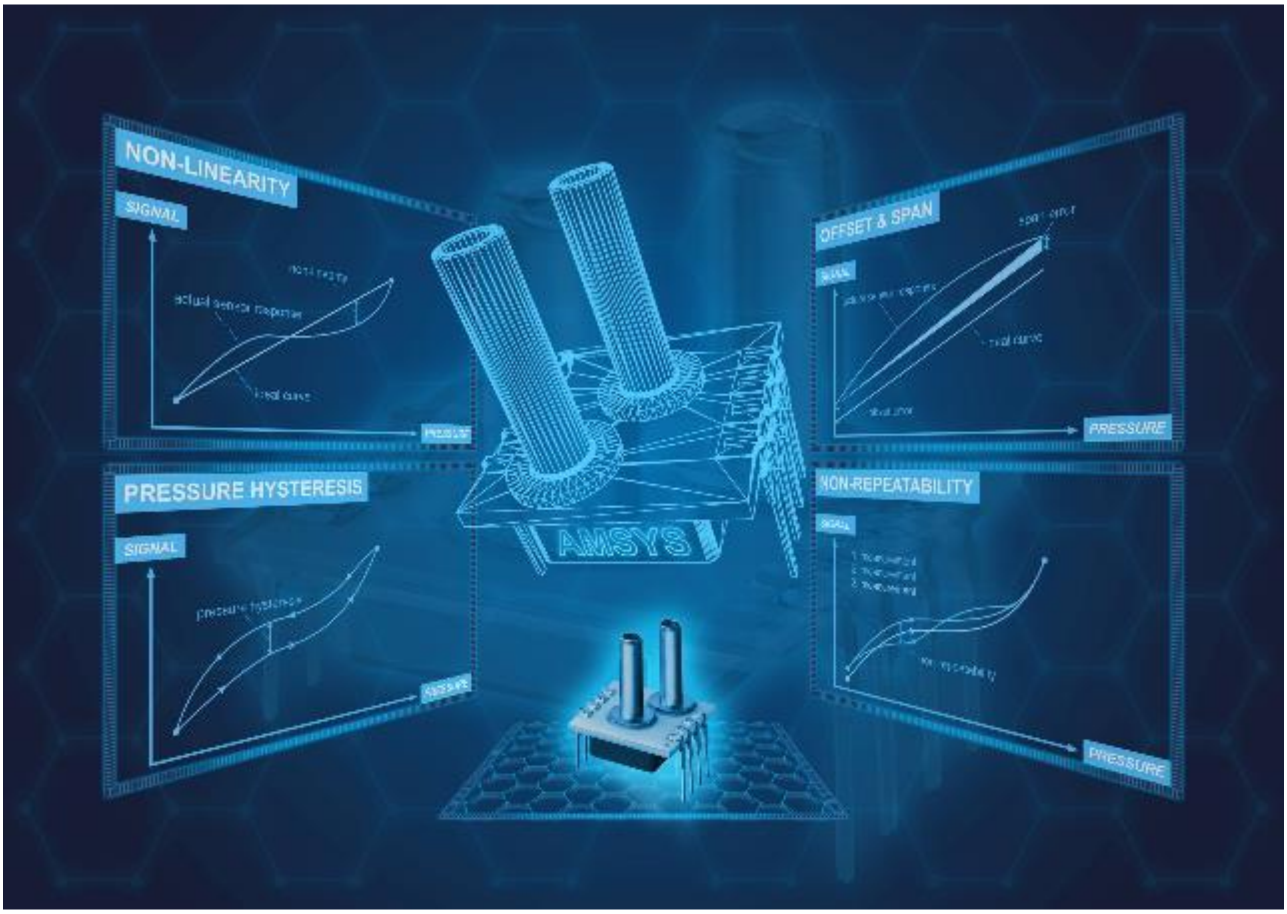
Accuracy in pressure sensing

When choosing a suitable sensor for an application, it's important to understand the errors that occur and to consider which of these are relevant to your project and which can be disregarded. Each and every user of pressure sensors initially enquires about the accuracy of a sensor – giving rise to the first misunderstandings.
As sensor accuracy is not a standardized concept, everyone uses it as they see fit. Conclusive comparison of products becomes a laborious mathematical exercise – provided that the manufacturers indeed supply the relevant information needed. Users merely want to know which errors they can actually reckon with when measuring pressure. This whitepaper is an attempt by AMSYS to define accuracy in the field of silicon-based pressure sensors.



From a linguistic perspective, the term "accuracy" is used incorrectly in most specifications. In practice it's used to describe the deviation from the ideal curve – which then in fact refers to the degree of inaccuracy. By definition, inaccuracy is a sum of errors. Thus, when clarifying the term "accuracy", the errors that determine the inaccuracy should first be considered. As these refer to individual specifications, these shall be taken as the basis for the following observations.

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Assembly of a modern silicon MEMS pressure sensor

The heart of a modern pressure sensor with a silicon base is the pressure sensing element (see *Figure 1*). All micromechanical pressure sensing elements made of silicon have a thin membrane as their pressure-sensitive element that is etched from the silicon chip. At suitable points on the surface of the membrane, impurity atoms are implanted in the silicon locally using the semiconductor process, creating zones with an altered electrical conductivity. As soon as pressure is applied to the membrane, the structure of the crystal is deformed as the thin silicon membrane deflects. These shifts in the crystal lead to a change in the electrical resistance of the doped areas (piezoresistive effect). These integrated resistors are then connected to form a Wheatstone bridge. When applying current or voltage a pressure-dependent, differential signal in millivolts is generated that can be logged and processed electronically using suitable amplifier circuits.

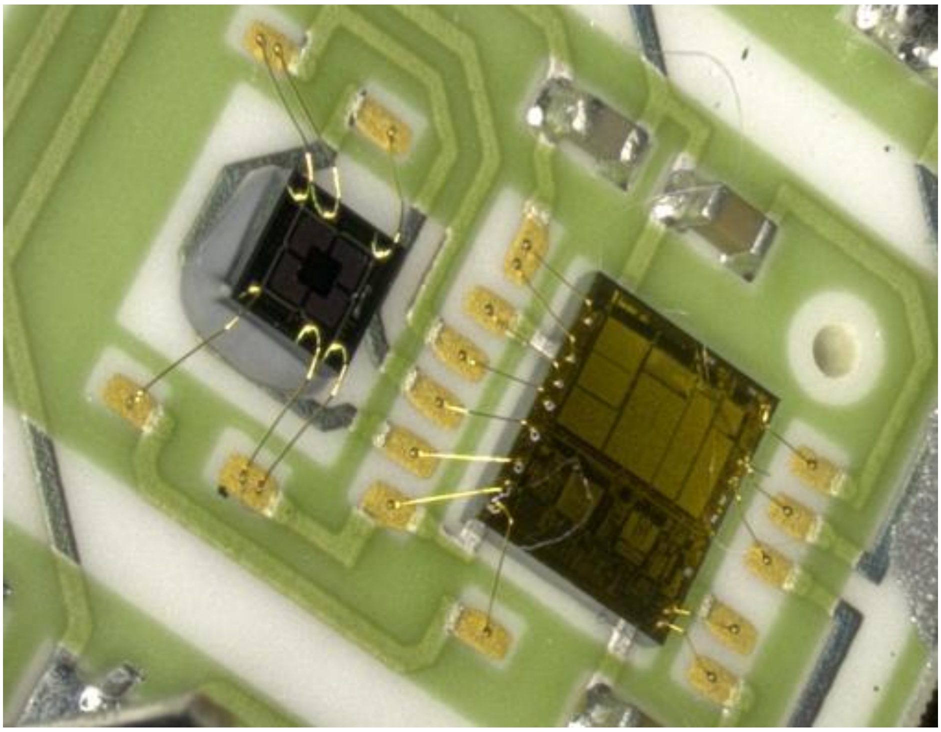

***Figure 1:** assembly of an amplified and calibrated silicon pressure sensor with the microstructured pressure die on the left and the ASIC with an amplifier, A/D converter and processor for calibration, EEPROM and output stage on the right. The pressure connectors on the differential pressure sensor are behind the pressure die (not visible) and on the top right of the ASIC.*

In order to obtain standardized output values that can be easily further processed, an additional application-specific IC (ASIC) is connected to the sensing element. Here, the signals previously digitalized in an A/D converter are electronically calibrated, temperature-compensated and linearized. To this end, correction coefficients are determined at various pressures and temperatures for each individual sensor regarding the ideal transfer characteristic and stored in the EEPROM during calibration by the manufacturer.

The integrated microprocessor compensates for the digital raw values of the pressure signal based on the respective pressure and temperature values with the help of the correction coefficients. As a result, both the pressure and temperature are available as digital data and output either via I²C/SPI or through an additional D/A converter as an analog signal.

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Measuring detector with errors: the pressure sensing element

The silicon sensing elements have a dimension of approximately 2 x 2 x 0.8 mm^3 for a pressure range of around 300 mbar to 30 bar, this being dependent on the pressure range and manufacturing technology used. Smaller pressure ranges require larger membranes and react more sensitively to production errors, with this being reflected in their cost.

Absolute sensing elements consist of a closed glass (Pyrex) base (gray), the silicon substrate (blue) and a membrane (light blue). The cavity is etched from the silicon substrate down to the thin membrane. The membrane itself has a thickness of between 10 and 50 µm, depending on the pressure to be measured.

Unlike in Figure 2, relative and differential pressure sensing elements contain no vacuum cavity under the membrane but instead a hole in the Pyrex base, through which a second pressure (P_2) can be compared to pressure P_1 applied from above.

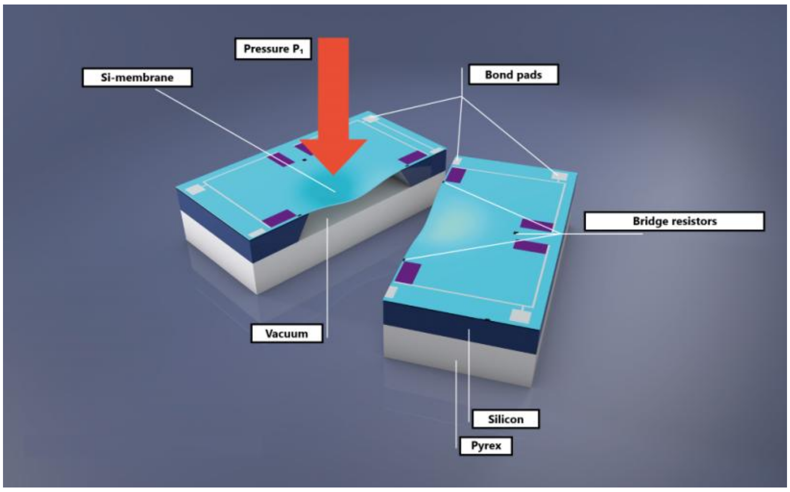

Figure 2: *typical silicon sensing element assembly for determining absolute pressure. The white lines on the surface of the silicon pressure sensing element are the aluminum strip lines with the aluminum pads (white squares) used to link the connecting bond wires to the outer circuit. The purple rectangles are diffused, conductive connectors for the piezoresistive resistors. The lower diffused piezoresistive resistors (not visible here) are thus situated between the purple rectangles at the edge of the deflection where there is the greatest mechanical tension. In the middle of the sensing element the deformation (deflection) of the membrane is visible, caused by the external application of atmospheric pressure P_1.*

The causes of the errors described in the following lie in the manufacturing process but also in the physical deficiencies of the material:

- The implanted resistors have a clear temperature dependency. This not only brings about a change in the individual resistors but also in the current and thus intrinsic heating when voltage is applied to the measuring bridge.
- The temperature is sometimes measured through the bridge resistance and sometimes by a diode in the ASIC. Both variants have their pros and cons with respect to signal path and speed.
- In reality, measuring resistors do not have completely identical values. This means that the measuring bridge has an offset and an error in the span.
- Owing to the high number of masking steps, the (dry) etching process often results in deviations from sensor to sensor. A more detailed description of the manufacturing process of low-pressure sensing elements can be found on the AMSYS homepage.
- During assembly of the sensor , offset errors can be caused by tension between the pressure die and the carrier substrate. These can be minimized by ceramic substrates featuring similar thermal expansion coefficients as silicon dies.

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Pressure sensor specifications

As there are no generally valid standards for describing pressure sensors, the specifications relevant to their errors should first be explained. If we assume that the silicon pressure sensor is ready to use, we must then differentiate between errors that can be corrected and those that cannot. A correctable error is one that can be reduced or fully remedied by a suitable algorithm in the signal conditioning unit during calibration.

Correctable errors	Non-correctable errors
Offset (zero offset) error	Thermal hysteresis
Span (output span/full-scale) error	Pressure hysteresis
Non-linearity	Long-term drift
Offset temperature error (TCO)	Supply voltage dependency
Span temperature error (TCS)	Nonrepeatability

Correctable errors

Offset error (zero offset error)

A zero offset error is understood to be the output value of the sensor in the instance that no pressure is applied to the sensing element at room temperature. This error can be caused by the sensor itself, by the integrated circuit packaging or by the downstream electronics (see Figure 3).

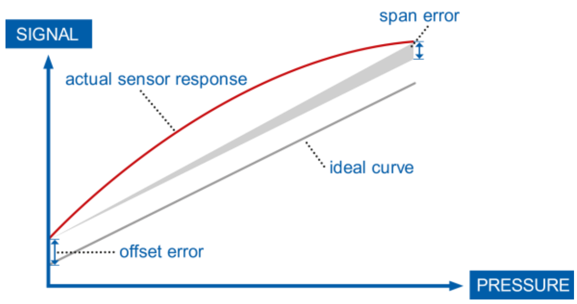

Figure 3: *offset and span errors.*

Span error (output span or full-scale error)

The span error (output span/full-scale error) is the difference of the output signal at minimum and maximum pressure application at room temperature and with a fixed supply voltage/current (see Figure 3). This results from the sensitivity of the sensing element and the amplification behavior of the evaluation electronics. This error is usually given without taking the offset value into consideration (in %FSO).

Non-linearity

The transfer function (output signal as a function of the applied pressure) of an ideal sensor is always linear. The deviation from this curve is called “non-linearity” (see Figure 4). In most cases, this is determined using the best-fit straight line (BFSL) method.

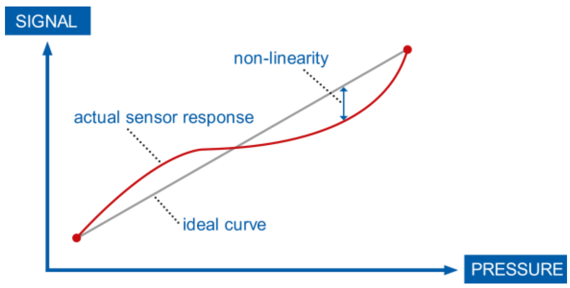

Figure 4: *non-linearity.*

Offset temperature error (TCO)

Unfortunately, the offset is always temperature-dependent (see Figure 5). The reason for this is the temperature dependency of the sensor's piezoresistors. The temperature coefficient of the offset (TCO) describes this error. This is the difference between the offset value at the lowest temperature to that of the highest temperature. It must be clarified on a case-by-case basis whether the datasheets refer to the calibration or operating temperature range. The TCO is expressed in %FS/°C.

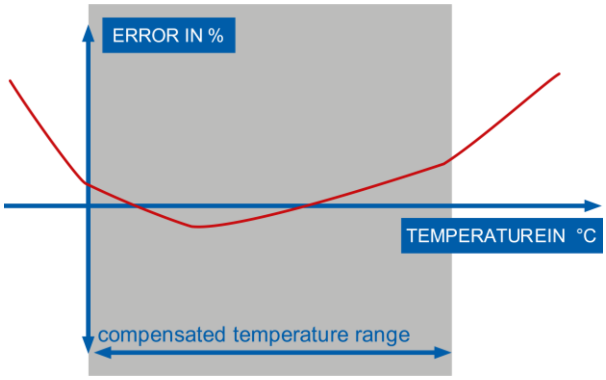

***Figure 5:** temperature errors TCO and TCS.*
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Span temperature error (TCS)

Like the offset, the span is also temperature-dependent. The temperature coefficient of the span (TCS; see Figure 5) describes this error. This is the difference between the span value at the lowest temperature to that of the highest temperature. The TCS is also expressed in %FS/°C.

Non-correctable errors

Thermal hysteresis

Thermal hysteresis (Figure 6) is measured without the application of pressure. It is the maximum deviation of the offset signal between the maximum and minimum temperature in the operating temperature range following a temperature cycle. Temperature hysteresis can depend on the cycle time and temperature interval.

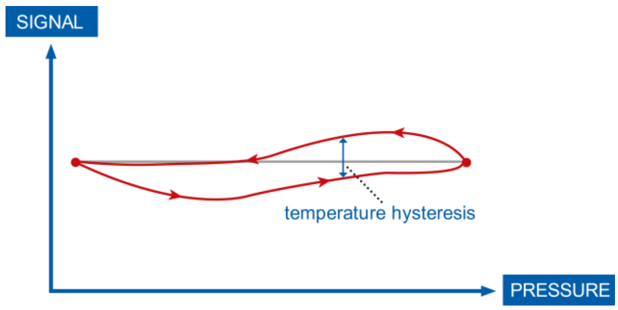

***Figure 6:** temperature hysteresis.*
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Pressure hysteresis

Pressure hysteresis (Figure 7) is often measured at room temperature. It is the maximum deviation of the full-scale signal between the maximum and minimum pressure in the pressure range following a pressure cycle. Pressure hysteresis can depend on the cycle time (speed of the change in pressure).

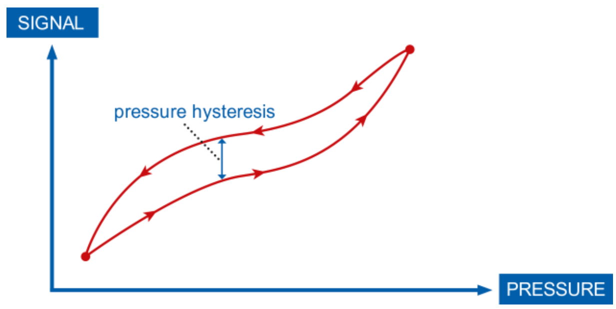

***Figure 7:** pressure hysteresis.*
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Long-term (in)stability

Long-term stability indicates how great the change in the signal is over time, typically one or ten years. It can be measured under operating conditions (e.g. with supply voltage applied and at room temperature) or following a suitable storage period. Various artificial sensor-aging methods are used to determine the long-term drift with accelerated procedures, usually higher temperatures and a high humidity. They should be listed in the datasheet and their relevance to the given long-term drift value identified. Here, it is important to understand how the various silicon pressure sensor designs are assembled and how they function; this is explained in detail in [1].

Supply voltage dependency (ratiometry)

The level of supply voltage also has a sizeable impact on the measurement, particularly with OEM sensors without voltage stabilization. Normally, the analog outputs on OEM sensors behave ratiometrically, i.e. the output voltage is proportional to the input voltage within a certain range (for further information, see [2]). This can be of benefit in battery-powered devices with a fluctuating supply voltage if it acts as a reference for further evaluation. This is irrelevant with stabilized input voltages; digital outputs and analog outputs on voltage-stabilized sensors are independent of the supply voltage.

Non-repeatability

Repeatability provides information on the variation in the transfer characteristic when pressure is measured under identical measurement conditions (Figure 8).
Repeatability, sometimes also referred to as precision, can be defined across several measurements of a single sensor or – more usefully – over several sensors from different production batches. We then also speak of sensor interchangeability.

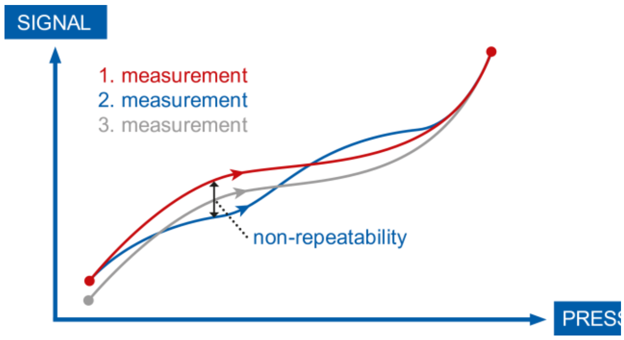

***Figure 8:** non-repeatability.*

The difference of this to accuracy is illustrated in Figure 9. You can imagine this like a dartboard: good repeatability is when the darts all hit a similar target – although this doesn't necessarily also have to be within a given error range.
Even with a high degree of accuracy, the measurements can be quite spread out. High repeatability is therefore often the true objective here, especially if the absolute measured value is not actually that relevant. Systematic error can cause measurements to lie beyond the required range, however, even with a high degree of repeatability, e.g. when operating a sensor outside the temperature specifications. It is therefore essential that (non-)repeatability is included as a statistical uncertainty in the analysis of errors.

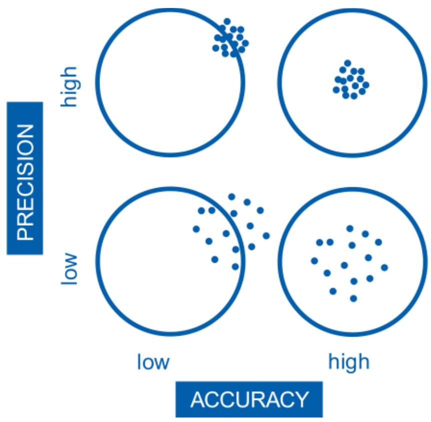

***Figure 9:** accuracy vs. repeatability.*

Condensed down to a single value: the total error

By definition, inaccuracy is the sum of the relevant errors. Strictly speaking, the errors attributable to various physical causes must be determined using the propagation of uncertainty method (square root of the sum of the squares of the individual errors). The resulting sum is the total error that is given either for ambient temperature or as the total error band (TEB) for the operative temperature range. This value is usually expressed in %FSO (full-scale output = span).
Much of the inaccuracy value results from the statistically distributed individual errors of the sensors. Lots of datasheets account for this by giving an error distribution for the individual errors with typical and maximum values. As individual measurements are taken during the calibration of each calibrated sensor, a smaller error can also be achieved by selection (at a higher cost).

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Summary

When choosing a sensor, it's important to understand the errors that occur and to consider which of these are relevant to your individual application and which can be disregarded. By making appropriate compromises, the best possible sensor can be selected for the project on hand, as priorities can be specifically assigned to certain subareas, such as repeatability within a small temperature band. The absolute error and temperature effects can be ignored in this application, for example. This is why focusing on the TEB often doesn't go far enough in many applications, even if this is a good starting point for individual observations.
Selecting a suitable sensor calls for comparison of the specific requirements of the application with the identified types of sensor error. The decision to opt for a particular sensor is often founded on an indeterminate concept and specifications in datasheets from various manufacturers that cannot be directly compared with one another. Individual consultation, as provided by AMSYS can thus spare users weeks of comparative trial and error.

Further reading

Website of AMSYS GmbH & Co. KG – the pressure sensor experts:

https://www.amsys-sensor.com/

[1] The various versions of pressure sensors – 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

[2] Ratiometry in pressure sensors
https://www.amsys-sensor.com/downloads/notes/ams5812-ratiometry-in-pressure-sensors-amsys-521e.pdf

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