Inexpensive Pressure Sensor Systems

Classic mechanical pressure converters are gradually being replaced by micromechanic pressure sensing elements, which today feature largely in automation and medical technology and in automobile applications. Under pressure from customers for inexpensive and reliable products, market acceptance for these pressure sensing elements has increased, in turn resulting in greater penetration of the market for silicon technology in sensor engineering.

Micromechanic Pressure Sensing Elements Made of Silicon

Micromechanic converter elements (transducers) are manufactured on a silicon base (see Figure 1) using semiconductor technology methods, some even on semiconductor lines. They thus meet high demands with regard to reliability, accuracy and economy, a feature which distinguishes integrated circuits, for example. The pressure-sensitive element of all micromechanic pressure sensing components made of silicon is a thin membrane which in current practice is generally etched anisotropically from the silicon chip. At suitable points, local foreign atoms are implanted in the silicon crystal, producing zones with an altered conductivity which function electrically as resistors. As soon as positive pressure is applied to the membrane, the molecular structure of the crystal is distorted as the thin silicon membrane bends. Strong shifts in potential occur, particularly around the resistors, leading to a measurable change in their electrical value (the piezoelectric effect). If these integrated resistors are configured as a bridge, a pressure-dependent, differential signal is obtained when current or voltage is impressed. This signal can be easily recorded and processed electronically with a suitable amplifier circuit.

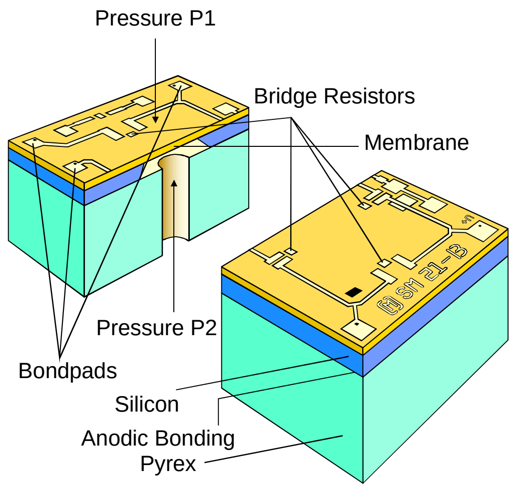

Figure 1: section of a piezoresistive silicon measuring cell (pressure die).

As it is not possible to process silicon measuring cells directly without suitable equipment, some manufacturers offer simple transducers as solderable components. Here, the measuring cell is affixed to a glass base (such as Pyrex, for example) using anodic bonding (an electrochemical process), glued onto thick-film substrates, connected to the substrate with gold wires and given a protective cap. These simple transducers are thus constructed, non-calibrated measuring cells which can be used as cheap SMT components or as dual in-line versions for a large number of applications.

Some manufacturers (including Silicon Microstructures and Motorola, among others) also sell transducers which have been temperature-compensated and calibrated, meaning they can be employed as basic elements in pressure sensor systems without the need for further compensation. They differ from those mentioned above only in that they have an additional network of resistors, with the aid of which the span, offset and the temperature coefficient of these quantities can be calibrated and compensated for. How these various transducers can be used for industrial applications, what must be taken in consideration in doing so and what the advantages and disadvantages of this are is the subject of this article.

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Selection Criteria for Pressure Sensor Systems

As we cannot make any general recommendations for the use of pressure sensors, we will mention a few boundary conditions here which apply to the following observations. These include:

- Cost pressure (average batch range ca. 1,000 to 25,000 devices)
- Miniaturisation (mounting on printed circuit boards)
- Accuracy (2.5% or 1.0% FS)
- Temperature range for accuracy (0 to 70°C)
- Industrial applications

If we compare the simple sensor constructions under the conditions given above, the discerning factors which remain are those of cost and demands for accuracy.

For an accuracy of better than 2.5%, the construction consisting of a non-compensated transducer and a matching signal conditioning IC seems to be the simplest and cheapest. However, this solution requires subsequent calibration and compensation, where the level of accuracy which can be achieved depends on how elaborate the compensation process is. For inexpensive sensors with an accuracy of over 2.5%, a combination of compensated transducer and matching signal conditioning IC is recommended, a solution which must be calibrated, yet not compensated for. Before we go into detail, a description of the circuitry environment shall be given.

The applications illustrated here were both realised using the AM442 integrated transducer IC from Analog Microelectronics, which has been conceived for piezoresistive bridge signals and which supplies an industrial current loop signal of 4–20mA. The only external discrete elements required to configure the circuit are a capacitor, various resistors for calibration and compensation purposes and a transistor. For these reasons it seems prudent to provide information on the integrated circuit itself.

Integrated Amplifier Circuit AM442

Current transmitter AM442 (Figure 2) is one of a series of transmitter ICs which cover all standard industrial requirements. AM442 can be broken down into four main function blocks:

a) A high-precision *instrumentation amplifier* (IA), enabling amplification to be set externally, serves as an input stage for differential voltage signals.

b) A *voltage/current conversion block* constitutes the current output of the IC. Here, an external transistor is activated in such a way that the output current can be adjusted to any value between 0 and 20mA.

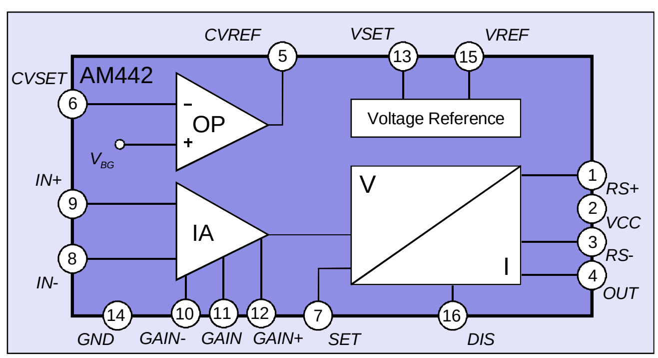

Figure 2: current transmitter IC AM442.

c) So that no additional voltage source is needed to power an external sensor, a high-performance *bandgap reference* is integrated on AM442. The reference voltage can be set to 5 or 10 volts via a simple pin connection. Any value between 4.5 and 10 volts is possible if an additional external voltage divider is connected.

d) An *operational amplifier*, which can be used as a current or a voltage source, is also integrated on the device.

The supply voltage for the IC ranges from 6 to 35V. The IC also features built-in protection against reverse polarity and an output current limit. AM442 can be used for both 2- and 3-wire applications.

Let us now come back to our comparison of transducer applications. The individual applications are:

Pressure Transducer Series AM5300

AM5300 pressure transducers (Figure 3) are a series of non-compensated and non-calibrated, SMD-mountable transducers for a pressure range of 10mbar to 15 bar. These pressure transducers consist of a silicon measuring cell and a thick-film substrate. The substrates are designed in such a way that they can be placed and soldered as SMT devices. The large pads on the underside of the substrate (SnPd) allow a sufficient placement tolerance and ensure good solderability. As AM5400, the transducers are also available as dual in-line versions. These pressure sensors come with a choice of cover and/or media coupling; these are either a plastic cap with an opening on the top side (for mounting with an O-ring) or a cap with an 1/8 inch tube. In conjunction with the signal conditioning IC, this simple assembly enables a miniaturised pressure sensor to be realised. Before the device is put into operation, however, the full-scale signal and the offset must be calibrated and the relevant temperature dependencies of the transducer compensated for, together with the errors of the evaluation circuitry. In doing so, the tolerances of the transducer and IC electrical specifications have to be taken into consideration for the calculation of dimensions, before the system as such is compensated for. This means that the compensation network necessary here must have suitable dimensions which enable the required resistor values to be set during the actual compensation procedure. This, in turn, is necessary as the values for the offset and span of the transducers vary greatly.

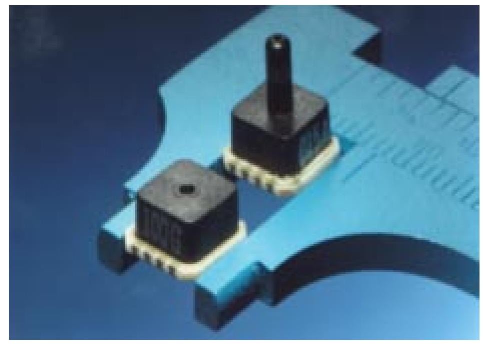

Figure 3: SMD pressure transducer in the AM5300 series

Before this can take place, the operating point of the IC must be set, as otherwise the pressure sensor system cannot be measured.

Determining the Operating Point

Figure 4 shows an application with AM442 and a pressure transducer. The bridge symbol represents a transducer with a compensation network (see Figure 5). The values and equations given in the following are based on the depicted circuitry.

The setting of the actual output current range (current swing) depends on the choice of external amplifier resistors R_1 and R_2. In general, the following applies for output current I_{OUT}:

$$I_{OUT} = V_{IN} \frac{G}{R_0} + I_{SET}$$

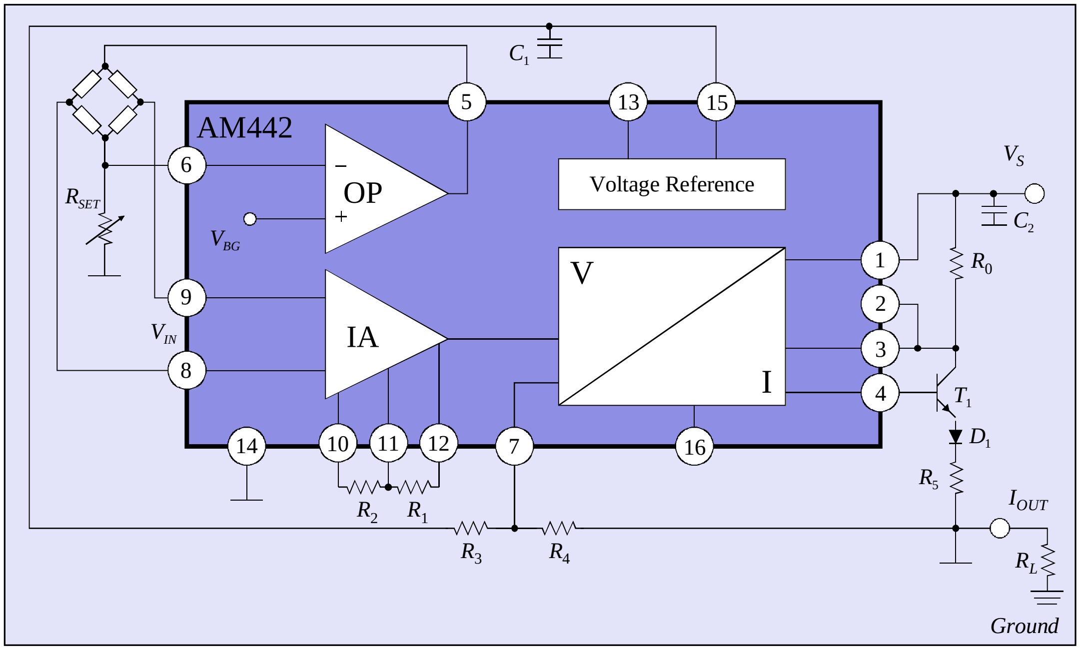

Figure 4: application diagram of a 2-wire application (4–20mA) of AM442 with a measuring bridge.

Gain factor $G = 1 + R_1 / R_2$ of the instrumentation amplifier is determined accordingly by the values for input voltage V_{IN} and the maximum output current (I_{OUTmax}) to be realised.

The offset current at the output is pre–set independent of this by a second voltage divider, R_3 and R_4. Fine adjustment of the offset, and incidentally also that of the output current range, is carried out later when the system as a whole is compensated for. For the offset of the output current to be calibrated initially the input must be short circuited ($V_{IN} = 0$). Here it is particularly important to ensure that the input pins of the instrumentation amplifier are at the designated voltage potentials (input common mode range). With the short circuit at the input, an output current $I_{OUT} = I_{SET}$ is produced with

$$I_{SET}(V_{IN} = 0) = \frac{V_{REF}}{2 R_0} \cdot \frac{R_4}{R_3 + R_4} \quad \Rightarrow \quad \frac{R_3}{R_4} = \frac{V_{REF}}{2 R_0 \, I_{SET}} - 1$$

The transducer should be supplied with 1.5mA by IC AM442, where the value of the current can be set via R_{SET}. With this, the additional OP is used as a current source. The following calculation is given for sensor bridge supply current I_S:

$$I_S = \frac{V_{BG}}{R_{SET}}$$

If we take the specifications of a 1bar transducer in the AM5310 series as the basis for calibrating the span, the following tolerances are given with 1.5mA power supply:

<u>Offset:</u>	0mV ± 50mV
<u>Span:</u>	145mV ± 30mV
<u>Bridge resistance:</u>	2.7...4.0 kOhm

For the offset current at the output,

$$I_{SET}\left(V_{IN}=0\right)=\frac{V_{REF}}{2\,R_0}\cdot\frac{R_4}{R_3+R_4}$$

For the resistance ratio of the offset resistors,

$$\frac{R_3}{R_4}=\frac{V_{REF}}{2\,R_0\,I_{SET}}-1=\frac{5\text{V}}{2\cdot 25\Omega\cdot 4\text{mA}}-1=24$$

For the output current,

$$I_{OUT}=V_{IN}\frac{G}{R_0}+I_{SET}$$

For the resistance ratio of the amplifier resistors,

$$\frac{R_1}{R_2}=G-1=\left(I_{OUT}-I_{SET}\right)\frac{R_0}{V_{IN\,\max}}-1=16\text{mA}\cdot\frac{25\Omega}{145\text{mV}}-1\approx 1{,}75$$

As opposed to the offset, which is corrected via resistors in the compensation network, the span must be compensated for using the amplifier resistors. This means that for a variation of the sensor output signal of 145mV ± 30mV, the resistors must be trimmable within a range of

$$\frac{R_1}{R_2}\left(V_{IN}=115\text{mV}\right)\approx 2{,}48 \qquad \text{and} \qquad \frac{R_1}{R_2}\left(V_{IN}=175\text{mV}\right)\approx 1{,}29$$

The following is given for the resistor via which the supply current is set:

$$I_S=\frac{V_{BG}}{R_{SET}} \quad\Rightarrow\quad R_{SET}=\frac{V_{BG}}{I_S}=\frac{1{,}27\text{V}}{1{,}5\text{mA}}\approx 846\Omega$$

Once the dimensions of the resistance values required for the principle function of the IC have been calculated, the temperature errors of the sensor and IC and the remaining absolute errors must be compensated for with the help of the resistance network on the transducer. The tolerances of the transducer and IC specifications must be derived from the values of the compensation resistors. In other words, the trim area of the resistors must be selected so that for example the entire range of the ±50mV offset can be calibrated. An example compensation network is depicted in Figure 5. As already mentioned, this network replaces the simple bridge symbol for the application in Figure 4.

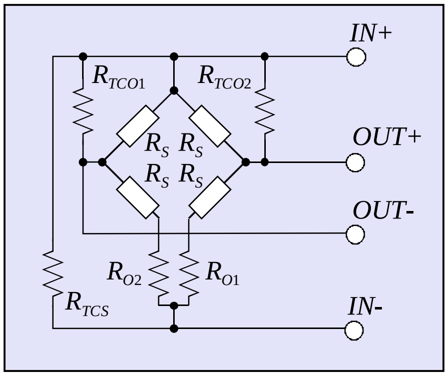

Figure 5: example compensation network with current supply of the measuring cell.

For the compensation procedure required here, the IC and transducer have to be measured separately or together, depending on the compensation algorithm. The compensation resistors must be trimmed using laser compensation or a potentiometer in such a way that the temperature errors of both the measuring cell and the IC are minimised. The temperature errors of the offset are compensated for via R_{TCO1} and R_{TCO2} and the error of the span via R_{TCS}. The error of the absolute offset value is compensated for with the aid of resistors R_{O1} and R_{O2}. As in the compensation process the IC and transducer are compensated for as a system, a reduction in system errors is achieved through calibration and compensation. In a limited temperature range, an accuracy of better than 1% can be achieved through a compensation process such as this.

Another Approach

Should such high levels of accuracy and thus such an elaborate form of compensation not be necessary, there is an alternative to the above solution. This entails combining a transducer which has already been compensated for (e.g. AM5600) with device AM442.

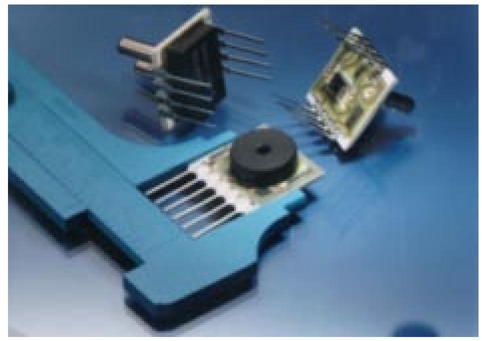

Figure 6: compensated and calibrated pressure transducers in the AM5600 series

Pressure transducers in the AM5600 series (Figure 6) are piezoresistive transducers which have been compensated for and pre-calibrated in a range of 0–60°C. With these sensors, the pressure chip is mounted on a hybrid together with the compensation network (we can presume that the network is as shown in Figure 5). The compensation network consists of various thick-film resistors which are trimmed with a laser to the necessary values during manufacture. However, these transducers are likely to be approximately twice as expensive as the non-compensated varieties.

The compensated transducers are connected to the AM442 IC, the operating point and function of the IC set and the span and offset calibrated. The setup procedures already described must be repeated for this example application, with the exception of the temperature coefficient compensation process, which does not have to be carried out here. The sensor is ready for operation. One consequence of this simple construction is, however, that the residual error of the transducer is added to that of the IC and cannot be corrected further. Thus only the temperature errors of the transducer are minimised with the compensation network; the errors of the IC remain.

If we take the values specified in the transducer and IC data sheets, an accuracy of ±2.5% for the entire system can be achieved within a temperature range of 0 to 60°C, without the need for any further compensation measures.

The Economy of the Various Solutions

There are a number of possible ways of measuring pressure and converting this to a current signal. The methods described here effect a comparison to other ways of recording and evaluating pressure. On the one hand, discrete assembly still plays a major role in this field; on the other hand, we observe that more and more evaluation ICs are being introduced to the market (e.g. by Maxim or ISS) which permit electronic compensation of the transducers. Comparison has shown that a pressure sensor system designed with IC AM442, for example, as suggested in the application given here (Figure 4), not only has all the advantages already described but is also approximately 30–50% less expensive in a batch of ca. 10,000 systems than a system built with discrete components. The IC costs for AM442 (also with a batch of 10,000) are also ca. 40% lower than those for adequate ICs which can be compensated for digitally. Although the time and effort for compensation for the versions introduced here is greater, the conventional solution using laser trimming for large batches is still the cheaper alternative to digital compensation. For smaller batches, for users who require a medium accuracy (1.5–2.5%) and for products which warrant higher component costs, solutions with evaluation circuits which can be digitally compensated for are interesting alternatives, although one must always ensure that the adjustable range of trim is compatible with the component tolerances of the pressure sensing element.

Additional Services from Analog Microelectronics

The solution described here has a further advantage, namely that with its integrated amplifier circuit AM442 it is suitable for even the smallest of structures. Above all, Analog Microelectronics also offers the IC **and** the pressure transducer as a die (in any quantity), producing interesting possibilities as to the miniaturisation of sensor systems.

Whilst on the subject of miniaturisation, Analog Microelectronics sells not only integrated circuits but also a measuring amplifier hybrid as a dual in-line package, where all external components for signal processing and the compensation resistors are mounted on the hybrid. With the hybrid, all features of AM442 can be used to the full, such as, for example, current supply to the measuring cell, adjustable voltage supply, amplification setup etc. The mode of operation (2- or 3-wire) and the output current range (0 or 4 to 20mA) can be set by cutting wires on the hybrid. The various operating parameters can be preset for users who do not have access to laser trimming. In this instance, it is also possible to compensate for the sensor system using external resistive dividers.

Analog Microelectronics also has integrated complete solutions for other standard signals, such as industrial or ratiometric voltage outputs. Details are available direct from the company's homepage at:

http://www.analogmicro.de