How to measure absolute pressure using piezoresistive sensing elements

In sensor technology several different methods are used to measure pressure. It is usually differentiated between the measurement of relative, differential, and absolute pressure. The following article explains what the user should know about measuring absolute pressure using piezoresistive pressure sensing elements [1].

Measuring absolute pressure

Definition: absolute pressure measurement is the measurement of pressure P_1 relative to the perfect vacuum P_0 ($P_0 = 0$ bar).

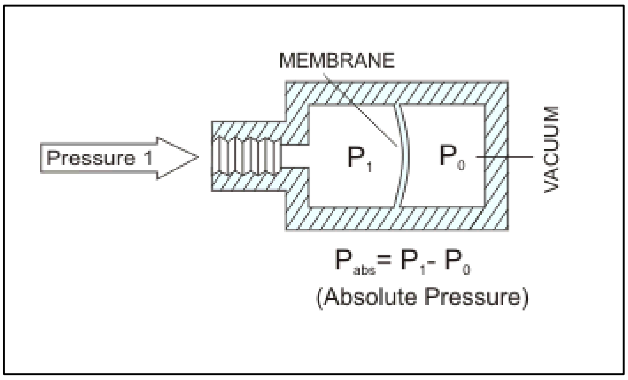

Figure 1: **Schematic diagram of an absolute pressure sensor**

Figure 2: **Industrial absolute presure sensor (AMSYS Transmitter U5100 [2])**

Micromechanical pressure sensing elements made of silicon (pressure die)

As micromechanical converter elements based on silicon are manufactured using semiconductor technology (see *Figures 3, 4, and 5*), they meet the high demands made of reliability and economy that are the hallmarks of this technology. All micromechanical pressure sensing elements made of silicon have a thin membrane as their pressure-sensitive element that is etched anisotropically from the silicon chip (silicon block), forming a cavity. At suitable points on the membrane local foreign atoms are implanted in the silicon crystal using the semiconductor technology, creating zones with a changed electrical conductivity that have the properties of resistors. As soon as pressure is applied to the membrane, the molecular structure of the crystal is deformed as the thin silicon membrane deflects. Particularly in the position of the resistors there are marked deformations in the crystal that lead to a measureable change in their resistive value (the piezoresistive effect). If these integrated resistors are connected up as a bridge, on the impression of current or voltage a pressure-dependent, differential signal in millivolts is generated that can be easily measured and using suitable instrumentation amplifier circuits.

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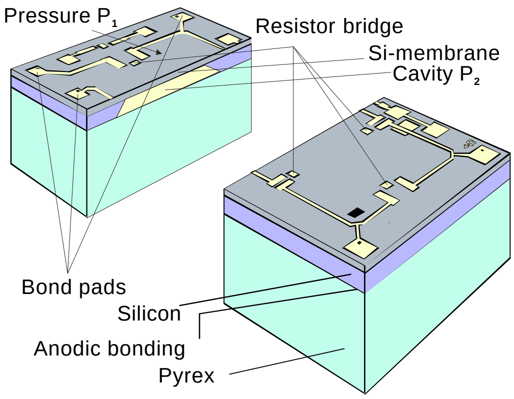

***Figure 3:* Typical silicon sensing element assembly for determining absolute pressure. P_1 is equal to pressure P_2 in the cavity.**

The dimensions of the silicon sensing elements are dependent on the pressure range and the manufacturing technology used. They are about 2 x 2 x 0.8 mm^3 for a pressure range of approximately 300 mbar to 30 bar.

The absolute sensing elements consist of an enclosed glass e.g. Pyrex base (blue-green), a silicon substrate (blue), and a membrane (light blue) which has been etched down to a thin layer. The membrane itself has a thickness of between 10 and 50 µm, depending on the pressure to be measured.

For more on the structure of the silicon sensing element, also see the comment on *Figure 5*.

Measuring absolute pressure using silicon sensors

When measuring absolute pressure (see *Figure 4*) measurement pressure P_1 is recorded in relation to a reference pressure of P_2 in the cavity, which must be so low as to be negligible compared to the pressure to be measured. In an ideal setup, P_2 would be equal to 0 bar (i.e. P_2 would be a perfect vacuum).

Numerical example. An absolute pressure measurement of 700 mbar indicates a measurement pressure of 700 mbar above the perfect vacuum and 313.25 mbar below normal pressure. (Normal pressure = 1,013.25 mbar at sea level, 0°C, and 45° latitude: in other words, a perceivable negative pressure compared with the normal pressure.)

The consequence of this for the absolute pressure sensor (*Figure 4*) is that the sensing element must be produced in a vacuum. To be more precise, at a corresponding negative pressure of P_2 the sensing element must be hermetically sealed with the Pyrex substrate. This is done in an electrochemical process known as anodic bonding. For stability of measurement, this negative pressure of P_2 (reference pressure) should permanently maintain the same value over the lifetime of the sensor.

When pressure P_1 is applied to the upper surface of the membrane, this bends towards the negative pressure. As $P_1 >> P_2$ applies, the membrane thus curves inwards into the vacuum cavity (see *Figure 5*).

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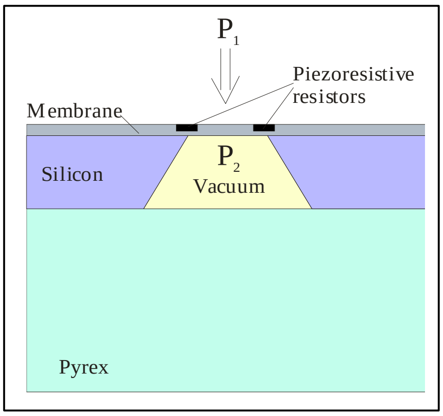

***Figure 4:* Cross section of a piezoresistive sensing element for determining absolute pressure P_1 with a resistor bridge circuit. (Here, the external pressure is $P_1 = P_2 =$ vacuum)**

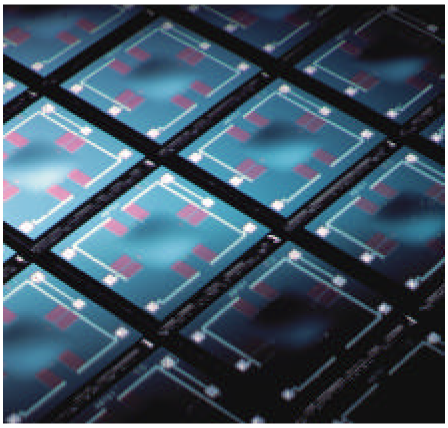

***Figure 5*: Silicon pressure sensing elements in wafer form for the measurement of absolute pressure (top view) at an external atmospheric pressure of P_1. $P_1 \gg P_2$**

Commentary on Figure 5: The white structures on the surface of the silicon pressure sensing element are the aluminum lines and pads (white squares) used to link the connecting wires to the outer circuit. The purple rectangles are diffused, conductive connectors for the piezoresistive resistors. The lower diffused piezoresistive resistors (not visible here) are thus situated between the purple areas at the edge of the deflection where there is the greatest mechanical tension. In the middle of the sensing element the deformation of the membrane is visible, caused by the external application of atmospheric pressure P_1.

Sensor assembly

The piezoresistive absolute pressure sensor consists of the sensing element mounted on a substrate, amplifier and evaluation electronics (ASIC), and the housing with a tube and its connections for the following electrical signal conditioning.

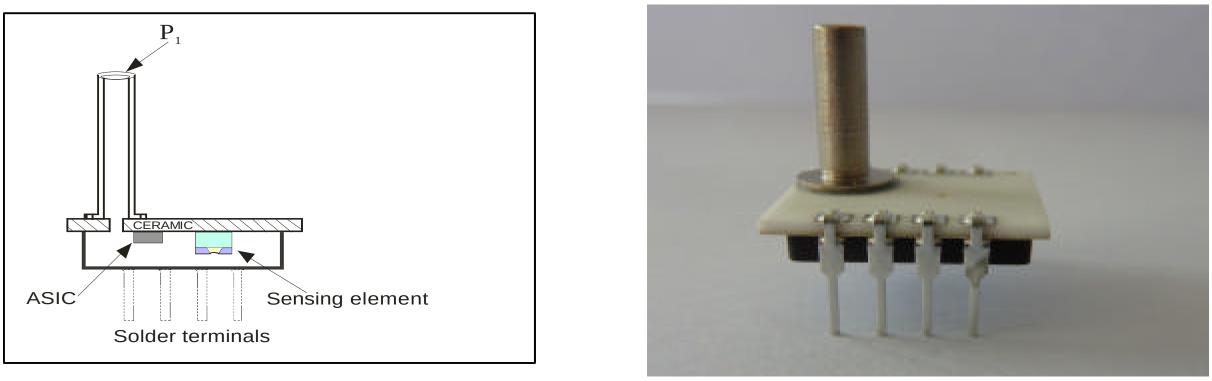

***Figure 6:* Absolute pressure sensor, using AMS 5812 as an example [3]**

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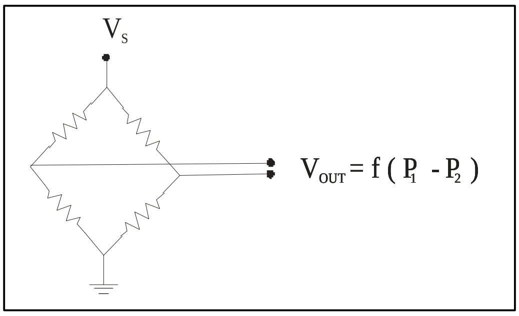
Output signal

The piezoresistive effect of the monocrystalline sensing element causes a signal, which is proportional to the active pressure at the output of the (implanted) Wheatstone bridge (*Figure 4*). The following applies (S = sensitivity):

$$V_{OUT} \approx S \cdot (P_1 - P_2)$$

This differential signal is amplified by a factor of g in the signal conditioning system's instrumentation amplifier (*Figure 8*).

With the proportionality the increase in the transfer characteristic of the sensor is determined; the offset and endpoint are yet to be fixed, however, i.e. conversion factor a must be set by suitable calibration.



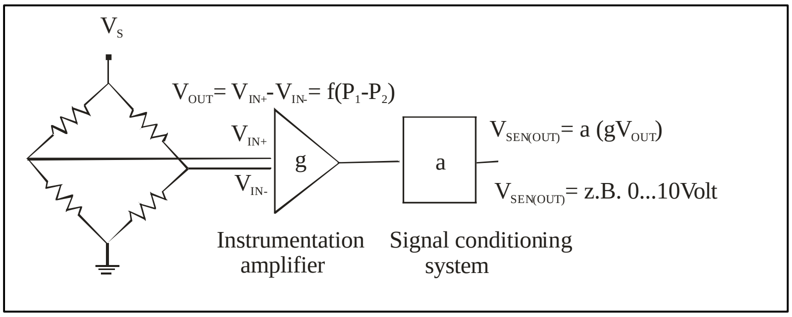


***Figure 7:* Wheatstone bridge circuit**

***Figure 8:* Schematic diagram of a sensor with evaluation circuitry**

Offset

When $P_1 = P_2$, the voltage V_{OUT} at the sensor bridge output is usually described as the offset voltage. This applies without restriction for all pressure sensors. When, by definition, the absolute pressure is to be measured in relation to the perfect vacuum, the cavity must have a value of P_o. However, a reference pressure of 0 bar in the cavity is technically not possible. In practice a pressure of P_2 is thus present which is greater than 0 bar in all cases. Taking the definition of absolute pressure into account, pressure P_2 ? 0 bar results in an offset that distorts the measurement. During offset calibration this value is calculated using an algorithm and electronically adjusted in the signal conditioning system (*Figure 8*). To this end the characteristic pressure curve of the sensor to be individually measured is recorded at two pressures, such as nominal pressure and low pressure, for instance. The straight line through these two points is extrapolated until it reaches the value $P_2 = 0$. The resulting y-axis section is equivalent to the offset voltage which must be calibrated to the required offset value, for example 0 V.

Full-scale signal (span)

The span (FSO) is defined as the output signal at maximum measurement pressure minus the offset voltage. With a sensor output signal of e.g. 10 V and an offset voltage of 0.05 V the span is 9.95 V. The FSO is not to be confused with the full-scale or FS signal which is defined as the measurement pressure including the offset and which is 10 V in the given example.
As with the offset, the full-scale signal must be calibrated to the required final output value, such as e.g. 10 V or other values.
In an absolute pressure sensor the span is always referenced to the perfect vacuum.

Determining the calibration of the offset voltage and span signal gives the sensor transfer characteristic at room temperature.

As both the offset and span signal are temperature dependent, these errors must be compensated for. For this purpose, during compensation the temperature errors of the offset (TSO) and span (TCS) are measured at various temperatures and corrected in the signal conditioning system in the same way as the offset and span.

With amplified sensors or transmitters, both of these procedures (calibration and compensation) are performed by the manufacturer.

Applications

In industrial plants, where the pressure within a system must be monitored and where ambient pressure has no effect on the pressure in the system, such as in enclosed air systems, for example, an absolute pressure sensor is a suitable means of recording pressure. One common example of the use of absolute pressure sensors is in the measurement of pressure in gas cylinders or in pneumatic systems (compressors). The advantage of absolute pressure sensors in such enclosed systems lies in their relatively simple construction. As opposed to relative pressure sensors, no additional connection must be made between the sensor and its environment; the absolute pressure sensor only has to be linked up to the interior of the system to be measured. Another example application is a system comprising a pump and connected receptacle (vacuum chamber) which is to be evacuated and monitored. Depending on how airtight the pump and system are, a negative pressure can be created in the vacuum chamber which, however, is only noted correctly up to the value of P_2 present in the cavity.

One popular application of the measurement of absolute pressure is the recording of barometric pressure e.g. between 700 and 1.200 mbar as the effective ambient pressure [4]. In this example the offset is calibrated to 700 mbar and the full-scale signal to 1.200 mbar to ensure optimum display dynamics.

With the measurement of the barometric pressure It’s easy to define the altidude with help of the following formular:

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As height h is coupled with effective atmospheric pressure p by the equation

$$h = \frac{288{,}15\ \text{K}}{0{,}0065\ \text{K/m}} \left[1 - \left(\frac{p}{101.325\ \text{Pa}} \right)^{0{,}0065\ \text{K/m}\ \frac{R}{g}} \right]$$

the geographical altitude can be calculated by determining the absolute pressure.

The approximation is based on the following assumptions:

- Pressure at sea level = 10,1325 Pa = 1,013.25 mbar
- Temperature at sea level = 288.15 K
- Temperature gradient = 6.5 K / 1,000 m
- R is the specific gas constant $R = R^* / M_0$ (R = 287.052 J/K kg)
- g is the acceleration due to gravity; g = 9.80620 m/s^2 at the 45th degree of latitude.

Regarding barometric sensors, pressure sensors are now available that operate with 24-bit processors and thus have a resolution of up to 0.012 mbar (˜ 10cm; [5]). They have been miniaturized to such an extent that they can be installed in mobile altimeters (watches).

Thanks to features such as these, modern absolute pressure sensors are now being used to monitor the height of aircraft, weather balloons, and parachutes, as well as finding application in model airplanes as mobile altimeters, for example.

Among the most recent areas of application for high-resolution absolute pressure sensors are intelligent clothing and personal navigation devices.

Conclusion

Absolute pressure measurement is only one means of measuring pressure. In this method pressure is measured in relation to the perfect vacuum, producing a value which is described as an absolute value. It is the easiest way of measuring pressure in enclosed systems that are independent of the outside pressure.

Further reading

[1] Detailed information on AMSYS pressure sensors: http://www.amsys.info[1]

[2] U5100 datasheet: http://www.amsys.info/products/u5100.htm

[3] AMS 5812 datasheet: http://www.amsys.info/products/ams5812.htm

[4] Application note: *Precise height measurement with pressure sensor MS5607*: http://www.amsys.info/sheets/amsys.en.aan509_e.pdf

[5] MS5803 datasheet: http://www.amsys.info/products/ms5803.htm

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