Introduction

MEMS thermal conductivity sensors such as the XEN-3880 that operate with thin membranes are family of the Pirani vacuum gauge and the thermocouple vacuum gauge, that are based on thin wires.

They are ideally suited for economic measurement of vacuum pressure between 100 kPa (atmospheric pressure at sea level) and 1 mPa, the so called low, medium and high vacuum ranges. An accuracy as good as 1% is obtained between 0.1 Pa and 1 kPa, and as such, the thermal sensor can go lower than mechanical pressure sensors.

Because the MEMS device is so small (3.3x2.5x0.3 mm for a naked die), an interesting application is found in the leak detection inside hermetically sealed housings encapsulating expensive devices that are sensitive to pressure variations.

Standard calibration curve

The output of the XEN-3880 sensor can very well be approximated using an oversimplified model of the sensor. The measured and calculated curves for air are shown in Fig. 1. This shows the transfer, which is the output voltage Uout of the XEN-3880, divided by the input heating power Pin. It is also possible to use the output voltage alone, although this is dependent upon heating voltage and resistance, while the transfer is mainly geometry determined.

In Fig. 1 the relative difference between the measurement curve and the calibration curve is less than 2% over the entire range. For clarity, calculated points are shown for different pressures than the measured points.

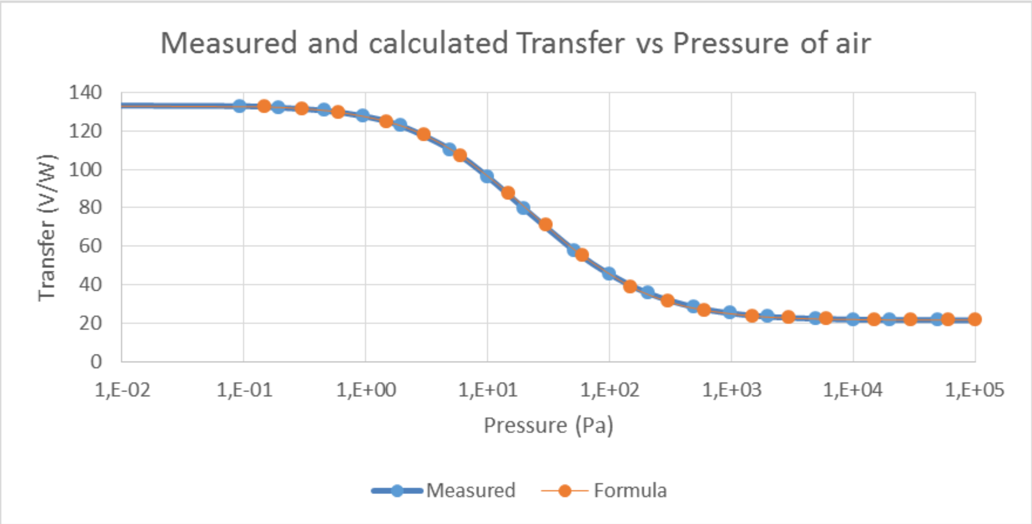

Figure 1: The measured Transfer of the XEN-3880-roof sensor (output voltage divided by input heating power in V/W) as a function of pressure, and the approximated curve from the pressure related formula.

Fig. 1 shows the ideal case, when we exactly know the transfer at zero pressure (well below 10 mPa) and at atmospheric pressure. In practice these data are not always precisely know, and the calibration curve can show deviations, especially at very low pressures (below 0.1 Pa) and high pressures (above 10 kPa). In general, between 0.1 Pa and 10 kPa a fairly accurate reading can be expected at room temperature, assuming the gas being measured is air, or the curve is adapted for the gas being measured.

Calculation method based on the transfer

The formula to calculate the pressure is obtained by the following extraction method, based on:

- the measured residual membrane conduction at zero pressure Gmem (in $W{\bullet}V^{-1}$);
- the measured low-pressure sensitivity Go (in $W{\bullet}V^{-1}Pa^{-1}$);
- the measured sensor conduction at atmospheric pressure Gtot, 100 kPa (in $W{\bullet}V^{-1}$);
- two transition pressures Pt1 & Pt2 (in Pa) that are derived by curve fitting.

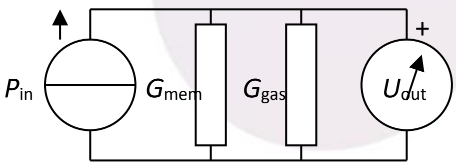

Figure 2: Discrete-element representation of the thermal characteristics of the XEN-TCG3880, with input power Pin and thermopile output voltage U_{out} and the sum of membrane conduction G_{mem} and Gas conduction G_{gas} determining their ratio.

Note that we do not include the thermopile sensitivity $N\alpha_s$ (in V/K) in the calculation, so the conductances have the dimension of W/V instead of W/K. As $N\alpha_s$ has in principle a fixed value, this does not make a difference for the calculation.

The method goes as follows:

The total conductance Gtot is at any pressure the inverse of the transfer (U_{out}/P_{in}) and is the sum of the membrane conductance and the gas conductance (instead of the transfer U_{out}/P_{in}, the output voltage U_{out} can also be used):

(1) $$G_{tot} = P_{in}/U_{out} = G_{mem} + G_{gas}$$

The residual membrane conductance Gmem is calculated using the measured zero-pressure transfer (where G_{gas} is zero):

(2) $$G_{mem} = P_{in}/U_{out,\ 0\ Pa}$$

The low-pressure sensitivity Go is calculated at a low pressure P around 0.5 Pa:

(3) $$G_o = (G_{tot} - G_{mem})_{\approx 0.5\ Pa}/P_{\approx 0.5\ Pa} = G_{gas \approx 0.5\ Pa}/P_{\approx 0.5\ Pa}$$

The sum of the transition pressures P_{t1} and P_{t2} is calculated by dividing the gas conductance measured at atmospheric pressure by the low-pressure sensitivity:

(4) $$½P_{t1} + ½P_{t2} = (G_{tot} - G_{mem})_{100kPa}/ G_o$$

Then the calibration curve for the vacuum pressure P is given by:

(5) $$G_{tot} = G_{mem} + G_{gas} = G_{mem} + G_o \{½P \times P_{t1}/(P+Pt1) + ½P \times P_{t2}/(P+P_{t2}) \}$$

In the low-pressure limit, this formula approaches the formula for gas conductance that is proportional to pressure:

(6) $$G_{tot,\ low\ pressures} - G_{mem} = G_o P$$

In the high-pressure limit, this this formula approaches the formula for gas conductance that is independent of pressure:

(7) $$G_{tot} - G_{mem} = G_o \{½ P_{t1} + ½ P_{t2}\}$$

Now the sum of the transition pressures is known, their individual values are determined by curve fitting, varying them until the measured and calculated curves coincide maximally.

Typical calibration curve for air

Fig. 1, repeated below, shows a measured curve for the XEN-3880 roof with a heat sink on top of the membrane (roof) at 100 µm distance, and the calculated curve with parameters shown in Table 1.

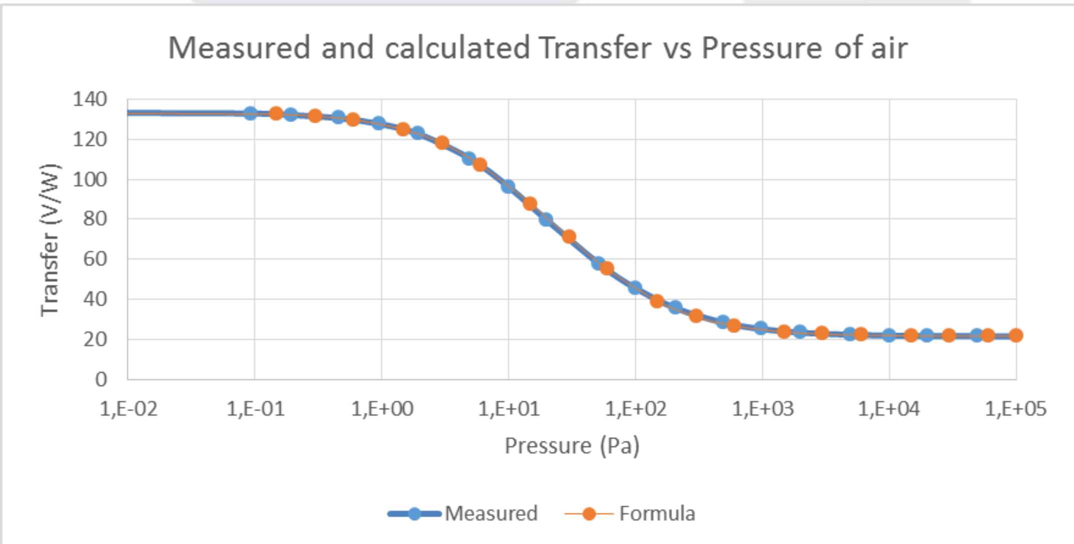

Figure 1 repeated.

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In Table 1 the calculation method outlined above is carried out for a sensor with air.

Table 1: Example of the procedure to approximate the vacuum-air response of XEN-3880-roof. First do 3 measurements, then 3 calculations, and finish with a curve fitting of the transition pressures.

Parameter	Procedure	Value	Units
1: Measure Gtot			
$U_{out}/P_{in, 0 Pa}$	At P << 1 mPa	133.32	V•W-1
$U_{out}/P_{in, 0.456 Pa}$	At P ≈ 0.5 Pa for air	130.49	V•W-1
Uout/Pin, 100 kPa	At P = 100 kPa for air	21.63	V•W-1
2: Calculate			
$G_{tot, 0 Pa} = G_{mem}$	$= P_{in} / U_{out, 0 Pa}$	7.500	mW•V-1
$G_{tot, 0.456 Pa}$	$= P_{in} / U_{out, 0.456 Pa}$	7.663	mW•V-1
$G_{tot, 100 kPa}$	$= P_{in} / U_{out, 100 kPa}$	46.23	mW•V-1
$G_{o, air}$	$= (G_{tot, 0.456 Pa} - G_{mem}) / 0.456$	0.3567	mW•V-1Pa-1
$P_{t1} + P_{t2}$	$= 2 \bullet (G_{tot, 100 kPa} - G_{mem}) / G_o$	217.1	Pa
3: Curve-fit			
P_{t1}	Curve fitted	17.5	Pa
P_{t2}	Curve fitted	199.6	Pa

As the parameters G_{mem}, G_o and $P_{t1} + P_{t2}$ will all depend somewhat on temperature, this will lead to errors in the calculation of the pressure as temperature changes. See the application note on the temperature behavior of the XEN-3880 for further details. And for gases other than air, the parameters G_o and $P_{t1} + P_{t2}$ will need to be adjusted, see Table 2.

An example using output voltages

An example for other gases is shown in Fig. 3, for a sensor without the roof.

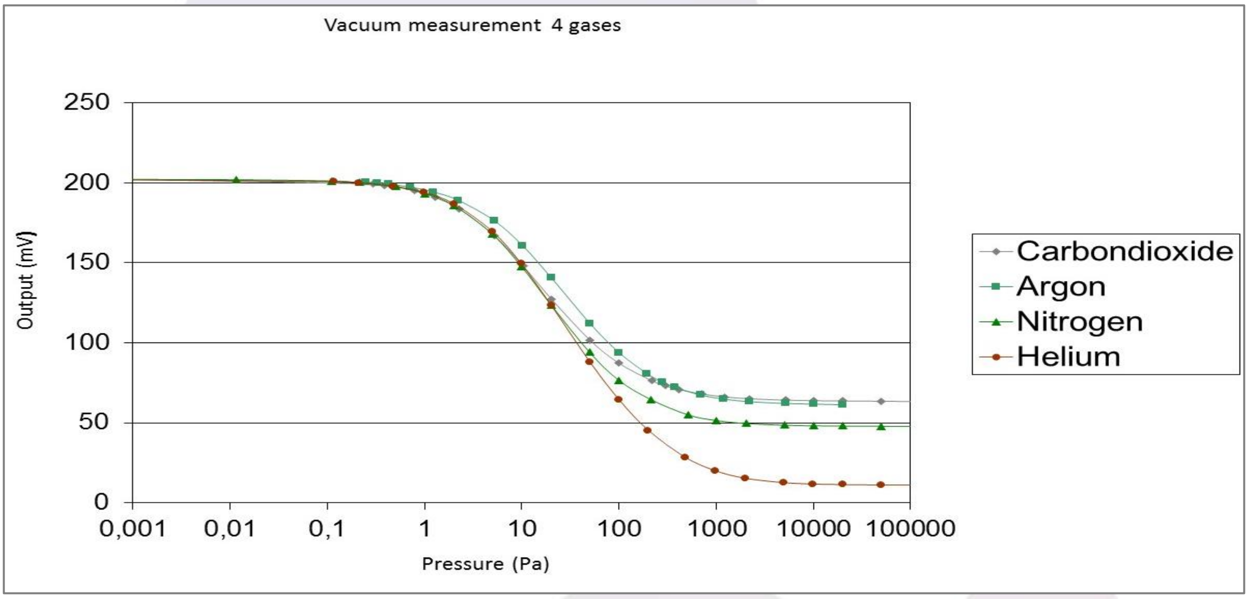

Figure 3: The output voltage of the XEN-TCG-3880 sensor for 4 different gases

In Fig. 3, at zero pressure, U_{out} for all gases is the same, as it should be. At low pressures the G_o for helium, nitrogen and carbon-dioxide are nearly the same, while argon is less sensitive. Near atmospheric pressure helium shows the most sensitivity, while carbon-dioxide tends towards the same output as argon and even crosses its curve. So, the sum of the transition pressures $P_{t1} + P_{t2}$ will be different for each of these 4 gases.

In Table 2 the parameters are given which approximate the curves of Fig. 2 (a sensor without roof), and not the transfer but the output voltage is approximated.

Table 2: Parameters to approximate the output voltage of the XEN-3880 (without roof).

Parameter	CO2	Nitrogen	Argon	Helium	Units
Measured					
Output at zero pressure	202.13	202.19	202.14	201.919	mV
Output at low pressure (≈0.5 Pa)	197.63	197.65	199.24	198.076	mV
Output at atmospheric pressure	63.34	47.77	54.32	11.142	mV
Calculated					
G_{mem}	4.947	4.946	4.947	4.952	(V)-1
G_o	0.230	0.229	0.170	0.205	(V*Pa)-1
$P_{t1} + P_{t2}$	93.1	140	132.6	833.8	Pa
Curve-fitted					
P_{t1}	14	20	14	18	Pa
P_{t2}	79.1	120	118.6	815.8	Pa