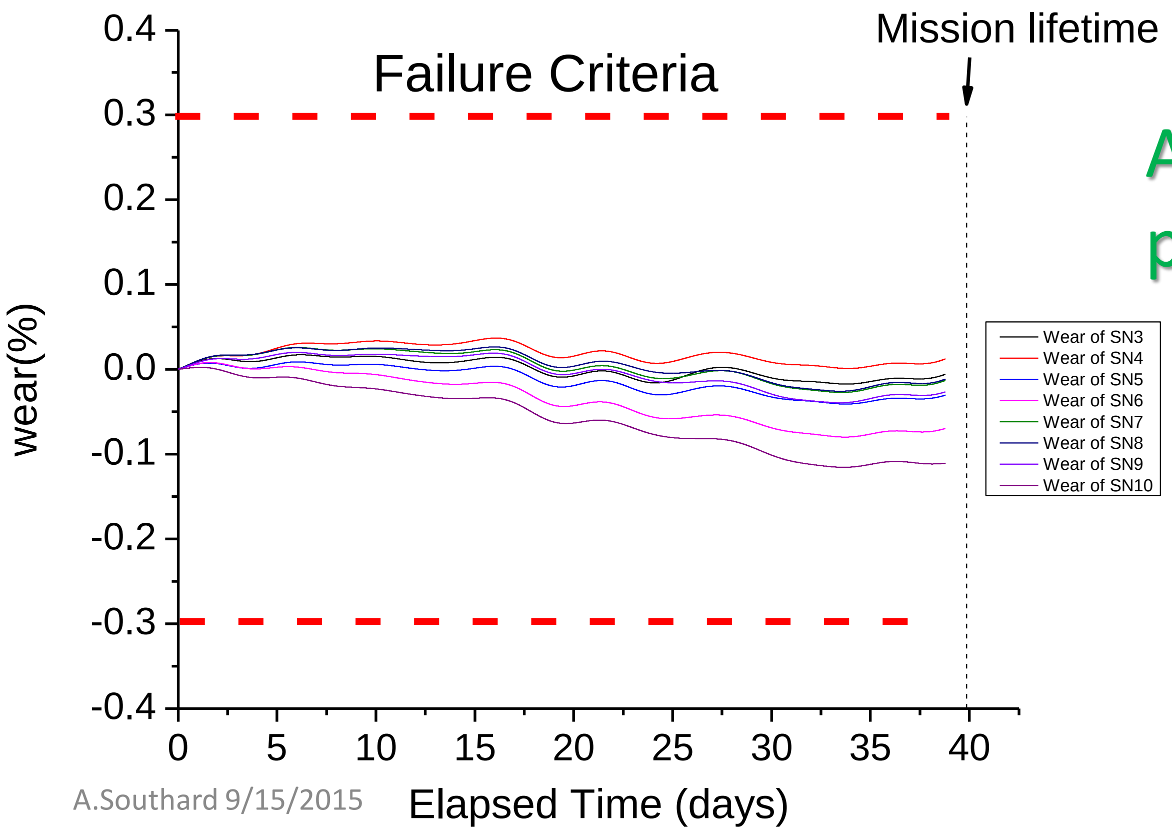
Biasing at 2.1 V lead to an acceptable drift in every phase of the experiment. This was consistent with suspected overpowering at a bias of 2.7 V. The most stressful condition for the 2.1 V group was at 100 °C.

Testing phase	Duration
800 power cycles @ -50 C	NA
Soak @ -50 C	550 hours
Soak @ 100 C	1010 hours



Lifetest Test Results

- Flight gauges had slightly lower nominal resistances (7 kohm instead of 8 kohm for the ETU gauges) so a high temperature soak was performed with them
- 9 flight gauges tested at 100 C for 950 hours
- Failure criteria: sense resistance change compensated for ambient temperature drift < resistance change at 80 °C when pressure changes from 0.1 to 0.2 mtorr.



All working gauges passed the lifetest!

Summary

A simple model was adapted to predict pressure with a MEMS pirani sensor from Heimann by determining physical properties of the sensor through a set of experiments. This resulted in an algorithm to predict pressure over operational temperatures from -30 to 80 °C, helium and mars mix gas compositions, and has a response time of 50 ms.

Accuracy was targeted to be within 0.1 mtorr of the reference in the sub-mtorr regime and within 20% otherwise.

In dynamic mode, accuracy was targeted to be 0.2 mtorr in the sub-mtorr regime most crucial to timing power-on of MOMA high voltage power supplies.

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