Absolute pressure measurement with piezoresistive sensing elements

Various methods are used in sensor technology to measure pressure. In general, a distinction is made between relative, differential and absolute pressure measurement. The following article by AMSYS, Mainz, explains what you should know about measuring absolute pressure with piezoresistive pressure sensing elements [1].

Absolute pressure measurement

Definition: Absolute pressure measurement is the measurement of pressure P1 relative to a perfect vacuum P0 (P0 = 0 bar). This must be distinguished from differential pressure measurement, which compares any two pressures, and relative pressure measurement, which measures the pressure difference relative to atmospheric pressure.

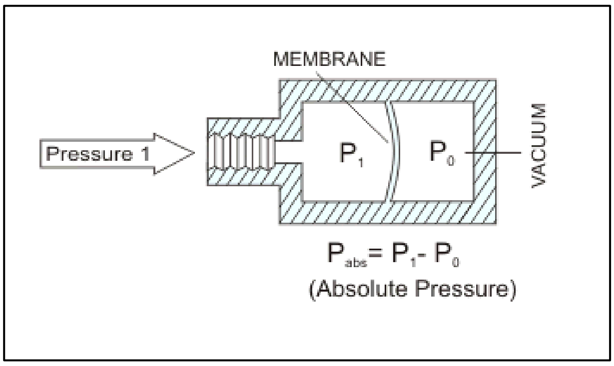

Figure 1: *Principle of an absolute pressure sensor*

Figure 2: *Industrial absolute pressure transmitter U5200 [2]*

Micromechanical pressure sensing elements made of silicon (pressure dies)

Micromechanical silicon-based pressure sensing elements (MEMS) have long since replaced mechanical transducers with elastic diaphragms and have proven themselves millions of times over, for example in ventilation technology (HVAC) and medical technology. Because these pressure sensor chips (see Figure 3 and Figure 4) are manufactured using semiconductor-industry methods and partly on chip-industry production lines, they meet the high standards of reliability, accuracy and cost-effectiveness that characterize integrated circuits (ICs). They are produced in batch processes on silicon wafers (Figure 4), with several thousand sensing elements (dies) on a single wafer. In a final process step, these dies are separated and form the central element of a pressure sensor.

All micromechanical silicon pressure sensing elements use a thin diaphragm etched out of the silicon chip as the pressure-sensitive element. At suitable positions on the diaphragm, foreign atoms are locally implanted into the silicon crystal during the semiconductor process, creating zones with modified conductivity that act electrically as resistors. As soon as pressure acts on the diaphragm, these resistors change in the mechanically highly stressed edge areas of the diaphragm due to the deformation of the thin silicon diaphragm (piezoresistive effect). If these integrated resistors are connected to form a bridge, current or voltage excitation produces a pressure-dependent differential signal in the millivolt range, which can be electronically detected and conditioned using suitable instrumentation amplifier circuits.

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The dimensions of the silicon sensing elements depend on the pressure range and the manufacturing technology. They are approximately 2 x 2 x 0.8 mm3 for a pressure range of approx. 300 mbar to 30 bar.

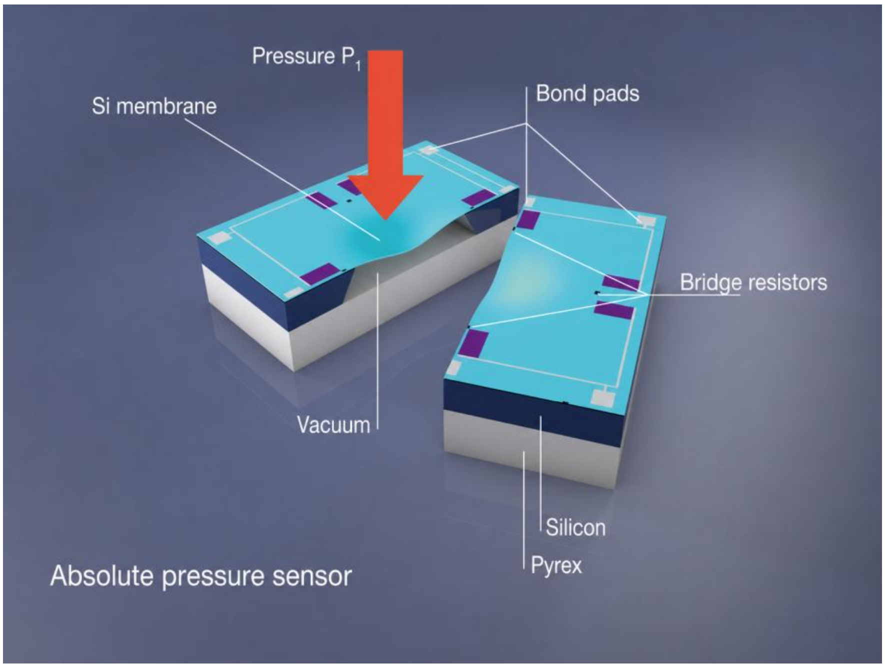

Figure 3 shows the structure of an absolute pressure sensing element. It consists of a glass base (white), the silicon body (blue) and a diaphragm layer (light blue). The silicon has been underetched so that only a thin diaphragm layer remains over a generally square area. Depending on the pressure to be measured, the diaphragm itself has a thickness of between 10 and 50 µm. Mounting the element on the glass base under vacuum creates an evacuated cavity, also referred to as a cavity. The glass is Pyrex glass, which has a particularly low coefficient of thermal expansion in order to keep mechanical stresses between the silicon sensing element and the glass carrier as low as possible during temperature changes.

Absolute pressure measurement with silicon sensors

In absolute pressure measurement (see Figure 3), the measuring pressure P1 is detected against a reference pressure P2 in the cavity, which should be low enough to be negligible compared with the pressure to be measured. Ideally, this would be P2 = 0 bar (i.e. P2 = perfect vacuum).

Numerical example - An absolute pressure measurement of 700 mbar means a measured pressure of 700 mbar above a perfect vacuum and 313.25 mbar below standard pressure. (Standard pressure = 1013.25 mbar at sea level at 0°C and at 45° geographic latitude), i.e. a significant negative pressure compared with standard pressure.

For the absolute pressure sensor, this has the design consequence that the sensing element must be manufactured under vacuum. Specifically: at the corresponding negative pressure P2, the sensing element must be hermetically sealed to the glass base (Pyrex substrate), which is done in an electrochemical process under high voltage (anodic bonding). For the sake of measurement stability, the negative pressure P2 (reference pressure) should permanently retain its value. The enclosed vacuum can be assumed to be 0 mbar for almost all practical cases, even though in reality it is only a technical vacuum of <1 mbar.

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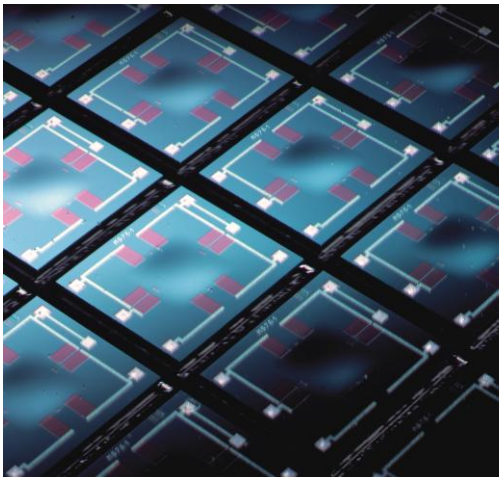

When pressure P1 is applied to the upper side of the diaphragm, it bends in the direction of the lower pressure. At P1 >> P2, the diaphragm consequently bends inward into the cavity (see Figure 4). The bright lines on the silicon pressure sensing elements in Figure 4 are the aluminium conductor tracks with the aluminium pads (bright squares) for connecting the bonding wires to the external circuitry. The violet areas are diffused conductive connections to the piezoresistive resistors. The more deeply diffused piezoresistive resistors (not visible) are therefore located between the violet areas at the edge of the deflection, in the region of maximum mechanical stress. In the center of the sensing element, the deformation (deflection) of the diaphragm can be seen, caused by the externally acting atmospheric pressure P1.

Sensor design

The piezoresistive absolute pressure sensor consists of the sensing element, which is mounted together with amplifier and evaluation electronics (ASIC) on a substrate and installed in a package with a pressure port and electrical connection (Figure 5). The ASIC (application-specific IC) defines the essential electrical performance characteristics such as interface (analog, digital) and resolution (of both the ADC and the DAC or I²C interface).

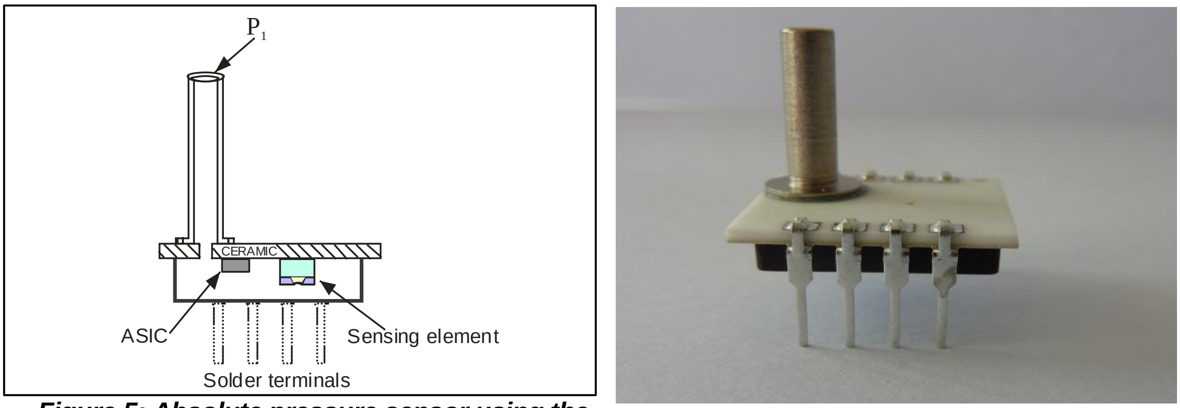

Figure 5: Absolute pressure sensor using the AMS 5915 [3] or 5812 [4] as an example

Output signal

Due to the piezoresistive effect of the monocrystalline sensing element, a signal VOUT = f(P1, P2) is produced at the output of the implanted resistor bridge (Figure 3; equivalent circuit, see Figure 7), which is proportional to the acting pressure. With S = sensitivity of the respective pressure sensing element:

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

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

The proportionality determines the slope of the sensor's transfer characteristic, but the zero point and full-scale point have not yet been defined; in other words, the mapping factor a must be determined by appropriate calibration.

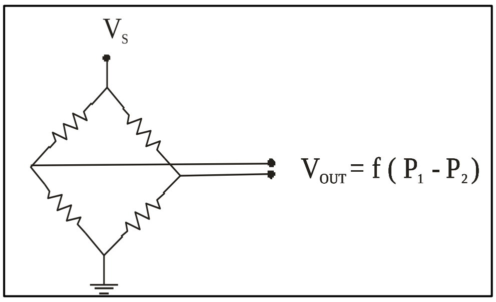

Figure 7: Wheatstone bridge

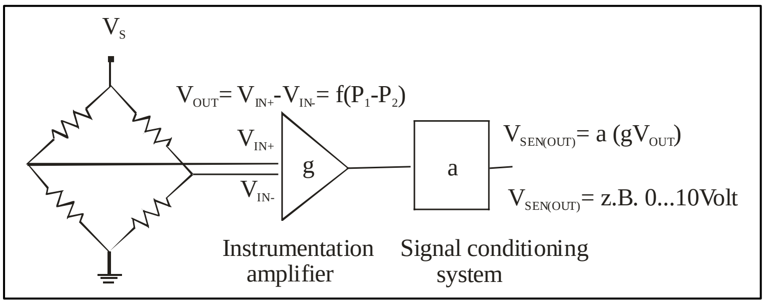

Figure 8: Schematic circuit: sensor with evaluation circuit

Zero point (offset)

The voltage Vout at the measuring bridge output under the condition P1 = P2 is generally referred to as the offset voltage. This applies without restriction to all pressure sensors. If, by definition, absolute pressure is to be measured against a perfect vacuum, then Po would have to prevail in the cavity. However, it must be taken into account that a reference pressure of 0 bar in the cavity cannot be technically realized. In practice, therefore, a pressure P2 will be present and will in any case be greater than 0 bar. From the perspective of the definition of absolute pressure, the pressure P2 ≠ 0 bar represents an offset that falsifies the measurement.

During zero-point calibration, this value is determined by an algorithm and stored electronically in the signal evaluation circuit (Figure 8). To do this, the pressure characteristic of the individual sensor to be measured is recorded at two pressures, for example nominal pressure and low pressure. The straight line through both points is extrapolated to the zero-pressure point. The resulting y-axis intercept corresponds to the offset voltage that must be calibrated to the desired zero-point value, for example 0.5 V.-

Full-scale signal (span)

The span (FSO) is defined as the output signal at maximum measuring pressure minus the offset voltage. For a sensor output signal of 0.5 to 4.5 V, the offset voltage is 0.5 V and the span is 4.0 V. The FSO should not be confused with the FS signal, which is defined as the measuring pressure including the offset and is 4.5 V in the numerical example.

Similar to the offset, the full-scale signal must be calibrated to the desired final output value, for example 4.5 volts (or other values), using a certified reference.

In absolute pressure sensors, the zero point is generally referenced to a perfect vacuum. However, there are also sensors calibrated for barometric applications whose zero point is, for example, 700 mbar in order to increase the resolution in the remaining range.

By determining the offset voltage and the span signal, the sensor's transfer characteristic is defined at room temperature. However, because both the offset and the span signal are temperature-dependent, these errors must be compensated. During compensation, the temperature errors of the offset (TSO) and span (TCS) are determined at different temperatures and corrected in the signal evaluation circuit in the same way as offset and span. These adjustment procedures (calibration and compensation) are already performed by the manufacturer for calibrated and amplified sensors.

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Applications

Absolute pressure sensors are used wherever either no connection to the atmosphere is possible, as would be required for relative pressure measurement (e.g. depth gauges in diving watches, in-vivo pressure measurement in the body during operations, etc.), or where an absolute pressure value is to be recorded without the influence of ambient pressure. Examples include pressure measurement in gas cylinders or vacuum chambers, where the pressure in a container is to be determined and controlled. Depending on the tightness of the pump and the system, a negative pressure can be generated in the vacuum chamber; however, it is only indicated correctly down to the value P2 prevailing in the cavity. The absolute pressure of the flowing gas is also decisive for determining mass flow through a volume flow meter.

The most popular application of absolute pressure measurement, however, is the determination of barometric or atmospheric pressure as the prevailing ambient pressure. In this case, because optimized display dynamics are desired, the zero point is calibrated to 700 mbar and the full-scale signal to 1200 mbar. A further AMSYS article on altitude measurement with absolute pressure sensors provides concrete application examples [5].

By measuring barometric pressure, the absolute pressure sensor can be used as an altimeter. Since the geographic altitude h is linked to the prevailing air pressure p by the following formula, the geographic altitude can be determined by measuring the absolute pressure:

Altitude determination formula

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

Die Approximation basiert auf folgenden Annahmen:

- Druck bei Normalnull = 101325 Pa = 1013,25 mbar
- Temperatur bei Normalnull = 288,15 K = 15°C
- Temperaturgradient = 6,5 K / 1000 m
- *R* ist die spezifische Gaskonstante
  $R = R^* / M_0$ (R = 287,052 J/K kg)
- *g* ist die Erdbeschleunigung $g = 9{,}80620\ \mathrm{m/s^2}$ auf dem 45. Breitengrad.

In the field of barometric sensors, pressure sensors are available that operate with 24-bit processors and can therefore resolve up to 0.012 mbar (≈ 10 cm) at 1000 mbar. These include, for example, the water-protected MS5849 [6], which is available in various pressure ranges up to 30 bar, and the miniaturized MS5607 [7], which can be installed in mobile altimeters (watches) (see Figure 9). Both are OEM pressure sensors that are soldered directly onto printed circuit boards, whereas the U5200 (Figure 2) is a robust transmitter with a plug connection. Further information on the different designs of pressure sensors and their advantages and disadvantages is described in the white paper [8].

These absolute pressure transducers are used, for example, as mobile altimeters for altitude monitoring in aircraft, parachutes and civil as well as military drones, but also for depth determination in diving watches or in pneumatics.

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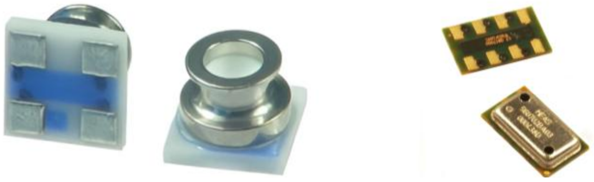
Summary

Absolute pressure measurement is only one method of pressure determination. With this method, pressure is measured against a perfect vacuum and the value determined in this way is referred to as an absolute value. It is the appropriate method for measuring pressure in closed systems that are, for example, independent of external pressure.



Further information

[1] Detailed information on piezoresistive pressure sensors: https://www.amsys-sensor.com/products/pressure-sensor/

[2] Product information for the media-resistant U5200 pressure sensor: https://www.amsys-sensor.com/products/pressure-sensor/u5200-mediaresistent-pressure-transmitter-up-to-689-bar/

[3] Product information for the AMS 5915 pressure sensor: https://www.amsys-sensor.com/products/pressure-sensor/ams5915-digital-pressure-sensor-5mbar-to-10-bar/

[4] Product information for the AMS 5812 pressure sensor: https://www.amsys-sensor.com/products/pressure-sensor/ams5812-pressure-sensor-with-analog-and-digital-output/

[5] Application Note 509: "Precise altitude measurement with the MS5611 pressure sensor module" https://www.amsys-sensor.com/downloads/notes/ms5611-precise-altitude-measurement-with-a-pressure-sensor-module-amsys-509e.pdf

[6] Product information for the MS5849 pressure sensor: https://www.amsys-sensor.com/products/pressure-sensor/ms5849-chlorine-resistant-absolute-pressure-sensor-30-bar/

[7] Product information for the MS5607 pressure sensor: https://www.amsys-sensor.com/products/pressure-sensor/ms5607-digital-high-resolution-barometric-pressure-sensor-10-1200-mbar/

[8] White Paper: "The different pressure sensor designs: From the silicon sensing element to the pressure transmitter": https://www.amsys-sensor.com/downloads/whitepaper/the-various-versions-of-pressure-sensors-from-the-silicon-sensing-element-to-the-pressure-transmitter.pdf

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