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THE HIGH COST OF LOW COST PRESSURE SENSORS

A Honeywell White Paper

Abstract



Viewing the pressure sensors exhibited at any major electronics trade show quickly shows that many companies are willing to sell unmounted, unpackaged (bare) pressure sensor dies. Even companies selling packaged pressure sensors appear willing to sell their sense dies to anyone.

This willingness may be evidence of how little innovation some pressure sensor die manufacturers have designed into their dies. More likely, these same manufacturers are attempting to serve a portion of the industry that find building their own pressure sensing solution is more financially attractive versus building a finished sensor, preferring to buy a low cost pressure sense die instead of a more costly packaged amplified pressure sensor.

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The High Cost of Low Cost Pressure Sensors

Reasons to Purchase Unpackaged Pressure Sense Dies

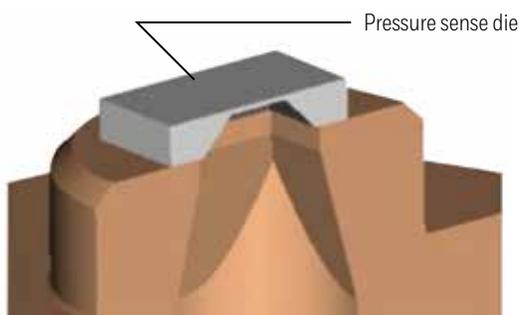
There are certainly some good reasons to buy unpackaged dies. A company producing pressure sensors may need its own source of dies. In other cases, an end product may be so small that there simply isn't room inside for a larger packaged sensor. However, it is also likely that pure cost factors are driving the decision to either start a design with a bare, unmounted die, or for that matter, to find the lowest cost packaged pressure sensor possible and then build up the system from that.

It is no small feat to mount and package a bare sense die. Aside from the capital equipment required to handle and wire bond the die, even seemingly mundane tasks, such as epoxying the die to a substrate, can be the source of many sensor performance issues. Even if a company isn't ready to deal with unmounted dies, it still may be tempted to use the lowest cost pressure sensor available and build up its own pressure measurement. Several extremely low cost board mount pressure sensors are available on the market. Uncompensated, uncalibrated, and unamplified sensors have the lowest cost. There are also more expensive sensors that are still unamplified but provide some calibration and temperature compensation. These sensors may reduce some of the costs presented here, but are still less than ideal solutions.

The Difference Between a Pressure Sensor and a Pressure Measurement

Whether starting with a compensated, unamplified sensor or a compensated, unamplified sensor, there is still a long way to go from the sensor to the pressure measurement ultimately required in the final product. Failure to take into account the difference between a pressure sensor and a pressure measurement can lead to significant problems, such as delays in launching a product, higher costs, and potential future production problems. It is important, therefore, to understand the true cost of a low cost pressure sensor.

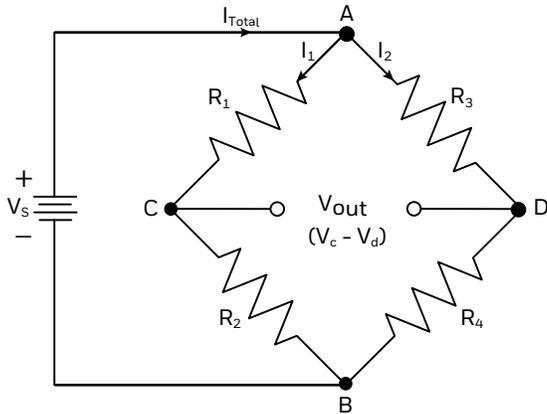
Figure 1. Cutaway View of a Pressure Sense Die



Defining a Pressure Sense Die

A pressure sense die is a classic MEMS (microelectromechanical system) that uses both the electrical and mechanical properties of silicon to convert a pressure difference to an electrical signal. In Figure 1, the grey component represents a cutaway view of a pressure sense die. An area of the silicon is chemically etched away until only a thin diaphragm is left. The die is ultimately mounted so that a differential pressure can be presented across it. This causes stresses in the diaphragm as it attempts to flex away from the higher pressure.

Figure 2. Wheatstone Bridge Circuit



Four piezoresistive elements are embedded into the surface of the diaphragm in a traditional Wheatstone bridge circuit. As a result, when a bias voltage is applied to the bridge, a differential pressure across the sense die results in a small difference voltage between the $-V_{out}$ and $+V_{out}$ outputs of the die (see Figure 2).

Designing a Useful Pressure Measurement Device

While this assembly is fundamentally a sensor, several things need to be done before it becomes a useful measurement device. It is also worth noting that while it is relatively simple to produce a workable pressure die, there are also great opportunities in which to add value in the design and production of the die. Honeywell has applied unique intellectual property (IP) to the design of its dies that has led to enhanced linearity, hysteresis and repeatability, as well as creating innovative design techniques to provide enhanced overpressure performance.

Three design attributes required to obtain a usable measurement from the pressure sense die are: signal conditioning, calibration, and temperature compensation.

• Signal conditioning

The output difference signal of a few 10 s of millivolts is superimposed on a much higher common mode voltage. Notionally, if no pressure is applied across the sensor, the two outputs will be at a common voltage (e.g. 2.5 V). If a 1 psi pressure difference is applied, the outputs may move to 2.495 V and 2.505 V. This is a signal of 10 mV on a common mode voltage of 2.5 V. The user must cancel out the common mode voltage and amplify the signal voltage.

• Calibration

If an unamplified sensor had very repeatable performance across a batch and between batches, the problem would be simpler to solve. However, normal production variation will cause the values of the piezoresistors to vary one from the other, leading to offset errors. This means that the signal voltage will not be zero when the pressure difference is zero. It is not uncommon for this offset or null error to be as large as the full scale span of the sense die. Also, variations in the diaphragm thickness or characteristics of the piezoresistive material will cause variations in the sensitivity of the dies across and between wafers.

Figure 3 depicts a common instrumentation amplifier circuit. This circuit is often used to provide the signal conditioning as well as the calibration of the sense die. The beauty of this circuit is that it cancels out the common mode voltage across the sense die and allows amplification of the signal (difference) voltage. Ignoring the variable resistors for the moment, the output of this amplifier is shown in Equation 1:

$$V_{out} = 1 + \left(\frac{2R_2}{R_1} \times \frac{R_4}{R_1} \right) \times (+V_{out} - -V_{out})$$

Figure 3. Common Instrumentation Amplifier Circuit

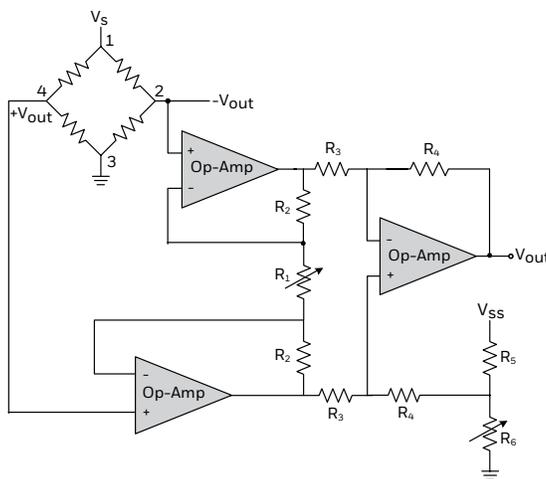


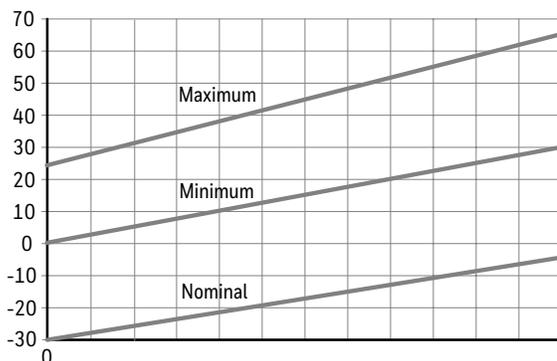
TABLE 1. SPECIFICATIONS OF A GENERIC “LOW COST” UNCOMPENSATED, UNCALIBRATED, UNAMPLIFIED PRESSURE SENSOR

Characteristic	Parameter
FULL SCALE PRESSURE	0 psi to 1 psi
FULL SCALE SCALE OUTPUT (5 V SUPPLY, AT 25°C)	-30 mV ±10 mV
OFFSET VOLTAGE (5 V SUPPLY, AT 25°C)	-25 mV

The instrumentation amplifier is well understood and is commonly available as a single IC integrated circuit (IC) requiring only a gain resistor. However, implementation requires additional design work, as well as additional component costs, and additional required printed circuit board (PCB) space.

The problem becomes greater when you consider the normal variability of low cost unamplified sensors is considered. Table 1 shows the specifications of a generic ‘low cost’ uncompensated, uncalibrated, unamplified pressure sensor. The common mode voltage is not specified. This could cause issues if the designer develops circuitry to the typical common mode voltage present in the current batch of sensors, only to find that this changes over time.

Figure 4. Sensor Transfer Function



Using this data, we see that the transfer function of the sensor can vary widely (see Figure 4). In one sensor, full scale could be -5 mV, while in another, the zero point could be 25 mV. In both cases, the sensors would be within their specs. Obviously, some amount of calibration is needed so that the system can make sense of the measurement.

This is straightforward enough with an instrumentation amplifier circuit, but would involve using variable elements as shown in Formula 1 with R1 changing the full scale span and R6 the offset. However, the implications of using variable resistors are significant. Not only is there the cost of resistors, but human intervention is required to calibrate each sensor, adding production time and expense. There is also the issue of the additional production equipment required to provide a calibrated pressure to accurately adjust span.

It is possible to automate the calibration process such that the system records the actual span and offset and uses this data later to correct measurements. Even this would require additional design and programming effort. In either case, there is always the issue of interchangeability should a sensor need to be replaced.

TABLE 2. SPECIFICATIONS OF A GENERIC “LOW COST” UNCOMPENSATED PRESSURE SENSOR

Characteristic	Parameter
FULL SCALE PRESSURE	0 mbar to 100 mbar
FULL SCALE SCALE OUTPUT (3 V SUPPLY, AT 25°C)	35 mV ±10 mV
OFFSET VOLTAGE (3 V SUPPLY, AT 25°C)	0 mV to 35 mV
SPAN VARIATION WITH TEMPERATURE	-0.22 %V _{FSS} /°C to -0.16 %V _{FSS} /°C
OFFSET VARIATION WITH TEMPERATURE	±15 µV/°C

• **Temperature compensation**

MEMS-based pressure sensors have a large intrinsic temperature dependence. Temperature changes cause mechanical expansion and contraction of the die as well as affect the sensitivity of the piezoresistive elements. Therefore, even if the sensor is calibrated at room temperature, the null and full scan span will change with temperature. For example, Table 2 shows the characteristics of another generic, uncompensated sensor.

Figure 5. Circuit Driven Using a Current Source Rather than a Voltage Source

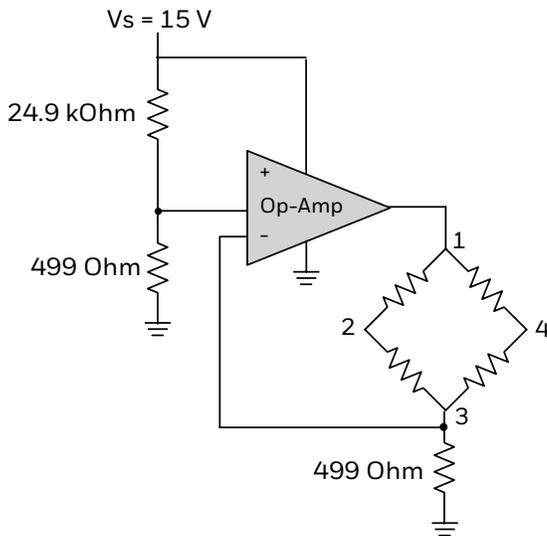
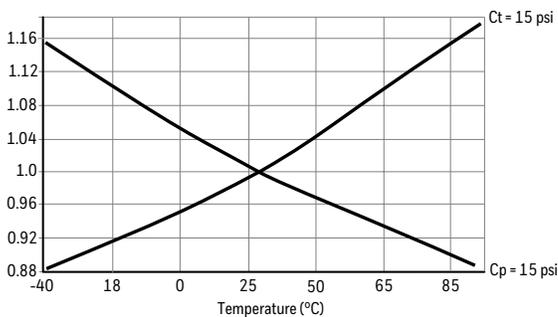


Figure 6. Piezoresistor Nominal Resistance and Sensitivity Change with Temperature



Over a $\pm 25^\circ\text{C}$ temperature variation, the temperature sensitivity of this sensor can add over 6% error to the measurement. While a very high error may be acceptable in some applications, it is assumed here that a reasonable accuracy is required. It is also possible that the end product will be designed to never expose the sensor to temperature variations. For most applications, however, there is the need to correct for the temperature variation in the sensor.

Correcting for Temperature Variation

Three potential techniques to correct for temperature variation are: driving the sense die with a current source, using a compensation network, and using real time correction.

• Driving the sense die with a current source

By driving the sense die with a current source rather than with a voltage source, it is possible to eliminate some of the temperature effects. This technique, as shown in Figure 5, makes use of the opposite effects temperature has on the nominal resistance values of the piezoresistors and the sensitivity of those piezoresistors to pressure changes.

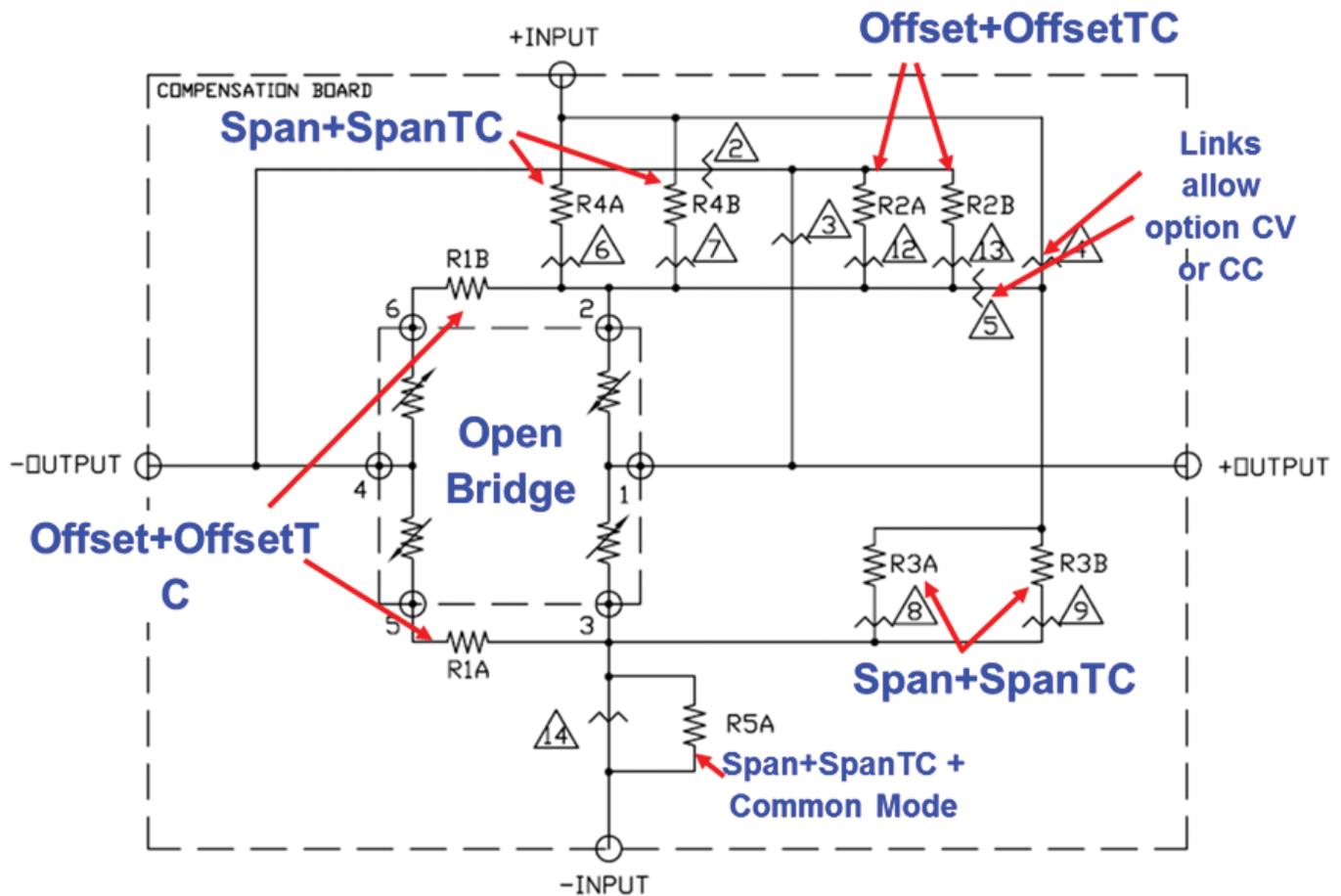
Figure 6 shows that the nominal resistance of the piezoresistors (C_t) increases with temperature while their sensitivity (C_p) decreases. The increasing resistance, when driven by a constant current, has the effect of increasing the full scale span which partially corrects for the decreased sensitivity of piezoresistors to pressure change. This is a relatively simple technique. However, experience has shown that, in practice, it only decreases the temperature effects by about 50 %.

• Using a compensation network

This technique can reduce calibration and temperature variation errors down to just a few percent (see Figure 7).

The combination of variable and temperature dependent resistors in the network can be adjusted to correct for both initial calibration and temperature variation. However, measurements need to be made at multiple temperatures. Also, given the large number of adjustments and the interdependence of these adjustments, this technique is only suitable for automated systems such as those using laser trimming of thick film resistors.

Figure 7. Compensation Network



- **Using real time correction**

This technique, used in most amplified pressure sensors, measures the actual output of the sense die at several pressures and temperatures and stores this data for each die. In amplified pressure sensors, this data is stored on the sensor and is either provided to the user to allow the calculation of the measurement, or the calculation is done in an on-board ASIC and the corrected pressure measurement is provided to the user.

However, there is no reason that this technique could not be duplicated with the data stored in the user's own system memory. For this to work, a temperature reading is also required. This can be done using a relatively low cost temperature sensor. In the case of amplified pressure sensors, the temperature sensing element is usually located on the sense die itself to improve accuracy and minimize the effects of ambient temperature variation.

Sensor Exchange in the Field

In the compensation network and real time correction techniques, each sensor would have to be measured at multiple temperatures and pressures. The cost of doing this includes the cost of a calibrated traceable pressure reference, the cost of and space required for an oven in production, and the additional time involved in production. Pressure sensors may also experience significant but temporary shift in performance following the soldering process. In some cases, the sensor must be allowed to sit until these transients subside before calibration can occur. This can add significant challenges to volume production.

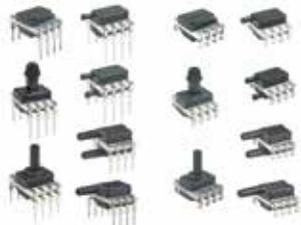
Source of Faulty Measurements

One consideration not yet mentioned is what happens when a pressure measurement system starts to generate faulty measurements. It can become impossible to determine whether a faulty measurement is attributable to the pressure sense die or the signal conditioning circuitry. It is also possible to unknowingly design one's signal conditioning circuitry with a small, but significant dependence upon an unspecified parameter of the sense die, such as output impedance. In time, this parameter may shift, causing the OEM's signal conditioning circuitry to stop working properly while the sensor die still remains within its published specifications.

Pressure Sensor Solutions

Honeywell offers amplified, temperature compensated board-mounted pressure sensors with a variety of features (see Table 3).

TABLE 3. AMPLIFIED, TEMPERATURE COMPENSATED PRESSURE SENSORS

Characteristic	TruStability™ RSC Series	TruStability™ HSC Series, SSC Series	Basic ABP Series
			
PRESSURE RANGE	±1.6 mbar to ±10 bar ±160 Pa to ±1 MPa ±0.5 inH ₂ O to ±150 psi	±1.6 mbar to ±10 bar ±160 Pa to ±1 MPa ±0.5 inH ₂ O to ±150 psi	60 mbar to 10 bar 6 kPa to 1 MPa 1 psi to 150 psi
OUTPUT	SPI-compatible 24-bit digital	ratiometric analog, I ² C- or SPI- compatible 14-bit digital	ratiometric analog, I ² C- or SPI- compatible 12-bit digital
PRESSURE TYPE	absolute, gage, differential	absolute, gage, differential	gage, differential
TOTAL ERROR BAND	as low as ±0.25 %FSS depending on pressure range (after auto zero)	HSC: ±1 %FSS to ±3 %FSS SSC: ±2 %FSS to ±5 %FSS	±1.5 %FSS
ACCURACY	±0.1 %FSS BFSL	±0.25 %FSS BFSL	±0.25 %FSS BFSL
OPERATING TEMPERATURE RANGE	-40°C to 85°C [-40°F to 185°F]	HSC: -20°C to 85°C [-4°F to 185°F] SSC: -40°C to 85°C [-40°F to 185°F]	-40°C to 85°C [-40°F to 185°F]
COMPENSATED TEMPERATURE RANGE	-40°C to 85°C [-40°F to 185°F]	HSC: 0°C to 50°C [32°F to 122°F] SSC: -20°C to 85°C [-4°F to 185°F]	0°C to 50°C [32°F to 122°F]
POWER CONSUMPTION	<10 mW, typ.	<10 mW, typ.	2 uA typ. when utilizing sleep mode option
PACKAGE TYPE	DIP, SMT	DIP, SIP, SMT	DIP, leadless SMT, SMT
PACKAGE SIZE	10 mm x 12,5 mm [0.39 in x 0.49 in]	10 mm x 12,5 mm [0.39 in x 0.49 in]	as small as 8 mm x 7 mm [0.31 in x 0.28 in]
OPTIONS	liquid media	liquid media	internal diagnostic function, liquid media, sleep mode, temperature output

Conclusion

For many years, it was common for OEMs to use an unamplified sensor and build up the pressure measurement themselves. The costs absorbed include:

- Additional design time
- Requirement for extra board space
- Extra BOM (Bill of Material) costs
- Additional production time
- Production delays to allow sensors to return to spec following soldering
- Capital expenses

Given the real costs and potential risks, it is an increasingly easy decision to spend less overall by using an amplified pressure sensor. Pressure sensors such as Honeywell's TruStability™ Board Mount Pressure Sensors and Amplified Basic Board Mount Pressure Sensors are available in a wide range of spans, and can be specially calibrated to a user's specific pressure range. In addition to options for analog or digital output, various packages and supply voltages, these products have some exciting capabilities, such as internal diagnostics, temperature reading and even the ability to tolerate liquid media.

Warranty/Remedy

Honeywell warrants goods of its manufacture as being free of defective materials and faulty workmanship during the applicable warranty period. Honeywell's standard product warranty applies unless agreed to otherwise by Honeywell in writing; please refer to your order acknowledgment or consult your local sales office for specific warranty details. If warranted goods are returned to Honeywell during the period of coverage, Honeywell will repair or replace, at its option, without charge those items that Honeywell, in its sole discretion, finds defective. **The foregoing is buyer's sole remedy and is in lieu of all other warranties, expressed or implied, including those of merchantability and fitness for a particular purpose. In no event shall Honeywell be liable for consequential, special, or indirect damages.**

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